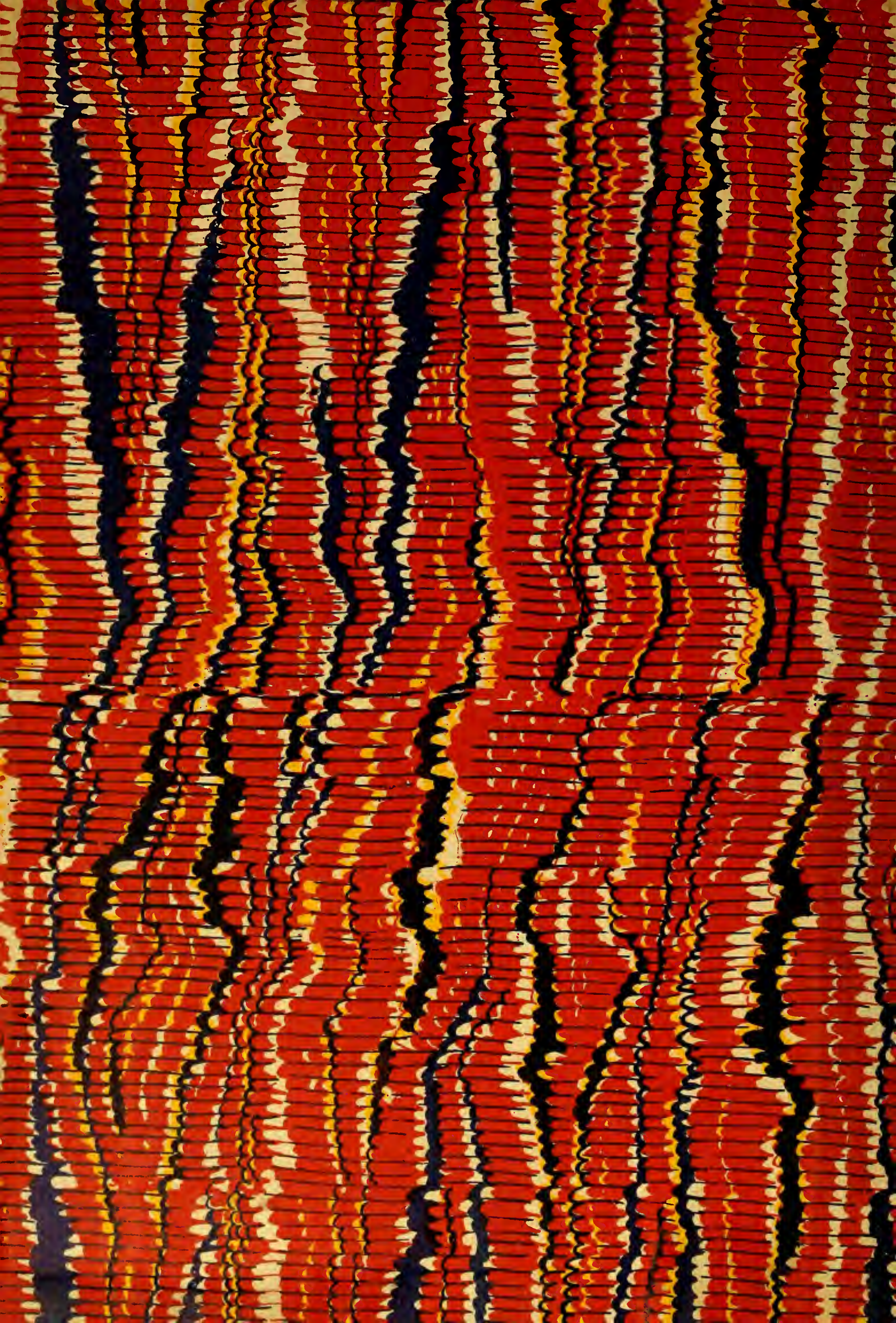

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OBSERVATIONS ON THE DAUBRÉE EXPERIMENT AND CAPILLARITY IN RELATION TO CERTAIN GEOLOGICAL SPECULATIONS

JOHN JOHNSTON AND L. H. ADAMS
Geophysical Laboratory, Carnegie Institution of Washington

Those who believe that meteoric waters are an important factor in the production of the phenomena of vulcanism have always met with difficulty in devising a means by which surface waters could reach deep-seated and highly heated regions. This difficulty they have, as they believed, obviated by instancing an experiment made by Daubrée on the passage of water through a porous sandstone against a certain excess counter pressure. That this experiment has no bearing on the question at issue has already been pointed out more than once; but this has apparently not attracted the attention of those who wish to believe in its applicability as a proof of the possibility of introducing accessions of meteoric water into the magma. Accordingly we propose to discuss this experiment and the laws governing capillary processes (of which it is an example); and we endeavor to point out the limitations which must be borne in mind when capillary effects are adduced as important factors in the production of geological phenomena such as vulcanism.

Daubrée's experiment.—In this experiment, which was performed in 1861, Daubrée found that water would pass through a disk of sandstone, 2 cm. in thickness, in spite of a certain excess counter pressure of steam; his apparatus is represented[1] schematically in Fig. 1. A disk of Strasburg sandstone was clamped between two chambers, the upper one (*L*), open at the top, containing water, the lower one (*V*), gas-tight and connected to a stop-cock (*C*) and manometer (*M*). The whole rested on carbon blocks, and was placed inside a loosely-closed metal box heated from beneath. Daubrée caused the temperature in the inside of the box (as measured by the thermometer *T*) to remain for some time at 160°, the cock *C* being open meanwhile. Upon closing *C* he observed that the mercury column rose gradually to a height of 68 cm. (0.9 atm.). On relieving the pressure by opening *C*, and subsequently closing it again, he observed the same effect again.

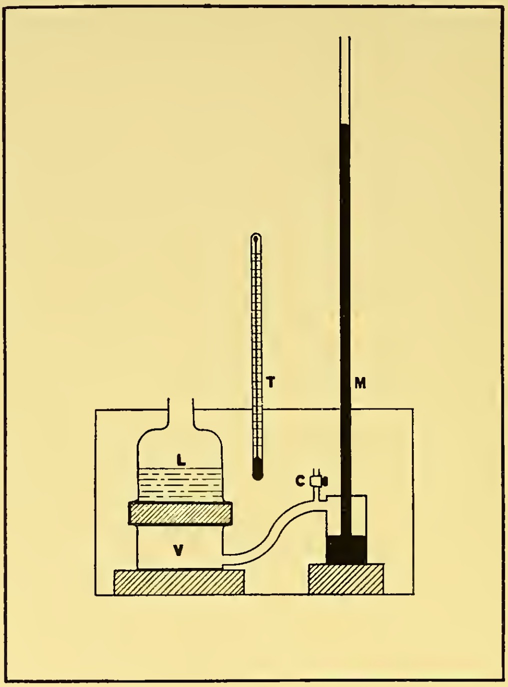

Fig. 1.—Diagram to illustrate the form of apparatus used by Daubrée

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[1] See Daubrée, *Géologie expérimentale*, Paris, 1879, p. 238.

The water was therefore passing through the sandstone against pressure.[1] Daubrée attributed this phenomenon, and rightly, to capillary action, but apparently he was without a clear conception of the physical principles involved; consequently his interpretation of the experiment is in part erroneous and some of his conclusions indefensible. Thus he writes:[2]

> Supposons une cavité séparée des eaux de la surface, marines ou continentales, par des roches qui ne soient pas tout à fait imperméables; admettons, en outre, que cette cavité soit à une profondeur assez grande pour que sa température soit très-élevée: les conditions principales de notre expérience ne se trouveraient-elles pas reproduites? De la vapeur s'accumulerait donc dans cette cavité, et sa tension pourrait devenir bien supérieure à la pression hydrostatique d'une colonne liquide qui remonterait jusqu'à la surface des mers ou des eaux d'alimentation. Et, si l'on est parvenu à mettre en quelque sorte en balance, par l'interposition d'une épaisseur de roche de 2 centimètres seulement, les pressions de deux colonnes, l'une de 2 centimètres d'eau à peine, l'autre de 60 centimètres de mercure, c'est-a-dire de plus de 500 fois supérieure a la première, on ne trouvera plus guère de difficulté à admettre que l'eau descendante devienne la cause du refoulement de laves trois fois plus denses qu'elle, et de leur ascension jusqu'à un niveau bien supérieur au sien. D'après les résultats de l'expérience, l'eau pourrait donc être forcée par la capillarité, agissant concurrement avec la pesanteur, à pénétrer, malgré des contre-pressions intérieures tres fortes, des régions superficielles et froides du globe jusqu' aux régions profondes et chaudes, où, à raison de la température et de la pression qu'elle aurait acquises, elle deviendrait capable de produire de grands effets mécaniques et chimiques.

The "atmometer."—The effect observed is, as Daubrée himself recognized, due to capillarity; similar results may be obtained much more simply and directly by means of the so-called "atmometer."[3] This consists of a somewhat narrow glass tube,[4] open

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[1] And against a temperature gradient too, since the upper surface of the sandstone was at 100°, the lower surface at some higher temperature; but the effect of this is, as we shall show, altogether subsidiary, except for extreme temperature differences.

[2] Daubrée, *op. cit.*, pp. 242–43.

[3] Tait, *Properties of Matter*, 4th ed., London, 1899, p. 264.

[4] If a capillary tube is used, a side tube, provided with a good stop-cock, sealed into the wider part of the vertical tube is required in order to enable one to fill the apparatus with water. This form possesses the advantage that under favorable circumstances the rise may amount to several centimeters in the course of a few minutes.

at one end and at the other end made fast[1] to a disk, ball, or other fragment of porous material; the tube is filled with water and inverted in a vessel of mercury (Fig. 2). The capillary effects in the fine pores of the material are such that not only is the water in the tube kept supported but, as evaporation from the surface proceeds, mercury rises to take the place of the water to a height

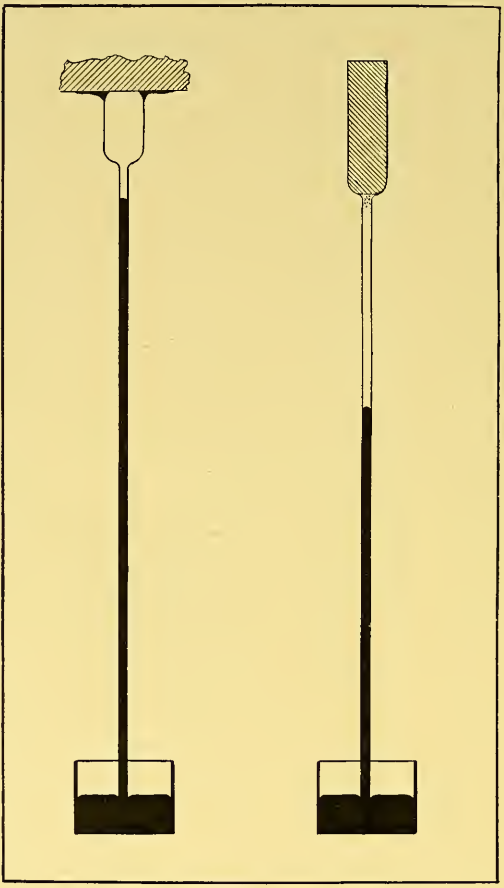

FIG. 2.—Forms of atmometer

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[1] By means of sealing-wax, beeswax-rosin, or in any other appropriate way. The joint must of course be absolutely gas-tight.

which may equal, or even exceed, the barometric height.[1] The mercury rises gradually—provided that the pores are not too fine—maintains the equilibrium position for some time, and then drops back rapidly; the rate of rise, which depends upon a number of factors, does not concern us here. The position of equilibrium is the important thing; it depends only upon the size of the widest pores at the free surface and the surface tension between water and the porous material; results for samples of various materials, as observed by us, are brought together in Table I. But before considering these results we shall give a brief outline of the theory of capillarity in so far as it concerns the question at issue; for the pores are in effect merely fine capillary tubes.

OUTLINE OF THE THEORY OF CAPILLARITY[2]

The general principle to be borne in mind is that the rise of liquid in any capillary tube is primarily a measure of the pressure discontinuity at the curved free surface of the liquid within the tube.

It can easily be shown that the pressure difference (Δp) between the two sides of a curved surface separating two fluids is expressed by the formula:

$$\Delta p = \sigma\left(\frac{1}{\rho}+\frac{1}{\rho'}\right) \tag{1}$$

where σ is the surface tension and ρ and ρ' the radii of curvature in two planes at right angles to one another. If the surface is spherical, $\rho=\rho'$ and the expression takes the simple form

$$\Delta p = \frac{2\sigma}{\rho}\,. \tag{2}$$

---

[1] Thus G. A. Hulett (*Zeitschr. d. physik. Chem.*, XLII (1903), 359, who made experiments of this type using a porous porcelain plate in which copper ferrocyanide had been deposited, observed in one instance a height of 110 cm. of mercury; in this case therefore there was a negative pressure, amounting to about half an atmosphere, acting upon the water close to the under side of the porcelain disk. Similar experiments had previously been made by E. Askenasy, *Verhand. naturh. med. Verein Heidelberg*, March, 1895. This process, it may be remarked, is the commonly accepted mode of accounting for the rise of sap in trees.

[2] Capillarity is treated in any textbook of physics, though not always well. The discussion of it by Tait in his *Properties of Matter* is exceptionally clear.

A slight modification of this formula is directly applicable to the capillary rise of liquids in fine tubes. Consider a tube, open at both ends, partly immersed in a vessel of liquid, which will rise in the tube to a certain height h (Fig. 3). When the rise is several times the diameter of the tube, the curvature of the free surface in the tube is sensibly uniform; in other words, the surface is a segment of a sphere whose radius is ρ. Now, according to equation 2, the pressure on the under side of the curved surface

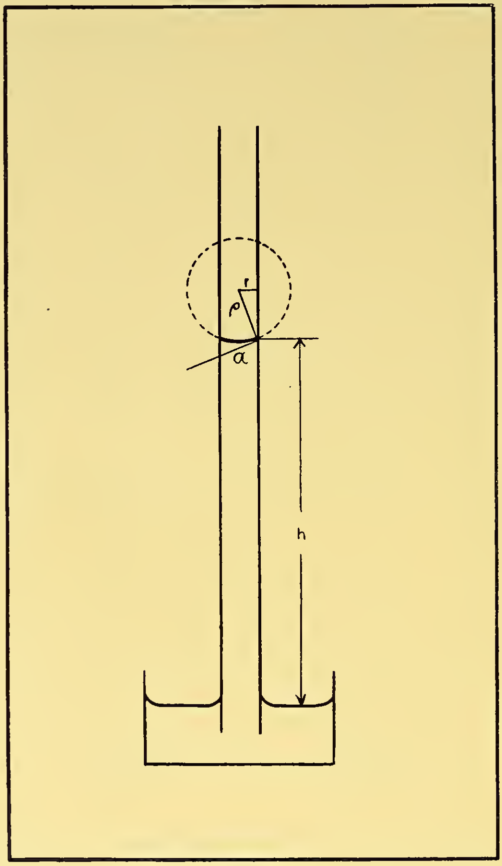

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FIG. 3.—Diagram

is less than that on the upper side by an amount equal to $\frac{2\sigma}{\rho}$; at the same time, however, this pressure difference is equal to the hydrostatic head of a column of the liquid of height h. That is,

$$\frac{2\sigma}{\rho}=hgd$$

where g is the intensity of gravitation and d the density of the liquid. Moreover, if α is the angle of contact between liquid and tube, $\rho=r\cos\alpha$, where r is the radius of the tube; hence,

$$h=\frac{2\sigma\cos\alpha}{rgd} \tag{3}$$

which is the familiar formula for the rise of liquids in capillary tubes.

In the case of water in contact with many substances, $\alpha=0°$ and the equation reduces to the form

$$h=\frac{k\sigma}{r}. \tag{4}$$

For water at a temperature of 18°, provided that h and r are expressed in centimeters,[1] k has the value 0.00204 and σ, the surface tension in dynes per cm., is 74. The development of this formula directly from the basis that there is a definite pressure discontinuity at a surface of separation seems worthy of emphasis since it affords us a clearer insight into the more complicated problems of capillarity.[2] Starting from this basis, a number of conclusions are immediately obvious; we state them here because they have not been

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[1] If h and r are expressed in millimeters, the constant k must be increased, not tenfold, but one hundred fold.

[2] Incidentally it may be remarked that by the same reasoning the pressure within a small drop of water is greater than the external pressure; the water is thus under greater pressure than the vapor derived from it. Now this type of pressure—"unequal" pressure—raises the vapor pressure of the liquid; consequently the vapor pressure of a drop is greater the smaller the radius of curvature of its surface—a well-known conclusion which is exceedingly important in regard to a large number of phenomena. In a perfectly analogous way the vapor pressure in equilibrium with the curved surface of a liquid in a capillary surface is smaller than its vapor pressure as ordinarily given; and this lowering of vapor pressure is greater the smaller the diameter of the tube. Similarly (if it be permissible to speak of the surface tension of solids) one may deduce the fact that the solubility of a substance increases as the size of grain decreases.

apparent to all who have adduced capillary effects as a means of accounting for geological phenomena.

(*A*) Since the pressure discontinuity occurs only at the *surface of separation*, a column of liquid (as in Fig. 2, for example) can be supported *only when there is a free liquid surface within the capillary;* in the case of porous materials, therefore, only when there are surfaces of separation within the pores.[1]

(*B*) When equilibrium has been established, the height attained by the liquid in a tube depends only upon the bore of the tube at the surface of separation (since it is this which determines the curvature) and not in any way whatever on the size or shape of the rest of the tube. This statement however by no means implies that liquid will rise in material containing pores of irregular diameter to the height corresponding to the width of pore observed at the surface of a fragment of the material.

(*C*) Consider an open tube, shorter than the height of column of water which it would support, which is filled with water and placed so that its lower end dips below a mercury surface. The free water surface assumes a curvature sufficient only to support the existing column of water; but if water be removed from the top (by evaporation, or otherwise) the curvature becomes greater, and consequently mercury is pulled up into the tube. This process continues until the surface is hemispherical, when it supports a column of mercury and water equivalent in weight to the (much longer) column of water alone which it would support. This is virtually the atmometer, the only difference being that in the latter there are a very large number of pores; we see moreover that the height at equilibrium is determined by the width of the largest pores in the material at the surface of separation.

(*D*) The pressure discontinuity at the surface of separation—which we may look upon as a pressure exerted by the surface film of water in an endeavor to contract itself—is precisely the same in amount whether it make itself manifest (*a*) by supporting a column of liquid; (*b*) by compressing the air in a tube closed at one end and wholly immersed in water; (*c*) in the form of the pressure

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[1] This of course includes the case where the liquid in the pores extends practically to the surface of the material as a whole.

required to cause air to begin to flow through a capillary tube (or pore) which originally contained water.[1]

(*E*) The capillary rise is affected by variation of those factors which influence the angle of contact and the density and surface tension of the liquid. The changes induced in the angle of contact and in density may for present purposes be neglected entirely. As regards the influence of temperature on the surface tension of water, all the investigations unite in showing that its surface tension decreases regularly with rise of temperature, becoming zero of course at the critical temperature, where there is no surface of separation. The relation is practically linear when the whole range is considered; it may be represented with sufficient accuracy by the formula

$$\sigma_t = 78 - 0.21\,t \text{ or } 0.21\,(370 - t)$$

where σ_t is the surface tension at t (temp. in Centigrade) expressed in dynes per centimeter.

The effect of pressure on surface tension is unknown, but is presumably small. For the changes in the properties of water induced by a pressure of, say, 1,000 atmospheres are usually similar in magnitude and direction to those observed when a relatively small quantity of a salt is dissolved in it; and the surface tension of such dilute (0.5 N or less) solutions differs by only a few per cent from that of pure water.

Experimental.—Before proceeding to the discussion of the geologic implications of the above principles, we shall mention the results of a few experiments on the atmometer principle, carried out with cylinders or fragments of various materials. It may be mentioned that the cylinders of cement and the plaster of paris were cast in glass tubes of appropriate length, which then served

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[1] Experiments of this kind have been made by Barus (*Am. Jour. Sci.*, XLVIII [1894], 452), by Bechhold (*Zeitschr. d. physik. Chem.*, LXIV [1908], 328) and by Bigelow and Bartell (*Jour. Am. Chem. Soc.*, XXXI [1909], 1194). The formula connecting pressure required (P, in atm.) with pore diameter (D, in millimeters) is $P = 0.00304/D$ (for room temperature); it is easily derived from formula 3. Bechhold's calculated pore diameters are tenfold too small, a fact which was noted by Bigelow and Bartell. The pressure P is of course not the same as that required to force water to flow through a capillary tube; for in the latter case we do not necessarily have a free surface within the tube.

directly for the experiment; this insured that evaporation occurred, not at the sides, but at the upper surface only. Likewise, evaporation of water at the lateral surface of the sandstones was prevented by coating them with wax. The observations are brought together in Table I, to which we append a few results obtained by Bigelow and Bartell,[1] who determined the air pressure required to just force water out of the pores of the material.

TABLE I

RESULTS OF ATMOMETER EXPERIMENTS WITH VARIOUS MATERIALS

Material		Relative Rate of Rise	Equivalent Height of Mercury Column Cm.	Virtual Height of Water Column Supported Cm.	Equivalent Pressure Difference Atm.	Calculated Diameter of Pores μ *
Kind	Thickness of Layer Cm.					
"Alundum"	0.5	50	10.5	143	0.14	21
Refractory clay	0.5	75	16.3	222	0.21	14
Pressed magnesia	0.6	35	18.5	250	0.24	12
Porcelain	0.2	100	59.6	810	0.79	3.8
Portland cement	5	20	Did not come to equilibrium; pressure difference at equilibrium presumably greater than 1 atm.			<3
Plaster of Paris	5	20				
Marble	3	5				
Diorite	3	0.1				
Sandstone (Daubrée)	2	......	....	....	0.8	2.7†
Porcelain	—	......	....	....	2.5‡	1.2
Porcelain	—	......	....	....	15.0‡	0.19

* 1 μ = 0.001 mm. The wave-length of the *D* line is 0.5 μ.

† Direct observations of Bigelow and Bartell.

‡ This result is calculated from Daubrée's data as follows: The pressure of 1.8 atm. recorded by him corresponds, as he himself points out, to a temperature of 113° at the lower surface of the sandstone. At this temperature the surface tension of water is 54.3; the pressure exerted by the capillary curved surface is 0.8 atm., corresponding to a column of water 830 cm. in height. Consequently from equation (4), $r = .000134$ cm. or $D = 2.7\ \mu$.

These results are not especially characteristic of the material; they pertain merely to the particular samples which we happened to use, and correspond to the widest pores in those samples. Moreover we have observed that the differences for layers of the same material of different thickness are no greater than one would expect from the probable variation in size of the widest pores.

From what has gone before, it is obvious that the Daubrée experiment is in principle identical with the experiments just

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[1] Bigelow and Bartell, *Jour. Am. Chem. Soc.*, XXXI (1909), 1194. Analogous experiments have also been made by others.

described; that his temperature and temperature difference played no part further than the subsidiary one of decreasing the surface tension of the water and hence the observed pressure difference. Thus it was possible to include in Table 1 the calculated pore diameter of Daubrée's sandstone as deduced from his values of temperature and pressure difference.

GEOLOGICAL BEARINGS

As long ago as 1881, Osmond Fisher pointed out[1] that the Daubrée experiment was effective merely because there was a surface of separation; and as Kemp,[2] in citing his opinion, writes:

> The experiment gives no ground for thinking that water would move through the heated walls confining a reservoir of molten rock and become involved in the latter.

To quote from Osmond Fisher:

> Capillary action can be made to do great things. . . . . But it cannot cause a liquid to flow continuously through a tube, however short; for, if it could, it would give us perpetual motion. . . . . If there were a cavity filled with vapor, it is possible that the density of the vapor, and therefore its pressure, might be increased to a certain extent, by the evaporation of the water from the extremity of the capillary tubes, and that was what occurred in the experiment of M. Daubrée. . . . . Still further, the existence of capillary communication of water from the surface may be doubted. For if there were supposed a capillary tube extending from the bottom of the ocean, the pressure at the lower end of this tube would be that of the water contained in it *plus* that, if any, arising from capillarity, while the pressure of the crust around its mouth would be that due to the weight of the crust. This latter would be the greater of the two: consequently the liquid upon which the crust rested, having a tension [being subject to a pressure] equal to the weight of the crust, would force back the water in the tube, and if it were not too viscous would itself occupy the tube.[3]

Now it is hard to imagine a permanent configuration, except for comparatively small depths, such that this closing-up of the

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[1] Osmond Fisher, *Physics of the Earth's Crust*, London, 1889, 2d ed., p. 143.

[2] J. F. Kemp, "Rôle of Igneous Rocks in the Formation of Veins," *Trans. Am. Min. Eng.*, XXXI (1901), 177.

[3] *Op. cit.*, pp. 144–45. We may note that the argument does not postulate that the material under the "crust" be liquid in the restricted sense of the word; it is valid if the rocks at that depth can flow, a condition which surely obtains except at comparatively shallow depths.

pores by the plastic rock should not occur. Indeed it is hard to conceive of the existence, at any considerable depth, of continuous spaces, unless they be very small;[1] and if they be small and traversed by water, it would appear that they must in a very short time become choked up with material deposited by the water when it evaporates. This point has already been discussed by R. T. Chamberlin,[2] who agrees in thinking that capillary force is quantitatively inadequate; and after adducing various lines of evidence writes: "All of these facts and deductions lead to the general conclusion that our surface-waters have been derived from the interior of the earth, and oppose the idea that to explain the presence of hydrogen, or water, in magmas and rocks, we have merely to appeal to the penetration of surface-waters."

In order to show the quantitative significance of capillarity we present in Table II calculated values of the pressure producible by capillarity at various depths, assuming a temperature gradient of (1) 1° C. per 30 meters, which is about the normal (so far as one can judge from the present very faulty data) (2) 1° C. per meter, which must be nearly the maximum gradient possible, even in the vicinity of volcanoes. In making these computations we have taken into account the variation of surface tension (σ) with temperature, but have neglected the (unknown) effect of pressure; we have also neglected the influence of temperature and pressure (*a*) on the angle of contact α (*b*) on the density of water, which enters as a factor (1) in the value of k proper to each temperature and (2) in the calculation of the hydrostatic pressure. In calculating the pressure due to the overlying rock, a mean rock density of 2.7 was assumed. The values given in Table II are therefore approximate only, but nevertheless are amply accurate for the present purpose. Such figures can be used to support geological speculations with regard to the penetration of water into deep-seated rocks only if both of the following restrictive conditions can be considered to be fulfilled: (1) that pores persist to the depth in question; (2) that the rock mass adjoining the mouth of the pore shall be

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[1] As to the depth to which spaces may persist, see F. D. Adams, *Jour. Geology*, XX (1912), 97–118, and L. V. King, *ibid.*, 119–38.

[2] "The Gases in Rocks" (*Carnegie Inst. Publication No. 106*, 1908), 70–75.

exposed to a pressure lower than the total pressure to which the water just within the pore is subject. The latter condition would appear to be equivalent to the assumption that, excepting the cases where the capillary pressures are relatively large (i.e., at small depths with very fine pores), the rock mass or magma in question is situated in some sort of cavity, the walls of which protect it from the full load due to the weight of the overlying strata.

TABLE II

To Indicate the Magnitude of the Pressures (in Kg. per Sq. Cm.*) Producible by Capillarity under Various Conditions; the Values Given Are Approximate and Subject to the Assumptions Stated Above

Depth Meters	Pressure Due to Hydrostatic Column	Capillary Pressures for Pore Diameters of			Total Pressure Inside Pores of Diam. 0.01 μ	Pressure Outside Pores Due to Overlying Rock
		100 μ	1 μ	0.01 μ		
Temperature Gradient, 1° C. per 30 Meters						
100	10	0.03	3.1	306	316	27
200	20	.03	3.0	302	322	54
500	50	.03	2.9	294	344	135
1,000	100	.03	2.8	278	378	270
2,000	200	.03	2.5	250	450	540
5,000	500	.02	1.6	160	660	1350
10,000	1000	.002	0.2	20	1020	2700
20,000	2000	.000	0.0	0	2000	5400
Temperature Gradient, 1° C. per Meter						
50	5	0.03	2.6	264	269	14
100	10	.02	2.2	220	230	27
200	20	.01	1.3	131	151	54
300	30	.005	0.5	50	80	81
400	40	.000	0.0	0	40	108

* 1 kg. per sq. cm. = 0.97 atm.

From this table it is evident that the pressure producible by capillarity is insignificant in comparison with the hydrostatic pressure, except for very fine pores. For each size of pore there is a definite depth above which the combined hydrostatic and capillary pressure exceeds the rock pressure, and below which the rock pressure (presuming that it is fully effective) predominates. For instance, in pores of 0.01 μ diameter and with the normal temperature gradient, the depth at which the opposing pressures just balance is about 1600 meters; and this depth varies inversely as the pore diameter.[1]

It is evident therefore that capillarity plays a minor rôle unless the pores are very small; and this minuteness of the pores leads us to inquire what amount of water could actually flow through them. This quantity can be calculated by application of the well-known Poiseuille formula, by means of which the rate of flow can be calculated if the radius of the tube, the pressure gradient, and the viscosity of the liquid are known. Hence, assuming the mean viscosity of the water to be 0.005 (its value at a temperature of 30°), the amount of water flowing through a pore of diameter 1 μ (i.e., $\frac{1}{25000}$ inch) would be about 15×10^{-6} c.c. per year; a value which will tend to be too high, since the Poiseuille formula applies to straight pores of uniform circular cross-section, whereas those in the rocks are zig-zag and altogether irregular in shape.

Now if we make the very generous estimate that 10 per cent of the volume occupied by the rock consists of pore-spaces, there will be one million (10^6) pores of 1 μ diameter in each square centimeter. On these assumptions, therefore, the quantity of water flowing would be only 15 c.c. per sq. cm. of surface per year; and the assumptions are such as to tend apparently to make this result too large, rather than too small. But from Table II it is evident that capillarity is quantitatively negligible at any considerable depth in pores of 1 μ diameter; in finer pores, on the other hand, where the pressure producible by capillarity is relatively important, the quantity of water in flow is absolutely insignificant. Thus, if the diameter of the pores is (*a*) 0.1 μ (*b*) 0.01 μ, and on the assumption again that the proportion of total pore space is 10 per cent,[2] the amount of water flowing would be (*a*) 0.15 (*b*) 0.0015 c.c. per sq. cm. of surface per year. In the latter case, in other words, a period of 1,000 years would be required for a quantity of water equivalent to 1.5 cm. (about one-half inch) of rain to flow past a given horizontal plane; moreover, the adoption of any reasonable assumptions other than those used above would not, we feel sure, increase these calculated values more than tenfold. In connection with this, we would remark only that water percolating

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[1] At least, this is true with sufficient approximation for the present purposes.

[2] This corresponds to (*a*) 10^8 (*b*) 10^{10} pores per sq. cm. of surface.

into a magma (presuming for the moment that it is possible) at this rate would be very little likely to produce any very violent effects.

The foregoing statements, of course, by no means imply that water cannot, and does not, penetrate, by capillary action or otherwise, to a considerable depth into the upper and cooler layers of the crust of the earth. Indeed the preceding figures and arguments tend to show that water would be likely to occur in appreciable quantities down to depths of about 500 meters (1,500 feet) and in minute quantities down to perhaps 1,500 meters (5,000 feet)—a conclusion which is, we believe, entirely borne out by experience.

CONCLUSION

The Daubrée experiment on the passage of water through a disk of sandstone against a certain counter pressure of steam is, as has indeed been pointed out by others, an example of the effects producible by capillarity. The same effect may be obtained, and much more simply, by atmometer experiments such as we describe. The magnitude of the possible effect under various conditions may therefore be deduced from the laws of capillarity. Capillary forces are effective only when there is a surface of separation within the pores; moreover they diminish steadily with rise of temperature, and vanish at the critical point of the liquid. Calculation shows that the effects producible at any considerable depth are, in comparison with the pressure due to the hydrostatic column, insignificant except in pores of such fineness that the amount of water which could flow through them is infinitesimal.

It appears therefore as if the probabilities were all against the notion that appreciable amounts of meteoric water can ever penetrate into deep-seated and highly heated rock masses. We feel therefore that the burden of proof should now be imposed on anyone who asserts the contrary, for, even if some unconsidered factors intervene to upset the calculations of the foregoing pages, he would still be confronted with the difficulty of imagining a reasonable configuration of the rock in depth, such as would insure that the total pressure within the pore is not overbalanced by the pressure to which the plastic rock surrounding it exerts.

THE VOLCANOES AND ROCKS OF PANTELLERIA

HENRY S. WASHINGTON
Geophysical Laboratory, Carnegie Institution of Washington

PART III

PETROLOGY

Chemical characters.—All of my analyses of the Pantelleria rocks, with their norms, are given in Tables I and II. Those of Foerstner are omitted for reasons to be given later. They are sharply divided into a large group with high silica, varying from 63.30 to 72.21, and a smaller, the basalts, with about 46 per cent of silica. So far as known, from Foerstner's publications, my own observations, and Butler's collection, there are no rocks of intermediate composition.

Considering the larger group first, rather high alumina is found only in two or three cases, this constituent being in most of the rocks unusually low for rocks of such moderately high silicity—if the coining of a new word on the analogy of acidity and basicity be permissible. On the other hand, the iron oxides are distinctly high, especially in the pantellerites, going hand in hand with low alumina. Magnesia is uniformly low, as is lime, the latter rarely attaining more than 1 per cent. The alkalies are distinctly high, with soda dominant over potash, the latter being remarkably uniform. Titanium is remarkably high for rocks of this silicity and alkalinity. Phosphorus and manganese are both rather above the normal, but zirconia is low for sodic rocks, and only traces of barium are present. Traces of nickel seem to be commonly present, but tests failed to reveal the copper reported by Foerstner.

The basalts are very uniform in composition and show only one especially noteworthy character—the high titanium content.[1] Magnesia is not high for basalts of this general composition (camptonose) and alumina is distinctly low, much lower indeed than the

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[1] H. S. Washington, *Q.J.G.S.*, LXIII (1907), 76.

TABLE I

Analyses of Pantellerian Lavas

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
SiO_2.....	65.27	63.43	63.30	64.54	63.77	72.21	70.14	69.79	67.32	69.91	66.07	69.33	67.85	46.40	46.22	45.72	44.83
Al_2O_3....	13.50	16.31	16.38	11.49	11.18	9.72	8.61	11.91	9.55	8.58	11.74	8.62	12.87	14.34	12.23	12.45	11.73
Fe_2O_3....	4.40	2.04	2.54	5.14	5.02	3.26	6.01	5.35	6.73	1.81	2.05	2.65	1.84	4.09	4.91	1.57	1.35
FeO.....	2.52	3.14	2.36	2.99	2.58	1.07	2.73	1.43	0.81	5.86	5.88	5.52	4.54	8.22	7.71	12.01	11.79
MgO.....	0.55	0.78	0.84	0.89	0.51	0.29	0.20	0.25	0.20	0.28	0.13	0.52	0.30	7.00	6.74	5.29	5.50
CaO.....	0.85	1.70	1.62	0.64	1.37	0.82	0.45	0.25	0.20	0.33	0.46	0.52	0.17	9.85	9.86	9.58	9.63
Na_2O....	5.19	6.71	6.36	5.46	5.55	4.42	5.44	5.66	5.71	6.41	6.89	4.78	6.03	3.59	3.39	3.40	3.34
K_2O.....	4.21	4.31	4.41	4.66	4.35	4.98	4.20	4.59	4.48	4.71	4.80	4.71	4.83	1.00	1.13	1.08	1.40
H_2O+...	1.98	0.18	0.83	1.11	2.72	1.96	0.35	0.17	3.15	0.22	0.43	2.35	0.13	0.14	0.17	0.40	0.81
H_2O-...	0.14	0.26	0.10	2.12	1.28	0.24	0.17	0.04	0.49	0.13	0.03	0.27	0.02	0.08	0.05	0.01	0.10
TiO_2.....	1.09	1.19	0.71	0.90	0.94	0.62	0.86	0.89	0.59	0.75	0.92	0.85	0.83	4.54	5.68	6.43	6.88
ZrO_2.....	......	0.06	......	0.08	......	......	0.14	......	......	......	0.12	......	......	none	......	......	......
P_2O_5.....	0.17	0.20	0.30	0.16	0.14	0.10	0.12	0.13	0.08	0.16	0.18	none	0.08	0.85	1.46	1.54	2.14
SO_3......	......	0.05	......	0.17	......	......	0.06	......	......	......	0.23	......	......	0.12	......	......	......
MnO....	0.27	0.04	......	0.13	0.26	0.05	0.38	0.20	0.24	0.24	0.16	0.27	......	0.25	......	0.16	0.20
NiO.....	......	......	......	......	......	......	......	......	......	......	none	......	......	......	......	0.15	......
BaO.....	......	0.05	......	none	......	......	none	......	......	......	......	......	......	0.09	......	......	......
SrO......	......	......	......	......	......	......	......	......	......	......	......	......	......	0.03	......	0.03	......
	100.14	100.45	99.75	100.48	99.67	99.74	99.86	100.66	99.55	99.39	100.09	100.39	99.49	100.59	99.55	99.82	99.70

A. Trachyte [I(II). 4. 1. (3) 4]. Costa Zichidi.
B. Trachyte [I (II). 5. 1. 4]. Montagna Grande.
C. Trachyte [I (II). "5. 1". "4]. Monte Gibele.
D. Pantelleritic trachyte [II. 4. 1. 3]. Costa Zeneti.
E. Pantelleritic trachyte [II. 4. 1. 3"]. Punta Pozzolana.
F. Comendite [(I) II. (3) 4. 1. 3]. Cuddia Nera.
G. Aegirite pantellerite [II. (3) 4. 1. 3]. Monte Sant' Elmo.
H. Aegirite pantellerite [II. 4. 1. 3]. Costa Zeneti.
I. Pantellerite pumice [II. 4. 1. 3]. Rione Buccarame.
J. Hyalopantellerite [II. 3 (4). 1. (2) 3]. Monte Gelkhamar.
K. Hyalopantellerite [II. 4. 1. 3]. Khagiar.
L. Hyalopantellerite [II. 3 (4). 1. (2) 3]. Cantina Ziton.
M. Pantellerite obsidian [II. 4. 1. 3]. Costa Zeneti.
N. Basalt [III. 5. 3. 4]. Cuddia Ferle.
O. Basalt [III. 5. 3. 4]. Monte Sant' Elmo.
P. Basalt [III. 5. 3. 4]. Dike, Costa Zeneti.
Q. Basalt [III. 5. (2) 3. 4]. Foerstner Volcano, 1891.

TABLE II

Norms of Pantellerian Lavas

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q'
Q	17.10	3.90	5.58	15.12	14.34	31.14	27.60	21.78	22.44	28.38	14.70	28.02	15.36	......	......	......	......
Or	25.02	25.58	26.13	27.80	26.13	29.47	25.02	27.24	26.69	27.80	28.36	27.80	28.36	6.12	6.67	6.12	8.34
Ab	44.01	56.59	53.97	33.01	33.01	22.01	20.44	35.63	24.10	17.82	33.54	17.82	39.30	28.30	28.82	28.82	28.30
An	0.83	1.67	3.06	......	......	......	......	......	......	......	......	......	......	20.02	14.73	15.57	12.79
Ne	......	......	......	......	......	......	......	......	......	......	......	......	......	1.14	......	......	......
Ac	......	......	......	11.55	12.47	9.24	17.56	10.63	19.40	5.08	6.01	7.85	5.54	......	......	......	......
Ns	......	......	......	......	......	1.10	1.34	......	0.49	7.08	4.15	3.17	1.22	......	......	......	......
Di	1.94	4.83	2.48	1.76	5.20	2.57	1.21	......	......	0.75	1.24	2.16	......	18.81	19.54	18.77	17.22
Hy	0.50	1.59	1.96	3.38	1.42	0.46	4.10	0.60	1.03	10.34	9.01	9.28	7.80	......	8.06	5.74	5.21
Ol	......	......	......	......	......	......	......	......	......	......	......	......	......	9.32	0.28	6.29	6.78
Mt	5.57	3.02	3.71	1.62	0.93	......	......	2.09	......	......	......	......	......	6.03	7.19	2.32	2.09
Il	2.13	2.28	1.37	1.67	1.82	1.22	1.67	1.67	1.42	1.37	1.82	1.67	1.52	8.66	10.79	12.16	13.07
Hm	0.64	......	......	......	......	......	......	0.32	......	......	......	......	......	......	......	......	......
Ap	0.34	0.34	0.67	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	......	0.34	2.02	3.36	3.36	5.04

general run of camptonose magmas. The iron oxides, lime, the alkalies, and manganese are about normal, while phosphorus is decidedly high.

The *norms* show some interesting features. The entire absence of anorthite, except in the most salic and most femic extremes, and the poverty in diopside, except in the basalts, are striking, as well as the abundance of excess silica (normative quartz) in all except the trachytes and basalts. Still more striking are the abundance of acmite and the prevalence of sodium metasilicate along with it in all except the extremes just mentioned, and the large amounts of ilmenite.

Foerstner's analyses.—It is always an unpleasant task to criticize adversely the work of another, but in the present case such a course seems to be unavoidable, as Foerstner's analyses, especially of the pantellerites, have been widely quoted and accepted as accurate, being the only ones heretofore available for these rocks. The numerous new analyses, most carefully made according to modern methods, indicate that those given by Foerstner are incorrect and incomplete in certain important particulars, and that many of them are subject to errors, apparently systematic in character. The comparison is shown in the accompanying table,

TABLE III

COMPARISON OF OLD AND NEW ANALYSES

		1	2	3	4	5	6	7	8	9	10
SiO_2...	F	61.43	61.47	67.48	70.30	69.61	68.75	68.33	49.87	49.35	44.64
	W	65.27	63.43	70.14	69.79	66.07	69.91	69.33	46.40	46.22	44.83
Al_2O_3..	F	17.51	18.09	9.70	6.32	8.02	5.91	10.94	14.80	15.71	12.74
	W	13.50	16.31	8.61	11.91	11.74	8.58	8.62	14.34	12.23	11.73
Fe_2O_3..	F	5.11	5.14	7.42	9.23	7.17	5.81	3.74	8.25	7.44	4.21
	W	4.40	2.04	6.01	5.35	2.05	1.81	2.65	4.09	4.91	1.35
FeO...	F	2.30	3.06	2.21	1.40	2.83	5.33	5.41	6.88	6.96	11.17
	W	2.52	3.14	2.73	1.43	5.88	5.86	5.52	8.22	7.71	11.79
MgO...	F	0.54	1.32	0.77	0.89	0.65	0.08	0.16	6.77	5.71	5.82
	W	0.55	0.78	0.20	0.25	0.13	0.28	0.52	7.00	6.74	5.50
CaO...	F	2.45	3.00	1.45	0.84	0.88	2.11	1.36	9.36	9.80	10.12
	W	0.85	1.70	0.45	0.25	0.46	0.33	0.52	9.85	9.86	9.63
Na_2O..	F	6.22	5.85	7.21	7.70	7.47	7.52	7.09	2.81	2.96	4.31
	W	5.19	6.71	5.44	5.66	6.89	6.41	4.78	3.59	3.39	3.34
K_2O...	F	3.95	2.83	2.94	2.50	2.88	4.28	4.08	0.68	1.31	1.41
	W	4.21	4.31	4.20	4.59	4.80	4.71	4.71	1.00	1.13	1.40
TiO_2...	F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	5.86
	W	1.09	1.19	0.86	0.89	0.92	0.75	0.85	4.54	5.68	6.88

1, 2. Trachyte
3, 4. Aegirite pantellerite
5, 6, 7. Hyalopantellerite
8, 9, 10. Basalt

in which, so far as possible, analyses by both of us of rocks from the same locality or flow are incorporated.

Foerstner's ferric oxide, lime, and soda are uniformly, and often much, higher than mine, except for the lime and soda in the basalts, and the tendency of his magnesia is also to run higher. His alumina is distinctly higher than mine in the trachytes, while in the pantellerites it is generally lower, as it would also be in his basalts were the 4 or 5 per cent of titanium dioxide and phosphoric oxide present subtracted. His potash is markedly lower in the salic group. Only his figures for silica and ferrous oxides run about the same as mine, though even here some great discrepancies are to be noted.

These differences, especially those in ferric oxide, lime, soda, potash, and alumina, are very striking, and so uniformly in the same respective directions as to suggest systematic errors in his analytical methods as the explanation. What these have been it is difficult, if not impossible, to decide definitely, but, without entering into a detailed discussion, they may be ascribed to the inadequate methods prevailing at the time (prior to 1883), and probably in part to impurities in his reagents. It will be noted that his latest analysis, that of the lava of 1891, most closely resembles the corresponding one of mine.

Whatever be the explanation, the discrepancies here pointed out are, for the most part, so serious and so systematic, and the incompleteness so marked, especially as regards titanium, phosphorus, and water, that Foerstner's analyses of the Pantellerian rocks must be considered as of inferior quality and doubtful utility.

Modal characters.—Leaving the basalts out of consideration the lavas of Pantelleria show some very striking modal characteristics. The small amount of quartz, considering the silicity of the rocks, and its great rarity as phenocrysts, are very unusual. Its small amount is, of course, due to the abundance of alkali feldspar and of aegirite. As Na_2O in aegirite takes up four times its amount of silica (molecularly), much less silica is left uncombined than would be the case in a rock of the same silicity but carrying only ordinary pyroxenes in which the ratio of RO to SiO_2 is 1 to 1.

The exclusively alkalic character of the feldspars, and the absolute lack of nephelite and soda-lime plagioclase are very striking. The soda-microcline phenocrysts very seldom show multiple twinning lamellae or the usual grating structure, but Carlsbad twins of simple individuals are common. The composition, judging from the rock analyses and norms, is somewhat variable, between Or_3Ab_2 to Or_2Ab_3, but will average somewhere about Or_1Ab_1.

Since this paper was written, Dr. H. E. Merwin has very kindly examined optically the feldspar phenocrysts of some of the lavas. In the pantellerites of Zeneti, Khagiar, Gelkhamar, and Cuddia Nera, he finds they have refractive indices (α=about 1.527) corresponding to an albite content of not more than 30 to 40 per cent. We have seen that the average feldspar of these rocks, while somewhat variable, is about Or_1Ab_1, which indicates that the small feldspars of the groundmass are much higher in albite than in orthoclase. The phenocrysts of the Montagna Grande trachyte, however, are relatively higher in albite and approach more nearly to the average composition, Or_1Ab_1. The study of these feldspars is, as yet, but preliminary, and a chemical and optical investigation will be taken up in detail in the near future, but the evidence goes to show that the soda tends to remain in solution longer than the potash.

The abundance of sodic pyroxenes and hornblendes, namely, aegirite, aegirite-augite, cossyrite, and possibly kaersutite, and the poverty in non-sodic augite and hypersthene are also notable. It is also interesting to remark on the absence of *blue* sodic hornblendes, as riebeckite, arfvedsonite, or crossite, riebeckite especially being commonly found in sodic rocks of high silicity. A paper by Murgoci,[1] in which he correlates the presence of riebeckite with zirconium and fluorine as "mineralizers," and katoforite (and cossyrite) with titanium, is interesting in this connection, since on Pantellaria we find titanium high and zirconium low, with no evidence of the presence of fluorine.

It is also noteworthy that only a small part of the aegirite and cossyrite is in the form of phenocrysts, the greater part of these minerals being in the groundmass, or, as is well seen in the hyalopantellerites, not crystallized at all. Here we see the same tendency of the soda to remain in solution as was observed with the feldspars.

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[1] G. M. Murgoci, *Am. Jour. Sci.*, XX (1905), 133.

The complete absence of biotite and the great poverty or generally absolute lack of the more salic rocks in magnetite and ilmenite are very characteristic. The rather common presence, though in very small amounts, of olivine in these rocks is interesting. The investigation of Soellner,[1] with analysis by Dittrich, shows that it is an almost purely ferrous fayalite. As is well known, the olivine found elsewhere in highly silicic rocks, as granite and rhyolite, is always fayalite, not common olivine or the magnesian forsterite. The entire absence of nephelite tephrites and basanites is remarkable in view of the highly sodic character of the general magma.

Norm and mode.—The rocks show some interesting relations between the norm and mode. They are quite normative as regards the quartz and feldspars, both soda-microcline and andesine-labradorite, and only slightly abnormative as regards the augite of the trachytes and basalts, and the aegirite of the aegirite pantellerites. The departure of the mode from the norm is, however, very marked in the presence of the sometimes abundant cossyrite and the presence of small amounts of fayalite in the pantellerites.

It is interesting to note that the presence of the soda-hornblende, cossyrite, goes hand in hand with normative sodium metasilicate. In some cases, as in the trachytes, a very little cossyrite is present with neither acmite nor sodium metasilicate in the norm, but in general the amount of this mineral is correlated directly with that of sodium metasilicate in the norm, the rocks richest in cossyrite, especially as phenocrysts, showing most excess of soda over alumina. On the other hand, the rocks, in which aegirite is largely dominant over cossyrite, the aegirite pantellerites, and comendites, show very little or no sodium metasilicate, but, in general, large amounts of acmite in the norm.

This relation between sodium metasilicate and cossyrite, the norm of which shows 8.66 per cent of sodium metasilicate, furnishes an instructive commentary on Harker's[2] criticism that the norm may contain compounds "which are foreign to igneous rocks and some of which are not known in nature." Cross[3] has briefly dis-

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[1] J. Soellner, *Zeits. Kryst.*, XLIX (1911), 138.

[2] A. Harker, *Natural History of Igneous Rocks*, London, 1909, p. 365.

[3] W. Cross, *Q.J.G.S.*, LXVI (1910), 499.

cussed this point, and points out that the great majority of the normative mineral molecules are those that Harker himself would necessarily choose.

In many of the rocks now under discussion accurate chemical analysis shows that more than enough soda is present to combine with silica and alumina, or with silica and ferric oxide, as potential or actual albite or aegirite respectively. This excess of soda is an important chemical feature of the rocks and, as among rock-making minerals we find soda always as silicates (except in the sodalite group), it is natural and justifiable to state this excess in the norm as Na_2SiO_3, of course without the implication that a mineral of this composition actually exists. When we find, as we do here, that the rocks showing this sodium metasilicate in the norm are likewise rich in cossyrite, and that this mineral itself contains a large excess of soda, presumably as metasilicate, the procedure adopted seems amply justified. A similar reasoning applies to the other "unnatural minerals" objected to by Harker, kaliophilite, akermanite, wollastonite, and potassium metasilicate. The last of these, by the way, is present in the norms of only three rock analyses.

TABLE IV

AVERAGES OF ROCK TYPES OF PANTELLERIA

	I*a*	1	I*b*	II*a*	II	II*b*	III
SiO_2	66.85	69.30	71.75	63.46	66.27	69.08	46.09
Al_2O_3	11.82	11.02	10.23	16.36	13.47	10.58	12.77
Fe_2O_3	5.29	5.12	4.94	2.29	2.20	2.11	2.95
FeO	2.91	2.12	1.33	3.26	4.38	5.50	9.99
MgO	0.73	0.49	0.25	0.81	0.56	0.31	6.17
CaO	1.04	0.78	0.52	1.66	1.02	0.37	9.82
Na_2O	5.32	5.25	5.18	6.55	6.32	6.10	3.43
K_2O	4.71	4.69	4.67	4.37	4.60	4.82	1.16
TiO	0.96	0.88	0.80	0.95	0.90	0.85	5.91
P_2O_5	0.16	0.14	0.12	0.25	0.18	0.11	1.51
MnO	0.21	0.21	0.21	0.04	0.10	0.17	0.20

Succession of magmas.—The change in composition of the magma during the successive eruptive phases offers some features of interest. The averages of the analyses of the several types—each representing a distinct volcanic episode—are shown in Table IV.

They are calculated to 100, free from water and the very minor constituents. The analyses of the comendite and of the Zichidi trachyte are not included, as their place in the succession is uncertain.

I*a* and I*b* are the averages respectively of the early pantelleritic trachytes and the aegirite pantellerites, I being the average of these, representing the composition of the first phase. II*a* and II*b* are the averages of the trachytes and the hyalopantellerites, II being the average of these and representing the composition of the second phase. III is the average of the final basalts, including that of 1891.

The first two phases show a marked repetition in the magmatic succession, a beginning of which is apparently repeated in the basaltic phase. Starting with the pantelleritic trachytes, there is first a rise in silica and a fall in the other constituents (that in K_2O being slight) to the pantellerites which formed the last flows of this phase. After the formation of the caldera the magma returns toward or beyond its original composition, as shown in the fall in silica (and potash) and the rise in the others. Then the change shown in the first phase is repeated, silica and potash rising and the others falling in the hyalopantellerites. After the cessation of these flows the basalts show a change in the magma in the same directions (except the alkalies) but to a greater extent as between phases I and II. The iron oxides do not conform to the courses of the other oxides, but there is a steady increase in the ratio of ferrous to ferric oxide, and first a decrease and then an increase in their total amount. The averages of the whole phases (I and II) show the general trend of the magma to a more femic composition.

In the absence of any accurate data as to the relative volumes of the various types no satisfactory estimate can be made at present of the average Pantellerian magma, but a general consideration of the various flows and cones suggests that probably the average I*a* roughly represents this. If this be so, the order of succession corresponds well with that enunciated by von Richtofen and Iddings, namely: beginning with the mean and ending with an extreme (generally the most femic) after few or more alternations.

The interesting feature about the present case is that the most abrupt changes in the magma seem to be correlated with maxima of intensity in vulcanicity, marked by the caldera formation and the dislocation of the Montagna Grande block. Far too little systematic study has as yet been made at any volcano of the change in the chemical characters involved in the succession of flows, in connection with variations in the intensity of the volcanic action, to permit any proper discussion or generalization. It may be said, however, that a causal connection between the two seems to be possible.

The general succession is strikingly like that seen in Sardinia, the rocks of which will be described in forthcoming papers. Here we find the pre-Tertiary sheets beginning with rhyolites, passing to trachytes, and apparently ending with basalts. The later large volcanoes of Monte Ferru and Monte Arci also poured out first trachytes and rhyolites, followed by large flows of basalt, which also forms the product of the most recent small cones.

Comparison with other regions.—Rocks analogous to the pantellerites, comendites, and trachytes of Pantelleria are not very abundant, but are quite widely distributed over the earth. The region most nearly like it is that of Afarland and French Somali described by Arsandaux.[1] The resemblance is very close and is emphasized by Arsandaux, who was able to study specimens from Pantelleria also. He describes both lithoidal and glassy pantellerites, which correspond to the two main types on Pantelleria, except for the irregular occurrence of quartz phenocrysts; and also "microgranites," trachytes, and glassy rhyolites with aegirite, riebeckite, and some cossyrite. Except for the occasional presence of quartz phenocrysts and the replacement of cossyrite by riebeckite, the resemblance between these rocks and those of Pantelleria is most striking, extending even to details such as the felt of aegirite needles and small areas of micropoikilitic quartz. Associated with these rocks are basalts of ordinary feldspathic types.

In their chemical features the Somali rocks are like those of Pantelleria, the only notable difference being the smaller amount of soda. Arsandaux did not determine titanium, so we are ignorant as to this.

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[1] H. Arsandaux, *L'Étude des roches alcalines de l'Est-africain*, Paris, 1906, pp. 39, 45.

It is of special additional interest to note that, analogously to Pantelleria, the Somali lavas are divided into a large group of pantellerites, rhyolites, and trachytes, with silicity from 76.0 to 66.5 per cent, and a smaller of basalts, the silicity of which runs from 50.1 to 46.2; and that there are no phonolites, kenytes, or other intermediate types here. A further resemblance is that the basalts are "always the most recent of the volcanic series to which they belong." The general silicity of the Somali rocks is higher than that of Pantelleria.

Another analogous region is that of British East Africa, including the Rift Valley, described by Prior,[1] and Mt. Kenya described by Gregory.[2] Both of these geologists call attention to the resemblance of some of the more silicic lavas to those of Pantelleria. These highly sodic rocks are accompanied by plagioclase basalts of ordinary types, though no analyses were made of them. At Mt. Kenya these basalts are the last eruptive products. This region differs from Pantelleria and Somali in the abundance of phonolite, kenyite, and other nephelite-bearing lavas.

Similar rocks have also been described from Eritrea, Abyssinia, Masai Land, Madagascar, Aden, and Sokotra; and farther away they have been met with in Japan, Australia, New Zealand, Germany, and Texas.

Closely allied to the Pantellerian lavas, both chemically and modally, but of paleotypal habit and occurring as intrusive dikes and other bodies, are grorudites, sölvsbergites, and paisanites of Greenland, Norway, Massachusetts, Texas, and elsewhere.

It is a noteworthy fact, bearing on the discussion of the norm on a previous page that sodium metasilicate usually appears in notable amount in the norms of these rocks which carry arfvedsonite, while it is either less or absent in the norms of those which contain only aegirite or aegirite-augite.

Attention may also be called to a feature of igneous rocks which carry aegirite or sodic hornblende, which is in accord with the principles adopted in establishing the norm. This is that such rocks

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[1] G. T. Prior, *Min. Mag.*, XIII (1903), 228.

[2] J. W. Gregory, *Q.J.G.S.*, LVI (1900), 205. No analyses given.

only rarely contain soda-lime feldspars, the felsic minerals being almost without exception alkali feldspars, with or without quartz or nephelite. Corresponding to this, the norms of such rocks seldom show anorthite, the apparent presence of this in some cases being certainly due to a too high figure for alumina because of the non-determination of titanium and phosphorus. The norms of such rocks very frequently show acmite, and less often sodium metasilicate, or would show it were the alumina correctly low, while acmite seldom occurs in the norms of any but such sodic pyroxene and amphibole-bearing rocks.

THE STRENGTH OF THE EARTH'S CRUST

JOSEPH BARRELL
New Haven, Connecticut

PREFACE

The publication of a series of papers on "Diastrophism and the Formative Processes" by T. C. Chamberlin was begun in the *Journal of Geology* in October, 1913. The second part, on "Shelf-Seas and Certain Limitations of Diastrophism," is nearly identical in substance with a portion of a paper read by Professor Chamberlin on August 13, 1913, at the Twelfth International Geological Convention at Toronto, Canada. In this part particularly it is pointed out that the parallel surface and bottom of the shelf-seas, also their occasional extension as shallow water bodies over considerable portions of the continent at certain times, indicate a relation to sea-level and wave base rather than to a delicate isostatic adjustment. The implications of this and other lines of argument given by Chamberlin are toward crustal rigidity, not crustal mobility.

The first four parts of the present article on "The Strength of the Earth's Crust" had been completed before the writer read Professor Chamberlin's paper, or knew that he was at work upon the subject; but the conclusions are so closely in accord with his, though reached by other lines of attack, that this article may be regarded as a continuation of the same subject, an added contribution in the large field of diastrophism and the formative processes, following out certain of its ramifications.

A somewhat general survey is given here of the problem of the strength of the crust, beginning with the lines of evidence which bear upon it and following out to some degree the conclusions drawn from it. It has in this way been cast into the form of those articles published by the *Journal of Geology* from time to time, under the caption of "Studies for Students."

PART I. GEOLOGIC TESTS OF THE LIMITS OF STRENGTH

INTRODUCTION AND SUMMARY

The capacity of the outer crust to resist vertical stresses is an important field in the theory of dynamical and structural geology. On the one hand, it is known that the larger segments, those of continental and oceanic proportions, rest to a large degree in isostatic equilibrium, the subcrust of the continental areas being lighter than that of the oceanic areas in proportion to the regional elevation. On the other hand, the minor features, those which enter into the composition of the landscape, are known to have been sculptured by external forces and are to be explained therefore as sustained by reason of the rigidity of the crust.

Between these two extremes in magnitude of terrestrial relief lie mountain ranges, plateaus, and basins; made in part by tangential forces, modified by erosion and sedimentation. To what extent can these constructional and destructional forces work in opposition to those other forces which by producing vertical movement make for isostatic equilibrium? The method of attack is from two directions. The geologist examines the structures imposed by tangential forces, the mountains built by igneous extrusion, the surfaces made by erosion, the strata consequent upon sedimentation. From them he may determine the amount of strain which the crust can endure before periodic movements occur in the direction of relief from strain. The geodesist, by means of the plumb-line and pendulum, determines the subcrustal densities and notes the degree to which these are balanced against the relief, pointing therefore to a relation of flotational equilibrium within the solid earth.

Most geologists in former years have utilized but little the principles of isostasy, as may be seen by reference to the standard manuals. On the one hand, the weight of sediments may be spoken of as the *cause* of downsinking with such equal pace that the condition of a shallow sea prevails for a geologic period, though perhaps accompanied by the deposition of thousands of feet of sediment. On the other hand, and without argumentation to explain the apparent inconsistency, the same geologist may state that tangential forces have built folded mountains miles in height which may be subsequently largely removed by erosion before marked vertical warping of the crust occurs.

In contrast to the geologists, certain geodesists have argued in recent years for a high degree of isostatic adjustment; isostasy being regarded by Hayford, for example, as largely complete in areas probably between one square mile and one square degree in size, the mean departure of these unit areas from the level of complete compensation being stated by him as ranging from 250 to 570 ft. These figures he does not regard, however, as of a high order of accuracy, the latter being probably the more reliable of the two. He states that their significance is mainly in showing that isostatic compensation is nearly perfect. It has even been argued by Dutton, Willis, and Hayford, as an outflow of geodetic studies, that those vertical movements of the outer crust which tend to give isostatic equilibrium are the ultimate causes of the periodic great compressive movements.

There is here between geologists and geodesists a tendency to a fundamental difference of opinion, resulting from the emphasis upon one or the other of those opposing forces which work in the outer crust. The truth must lie within the broad zone between these two extremes of theory. To try to bring them together in harmony is the problem before us.

The first part of the paper, on the geologic tests of the limits of strength, opens with a brief review of the lines of geologic evidence which may be used as tests of the degree of resistance or response by the crust to vertical stresses, having regard to both area and intensity. Deltas built into deep seas seem best adapted to give quantitative measurements. Those of the Nile and the Niger therefore are subjected to detailed study. They indicate that the earth is competent over those regions to sustain stresses due to sedimentation which are measured by the weight of several thousand feet of rock, even where the load is continuous over tens of thousands of square miles. Whatever response there may be is so slow that the deposition is able to keep pace with subsidence and maintain the load as a permanent stress of this magnitude upon the crust. By analogy the conclusion may be applied to other parts of the earth, and to those negative loads created by the erosion to base-level of regions previously unwarped to an elevation presumably near to that which would give isostatic equilibrium. Consequently, also, the crust should be able to bear in considerable degree the folded and overthrusted structures piled up by the tangentially compressive forces which periodically operate to such large degree within its outer shell. Deeper changes, involving changes of density, are involved, however, in orogenic processes and express themselves in vertical warpings associated with, and following after, folding. This association of vertical and tangential forces complicates the problem of the crustal strength needed to support mountain ranges.

The measures derived from the study of deltas are more in accord with those larger estimates of the strength of the crust obtained by Putnam and Gilbert in 1895 from a transcontinental series of gravity measurements in which was developed and employed for the first time the conception of local rigidity but regional isostasy.[1] Their conclusions have been thought to be superseded and controverted, however, by much more elaborate and complete geodetic studies, first by Hayford, and later by Hayford and Bowie, which went to show that the crust was very much weaker and in much more perfect static equilibrium.

The calculations of Hoskins tended to show also that the crust within the zone of isostatic compensation could not bear permanently loads as great as those apparently imposed by these deltas. If, however, the great hydrostatic pressures within the deeper crust

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[1] *Bull. Phil. Soc. Wash.*, XIII (1895), 31–75; *Jour. Geol.*, III (1895), 331–34.

give to it an added resistance to stress differences as great as indicated by the experiments of Adams, then the strains imposed by the deltas may be permanently borne.

This confrontation of the conclusions drawn from various paths of approach raises the problems which are treated in the second part.

MOUNTAINS BUILT BY COMPRESSION OR IGNEOUS ACTIVITY

Mountain ranges made by folding or extravasation must be independent to some degree from vertical forces, but these are not suitable geologic tests of the rigidity of the crust, since it is known, as noted in the introduction, that they are secondarily connected with diminutions of density in the zone of isostatic compensation and in many cases are rejuvenated after partial erosion by later upwarping.

The individual mountains or plateau remnants left standing by circumdenudation, or piled up as volcanic cones are clearly burdens upon the earth. The volume which rises above the average level is a measure of the stress. Gilbert has so used them and obtained values ranging from 40 to 700 cubic miles.[1] These volumes, however, might be called minimum estimates, as may be seen upon examination of their nature.

If a certain broad upwarping reduces the vertical stresses to a minimum and erosion follows without further adjustment, it is the volume of the valleys rather than the mountains which soon comes to measure the larger possible departures from equilibrium. The remaining mountains by their weight produce local downward stresses, but the more regional stresses are upward and are due to the breadth of the field of erosion. These regional stresses will become larger ultimately than the local stresses due to the residual masses.

Volcanic cones do not continue to be built up until their base begins to sink into the crust as fast as the upward growth takes place. On the contrary, their growth ceases when the hydrostatic pressure of the high column of lava or a decadence of pressure in the reservoir below leads finally to a shifting of the vents.

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[1] "The Strength of the Earth's Crust," *Bull. Geol. Soc. Am.* (1889), I, 25.

Regional igneous activity has poured out lavas and breccias, burying previous mountainous topography and adding thousands of feet to the outer crust. Lack of simultaneous erosion, as in the Miocene flows of the Columbia plateau, shows that subsidence progressed, perhaps with approximately equal pace. The present altitude of the Columbia plateau is youthful, as shown by the steep canyon walls and undissected interfluvial areas. The initial subsidence accompanying igneous outpouring and the distinctly later upwarping without compression suggest that here isostasy has prevailed. But in such regions the geologic evidence points toward a minimum strength of the crust. The wide area of activity, the numerous vents, the general absence of localization, all are suggestive of widespread fluid rock beneath, magmas which are probably far above the level where the accompanying temperatures are normal. Such conditions would seem to imply the impossibility of the outer crust carrying over such regions the stresses which are possible in regions long free from igneous activity. More reliance as maximum measures of the strength of the crust should be placed therefore upon those external changes which are entirely independent in origin from the interior of the earth locally beneath them.

SHIFTINGS OF LOAD DUE TO CLIMATIC CHANGE

Some of the most striking examples of loading and unloading of the crust are those connected with the climatic fluctuations of the Pleistocene. The continental ice sheet formed, advanced, and retreated rather rapidly, as viewed from the geologic standpoint. As it retreated, the lacustrine and estuarine shores show that the land was rising with the melting of the ice. The upwarping accompanying deglaciation was limited to the approximate region of maximum glaciation and was greatest in the direction where the ice was thickest, in the St. Lawrence valley the maximum uplift being more than 600 ft. These relations suggest strongly an isostatic response to the relief of load. It is not known, however, to what degree the previous downwarp compensated for the burden of the continental ice sheet and what degree of regional stress the crust was able to bear. The lack of close response is seen in that the upwarp continued as a residual movement after the ice departed.

The movement of the crust could not keep pace with the climatic change but it shows by means of these fossil water planes its incompetency to bear without at least partial yielding a burden as broad and as heavy as the Pleistocene climates placed upon it.

Gilbert, in 1889, was led by reflection upon the changes of load imposed by the waters of extinct Lake Bonneville to use them as a measure of the strength of the earth's crust to resist isostatic adjustments,[1] and as previously stated, tested the conclusions drawn therefrom by comparisons with the volumes of mountains made by extravasation, or circumdenudation, or their combination, and of valleys of erosion. Of Lake Bonneville he states:

> Considering the main body of Lake Bonneville, it appears from a study of the shorelines that the removal of the water was accompanied, or accompanied and followed, by the uprising of the central part of the basin. The coincidence of the phenomena may have been fortuitous, or the unloading may have been the cause of the uprising. Postulating the causal relation, and assuming that isostatic equilibrium, disturbed by the removal of the water, was restored by viscous flow of crust matter, then it appears (from observational data) that the flow was not quantitatively sufficient to satisfy the stresses created by the unloading. A stress residium was left to be taken up by rigidity, and the measure of this residuum is equivalent to the weight of from 400 to 600 cubic miles of rock.
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> From these phenomena and theoretic considerations arises the working hypothesis that the measure of the strength of the crust is a prominence or a concavity about 600 cubic miles in volume.

THE EVIDENCE FROM EROSION CYCLES

Erosion base-levels folded and uplifted tracts, leaving for a time during the process mountains of circumdenudation whose local stresses have previously been discussed. The development of peneplains implies a rigidity of the crust sufficient to prevent responsive vertical movement until after the completion of the cycle of denudation. It may be difficult to determine the original average elevation and the degree of progressive uplift *pari passu* with erosion which preceded the peneplanation, but the fact that broad areas become flat and are controlled until the next deformative movement by the level of the sea suggests that they cannot

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[1] *Bull. Geol. Soc. Am.*, I (1889), 23–27.

lie after erosion in close isostatic equilibrium; that whatever stress this implies can be carried by the earth for long periods of time.

The ancient peneplains are now broadly warped and uplifted. The rivers, as a rule, are intrenched in youthful valleys; or their seaward courses are drowned and not yet reclaimed by delta building. These features testify to the recency of world-wide crustal unrest, marked chiefly by movements of a vertical nature; movements which presumably diminished the vertical stresses in the outer portions of the earth and has produced at the present time, as Willis has argued, a higher degree of isostatic compensation than has been customary through the long periods of quiet which separate the epochs of movement.

There are difficulties, however, in using ancient base-leveled surfaces now upwarped as measures of the previous stress. It is known that a region like the Colorado plateaus which now stand markedly high tended to lie near sea-level from the beginning of the Paleozoic to the end of the Mesozoic. Presumably a decrease of density within the zone of isostatic compensation has taken place here during the Cenozoic and the uplift has accompanied or followed the internal change.

Furthermore, if there are stages in the uplift, a considerable volume of rock is removed during each stage, so that at no one time has the average elevation of the region been as high as the residual masses might be thought to imply. Allowing for these qualifications, however, there seems no doubt that the study of erosion cycles will throw light upon the limits of stress due to unloading which the crust can resist, and also upon progressive changes in subcrustal densities through geologic times. This evidence of considerable crusted rigidity, shown by freedom from compensating movements during a cycle of erosion, or by warpings not in sympathy with isostatic stresses during cycles of crust movements, has been pointed out before. Hayford has sought to explain it away by invoking, first, the slight crustal cooling which would occur in regions of erosion because of removal of the upper rock, heating in regions of deposition. Second, he assumes as probable the existence of a high coefficient of compressibility sufficient to make eroded regions rise in appreciable ratio to the thickness of the load eroded. Third, he assumes a crustal undertow from heavy toward high areas which would not only fold the surface rocks and heat them in the region of undertow but restore the equilibrium of mass in the regions of erosion and deposition.[1] It may be said of all of these factors that when they are subjected to quantitative statement they appear so trifling as to fail wholly to explain the magnitude and breadth and periodicity of crust movements. The inadequacy of the temperature effects has been pointed out clearly by Harmon Lewis.[2] The assumption of the high coefficient of compressibility involves more instead of less difficulty for the high isostasist. The inadequacy of isostatic undertow to account for folding has been discussed briefly by the present writer elsewhere.[3] On the other hand, the control of the level of the earth's surface during epochs of quiet by the forces of planation and not by forces making for close isostatic adjustment has been discussed convincingly by Chamberlin in his present series of articles. It seems clear, then, that in the study of cycles of erosion and deposition much may be determined in regard to the limits of terrestrial rigidity. The subject could be developed further, but it is preferred to place the emphasis of this paper upon the more readily estimated loads produced by the building of deltas.

THE EVIDENCE FROM DEPOSITION

Preliminary statement.—The waters deposit sediment upon the depressed areas of the crust. To what extent may such areas be loaded before yielding of the base and resultant subsidence take place? The geologic record makes it clear that subsidence and deposition are necessarily related. It has been stated often that deposition was the cause and subsidence the effect, the two being regarded as in delicate isostatic adjustment. But this is in reality an assumption, for such a supposed relationship overlooks the extent to which subsidence might have gone forward without deposition and ignores the external load which may have been necessary to

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[1] "The Relations of Isostasy to Geodesy, Geophysics, and Geology," *Science*, N.S., XXXIII (1911), 199–208.

[2] "The Theory of Isostasy," *Jour. Geol.*, XIX (1911), 622, 623.

[3] Joseph Barrell, *Science*, N.S., XXIX (1909), 259, 260.

perpetuate and add to a crust movement initiated by internal causes. Sedimentation is dependent upon the rate and continuity of subsidence as well as upon the rate of deposition. Thus, although the sediments give the most complete record of crustal movements, for the distant past it is not easy to separate cause and effect and ascribe to each its part. Where the thickness of sediments, however, is small, as over much of the continental interior, the cause of submergence is presumably almost wholly independent of the local load. Where the sediments are thick and subsidence rapid, as within the geosynclines, the load imposed by sedimentation may on the contrary become the controlling force. It is a particular phase of deposition, however, which will be considered in this article, a study of the load imposed upon the crust by certain deltas. As long as the water plane lies at a constant level the delta builds out at its front. Upon subsidence of the supporting crust the shore retreats inland; less sediment reaches the now submerged front, and the delta in consequence grows chiefly by additions to the shoreward part of its upper surface. The two methods of growth not uncommonly alternate upon the same delta, showing the discontinuity of subsidence. In building outward a delta acquires a convex shoreline. This form is clearly related to aggradation, not to isostatic uplift, and its volume is a measure of a load inclined to further sinking, the larger rivers tending to drain toward and into the downwarps of a continent. To what degree, then, can a region of the crust which is possibly already resisting downward strain bear this added burden? A preliminary examination will be made of several classes of deltas in order to choose those best adapted to test this question.

Most of the deltas of Eurasia and South America are at present advancing rapidly into shallow embayments and the faunas of the continental islands show that the latter were recently a part of the land. The physical and organic evidence thus concur in showing that a very recent subsidence has taken place. It is to be concluded that a submergent phase in the Cenozoic crustal oscillations has marked the short interval since the last retreat of the Pleistocene ice. The great deltas constructed during the late Tertiary and in the Pleistocene are consequently now in great part drowned.

Their location, volume, and limits in most cases are not known. Their modern and smaller representatives, as they build out into shallow water, do not greatly increase the load upon the crust. Deltas recently drowned are therefore not well adapted to serve as tests of the strength of the crust.

Deltas which lie in re-entrant angles of the continents are also poorly adapted to be used as a test. Those of the Indus, the Ganges, and the Colorado are illustrations. As they fill up the heads of gulfs and are without the typical convex outline, it is not only difficult to compute their volume but their situation is such as to suggest that even without the construction of the delta the region might be far out of isostatic adjustment.

Certain rivers, which face the open ocean, such as the Columbia, do not build deltas because of the power of the waves and currents which sweep laterally the fine detritus.

Many rivers, however, build considerable submarine deltas even where the in-planing forces of the ocean prevent a terrestrial outward growth. Such submarine deltas, owing probably to the power of the waves rather than to recent submergence, are marked by convexities in the bathymetric contours opposite the river mouths. The Congo, the Orange, and the Zambesi are examples. These hidden deltas which are built out into deep waters cannot reach more than a certain distance from the shore and part of their detritus is carried laterally along shore by the waves, but nevertheless they possess a very considerable volume and the convexity which they make upon the ocean floor shows to that degree the rigidity of the crust.

The maximum test is found where great rivers have carried forward subaerial topset beds of their deltas over what was previously deep ocean. Fluviatile construction in such examples has dominated over marine destruction, giving a convex outline to the shore; but the subaqueous deposits may still make up the greater part of the volume. Even in these cases the question may be raised whether the deltas have attained the maximum possible size permitted by the strength of the crust. Their size may, on the contrary, be limited even here by the balance of the surface agencies and the limited time during which the river has dominated over the sea. It is a fair presumption, however, that the largest deltas have reached a size where subsidence keeps pace with added volume.

The deltas of the Nile and Niger.—Only the most powerful rivers, laden with abundant waste and protected by their situation from the heavier wave and current action, can build deltas of this last class directly into ocean basins. Perhaps the two best of the few good examples are those of the Nile and the Niger. Both have built out great deltas from regularly curving shores of the Atlantic type—the type where recent folded mountains do not mark the line between continent and ocean, the type where tangential forces cannot be supposed to have disturbed recently the isostatic balance of continent and ocean.

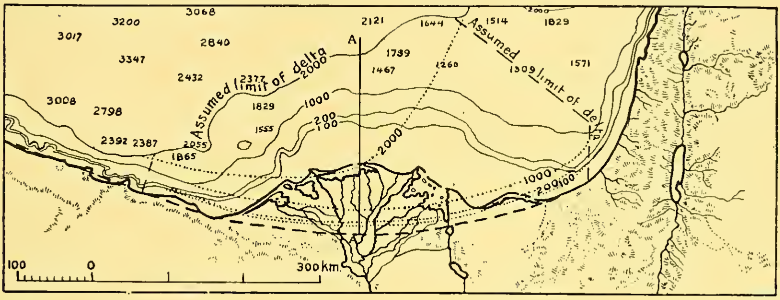

FIG. 1.—Delta of the Nile. Scale 1: 10,000,000. From Andree's *Allgemeiner Handatlas*, vierte Auflage.

To determine the areas, depths, and volumes of the deltas from the standpoint of isostasy, a smooth curve, as shown in Figs. 1 and 3, was continued through them from the shore beyond. The submarine contours were also projected in dotted lines, giving the form of the bottom as it presumably would now be if no rivers at these places had entered the sea. The volume of the deltas may then be determined by computing the volume included between these two sets of contour lines.

In both cases, in so far as the positions of the hypothetical bottom contours are open to doubt, they have been located somewhat above a most probable position, so as to tend to throw the error of computation in the direction of too small rather than too large a volume. For instance, the easterly drift of the water facing the Nile delta may have carried considerable mud in suspension to beyond the line assumed here as its limits. In consequence, the hypothetical 2,000-meter contour should be drawn perhaps much closer to the coast of Palestine than has been done. Beneath the Niger delta the contours lie close together on the west but have been drawn as spreading apart toward the east. It would perhaps be nearer the truth to project the steep character of the coastal slopes to the east of the Niger delta under it to where the contours meet the chain of volcanic island mountains extending from the Cameroons out to sea. This appears to be especially probable, since Buchanan has shown that the gentle slopes of the Guinea coast even beyond the limits of the deltas, and extending from long. 2°30′ E. to lat. 8° S., are mantled throughout by very soft, black, oozy mud, characteristic of river estuaries.

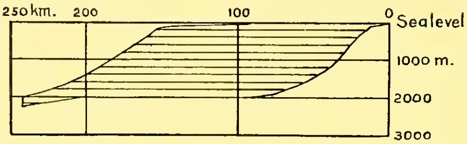

FIG. 2.—Vertical section of the delta of the Nile on *A-A*, Fig. 1. Horizontal scale 1: 5,000,000. Vertical scale 1:200,000. Area of section, 295 kilometers.

All the way down the coast as far as Loanda, lat. 8° S., the same gentle gradients and the same very soft river mud were found. It appears that the land débris brought down by the Niger and Congo, and by other less important rivers, is collected and concentrated in this district. The prevailing current past the mouth of the Congo is a northerly one, while all along the coast from Cape Palmas to the Niger an easterly current sets. These help to confine the drainage matter of both rivers to a comparatively small extent of littoral. If from the soundings west of Cape St. Paul we compute the mean continental slope, we find that the 500-fathom line is at a mean distance of 4.1 miles, the 1,000-fathom line at 11.7 miles, and the 1,500-fathom line at a distance of 17 miles from the 100-fathom line. If it is assumed that in the absence of the Niger and the Congo the continental slope would be much the same as the average found in the profiles west of Cape St. Paul, it may be concluded that the excess of mud forming the flatter talus along the coasts affected by these rivers is due to the mud brought down by them.[1]

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[1] J. Y. Buchanan, "On the Land Slopes Separating Continents and Ocean Basins, Especially Those on the West Coast of Africa," *Scottish Geographical Magazine*, May, 1887, pp. 7, 8.

Buchanan states that this gentle bottom slope extends for 1,100 miles along the coast, and computes the volume contained between the steep gradient presumably once existing and the flatter gradient of the present bottom. This represents a deposit of 66,000 cubic nautical miles of detritus due principally to the Niger and the Congo.[1] This great volume cannot be used safely, however, as the measure of a load upon the crust, since a believer in the theory of close isostatic compensation could claim with some degree of reason that the initial slope of the concave shores of the Gulf of Guinea need not have been as steep as the bold convexity of Africa to the west, or that the load may have depressed the bottom so as to have equalized the pressures. Furthermore, Buchanan does not include any of the land area of the Niger delta. The following estimates will give the volume only of the clearly constructional part of the Niger delta, including both the land and

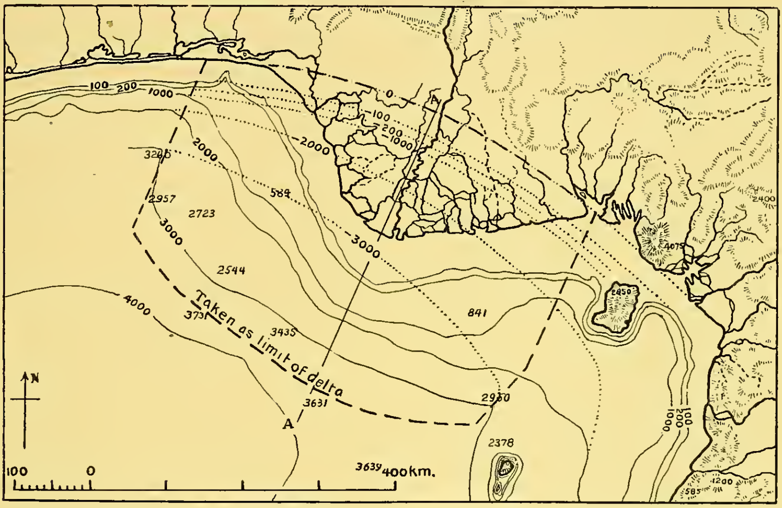

FIG. 3.—Delta of the Niger. Scale 1:10,000,000. From Andree's *Allgemeiner Handatlas*, vierte Auflage.

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[1] *Op. cit.*, p. 8 and Fig. 3. The volume stated by Buchanan appears to be correct if the two profiles have a common point taken upon the *shoreline*. In his figure, however, the common point A is shown as upon the 100-fathom contour. From this error in the diagram given by Buchanan the volume estimated from the diagram would be much less than 66,000 cubic nautical miles.

the sea portion. But it will be seen, from Buchanan's statements, that this is a minimum estimate of the areal load imposed by the rivers, for a more or less continuous burden on the crust would appear to stretch for a thousand miles along this African coast, reaching a maximum unit value, however, in the great delta of the Niger.

The outer limits of the deltas were taken where the convex slopes fade out into the general ocean bottom.

The results of computing the volumes shown between the two sets of contour lines are as follows:

TABLE I

Delta of the Nile

Area within 1,000-m. contour	71,000 sq. km. (27,400 sq. mi.)
Area within 2,000-m. contour	106,000 sq. km. (38,800 sq. mi.)
Radius of equivalent circle	175 km. (110 mi.)
Equivalence in equatorial square degrees	8.6 sq. degr.
Average thickness within assumed limits	0.84 km. (2,800 ft.)
Equivalence in rock upon land	0.46 km. (1,540 ft.)
Ratio to 76 miles of crust	1 to 260 = 0.0038
Maximum thickness	2.0–2.3 km. (6,600–7,600 ft.)
Equivalence in rock upon land	1.1–1.3 km. (3,600–4,200 ft.)
Volume within assumed limits (extending on the east to somewhat below 2,000 m.)	89,000 cu. km. (21,300 cu. mi)
Equivalence in rock upon land	50,000 cu. km. (11,700 cu. mi.)

TABLE II

Delta of the Niger

Area within the assumed limits	195,000 sq. km. (75,300 sq. mi.)
Radius of equivalent circle	250 km. (155 mi.)
Equivalence in equatorial square degrees	15.8 sq. degr.
Average thickness within assumed limits	1.1 km. (3,600 ft.)
Equivalence in rock upon land	0.6 km. (1,980 ft.)
Ratio to 76 miles of crust	1 to 200 = .005
Maximum thickness	3.0 km. (9,900 ft.)
Equivalence in rock upon land	1.65 km. (5,450 ft.)
Volume within assumed limits	217,000 cu. km. (52,000 cu. mi.)
Equivalence in rock upon land	120,000 cu. km. (27,000 cu. mi.)

The deltas in their growth had displaced their volume of water. The added loads which they throw upon the crust are measured by subtracting the weight of the water from that of the sediments. A specific gavity of 2.67 has been taken by geodesists as the average for the outer shell of the earth. The degree of consolidation of the deeper parts of the deltas is not known, but for present purposes the specific gravity of their sediments as a whole may be assumed as 2.50. This will be near the truth if the composition is that of the average shale, if 10 per cent of pore space be assumed and this is wholly filled with water. The specific gravity of sea water is 1.03, leaving an effective specific gravity for the sediments of 1.47. The ratio of 1.47 to 2.67 is 0.55. The thicknesses given for the deltas should therefore be multipled by this factor for estimating the equivalent burdens of rock of specific gravity of 2.67 above sea-level.

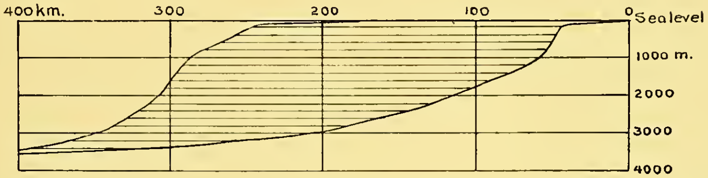

FIG. 4.—Vertical section of the delta of the Niger on *A–A*, Fig. 3. Horizontal scale 1:5,000,000. Vertical scale 1:200,000. Area of the section, 645 kilometers.

It is seen that the deltas are in the form of inclined double convex lenses. Thicknesses approaching the maximum are found over considerable areas in the middle. The load imposed by this thickness is equivalent in the Nile delta to 3,600–4,200 ft. of rock above sea-level; in the Niger delta to 5,000–5,500 ft.

Discussion of results.—The region of the southeastern Mediterranean is held by Suess to be geologically of very recent origin, downfaulted from the continent. The delta of the Nile, much smaller than that of the Niger, is therefore to be regarded as young and may be still increasing in volume.

The great size of the Niger delta suggests, on the other hand, that it may have reached the limit permitted by the strength of the crust. Subsidence may now intermittently keep pace with deposit. If the 1,000-meter contour has been located correctly, as shown in Fig. 3, it suggests that such may be the case, since it is seen that in contrast to the Nile delta the slopes are much steeper between the 1,000- to 2,000-meter than between the 200- to 1,000-meter contours. This can be explained by assuming that the steep slope lying below and beyond a flatter slope was once a foreset slope just below wave base, whereas it now lies at least 800 meters below. If such a subsidence has occurred, it appears, however, to have been confined to within the limits of the delta; since a peripheral overdeepening of the ocean floor is not evident. On the other hand, it is noted by Penck, but probably too sweepingly, that all bathymetric curves have their steepest slopes between 1,000 and 2,000 meters in depth.[1] Such a phenomenon might be due to lateral flow of sediment under a certain depth of load and without relation to subsidence of the base. The question whether the load of the Niger delta is as great as the crust can bear is therefore an open one.

The Gulf of Guinea, where now the delta is built, is regarded by many geologists as having originated since the Middle Mesozoic by a breaking-down from the continent of Gondwana, but the presence of Middle Cretaceous marine beds skirting much of the coast of West Africa suggests perhaps that the delta in its construction does not go back of the Tertiary. In fact it would seem possible from the youthful relief of the continental plateau that the delta built from its waste is of Upper Tertiary and Pleistocene growth.

A single delta might happen to be a mere veneer of sediment upon an originally slightly submerged projecting part of the coast. Such a fortuitous coincidence of unrelated circumstances may, however, be dismissed as highly improbable in the case of two great rivers draining in opposite directions from the same continent. The conclusion that these deltas are really externally constructive features and measure a real strain upon the crust is strengthened by noting the submarine deltas opposite the other great rivers of Africa, built into the ocean, even though the waves and currents have limited them by preventing their subaerial seaward growth.

In the mechanics of the relation of the delta to the stresses in the crust an important factor is the nature of the marginal land. Shores of the Pacific type have great mountain systems marginal

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[1] *Morphologie der Erdoberfläche*, I (1894), 146.

to the continents. Parallel to them the sea has great fore-deeps. It appears as though the mountain ranges had been piled too high by tangential forces, and, by virtue of the partial rigidity of the crust, had depressed the neighboring ocean bottoms. Erosion of the coastal mountains and deposition of their waste in the fore-deep would tend, up to a certain limit, to equalize the strain in the crust. In that case it might happen that, although the mass of the delta measures a stress, this might be opposite in character to pre-existing stresses, with the result that the strain upon the crust beneath the delta before the infilling might be as great or greater, but in an opposite direction. The greatest remaining strain within the sea-bottom could conceivably be an upward strain under the parts of the fore-deep not filled.

Such relations are not found around abyssal slopes of the Atlantic type. These are regarded by many geologists following the lead of Suess as made by marginal downbreaking of the continents. They have but little or no relation to the older folded structures and no excessive deeps parallel to the continental margins. If these relations of the Atlantic and Indian oceans to the continents are rightly interpreted as to cause, it is probable that the stresses which make for downsinking extend beyond the parts already foundered. The margin of continents and ocean basins are not likely to be depressed too low, but if remaining out of isostatic adjustment they would tend rather to stand too high. There is no theoretic reason to believe, therefore, that the Nile and Niger deltas have neutralized pre-existing strains. They are best regarded as real and present burdens sustained by the rigidity of the crust.

Whether or not, however, the building of deltas produced stresses of a character identical with, or opposite to, those previously existing in the region, the stress gradient between the areas of the delta and the surrounding areas would be measured by the weight of the sediments, and this would tend to produce differential flexure. It would seem to be a logical conclusion, therefore, from these tests, that certain parts of the earth's outer crust can resist for considerable periods of time vertical stresses at least equivalent to the weight in air of 10,000–25,000 cubic miles of rock in lenslike forms spread over areas of 40,000–75,000 square miles and reaching thicknesses in air over considerable areas of 4,000–5,000 feet.

The tabulation of the data regarding the deltas shows the area of the Niger delta to be equivalent to a circle 310 miles in diameter and that over this area the load of the delta is one two-hundredths the weight of the crust to a depth of 76 miles, this being the depth of the zone of isostatic compensation given by the latest determination of Hayford.

According to Hoskins, in a calculation made for Chamberlin and Salisbury,[1]

> a dome corresponding perfectly to the sphericity of the earth and formed of firm crystalline rock of the high crushing strength of 25,000 pounds to the square inch, and having a weight of 180 pounds to the cubic foot, would, if unsupported below, sustain only $\frac{1}{525}$ of its own weight. This result is essentially independent of the extent of the dome, and also its thickness, provided the former is continental and the latter does not exceed a small fraction of the earth's radius.

The delta, though large, is so limited in size in comparison with continental areas that it would be somewhat more effectively supported, but its externally convex form can hardly be supposed to give it added domal strength, since it consists of more or less unconsolidated material piled upon a concave floor.

The theory of isostasy holds that at a certain depth in the crust there is an approach to equal pressures, the larger relief of the surface being balanced in large part by subsurface variations in density. The larger segments of the crust tend to rise or sink until the elevations are in adjustment to the density beneath. A corollary of this theory is that unbalanced surface loads are largely sustained by the strength of the crust above this level of equal pressures; in other words, but little of the load is transmitted to the deeper earth below. For purposes of discussion it may then be assumed that the load of the Niger delta is supported by the outer 76 miles of crust. This depth is one-fourth of the diameter of the circle equivalent in area to the delta. The load over this area, as stated, is one two-hundredths of the weight of the supporting crust. Allowing something for the limited area of the delta, it is seen never-

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[1] *Geology,* I, 555, 1904.

theless to imply a strength of the crust about twice that assumed as a maximum by Hoskins as a basis for his calculation. There are several contributing factors which may explain the disagreement between the figures obtained by observation of the deltas and the calculation given by Hoskins and others: First, part of the stress is transmitted laterally to some extent into the deeper layers, but as the diameter of the loaded area is four times its depth this can be a partial explanation only and has, furthermore, been allowed for. Second, part of the stress may be transmitted into the deeper earth below the 76-mile zone of isostatic compensation. This is about equivalent to third, that the zone of isostatic compensation may extend deeper, at least locally, and fade out more after the suggestion made by Chamberlin.[1] Fourth, a consideration which the writer regards as most important is that the crust may in reality possess greater crushing strength than the 25,000 pounds per inch postulated by Hoskins. At the time that Hoskins made this calculation it seemed that this figure was the highest which could be chosen, since it is higher in fact than the crushing strength of the average surface rock when subjected for even a short time to compression in a testing machine, and in the earth the stresses must be carried for indefinite periods. The experiments by Adams[2] have shown, however, that under the conditions of cubic compression which exist in the earth the rocks are capable of sustaining for indefinite times far higher stress differences than they could bear even for a short time when subjected to stress in one direction only, as at the surface of the earth. These experiments showed that:

> At ordinary temperatures but under the conditions of hydrostatic pressure or cubic compression which exist within the earth's crust, granite will sustain a load of nearly 100 tons to the square inch, that is to say, a load rather more than seven times as great as that which will crush it at the surface of the earth under the conditions of the usual laboratory test.
>
> Under the conditions of pressure and temperature which are believed to obtain within the earth's crust empty cavities may exist in granite to a depth of at least 11 miles.[3]

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[1] *Jour. Geol.*, XV (1907), 76.

[2] "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *Jour. Geol.*, XX (1902), 97–118.

[3] *Op. cit.*, p. 117.

It appears then that, even allowing for the great increase in temperature within the earth's crust at depths greater than can be reached by the limitations of experiment, the demands made upon the strength of the crust by the load of the Niger delta are not greater than can be explained by the theory of the mechanics of materials as now understood. This theory rests, however, even after Adams' experiments, upon only a limited range of laboratory observation, and extending over but limited periods only, thus demanding extrapolation both of stress and of time when applied to the whole thickness of the outer crust and over hundreds of thousands of years. Therefore the study of the direct evidence supplied by geologic observation is more convincing in regard to the limits of crustal strength.

These deltas point toward a measure of crustal rigidity capable of sustaining to a large degree the downward strains due to the piling-up and overthrusting of mountains built by tangential forces, or those resulting from the load of sediments in areas of deposition, or those upward strains produced by the erosion of plateaus previously uplifted toward isostatic equilibrium. A final conclusion must, however, await a further discussion in the later parts.

[*To be continued*]

BROILIELLUS, A NEW GENUS OF AMPHIBIANS FROM THE PERMIAN OF TEXAS

S. W. WILLISTON
University of Chicago

The material upon which this genus is based comprises two specimens, Nos. 684 and 685, University of Chicago, collected by Mr. Paul Miller on Timber Creek, Texas. Both specimens, when found, were almost completely inclosed in hard clay nodules. The matrix has been removed from the surface of the bones very cleanly, but no attempt has been made to separate any of them. The larger and more complete of the two specimens, No. 284, the holotype, includes the complete skull, but very slightly distorted, connected with the complete series of dorsal shields; the right humerus in position with the somewhat crushed scapula; the incomplete clavicular girdle; the incomplete left humerus and a part of the hand; the right femur, tibia, fibula, three tarsals, and two metatarsals. There is also a fragment of the pelvis. Specimen No. 285, of slightly smaller size, has the complete skull less compressed than that of the other specimen. It also is connected with the complete series of dorsal shields, and their corresponding vertebrae; also the clavicular girdle is in place; and an imperfect humerus. Only slight indications of the ribs are present in either specimen.

SKULL

Few other specimens of amphibian skulls in the University collection are in better preservation. The skull is sub-triangular in shape, a little longer than broad, with the face broadly rounded in front. The nares are rather large; they are situated near the anterior extremity of the face, and are separated by about their own diameter. The orbits are rather large, nearly circular in outline, with their hind borders a little beyond the middle of the skull anteroposteriorly. In the middle of each orbit of the larger specimen there are several osseous plates. Those of the left orbit seem complete; they form a continuous, convex surface, occupying more than half the diameter of the orbit. The plates are five or six in number; they are not arranged in a ring about a pupillary opening, but the surface is continuous. They could not have been sclerotic plates, and it seems not at all improbable that they were merely ossifications in a nictitating membrane, and served for the protection of the eyeball. The parietal foramen is of the usual size and is situated a little distance behind a line drawn through the hind margins of the orbits.

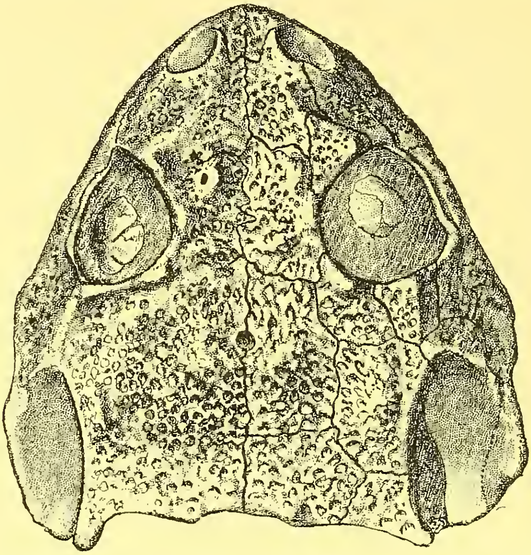

FIG. 1.—*Broiliellus texensis* Williston. Skull, from above, three-fourths natural size. No. 684, University of Chicago.

The otic notch is large, occupying most of the postero-lateral surface of the skull, and extending forward fully two-thirds the distance to the hind margin of the orbit. The ear-opening itself is rather large, extending forward more narrowly nearly to the front margin of the notch. Below the opening there is a broad, smooth surface, looking obliquely upward, backward, and outward. The excavation throughout is quite like that in the species from New Mexico provisionally referred to *Aspidosaurus* under the specific name *A. novomexicanus* Williston. It is also like that of *Cacops* except that it is not closed behind. The tabulare is a little elongate posteriorly, but is not turned downward to meet the quadrate, as in *Cacops* and *Dissorophus*.

The surface of the skull is everywhere deeply marked with small, oval, or rounded pits. The most striking characteristic of the species, however, is the presence of numerous tubercular tuberosities, which must have given the animal when alive a peculiar aspect. Each element of the upper surface of the skull has at least one such spiny tubercle, and on each frontal there are at least two. The most prominent ones, however, almost approaching the character of short spines, are situated on the immediate margins of the orbits, one on each prefrontal, frontal, postfrontal, postorbital, and a smaller one below on each jugal.

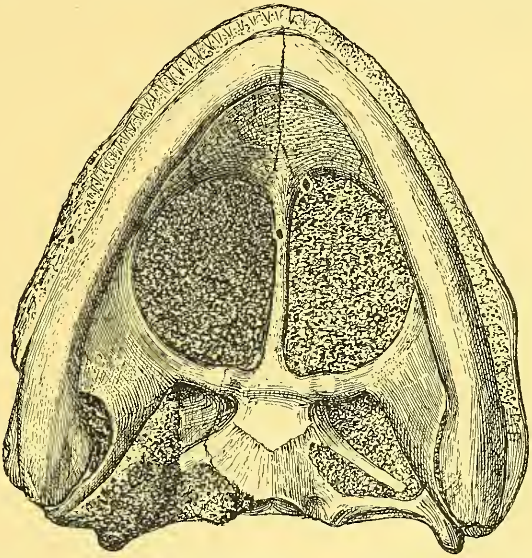

FIG. 2.—*Broiliellus texensis*. Skull, from below, three-fourths natural size. No. 684, University of Chicago.

The sutures throughout are easily distinguishable with the aid of a hand lens as slender, impressed, sinuous, or zig-zag lines. They have been corroborated throughout, not only on the two sides of each skull, but on the two skulls as well, though there is a slight individual variation in their courses in the two skulls. The shapes and relations of the elements conform so closely to the recognized plan in the temnospondyl skull that a detailed description of them will be superfluous. The lacrimal, as more usual in the temnospondyl skull, extends from the nares to the orbits, as has

Fig. 3.—*Broiliellus texensis.* Specimen No. 684, University of Chicago. One-half natural size.

been described and figured by Watson, and before him by Broili in *Cochleosaurus*.

The palate has been exposed only so far as is possible in each specimen with the mandibles tightly closed and the clavicular girdle in position. Doubtless the structure throughout is like that of *Cacops*,[1] but the nares and all evidences of enlarged teeth are concealed. The interpterygoidal vacuities are very large, though less elongated than in *Cacops*. Sutural lines for the vomers are apparent, as I have figured them. The whole surface in front, between the mandibles, is covered with minute chagrin-like teeth.

Indications of the stapes, as in *Cacops*, are present, as also the sutural division between the parasphenoid and the exoccipitals.

The sutures of the mandibles, in their closed condition, are not distinguishable. The teeth are shown in both specimens. They are small, pointed cones, of nearly uniform size, throughout.

DORSAL CARAPACE

The general shape of the dorsal shields is shown sufficiently well in the photograph of the larger specimen. In this specimen the vertebrae, with two exceptions, back of the clavicular girdle had been separated and lost before fossilization, as has been demonstrated by excavating the under side in the middle. In the smaller specimen, the vertebrae are all in position as far as the hind end of the carapace, though the last two or three are somewhat disarranged. Furthermore, in the smaller specimen, several of the shields have been cleanly removed from the matrix, proving that they had no connection whatever with the underlying spines; indeed they lie some distance above the vertebrae, with the matrix intervening. The plates in this specimen correspond in number with the vertebrae below, that is, each vertebra corresponds to a single plate and not to two as in *Cacops* and *Dissorophus*. The plates are not of uniform width anteroposteriorly; the third, fifth, and seventh at least are narrower than the intervening ones, which suggested at first that each vertebra had two plates, but this is positively not the case; all of which goes to prove that the plates were entirely distinct from the spines. Indeed the spines, so far

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[1] Williston, *Bull. Geol. Soc. Am.*, 249, 1910.

as can be made out, are short and small. The first and last plates are larger than the others, the first subcrescentic in outline, the last oval, with its two diameters nearly equal. The carapace is broadest transversely in front, and tapers to the end. The shields are fifteen in number in each specimen, which singularly is the same number as that of *Cacops*, and probably also that of *Dissorophus*. Each plate is strongly pitted, like the surface of the skull. They are not at all imbricated, but lie side by side, touching each other in both specimens.

APPENDICULAR SKELETON

So far as the clavicular girdles are visible, they show but little difference from that of *Cacops*. The interclavicle and clavicle are smooth externally and are of moderate size; the clavicle has an elongate process for attachment to the scapula. The scapula is for the most part hidden below the carapace; that part which is visible is not unlike the scapula of *Cacops*. The humerus is stouter than in *Cacops*, the extremities are less dilated, and the lateral process is not as stout. What appears to be the right ulna and a part of the hand are shown on the same side of the block as that of the carapace. Six, perhaps seven, carpal bones are seen, together with indications of three fingers, the fifth one with the metacarpal and first phalange in place, the fourth and third represented by fragments of the metacarpals only. The hand clearly was short and broad.

Of the hind extremity, the right femur, tibia, fibula, three tarsals, and two metatarsals are in position. The femur has very prominent adductor crest like that of *Cacops*, but is distinctly stouter than in that genus. The tarsals are probably the third and fourth distalia and a centrale; and the metatarsals doubtless correspond with the distalia. The feet were evidently more elongate than the hands.

As regards the species, it is very probable the genus includes that to which I gave the name *Aspidosaurus peltatus* from the Craddock bone bed. However, inasmuch as there is yet no evidence of a slender inferior process on any of the shields of these specimens, the present species may be provisionally called *texensis*.

It gives me great pleasure to name the genus in honor of my friend Dr. Ferdinand Broili, who has contributed much to our knowledge of the American Permian vertebrates.

MEASUREMENTS

	684	685
Length of skull in midline	92	80
Width posteriorly	85	74
Anteroposterior diameter of orbits	24	20
Interorbital width	27	25
Length of carapace	120	100
Greatest width of carapace	43	36
Length of humerus	46	
Length of femur	54	
Length of tibia	35	
Length of median metatarsal	12	

The present genus is the fifth that has been described of the peculiar "batrachian armadillos" from the Permocarboniferous of Texas and New Mexico, namely: *Dissorophus* Cope, *Cacops* Williston, *Aspidosaurus* Broili, *Algeinosaurus* Case, and *Broiliellus* Williston. The first two of these genera may at once be differentiated by the completely closed otic notch; *Aspidosaurus* and *Broiliellus* have the otic notch open behind; in *Algeinosaurus* the skull is unknown. *Aspidosaurus* has typically a single dorsal shield for each vertebra, firmly co-ossified to the expanded spine of the vertebra, the shields are roof-shaped and narrow transversely. *Algeinosaurus* has imbricated shields like those of *Aspidosaurus*, narrow and shallowly V-shaped, but free from the broadly expanded neural spines. It is possible that this freedom of the shields is due to age, for I am convinced that the shields in all these forms are of dermal origin. Until the skull of *Algeinosaurus* is discovered its precise relations to the other genera cannot be determined. I am convinced that it is nearly related to *Aspidosaurus*, but believe that it is a distinct genus. It will at once be distinguished from the present genus by the narrow, shallowly V-shaped, imbricated shields.

Aspidosaurus glascocki Case can only be provisionally located in this group. Its dorsal shields seem to be real expansions of the spines, meeting each other closely, but not imbricated. Nor can *A. crucifer* and *A. apicalis* be located here. I am confident that all these forms belong in an entirely distinct group, possibly the Zatrachydidae.

That all the forms discussed above show a genetic relationship there can be no doubt. Just what value the differential characters present, however, is a question. If we give to *Dissorophus* and

Aspidosaurus family rank it will be necessary to erect a larger group to comprise them all. I would rather place them all in the family Dissorophidae, in two subfamilies, the *Dissorophinae* and *Aspidosaurinae*.

Family **Dissorophidae**

Temnospondyl amphibians of small size, provided with dorsal osseous shields. Skull broad, depressed, more or less rugose, without mucous canals. Lacrimal entering orbit. Probably orbital ossifications in all. Otic notch greatly developed, extending far toward the orbit. Palate with slender parasphenoid; in front at least covered with chagrin-like teeth; two enlarged teeth only. Occipital condyles separated. Cleithrum large; clavicles and interclavicle small, not sculptured. Sacrum with two vertebrae (in all?); pelvis fully ossified, platelike. Femur with high, thin adductor crest. Feet fully ossified, short and rather broad. No ventral armature.

Subfamily DISSOROPHINAE

Otic notch closed posteriorly by the union of tabulare with quadrate below. Each vertebra with two dorsal shields, the under one either an expansion of the spine or a dermal ossification and smooth, the intercalated external shields sculptured.

Genus *Dissorophus*

Shields covering nearly the whole of the dorsum, the first one of large size.

Genus *Cacops*

Shields narrow, the first one small.

Subfamily ASPIDOSAURINAE

Each vertebra covered by a single, sculptured shield. Otic notch open behind. Ribs with uncinate process.

Genus *Aspidosaurus*

Spines greatly expanded above, with shields not much wider than vertebrae, and imbricated; more or less V-shaped. Orbits more posterior.

Genus *Algeinosaurus*

Like *Aspidosaurus* but the shields not coossified with spine.

Genus *Broiliellus*

Shields much broader than the vertebrae, not imbricated and not V-shaped; free from slender neural spines; skull spinose.

Dissorophus multicinctus Cope. Texas.
Cacops aspidophorus Williston. Texas.
Aspidosaurus chiton Broili. Texas.
Aspidosaurus novomexicanus Williston. New Mexico.
Algeinosaurus aphthitos Case. Texas.
Broiliellus texensis Williston. Texas.
Broiliellus peltatus Williston. Texas.

RESTORATIONS OF SOME AMERICAN PERMOCARBONIFEROUS AMPHIBIANS AND REPTILES

S. W. WILLISTON
University of Chicago

(WITH ILLUSTRATIONS BY THE AUTHOR)

The drawings illustrating the present paper were made in the hopes thereby of learning more concerning the animals as living organisms. Depending exclusively upon dried and petrified bones, the paleontologist is apt to forget that his fossils were once parts of living, active beings. Nearly all the restorations are based upon practically complete skeletons preserved in the museums of the University of Chicago or Yale University, technical descriptions of which have been published in various places during the past few years. Their living restorations, except that of *Eryops*, are here attempted for the first time. I will not attempt to give any technical details of their structure here; my only desire is to place before the general student of geology something of what I see, after years of study of the fauna, in some of the animals that lived in Texas and New Mexico during the closing times of the Pennsylvanian and the early times of the Permian.

The land vertebrate fauna of those times in America must have been very rich. More than forty distinct genera of amphibians and reptiles are represented in the collections of the University of Chicago, and the remains of at least a dozen more are preserved in the American Museum and at Yale University. It is the oldest fauna of reptiles known in the world, and by far the most comprehensive of the older amphibians known. The animals of the South African Karoo system are nearly all of later age, Upper Permian as distinguished from Lower Permian and Carboniferous, and they were, for the most part, more highly specialized and less primitive.

And the light these animals of the American Permocarboniferous have thrown upon the evolution of the higher vertebrates is very great, though there is very much more to learn. The primitive

Fig. 1.—A permocarboniferous landscape, with two figures of *Eryops* upon the land, each of about seven feet in length, and *Limnoscelis*, a cotylosaur of the same length, in the water.

structure of the skull in air-breathing animals, in part at least, of the mandibles, shoulder and pelvic girdles, wrist, ankle, and digits has been determined almost exclusively from these forms.

Three very distinct groups or orders of amphibians are known from these deposits, including more than twenty known genera. The first of these groups is represented by small animals of the water which must have existed in enormous numbers. There are places in Texas where the nodules containing their remains, usually nearly complete skeletons, may be obtained literally by the wagonload. They resembled so closely in shape, and doubtless also in habits, the living *Amphiuma means* of the southern states, that a picture of that creature will almost serve for a restoration of this, which is known as *Lysorophus*. Most interesting is the fact that not only did *Lysorophus* resemble *Amphiuma* in size, shape, and habits, but it seems to be actually related to it, being the first representative known of the modern salamander type, not again known in geological history till the beginning of Cretaceous time.

A second group of very remarkable aquatic amphibians, whose relationships are still in doubt, is represented by *Diplocaulus*, a creature which reached a length of about three feet, having an extraordinary arrow-shaped head, and tiny, feebly ossified limbs of no terrestrial and little aquatic use. It, too, was a purely aquatic animal, whose remains are often found associated with those of the early sharks. A restoration of the skeleton of *Diplocaulus* will shortly be published in this *Journal* by Mr. Douthitt of the University of Chicago.

The third and most important order of all our Permocarboniferous amphibians is that known as the Temnospondyli, stegocephalians especially characterized by the divided condition of the vertebrae. They varied greatly in size, and doubtless also in habits, though none known were of upland habit. The most famous of these is *Eryops*, shown in Fig. 1 in what I have tried to represent as a characteristic landscape of the period in which they lived. It was an amphibian which reached a length of perhaps eight feet, and had a relatively large, broad, and flat head, no neck, a thickset body, and short, broad, probably webbed feet. The length of its tail is still in dispute, as may be inferred from my restorations of the creature with that part of the body hidden in the water or under the ferns. Its skin was doubtless bare, and its tail more or less flattened for use in the water, like that of a gigantic salamander, its nearest living modern relative.

There can be no doubt that the creature was amphibious, though probably not strictly aquatic in habit, like *Trimerorhachis*, remains of which are sometimes found in bone beds in great numbers. This animal, of which a restoration will be given in a future number of this *Journal*, had a more elongate and flattened head with the eyes far in front, and with almost vestigial limbs, as has *Diplocaulus*, which is often found associated with it.

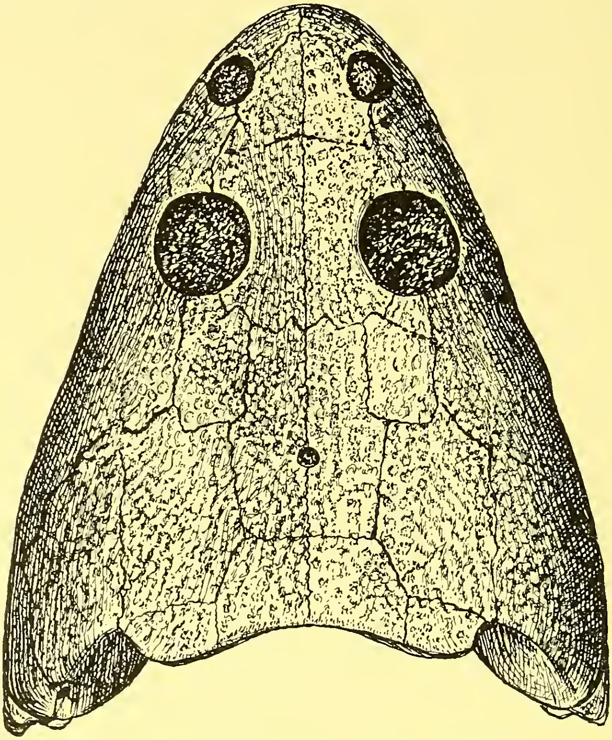

Fig. 2.—Skull of *Trimerorhachis insignis*, an aquatic amphibian about three feet in length.

Another animal of this order, which must be placed in a family all its own, the Trematopsidae, is shown in Fig. 3, as based upon the only known specimen, preserved in the University of Chicago collections, consisting of a skull in connection with body and limb bones, except the front digits, and an imperfect tail. Its restoration, therefore, is subject to minor corrections when additional specimens are found. It was more of a terrestrial animal than any other known amphibian from this fauna, though it cannot be called an upland animal, and doubtless it, too, could swim well. This creature was about two feet in length and has a relatively very large skull, fully two-thirds the length of its body to the tail. Its teeth also were more powerful than in other forms, though of the same general character. It is peculiar in showing an orifice in the skull for a facial gland, like that found in some modern amphibians.

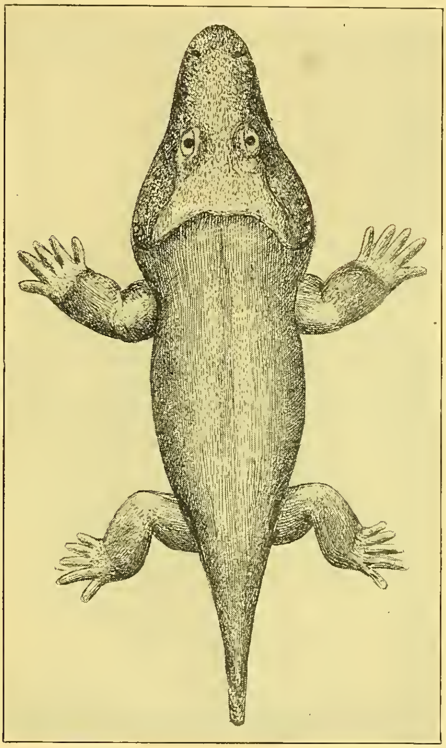

FIG. 3.—*Trematops milleri*, a stegocephalian about three feet long. From Texas

A fourth and very peculiar type of the temnospondylous amphibians is represented in the restoration of *Cacops* (Fig. 4), as based upon a marvelously complete skeleton, one of a dozen or more found associated with as many more of *Varanosaurus* and *Casea*, shown in Figs. 9 and 10. This animal, twenty inches in length, is one of a group of armored amphibians, very appositely called by Cope "batrachian armadillos," of which four or five genera are known, nearly all of the animals of approximately the same size. As suggested by Cope's name, they are all peculiarly characterized by a carapace of bony plates over the back; in some almost completely covering it, in others like *Cacops*, forming only a narrow row along the middle. In some of these has been found a peculiar bony plate in the orbits which could only have been used as a protection for the eyeball, possibly an ossification of the nictitating membrane. And one genus has the head covered with small, spiny excrescences. The ear, too, was conspicuously large, completely surrounded by bone in some, as shown. These amphibians, like most of the other small ones, must have been chiefly insectivorous, or invertebrate-feeding in habit, though the presence of stout teeth on the palate suggests that any seizable living prey was acceptable as food. They were all probably lowland animals, though *Trematops* may have lived more in the forests. *Eryops*, the largest known, has a skull sometimes nearly two feet in length; other small forms associated with it have skulls no larger than one's thumb nail. Doubtless the lowlands in the vicinity of water in late Pennsylvanian and early Permian times swarmed with these creatures and with cotylosaurian reptiles of similar form and habits.

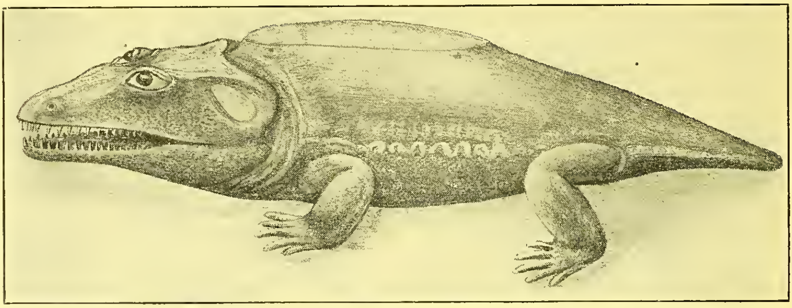

FIG. 4.—*Cacops aspidephorus*, a stegocephalian amphibian twenty inches in length. From Texas.

Varied as were the amphibians, they were not nearly so numerous or so diverse in habit and structure as were the contemporary reptiles. While it is comparatively easy to classify the amphibians, the problems which the reptiles present are vastly greater. Hitherto they have been generally classed in two main groups or orders, the Cotylosauria and Pelycosauria, but the many discoveries of recent years have broken all boundaries and opened up most complicated problems of relationships, problems which will probably not be wholly solved in many years to come. It may be twenty-five years hence before we shall have a tolerably good bird's-eye view of the complete fauna. Especially are the smaller animals, those very difficult to collect and to study, for the most part yet awaiting laborious research.

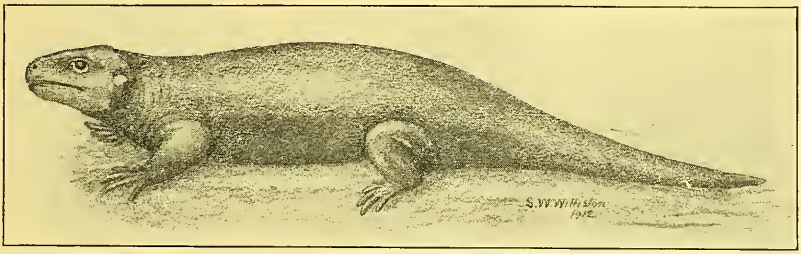

FIG. 5.—*Diasparactus xenos*, a cotylosaur reptile of about seven feet in length. From New Mexico.

But there are about one dozen of these reptiles of which we know nearly all that we may ever hope to know, forms of which complete or nearly complete skeletons have been assembled and mounted. And it is of some of these that I have attempted restorations, and will briefly discuss here.

The order Cotylosauria, whose ultimate distinctions from other reptiles consist solely of the roofed-over skull, without holes in the sides behind, and a short neck, comprises a large group of the most primitive reptiles that we know. All that are known have practically no neck, short and stout limbs, a rather thick-set body, and for the most part not very long tails. They belong to three or four groups, that have been called suborders, and six or more strongly differentiated families. The first of these is represented by *Diasparactus* (Fig. 5), so nearly related to *Diadectes* that one restoration will do for both. It is a reptile of seven or more feet in length, with short, stout legs, not very long tail, and with the head short and high, provided with crushing teeth behind and conical teeth in front. It has an enormous parietal opening in the skull, possibly suggesting a functional "pineal eye." These animals were at first thought to be burrowing in habit, because of the nature of their limbs; but burrowing would have been impossible, since by no possibility could the creatures have reached far enough forward to dig a hole for the head to enter. Nor do they show any decided aquatic characters, though doubtless they swam well. Like the amphibians and most other cotylosaurs and some of the pelycosaurs, they were lowland or littoral creatures, living in and about the old lagoons and lakes.

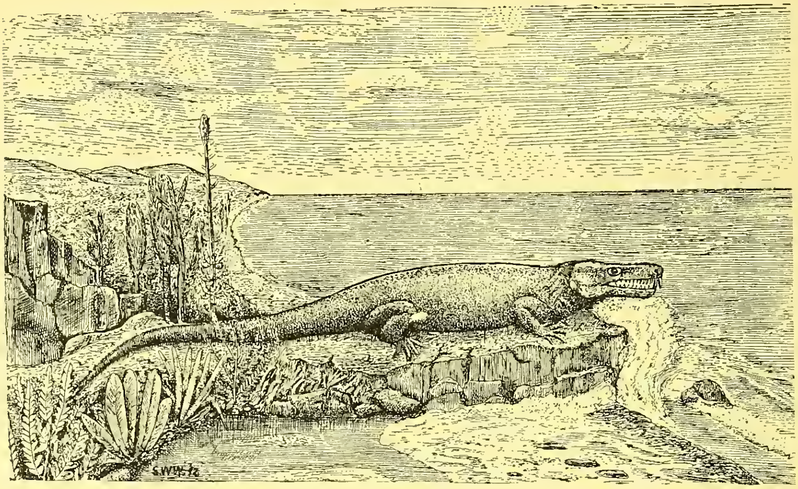

FIG. 6.—*Limnoscelis paludis*, a cotylosaur reptile, seven feet in length. From New Mexico.

The next type, the restoration of which is based upon a marvelously complete skeleton in the Yale Museum from New Mexico, is shown in Fig. 6, as also in part in Fig. 1. It had a much longer tail, and a more elongated and more powerful skull, beaklike in front, armed with strong, conical teeth, the foremost of which in the upper jaws were elongated and curved, as in the next group. Doubtless this was also a lowland reptile, as I have suggested in its name, *Limnoscelis paludis*, meaning marsh-footed reptile of the swamps. This reptile reached a length of seven feet, and evidently had food habits somewhat like those of the next group, though more distinctly carnivorous and rapacious.

The third group, which is composed of numerous known species, varying in length from less than one foot to more than three, is represented by *Labidosaurus* (Fig. 7). I am less certain of the precise details of this creature, since, aside from the skull, the skeletons of the Chicago collection have not been fully worked out. The restoration is based largely upon the figures of the mounted skeleton in the museum at Munich, aided by various nearly complete skeletons of smaller forms. This group of cotylosaurs, the most highly specialized of our American forms, appears to have been of more distinctly terrestrial type than the others. Its limb bones are more slender, and the claws are sharp and curved, unlike those of other groups, where they are flattened terminal nails. Especially striking is the narrowed, beaklike skull in front, and the long, curved, sharp, and rakelike teeth, which suggest their food-habit, that of prodding in the mud and sand for soft-bodied invertebrates, or possibly for detaching limpet-like creatures from the rocks. The teeth of the jaws are arranged in two or more rows, used chiefly for crushing their food, not so much for cutting or tearing.

FIG. 7.—*Labidosaurus hamatus*, a cotylosaur reptile about four feet in length. From Texas.

Still another family, the most lowly organized of all cotylosaurs that are known, is represented by *Seymouria* (Fig. 8). It reached a length of not more than two feet, and had the shortest and broadest feet of all. Its skull is so nearly like that of the contemporary amphibians, especially that of some of the armadillo forms, not only in appearance, but also in actual structure, that close observation is necessary to distinguish them. The teeth are all slender and small, indicating insectivorous habits like those of the amphibians. Doubtless this too was a littoral inhabitant of more or less aquatic habit.

Still another group, one of the most peculiar of all, is unfortunately known only from the skull, of which the best specimens are in the Chicago museum, and known as *Pantylus*. In size this animal was probably no longer than *Seymouria*. It is peculiar in having a broad, flat, and firm skull with the mouth filled everywhere, on jaws and palate, with low, stumpy teeth, suitable only for crushing shellfish.

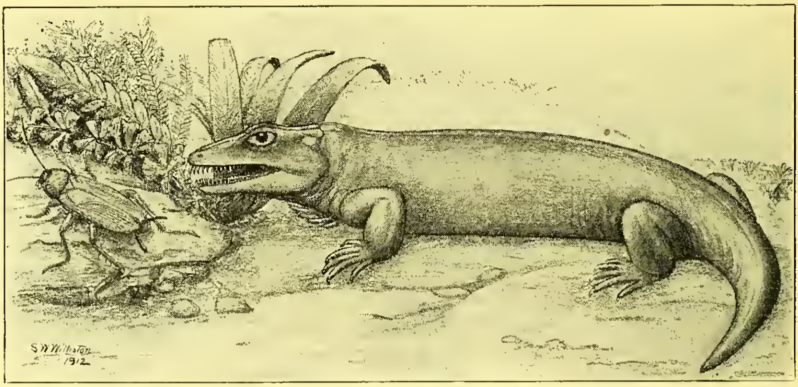

FIG. 8.—*Seymouria baylorensis*, a cotylosaur reptile about two feet in length. From Texas.

Remarkable as is the diversity of structure and habit of these primitive cotylosaurs, that of the next group, commonly called the Pelycosauria, is vastly more so. The reptiles of this group or order, which I prefer to call the Theromorpha, after Cope, are all of a distinctly higher type, especially characterized by the lightened skull, which has one or more holes in its roof behind the eyes, and by the longer neck and longer, more prehensile legs, and usually longer tails.

The best known of all these is *Dimetrodon*, various good restorations of which have been published. It was the largest of all the well-known animals of the American Permocarboniferous, especially characterized by its enormous crest, formed by the spines of its vertebrae, probably bound together by the skin. The skull was fiercely carnivorous in shape and in its teeth, and the largest species must have measured ten feet in length, though the length of the tail is not surely known. Our chief knowledge of the animal is due to Professor Case. It was the Bengal tiger of the fauna.

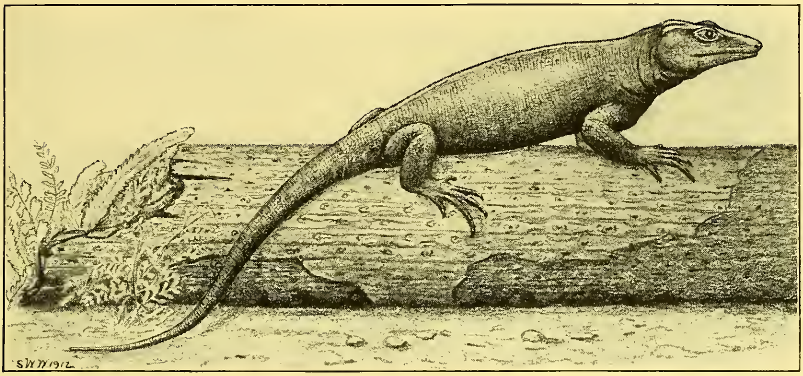

FIG. 9.—*Varanosaurus brevirostris*, a pelycosaurian reptile, forty-four inches long. From Texas.

Unfortunately the reptile whose restoration is most often seen in textbooks and popular works, as the most bizarre and the strangest of the fauna, is one whose real form and habits are very different from what they have been supposed to be. It has hitherto been called *Naosaurus* but its real name is *Edaphosaurus*, since only recently has its true skull, originally so named, been found connected with the vertebrae and with its true legs. A restoration of this strange animal will shortly be published by Professor Case.

Definitely and positively we know nearly every detail of the structure of the animal shown in Fig. 9, as *Varanosaurus*. The mounted skeleton of this reptile in the museum of the University of Chicago is one of a dozen or more found associated in a bone deposit with as many more of *Cacops* and *Casea.* This reptile attained a length of nearly four feet. It had a rather slender body, a slender tail, and rather slender legs, and was marvelously lizard-like in form, and doubtless also in habits. Its teeth are slender and pointed, and were adapted only for the capture of insects and small animals. Its claws are sharp and its toes long. Without great climbing powers, *Varanosaurus* and its allies, of which there are several genera, were fleet-running reptiles, living in the forests, hiding under logs, and feeding upon the numerous cockroaches and other insects.

Fig. 10.—*Casea broilii,* a pelycosaurian reptile forty-three inches in length. From Texas.

Associated with *Varanosaurus* in the same deposit of bones, were a number of skeletons of *Casea*, a restoration of which is shown in Fig. 10. It, too, was nearly four feet in length, but of very different habits from those of *Varanosaurus.* Its skull was remarkably short and thickset. It, too, has a very large pineal vacuity, which curiously seems often associated with herbivorous or malacophagous habits. The teeth were relatively few in number on the jaws, but the palate was completely covered with conical teeth. Its body is extraordinarily broad and long, and of great stomach capacity; its shape is scarcely appreciable in the side view of the restoration. Its front legs were unusually powerful, and its sharp claws may have been used in burrowing. *Casea* was a relatively slow-moving, dry-land reptile.

Still more remarkable was the animal shown in Fig. 11, from New Mexico, a very perfect skeleton of which has recently been mounted in the University of Chicago museum. *Ophiacodon*, so named by the late Professor Marsh because of its slender, snake-like teeth, was fully seven feet in length, and is especially noteworthy because of its apparently enormous skull—apparently, though not really, since it is very narrow, and composed of delicate bones. The feet of *Ophiacodon* are the shortest and stoutest known among pelycosaurian reptiles, and its claws were blunt and nail-like, suggesting lowland or littoral habits, not unlike those of

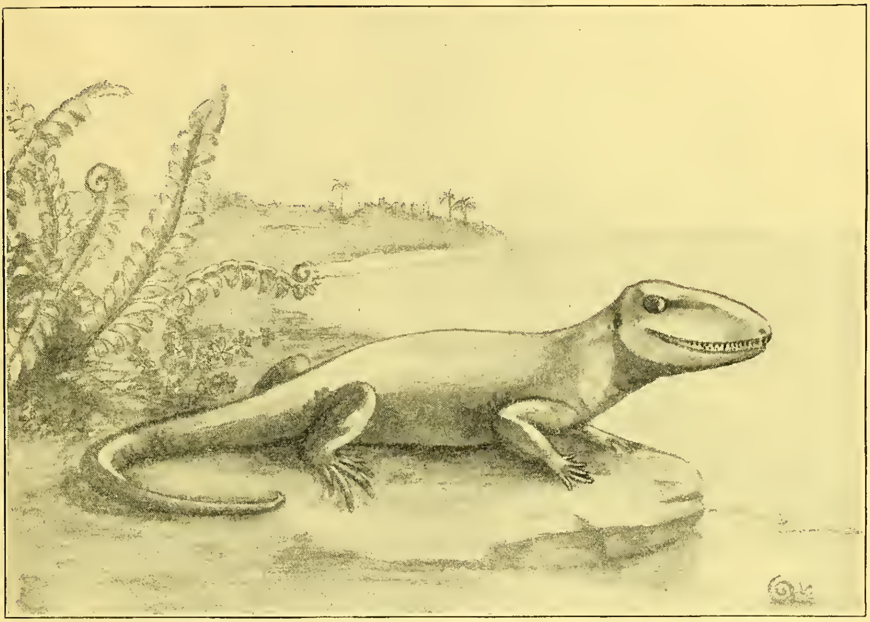

FIG. 11.—*Ophiacodon mirus*, a pelycosaur reptile about seven feet long. From New Mexico.

most cotylosaurs. Its delicate and slender teeth could have been of no use in the capture of large prey; perhaps it preyed upon the numerous small amphibians and reptiles that swarmed in such regions. And doubtless it was more or less at home in the water, though not strictly an aquatic animal. From Texas, however, a very closely allied genus—*Theropleura*—is known to have more flattened and cutting teeth, suggesting more active carnivorous habits.

Finally, the last and most divergent group of all the known paleozoic reptiles of America is represented by a little, very slender, and slender-legged reptile of about one foot and a half in length, which I have called *Araeoscelis*. A description of this animal, giving nearly every detail in its structure, is now in preparation by the writer. Suffice it to say here that *Araeoscelis* is not only wonderfully lizard-like in form, but actually lizard-like in its structure, or as nearly lizard-like as one could expect in such ancient creatures; so lizard-like indeed that I firmly believe that it was actually closely akin to the ancestors of all our lizards and snakes, without a single character that would not be expected in the most primitive lizard. *Araeoscelis* was an exceedingly fleet, climbing and running reptile of the uplands, of purely terrestrial habits.

In conclusion I may add that, whatever may be the merits of these restorations as works of art, they have been drawn with most scrupulous accuracy so far as form and proportions are concerned, the musculature derived from the study of living reptiles. And, as I have said, they are all based upon practically complete skeletons; in a few only the precise length of the tail is yet unknown, or the front toes in *Trematops* and *Cacops*.

MECHANICS OF FORMATION OF ARCUATE MOUNTAINS

WILLIAM H. HOBBS
University of Michigan, Ann Arbor, Michigan

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PART I

INTRODUCTION

The Alps the European type of the Asiatic mountain arc.—Studies of mountain structure have made use chiefly of profiles, or cross-sections, at right angles to the crests of the ranges. In recent years and to a relatively small extent only, longitudinal sections have also been figured in order to take account of the directions of pitching folds. In the geological map the plan of the region is of course represented, but chiefly with a view to fixing the areal distribution of the formations; and so far as known the discussion of the mechanics of the folding process has been restricted to the two dimensions included in the normal profile. While the reason for this may be in part the difficulty of representing more than two dimensions of space, it is no doubt due largely to a general belief that all significant elements in the problem can be properly set forth in the transverse section.

It was Eduard Suess who first clearly demonstrated the deep significance of the plan of arrangement of Asiatic or Euro-Asiatic mountain arcs. The Alps are to be regarded, as Suess has clearly shown, as an extension into Europe of the Asiatic mountain system, which includes also most of the ranges of southern and southeastern Europe. The name "Asiatic arcuate structure" or "Asiatic structure" is well chosen for the reason that this entire political division of Asia with the single exception of the peninsula of Hindustan, but including the entire group of island fringes as far out as the Bonin Islands and the Mariannes, is characterized throughout by the most pronounced of mountain arcs. Generally less typical, the same structure is represented upon the western continent by the sweeping arcs of Alaska, certain northern ranges of the Rocky Mountain system, and the Appalachians and West Indian ranges; while the only marked example upon the African continent is the Atlas range in the northwest.

In view of this extent and evident importance of the mountain arc, and its typical illustration in the Alps, no structural geologist can afford to remain in ignorance of at least the broad outlines of the Alpine problem. Whatever may be true of some other mountain districts that have been studied, here at least the plan as well as the vertical sections must be fully considered in the discussion of the mechanics of the folding process.

Conditions favorable for tectonic studies of the Alps.—No mountain region has excited so much interest in its structural problems as has the Alps. This is in part to be explained by its location in the very heart of Europe easily accessible to the geologists of every European nation, and in part by the scenic and hygienic qualities of the Swiss highland which have made it the playground not only of Europe but of the world as well. Its rugged features have been mapped in much detail and with praiseworthy accuracy, and the cartography of the country is the pride of every enlightened Swiss. Switzerland has, moreover, produced structural geologists who have ranked high among their fellows, and the complex problems of Alpine tectonics have gradually evolved from the early conception of Escher von der Linth to the brilliant theory of

Bertrand, later worked out by Schardt, Suess, Lugeon, Termier, Heim, and others.

It should not be forgotten that there are in the Alps some natural conditions which are favorable to the solution of its structural problems, and without which it seems likely that we should have advanced but slowly toward the goal. The rocks of which the Alps are composed are very largely sediments, which in a considerable portion of the area are uncrystalline and so richly fossiliferous that it has generally been possible to determine the place of each local bed within the vertical column. Almost as important in view of the peculiar character of the deformation, there is a horizontal differentiation of the beds from the northwest to the southeast which is recognized both in the petrographic character and in the fossils of the several formations. Thus it has been possible upon this basis to determine in some measure the lateral as well as the vertical displacements of the beds.

To a small extent only and in relatively few of the significant localities have the beds been greatly altered through the intrusion of igneous masses; and the regional metamorphism has seldom been so great as completely to destroy the identity of formations. Sculptured by glaciers into a fretted upland, the sheer mountain walls of the Alps, bare as they are of vegetation, often reveal in wonderful perfection all the intricacies of their complex structure. Thus with all its complexity the great problems of Alpine structure appear to be soluble, and it is easy to see that if differences of opinion still exist, we are none the less slowly approaching the goal.

To all these natural advantages for study there are to be added the network of mountain railways which surpass anything of the kind to be found elsewhere, a wealth of good hostelries, even at high and not easily accessible points, the numerous refuges, and the fraternity of competent and hardy guides.

For some other regions, such for example as that of southwestern New England, no one of the above-mentioned natural conditions is realized, and there is therefore good ground for believing that the problems of structure are in consequence practically insoluble. It is the author's belief, based upon many years of study in the region, that though in certain favored districts maps and sections revealing internal structure may be prepared, for the larger portion of the region the most that can be expected is to derive a general notion from the study of the key localities.

The blanketing series of slices which make up the Alps.—It is not our primary purpose to present in detail at this time the modern Swiss interpretation of Alpine structure, or the objections which have been raised against it. Such an outline, important as it is for American students, who are likely to be bewildered by the many new terms, particularly when these terms are found in the original German and French sources, must be deferred until after the mechanics of the process has been considered. It is perhaps sufficient to allude here to the fact that the conception of series of blanketing slices (*Decken* or *nappes de recouvrement*), which originated in the mind of Bertrand in 1884,[1] was worked out independently and applied by Schardt in 1890–93 in the Voralpzone, and again by Lugeon in 1896, has now overcome all opposition in Switzerland, and, following its adoption by Heim himself in 1903, it has been the accepted doctrine of all Swiss workers without exception.

The story of the gradual acceptance of this theory reads like a romance and probably has no parallel in the history of geology. When the idea was first suggested by Bertrand upon the basis of his studies of the coal basin of northern France, no one seems to have taken the theory seriously as it applied to the Alps, since its author had never studied that region upon the ground. When nine years later Schardt was independently forced to similar conclusions in order to explain the structure within the area between the lakes of Geneva and Thun, he was vigorously opposed, by Lugeon among others. Hardly three years later Lugeon had been forced by his own studies to accept the new doctrine, and he is now its most prominent champion. Heim himself, whose name for almost a generation had been identified with the earlier theory of the double fold, accepted the new theory in 1903, and thereafter

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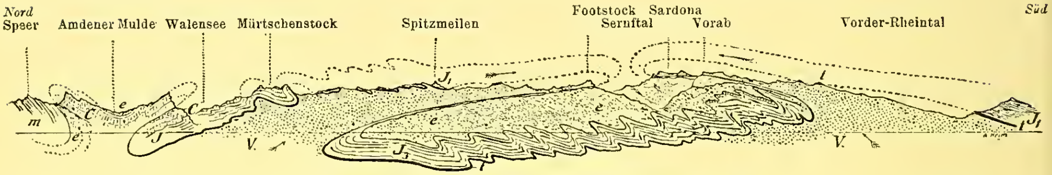
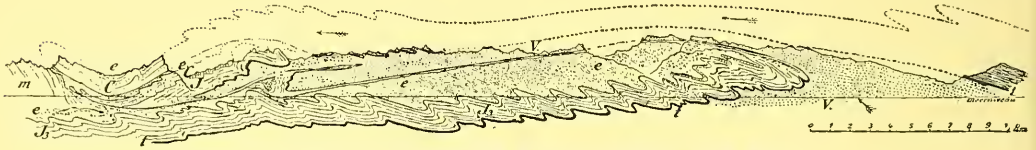
[1] Marcel Bertrand, "Rapports de structure des Alpes de Glaris et du bassin houiller du Nord," *Bull. soc. géol. de France* (3), XII (1884) 318–30, Pl. 11.

it became standard doctrine throughout Switzerland. From Alpine countries outside Switzerland there have come examples of prominent structural geologists long identified with Alpine studies who first fought and later defended the Bertrand-Schardt conception of Alpine structure.

If a personal incident may be permitted, the writer's own experience has not been greatly different. In the summer of 1912 he entered the central Alps with the paper of Willis[1] in hand, much impressed by the simplicity and the ingenuity of its conception; but after devoting the greater part of the season to examination of critical districts and to a study of sections across the central Alps, he became convinced of its insufficiency and of the general correctness of the now accepted Swiss view. There can be little doubt that this view is steadily gaining ground among those structural geologists who have given their attention to the subject.



A. „Glarner-Doppelfalte" 1870 bis 1902 Escher und Heim.



B. „Glarner-Deckfalten" 1883 Bertrand, 1892 Suess, 1903 Heim.

m = Molasse (Nagelfluh, mitteltertiär)
e = Flysch (alttertiär)
C = Kreide
J = Jura
t = helvetische Trias (Röthidolomit)
V = Verrucano (Sernifit).

Fig. 1.—The Glarus folds and thrusts upon (*A*) Escher's conception of the double fold, and (*B*) Bertrand's view of overfolding and overthrusting (after Heim).

Necessity for considering the mechanics of formation of arcuate mountains.—Though it be true that the theory of "overfolding and

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[1] Bailey Willis, "Report on an Investigation of the Geological Structure of the Alps," *Smithson. Misc. Coll.*, LVI, No. 31 (1912), 1–13.

overthrusting" as an explanation of Alpine structure is steadily gaining ground, it is none the less a fact that there is much criticism of the mechanics of the processes which have been invoked, and the writer believes that this criticism is well founded. Swiss geologists profess to regard this phase of the subject as of slight importance; but so long as it is necessary to reconstruct from incomplete surface indications folds which are in part concealed below the surface, the contention of these geologists can hardly be admitted to be justified. No better illustration could be offered than contrasting the "double fold" and the "blanketing nappes" theories as applied to the classical district of the Glarus (Fig. 1). Both theories involve complex structures which have never yet been found complete in any region, and discrimination between them must of necessity depend in some measure upon the possibility of accounting for their formation as a result of conceivable stress-strain conditions during a profound deformation of the region. In order to throw light upon their origin, all that is known of the mechanics involved in the folding process should be brought to bear, with due consideration of the fact that the Alps furnish a perfect illustration of the Asiatic type of mountain arc.

THE FOLDING PROCESS STUDIED IN THE PLAN—ARCUATE STRUCTURE

Areal and morphological characteristics of Asiatic ranges.—Study of a modern map of Asia upon which the relief has been indicated brings out some quite remarkable facts of distribution of the mountain ranges (Fig. 2). These facts might be stated in somewhat categorical form as follows:

1. The ranges are arcs which present their convex sides to the oceanic areas.

2. The arcs taken together in part inclose a relatively rigid mass of ancient rocks which from earliest geological times has been a land area and has become known to geologists as the Angara coign or shield.

3. The inner arcs of the series are the older and simpler in form and have the largest radius of curvature.

4. The intermediate and outer groups of arcs of the imperfectly concentric series are of later date and consist of festoons, or spring from a number of cuspate areas. This arrangement is described as "linking" or "syntaxis."

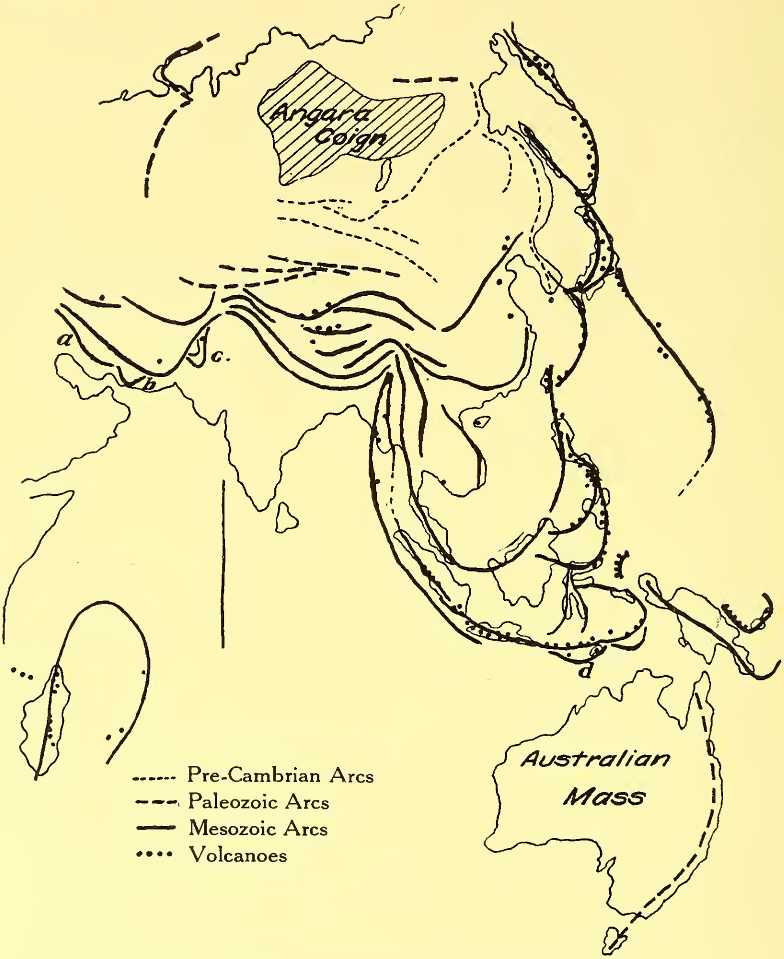

FIG. 2.—Sketch map of Asia to bring out the plan of the principal mountain ranges with indications of the partially submerged chains.

5. Several arcs of different radii in some cases spring from the same pair of linking areas which thus become centers of "virgation." The nearly parallel ranges near where they are linked are sometimes referred to as *coulisses* (Fig. 3).

6. Within the geologically recent peninsula which comprised the present Malayan peninsula, Indo-China and Malaysia, the arcs are developed in relatively much narrower and deeper festoons than elsewhere, thus giving the impression of having been subjected to strong lateral compression.

7. Locally and upon the outermost series of arcs, particularly, are superimposed arcs of smaller order of magnitude arranged after the manner of a scalloped border (Sewestan, Timor, etc., Fig. 2, *a*, *b*, *c*, *d*).

8. The outer group of arcs is paralleled by near-lying arcs of volcanoes generally upon the concave margin, and these vents are characterized by unusually strong activity (see Figs. 2, 4, and 5).

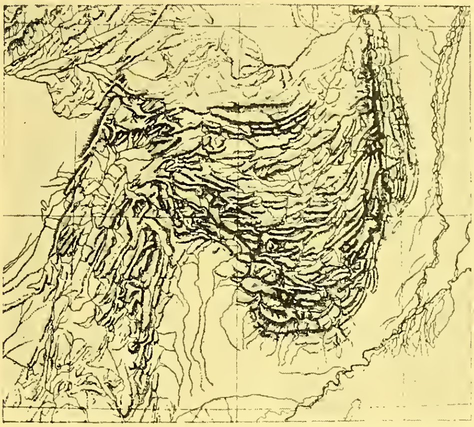

FIG. 3.—The multiple arc of Sewestan, British India (after de Saint Martin and Schrader).

9. Upon the convex margin of the outer series of arcs particularly lie "fore-deeps" (Fig. 5).

10. The outer series of arcs is characterized by extraordinary seismic activity (Fig. 6).

11. The outer arcs lying between the ancient Angara land-mass and the Pacific Ocean are to a marked degree asymmetric, each succeeding arc in the series springing from the side of its neighbor (see Fig. 2).

Structural peculiarities of the arcs.—Of all mountain arcs of strongly marked Asiatic type, the Alps have been most carefully studied with respect to tectonic structure. Speaking broadly and in the usual terms, this arc consists largely of a series of sediments folded into closed recumbent flexures with axial planes which incline (except where the crown has sunk) toward the interior of the arc, and which are further extensively "overthrust" and "overridden" in the same sense. Such knowledge as we have of the arcs of Asia, now fortunately assembled and analyzed by Suess, indicates that in a very general way close recumbent folding and "overthrusting" is characteristic of them, and that the dip of the axial planes and the "thrusts" takes the same direction toward the interior of the arc. Quite recently a somewhat comprehensive tectonic study

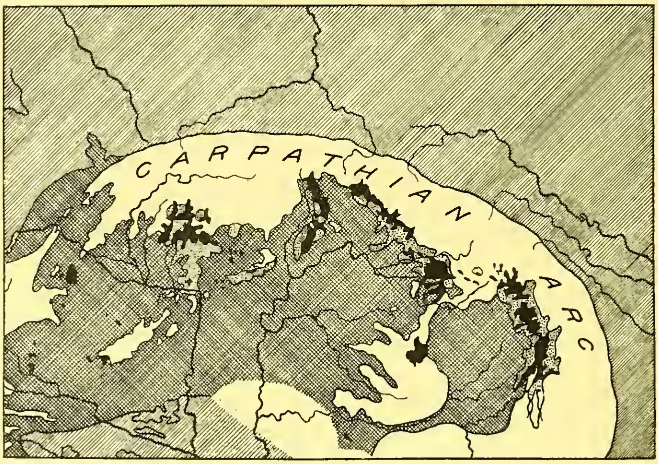

Fig. 4.—Arc of the Carpathians with volcanoes ranged upon the concave margin (after de Martonne).

Fig. 5.—Sketch map to show the relation of fore-deeps and arcs of volcanoes to Asiatic arcs.

of the Timor arc (*d*, Fig. 2) by Molengraaff[1] has shown a quite remarkable parallel with the *Deckenbau* of the Alps. Examples of "overthrusting" in extra-Asiatic arcs seem to be augmenting as these are studied with greater thoroughness.[2]

Centrifugal versus centripetal distribution of the active forces which produce mountain arcs.—In a broad way the great Asiatic mountain arcs no doubt owe their location to the presence of lenses of sediments laid down in former epicontinental seas along the borders of the growing continent of Angara. This fact alone would account for their essentially annular arrangement about the ancient coign of the continent as a center. It does not, however, explain the formation of the flexures or the places of location of the individual mountain arcs. There seems to be no difference of opinion that in some way the arcs are due to a system of tangential stresses which operated within the earth's outer shell. Suess has assumed that the system of stresses which produced the Asiatic arcs acted from *within the arcs outward*, or, in other words, was centrifugal, the more rigid and

FIG. 6.—Outline map of the Asiatic continent and neighboring archipelagoes to show (in black) the seismic zones. Note the close correspondence with the outer series of mountain arcs (Fig. 2) and with the zones of volcanoes (after de Montessus de Ballore).

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[1] Paper read at the Twelfth International Geological Congress in Toronto, August, 1913.

[2] See A. Hamberg, "Die schwedische Hochgebirgsfrage und die Häufigkeit der Überschiebungen," *Geol. Rundsch.*, III (1912), 226–35; also Bailey Willis, "Überschiebungen in den Vereinigten Staaten von Nordamerika," *C.R. IX Cong. Géol. Intern.*, Wien, 1903 (1904), 531, 539–40.

hence resistant masses lying outside;[1] a view which has been rather generally accepted, it would seem, and which is followed, among others, by Arldt.[2]

To accepting this conception there is an insuperable objection from the standpoint of mechanics. The necessary reduction in area of the strata through duplication by folding and "overthrusting" is certainly great, and if this duplicated and often reduplicated expanse of strata has come from within the area inclosed by the arc, one of two consequences must have followed. Either a hiatus must have developed near the center of the area, or else the strata must have become greatly attenuated, an effect which should be increasingly apparent in the upper and later folds of the series and throughout in the upper limbs more than in the lower (Fig. 7, *Aaa′*). If, upon the other hand, the arcs are to be explained as a result of centripetally distributed forces coming from outside the area inclosed by the arc, these difficulties are not encountered for the reason that contraction of surface of large portions of the earth's outer shell may be assumed to supply the

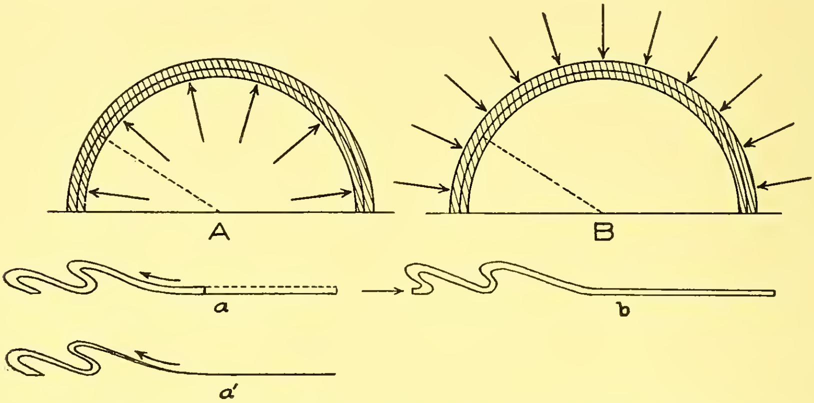

FIG. 7.—Diagrams to contrast the conceptions of centrifugally distributed (*A*) and centripetally arranged (*B*) forces in the production of mountain arcs. The lower figures are enlarged sections along the dotted lines, and the arrows in all cases give the directions of the (assumed) active forces.

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[1] Ed. Suess, *Antlitz der Erde*, III, 1–2.

[2] Th. Arldt, *Die Entwicklung der Kontinente und ihrer Lebewelt*, Leipzig, 1907.

strata which are duplicated and reduplicated in the recumbent and "overthrust" folds (Fig. 7, *Bb*).

A centrifugal system of active forces implies that a mass relatively rigid and resistant with respect to that within surrounds the arc. Centripetally distributed thrusts, upon the other hand, imply that the area within the arc is relatively the more rigid and less capable of lateral migration.

Deductions concerning the relative age of Asiatic arcs.—If now we apply this criterion of distribution of thrusts, not to individual arcs alone, but to the Asiatic series as a whole, the centrifugal system of thrusts meets with a no less serious additional difficulty; for it would in this case be necessary to assume that the outer arcs were the first formed and the inner arcs the latest. Upon the other hand, a centripetal arrangement of active forces requires that the reverse should be true. That such is the case appears to be supported by at least four important considerations: namely, (1) the plan of distribution; (2) the position of the more rigid mass; (3) the known geological age of the ranges; and (4) the present locus of seismic and volcanic activity.

That the outer arcs of the system are, so to speak, laid on or applied to the inner ones is apparent from observation of the outline map (Fig. 2). More especially is this the case for the smaller arcs attached to the eastern wing of the great Burman Malaysian series and its extension to the north; as it is also for the arcs of Seyestan (Fig. 2, *c*) and Timor (Fig. 2, *g*).

As regards the position of the relatively more rigid area, we know that the Angara platform is an ancient land-mass which has been undisturbed since the Cambrian, whereas outside of the area of the arcs, if we except the remnant of the Gondwana continent in Hindustan and the separated mass of Australia, we encounter only the depressed oceanic basins.

The inner series of arcs, less clearly marked out morphologically as a result of long-continued erosion, we find to be of pre-Cambrian and Permo-Carboniferous age, though accompanied in some instances by later foldings. Farther out we encounter the great Tertiary welts of the Himalaya, Hindu-Kush, and their extensions which have been so recently elevated that erosive processes have not yet succeeded in reducing their excessive relief. Still farther outward and upon the margins of the system, we have mountains which may more properly be described as in the making, with all the accompaniments of strong earthquake and violent volcanic eruption.

The ocean basins the loci of dispersion of tangential thrusts.—To this conclusion we are led by the considerations of the last section.[1] To the tectonic argument modern seismology has made a contribution of the first importance. Until within a quarter of a century it had been the custom to regard the continents as the regions of the most active geological movement upon our planet—a striking illustration of the assumed dominance of phenomena near at hand and often observed in fixing the basis of judgment. Yet a moment's thought shows us that the floors of the oceans are masked beneath a mobile cover which must effectively damp all disturbances that emanate from them. Now that a means has been discovered for seismically exploring this vast area and subjecting its movements to measurement, we have been surprised to learn that its mass movements are, area for area, vastly greater than those of that portion of the lithosphere which projects above the seas.

If we except the immediate vicinity of the continents, there is evidence that as a whole the movements upon the ocean floor are downward toward the earth's center, and hence the greatest reduction in superficies is there today in progress. Of this the evidence is twofold. By far the greatest of all macroseisms proceed from the deeper portions of the ocean floor, and we may draw the conclusion that if the mass movements were not in general downward rather than upward, these areas could hardly remain the deeps. On the other hand, except in the neighborhood of great deltas, most mountain shores of the continents are today rising. This is eminently true of that remarkable fringe of island arcs which lie to the eastward of the Asiatic continent, a fact amply demonstrated by the elevated shore lines and high coral reefs. The amounts of elevation are here further in direct proportion to

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[1] See also T. C. Chamberlin and R. D. Salisbury, *Geology*, I, 517–18, 520–21.

the breadth of the fringes.[1] The narrow Liu Kiu and Kurile island arcs—mere lines of volcanic summits with no visible cordillera—show evidence of relatively slight elevation only, and these lie opposite the great sinking deltas of the Hoang and Yangtse in the one case and the Amur in the other. Still farther out toward the center of the Pacific, the Bonin group indicates some islands rising, others sinking, and still others rising after a depression—the group as a whole without as yet very strong indications of general uplift.

There is still the further argument that throughout the area of the coral seas, as was first pointed out by Charles Darwin and James D. Dana, working independently, the ocean floor has long been sinking, since in no other way can atolls be adequately accounted for.[2]

Any general movement of the ocean floors in the direction of the earth's center which is in excess of movement in the same direction in the continental areas must be accompanied by an out-thrusting against the continental margins such as would be required to explain the formation of mountain arcs uniformly facing the sea. That such thrusts are in reality carried out to the continents from the oceanic areas and cause landward migration of strata is also necessary to account for the fact that the elevation of mountains is not accompanied by tensional phenomena such as the gaping of fissures, etc. Mountain growth accompanied by strong earthquakes reveals in the behavior of rails, pipes, bridges, etc., the fact that not expansion but contraction of the surface has resulted from the movement.[3] The so-called block or *Schollen* theory of formation of mountains, amply demonstrated by observation in many regions, has had to contend with the supposed theoretical difficulty that opening of fissures by tension should result.[4]

[1] *Bull. Geol. Soc. Am.*, XVIII, (1907) 233–50, Pl. 5.

[2] The ingenious rival theories of Sir John Murray and other biologists fail utterly to explain certain necessary geological consequences. Professor Davis has utilized the Dana centennial to recall Dana's decisive discussion upon this point and to strengthen it by his own arguments.

[3] "A Study of the Damage to Bridges during Earthquakes," *Jour. Geol.*, XVI (1908), 636–53.

[4] *Proc. Am. Phil. Soc.*, XLVII (1909), 27–29.

So soon as we attempt to estimate the lateral migration of a point at the shore due to any given sinking of a definite arc upon the ocean floor, we find that the measure of the movement is probably insufficient to account for the duplication of strata in mountain folds. The landward migration corresponding to a uniform descent to a depth of one mile within an arc a thousand miles in width, if divided equally between the coasts on either hand, would amount to only about 1½ miles, or, if concentrated upon one coast, to double that amount.[1] Account is to be taken, however, of a concomitant change in volume due to a relative elevation of isogeotherms into the descending sector of shell. Sedimentary rocks expand upon the average about $\frac{1}{190192}$ for each degree Fahrenheit, or 2.75 feet per mile per hundred degrees.[2] An arc of a thousand miles should thus be extended, from elevation of temperature in a uniform descent of one mile, a distance of between 1,985 and 2,770 feet, according to what figure is taken for the geothermic gradient. If this effect be added to that which is due to shortening of the arc, the expansion of the strata in the arc would be about 3½ miles per thousand miles of arc. This figure, though somewhat small, is probably of the right order of magnitude to account for the duplicating of strata in mountain ranges.

If now we consider the possible effect of a disappearance through depression of the Gondwana continent upon outthrust toward the continent of Asia, we are warranted in assuming for Gondwana Land a fairly high level, for the reason that even within the tropics there was extensive glaciation. The average depth of the Indian Ocean may be taken as 4,200 meters, and the average descent of some three miles over an arc of 5,000 miles is not improbable. If this outthrust caused landward migration of strata upon the Asiatic shore only, the outthrust northward would correspond to a displacement of about 52 miles. This is, however, a maximum figure, and

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[1] J. D. Dana estimated that within an arc corresponding to a quarter of the entire circumference of the globe, a uniform descent of 8 miles would cause a lateral displacement of 12 miles ("On the Origin of Continents," *Am. Jour. Sci.* (2), III [1847], 97).

[2] T. Mellard Reade, *The Origin of Mountain Ranges*, London, 1886, pp. 109–12.

should be diminished by any folding upon the opposite end of the arc, by reduction in volume of the strata, by any closing-up of joint spaces, etc.

In this connection it should not be overlooked that when the stage of sliding has been reached in the process of folding, the surfaces of dislocation in nearly horizontal attitude so facilitate underriding of strata that this may follow contraction without the necessity of infall of the depressed areas.

Form of the arcs and their distribution an expression of the space relations of continental pedestal and ocean floor.—If we are to assume the ocean basins to be the great loci of dispersal of compressive tangential stresses within the earth's shell, as brought out in the last section, we should examine each one of the Asiatic series of arcs to note whether it correctly expresses what is known of the distribution of ocean and continent and of deepening or shallowing conditions in the former at the time of arc evolution. In pursuing this inquiry we note that the Permo-Carboniferous arcs to the southward of the Angara coign should have a general east-and-west trend in order to correspond to thrust from the Tethys Sea which at the time of their formation stretched in that direction over what is now southern Asia and separated Angara land from the great Gondwana continent to the south. To the eastward of the ancient coign the general trend of the arcs should not, however, differ greatly from that of the later arcs in the same vicinity or of the shore line of today.

The extension of the Angara continent southward over the Paleozoic Tethys, and the formation of the Indian Ocean by the breaking-up and partial sinking of the Gondwana continent previous to the folding of the early Tertiary period, is likewise in conformity with the greater accentuation of the curvature of the Tertiary welts across southern Asia. The growing peninsula which in Tertiary time connected the Malaysian archipelago to Asia was partially protected from southerly thrust by the mass of Australia, while being pinched between the eastern sea in the Indian Ocean and the vast Pacific. We may thus perhaps account for the elongation of the Burman-Malay arcs and their noteworthy lack of symmetry as well.

The great central remnant of Gondwana land which in Cretaceous time joined Madagascar to Hindustan, stretching across the central zone of the present Indian Ocean, persisted in large part through the early Tertiary and may account for the main subdivision of the Tertiary arcs to the north of Hindustan as well as the well-defined compressed arc which still exists in part submerged to the northward of Madagascar.[1]

In later Tertiary time the Malaysian extension of the continent grew to the southeastward and the union of the two great seas to form the present Indian Ocean increased the thrust from the southwest and opposed more strongly that from the Pacific. From the south-southeastward the shielding mass of Australia should reduce the thrust upon the front of this arc and so favor its lateral compression from the oceans on either side. The smaller marginal arcs ranged in series, such as we find in the Philippine archipelago, show in macroseisms continued depression of their fore-deeps, and this indicates that the growth of the arcs may continue at a rapid rate after new arcs (here the Bonin) have begun to form farther out toward the central area of the ocean.

THE FOLDING PROCESS STUDIED IN THE PLAN—EXPERIMENTS WITH CONTRACTING FILMS

An imitation of arcuate structure may be produced by allowing slightly plastic films on stretched rubber sheets to contract after being locally rigified. This is best accomplished by use of hot Canada balsam spread in thin layer upon a sheet of stretched rubber such as is in use for the manufacture of bellows. An apparatus designed for such experiments is represented in Fig. 8 and consists of a strong metal frame within which three brass springs are so related to each other as to outline in the plan a plane equilateral triangle when in unstrained condition. When this triangle is manipulated by simple rods of metal notched upon the lower side, the degree of expansion of the triangle may be varied and maintained for any desired length of time. The springs which

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[1] This arc is outlined upon Madagascar and in the Farquahar, Amirante, Seychelles, and Coetivy islands, the Saya de Malha Bank, and the Cargados, Mauritius, and the Réunion islands (see Fig. 2, p. 78).

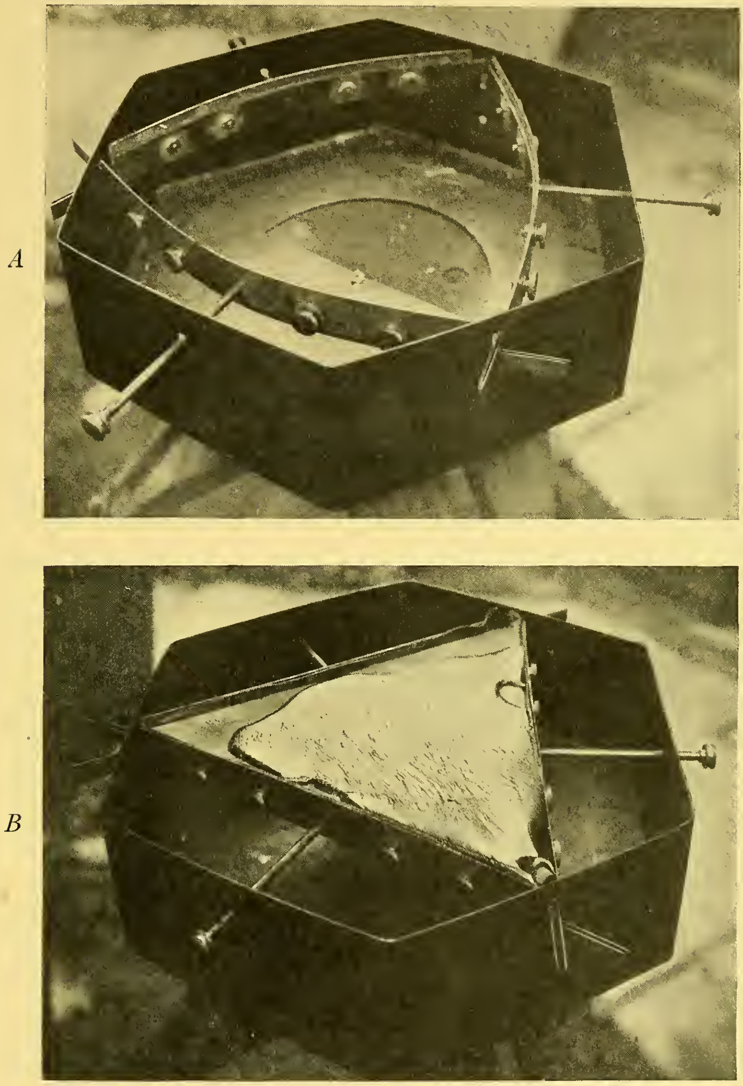


Fig. 8.—Apparatus for the simulation of mountain arcs through the contraction of locally rigified films of plastic material. *A*. View of frame with metal triangle in extended position. *B*. The same with sheet of rubber supporting a layer of Canada Balsam which was poured hot and when the rubber sheet was stretched, but was locally rigified and then forced to contract upon the relief of tension in the rubber.

compose the sides of the triangle are double and provided with clamp screws to permit of fastening the rubber sheet at its margins. When in use, the frame is placed upon a ring tripod, and since the frame is supplied with a window in its bottom, cold masses of metal of any desired shape may be introduced below and brought in contact with the under surface of the rubber sheet in order to induce local premature rigifaction of the cooling layer of balsam resting upon the sheet.

The principal difficulties encountered in carrying out the tests are due to the necessity of evaporating the balsam so that it will rapidly rigify in cooling and still be sufficiently fluid when poured upon the sheet to spread out into a thin layer. The evaporation can be accomplished upon a water bath, but a slightly higher temperature given it just before pouring is desirable. If the temperature is carried too high the surface of the rubber may be seriously affected.

The series of concentric arcs which appear in the balsam layer represented in Fig. 8 are due to the local rigifaction of a circular area near one side of the triangle but not centered upon a bisectrix, with the principal contraction of the sheet from the two sides opposite the convexity of the arc.

REVIEWS

Structural Geology. By C. K. LEITH. New York: Henry Holt & Co., 1913. Pp. 169; figs. 68. $1.50.

The central feature of this admirable work is the interpretation of rock structures as expressions of dynamic processes, rather than descriptions simply. Students of geology are generally more or less familiar with the different kinds of rock structure, simply as such, but they are not so generally accustomed to interpret these structures as related parts of a record or of a process. In this work the author has adopted a philosophical mode of treatment by approaching rock structures from the point of view of the forces and processes which have produced them. The structural phenomena are aligned chiefly as the products of fracture or of flow.

As the book is relatively short, the author plunges at once into a critical discussion of rock fracture and rock flowage and of the controlling conditions which express themselves in one or the other of these two methods of deformation. Then in the light of the principles of rock fracture which have been developed, he takes up in detail the treatment of the leading rock structures resulting from this type of deformation. Of these, faults naturally receive the greatest attention, but a fair apportionment is given to joints, fracture cleavage, breccias, and autoclastics. Earthquakes, both as causes and effects of rock fracture, complete the first half of the book.

In the second half, under the heading of rock flowage, are treated in order flow cleavage, gneissic structure, and porphyritic textures developed by rock flowage. These lead to a digression on the identification of schists and gneisses, in which the stand is taken that with our present knowledge, field observations are likely to yield more satisfactory conclusions as to the igneous or sedimentary origin of given gneisses and schists than either mineral or chemical composition. Folds are treated as structures common to both the zone of fracture and the zone of flow, but folds developed in these two zones may be discriminated by the contrasts which they exhibit in a number of particulars.

Mountains and the other major units of structure each receive a brief but pointed consideration. Isostasy as an agency to explain these relief features is analyzed and then criticized on a number of grounds. Dr. Leith states squarely that isostasy and rigidity in any high degree are mutually exclusive and as between the two he favors rigidity. The rigidity of the earth is a matter whose importance has been very generally passed over lightly, or carelessly swept aside by students of mountain building. But the brilliant determination of earth rigidity now in progress by Michelson, Gale, and Moulton firmly establishes the view favored by the author. The results seem indeed already to foreshadow that rigidity is the rock upon which not a few favorite theories are destined to be wrecked.

The average reader will perhaps be struck with the absence of numbered chapters. The framework of the book is really a skeleton outline—the familiar blackboard device of the systematic lecturer—with a few principal headings, under which are marshaled a graded series of subheadings. The relative importance and correlation of these are rendered easy by different styles of type. For systematic study as well as classroom presentation this method has its advantages.

The treatment is strong and judicial; the discussion closely woven and effective, and while conciseness and brevity were doubtless sought, they result in very concentrated nourishment. The reviewer is of the opinion that the average working geologist will wish that the book were about twice as long. The treatise is a distinctly valuable contribution. It has no equal in its field.

R. T. C.

The Devonian and Mississippian Formations of Northeastern Ohio. By Charles S. Prosser. Geological Survey of Ohio, 4th Ser., Bulletin No. 15. Pp. ix+574, 33 plates. Columbus (1912), 1913.

The author devotes five chapters, or a major part of the bulletin, to a detailed description and discussion of the more important rock sections exposed in northeastern Ohio, together with observations on the fossils usually found associated therewith, and to a review of the literature bearing on the geology of that section of the state. This is followed by a chapter on correlation, and the bulletin concludes with the description and illustration of the major part of the Chagrin fauna, in which are included four new species and two new varieties.

The sections alone are a valuable addition to our knowledge of the geology of that region, as they bring out clearly the varying character of the rocks which have usually been classed together as a single formation. A great many of the sections and plates emphasize the importance of the erosional surface on which the Berea sandstone often rests.

The following classification of the rocks exposed in the region under discussion gives the formational relationships as used:

Pennsylvanian	Sharon conglomerate	
Mississippian	Royalton formation	
	Sharpsville sandstone	
	Orangeville formation	Brecksville shale
		Aurora sandstone
		Sunbury shale
	Berea grit	
Devonian	Bedford formation	
	Cleveland shale	
	Chagrin formation	

On the evidence of its fossil content, the author has definitely correlated the Chagrin formation with the Chemung of Western New York, and the Huron shale in general is regarded as the western stratigraphic equivalent of the Chagrin formation. The fact that the Cleveland shale thickens to the southwestward is observed to be due "largely to the downward encroachment of the black deposits upon the Chagrin" and to a similar "encroachment of the typical Cleveland black shales upon the lower deposits of the Bedford formation." To the eastward, however, the Cleveland shale is found to decrease in thickness and to be wanting in the sections near the Ohio-Pennsylvania line, possibly in all those east of the Grand River valley.

In the Bedford formation, the Euclid sandstone lentil near the base and the Sagamore sandstone lentil at a somewhat higher horizon are described. The disposition of the Bedford formation is not quite so clearly made but it apparently either thins out entirely before the Pennsylvania state line is reached or is represented by a part of the Venango sandstones and shales, possibly including the Riceville shale, of Pennsylvania. As evidence of its thinning out the finding of Chagrin fossils in deposits below but very near the base of the Berea sandstone is cited. "The results obtained in this bulletin seem to show conclusively that the Berea formation of Ohio is the western equivalent of the sandstone of western Crawford County, Pennsylvania, identified by Dr. White as the Corry sandstone and the subjacent Cussewago shales and Cussewago sandstone." The sections given for this eastern region show that the splitting up of the Berea sandstone begins at least as far west of the Pennsylvania state line as Windsor Mills, near the west line of Ashtabula County.

The most important change made in the classification, as formerly used, is the breaking up of the old Cuyahoga formation into the Orangeville formation, Sharpsville sandstone, and Royalton formation, while the Sunbury shale becomes merely a subdivision of the Orangeville. The two lower divisions of the Cuyahoga are considered to be the western extensions of the formations of the same names in western Pennsylvania, while the Royalton formation is apparently the Meadville, with perhaps also the Shenango, of the Pennsylvania classification.

This volume is by far the most important stratigraphic publication issued by the Geological Survey of Ohio in recent years. It deals with a part of the state which has been very much misunderstood by many of the former workers in that region and therefore misrepresented to the geological world. Undoubtedly the greatest importance of the bulletin lies in its bearing on the boundary line between the Devonian and Mississippian of Ohio, which is still a subject of much controversy. It appears that Dr. Prosser favors drawing this line at the base of the Berea sandstone, but he makes the statement that he "has not yet reached a positive conclusion concerning the age of this [Bedford] fauna," which is now used as marking the introduction of Mississippian sedimentation. The reader is therefore allowed to draw his own conclusions from the evidence presented.

C. R. S.

Geologische Diffusionen. Von Raphael Liesegang. Dresden und Leipzig: Theodor Steinkopf.

The newer advances in mineralogy and petrology owe much to the work of the German chemists during the last quarter of a century. One of the most recent fields of investigation, which German workers have made peculiarly their own, is colloidal chemistry. The field is yet so new that geologists are only now beginning to realize the importance of its applications to their own science. At such a stage a book written from the point of view of the colloidal chemist is decidedly welcome. While it is today impossible for one man to be a specialist in two sciences, it is in the best interests of scientific progress that the applications of this branch of chemistry to geology be first made by an authority on colloids, rather than by a geologist. A study of the book before us is calculated to convince those who may be skeptical on this point.

The very special value of the book to the geologist lies in the detailed description of such experiments on the diffusion of colloids as may have a bearing on geological processes. To a large extent the author has drawn on his own work, and has provided material which it would be very difficult, if not impossible, for the geologist to obtain elsewhere. Most important are the experiments on "rhythmic precipitation" or banded structure, which is formed, for instance, when silver nitrate diffuses through a gel containing potassium bichromate. The silver chromate forms in concentric bands separated by clear interspaces, at once suggestive of the ring structure of the agate.

In applying the results of the experiments to geological structure, the author displays—for a specialist in another science—a remarkably good knowledge of geological literature. Few economic geologists would be prepared to give such an important place to lateral secretion as the agency by which veins are filled, but many objections to the theory are met by reference to actual experiment. The chief value of the book lies in the application of "rhythmic precipitation" to agate structure, banded flints, eozoön, banded clay concretions, and "weathering rings." The treatment of alternating gold and pyrite layers in quartz from the same point of view will be subjected to question. The author has at least added another to the explanations which have been offered for the gold deposits of the Rand.

Without doubt the author has provided geologists with material which will be the means of opening up a new and fascinating field for investigation in the very near future.

R. C. Wallace

Fosseis Devonianos do Paraná. By Dr. John M. Clarke. "Monographias do Servico Geologico e Mineralogico do Brazil," Vol. I. Rio de Janeiro, 1913.

In his recent monograph on the Devonian faunas of the southern hemisphere Dr. Clarke has placed Brazil in the same position of honor in the southern continent that New York has always held in North America, as the holder of the standard Devonian column and geologic record of that time. The work in its philosophic treatment and broad learning, as well as in its perfection of illustration and text, is beyond all criticism.

The paleogeography of the Devonian is discussed thoroughly, and a map is given showing the distribution of land and water in that age, to express the relations of the faunas. This map shows the austral continent connecting South America with South Africa, some central island masses in northern South America and central Africa, and the great boreal continent connecting North America with Eurasia. The austral faunas flourished on the northern strand of the austral continent, separated from the northern facies by the broad central ocean. The two types seem to have sprung from the same Silurian ancestors, to have diverged slightly in isolation under the influence of their environment, but to have developed along similar lines on account of "long-standing impulses in definite development which realize themselves notwithstanding conditions of geographic isolation." It would seem that we have here one of the most remarkable and definite cases of orthogenesis in the world's history.

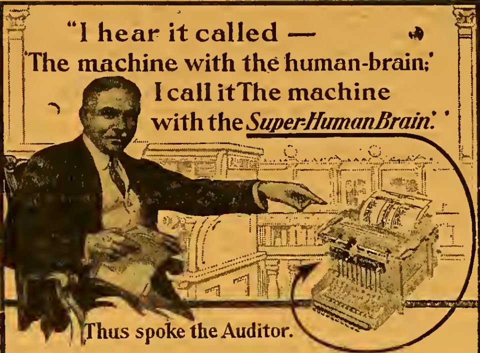
There are in the fauna thirteen species of Trilobites of the genera *Homalonatus*, *Cryphaeus*, *Calmonia*, *Proboloides*, *Pennaia*, rarely agreeing fully with their boreal kindred, but usually differing subgenerically, at least. The Cephalopoda are represented by only two species, *Orthoceras* and *Kionoceras*. *Conularia* is abundant, and the Pteropods have one genus *Hyolithus*. Gastropods are not abundant, having only six species. The Pelecypods are abundantly represented by twenty-four species of *Palaeoneilo*, *Nuculites*, *Nuculana*, *Janeia*, *Leptodomus*, *Modiomorpha*, *Sphenotus*, *Pholadella*, etc. The complete absence of the Aviculids and Pterineids shows a sharp contrast with the northern Devonian faunas, as does also the overwhelming development of the Taxodonts (Arcacea) in both numbers and size. The Brachiopods are numerous with twenty-four species of which the most noteworthy are *Spirifer jheringi*, *S. antarcticus*, *S. kayserianus*, and the numerous *Schuchertella*, *Leptostrophia*, *Chonetes*, and Discinacea. There are two starfishes and two sponges. Corals are almost entirely lacking, and Bryozoöns completely so.

The volume is illustrated by twenty-seven beautiful lithographed quarto plates of fossils done in the best style of Werner and Winter of Frankfort, that make the best of half-tones look tawdry in comparison. There are also several excellent text-figures.

Brazil may well be proud of the first volume of the monographs of its geological survey, for it has set an unusually high standard in subject-matter and in mechanical execution.

James Perrin Smith

Leland Stanford Junior University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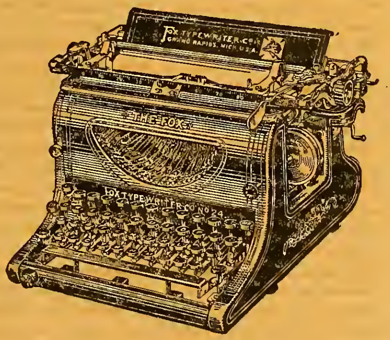
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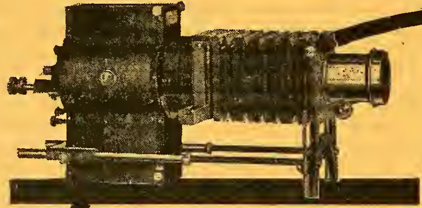

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VOLUME XXII NUMBER 2

THE JOURNAL OF GEOLOGY

A SEMI-QUARTERLY

FEBRUARY-MARCH 1914

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FEBRUARY–MARCH 1914

PRELIMINARY RESULTS OF MEASUREMENTS OF THE RIGIDITY OF THE EARTH

A. A. MICHELSON
Ryerson Physical Laboratory, University of Chicago

Installation and observations by H. G. GALE assisted by HAROLD ALDEN. Calculations by W. L. HART under the direction of F. R. MOULTON

Measurements of the temperature of the crust of the earth as found in the deepest mines show that it rises on the average about 0.02° C. for every meter below the surface; and as the rate of increase is even greater at greater depths it follows, as Lord Kelvin pointed out,[1] that the temperature in the interior must be high enough to melt the substances composing it, and for a long time it was considered that the vast bulk of the earth must be in a fluid, or at least semi-fluid, condition, a conclusion which was strongly supported by the fact of the ejection of molten lava from volcanoes.

The theoretical investigations of Lord Kelvin in 1863[2] indicated, however, that the earth must be considered a very rigid body, opposing an enormous resistance to changes of form such as tend to occur in consequence of the attractions of the sun and moon. It is evident from these investigations that the old idea (which is not entirely extinct) that we are living on a thin rock crust over an immense mass of molten lava must be abandoned.

[1] *Philosophical Transactions*, 1863. [2] *Ibid.*

The first attempt to measure the rigidity of the earth, that is, the resistance which it offers to change of shape, was made by G. H. and Horace Darwin in 1880.[1] They employed a horizontal pendulum by the use of which they hoped to measure the change in the direction of the gravitational vertical due to the attractions of the sun and moon; from which, by comparison with the values calculated on the basis of absolute rigidity, the effective rigidity could be determined. The results were so irregular and contradictory that no conclusion could be formed, and the Darwins express the belief that such experiments are not likely ever to furnish the desired results.

In the hands of Rebeur-Paschwitz this method did, however, give positive results confirming the deductions of Kelvin. Since then the method of the horizontal pendulum has been successfully employed by Ehlert, Kortazzi, Schweydar, Hecker, and Orloff, with essentially the same result, namely, that the coefficient of rigidity is found to be of the order 6×10^{11} c.g.s. (about the same as that of steel). The results deduced from Chandler's observations of the variation of the latitude give a value nearly twice as great.

But, in addition to the elastic yielding of any body ordinarily looked upon as solid there is a plastic yielding, characterized by a constant termed by Maxwell the "modulus of relaxation," and evidenced by a lag of the distortion of the earth relative to the forces producing it. Such experiments as these should be capable of determining the plasticity as well as the rigidity of the earth. To show what measure of reliability may be accorded to the observations mentioned, the following extract, Table I, is made of a discussion of these by Schweydar.[2]

Here $1-K$ represents the ratio of the observed amplitude of oscillation to that calculated on the assumption of absolute rigidity. κ represents the retardation (which should always be negative) of the phase of the observed motion relative to the phase of the disturbing forces.

---

[1] *B.A.A.S. Reports*, York meeting, 1880.

[2] Dr. Wilhelm Schweydar, *Untersuchungen über die Gezeiten der Festen Erde.* Potsdam, 1912; Leipzig: B. G. Teubner.

The observations are divided into two classes, the latter being considerably more reliable than the former.

TABLE I

	Experimenter	K	κ
	v. Rebeur	0.362	+ 7°30′
	Kortazzi	.608	0
	"	.414	− 2°54′
	Ehlert	.448	+12° 1′
	Schweydar	.338	− 8°31′
	"	.158	+ 8°29′
N.-S.	Hecker	.643	−11°.9
	"	.565	− 0°.7
	"	.544	+13°.4
	Orloff	.412	+ 0°.8
E.-W.	Hecker	.259	− 7°.0
	"	.382	+ 5°.2
	"	.468	+20°.1
	Orloff	0.326	+ 3°.2

While the numbers in the second column agree in showing that the earth's rigidity is of the order of that of steel, the differences are so considerable that it is hardly likely that they can be relied upon to within 20 per cent.

If accurate, the third column would give a measure of the plastic yielding of the body of the earth to the action of the distorting forces of the sun and moon. As mentioned before, these should all be negative, whereas the great preponderance is in the direction of positive lag, which is meaningless; so that further than showing that the lag is small (and therefore the viscosity high) these results are practically valueless.

It will be conceded that there is great need for more accurate determinations, if our knowledge of the properties of the matter constituting the earth's interior is to be increased; and it was in the hope of obtaining results of a higher order of accuracy, as well as such directness and simplicity of apparatus as practically to eliminate all the difficulties and uncertainties which seem to be unavoidable in the use of the horizontal pendulum, that the experiments recorded here were undertaken.

The prime object of the investigation is the determination of the direction of the gravitational vertical, or rather of the changes to which it is subject in consequence of the attraction of the sun and moon and as modified by the resulting distortion of the body of the earth. But this may be furnished with any desired degree of accuracy by the changes in the position of the level of a liquid surface which is necessarily normal to the resultant of all the forces acting. If from these we can eliminate all but the gravitational forces the problem is solved.

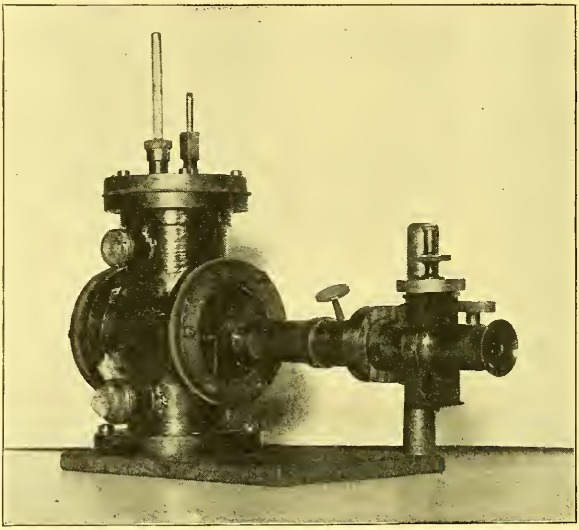

Fig. 1.—Microscope and gauge

A very sensitive method of measuring the changes in level is furnished by the interferometer; and a method of carrying this into practice was devised and the apparatus constructed[1] in 1910.

But before attempting to utilize so delicate an appliance it was deemed advisable to make these preliminary experiments with the microscope. Accordingly a 6-inch pipe, 500 feet long, was half filled with water,[2] the level of which could be read off through the glass sides of the end vessels, as shown in Fig. 1.

---

[1] An interference apparatus for this purpose was independently devised by Professor A. G. Webster.

[2] The vessels at the ends were at first connected by a pipe filled with water, but with this arrangement temperature changes produced enormous disturbances in the level.

This pipe was laid in a trench six feet deep, terminating in two pits, eight feet square and ten feet deep, walled with concrete, in a soil of sandy clay on the grounds of the Yerkes Observatory at Williams Bay, Wisconsin. The direction (E.–W.) of the pipe was laid out by measuring from the meridian line and is probably correct to within one foot in five hundred. The pipe was then carefully leveled, and after verifying the continuity of the water and of the air space above it, the pipe was closed so that it was effectively air-tight, and the trench was filled with clay.

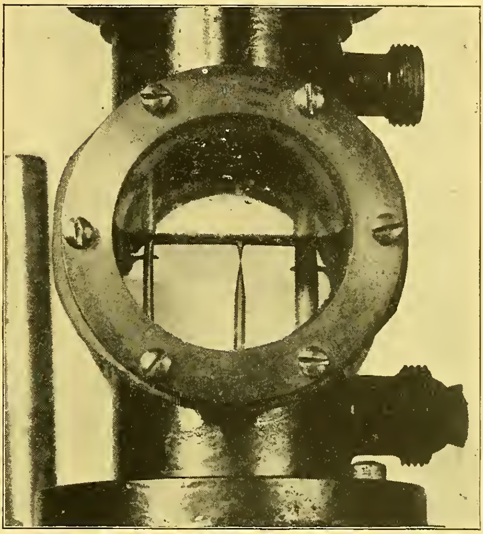

FIG. 2.—Point and totally reflected image

The distance between the total reflection image of a pointer, Fig. 2, and the direct image was read by micrometer microscopes of about 2-inch focus. These were calibrated at first rather roughly by measuring the diameter of a wire immersed in the water at the focus; and subsequently with much greater accuracy by measuring the known distance between two lines ruled on glass and placed in the focus, under water.

A preliminary series of observations was begun August 5 and continued until September 2 with such encouraging results that it was decided to supplement the work by observing on a N.–S. line which was accordingly laid out in the same manner as the E.–W. line.

The final calibration of the microscopes gave the following results:

West	17.52 turns	= 1 mm
East	17.60 "	= 1 mm
North	17.00 "	= 1 mm
South	17.60 "	= 1 mm

The mean for the E.–W. line is 17.56, and for the N.–S. line, 17.30. Accordingly the factor by which the calculated difference in level in mm should be multiplied to reduce to micrometer divisions is

For the E.–W. line, 285
For the N.–S. line, 289

The factor actually used in the computation was 293, and accordingly these should be diminished by 2.8 per cent for the E.–W. line, and by 1.4 per cent for the N.–S. line.

A continuous series of observations was conducted on both lines, beginning September 27 and ending November 29. The observations were made by setting the cross-hair of the micrometer on the pointer and taking a number of readings, the mean of which gave the fiducial reading to be subtracted from the readings of the reflected image. This difference was subtracted from a similar difference taken at the other end of the pipe, and the final differences from hour to hour (plus a constant) gave the observed curves. These readings were taken every hour from 6 A.M. until midnight, and every two hours from midnight until 6 A.M. The order of the observations was usually south end, north end, east end, west end. The time between readings at south end and north end, or between east end and west end, was about four minutes, and the mean between the two was taken to represent the time of observation. The mean time of the two observations gives the same result as though the observations had been simultaneous.

Occasionally the reflected image would be obscured by floating particles, and in clearing these away the value of the constant would be altered. The new constant was accordingly chosen so that the succeeding observations continued with the smallest discontinuity in the curve.

It was found that there was a gradual downward trend in the E.–W. curve during August, but little or none in the October-November series. The N.–S. line, however, on which readings were started the day after the pipe was covered, shows a considerable gradual drop. This was undoubtedly caused by uneven settling at the ends of the pipes. This was too slow to affect the result for the semi-diurnal period, but made doubtful the results for the fortnightly period.

The observations and their graphs are given in Tables III and IV and in Figs. 3 and 4.

In Figs. 5 to 12 these graphs are reproduced on a larger scale, together with those of the calculated values of the readings, multiplied by the factor 0.7 for the E.–W. line and 0.5 for the N.–S. line. The zero line of the observed readings is corrected to coincide with the calculated curve.

These curves were divided into periods corresponding to the semi-diurnal lunar tide, 12.42 hours, and the values at corresponding intervals of two hours tabulated and divided into groups of ten periods each.

The results of the comparison of the observed and calculated curves is given in Table II, in which the first column gives the ratio of the observed amplitudes to the calculated, on the assumption of an absolutely rigid earth, and the second the retardation of phase in hours.

TABLE II

Ratio of Amplitudes		Retardation in Phase	
E.–W.	N.–S.	E.–W.	N.–S.
0.69	0.50	$-0^{\mathrm{h}}.05$	$-0^{\mathrm{h}}.06$
.79	.54	+ .30	+ .30
.65	.53	− .14	− .08
.71	.50	− .01	− .03
.82	.53	− .08	+ .12
.64	.52	− .14	− .20
.66	.50	− .08	.00
.70	.50	− .03	.00
.70	.50	− .12	− .06
.74	.50	− .16	− .02
.70	.48	− .12	+ .08
0.71	0.52	−0.08	+0.04
Mean=0.709×1.028	0.510×1.014	−0.059	+0.0075

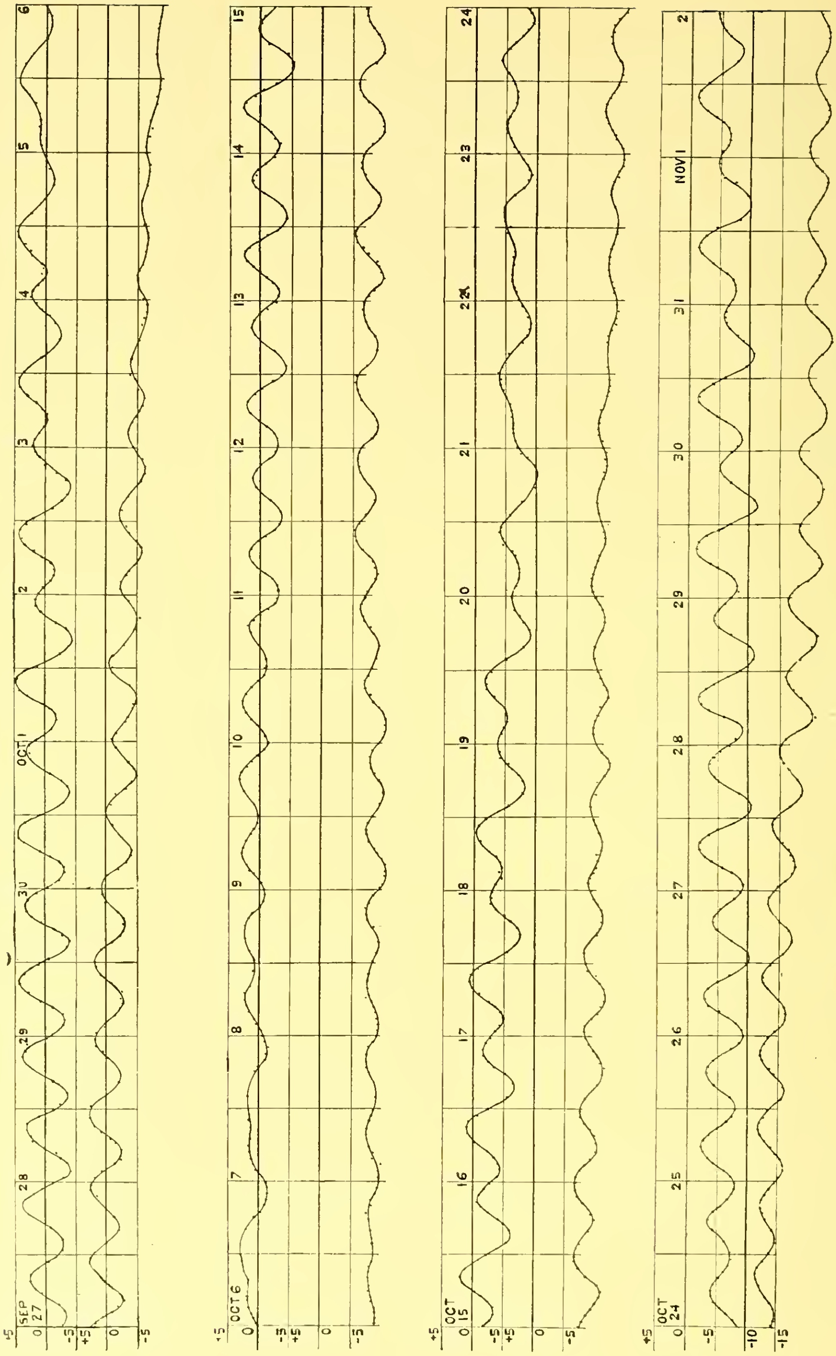

Fig. 3.—Upper curves, 10(E.–W.+C); lower curves, 10(S.–N.+C)

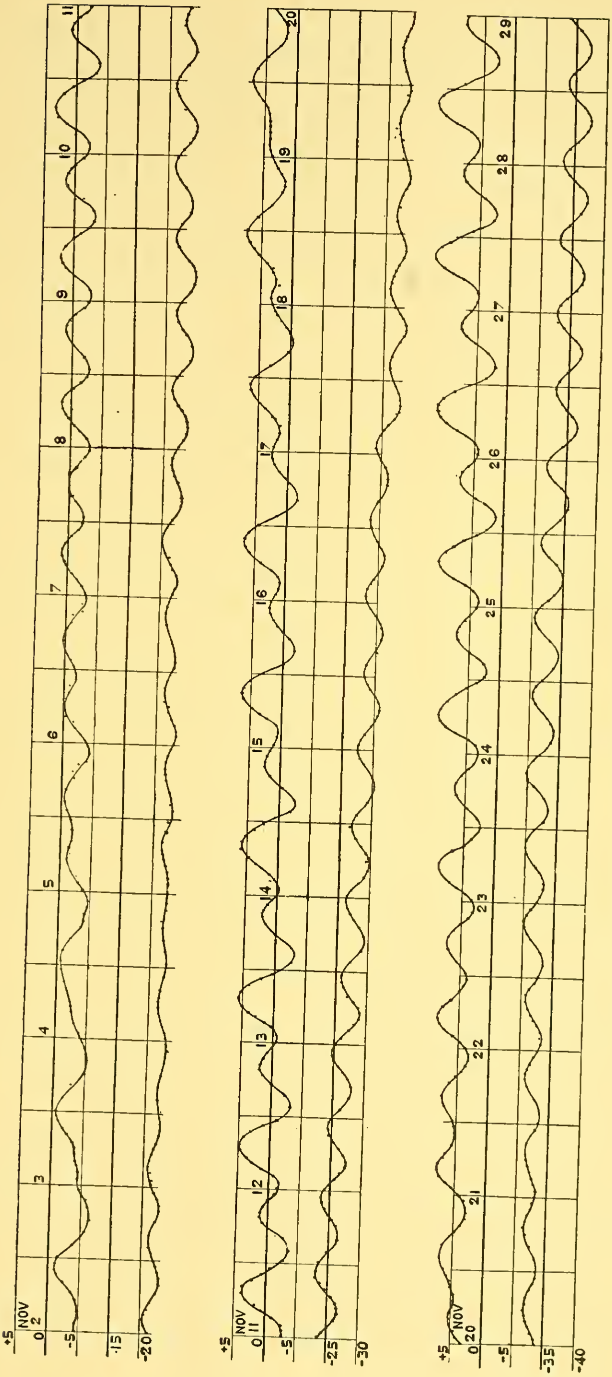

FIG. 4.—Upper curves, 10(E.—W.+C); lower curves, 10(S.—N.+C)

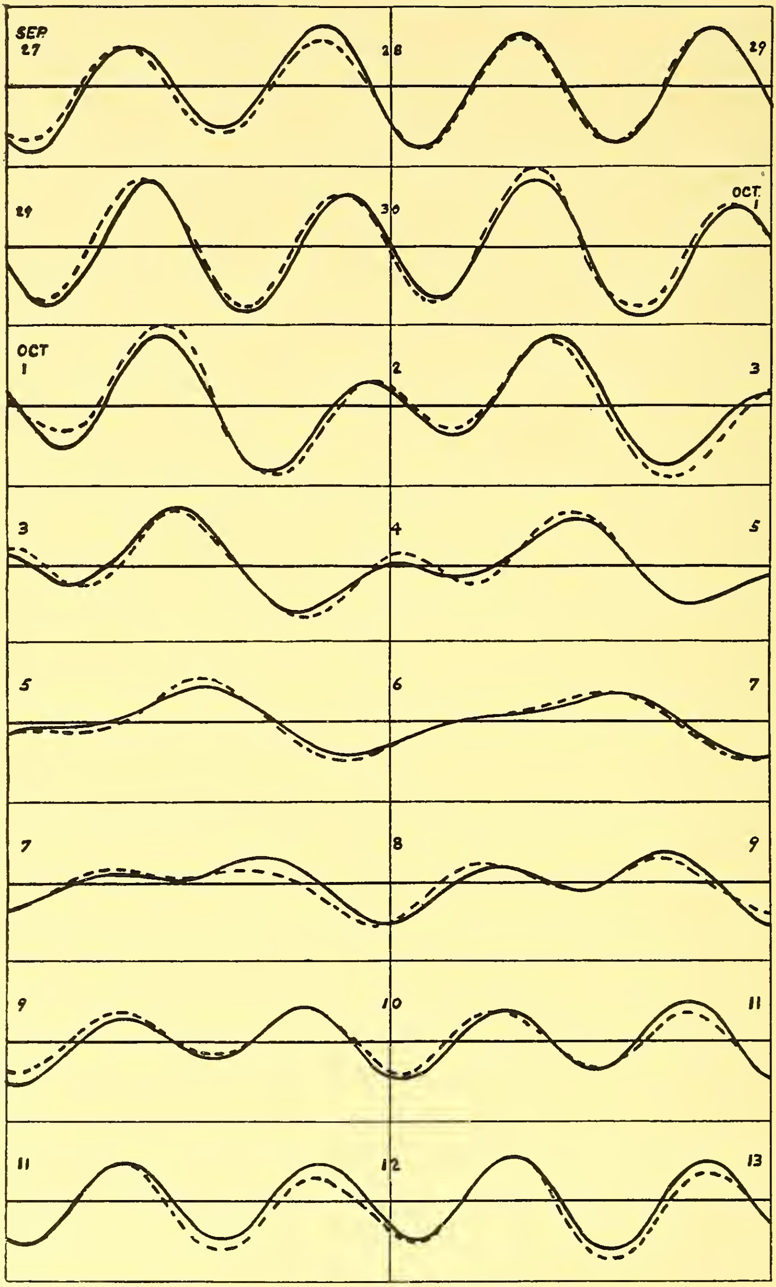

FIG. 5.—E.-W. Dotted curve, observed values; full curve, 0.7 of calculated

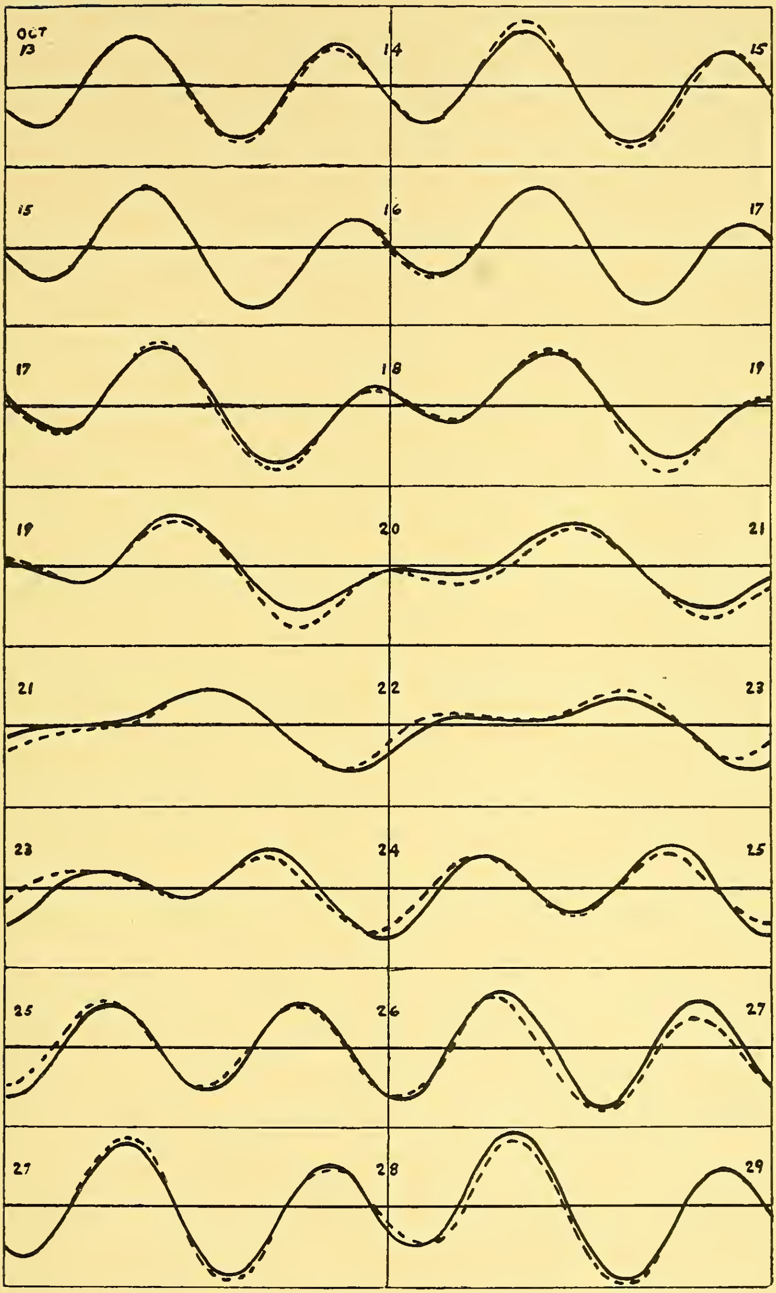

Fig. 6.—E.-W. Dotted curve, observed values; full curve, 0.7 of calculated

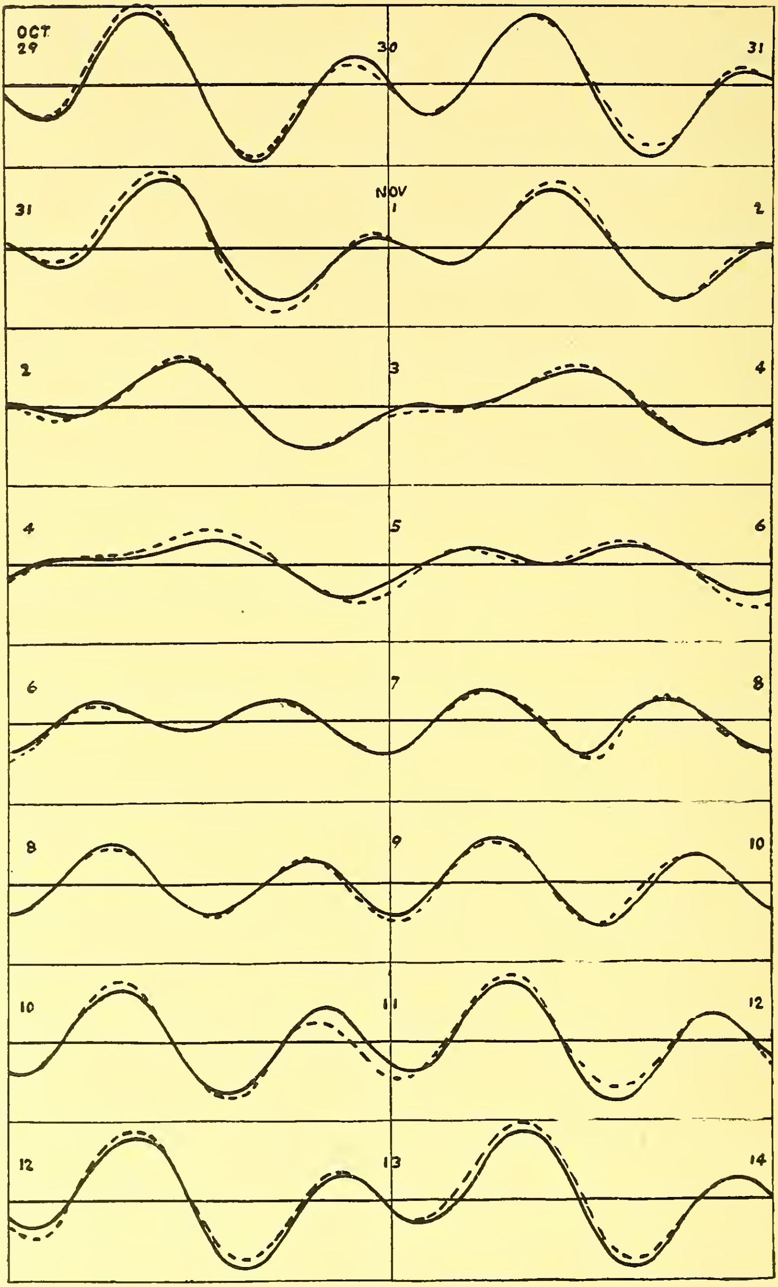

Fig. 7.—E.-W. Dotted curve, observed values; full curve, 0.7 of calculated

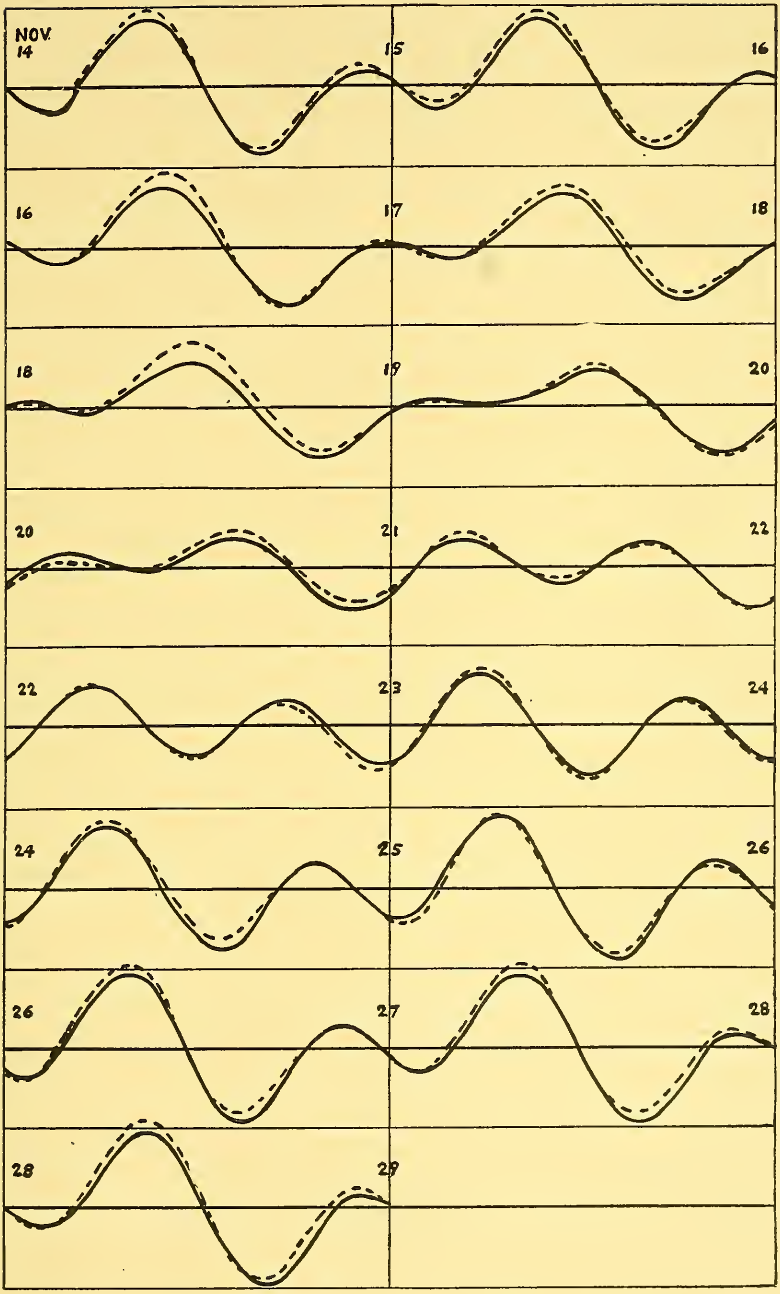

FIG. 8.—E.-W. Dotted curve, observed values; full curve, 0.7 of calculated

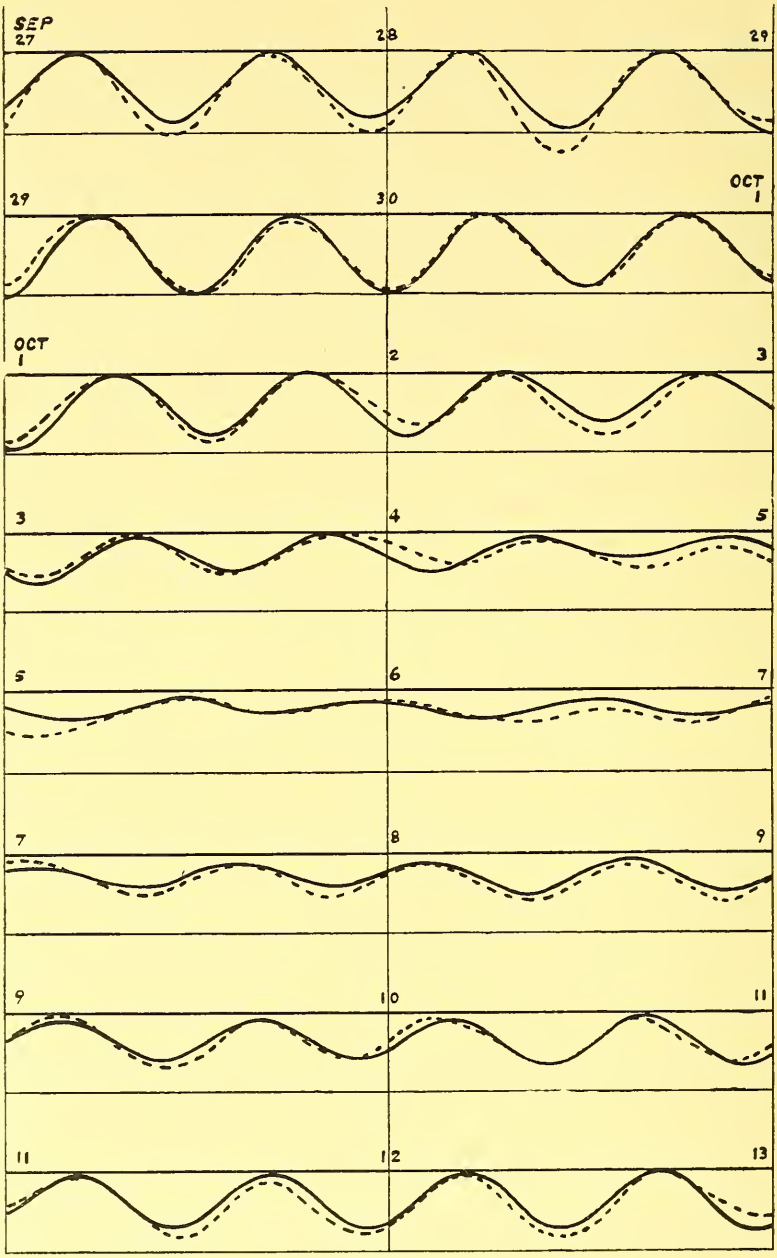

FIG. 9.—N.-S. Dotted curve, observed values; full curve, 0.5 of calculated

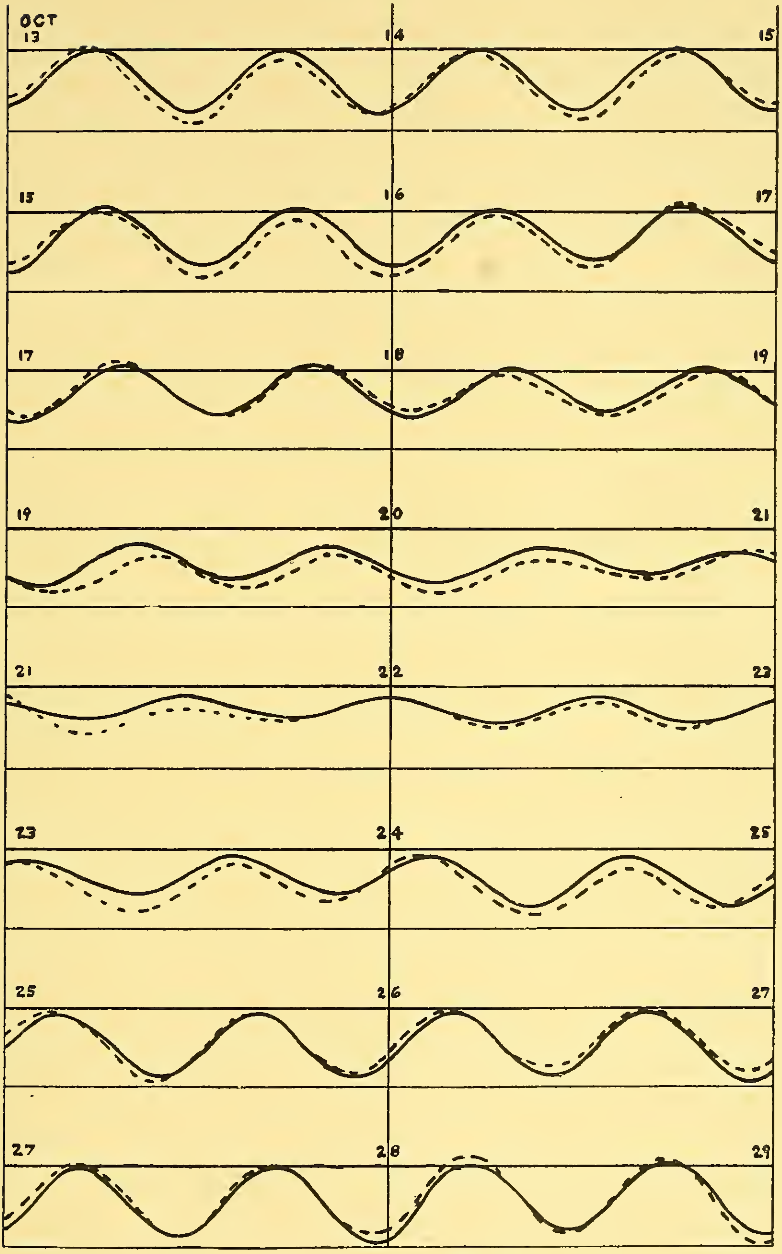

FIG. 10.—N.-S. Dotted curve, observed values; full curve, 0.5 of calculated

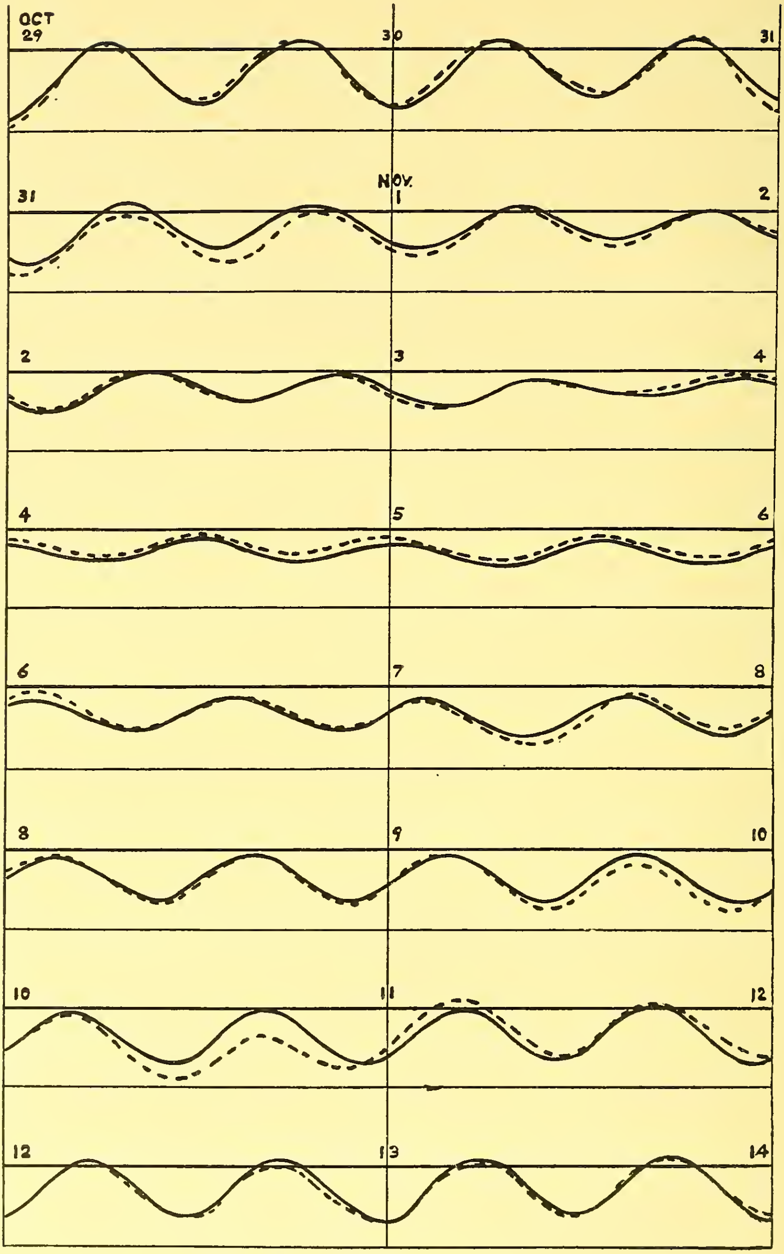

FIG. 11.—N.-S. Dotted curve, observed values; full curve, 0.5 of calculated

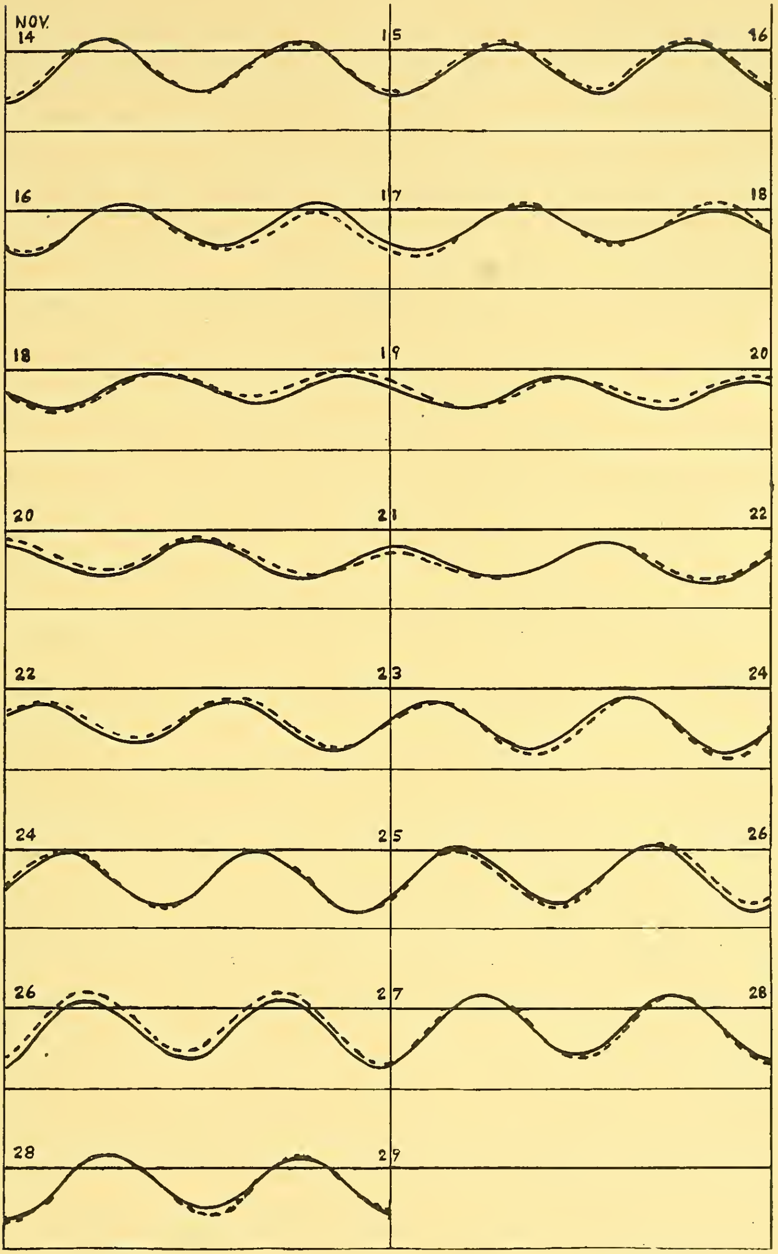

FIG. 12.—N.-S. Dotted curve, observed values; full curve, 0.5 of calculated

The resulting mean of all observations, for this method of grouping, is that the observed amplitude of the oscillation for the E.–W. line is 0.709 of that calculated on the assumption of absolute rigidity; while for the N.–S. line it is 0.510. The acceleration of phase of the observed oscillations relative to the calculated is $+0^{\mathrm{h}}.059$ for the E.–W. line and $-0^{\mathrm{h}}.007$ for the N.–S. line. The graphs of the final means of all the observations and the calculated values are reproduced in Figs. 13 and 14.

The curves correspond very closely with the following formulae:

$$\text{E.–W.}\quad y=-a\sin\frac{2\pi}{T}(t-\tau)+b$$

$$\text{N.–S.}\quad y=-a\cos\frac{2\pi}{T}(t-\tau)+b$$

with the following values for the constants:

E.–W.

Calculated × 0.7	Observed
$a=20.56$	$a=20.30$
$\tau=0.99$	$\tau=0.88$
$b=0.33$	$b=0.30$

N.–S.

Calculated × 0.5	Observed
$a=13.18$	$a=13.60$
$\tau=0.99$	$\tau=0.97$
$b=0.16$	$b=0.13$

Accordingly the ratio of the observed to the calculated amplitude for E.–W. is 0.691, and for N.–S. is 0.516, while the phase accelerations are $0^{\mathrm{h}}.11$ and $0^{\mathrm{h}}.02$ respectively.

These last results are slightly different from the preceding. The preference is for the latter as regards amplitude ratios, but these give relatively too much weight to the large oscillations in deducing the phase-difference, and for these the former results are preferred.

Multiplying the second set of values obtained for the amplitude ratios by the factors given above, 1.028 for E.–W. and 1.014 for N.–S., the final results are:

Amplitude Ratio	**Phase Acceleration**
E.–W. 0.710	**E.–W. . . . . . . +0.059 hour**
N.–S. 0.523	**N.–S. . . . . −0.007 hour**

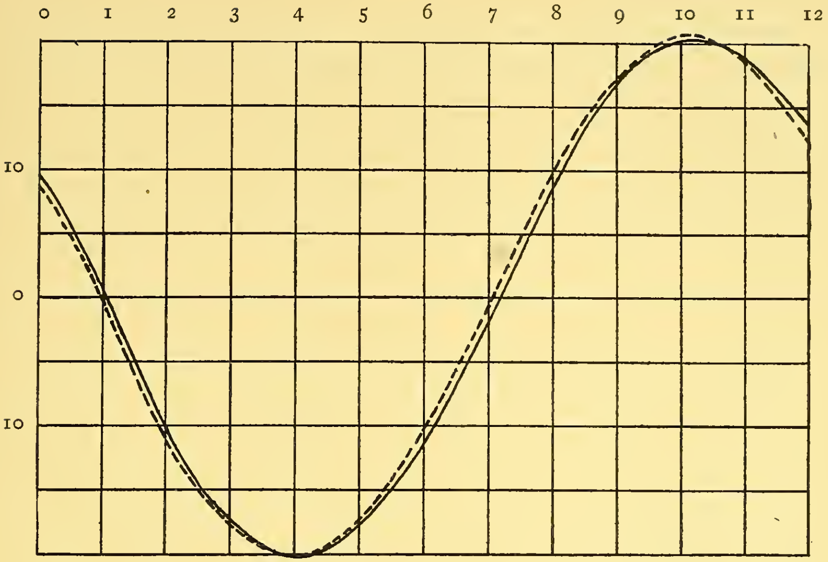

FIG. 13.—Mean of all observations, semi-diurnal Lunar tide. Dotted curve, observed values; full curve, 0.7 of calculated.

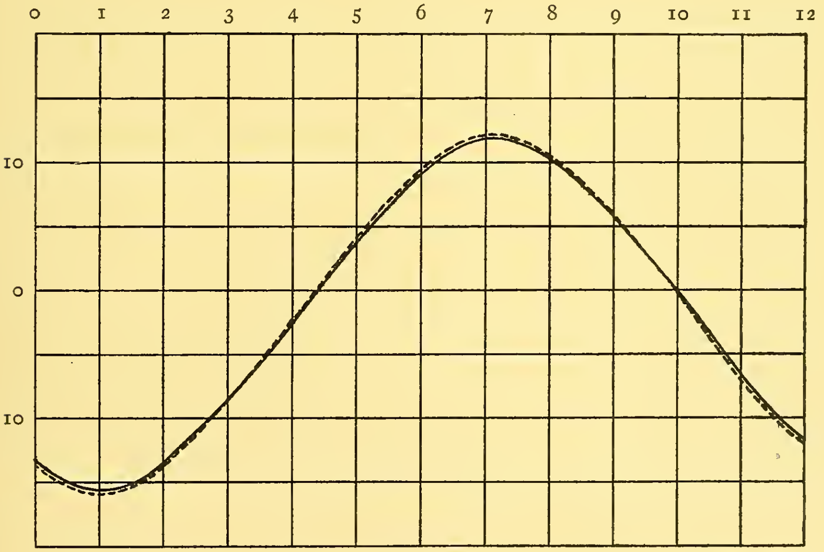

FIG. 14.—Mean of all observations, semi-diurnal Lunar tide. Dotted curve, observed values; full curve, 0.5 of calculated.

It is estimated that the errors in the amplitude ratios are under 1 per cent. The phase acceleration is probably correct to within $0^{h}.03$, but is so small as to leave some doubt as to whether or not it is real.

The disagreement between the E.–W. and N.–S. directions has been interpreted by Hecker, who found a similar difference, as indicating an actual difference in the earth's rigidity in the E.–W. and N.–S. directions.

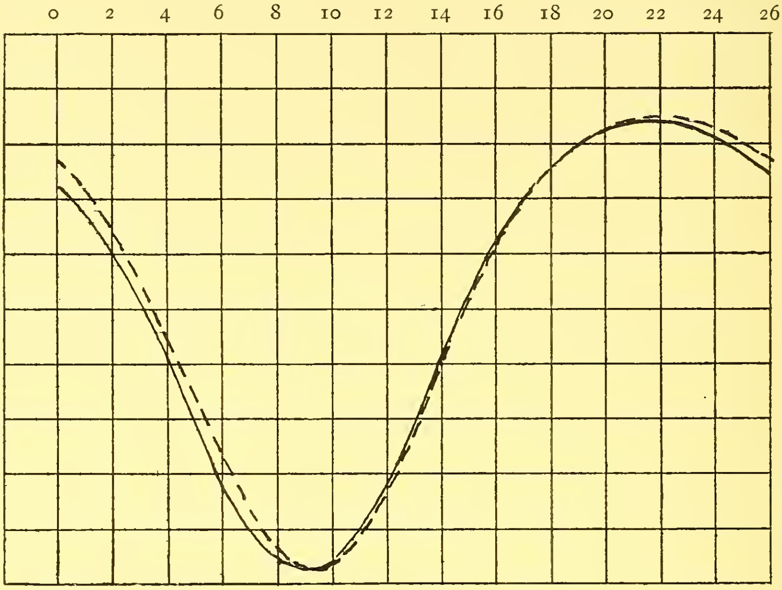

FIG. 15.—E.–W. Mean of observations of diurnal Lunar tide. Dotted curve, observed values; full curve, 0.7 of calculated.

Schweydar agrees with A. E. H. Love in attributing the difference to the effect of ocean tides, and shows on the assumption of an ocean covering the earth uniformly to a depth of 5000 meters that the tides have the effect of increasing the elastic earth tides, so that the ratio of the observed amplitudes to the theoretical is diminished by something like 40 per cent.

The mean values of the ratio adopted by Schweydar are 0.61 for E.–W. and 0.46 for N.–S., which should therefore be increased to 0.85 and 0.64 respectively. A similar correction applied to the results of these experiments would give, instead of 0.71 and 0.52, the values 0.99 and 0.73. The E.–W. value would mean that the earth's rigidity is practically infinite, and it is undoubtedly too high.

The ocean is, however, anything but uniform in depth, and this and the irregularities in coast lines, make an accurate calculation of the disturbing effect of the ocean tides almost impossible. Accordingly Schweydar, considering that the results furnished by the consideration of the semi-diurnal tides is not reliable, investigated the problem of the diurnal period, especially that corresponding to the "declination tide" whose period is $25^{\mathrm{h}}.812$. The dynamical theory shows that for an ocean entirely covering the earth, such tides should vanish; a result which is approximately true, at least for the Atlantic.

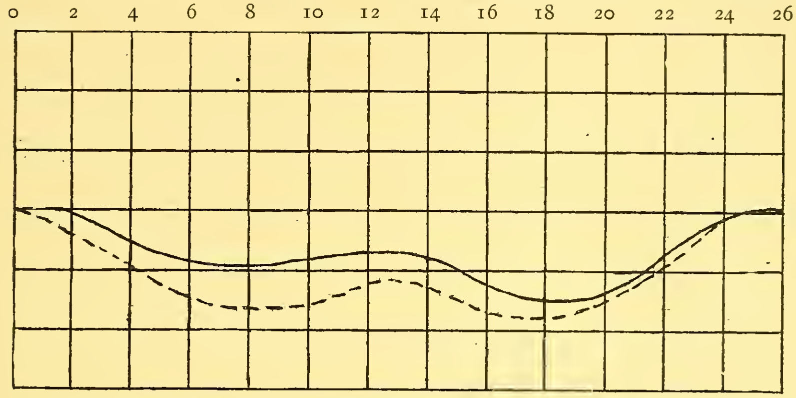

FIG. 16.—N.–S. Mean of observations of diurnal Lunar tide. Dotted curve, observed values; full curve, 0.5 of calculated.

This analysis applied to Hecker's observations gives 0.85, as the value of the ratio, which, it will be noticed, agrees with the value for the semi-diurnal period when corrected for the calculated perturbation of the ocean tides.

The result of grouping the present observations into six groups of two periods each (of $25^{\mathrm{h}}.81$) is reproduced in the graphs of Figs. 15 and 16.

These were analyzed by means of the harmonic analyzer, and gave the following results, in which R is the ratio of the observed amplitude to the calculated, and ϕ the phase acceleration:

	R	ϕ
E.–W.	0.72	-0.4 hour.
N.–S.	0.66	$+1.0$ "

It appears therefore that the diurnal period gives for the amplitude ratios numbers which are decidedly in better agreement than those furnished by the semi-diurnal period.

It is to be noted that while the agreement between the E.–W. and the N.–S. results is considerably improved, the value of R for the E.–W. direction has not been altered, whereas according to Schweydar's investigation it should have been much larger (0.90 or more). It may be, however, that first, in consequence of the smaller number of periods entering the calculation, and secondly, on account of the smaller value of the resulting amplitude (41:100), these numbers have a considerably larger probable error than that of the semi-diurnal period.

Possibly a closer analysis of the actual ocean tides would show that the effect is small for the E.–W. direction, while in the N.–S. direction it may be considerable.

Regarding the acceleration of phase, it may be noted that the difference between the E.–W. and the N.–S. direction is much greater for the diurnal period than for the semi-diurnal, whereas, if the results of the latter were seriously affected by the ocean tides, the reverse should hold. The mean of the semi-diurnal accelerations is $0^{h}.03$, a quantity so small that it is within the probable error. Taking this value together with 0.70 as the ratio of the observed to the calculated amplitudes, the corresponding values of the earth's rigidity n and viscosity ϵ are:

$$n = 8.6 \times 10^{11} \text{ c.g.s.}$$
$$\epsilon = 10.9 \times 10^{16} \text{ c.g.s.}$$

This calculation is based on the assumption of uniform rigidity throughout the body of the earth, a condition which is certainly not fulfilled; and that as the time increases in arithmetical progression the stresses diminish in geometrical progression. It is clear, however, that the earth's rigidity is greater than that of steel. If the ocean tides have the effect of diminishing the ratio R by from $\frac{1}{2}$ to $\frac{1}{3}$, as admitted by Schweydar, the rigidity is enormously greater.

The viscosity is also very great and probably of the same order of magnitude as that of steel.

The main object of this investigation was to demonstrate the feasibility of the method and to determine the order of magnitude of the earth's rigidity and viscosity. Evidently the method is capable of giving results of a high order of accuracy by recording a much longer series of observations. Such a series, in which the microscope will be replaced by the interferometer and in which the record is to be made automatic, is now in preparation. It is expected that the results will furnish a record of the earth tides which will be correct to within a tenth of 1 per cent.

Whether it may thereby be possible to obtain a more accurate value of the coefficients of rigidity and of viscosity will depend on the advance which may be made in the theory of the ocean tides and of their perturbing action. Doubtless it would be of importance to repeat the experiments at widely different stations, some in the southern hemisphere, some on islands in mid-ocean, and some on the continent as far as possible from the coast.

It may also be possible by a comparison of the moon and the sun tides to obtain an independent and perhaps more accurate value of the moon's mass.[1]

The conclusions from these and similar experiments and observations, including precession and variation of latitude, all agree substantially in refuting the old notion that the internal temperature, sufficiently high to melt most of the materials constituting the earth's crust, necessarily involves a fluid or semi-fluid earth supporting a relatively thin solid crust.

From the definitely ascertained result that the coefficient of rigidity and the coefficient of viscosity are both very large (of the order of, and perhaps exceeding, those of solid steel, whereas under normal pressure all substances at this temperature would be fluid), it follows that pressure increases the rigidity and the viscosity, at least of the substances which form the body of the earth.

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[1] It would probably be necessary to make use of a tunnel sufficiently deep to eliminate the thermal effect, which even in the semi-diurnal period would be appreciable.

It would be interesting to confirm this important conclusion, even qualitatively, by experiments on the effect of such relatively small pressures as we are able to obtain in the laboratory.

Such experiments are now in progress; and while the highest pressures obtainable are a thousand times smaller than the pressure in the interior of the earth, it may be stated that there are distinct indications of an increase in the coefficient of rigidity, and a marked increase in the coefficient of viscosity of the few materials thus far investigated.

I would take this opportunity of expressing my appreciation of the interest taken in this work by Professor T. C. Chamberlin, at whose instigation the investigation was undertaken, and of tendering thanks to him and to President H. P. Judson for their efforts in securing the necessary funds. I would also gratefully acknowledge the friendly co-operation of Professor Frost and the members of the staff of the Yerkes Observatory.

TABLE III 10(E.−W.+C.)

A.M. September 27	A.M. September 30	P.M. October 2	A.M. October 5	A.M. October 8
C=+1.30	12:12 − 0.6	4:10 − 1.3	11:32 ± 0.0	6:29 + 0.7
	2:12 − 3.6	5:08 − 1.0	1:02 + 0.9	7:03 + 0.2
8:16 + 1.6	3:12 − 4.1	6:08 + 0.7	2:46 + 1.0	8:08 − 0.9
9:11 + 0.7	4:14 − 2.8	7:14 + 1.8	4:04 + 1.1	9:06 − 1.0
10:12 − 0.8	5:12 − 1.3	8:11 + 3.4	5:17 + 0.9	10:22 − 1.5
11:16 − 2.4	6:18 + 0.6	9:09 + 3.9	6:07 + 1.2	11:14 − 0.8
11:56 − 2.7	7:18 + 2.3	10:31 + 4.2	8:08 + 1.9	12:14 − 0.5
1:10 − 3.3	8:20 + 3.1	11:30 + 3.0	9:22 + 2.9	1:08 − 0.3
2:10 − 3.2	9:56 + 3.0	12:30 + 2.0	10:27 + 3.9	2:08 + 0.4
3:15 − 2.1	11.02 + 1.5	2:02 − 1.2	12:06 + 4.4	3:10 + 0.8
4:06 − 0.1	12:04 − 0.3	3:18 − 2.6	2:24 + 3.6	4:06 + 1.7
5:14 + 0.6	1:12 − 2.3	4:14 − 3.6	4:11 + 2.1	5:09 + 2.1
5:48 + 1.8	2:20 − 3.1	6:40 − 3.3	6:31 ± 0.0	5:53 + 2.2
7:08 + 2.5	3:20 − 3.0	7:58 − 1.8	8:34 − 1.1	7:05 + 2.7
8:16 + 2.5	4:14 − 2.2	9:10 ± 0.0	9:18 − 0.8	8:06 + 1.7
9:19 + 1.2	5:10 − 0.8	10:20 + 1.0	**C= +3.00**	9:22 + 1.1
10:26 − 0.4	5:52 + 0.8	11:10 + 1.5		10:35 + 1.1
11:12 − 1.8	7:11 + 3.4	12:06 + 2.2	10:18 − 0.7	12:23 + 0.8
12:14 − 2.8	7:53 + 4.2	1:18 + 1.8	11:22 − 0.1	1:54 + 1.7
2.04 − 2.9	10:32 + 3.3	2:14 + 1.1	12:15 + 0.3	4:19 + 2.4
4:04 − 0.8	1:46 − 3.0	3:14 + 0.2	1:23 + 0.9	6:10 + 2.5
6:09 + 2.8	3:31 − 3.9	4:15 − 0.2	2:16 + 1.2	7:10 + 1.9
9:30 + 1.8	4:21 − 3.7	5:06 − 0.2	3:18 + 1.6	8:02 + 1.2
10:26 + 0.4	5:28 − 2.6	5:45 + 0.2	4:24 + 1.7	9:12 + 0.1
11:15 − 1.1	6:30 − 0.8	7:09 + 1.7	5:02 + 1.7	10:06 − 0.5
12:22 − 3.0	8:39 + 2.4	8:22 + 3.1	5:54 + 1.9	11:12 − 0.9
1:17 − 4.1	9:48 + 2.7	9:48 + 4.2	7:04 + 1.5	12:08 − 0.7
2:40 − 3.7	11:12 + 2.8	11:14 + 4.4	8:24 + 2.1	1:08 − 0.3
3:33 − 2.4	11:59 + 1.5	12:06 + 3.5	9:18 + 2.5	2:15 + 0.7
4:12 − 1.8	1:38 − 0.9	2:38 + 0.8	10:14 + 2.5	3:06 + 0.7
5:04 + 0.1	3:20 − 1.8	5:42 − 2.1	11:10 + 2.7	4:16 + 2.0
6:12 + 2.1	4:10 − 1.7	8:02 − 1.6	12:05 + 3.1	5:14 + 2.8
7:08 + 2.3	5:13 − 0.6	9:09 − 0.6	2:07 + 3.1	5:54 + 2.9
8:06 + 3.0	5:51 + 0.5	10:10 + 0.8	4:18 + 2.1	7:00 + 2.8
9:08 + 3.0	7:17 + 3.1	11:19 + 1.5	6:19 + 0.6	8:10 + 2.4
10:20 + 1.0	8:05 + 4.3	12:16 + 2.5	7:10 − 0.2	9:22 + 1.5
11:28 − 1.4	9:22 + 5.0	1:22 + 2.2	8:22 − 0.8	10:06 + 1.0
12:20 − 2.5	**C= −1.32**	2:08 + 1.2	9:12 − 1.2	11:12 + 0.3
2:11 − 3.6		3:23 + 0.4	10:16 − 1.0	12:22 + 0.3
4:18 − 1.2	10:12 + 4.7	4:10 + 0.8?	11:14 − 1.1	2:10 + 0.8
8:20 + 3.8	11:14 + 3.2	5:01 + 0.3	12:01 − 1.1	4:25 + 2.5
9:14 + 3.3	12:10 + 1.2	5:58 + 0.7	1:04 − 0.6	6:16 + 3.3
10:08 + 3.1	2:10 − 2.4	7:16 + 2.2	2:08 + 0.3	7:20 + 3.1
11:18 − 0.2	4:16 − 4.6	8:02 + 2.5	3:06 + 0.9	8:13 + 2.0
11:58 − 1.2	6:28 − 3.4	9:06 + 3.5	4:10 + 1.2	9:08 + 1.3
1:19 − 3.0	7:15 − 1.8	10:16 + 4.6	5:08 + 1.7	10:08 + 0.5
2:06 − 3.3	8:22 − 1.4	11:08 + 4.7	6:02 + 1.8	11:10 − 0.7
3:10 − 3.0	9:10 + 0.6	12:12 + 4.4	7:17 + 1.5	11:58 − 1.4
4:20 − 1.2	10:05 + 1.5	2:09 + 2.4	8:08 + 1.4	1:10 − 0.8
5:21 + 0.8	11:12 + 1.6	4:20 + 0.3	9:05 + 1.3	2:10 − 0.5
6:49 + 2.9	12:00 + 1.1	6:39 − 1.1	10:12 + 1.8	3:12 + 0.4
8:32 + 4.4	1:08 + 0.4	7:40 − 1.2	11:11 + 1.7	4:10 + 1.3
9:50 + 3.5	2:21 − 1.0	9:10 − 0.5	12:05 + 1.7	5:12 + 2.3
11:15 + 1.2	3:09 − 1.4	10:33 ± 0.0	2:16 + 1.9	5:59 + 2.8

TABLE III—*Continued*

P.M. October 10	P.M. October 13	A.M. October 16	P.M. October 18	P.M. October 21
6:53 + 2.9	1:18 − 2.9	6:00 − 4.1	6:51 − 2.4	2:12 − 6.7
8:10 + 2.2	2:24 − 2.9	7:13 − 2.4	8:30 − 0.9	3:20 − 6.4
9:18 + 1.4	3:27 − 1.9	8:02 − 1.4	9:52 − 0.2	4:10 − 6.3
10:14 + 0.3	4:14 − 1.0	9:06 − 0.7	11:00 − 0.7	5:04 − 6.4
11:14 − 0.8	5:11 + 0.2	10:10 − 1.0	12:00 − 1.7	6:00 − 6.0
12:34 − 1.1	5:59 + 1.3	11:06 − 1.8	2:05 − 5.3	7:00 − 5.9
1:50 − 1.1	6:52 + 2.2	12:06 − 2.5	4:06 − 7.9	8:02 − 5.8
4:11 + 0.2	8:17 + 2.5	1:14 − 4.0	6:11 − 8.0	9:26 − 5.1
6:12 + 1.7	9:16 + 1.9	2:12 − 4.3	7:16 − 7:3	10:16 − 4.7
7:12 + 2.0	10:12 + 0.7	3:12 − 4.1	8:03 − 6.2	11:10 − 4.2
8:18 + 1.3	11:10 − 1.0	4:14 − 3.6	9:09 − 5.5	12:05 − 4.2
9:08 ± 0.0	12:07 − 2.5	5:18 − 2.6	10:08 − 4.1	1:08 − 3.9
10:18 − 1.0	2:13 − 4.2	6:52 − 0.3	11:03 − 4.0	2:00 − 4.4
11:14 − 2.2	4:16 − 3.4	8:14 + 0.9	2:03 − 4.3	4:11 − 5.5
12:02 − 2.6	6:14 − 0.5	9:09 + 1.1	3:02 − 4.7	6:14 − 7.6
1:10 − 2.8	7:09 + 0.8	10:09 + 0.9	4:04 − 5.2	7:12 − 8.6
2:04 − 2.8	8:21 + 1.3	11:09 − 0.6	5:04 − 5.2	8:13 − 9.0
3:18 − 1.9	9:20 + 0.9	12:12 − 2.3	6:12 − 4.9	9:14 − 9.1
4:06 − 0.7	10:10 + 0.4	2:14 − 5.4	7:58 − 3.1	10:10 − 8.6
5:01 + 0.4	11:04 − 0.8	4:26 − 6.6	9:15 − 1.9	11:08 − 8.5
5:51 + 1.3	12:01 − 2.1	6:06 − 5.0	10:08 − 1.8	12:00 − 7.8
6:56 + 1.8	1:06 − 2.7	7:14 − 3.4	11:02 − 1.8	1:09 − 7.2
8:11 + 1.6	2:17 − 3.3	8:10 − 2.5	12:06 − 2.7	2:11 − 6.6
9:26 + 0.4	3:09 − 2.3	9:04 − 1.7	2:10 − 5.0	3:05 − 6.3
10:15 − 0.7	4:08 − 1.7	10:00 − 1.6	4:12 − 7.9	4:04 − 6.2
11:10 − 2.1	5:02 − 0.6	11:05 − 2.0	6:55 − 8.9	5:07 − 6.1
12:11 − 3.1	5:41 + 0.3	12:00 − 2.8	8:12 − 8.0	6:44 − 6.3
2:12 − 3.2	7:03 + 2.0	1:08 − 3.5	9:10 − 7.4	8:01 − 6.3
4:05 − 1.5	8:06 + 2.7	1:54 − 4.1	10:16 − 6.5	9:03 − 6.5
6:10 + 0.7	9:05 + 2.4	3:20 − 4.9	11:10 − 6.3	10:08 − 6.3
7:40 + 1.1	10:06 + 0.9	4:10 − 4.4	12:02 − 6.0	12:09 − 5.3
8:46 + 0.6	11:02 − 0.5	5:10 − 3.5	1:07 − 6.5	1:56 − 4.9
9:46 − 1.0	12:05 − 2.6	5:49 − 2.7	2:08 − 6.8	4:08 − 4.9
10:52 − 1.3	3:31 − 5.2	7:14 − 0.9	3:17 − 7.1	6:06 − 6.5
11:53 − 2.3	5:10 − 4.5	8:10 + 0.2	4:07 − 7.1	7:21 − 7.9
12:51 − 2.8	6:39 − 1.3	9:08 + 0.7	5:06 − 7.3	8:34 − 8.7
2:10 − 2.8	8:18 ± 0.0	10:23 + 0.3	5:53 − 7.0	9:26 − 9.1
2:52 − 2.3	9:11 + 0.2	11:20 − 0.6	6:58 − 6.6	10:16 − 8.8
4:01 − 1.0	10:12 − 0.2	12:20 − 2.6	8:08 − 6.1	11:09 − 8.4
5:06 + 0.2	11:05 − 0.8	2:06 − 5.3	9:16 − 4.7	11:56 − 7.8
6:21 + 1.8	12:04 − 1.8	5:00 − 7.6	10:20 − 4.6	1:07 − 7.0
8:12 + 2.0	1:08 − 2.7	5:58 − 7.2	11:16 − 4.1	2:07 − 6.2
9:22 + 0.9	2:03 − 3.3	7:06 − 6.1	12:09 − 4.3	3:26 − 5.7
10:06 − 0.2	3:15 − 3.3	8:05 − 5.0	2:13 − 5.8	4:12 − 5.3
11:17 − 2.0	4:10 − 2.5	9:08 − 3.7	4:23 − 7.8	5:00 − 5.2
12:14 − 3.4	5:08 − 1.3	10:06 − 2.9	6:28 − 9.8	5:46 − 5.1
1:58 − 4.1	5:49 − 0.5	11:10 − 2.8	7:56 − 10.0	7:00 − 5.6
4:26 − 2.2	7:37 + 1.8	12:02 − 2.8	9:02 − 10.1	8:00 − 6.1
6:59 + 0.9	8:48 + 2.1	1:18 − 3.4	10:12 − 9.8	9:16 − 6.7
8:14 + 1.4	10:12 + 1.2	2:15 − 4.4	C = +1.30	10:18 − 6.8
9:11 + 1.1	11:16 − 0.6	3:11 − 4.0		11:07 − 6.8
10:13 + 0.2	12:03 − 2.2	4:04 − 4.4	11:21 − 8.7	12:24 − 6.3
11:10 − 1.1	2:06 − 5.4	4:58 − 4.1	12:04 − 7.6	2:03 − 5.2
12:10 − 1.8	4:16 − 6.0	5:48 − 3.7	1:08 − 7.1	4:19 − 4.1

TABLE III—*Continued*

A.M. October 24	P.M. October 26	A.M. October 29	A.M. November 1	P.M. November 3
6:06 — 5.3	6:29 — 2.8	9:10 — 4.2	12:42 — 5.3	2:11 — 4.2
7:07 — 6.2	8:05 — 3.6	10:08 — 5.0	2:20 — 8.3	3:15 — 4.3
8:11 — 7.3	9:17 — 5.1	11:12 — 6.0	4:12 — 9.9	4:10 — 3.8
9:08 — 8.2	10:16 — 6.9	12:08 — 6.9	6:06 — 9.3	5:12 — 3.7
10:05 — 9.1	12:11 — 9.6	1:10 — 8.1	7:12 — 8.8	5:50 — 3.8
11:04 — 9.3	2:02 — 9.8	2:14 — 8.0	C=−2.64	6:52 — 3.6
11:55 — 8.6	4:10 — 7.2	3:18 — 7.5		8:16 — 2.3
1:09 — 7.9	6:00 — 4.5	4:13 — 6.2	8:08 — 7.3	9:19 — 1.7
2:10 — 6.5	7:20 — 4.2	5:08 — 4.7	9:04 — 5.6	10:20 — 0.9
3:04 — 5.6	8:16 — 4.4	5:51 — 3.5	10:15 — 5.0	11:14 — 0.7
4:08 — 4.5	9:21 — 5.4	6:58 — 1.8	11:16 — 4.6	12:10 — 0.4
5:05 — 4.1	10:15 — 6.4	8:08 — 1.2	12:02 — 4.8	2:17 — 1.5
5:56 — 3.8	11:07 — 7.6	9:24 — 1.5	1:06 — 5.0	C=−1.84
6:56 — 4.4	12:02 — 8.6	10:21 — 2.9	2:09 — 5.9	
8:12 — 5.1	1:00 — 9.0	11:16 — 5.0	3:15 — 6.1	4:16 — 2.9
9:04 — 6.0	2:16 — 8.4	12:14 — 6.9	4:16 — 6.3	6:17 — 4.6
10:10 — 6.9	3:12 — 7.1	2:15 —10.7	5:20 — 6.0	7:19 — 5.2
11:16 — 7.5	4:16 — 5.5	4:16 —10.8	5:53 — 5.3	8:18 — 5.2
12:23 — 7.2	5:14 — 3.5	6:14 — 8.2	6:54 — 4.1	9:11 — 4.9
2:06 — 6.2	5:52 — 2.6	7:14 — 7.0	8:12 — 2.4	10:13 — 4.9
4:16 — 4.2	6:49 — 2.0	9:16 — 5.4	9:14 — 1.2	11:16 — 4.1
6:16 — 3.5	8:15 — 2.0	12:09 — 7.0	10:17 — 1.0	12:04 — 4.1
7:13 — 4.4	9:09 — 3.3	1:08 — 8.0	11:21 — 1.3	1:11 — 3.4
8:10 — 5.5	10:08 — 4.9	2:05 — 8.7	12:36 — 2.6	2:16 — 3.0
9:25 — 6.7	11:12 — 7.3	3:16 — 8.3	2:19 — 5.1	3:17 — 2.7
10:22 — 7.6	12:08 — 9.1	4:15 — 7.3	4:17 — 7.4	3:28 — 2.2
11:14 — 7.9	2:13 —10.5	5:08 — 6.2	6:14 — 8.3	4:18 — 2.6
12:01 — 7.9	4:12 — 8.3	5:56 — 4.6	8:17 — 6.1	5:07 — 2.6
1:08 — 7.2	6:49 — 4.2	6:58 — 3.3	9:19 — 5.5	5:54 — 2.3
2:10 — 6.1	7:30 — 3.8	8:13 — 1.6	10:17 — 4.8	6:50 — 1.8
3:20 — 4.5	8:18 — 3.5	9:18 — 1.6	11:10 — 4.3	8:05 — 1.7
4:19 — 3.6	9:06 — 3.6	10:18 — 2.3	12:15 — 4.2	9:14 — 1.5
5:09 — 2.7	10:06 — 4.4	11:20 — 3.7	1:18 — 4.2	10:09 — 1.1
5:53 — 2.4	11:07 — 5.4	12:33 — 6.0	2:25 — 5.0	11:10 — 0.6
7:08 — 2.7	12:02 — 7.0	2:16 — 9.4	3:15 — 4.7	12:23 — 0.3
8:02 — 3.7	1:14 — 7.6	4:16 —10.6	4:14 — 4.7	2:12 — 0.6
9:13 — 5.0	C=+0.90	6:25 — 8.9	5:18 — 4.5	4:11 — 1.7
10:17 — 6.7		7:18 — 7.9	6:24 — 3.5	6:12 — 3.4
11:12 — 7.5	3:06 — 8.8	8:27 — 6.5	8:04 — 2.4	7:12 — 3.7
12:02 — 7.9	3:48 — 7.9	9:34 — 5.8	9:16 — 1.2	8:15 — 4.1
2:19 — 7.0	4:46 — 5.7	10:17 — 5.6	10:06 — 0.7	9:16 — 4.6
4:12 — 4.5	5:20 — 4.4	11:12 — 6.0	11:09 — 0.9	10:27 — 4.4
6:14 — 3.1	5:49 — 3.2	12:04 — 6.3	12:16 — 1.4	11:08 — 4.5
7:14 — 3.6	6:54 — 2.2	1:05 — 7.0	2:17 — 3.2	12:04 — 3.6
8:16 — 4.3	8:07 — 1.7	2:29 — 7.5	4:38 — 5.6	1:12 — 2.7
9:16 — 5.9	9:06 — 2.7	3:31 — 7.2	6:24 — 6.5	2:12 — 2.4
10:15 — 7.3	10:10 — 4.2	4:20 — 7.1	8:19 — 5.9	3:10 — 1.6
11:13 — 8.7	11:19 — 6.4	5:13 — 6.0	C=−0.84	4:04 — 0.9
12:09 — 9.2	12:18 — 8.4	5:56 — 4.9		5:04 — 0.9
1:14 — 8.9	2:11 —10.5	6:52 — 3.6	9:26 — 5.7	5:52 — 1.4
2:28 — 8.1	4:08 —10.1	8:22 — 2.0	10:10 — 5.0	6:51 — 1.3
3:27 — 6.7	6:10 — 6.7	9:19 — 1.3	11:12 — 4.7	8:00 — 1.5
4:14 — 5.5	7:18 — 4.9	10:10 — 1.8	12:06 — 4.2	9:45 — 1.7
5:21 — 3.5	8:18 — 4.2	11:30 — 2.8	1:08 — 4.4	11:04 — 1.4

TABLE III—*Continued*

A.M. November 6	P.M. November 8	A.M. November 11	P.M. November 13	P.M. November 16
1:04 − 0.9	12:06 − 3.0	8:27 + 0.4	8:00 + 5.8	1:17 + 1.5
2:19 − 0.1	1:05 − 2.4	9:23 − 0.6	9:10 + 5.4	2:30 + 1.1
4:19 − 0.7	2:13 − 1.4	10:14 − 1.6	10:07 + 4.0	3:17 + 1.0
6:17 − 1.8	3:14 − 0.5	11:10 − 2.4	11:08 + 2.2	4:06 + 1.2
7:12 − 1.7	4:18 + 0.7	12:04 − 2.8	12:08 + 0.3	5:12 + 2.3
8:04 − 2.7	5:10 + 0.8	1:04 − 2.7	2:10 − 2.5	6:24 + 4.2
9:05 − 3.5	5:55 + 1.5	1:55 − 2.6	4:16 − 2.6	8:00 + 5.7
10:07 − 4.3	6:55 + 1.6	3:08 − 1.0	6:38 + 0.1	9:17 + 6.4
11:07 − 3.9	8:03 + 0.9	4:18 + 0.7	8:06 + 1.7	10:16 + 6.7
12:07 − 3.5	9:11 − 0.3	5:11 + 1.9	9:13 + 2.3	11:06 + 6.1
1:19 − 2.8	10:10 − 1.2	5:56 + 3.1	10:10 + 2.0	12:19 + 4.5
2:12 − 1.8	11:18 − 2.3	6:59 + 3.8	11:09 + 1.5	2:07 + 1.8
3:08 − 1.5	12:20 − 2.6	8:10 + 3.8	12:07 + 0.8	4:38 − 1.4
4:06 − 0.2	2:10 − 1.8	9:11 + 2.3	1:08 − 0.4	7:22 − 0.1
5:06 ± 0.0	4:17 − 0.1	10:12 + 0.8	2:01 − 0.4	8:15 + 0.5
5:50 − 0.2	6:18 + 1.0	11:10 − 0.7	3:09 + 0.5	9:10 + 1.5
6:48 − 0.4	7:08 + 1.0	12:32 − 2.6	4:09 + 1.3	10:12 + 2.4
7:59 − 0.9	8:15 + 0.2	2:08 − 3.4	5:06 + 2.6	11:14 + 2.8
9:08 − 0.9	9:16 − 0.6	4:10 − 2.5	5:56 + 3.5	12:10 + 2.6
10:10 − 1.8	10:16 − 1.9	6:28 + 0.8	6:50 + 4.6	1:07 + 2.5
11:08 − 1.7	11:16 − 2.4	7:24 + 1.4	8:12 + 6.1	2:10 + 1.8
12:14 − 1.4	1:13 − 2.7	8:16 + 1.3	9:12 + 5.8	3:15 + 1.7
1:11 − 0.8	2:29 − 1.5	9:18 + 0.8	10:20 + 5.1	4:03 + 1.6
2:10 − 0.3	3:27 − 0.3	10:14 + 0.1	11:14 + 3.9	5:05 + 2.3
4:18 + 0.4	4:36 + 1.3	11:18 − 1.0	12:04 + 2.3	5:52 + 2.6
6:12 − 0.3	5:25 + 1.8	12:08 − 1.4	2:11 − 1.9	7:12 + 3.9
7:12 − 0.7	6:13 + 2.1	1:08 − 1.7	4:16 − 2.4	8:08 + 4.8
8:08 − 1.1	8:25 + 1.4	2:12 − 1.7	6:08 − 0.6	C = +2.66
9.13 − 2.4	9:18 − 0.1	3:10 − 0.7	7:58 + 1.8	
10:09 − 2.5	10:18 − 1.1	4:04 + 1.1	9:06 + 2.6	9:16 + 5.7
11:05 − 3.3	11:20 − 2.6	5:05 + 2.8	10:18 + 2.5	10:09 + 6.3
12:04 − 3.0	12:20 − 3.3	6:00 + 3.7	11:08 + 2.3	11:09 + 6.4
1:07 − 2.2	2:04 − 3.2	7:05 + 4.7	12:04 + 1.7	12:12 + 5.7
2:22 − 1.3	4:08 − 0.3	8:08 + 4.9	1:12 + 1.1	2:08 + 3.4
3:12 − 0.7	6:04 + 1.1	9:17 + 3.9	2:16 + 0.6	4:12 + 0.4
4:17 + 0.3	8:20 + 1.0	10:08 + 3.0	3:16 + 0.7	6:13 − 0.2
C = −2.83	9:32 − 0.2	11:08 + 1.0	4:11 + 0.8	7:30 ± 0.0
	10:51 − 1.5	12:15 − 1.0	5:16 + 2.4	8:23 + 0.9
5:12 + 0.5	12:07 − 2.4	2:27 − 3.2	5:57 + 3.5	9:19 + 1.7
5:56 + 1.0	1:10 − 2.2	4:18 − 2.0	6:51 + 4.7	10:14 + 2.1
6:52 + 1.1	2:08 − 1.4	6:12 − 0.1	8:17 + 6.4	11:10 + 2.4
7:48 + 0.2	3:08 − 0.2	7:30 + 1.6	9:13 + 6.4	12:03 + 3.1
9:16 − 0.4	4:20 + 1.3	8:26 + 2.2	10:08 + 6.3	1:12 + 3.2
10:10 − 1.7	5:16 + 2.9	9:23 + 2.0	11:05 + 5.2	2:08 + 3.0
11:13 − 2.0	5:52 + 2.9	10:12 + 1.3	12:18 + 3.1	3:05 + 2.0?
12:13 − 2.1	6:52 + 3.3	11:06 + 0.5	2:06 − 0.1	4:04 + 2.7
2:44 − 0.9	9:01 + 1.6	12:06 ± 0.0	4:22 − 1.9	5:04 + 3.4
4:24 + 0.1	10:10 + 0.4	1:03 − 0.7	6:14 − 0.8	5:53 + 3.1
6:13 + 0.2	11:13 − 1.3	2:04 − 0.6	7:12 + 0.2	6:49 + 4.0
7:22 − 0.3	12:26 − 3.4	3:12 + 0.3	8:12 + 0.9	8:08 + 5.3
8:16 − 1.1	2:10 − 3.7	4:10 + 1.3	9:09 + 1.7	9:24 + 6.2
9:12 − 1.6	4:18 − 1.8	5:15 + 2.8	10:13 + 2.5	10:11 + 6.9
10:10 − 2.3	6:14 + 0.5	5:58 + 4.0	11:10 + 2.4	11:10 + 7.4
11:09 − 3.1	7:20 + 0.8	6:50 + 4.8	12:15 + 2.2	12:11 + 7.3

TABLE III—*Continued*

A.M. November 19	A.M. November 21	A.M. November 23	A.M. November 25	A.M. November 27
2:14 + 5.8	4:12 + 6.8	6:12 + 7.0	10:06 + 4.8	11:06 + 6.3
4:15 + 3.7	6:04 + 4.8	7:11 + 6.1	11:04 + 3.8	12:08 + 5.5
6:16 + 1.7	7:15 + 4.0	8:10 + 5.1	12:06 + 3.4	12:48 + 5.2
7:16 + 1.3	8:12 + 3.4	9:10 + 3.9	1:05 + 3.6	2:05 + 4.9
8:08 + 1.3	9:09 + 3.1	10:12 + 3.2	2:05 + 4.4	3:17 + 6.2
9:21 + 2.0	10:08 + 3.2	11:08 + 2.9	3:09 + 5.9	4:17 + 7.4
10:12 + 2.4	11:12 + 3.5	12:08 + 3.4	4:10 + 7.6	5:12 + 9.1
11:08 + 3.0	12:06 + 4.3	1:12 + 4.4	5:08 + 9.0	6:17 +10.6
12:12 + 3.7	1:09 + 5.4	2:18 + 6.0	5:55 + 9.7	7:30 +11.9
1:23 + 4.0	2:10 + 6.3	3:08 + 7.1	6:54 +10.0	8:16 +11.8
2:25 + 4.1	3:03 + 7.4	4:07 + 8.4	8:10 + 8.8	9:28 +11.0
3:12 + 4.2	4:09 + 7.8	5:03 + 8.6	9:08 + 7.7	10:18 + 9.6
4:14 + 4.1	5:14 + 7.8	6:08 + 8.7	10:05 + 6.0	11:08 + 7.9
5:13 + 4.1	5:50 + 7.2	8:02 + 6.9	11:08 + 4.0	12:09 + 5.9
5:50 + 4.0	6:53 + 6.6	9:06 + 5.1	12:08 + 2.5	2:03 + 2.7
7:06 + 4.3	8:06 + 5.6	10:09 + 3.8	2:10 + 1.1	3:52 + 2.4
8:11 + 4.4	9:16 + 5.1	1:15 + 2.8	4:05 + 2.8	5:35 + 4.1
9:19 + 5.3	10:14 + 5.0	3:07 + 4.5	5:56 + 5.7	6:37 + 5.6
10:12 + 5.7	11:14 + 5.3	5:06 + 6.5	7:18 + 6.9	8:19 + 7.4
11:05 + 6.3	12:12 + 5.6	7:11 + 6.4	8:20 + 7.1	9:06 + 7.6
12:16 + 6.8	2:34 + 6.8	8:18 + 5.6	9:18 + 6.4	10:04 + 7.6
2:09 + 5.9	4:10 + 7.3	9:18 + 4.4	10:16 + 5.7	11:06 + 7.2
4:12 + 4.5	6:10 + 6.2	10:07 + 3.6	11:09 + 4.7	12:06 + 6.2
6:07 + 2.7	7:20 + 5.1	11:14 + 3.1	12:06 + 4.1	1:07 + 5.7
7:14 + 1.9	8:12 + 4.3	12:04 + 2.9	1:02 + 3.9	2:08 + 5.2
8:08 + 1.6	9:08 + 3.5	1:10 + 3.6	2:06 + 4.7	3:16 + 5.8
9:22 + 1.8	10:14 + 3.2	2:07 + 4.8	3:10 + 6.0	4:08 + 6.6
10:18 + 2.1	11:09 + 3.3	3:19 + 6.9	4:08 + 7.4	5:05 + 7.9
11:09 + 2.9	12:02 + 3.7	4:14 + 8.3	5:06 + 9.3	5:48 + 9.0
12:09 + 3.4	1:09 + 4.9	5:09 + 9.4	6:00 +10.3	6:56 +10.8
1:05 + 4.3	2:14 + 5.9	6:00 + 9.6	6:52 +11.0	7:54 +11.8
2:04 + 4.7	3:18 + 7.4	6:54 + 9.2	8:02 +11.0	8:44 +11.9
3:07 + 5.3	4:14 + 8.0	8:12 + 8.3	9:10 +10.0	10:03 +11.2
4:05 + 5.2	5:08 + 8.4	9:10 + 6.8	10:12 + 8.1	12:00 + 7.8
5:03 + 5.3	5:52 + 8.2	10:13 + 5.1	11:18 + 5.9	3:15 + 2.6
5:56 + 4.9	6:48 + 7.5	11:05 + 3.4	12:36 + 3.4	5:16 + 3.0
6:56 + 4.8	8:02 + 6.5	12:08 + 2.2	2:08 + 1.8	7:06 + 5.3
8:04 + 4.8	9:20 + 5.1	2:12 + 2.5	4:26 + 3.1	8:21 + 6.9
9:08 + 5.2	10:06 + 4.3	4:16 + 4.7	6:04 + 5.2	9:30 + 7.8
10:14 + 5.4	11:17 + 3.7	6:10 + 6.9	7:16 + 6.7	10:48 + 7.5
11:07 + 6.0	12:18 + 4.1	7:20 + 6.9	8:21 + 7.5	12:03 + 7.0
12:12 + 6.6	2:12 + 5.6	8:24 + 6.4	9:18 + 7.4	1:22 + 6.2
2:06 + 7.2	4:12 + 7.0	9:14 + 5.6	10:04 + 7.0	2:18 + 6.0

TABLE IV 10(S.−N.+C.)

A.M. September 27	P.M. September 29	P.M. October 2	A.M. October 5	P.M. October 7
C = +0.70	9:36 + 0.8	3:59 − 3.6	9:01 − 6.8	10:01 − 8.1
8:04 + 2.9	11:01 + 1.6	5:01 − 4.6	10:02 − 7.0	11:00 − 8.4
9:00 + 3.2	11:59 + 1.9	5:59 − 5.3	**C = −2.30**	11:55 − 8.5
10:00 + 3.3	2:00 + 0.9	7:02 − 5.8	11:51 − 6.3	2:06 − 9.0
11:04 + 3.2	3:00 − 0.9	8:00 − 5.5	12:52 − 6.1	6:20 − 7.9
12:06 + 1.9	4:02 − 2.2	8:58 − 4.9	2:37 − 6.8	6:54 − 7.6
12:58 + 0.6	5:02 − 2.8	10:20 − 3.6	3:56 − 7.3	7:56 − 7.6
2:00 − 0.9	6:06 − 2.8	11:17 − 3.2	5:08 − 6.9	8:58 − 7.7
2:58 − 1.8	7:10 − 2.9	12:19 − 2.3	6:18 − 7.4	10:12 − 7.9
3:56 − 3.0	8:09 − 1.9	1:51 − 2.5	7:55 − 8.2	11:06 − 8.5
5:03 − 2.2	9:43 ± 0.0	3:05 − 2.8	9:12 − 8.0	12:06 − 9.2
5:58 − 0.9	10:52 + 0.4	4:04 − 3.6	10:18 − 8.6	1:00 − 9.4
6:54 − 0.1	2:08 − 0.1	6:29 − 5.6	11:55 − 8.7	1:59 − 9.3
8:02 + 0.7	3:10 − 1.9	7:49 − 6.1	2:12 − 8.1	3:01 − 9.1
9:03 + 2.0	4:05 − 3.2	8:58 − 6.2	4:02 − 7.9	3:58 − 9.1
C = +0.80	5:02 − 3.9	10:12 − 5.8	6:20 − 8.2	5:01 − 8.6
10:13 + 2.8	6:04 − 4.2	10:56 − 4.9	8:24 − 8.2	6:00 − 8.4
11:01 + 2.7	6:57 − 3.8	12:16 − 4.1	9:08 − 8.4	6:56 − 7.9
12:02 + 1.9	8:06 − 2.7	1:10 − 3.6	10:09 − 8.8	7:58 − 7.7
1:52 − 0.1	10:20 − 1.0	2:04 − 3.4	11:12 − 8.5	9:15 − 7.6
3:48 − 2.0	1:31 − 0.7	3:04 − 3.5	12:24 − 9.0	10:26 − 7.9
5:56 − 1.2	3:14 − 1.4	4:05 − 4.0	1:15 − 9.1	12:12 − 8.5
9:18 + 1.5	4:06 − 3.2	4:54 − 4.7	2:08 − 9.0	1:45 − 9.1
10:18 + 2.6	5:13 − 4.0	5:58 − 5.2	3:09 − 8.9	4:08 − 9.3
11:04 + 2.5	6:18 − 5.0	6:50 − 5.7	4:04 − 8.5	6:00 − 8.7
12:13 + 1.9	7:24 − 4.7	**C = +1.10**	**C = −1.76**	6:58 − 7.6
1:26 + 0.7	8:25 − 3.6	8:08 − 6.0	4:53 − 8.5	7:54 − 7.5
2:32 − 1.3	10:48 − 1.7	9:37 − 5.0	6:04 − 8.0	9:04 − 7.4
3:23 − 2.3	12:10 − 0.9	11:04 − 4.4	6:52 − 8.1	9:56 − 7.9
4:03 − 2.3	1:22 − 1.5	11:56 − 3.8	8:14 − 7.9	11:02 − 8.6
4:54 − 2.5	3:08 − 3.2	2:28 − 3.9	9:08 − 8.1	12:16 −10.0
6:00 − 1.6	4:00 − 3.5	5:33 − 5.1	10:05 − 7.9	12:58 −10.1
6:56 − 0.7	5:04 − 4.3	7:52 − 5.7	10:58 − 8.8	2:23 −10.4
7:54 + 0.6	6:02 − 4.5	8:58 − 6.0	11:55 − 8.9	2:57 −10.5
8:56 + 2.0	7:04 − 5.7?	10:01 − 6.3	1:56 − 8.5	4:07 −10.5
10:04 + 2.5	8:15 − 6.1?	11:11 − 6.7	4:07 − 8.2	5:05 − 9.9
11:12 + 3.4	9:08 − 3.8	12:06 − 5.9	6:09 − 8.0	6:02 − 9.2
12:04 + 2.6	**C = +1.92**	1:14 − 5.5	6:56 − 7.5	6:52 − 8.7
1:57 − 0.1	10:03 − 2.4	2:00 − 5.2	8:12 − 8.3	8:02 − 7.9
4:06 − 2.0	11:03 − 1.0	3:15 − 4.9	9:04 − 8.1	9:15 − 7.5
8:07 − 0.3	12:00 − 1.0	4:01 − 4.9	10:08 − 8.9	9:58 − 7.3
9:03 + 0.4	1:57 − 1.2	4:53 − 5.3	11:06 − 9.4	11:03 − 7.8
9:58 + 1.6	4:01 − 3.4	5:47 − 5.7	12:12 − 9.6	12:11 − 8.4
11:10 + 1.8	6:14 − 4.7	7:04 − 6.1	12:56 − 9.6	2:00 − 9.5
12:09 + 1.6	7:06 − 5.0	7:53 − 6.1	2:00 − 9.7	4:12 −10.2
1:11 + 0.1	8:12 − 5.3	8:56 − 6.4	2:55 −10.0	6:04 − 9.2
1:56 ± 0.0	9:01 − 5.0	10:04 − 6.7	4:01 − 8.5	7:09 − 8.8
2:58 − 1.4	9:57 − 4.4	10:56 − 6.6	4:56 − 8.6	8:02 − 8.2
4:05 − 2.2	11:06 − 3.7	12:02 − 6.1	5:51 − 8.0	8:58 − 8.0
5:07 − 2.8	12:10 − 2.6	2:00 − 5.7	7:07 − 7.7	10:00 − 8.0
5:52 − 2.3	1:00 − 2.4	4:09 − 5.6	7:58 − 7.5	10:59 − 8.3
7:04 − 2.5	2:12 − 2.3	6:28 − 6.5	8:56 − 7.7	12:11 − 9.3
8:19 − 0.8	3:10 − 3.2	7:30 − 5.9		12:58 −10.0
				1:56 −10.2

TABLE IV—*Continued*

P.M. October 10	A.M. October 13	P.M. October 15	P.M. October 18	P.M. October 21
3:02 −10.4	9:04 − 7.3	11:08 − 6.6	3:04 − 9.3	12:11 −11.6
4:03 −10.4	10:05 − 6.9	11:54 − 6.7	3:55 − 9.8	12:57 −11.1
5:02 −10.1	11:03 − 6.6	1:56 − 7.3	4:50 −10.1	2:03 −10.9
6:07 − 9.4	12:16 − 6.8	4:07 − 8.9	5:58 −10.6	3:10 −10.2
6:46 − 8.4	1:09 − 7.4	5:53 −10.1	6:42 −10.8	4:00 −10.1
8:01 − 8.0	2:16 − 8.4	7:05 − 9.5	8:19 −11.0	4:56 −10.4
9:10 − 7.1	3:04 − 9.2	7:55 − 9.2	9:42 −10.5	5:52 −10.5
10:06 − 7.1	4:06 −10.1	8:58 − 8.1	10:52 − 9.8	6:52 −10.7
11:02 − 7.7	5:02 − 9.5	10:02 − 7.1	11:52 − 9.7	7:53 −11.1
12:26 − 8.1	6:08 − 9.1	10:58 − 6.9	1:54 − 9.0	9:17 −11.6
2:00 − 8.8	6:44 − 8.9	12:12 − 6.8	3:54 − 9.9	10:06 −11.7
4:00 − 9.3	8:06 − 7.4	1:07 − 6.9	5:59 −10.1	11:01 −12.0
6:01 − 8.3	9:08 − 6.5	2:04 − 7.6	7:05 −11.4	11:54 −12.0
7:02 − 7.9	10:02 − 5.8	3:04 − 8.2	8:15 −11.8	12:58 −11.8
8:08 − 6.7	11:00 − 5.5	4:06 − 9.2	9:00 −12.3	1:50 −11.8
8:58 − 6.7	11:58 − 5.6	5:08 −10.2	9:59 −11.8	4:00 −11.7
10:09 − 6.3	2:02 − 7.6	6:38 −10.3	10:54 −10.9	6:05 −11.7
11:06 − 6.5	4:02 − 9.1	8:02 − 9.9	1:56 − 9.4	7:00 −11.8
12:12 − 7.1	6:03 − 9.2	8:56 − 9.4	2:54 − 9.4	8:04 −12.3
1:02 − 7.5	6:58 − 8.3	9:59 − 8.5	3:56 − 9.7	9:05 −12.9
1:54 − 8.0	8:13 − 7.5	10:58 − 7.7	4:56 −10.1	10:01 −13.0
3:10 − 8.8	9:12 − 7.1	12:00 − 7.6	6:22 −10.7	10:59 −13.4
4:00 − 9.1	10:02 − 6.4	2:02 − 8.4	7:50 −11.9	12:10 −13.2
4:55 − 8.8	10:56 − 6.4	4:16 −10.3	9:06 −11.8	1:00 −13.2
6:02 − 8.3	12:10 − 6.7	5:56 −11.1	9:59 −11.2	2:00 −12.7
6:49 − 7.7	12:58 − 7.2	7:08 −11.5	10:54 −10.8	2:57 −12.7
8:00 − 6.6	2:10 − 8.1	8:02 −10.9	11:58 −10.4	3:57 −12.3
9:18 − 5.7	3:00 − 9.3	8:55 −10.4	2:02 − 9.5	4:59 −12.0
10:08 − 5.5	4:00 −10.1	9:52 − 9.9	4:04 − 9.7	5:55 −11.8
11:03 − 5.4	4:53 −10.0	10:58 − 9.1	6:46 −10.9	6:54 −11.9
12:03 − 5.9	5:55 −10.0	12:09 − 8.5	8:03 −11.4	7:52 −11.9
2:00 − 7.3	6:53 − 9.6	12:58 − 8.2	9:04 −11.3	8:55 −12.2
3:55 − 8.6	7:58 − 8.9	2:03 − 8.3	10:10 −10.9	9.59 −12.6
6:00 − 8.1	8:55 − 7.7	3:07 − 9.3	11:02 −10.5	12:02 −13.3
7:28 − 6.8	9:55 − 6.8	4:02 −10.1	12:08 −10.0	1:47 −13.4
8:34 − 6.2	10:52 − 6.4	5:00 −10.8	12:54 − 9.5	4:00 −12.9
9:38 − 6.0	11:54 − 6.2	5:59 −11.4	2:00 − 9.1	5:56 −12.1
10:43 − 5.8	3:22 − 8.7	7:04 −11.4	3:10 − 9.2	7:12 −12.2
11:44 − 6.0	5:02 −10.2	8:00 −11.3	3:58 − 9.4	8:24 −12.5
12:44 − 6.6	6:31 −10.1	8:55 −10.6	4:56 − 9.7	9:11 −13.2
2:02 − 8.0	8:10 − 9.2	10:12 −10.0	6:02 −10.0	10:03 −13.4
2:46 − 8.8	9:03 − 8.6	11:07 − 8.9	6:48 −10.3	11:00 −14.1
3:54 − 9.1	10:04 − 7.9	12:11 − 8.5	7:58 −10.6	11:48 −14.2
4:58 − 8.9	10:58 − 7.6	1:54 − 8.1	9:04 −11.3	12:58 −14.1
6:14 − 8.2	12:12 − 7.4	4:50 −10.1	10:10 −11.2	1:58 −14.1
8:20 − 6.5	12:58 − 8.0	5:47 −10.7	11:05 −11.0	3:18 −12.8
9:14 − 6.2	1:54 − 8.3	6:58 −11.0	11:58 −10.9	4:02 −12.7
9:59 − 5.8	3:08 − 9.4	7:57 −11.2	2:02 −10.2	4:53 −12.2
11:10 − 5.4	4:03 −10.0	9:00 −11.1	4:09 −10.0	5:54 −11.6
12:06 − 5.7	5:02 −10.6	9:57 −10.3	6:14 −10.4	6:52 −11.4
1:51 − 7.3	5:58 −10.9	11:02 − 9.6	7:43 −11.1	7:54 −11.1
4:17 − 9.0	7:12 −10.3	12:10 − 9.1	8:52 −11.1	9:09 −11.2
6:50 − 8.4	8:36 − 8.6	1:12 − 8.6	10:01 −11.6	10:11 −11.9
8:07 − 7.6	10:02 − 7.4	2:07 − 8.8	11:06 −11.3	11:00 −12.5

TABLE IV—*Continued*

A.M. October 24		P.M. October 26		A.M. October 29		P.M. October 31		A.M. November 3	
12:16	−13.2	3:17	−16.0	9:01	−17.5	5:04	−21.1	11:03	−21.7
1:55	−13.9	4:07	−16.0	10:00	−16.7	5:47	−21.5	12:14	−21.3
4:09	−13.6	5:14	−15.7	11:04	−16.3	6:44	−22.1	12:58	−21.5
5:56	−12.5	6:35	−14.7	12:18	−16.3	8:13	−21.9	2:04	−21.0
6:58	−12.0	8:16	−13.1	12:56	−17.0	9:08	−21.1	3:07	−20.6
8:03	−11.9	9:10	−12.4	C = −1.60		10:00	−20.8	4:02	−20.9
9:00	−12.4	10:09	−12.4			11:19	−19.9	5:04	−21.1
9:56	−12.5	12:04	−13.5	2:03	−17.9	12:34	−19.4	5:58	−21.5
10:54	−13.3	1:54	−15.6	3:05	−19.6	2:10	−19.2	6:44	−21.8
12:04	−14.3	4:01	−16.9	4:01	−20.4	4:02	−20.3	8:07	−22.4
12:59	−14.7	5:52	−16.3	5:00	−21.4	5:57	−21.6	9:07	−22.4
2:00	−15.0	7:12	−14.9	5:42	−21.7	7:18	−22.2	10:11	−22.4
2:56	−14.7	8:08	−14.1	6:48	−21.4	7:58	−22.3	11:06	−22.1
4:00	−14.1	9:16	−13.3	7:56	−20.9	8:54	−22.3	12:00	−22.3
4:55	−13.3	10:07	−13.1	9:10	−19.7	10:04	−21.4	2:06	−21.9
6:05	−12.6	11:00	−13.2	10:10	−18.4	11:08	−20.5	4:07	−22.0
6:48	−12.4	12:10	−13.9	11:04	−18.1	12:10	−19.8	6:06	−22.2
8:00	−11.8	12:52	−14.6	12:02	−18.2	1:02	−19.4	7:08	−22.6
8:55	−11.5	2:07	−15.8	C = +0.60		2:00	−19.5	8:11	−22.8
10:02	−11.8	3:03	−16.8			3:02	−19.6	9:02	−22.9
11:08	−12.6	4:08	−17.5	2:04	−19.6	4:04	−20.4	10:03	−23.1
12:16	−13.6	5:07	−17.3	4:08	−21.2	5:09	−21.1	11:08	−22.9
1:57	−14.7	6:01	−16.9	6:04	−22.2	6:02	−22.0	11:56	−22.9
4:04	−14.1	6:42	−16.5	7:05	−21.9	6:45	−22.5	1:05	−22.6
6:00	−13.2	8:04	−15.4	8:04	−21.1	8:00	−22.4	2:08	−22.5
7:03	−12.5	8:58	−14.3	9:26	−19.8	9:04	−22.5	3:09	−22.1
8:00	−12.2	9:56	−13.7	10:19	−18.9	10:06	−21.8	3:19	−21.9
9:17	−12.5	10:58	−13.7	11:06	−18.4	11:10	−21.2	4:08	−21.6
10:14	−13.0	11:58	−14.0	12:17	−18.3	12:25	−20.9	4:58	−21.4
11:05	−13.5	2:00	−16.6	12:56	−18.5	2:06	−20.2	6:02	−21.5
11:53	−14.4	4:02	−18.3	1:58	−19.0	4:05	−21.1	6:41	−21.7
12:59	−15.0	6:37	−17.8	3:02	−20.2	6:01	−21.8	7:57	−21.9
2:01	−15.8	7:20	−16.9	4:05	−21.5	8:04	−22.4	9:07	−22.2
3:12	−15.7	8:10	−16.2	4:59	−22.2	9:04	−22.5	10:00	−22.4
4:11	−15.1	8:59	−15.4	5:47	−22.6	10:09	−22.1	11:02	−22.5
5:00	−14.5	9:58	−14.9	6:48	−22.7	11:01	−21.6	12:14	−22.6
6:00	−13.9	10:59	−14.8	8:00	−22.0	12:08	−21.4	2:03	−22.3
7:01	−13.0	12:09	−15.0	9:08	−21.5	1:09	−20.8	4:00	−22.0
8:08	−12.0	1:05	−15.9	10:08	−20.6	2:17	−20.5	6:01	−22.0
9:06	−11.7	4:05	−20.2	11:10	−20.1	3:06	−20.8	7:02	−21.9
10:10	−11.9	4:34	−20.7	12:21	−19.7	4:06	−21.0	8:06	−22.2
11:04	−12.5	5:10	−20.2	2:08	−20.1	5:07	−21.7	9:02	−22.4
11:54	−13.2	5:40	−20.2	4:07	−21.8	6:34	−22.4	10:15	−22.5
2:06	−15.4	6:44	−19.5	6:17	−23.5	7:56	−22.9	10:59	−22.5
4:00	−15.7	7:57	−18.5	7:10	−23.3	9:08	−22.5	11:56	−22.5
6:03	−14.2	8:56	−17.4	8:20	−22.7	9:58	−22.5	1:05	−22.7
7:04	−13.4	10:00	−16.5	9:27	−21.6	11:01	−22.1	2:02	−22.4
8:26	−12.2	11:10	−15.9	10:07	−21.0	12:06	−21.9	3:00	−22.3
9:08	−12.1	12:10	−16.4	11:04	−19.9	2:08	−21.3	3:56	−22.1
10:07	−12.0	2:00	−18.3	12:12	−19.1	4:30	−21.4	4:56	−21.8
11:06	−12.7	3:56	−20.3	12:58	−19.0	6:14	−22.0	6:00	−21.6
12:01	−13.1	5:56	−21.1	2:22	−19.5	8:10	−22.7	6:43	−21.4
1:06	−14.3	7:05	−19.6	3:20	−20.2	9:18	−22.6	8:08	−21.4
2:20	−15.8	8:09	−18.7	4:11	−20.8	10:02	−22.4	9:37	−22.2

TABLE IV—*Continued*

P.M. November 5	P.M. November 8	A.M. November 11	P.M. November 13	P.M. November 16
10:56 −22.3	12:57 −23.1	9:15 −22.5	9:03 −26.8	2:24 −28.4
12:56 −23.0	2:04 −23.5	10:06 −22.7	10:00 −26.1	3:09 −28.9
2:10 −22.7	3:06 −23.8	11:04 −23.2	11:00 −25.6	3:58 −29.4
4:08 −22.5	4:10 −23.5	12:12 −23.5	12:00 −25.7	5:01 −29.9
6:07 −21.8	5:01 −23.2	12:56 −24.2	2:00 −27.1	6:16 −30.7
7:03 −21.8	6:02 −22.6	1:48 −25.0	4:08 −28.8	7:52 −30.9
7:54 −21.8	6:48 −22.0	3:01 −26.0	6:29 −29.1	9:05 −30.4
8:57 −21.8	7:55 −21.4	4:10 −26.6	8:00 −28.4	10:09 −29.7
9:59 −22.2	9:02 −21.2	5:02 −26.5	9:06 −27.5	10:58 −29.2
11:00 −22.6	10:03 −21.2	5:48 −26.3	10:02 −26.9	12:12 −28.6
11:56 −22.9	11:10 −21.7	6:46 −25.5	11:02 −26.6	1:59 −28.5
1:10 −23.4	12:14 −22.6	8:00 −24.6	11:59 −26.0	4:30 −29.8
2:03 −23.4	2:00 −23.9	9:02 −23.7	12:58 −26.3	7:09 −31.0
2:58 −22.8	4:04 −24.2	10:04 −22.9	1:54 −26.9	**C=+4.54**
3:58 −22.6	6:04 −23.2	11:00 −23.0	3:00 −28.2	
4:57 −22.0	6:58 −22.5	12:24 −23.4	4:00 −28.9	8:06 −31.2
5:58 −21.9	8:04 −21.8	1:58 −24.9	4:56 −29.3	9:04 −31.1
6:38 −21.3	9:04 −21.5	4:01 −26.4	6:04 −29.6	10:05 −30.8
7:50 −21.3	10:05 −21.6	6:20 −26.0	6:42 −29.8	11:06 −30.0
9:00 −21.3	11:25 −22.4	7:14 −25.4	8:04 −29.0	12:04 −29.4
10:02 −21.7	1:07 −23.7	8:06 −24.8	9:03 −28.2	1:00 −29.2
11:00 −22.0	2:22 −24.3	9:08 −24.1	10:12 −27.3	2:04 −28.9
12:08 −22.6	3:33 −24.5	10:06 −23.6	11:06 −26.9	3:07 −29.6
1:03 −22.9	4:28 −24.5	11:10 −23.7	11:57 −26.6	3:56 −30.0
2:03 −22.9	5:18 −24.1	12:16 −24.0	2:02 −27.5	4:57 −30.8
4:06 −22.5	6:06 −23.6	12:58 −24.6	4:02 −29.0	5:46 −31.8
6:03 −21.6	8:16 −21.8	2:03 −25.6	5:59 −30.0	7:02 −32.5
7:04 −21.5	9:11 −21.4	3:01 −26.5	7:49 −29.8	8:00 −32.6
8:00 −21.1	10:10 −21.4	3:57 −27.3	8:58 −29.0	9:08 −32.6
9:05 −21.1	11:13 −21.5	4:57 −27.5	10:10 −28.5	10:02 −32.5
10:02 −21.2	12:12 −22.2	5:52 −27.3	11:00 −27.8	11:00 −31.9
10:57 −21.4	1:56 −23.6	6:58 −26.8	11:55 −27.2	12:04 −31.3
11:57 −22.0	3:57 −23.9	7:59 −25.9	1:03 −27.4	2:00 −30.9
12:59 −22.4	5:55 −22.9	9:03 −25.2	2:08 −28.0	4:02 −31.2
2:12 −22.8	8:12 −21.2	9:59 −24.3	3:08 −28.5	6:03 −32.7
3:04 −22.5	9:24 −21.2	11:00 −24.2	4:04 −29.5	7:20 −33.0
4:08 −21.9	10:44 −21.4	12:08 −24.2	5:08 −30:0	8:14 −33.4
5:02 −21.7	12:14 −22.5	2:18 −26.3	5:49 −30.5	9:12 −33.3
6:01 −21.3	1:01 −23.0	4:09 −27.6	6:42 −30.5	10:04 −33.0
6:45 −20.8	2:00 −23.6	6:02 −27.7	8:09 −30.5	11:02 −32.6
7:42 −20.2	3:00 −24.3	7:22 −27.1	9:06 −29.9	11:56 −31.7
9:04 −20.3	4:06 −24.5	8:18 −26.3	10:01 −29.2	1:03 −31.3
10:03 −20.3	5:08 −24.1	9:16 −25.4	10:58 −28.6	2:00 −30.9
11:05 −20.7	5:56 −23.7	10:04 −24.9	12:10 −28.1	2:56 −30.8
12:04 −21.7	6:48 −22.5	11:00 −24.4	1:58 −28.3	3:55 −30.9
2:36 −23.0	8:54 −21.3	11:58 −24.6	4:11 −30.0	4:56 −31.0
4:11 −23.0	9:59 −20.9	12:55 −25.2	6:06 −30.8	5:46 −31.6
5:59 −22.0	11:03 −21.0	1:58 −26.0	7:04 −31.0	6:40 −32.0
7:09 −21.5	12:04 −21.4	3:06 −27.1	8:02 −31.0	8:02 −32.7
8:04 −21.4	2:01 −23.0	4:02 −28.0	9:02 −30.5	9:14 −33.0
9:00 −21.2	4:05 −24.3	5:07 −28.6	10:04 −29.7	10:00 −33.0
10:02 −21.4	6:03 −23.6	5:50 −28.9	11:01 −28.9	11:02 −32.9
11:00 −21.6	7:10 −22.8	6:42 −28.4	12:08 −28.3	12:02 −32.3
11:56 −22.1	8:20 −22.3	7:54 −27.7	1:10 −27.9	2:01 −31.7

TABLE IV—*Continued*

A.M. November 19		A.M. November 21		A.M. November 23		P.M. November 25		P.M. November 27	
4:05	−32.0	4:03	−32.3	7:00	−30.8	12:13	−31.7	2:01	−34.4
6:06	−32.2	5:54	−31.7	8:00	−30.2	12:58	−32.7	3:09	−35.8
7:08	−33.0	7:08	−31.2	9:03	−30.5	1:58	−33.4	4:09	−36.7
8:00	−33.5	8:01	−31.6	10:02	−30.6	3:02	−34.4	5:03	−36.9
9:12	−33.6	9:00	−31.8	11:00	−31.1	4:02	−34.8	6:10	−36.7
10:02	−33.3	9:59	−32.3	12:00	−32.2	5:00	−34.6	7:22	−36.2
11:00	−33.0	11:02	−32.5	1:05	−32.6	5:48	−34.1	8:09	−35.5
12:02	−32.6	11:57	−32.8	2:12	−33.2	6:47	−33.6	9:20	−34.7
1:16	−32.5	1:00	−33.1	3:01	−33.2	8:00	−32.4	10:09	−33.8
1:52	−32.3	2:00	−32.7	4:00	−33.1	9:00	−31.6	11:00	−33.3
C = −1.25		2:56	−32.5	4:55	−32.4	9:57	−31.2	12:00	−33.3
		4:01	−32.0	6:02	−31.5	11:00	−31.3	1:54	−34.4
2:58	−32.3	4:55	−31.6	7:55	−30.2	12:00	−32.0	3:42	−36.1
4:04	−31.6	5:56	−31.6	8:59	−30.1	2:02	−34.0	5:28	−37.2
5:04	−31.2	6:46	−31.3	10:01	−30.1	3:57	−35.2	6:29	−37.1
5:42	−32.0	7:58	−31.3	1:07	−32.7	5:48	−35.2	8:11	−35.9
6:57	−32.0	9:10	−31.5	2:59	−33.3	7:09	−34.2	8:58	−35.1
8:03	−32.4	10:07	−32.3	4:58	−32.7	8:10	−33.1	9:58	−34.3
9:12	−33.3	11:06	−32.7	7:03	−31.0	9:10	−32.2	11:00	−33.7
10:04	−33.1	12:05	−33.2	8:10	−29.9	10:08	−31.7	12:10	−33.2
10:58	−33.6	2:25	−32.4	9:12	−29.7	11:03	−31.7	1:00	−33.4
12:06	−33.3	4:00	−32.5	10:00	−29.9	12:12	−32.4	2:01	−34.3
2:00	−32.6	6:00	−31.4	11:08	−30.9	12:56	−33.2	3:10	−35.5
4:03	−32.2	7:06	−30.9	11:58	−31.8	1:58	−34.2	4:00	−36.3
5:55	−32.1	8:00	−31.0	1:04	−32.9	3:02	−35.3	4:58	−37.0
7:04	−32.4	9:00	−31.3	2:00	−33.7	4:00	−36.0	5:54	−37.5
8:00	−32.6	10:07	−31.7	3:12	−34.1	4:57	−36.6	6:49	−37.4
9:16	−33.3	11:00	−32.1	4:07	−33.9	5:51	−36.4	8:00	−37.0
10:10	−33.3	11:54	−32.8	5:01	−33.5	6:44	−35.8	8:39	−36.4
11:00	−33.4	1:00	−33.4	5:55	−32.8	7:54	−34.5	10:10	−35.1
12:02	−33.6	2:04	−33.2	6:44	−32.1	9:00	−34.1	11:52	−34.1
12:57	−33.4	3:11	−33.3	8:04	−30.8	10:04	−33.0	3:07	−35.4
1:55	−32.9	4:06	−32.7	9:02	−30.5	11:08	−32.7	5:09	−36.9
3:00	−32.4	5:01	−32.1	10:05	−30.6	12:27	−33.4	6:58	−37.2
3:58	−32.0	5:48	−31.8	10:56	−30.9	1:58	−34.6	8:14	−36.5
4:56	−31.8	6:40	−31.2	12:00	−31.8	4:17	−36.6	9:22	−35.6
5:49	−31.6	7:54	−30.8	2:02	−33.6	5:57	−36.6	10:41	−34.7
6:46	−31.9	9:09	−31.0	4:08	−34.4	7:07	−35.6	11:56	−33.7
7:56	−32.0	9:58	−31.4	6:00	−32.9	8:14	−34.8	1:15	−33.8
9:00	−32.5	11:10	−32.1	7:11	−32.0	9:10	−33.7	2:10	−34.3
10:06	−33.0	12:12	−32.9	8:16	−31.1	9:58	−32.9		
10:59	−33.3	2:01	−33.3	9:06	−30.6	10:58	−32.8		
12:04	−33.3	4:01	−33.0	9:59	−30.3	12:01	−32.7		
1:57	−33.1	6:02	−31.4	10:57	−30.7	12:42	−33.2		

DIASTROPHISM AND THE FORMATIVE PROCESSES. V

THE TESTIMONY OF THE DEEP-SEA DEPOSITS

T. C. CHAMBERLIN
University of Chicago

Deposits laid down immediately after a deformation of the earth-shell adjust themselves more or less closely to the new inequalities of surface. This adjustment takes place at any level at which deposition occurs, shallow or deep. This follows from the nature of the case and needs no discussion. But in the stages that follow the deformation at some interval, when cumulative effects begin to be felt, the shaping of the deposits bears larger evidences of the agencies that work from the general environment and that shape into conformity with themselves the new configurations which the bottoms assume in the process of growth. In the preceding articles we have tried to draw out certain diastrophic significances from the nature of deposits laid down on shallow bottoms which, in the process of growth, came sufficiently near the water surface to be given shape by its agitation.

It falls to us now to inquire what diastrophic import there may be in the deposits of the deep sea on which surface agitation has slight effect and to which contributions from the bordering lands are limited. We may then turn to deposits that lie between the deep-sea deposits and the shelf-sea deposits, and that partake measurably of the qualities of both without having the distinctive characters of either.

The deep-sea deposits form a distinctive class sharply distinguished from sea-shelf deposits. They have been made so familiar by the labors of Sir Wyville Thompson, Sir John Murray, and their colleagues of the Challenger Expedition, and by the contributions of Professor Alexander Agassiz, the Prince of Monaco, and others, that we need here dwell only on those features that bear testimony to the nature, extent, and limitations of the diastrophism that has affected them.

By way of approach and qualification let it be noted that while these deposits mantle the bed of the deep sea very generally and must be presumed to have been essentially free from the agitating effects of sea waves and similar superficial agencies, the special locations in which such deposits accumulated most largely were yet somewhat influenced by even such currents as affect the abysmal waters. The larger part of the finely divided material of the abysmal deposits, whether it came from surface organisms or from dust or wash, floated long before it finally found lodgment at the bottom of the deep sea, and hence slight differences of motion determined whether given particles came to rest at a particular point or floated on to a quieter spot. The circulation of the deep sea is relatively gentle, but still there is the circulation actuated by the differences of temperature between the equatorial and polar regions, and the differences of density between the belts of heavy precipitation and the belts of active evaporation, not to speak of motion communicated by friction from the surface currents actuated by the winds, tides, and other familiar agencies. If the great sea basins have been essentially permanent throughout geologic history, a point we shall urge a little later, the long persistence of the currents of the deep circulation have made cumulative differences in the growth of the abysmal deposits, and some fraction, greater or less, of the undulations and the smoothed surfaces that characterize the ocean bottoms signify differences of deposition, even though the deposition at any one time has been small compared with the volume of sedimentation that took place in an equal time near the sea border. It is observed that on many submarine slopes and ridges no fine mud is deposited because of the strong currents that sweep the bottom clear.[1] In the upper half of the ocean depth the movement of the currents has been measured instrumentally; in the lower half, positive data are scant, but it is clear that the diversion of the great abysmal currents of water, as they encounter continental or other obstacles to their progress, is likely to give rise to concentrated or quickened currents at the critical points of arrest and deflection.

But, although such inequalities of deposition must be recog-

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[1] Murray and Hjort, *The Depths of the Ocean* (1912), p. 272.

nized, they do not alter the great fact that the abysmal bottoms are mantled almost universally by a characteristic deposit, nor is there ground to suppose that these inequalities of deposition are sufficient to conceal any great deformation that has affected the abysmal bottoms since the earth came to mature form. Mountain ranges, if they once existed on the sea bottom, can scarcely have been seriously obscured by deep-sea deposits, and, if there have been protrusions from the sea bottom of a continental order, their configurations should still be visible.

Among the characteristics of the deep-sea deposits that have diagnostic value in our study are those especially which imply that given deposits must have been formed at given abysmal depths. There is need to consider the following factors:

(1) The relics of life that lived in the surface waters of the clear ocean or within photosynthetic depths or depths that have distinct relations to surface conditions, the pelagic life or plankton. Where the surface life mingled freely with terrigenous silt, as it generally did near extensive land, the silt tells the tale of its relationship. Where the surface life made deposits essentially free from admixture with terrigenous silts, open oceanic conditions are generally implied, but the deposits in themselves do not imply any special depth of sea. They do not even necessarily imply distance from land, for if the set of the ocean currents is constantly and steadily toward the land, the pure oceanic waters may effectively keep back the land silts and give origin to a pure oceanic deposit close up to land. So too, measurably, if currents of pure oceanic waters set steadily and persistently into mediterranean bodies of water, relatively pure pelagic deposits may be formed when the conditions are such that basal and marginal agitation is held in abeyance. When the land has been well base-leveled and is densely clothed with vegetation and bordered by sea-encroaching plants, the conditions are favorable for relatively pure oceanic deposits even in waters that indent or intersect the land. Some of the earlier extravagances in the interpretation of chalk deposits have found a check in considerations of this kind. The measure of shallowness of the bottom in such cases is likely to be revealed by the nature of the bottom life. Submerged platforms, however, when isolated

from all migratory connections with land-girting bottoms of like depth, may come to bear a pure pelagic deposit free from clear evidences of shallow-water bottom life and yet without necessarily implying any great depth.

(2) The relics of the life of the zone that lies below the superficial and photosynthetic zone and above the bottom. Normally the life relics of this median zone, as well as the relics from the surface zone above, fall together to the bottom and are there mingled with the relics of organisms that live at the bottom. Only a part of the mixture is diagnostic of depth, the benthos. A possible source of error of interpretation may arise in those areas in which the lower waters are constantly welling up and so displace the usual surface layer and more or less of its life. This displacement of the surface life is most likely to be effective where the temperature or the salinity of the rising waters is uncongenial to the surface life. In such areas the lower life is likely to follow the rising water to unusual heights and perhaps thus to vitiate more or less the usual bathymetric interpretations.

(3) The relics of the bottom life. In so far as this life is strictly confined to the bottom and can be proven to be limited to given depths, it constitutes a firm criterion for determining the depth at which the deposits containing it were formed. Positive proof that any particular form of life is strictly confined to given great depths is attended by inherent difficulties. In the great depths of the ocean basins there is a complication of the influences that affect living organisms, (1) pressure, (2) temperature, (3) salinity, (4) gas-content, as well as less tangible agencies, and it is improbable that the individual effects of these have as yet been wholly disentangled and the influence of pressure, as such, separately discriminated. *Pressure*, however, is the only true criterion of depth; the associated temperatures, salinities, and gas-contents are incidental; indeed just now they are probably the special results of the present polar phase of the deep-sea circulation; they are perhaps to be regarded as but a lingering feature of the recent glacial period, and as more or less inapplicable to other periods. It would probably be quite unsafe to assume similar temperatures, salinities, and gas-contents at all other times. In the period, for example, during

which life of sub-tropical aspect flourished in the surface seas of polar latitudes, it is not apparent how ice-cold waters could fill the abysmal depths in low latitudes as they do now; nor can similar salinities or gas-contents be safely assumed. The gas-content of the deep-sea waters at present seems clearly to be the result of high absorption in the cold polar regions where the absorption of oxygen is about doubled for a lowering of temperature of 30° C. and the absorption of carbon dioxide doubled for a lowering of about 20° C. I have elsewhere urged that there was a reversal of present deep-sea temperatures at the times when the remarkable stages of polar warmth prevailed, and that the reversal was the cause of such warmth.[1] If such reversal took place, it would probably modify rather radically the gas-content, as, by hypothesis, it did the salinity and temperature of the deep-sea waters, and hence, no doubt, their life. Whether this view be accepted or not, the difficulty of rationally postulating the persistence of ice-cold abysmal water in a stratum lying between the heated interior of the earth and a surface stratum sufficiently warm to sustain reef-growing corals in high latitudes is manifest. It is a much safer assumption that the temperature of the abysmal waters is variable, and has usually followed the climatic episodes that have dominated the earth's temperature in general.

It is almost certain that oceanic life is more responsive to such changes of temperature as occur in nature than to such changes of pressure as it usually encounters. Life is indeed seriously affected by changes of pressure that are so rapidly forced upon it as to prevent a distribution of the pressure increment or decrement throughout the tissues, but organisms do not often suffer such sudden changes in the course of nature. A change sufficiently slow to permit a gradual equalization of pressure seems to be tolerated by sea life with relative indifference. According to Murray and others some species of rather free-moving forms have a bathymetric range of 3,000 meters and more. Some species indeed seem to pass from one pressure to another in short periods without ill effects. The present adaptations of abysmal life may therefore be

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[1] T. C. Chamberlin, "On a Possible Reversal of Deep-Sea Circulation and Its Influence on Geologic Climates," *Proceedings of the Amer. Phil. Soc.* (1906), Vol. XLV.

regarded rather as adaptations to existing temperatures, salinities, and gas-contents which happen to vary with depth, than as adaptations to pressure simply. The present distributions of abysmal deposits are therefore probably the products of a complex of variables of which temperature, salinity, and gas-content are not unlikely more potent than pressure.

Deep-sea deposition is at present singularly conditioned by the action of the sea-water. If the surface life were essentially uniform, and if some appreciable amount of life occupied all lower depths, as seems to be the case, the deposits of any period, if unmodified, should increase in thickness with increase of sea depth; but almost the reverse seems to be the real fact. This reversal is assigned to the solvent action of the sea-water. The larger portion of all the life relics assignable to the upper levels is wanting at the greatest depths. It is nearly absent over a large fraction of the abysmal area. The calcareous element is more largely removed than the silicious, but the latter seems to suffer also. This selective action gives to the residue of the extreme abysmal deposits their striking character more largely perhaps than any abundance of life relics that are known to be confined to great sea depths. This solvent action is most plausibly assignable at present to the exceptional absorption of oxygen and carbon dioxide in the polar seas whence it is carried to all the abysmal depths, giving them at once their low temperature and their high content of these active gases. The sections of Brennecke showing the distribution of oxygen in the North Atlantic between latitude 60° N. and 50° S. are very instructive in this respect.[1] The oxygen acting on organic matter gives rise to carbon dioxide and this, added to the original content, gives competency to dissolve the calcareous shells that fall from above. The loss of the silicious relics is not so well determined nor so well explained so far as it may be a fact.

In interpreting oceanic deposits of other ages than the present, the possibility, if not the probability, that different groups of organisms and different solvent results marked the various bathymetrical horizons, because the gas-contents, the salinities, and the temperatures were probably different, is not to be overlooked.

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[1] Murray and Hjort, *The Depths of the Ocean* (1912), pp. 255, 256.

But these prudential considerations do not affect the general diagnostic nature of the oceanic deposits. They only bear on certain special bathymetrical inferences.

It appears from all the considerations that bear upon the case that the diagnostic character of the abysmal deposits is of a most declared and convincing type when broadly applied with due circumspection. Grounds for a critical attitude only arise in respect to ultra-inferences based on small remnants of ancient deposits in limited areas.

Now the broad facts are these: At the present time nearly two-thirds of the area of the earth's surface is covered by deep-sea deposits of recent origin. About one-half of the present surface is covered by truly abysmal deposits. What lies below these abysmal deposits, representing earlier periods, is unknown, because inaccessible. There is a strong presumption that similar deposits lie below the recent ones representing the earlier ages. This presumption rests on the more primary assumption that oceans of great volume existed all through those earlier ages and were giving rise to oceanic deposits, since the requisite forms of life and of débris are known to have then existed, and this, taken in connection with the even more significant fact that such abysmal deposits do not form appreciable members of the terranes of the continents, leaves no other presumption available. Sir John Murray says: "With some doubtful exceptions, it has been impossible to recognize in the rocks of the continents formations identical with those of the pelagic deposits."[1] And again he remarks: "It seems doubtful if the deposits of the abysmal areas have in the past taken any part in the formation of the existing continental masses."[2] With few exceptions, the marine members of the continental deposits belong to the shelf-sea series and to deposits of the foreset terrigenous type. These are facts of the first order of moment, and in them lies strong evidence of the permanence of the continents. The marine deposits of the continents are either epi-continental or terrigenous, the deposits of the ocean basins are oceanic and probably always have been as far back as the record permits us to go.

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[1] Murray and Renard, "*Challenger*" *Report on Deep Sea Deposits* (1891), p. 189.

[2] *Op. cit.*, Introduction, p. xxix.

The exceptions, so far as there are any, probably all lie in the disrupted border tracts on the edge of the ocean basins or the borders of the continental protuberances, i.e., on the junction tracts between the great elevations and depressions.

The conclusion that continents and the ocean basins have been permanent in their essentials, thus so strongly supported by stratigraphical and paleontological evidence, is in complete harmony with the modern geodetic argument from the distribution of gravity and with the theory of isostasy, whichever of its phases be accepted. It is, at the same time, consonant with the dynamical inferences that spring from the deep differentiation of the specific gravities of the crust. It falls in with all the views drawn from other sources thus far set forth in this series of articles. Permanent ocean basins, gathering abysmal sediments ever since deep oceans began, alternating with permanent continents, always girt about and overlain by sea-shelf deposits and foreset bordering sediments, are regarded as the great fixed features of the earth's mature history.

The view that the continents and the oceanic basins have been permanent since the earth-body attained its maturity does not of course go so far as to affirm that there were no encroachments of the oceans upon the continents or of the continents upon the oceans, or that there were no transfers of bordering blocks or folds from the one to the other. In the very nature of the case, there must have been pressure contests along the borders, and the dividing lines may well have shifted more or less. Growth and creep seaward from the continents is assumed as probable, and periodic counterthrusts landward from the ocean basins are assumed as more than probable. Advances and recessions on the border lines and oscillations up and down are thus of the nature of the case.

Though the continental segments, because of their lesser specific gravities and their convex attitudes, tended, when under lateral pressure, to upward movement, and the sub-oceanic segments, because of their higher specific gravities and their concave forms, tended, under lateral pressure, to downward movement and underthrust, reversals of these natural movements would be probable in exceptional cases because of the complexity of the conditions; and so continental folds or blocks might well become abysmal, and abysmal folds or blocks might well become continental occasionally, while, in still other cases, oscillations between the two extremes might arise. It does not militate, in any proper sense, against the view of permanency of the continental and abysmal segments, that there should be these diversities of local action on the hinge lines of the great segments.

Now there are not only simple hinge lines along the junctions of continental and abysmal segments but there are complex hinge areas, as for example areas in which the angles of a pair of continents and also the angles of a pair of abysmal segments approach one another, as the angles of the two Americas and of the Atlantic and Pacific basins, respectively, approach one another in the Antillean region, and as similar approaches are made elsewhere. These "four-corners" of the earth's segmentation are regions of exceptional instability and are affected by unusual seismic and volcanic activities.[1] In these complex hinge areas it is natural that there should be some exceptional behaviors of blocks and folds on the borders of the four contesting segments, or between them. More than that, these seem to be regions in which gigantic hooks, loops, and spits were built out from the continents, because they are regions in which conflicting shore drifts, as well as drifts of a deeper sort, actuated by the profounder currents of the great water bodies, prevailed. All the lands that lie between the massive portions of North America and South America, including Florida, Mexico, the Gulf of California, Central America, the Isthmus of Panama and the Antillean ridges, bear the aspect of gigantic hooks, loops, and spits formed in the progress of the ages between the massive nuclei of the two American continents. A similar aspect is borne by the hooks, loops, and spurs that connect southeast Asia with Australia. Less notable ridges and bridges of a similar kind appear in other junction areas.

Now if these are in reality constructive features of this kind, built out from the primitive continental segments upon the adjacent borders of abysmal segments, they cease to be typical features of either continental or abysmal type; they are rather conjoint products, with dynamic habits of their own, and they are to be interpreted on the basis of their own idiosyncracies.

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[1] Chamberlin and Salisbury, *Geology* (1904), pp. 573–75.

These considerations give point to the following observations:

1. The cases in which true abysmal deposits, or close imitations of true abysmal deposits, now appear above the sea-level do not, when all are put together, appear to attain in area so much as one per cent of the total earth surface. So that, even if we assume that all cases plausibly interpreted as abysmal are truly so, the fraction of the crust in which a reversal of the dominant habit obtains is still so small that it cannot be regarded as other than exceptional.

2. So far as my present information goes, all the cases that call for serious consideration as real or plausible instances of the lifting of abysmal deposits above sea-level lie in the notable hinge areas where exceptional instability now prevails and apparently has prevailed far back in geologic history. By far the best of all cases of supposed oscillation between abysmal and subaërial attitudes is that offered by the "oceanic deposits" of the island of Barbados in the Windward group of the Lesser Antilles. To be associated with this in interpretation are the "oceanic deposits" of Trinidad, Jamaica, Cuba, and Haiti, all in the same hinge area between North and South America and between the Atlantic and Pacific basin segments. These additional oceanic deposits have not been as well studied as those of Barbados, but from what is known they seem to hamper rather than strengthen the interpretation that the Barbados deposits are really abysmal. But to this we will return later.

The supposed deep-sea deposits of Sicily are perhaps entitled to rank next to those of Barbados in type and importance. These, like the preceding, are associated with similar deposits adjacent to the Mediterranean on the north and on the south. These, like the collateral deposits of the Antilles, perhaps hamper rather than strengthen a strictly abysmal interpretation of the deposits. But neglecting this, the notable feature of the case is that these deposits lie in one of the most remarkably unstable regions of the globe, the hinge area between the more stable parts of Eurasia and the stable part of Africa. This hinge line has its eastward projection along the ancient Tethys Straits and thus becomes connected with the East Indian tract which also is one of notable instability. The

Nicobar Islands in this tract are isolated much as are the Windward Islands, and bear deposits interpreted as oceanic.

It appears therefore that all the more notable cases of this class are situated on hinge-line areas where notable flexures of the shell have been pronounced features, and where all movements are perhaps to be regarded as of a special order rather than as typical.

If we grant that all these are cases in which the crust has really oscillated from abysmal depths to atmospheric levels, they can scarcely be said to affect seriously the broad conclusion of permanency of the true continents and ocean basins drawn from the absence of abysmal deposits in the continental terranes, and from the probable presence of these beneath the recent accumulations on the abysmal segments.

Returning to the Barbados case, the gist of the local problem is found in (1) a lower deposit unquestionably formed in shallow water, (2) a middle "oceanic deposit," consisting of some beds resembling globigerina ooze and of others resembling radiolarian ooze and "Red Clay"—the group thought to imply a depression to 10,000 or 12,000 feet—and (3) an upper stratum of coralline rock, implying a return to shallow waters, and later (4) an elevation of 1,100 feet above the sea. The series has been made the subject of an elaborate study by A. J. Jukes-Brown and J. B. Harrison,[1] and of shorter papers by G. F. Franks and J. B. Harrison,[2] J. W. Gregory,[3] and J. W. Spencer.[4] The chemical, physical, and biological comparisons of Jukes-Brown and Harrison make distinctly plausible an abysmal descent between the formation of (1) and the formation of (3), during which the oceanic beds were laid down. The island stands by itself and was completely submerged; its uppermost parts are mantled by the oceanic deposit.

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[1] A. J. Jukes-Brown and J. B. Harrison, "The Geology of the Barbados," *Quart. Jour. Geol. Soc. London*, XLVII (1891), 197–250; XLVIII (1892), 170–226.

[2] G. F. Franks and J. B. Harrison, "The Globigerina Marls and Basal Reef-Rocks of Barbados," *ibid.*, LIV (1898), 540–55.

[3] J. W. Gregory, "Contributions to the Paleontology and Physical Geology of the West Indies," *ibid.*, LI (1895), 255–310.

[4] J. W. Spencer, "On the Geological and Physical Development of Barbados with Note on Trinidad," *ibid.*, LVIII (1912), 354–67.

After moderate submersion, no land detritus would reach it, for it stood on the windward side of the Antilles and of South America, as the name of the group to which it belongs implies. The only deposits that could well accumulate, after this stage was reached, were those of the oceanic plankton or of the benthos, if it sank so deep. The life relics of a portion of the deposits supports the interpretation that the island actually sank to the benthos zone, but there is the alternative assumption that the benthos life and correlated conditions were carried up to unusual levels by upwelling currents about the island after it reached the stage of moderate submersion. The supposition of an elevated benthos zone might well seem gratuitous, or even an improbable special pleading, if there were not two considerations that seem to force on the case a choice between alternative special pleadings.

1. In the common interpretation it is assumed that a portion of the crust was depressed 10,000 feet or more to reach the horizon of the benthos and then raised again a somewhat greater amount, while the benthos horizon remained stationary. This is a special pleading where all the burden is thrown on crustal dynamics. This may well seem to the dynamic student as inherently improbable as an upwelling of abysmal waters carrying up the benthos zone does to the biological student.

2. On the island of Jamaica oceanic beds occur which likewise imply depression to at least moderate depths; but the summit heights of the island do not seem to have been submerged, and a similar negation seems to be predicable of Cuba and Haiti, though investigation in these cases is incomplete. The summits of none of these three islands seem to be mantled or ever to have been mantled by oceanic deposits as is the case with Barbados; they merely bear such deposits on their flanks. A special pleading that would carry these down to the usual level of the benthos requires a supplementary special pleading to account for the absence of oceanic deposits over the upper levels generally. Careful study of the whole problem is yet a thing of the future, but if this is a representative picture of the case, it would seem to be in the line of the least expenditure of energy and of the highest probability to avoid the extremes on both sides and to assume that an upwelling of the

deep sea-waters about the islands carried the benthol life and conditions to higher levels than they usually occupy now, while crustal oscillations of moderate range met this by adequate depression. This seems to explain at once, and without violence, the decided oceanic phenomena of Barbados and the divided oceanic and insular phenomena of Jamaica and the loftier islands.

But, however this may be, the total import of the distribution, positive and negative, of the deep-sea deposits furnishes a cogent argument against the view that any large part of the abysmal bottoms of the ocean basin has, at any time since the beginning of systematic stratigraphic history, been so elevated as to become a part of the present continents.

The argument has an indirect bearing on the reciprocal view that former continents have been submerged so deeply as to become parts of the present abysmal bottoms. The depression of any great continent to abysmal depths must necessarily have drawn into the cavity it left a great volume of the oceanic waters, and, if there was no reciprocal elevation of the ocean bottom elsewhere—and the preceding argument bears against that—there must have been a lowering of the sea-level about all the continents, with a profound effect on the shelf-sea work. Such profound effects have not been, I think, inferred from the stratigraphical or paleontological record itself. It is very doubtful if they can be successfully superimposed by special pleading. No great movement in any part of the complex oceanic basin can properly be assumed without specifically assigning its consequences in the changes of sea-level implied by it nor without supporting this by stratigraphical facts. Otherwise it is a speculation entertained in negligence of its physical consequences.

The direct adjudication of the hypothetically lost continents lies in a simple appeal to the configuration of the part of the sea bottom involved. It cannot reasonably be supposed that a continent could be submerged so as to completely obliterate its configuration. Its outlines should be still discernible and constitute its credentials. Without these it would seem hazardous to entertain the conception, even if there were not strong presumptions against it springing from other considerations.

There are well-known ridges on the bottoms of the oceans and others of minor order will not unlikely yet be disclosed. It is quite consistent with sound dynamics and a conservative attitude to suppose that these may have once been more bowed, or less bowed, than now, and that they may once have cut the sea surface and constituted linear islands, or land bridges, and have played their part in the migrations of plants and animals, just as present bridges may have been once submerged. And these conservative deformations, together with the oscillations and displacements of the segment borders, seem to be about the limit of probable interchange between the real continents and the real ocean basins. Their dominant feature was, as Dana, Wallace, and others long ago urged, permanency.

THE STRENGTH OF THE EARTH'S CRUST

JOSEPH BARRELL
New Haven, Connecticut

PART II. REGIONAL DISTRIBUTION OF ISOSTATIC COMPENSATION

INTRODUCTION AND SUMMARY

The strength of the crust has been tested in the first part of this paper by those geologic changes which alter the surface of the earth, but not the density of its interior. If these changes in load initiate rather than merely coincide with vertical movements which serve to diminish the stress, they are thereby shown to be greater than the earth can permanently endure. If, on the other hand, the constructional forms persist, as in the two great deltas studied, then the movements which may exist in the crust due to those loads must be slower at least than the process of surface construction. Such loads consequently, unless counterbalanced by some factor not apparent, are within the limits of crustal strength.

But surface changes and the loads implied can be measured only in special cases. The previous attitude of the crust and the degree and direction of strain then existing in it are complicating factors which it is difficult quantitatively to evaluate. For these reasons the evidence yielded by geodetic investigation promises, in the end, more general and more accurate results.

It is an important conclusion, established by geodetic evidence, that the ocean basins are underlain by heavier matter than that beneath the continental platforms; the tendency through geologic time for the continents to rise relatively to the oceans may be correlated with this difference in density and the lightening of the land areas by the progressive erosion of the land surfaces. It is believed that the rejuvenative movements are in the direction of isostatic equilibrium. Fortunately for land-dwelling vertebrates, the crust is too weak for readjustment to be deferred until after the erosion of the lands, begun by the subaërial forces, shall have been completed by the sea.

But the power of geodetic research does not cease with the establishment of this cause of the maintenance of the differential relief between land surface and ocean floors. Beneath the surface of the continents it reveals heterogeneities of density and measures them against the more or less local relief above. To the extent to which areas of lighter or denser matter do not correspond to proportionately higher or lower relief, real strains either upward or downward are shown to exist through the crust. Over areas of plains which have not suffered much change for geologic ages, geodesy may thus reveal the existence of large crustal strain. On the contrary, in regions of mountainous relief, although the individual mountains are sustained by rigidity and bring local strains upon the supporting basement, geodetic study may show that there is close regional compensation of density balanced against relief, obliterating with depth the stress differences due to topography. These methods of research are thus capable of attacking the problem of the amount and direction of vertical strain existing in the crust under any part of the land surface and, to a lesser degree of accuracy, the crust beneath the sea. The breadth of the individual areas which depart from equilibrium in one direction may constitute also a vital part of the problem.

But although these are fields of research open to the geodesist, they are cultivated with much labor. The position of many stations on the surface of the earth must be determined by astronomic observations to within a fraction of a second of arc. Then a triangulation network, continent-wide, ties these together and shows at each station, after allowing for the small errors of observation, what are the deflections of the vertical produced by the variations of relief and density. But this deflection for each station is the net result of all the relief from mean level and all the subsurface departures from the densities necessary to sustain that relief for distances of hundreds and, to a diminishing extent, even thousands of miles. The problem is made more soluble, however, by another and independent mode of attack. Observations on the intensity of gravity, when corrected for latitude, for elevation, for the surrounding relief and the density theoretically needed to sustain that relief, show the vertical component of those outstanding forces whose horizontal component was measured by astronomic determinations. It is seen that if the topography is known and its influence evaluated, and sufficient observations are reduced, the distribution of subcrustal densities and consequently the amount of crustal strains form soluble but complex problems.

The mathematical mode of investigation of such problems has, however, both its advantages and disadvantages. The advantages lie in giving quantitative results and in the test of the accuracy of the trial hypotheses by means of the method of least squares. A disadvantage lies in the necessity of erecting simple hypotheses in place of the complex realities of nature, in order to bring the data within the range of mathematical treatment. The precision of mathematical analysis is furthermore likely to obscure the lack of precision in the basal assumptions and through the apparent finality of its results tends to hide from sight other possibilities of the solution.

It is because of the geologic nature of the hypotheses on which the calculations concerning isostasy rest, and the geologic bearing of the results, that it is no act of presumption for the geologist to enter into this particular field of the geodesist.

The measurements of isostasy have been placed most fully on a quantitative basis by Hayford, and the science of geology is indebted to him in large measure. In the following consideration of the geodetic evidence attention will be confined almost entirely to his work, supplemented by that of Bowie. Hayford was the first to consider the influence of the topography and its compensation to very great distances from each station, the first to make a considerable number of trial solutions upon various assumptions as to the depth of the zone of isostatic compensation, with the result that the reduction of the observations gave the dimensions of the earth with a considerably smaller probable error than any previous computations.[1]

But the conclusions in regard to the strength of the crust, drawn in the first part of this article from the study of deltas, stand in strong contrast to certain statements by Hayford and later by Hayford and Bowie. This second part must therefore outline the results reached by them and show what reconsiderations are necessary in order to bring into harmony their conclusions and the evidence derived from the previous geologic study. A preliminary review without criticism is given of their work in order to bring out their methods and results, and the geologic conclusions which they draw from those results. It is followed by a re-examination of the subject of regional versus local compensation. This is the problem of the size of the area over which, by virtue of the rigidity of the crust, irregularities of density and topography do not have individual relationships but do largely compensate each other over the region as a whole. It is a measure, therefore, of the areal limits of crustal strength. The tests employed by Hayford and Bowie are, as they note, indeterminate up to radii above 58.8 but less than 166.7 km. in length. Consequently Hayford did not change his opinion, based upon previous investigations, that regional compensation was limited to areas of less than one square degree. In

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[1] The final publications have been issued by the United States Coast and Geodetic Survey and are as follows: Hayford, "The Figure of the Earth and Isostasy from Measurements in the United States (up to 1906)," 1909; referred to in this paper as Hayford, 1906; Hayford, "Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy," 1910; referred to in this paper as Hayford, 1909; Hayford and Bowie, "The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity," 1912; referred to in this paper as Hayford and Bowie, 1912; Bowie, "Effect of Topography and Isostatic Compensation upon the Intensity of Gravity" (second paper), 1912; referred to in this paper as Bowie, 1912.

In addition Bowie has published in the *American Journal of Science*, "Some Relations between Gravity Anomalies and the Geologic Formations in the United States," (4) XXXIII (1912), 237–40.

The following discussion of their geodetic measurements and results will be confined to the work in these five papers.

this article, however, two other tests are applied which indicate that although in some areas compensation does not extend to 166.7 km. radius, in other areas it extends farther. It is concluded that the United States shows regional departures from isostasy over areas many times larger than Hayford thought to exist, as broad and in some regions probably somewhat broader than the areas of the Nile and Niger deltas, the breadth depending in considerable part upon the magnitude of the loads per unit of surface.[1]

GEODETIC MEASUREMENTS OF ISOSTASY BY HAYFORD AND BOWIE

Hayford's conclusions from deflections of the vertical.—The positions of many stations over the United States were determined with great accuracy by geodetic measurements from other stations, thus making a closed network. The positions were also determined by astronomic observation. The differences in latitude and longitude between the geodetic and astronomic positions give the observed deflections of the vertical due to the attraction of the surface irregularities and internal heterogeneities of the geoid. To account for these deflections the gravitative attraction upon the plumb-line at each station of all the topography from ocean bottoms to mountain tops within 4,126 km. was computed. The influence of the topography alone upon the direction of the vertical is known as the topographic deflection and averages a little over 30″. The average of the actually observed deflections are, however, but a fraction of this value. Consequently the excesses of volume represented by continents above oceans, and by plateaus on continents must be very largely balanced and neutralized by corresponding deficiencies of density in the crust beneath, which in turn explains how the larger relief is sustained. This is the theorem of isostasy. Various hypotheses in regard to the magnitude and distribution of these deficiencies in density under the continents, of excesses under the oceans, may be made, and the deflections recomputed on these successive suppositions and compared with the observed deflections.

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[1] At the recent meeting of the Geological Society of America, December 30, 1913, to January 1, 1914, Professor W. H. Hobbs gave a paper on "A Criticism of the Hayfordian Conception of Isostasy Regarded from the Standpoint of Geology." The writer did not have the pleasure of hearing this paper, but it is clear that Professor Hobbs has attacked independently the same problems as here discussed.

The difference is the residual error due to the partial incorrectness of a hypothesis. The exactly correct hypothesis would reduce all residual errors to zero except for the errors of observation and computation. A hypothesis which approximates to the truth will give small residual errors. In a large mass of data the sum of the squares of the residuals as derived from different hypotheses serves as a test of the relative agreement of the hypotheses with nature, that hypothesis applying best for which the sum of the squares is a minimum. In all of the complete solutions a uniform distribution of compensation was assumed to exist from the surface to the bottom of the zone of isostatic compensation. That is, if the column under a certain portion of land was 3 per cent lighter than under a certain portion of water, then it was assumed that at any and every depth the two columns differed in density by 3 per cent. The differences abruptly terminate at the level where the two columns, the long but light land column and the short but heavy sea column, become of equal weight. At the level of this surface isostatic compensation is complete and there is hydrostatic equilibrium.

A tabulation of the probabilities of these hypotheses as applied to the whole of the United States is as follows:

TABLE III

Hypothesis	Sum of Squares of 765 Residuals
Solution B (extreme rigidity; depth of compensation infinite)	107,385
Solution E (depth of compensation 162.2 km.)	10,297
Solution H (depth of compensation 120.9 km.)	10,063
Solution G (depth of compensation 113.7 km.)	10,077
Solution A (depth of compensation zero)	18,889

The first investigation, that of 1906, favored Solution G, the final, that of 1909, as shown in this table, favored H. The most probable depth on the hypothesis of uniform compensation with depth and of equal depth of compensation for the whole United States was a little greater, being 122.2 km., 76 miles. It is seen, however, that there is but little change in the sum of the squares for a considerable range in the assumed depth. Further, Hayford states that the hypothesis of all compensation being attained in a 10-mile stratum whose bottom is at a depth of 35 miles is about as probable as the solution which he adopted.[1] Other variations in the hypothesis are also possible with about the same probable error.[2]

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[1] 1906, p. 151.

[2] 1906, p. 153.

A distribution suggested by Chamberlin, of compensation greatest a little below the surface and diminishing to nothing at 178.6 miles, is also about as probable. Hayford therefore does not claim that his geodetic studies determine with precision the nature or depth of the distribution of compensation. The figure of 76 miles should therefore be used always with this reservation.

The residuals were classified into fourteen geographic groups. The most probable depths of compensation indicated for the several groups range from 66 to 305 km. According to Hayford, the evidence from these groups is, however, so weak and conflicting that he sees no indication that the depth of compensation is not constant over the whole area investigated.[1] He notes that, so far as the evidence goes, it indicates the depth of compensation to be greater in the eastern and central portions of the United States than in the western portion.[2] The subject is one which will be taken up later in the discussion of geodetic results.

In regard to the completeness of compensation, Hayford states:

> From the evidence it is safe to conclude that the isostatic compensation is so nearly complete on an average that the deflections of the vertical are thereby reduced to less than one-tenth of the mean values which they would have if no isostatic compensation existed. One may properly characterize the isostatic compensation as departing on an average less than one-tenth from completeness or perfection. The average elevation of the United States above mean sea-level being about 2,500 feet, this average departure of less than one-tenth part from complete compensation corresponds to excesses or deficiencies of mass represented by a stratum only 250 feet (76 meters) thick on an average.[3]
>
> It is not intended to assert that every minute topographic feature, such, for example, as a hill covering a single square mile, is separately compensated. It is believed that the larger topographic features are compensated. It is an interesting and important problem for future study to determine the maximum size, in the horizontal sense, which a topographic feature may have and still not have beneath it an approximation to complete isostatic compensation. It is certain, from the results of this investigation, that the continent as a whole is closely compensated, and that areas as large as states are also compensated. It is the writer's belief that each area as large as one degree square is generally largely compensated. The writer predicts that future investigations will show that the maximum horizontal extent which a topographic feature may have and still escape compensation is between 1 square mile and 1 square degree. This prediction is based, in part, upon a consideration of the mechanics of the problem.[4]

[1] 1909, pp. 55–59.

[2] 1906, pp. 143, 146.

[3] 1909, p. 59.

[4] 1906, p. 169.

These conclusions imply a weakness of the crust surprising to the geologist and stand in marked contrast to those figures derived from the study of the deltas of the Nile and Niger. This subject also will be discussed later, as here it is desired to give only a summary statement of the methods and conclusions.

Hayford and Bowie on variations of gravity.—Regarding the relations of variations in gravity to isostasy, Hayford and Bowie state:

> As soon as it was evident that the proper recognition of isostasy in connection with computations of the figure and size of the earth from observed deflections of the vertical would produce a great increase in accuracy, it appeared to be very probable that a similar recognition of isostasy in connection with computations of the shape of the earth from observations of the intensity of gravity would produce a similar increase of accuracy. Logically the next step to be taken was therefore to introduce such a definite recognition of isostasy into gravity computations. Moreover, it appeared that if this step were taken it would furnish a proof of the existence of isostasy independent of the proof furnished by observed deflections of the vertical, and would therefore be of great value in supplementing the deflection investigations and in testing the conclusions drawn from them. In other words, the effects of isostasy upon the direction of gravity at various stations on the earth's surface having been studied, it then appeared to be almost equally important to investigate the effects of isostasy upon the intensity of gravity.[1]

In order to make the computations, the isostatic compensation was assumed to be complete under every topographic feature and uniformly distributed to a depth of 114 km. below sea-level, producing hydrostatic equilibrium at this depth. The mean density of 2.67 was taken as applying to the whole zone to this depth. Under land 3 km. high this gives a density of 2.60 from sea-level to a depth of 114 km.; under ocean 5 km. deep a density of 2.74 from ocean bottom to 114 km. below the bottom.[2]

The authors show that the topography and its compensation for the whole earth must be taken into consideration. On these assumptions the theoretic value of gravity was computed for every station, 124 in the final publication. This computed value is subtracted from the observed value and gives the "new-method" anomaly for each station. The results are shown in Fig. 5.

[1] Hayford and Bowie, 1912, p. 5.

[2] Hayford and Bowie, 1912, pp. 9, 10.

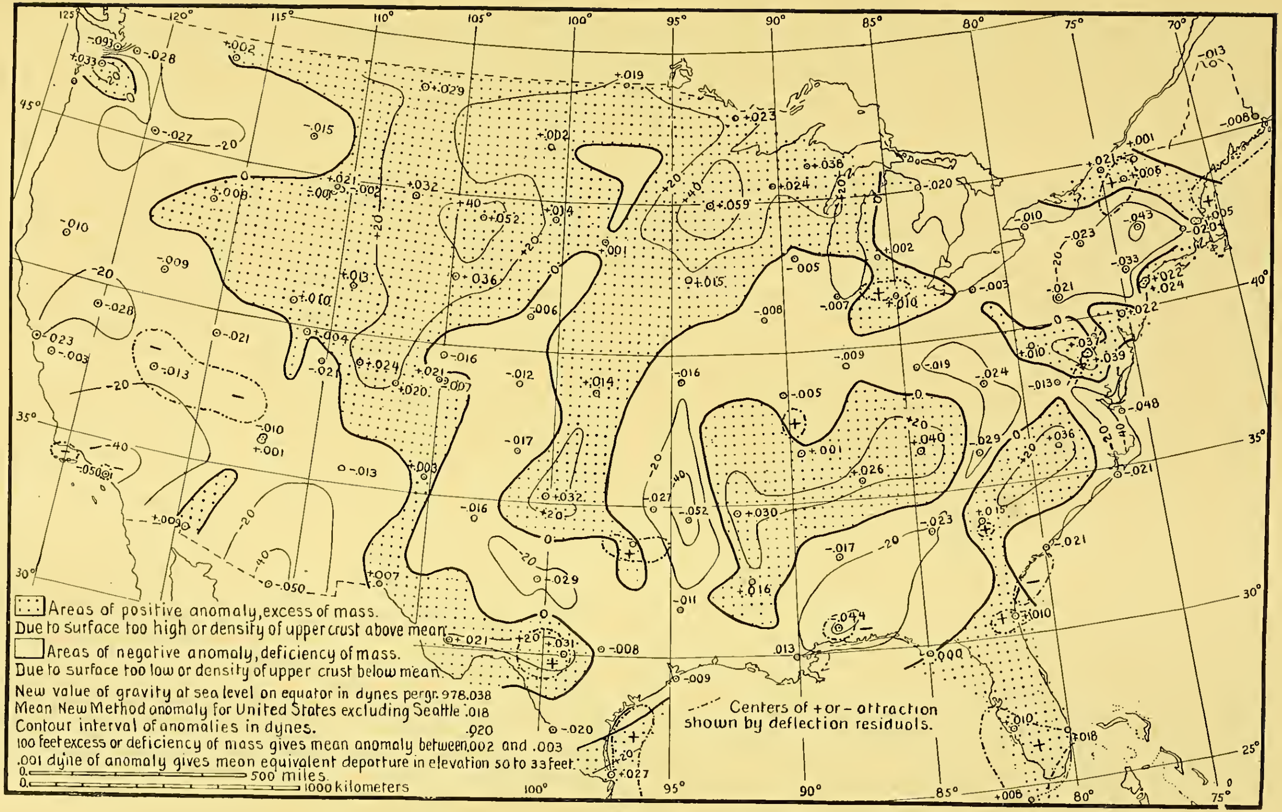

FIG. 5.—Lines of equal anomaly for new method of reduction, after Bowie

Of the two other principal methods of gravity reduction which have been previously used, the Bouguer reduction takes no account of isostatic compensation, postulating a high rigidity of the earth's crust, and neglects all curvature of the sea-level surface. The "free-air" reduction assumes that each piece of topography is compensated for at zero depth. These two reductions correspond thus to the limiting solutions tried for deflections of the vertical. The sum of the squares of the new method anomalies, when compared respectively with the similar sums derived from the hypothesis of rigidity and the hypothesis of compensation at depth zero, shows that the assumption of isostatic compensation uniformly distributed to a depth of 114 km. gives on the average smaller anomalies; is therefore much more probable and yields a more accurate value for the intensity of gravity. The mean anomaly of all stations in the United States without regard to sign, omitting the exceptionally large anomalies of the Seattle stations, is as follows:

New method	0.018 dyne[1]
Bouguer	0.063
Free air	0.028

The value of gravity for the United States Coast and Geodetic Survey office at Washington was determined as 980.112 dynes per gram. The mean new-method anomaly is consequently about 0.00002 of the value of gravity. The probable error of observation and computation is about 0.003 dyne. The errors may, however, frequently exceed 0.004 dyne and in rare cases may be as great as 0.010 dyne.[2] The fact that these measures of gravity are the forces acting on one gram will be understood through the rest of the paper.

Of the 124 stations, 32 have anomalies between 0.020 and 0.030, 12 have anomalies between 0.030 and 0.040.[3] Still smaller numbers of stations have higher anomalies. These anomalies measure departures in the earth's crust from the conditions of isostasy which were postulated. In the interpretation of the anomalies in terms of mass it is shown that a small excess of mass immediately below

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[1] Bowie, 1912, p. 12.

[2] Hayford and Bowie, 1912, p. 79; Bowie, 1912, p. 13.

[3] Bowie, 1912, p. 13.

the station or a large excess at great depth or to one side may have the same effect. Therefore it is necessary to speak of the net effective excess or deficiency of mass.[1] A table is given showing these relations, and as a mean working hypothesis it is assumed that ordinarily each 0.0030 dyne of anomaly is due to an excess or deficiency of mass equivalent to a stratum 100 ft. thick. In the final paper it is concluded:

> From the evidence given by deflections of the vertical the conclusion has been drawn that in the United States the average departure from complete compensation corresponds to excesses or deficiencies of mass represented by a stratum only 250 feet thick on an average. The gravity determinations indicate this average to be 630 feet instead of 250 feet. In neither case is the average value determined or defined with a high grade of accuracy. The difference between the two determinations of the average value is therefore of little importance. The determination given by the gravity observations is probably the more reliable of the two. Each determination is significant mainly as showing that the isostatic compensation is nearly perfect.
>
> The average elevation in the United States above mean sea level is about 2,500 feet. Therefore, from gravity observations alone the compensation may be considered to be about 75 per cent complete on an average for stations in the United States.[2]

This conclusion implies a somewhat greater rigidity to the crust than that which is stated for the deflections of the vertical, but in regard to the maximum horizontal extent which a topographic feature may have and still escape compensation the authors still express the belief that the limit is between one square mile and one square degree. "It appears from the inconclusive evidence furnished by the gravity observations that the radius of this area is probably less than 18.8 kilometers."[3]

This review of the work of Hayford on deflections of the vertical, and of Hayford and Bowie on the gravity anomalies has been given in order that the methods of the work, its bearings on the strength of the crust, and the conclusions which were reached, may be perceived. It is seen that a large difference of view as to the strength of the crust exists between this interpretation from the geodetic evidence and that from the geologic. In the following pages will be

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[1] Hayford and Bowie, 1912, pp. 108–12; Bowie, 1912, p. 22.

[2] Bowie, 1912, pp. 22, 23.

[3] Hayford and Bowie, 1912, p. 102.

given a discussion which it is thought brings out certain errors in the conclusions drawn from the geodetic work and thereby reconciles the two lines of evidence.

REGIONAL VERSUS LOCAL DISTRIBUTION OF COMPENSATION

Conclusions on this topic by Hayford and Bowie.—Under this heading Hayford and Bowie state:

> The question whether each topographic feature is completely compensated for by a defect or excess of mass exactly equal in amount directly under it, or whether the topographic feature is compensated for by a defect or excess of mass distributed through a more extensive portion of the earth's crust than that which lies directly beneath it, is a very important one. The theory of local compensation postulates that the defect or excess of mass under any topographic feature is uniformly distributed in a column extending from the topographic feature to a depth of 113.7 kilometers below sea level. The theory of regional compensation postulates, on the other hand, that the individual topographic features are not compensated for locally, but that compensation does exist for regions of considerable area considered as a whole.
>
> In order to have local compensation there must be a lower effective rigidity in the earth's crust than under the theory of regional compensation only. In the latter case there must be sufficient rigidity in the earth's crust to support individual features, such as Pikes Peak, for instance, but not rigidity enough to support the topography covering large areas.
>
> Certain computations have been made to ascertain which is more nearly correct, the assumption of local compensation or the assumption of regional compensation only. In making such computations it is necessary to adopt limits for the areas within which compensation is to be considered complete. A reconnoissance showed that the distant topography and compensation need not be considered, for their effect would be practically the same for both kinds of distribution. As a result of this reconnoissance it was decided to make the test for three areas, the first extending from the station to the outer limit of zone K (18.8 kilometers), the second from the station to the outer limit of zone M (58.8 kilometers), and the third, to the outer limit of zone O (166.7 kilometers).[1]
>
> The average anomaly with regard to sign by the new method with local compensation, and the average anomaly by each of the three new-method reductions with regional distribution of the compensation are respectively −0.002, −0.001, −0.001, and −0.002 dyne. The means without regard to sign for the different distributions of the compensation are respectively, 0.020, 0.019, 0.019, and 0.020 dyne. These mean anomalies give only negative evidence.[2]

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[1] Hayford and Bowie, 1912, p. 98.

[2] Bowie, 1912, p. 22.

The problem may be tested in another way.

If local compensation be true, an unusually high mountain is underlain by unusually light matter and the intensity of gravity at a station on its top is less than if the mountain was supported by regional compensation and had matter of the mean regional density below it.

If the station is much below the average level of a mountainous region, local compensation implies, on the contrary, denser matter beneath and a higher value of gravity than would be given by regional compensation. These relations result in the following principle: For stations above the mean level, if local compensation be nearer the truth the hypothesis of regional compensation would tend to show its error by large negative anomalies. If regional compensation be nearer the truth, the hypothesis of local compensation would tend to show its error by giving large positive anomalies. For stations below the mean level the reverse would be true. But for any individual station other departures from the truth of that hypothesis of isostasy which gives the basis for the calculations may have greater influences and give larger anomalies than the question to be tested. Following this principle it is stated:

> There are 22 stations in the United States in mountainous regions and below the general level and the means, with regard to sign, of the anomalies by the four methods of distribution are 0.000, +0.001, +0.003, and +0.005 dyne, while the means without regard to signs are respectively 0.017, 0.017, 0.018, and 0.019 dyne. For the 18 stations in the United States in mountainous regions and above the general level the means, with regard to sign, of the anomalies by the several methods of distribution of the compensation are +0.003, +0.003, 0.000, and −0.10 dyne. The means, without regard to sign, are respectively 0.018, 0.018, 0.017, and 0.020 dyne.
>
> The mean, with regard to sign, of the anomalies for the stations at each of the two mountain groups, indicates that the theory of regional distribution of compensation to the outer limit of zone O, 166.7 kilometers is far from the truth. So far as may be judged from the other average anomalies no one method seems to have any decided advantage (see pp. 98–102 of *Special Publication No. 10*).[1]

Review and analysis of the evidence.—The present writer does not see in these computations any support for the hypothesis of local

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[1] Bowie, 1912, p. 22.

compensation of the topography to between limits of one square mile and one square degree with the added suggestion of a radius less than 18.8 km., which has been advanced on other pages by the authors.[1] These figures merely show that, to the outer limit of zone M, radius 58.8 km., and probably to outer limit of zone N, radius 99 km., one method is as good as another for purposes of computation, which is not true in nature. The errors introduced by observation and computation, the errors introduced by the lack of recognition necessary in the preliminary hypothesis regarding the irregularities in the depth and distribution of compensation—these produce effects which overshadow the small systematic differences due to the hypotheses of local versus regional compensation. For the outer limit of zone O, radius of 166.7 km., a real distinction does, however, begin to appear in the data for the two groups of mountain stations. It is, however, very small and based upon a rather too limited number of stations to give quantitative reliability to the mean. Furthermore, as discussed in detail under a later heading, there is quite possibly a real difference between the limits of regional compensation and depth of compensation in the mountain regions of the West compared to other parts of the continent. Evidence drawn from the Cordillera cannot, therefore, be applied safely to the other portions of the United States.

Let the assumption be introduced that the limits of regional compensation are variable, ranging from 100 to 500 km. in radius. Such variable limits may well exist because of several factors; first, because of a real variability in the strength of the crust; second, because the greater vertical stresses could be carried only by smaller areas. In regions of mountainous relief due to folding, or of high anomalies due to great irregularities of density, the mean size of unit areas should therefore be less. On the whole the anomalies as well as the relief appear to be somewhat greater over the western United States. Third, in regions of recent block faulting or warping the stresses have presumably been lessened from what they were immediately before the movement. Such diminution of strain could take place by the breaking-up of a large unit area of crust into smaller units with differential movement among them, as

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[1] Hayford and Bowie, 1912, p. 102.

well as by vertical movement of the whole area to a level best satisfying the stress. The western United States is known to be such a region, which in the late Tertiary and up to the present has been markedly affected by block faulting and differential vertical movements.

Suppose, then, that the mean radius of regional compensation in a mountainous region is 300 km. but that unit areas exist ranging in radius from 100 to 500 km. Of mountain stations located at random, a fraction of the total number would be situated within or near areas where regional compensation did not extend to 166.7 km. Let the stations be divided into one group consisting of those below the mean regional elevation and another group above the mean regional elevation. Let the anomalies be computed successively according to hypotheses of regional compensation to successive limits and the mean of the group for each limit be taken. This is the test applied by Hayford and Bowie. It has been seen that for radii of 18.8 and 58.8 km. the results are indeterminate. For a larger radius the group anomaly might be expected to show an increase as soon as the assumed radius exceeded the actual radii of a part of the areas. Consequently, if the hypothesis be true that the areas of regional compensation are variable in size, the mean anomalies of the two groups of 22 and 18 stations, found with regard to sign to be +0.005 and −0.010 respectively for radius of 166.7 km., do not show that regional compensation on the whole does not exist to those limits. It may indicate only that some areas are less than that radius. The mean radius of regional compensation may be 166.7 km. or possibly even larger. Other tests must therefore be sought which will give a more conclusive answer.

Further, it is to be noted that the mean anomalies with regard to sign for the hypothesis of regional compensation to radius of 166.7 km., although somewhat greater than for the other hypotheses, are yet of the same order of magnitude; and in all cases are but a fraction of the mean anomaly without regard to sign. Apparently, then, the assumption of regional compensation to 166.7 km. introduces a smaller error than the assumption of uniform and complete compensation with an average specific gravity of 2.67 to a constant depth of 114 km.

The test by adjacent stations at different elevations.—There is, however, another way of using the data given for stations situated well above and below the mean elevation of mountainous regions. If a pair of stations be taken close together, one far above the mean elevation, the other far below, they will presumably, because of their juxtaposition, be affected in much the same way by the errors incident to the hypothesis of uniform compensation through a depth of 114 km., with complete compensation at that depth. In order that good results may be obtained, however, the specific gravity of the local rocks should be carefully determined in order to have a correction for the mass between the stations. The parts of the anomalies due to the irregularities and incompleteness of compensation will ordinarily have the same sign and be of nearly the same value at the adjacent stations. This is indicated by the contour lines of Fig. 5, which show that in the same region the anomalies are of sufficiently regular gradation in magnitude to make the drawing of contour lines possible. The parts of the anomalies at the high and low stations due to errors in the hypothesis of local or regional compensation will, however, be of opposite sign. If, then, the algebraic difference of the anomalies for such a pair of stations be computed for successive hypotheses of broader regional compensation, the part of the anomalies due to *vertical* imperfection of the hypothesis will be largely eliminated. The algebraic difference measures the *horizontal* imperfection of the hypothesis. That hypothesis is favored whose assumed radius of regional compensation gives a minimum value to this algebraic difference. This test may be made by combining data given on p. 100, Hayford and Bowie, with p. 15, Bowie; although, because of incompleteness of the tables, this combination gives the data for only a few of the properly situated mountain stations. The best couple of stations for the application of this test consist of 42, Colorado Springs, and 43 Pikes Peak. Somewhat more distant stations—44, Denver, and 45, Gunnison—may also be added to the group. The tabulation is shown on p. 161 (Table IV).

It is seen that for three of the four Colorado stations the absolute value of the anomaly is least with regional compensation to 166.7 km. For the fourth station it remains practically constant for all the cases. The anomalies were not computed for greater radii. The more convincing argument, however, for regional compensation to at least 166.7 km. radius in the vicinity of Pikes Peak is the fact that the *algebraic difference* of the anomalies between the top and bottom of the mountain, stations 43 and 42, is less than one-half for regional compensation to 166.7 km. radius than for the corresponding value given by the hypothesis of local compensation. The decrease in the difference is furthermore progressive with each assumed widening of the zone. The result of adding the more distant stations, 44 and 45, favors regional compensation more markedly but is indeterminate between M and O. It would seem, then, that the front range of the Rocky Mountains in Colorado is upheld above the surrounding plains and parks by virtue of the rigidity of the earth.

TABLE IV

Number and Name of Station	Elevation of Station in Meters	Distance from Mean Elevation in Meters within 100 Miles	Anomaly with Regional Compensation within Outer Limit of			
			Local Compensation. Radius 0.0 Km.	Zone K, Radius 18.8 Km.	Zone M, Radius 58.8 Km.	Zone O, Radius 166.7 Km.
COLORADO						
42. Colorado Springs......	1,841	−420	−0.009	−0.009	−0.010	−0.010
43. Pikes Peak.....	4,293	+2,035	+ .019	+ .011	+ .006	+ .002
44. Denver........	1,638	−574	− .018	− .016	− .009	− .001
45. Gunnison......	2,340	−380	+ .018	+ .021	+ .026	+ .016
Mean of 42, 44, and 45..........	....	−458	− .009	− .004	+ .007	+ .005
Algebraic Difference 43−42.......	....	....	+ .028	+ .020	+ .016	+ .012
43−(mean of 42, 44, 45).........	....	....	+ .028	+ .015	− .001	− .003
ARIZONA						
68. Yavapai.......	2,179	+512	− .001	− .001	− .001	− .009
69. Grand Canyon..	849	−824	− .012	− .011	− .011	− .021
Algebraic difference 68−69......	....	....	+0.011	+0.010	+0.010	+0.012

The two stations in Arizona at 68 and 69 are well situated also to test the question of local versus regional compensation, but the difference in the anomalies in this case is so nearly constant as to give an indeterminate answer. In the absence of more detailed statements by Hayford and Bowie the reason why the anomaly at the Grand Canyon station 69 reaches a larger *negative* value for regional compensation to 166.7 km. than for more limited compensation is not evident. The usual rule is that the progressive change in the anomaly for stations below the regional level for successive assumptions of wider regional compensation is by increments with a *plus* sign. Here, on the contrary, the change in the limits from zone M to zone O involves a *minus* increment of 0.010 in the anomaly. The cause of this reversal of sign, which the writer does not understand, seems in this case to be the cause of the indeterminate result.

Another line of evidence as to the effective limits over which the rigidity of the earth may extend is derived from a study of the grouping of the deflections of the vertical shown in illustrations 2, 3, 5, 6, Hayford, 1909, and the lines of equal anomaly for the new method of reduction, illustration No. 2, Bowie, 1912, the latter giving the basis for Fig. 5 of this article.

The test by areas of grouped residuals.—Illustration No. 5, Hayford, 1909, shows the grouping of the residuals of solution H for the north and south components of the deflections. An area with a plus sign corresponds to an excess of density to the south, or deficiency to the north. An area with a minus sign corresponds to a deficiency of density to the south, or excess to the north. A north-south chain of stations is therefore best for ascertaining the limits of the areas of north-south deflection of like sign. Such a belt extends across the United States between long. 97° and 98°, showing 9 areas covering 1,620 miles. The mean intercept is therefore 180 miles. This mean intercept must be somewhat less than the mean diameter.

Illustration No. 6, Hayford, 1909, shows the grouping of the residuals of solution H for the east and west components of the deflections. An area with a plus sign corresponds to an excess of density to the east, or deficiency to the west. An area with a minus sign corresponds to a deficiency of density to the east, or excess to the west. An east-west chain of stations is therefore best for ascertaining the limits of the areas of like sign. Such a belt extends across the United States between lat. 38° and 39°.

The following adjustments in groups seem, however, fair to make, considering the lack of exact accuracy in any one station. At Cincinnati is a station showing small residuals opposite in sign to the stations on each side. If this is overlooked, three small groups become one of average size. In central Kansas a small minus area depending on a single observation may be likewise omitted. In western Colorado several small areas depending each upon two observations had their number diminished by one. The same was done in California. This gave 14 areas extending over 2,580 miles, a mean individual intercept of 184 miles. If 16 areas be taken, a mean value is derived of 161 miles. More weight, it is thought, is to be attached to the determination of 184 miles, and this is supported by the 180 miles shown by the north-south chain of stations.

The areas of like sign are between centers of excess and defect of mass. They are not, therefore, coincident with the areas of excess and defect, but in discussing the average size of areas, the one may be used as a measure of the other.

It may be concluded, therefore, that the deflections of the vertical show areas with departures from isostatic equilibrium in one direction and these areas average about 180 miles, 290 km., in mean intercept. The mean diameters of the areas of like sign are presumably somewhat greater. This would make the mean radius of areas of regional compensation, as indicated by similarity of sign among residuals, at least 166.7 km.—the radius of the outer limit of zone O used in the discussion of the gravity anomalies.

If we turn now to the anomalies shown by the determinations of gravity, Fig. 5, adapted from Bowie, shows their segregation into areas of like sign. The mean value without regard to sign for all stations excluding Seattle is 0.018 dyne per gram. Including the two Seattle stations the mean is 0.020 dyne. Between the contours for −0.020 and +0.020 lie tracts where the anomalies are within the mean limits. The areas of exceptionally large anomalies are above those limits. It is only these which form on this illustration well-defined inclosed areas, but even these are far from regular in outline. The areas showing positive anomalies of more than 0.020 dyne were estimated roughly to average 130 by 240 miles across, a mean diameter of 175 miles. The areas showing negative anomalies of more than 0.020 dyne were found to average roughly about 190 by 250 miles, a mean diameter of 220 miles. The long narrow connections were neglected in making this estimate. Unit areas of more than mean anomaly may therefore be taken to average about 200 miles or 320 km. in diameter. The mean radius is therefore approximately that of the outer limits of zone O, 166.7 km.

The figures, although they correspond fairly closely to those derived from the deflections of the vertical, cannot in reality be very well compared, since these are areas selected because the anomaly rises above a certain magnitude; the others represent, on the contrary, a succession of contiguous areas between centers of excess and defect in mass without reference to magnitude. Apparently some influence blurs out the limitations of areas of small gravity anomaly. This will be discussed in a later part.

Now assume for the moment that isostatic compensation is uniform to the bottom of the zone, as postulated by the hypothesis; that is, that the residuals and anomalies are due to excesses or defects of mass which are uniformly distributed. Then, over any one area of excess or deficiency of mass, the deflections around it and anomalies within it signify a departure from compensation in one direction. This is a regional departure. If the strength of the crust was so small that it was able to support notable departures from compensation over areas of only one square degree or less, then these large unit areas could not exist. A vertical warping up or down would immediately take place until the broad region as a whole lay so close to complete compensation that its surface irregularities became subdivided into subordinate positive and negative areas of the limiting size. The sum of the excesses and defects of mass would approach zero in broad areas containing many unit departures. It would seem, therefore, that the geodetic results shown in Fig. 5, instead of indicating local compensation to limits of less than one square degree, show on the contrary a ready capacity of the crust under the United States to carry over areas of from 5 to 10 or 15 square degrees, and exceptionally over even larger areas, departures from equilibrium greater than the mean. This agrees in order of areal magnitude with the Nile and Niger deltas. However, the influence of irregularity in the distribution of compensation with depth, and the magnitude of stress per unit area remain to be investigated.

[*To be continued*]

MECHANICS OF FORMATION OF ARCUATE MOUNTAINS

WILLIAM H. HOBBS
University of Michigan, Ann Arbor, Michigan

PART II

THE FOLDING PROCESS STUDIED IN THE PROFILE—GENERAL CONSIDERATIONS

Active and passive forces involved in folding.—So soon as we take up the mechanics of rock folding, we again encounter the vital question of the location relative to the fold of active and passive forces in the process. Among the Swiss geologists it is universally held that the active force (*Schub*) which caused the folding and slicing of the Alpine highland came from the southeast and was directed toward the northwest. This view would appear to rest upon the widely accepted notion that folds which are unsymmetrical have been produced by an active force which operated from *above* and *behind* the arch with the effect of pushing over the crown so that in later stages it overhangs the base. This conception is involved in the term "overturned fold" and its many variations.[1] If we may for the moment liken a fold to an overturned free wave upon the surface of a body of water—a so-called "white cap"—the active force which is generally assumed to produce the fold has the same direction relatively as the wind. Like the wave, the fold bends over toward the lee side because, as has been believed, the active force operates above and directly upon the arch of the fold, and not upon its base (Fig. 9, *a* and *b*). The effect of this system is a couple—two parallel forces of which one is in this case a passive force of resistance, which act in opposite directions and are separated by a certain distance referred to as the arm of the couple. In

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[1] See Margerie et Heim, *Les dislocations de l'écorce terrestre, essai de définition et de nomenclature*, Zürich, 1898, p. 54. Dr. E. A. Smith has, however, given the name "underthrust folds," to what he evidently regards as exceptional cases of folding ("Underthrust Folds and Faults," *Am. Jour. Sci.* (3), XLV (1893), 305–6).

all such cases there is a tendency to produce rotation, as appears from the example of the water wave. So far as the *form* of the resulting fold is concerned, the result would be similar if the active and passive forces were to be reversed; and though conscious of an appearance of presumption in again opposing his own view to such weight of authority, the writer will endeavor to show not only that the principal active force involved in the folding of the Alps must have been directed from the northwest toward the southeast,[1] but that the mechanical difficulties which have stood in the way of a more general acceptance of the views of the Swiss geologists, with this modification in large measure disappear.

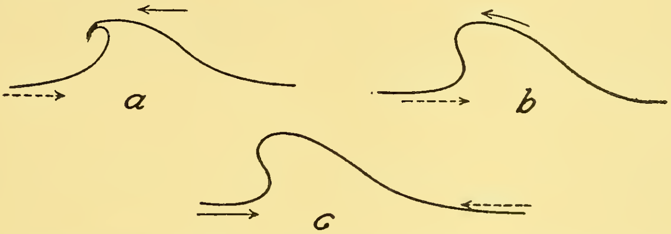

FIG. 9.—Diagrams to illustrate the active and passive forces involved in folding: *a*, position and direction of forces involved in the overturning of a free water wave; *b*, system of forces assumed by the Swiss geologists to account for the folding of the central Alps; *c*, the author's modification of this view.

It is of course to be understood that the active force tending to produce movement may not be solely from a single direction; but of the two opposed directions parallel to the chief compression, the active force as here understood is that one which represents the greater movement. If in Fig. 10 two active forces or thrusts[2] which tend to compress a given section of the earth's shell be represented in intensity by the distances *a* and *b*, the active force which becomes effective in producing unsymmetrical flexures such

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[1] Willis has expressed his opposition to the conception of overturning which is apparently the standard doctrine of the day ("The Mechanics of Appalachian Structure," *13th Ann. Rept. U.S. Geol. Surv.*, 1893, Pt. II, p. 233); see also W. H. Hobbs, *Earth Features*, New York, 1912, pp. 436–38.

[2] This term is not to be confused with that generally applied to the surface of failure in folds, which latter should, we believe, be abandoned for reasons which will be given below.

as are the rule in all much compressed mountain districts is the difference between the two forces, *c*. Had the active forces *a* and *b* been just equal and the beds under compression offered uniform resistance, the folds produced should be symmetrical, and in the end have constituted a series of vertical isoclinal flexures, which are as rare in nature as they would upon this assumption be expected to be (Fig. 11).[1] The lack of a fore-and-aft symmetry in mountain arcs clearly indicates that the radially directed thrusts are not in equilibrium, but that one notably overbalances the other.

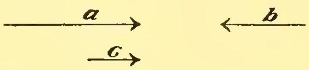

FIG. 10.—Diagram to illustrate the resultant of two parallel but opposed active forces, or that effective in producing unsymmetrical flexures.

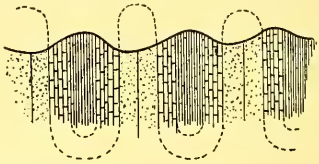

FIG. 11.—Vertical isoclinal folds

Incompetence of folding layers to transmit compressive stresses to long distances.—At the outset it is important to emphasize that the capacity of bodies to fold shows that they cannot transmit compressive stresses to long distances, due to the dissipation of energy in producing internal strains within the folding mass. With constant diminution of intensity, therefore, the active force is transmitted to certain moderate distances only from its place of application. Although perhaps self-evident, this fact has been demonstrated in experiments by Cadell, who has expressed its application to folding strata in the following sentence: "Horizontal pressure applied at one point is not propagated far forward into a mass of strata."[2] The distance to which the active force is carried

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[1] This discussion obviously rests upon the assumption that the folding of any given district is due to forces from without the area itself, though independent of any special theory of planetary contraction. Any assumption which requires that the active force causing compression originate *within* the district itself requires a wholly different analysis. Thus the view of Mellard Reade, which conceives the cause of folding to be expansion by heat of areas of sediments due to depression and consequent rise (relative to the beds) of isogeotherms, would require that the active forces proceed outward toward relative rigid formations, and zones of folding should develop simultaneously on opposite margins of the more plastic interior area.

[2] Henry M. Cadell, "Experimental Researches in Mountain Building," *Trans. Roy. Soc. Edinburgh*, XXV (1890), 356.

in sufficient intensity to produce appreciable deformation or folding may be referred to as the *reach*. In rock masses which offer a uniform resistance to folding throughout a given area, the limited reach determines that folds will begin to form upon the side which is toward the active force.[1] The very existence of an area which folds, surrounded by one which does not, implies that but for this central folding area the rock masses would be competent to transmit the tangential force without extensive deformation. The fact that folds first develop upon that side of the folding area which is toward the active force is amply demonstrated by simple experiments which were performed by Daubrée.[2] In these experiments a vertical section of the unyielding and encompassing area of the earth's shell was represented by a stiff piston-rod through which the active force was transmitted to a flexible leaden strip which therefore takes the place of the folding rock masses. When the strip of lead was made of uniform thickness, and hence of uniform strength, the folds within it formed first upon the side which was toward the piston. Only by thinning and thereby weakening the strip at the farther end could the folds be first produced at that end. The experiments of all later investigators working with materials and under conditions which must more nearly simulate those obtaining within the earth's shell have only confirmed the correctness of these simple deductions from Daubrée's experiments.

It is because of this limited reach of the deforming stress that anticlinoria which by construction imply the *simultaneous* development of similar and approximately equal anticlines throughout the length of a flatly extended arch of strata[3] are apparently unrealized in nature. Most of the supposed classical examples have been drawn from the Alps as represented upon old sections, and these may today be adequately explained upon the assumption of the development of *successive* anticlines as detailed below (p. 172).

The strength of rock formations as modified by temperature and load no doubt sets a definite limit upon the initial span of anticlines

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[1] See note on Paulcke's experiments on p. 172.

[2] A. Daubrée, *Géologie expérimentale*, pp. 292–300.

[3] See, for example, Van Hise, *Principles of North American pre-Cambrian Geology*, pp. 608–9.

developed in series, and a fruitful inquiry would be to fix, by thorough examination of folded districts, the maximum span of fully disclosed, as against merely inferred, anticlinal arches.

Importance of lenses of sediments in inducing folding.—Lest too large importance be ascribed to local weakness of strata in fixing the location of initial folds, it is well to remember that folded areas do not appear to be those which are thinnest, but, on the contrary, that they are the thick lenses of sediments in which formations are present in fullest development—areas of continuous deposition in former epi-continental seas. The explanation of this fact is found in the peculiar cross-section of a lens of sediments. Obviously a perfectly straight rod of more or less rigid material whose axis is parallel to the direction of compression will transmit larger stresses than one which may be considerably thicker and stronger but is initially slightly bent from the direction of the compressive stress (Fig. 12, *a* and *b*). In the first instance (*a*), the applied force being directly opposed by the resistance, the rod tends merely to be slightly thickened, whereas in the second case (*b*), the active force is deflected parallel to the tangent to the curve, and at a rapidly accelerated rate this deflection is augmented with increasing pressure. It is thus easy to see that the cross-section of basins of deposition, being lenticular, may have been more important in favoring the location of folds than their greater thickness could have been as a hindrance. Willis, who discovered the importance in the location of folds of what he has called "initial dip," has thus stated the law of competent structure:

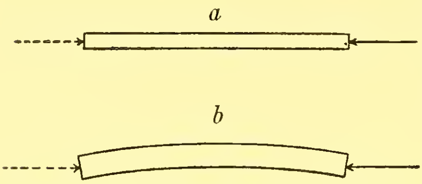

FIG. 12.—Diagram to illustrate the relative tendency to fold, or buckle, of: *a*, a straight rod; and *b*, a thicker but slightly curving rod.

> The transmission of pressure through a folding, stratified mass may be stated as follows: So long as the stratification is parallel to the original direction of pressure, the force is transmitted as a whole and tends to reduce the volume of the mass; when the strata are inclined to the direction of pressure the thrust is resolved into two components, the one parallel to the bedding, the other perpendicular to it; the former produces movement when it overcomes the

> friction on bedding planes, the viscosity of the strata, and any opposing force, as that of the load; the latter becomes active when it can cause some part of the resisting mass to move. . . . .
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> In strata under load an anticline arises along a line of initial dip, when a thrust, sufficiently powerful to raise the load, is transmitted by a competent stratum. The resulting anticline supports the load as an arch, and being adequate to that duty it may be called a competent structure. From the conditions of the case it follows that none other than a competent structure can develop by bending. If the thrust be not powerful enough to raise the load there will be no uplift. . . . .[1]

What has been brought out above concerning the direction of the active force would indicate that, coming as it does from the ocean basins, the thrust, instead of being influenced by initial dip at the shoreward end of a section of epicontinental deposits (which should develop there an initial syncline), is received at the off-shore end of the section and should be first diverted upward by the steeper beds upon the continental slope and so yield an initial anticline. This is, moreover, more in harmony with the results of experiment.

It seems proper to speak of the competence of an arch or anticline as its capacity in any stage of formation to lift load resting upon it.[2]

In order to simulate rock folding under as nearly as possible natural conditions, Willis in his experiments made use of layers which were of nearly uniform thickness and strength throughout and which, though sufficiently rigid to be deformed by failure under ordinary testing conditions, became potentially plastic under the load of shot which was applied in the experiments. In confirmation of the results at which one arrives from a purely theoretical treatment of the subject, it is important to note that in all Willis's experiments except when special conditions were introduced, anticlines developed on the side of the mass toward the active force

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[1] *The Mechanics of Appalachian Structure*, pp. 246, 250.

[2] It is little likely that, barring exceptional cases of small anticlines, a competent stratum can lift the entire load from beds beneath, as seems to have been implied by Willis. We should in that case approach to surface conditions within a well-cemented masonry arch in which the accelerated rate of increase of weight of arch relative to its strength sets such a low limit upon the span as to be prohibitive.

or thrust, and that in successive stages of its evolution the anticline became increasingly unsymmetrical with the axial plane dipping away from the active force and finally was underthrust in the same sense. In recent experiments by Paulcke[1] which were carried out with the idea of simulating Alpine tectonics, *but with the presupposition that there had been overthrusting from behind the anticlines*, the arches were in normal cases generally either bent over toward the active (moving) force, or else a stiff plate (*Druckplatte*) was introduced and prevented their natural manner of deformation.

From the nature of rock materials we conceive that folds develop within a zone probably some miles below the earth's surface, since we believe that at such depths only can the rocks become sufficiently plastic under their load. Nearer the surface rock materials, which are normally highly elastic, must be deformed by failure or fracture, and over a rising anticline must be adjusted in block sections whose movements become manifest at the surface in earth shocks or quakes (note conditions in Bonin arc, p. 79).

A consequence of the studies by Adams, which have for the first time revealed the enormous hydrostatic compressive strengths of rocks, is certain to be a modified conception of the zone of flow (better, zone of folding) within the earth's surface shell. To assume that more than eleven miles of sediments have been eroded from those folded beds which outcrop at the earth's surface must make the hardiest theorist pause and consider whether the closing of pores necessary to permit of folding may not be due to an excess of tangential compressive force over that of the radially directed load—or, in other words, that hydrostatic conditions of compression were seldom realized in the folding of those strata, at least, which we find exposed at the earth's surface.

THE FOLDING PROCESS STUDIED IN THE PROFILE—ANTICLINE EVOLUTION

Successive sectional curves of a growing anticline.—Since, when the anticline begins to rise, the radial component of the compressive stress has the least value, and the tangential component the

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[1] W. Paulcke, "Das Experiment in der Geologie," *Festschrift z. Feier des Geburtstags Seine Kön. Hoheit*, etc., herausg. v. d. Tech. Hochschule, Karlsruhe, 1912, pp. 108, figs. 44 and pls. 29. Note the *Druckplatte* in the apparatus which is figured in Pl. 8.

greatest, the span of the arch must at that time be a maximum.[1] The point from which the arch springs upon the side away from the active force thus becomes established as an abutment, so to speak, and the length of the arch is maintained constant up to a limiting stage to be presently discussed. The general shapes of simple anticlines of increasing asymmetry are well known upon the basis of experience, and the attempt has here been made to represent successive stages arbitrarily spaced in the process of anticline evolution. Six of these belong in the class denominated unsymmetrical, whereas the remaining three are "overturned" (Fig. 13). Throughout, the assumptions have been made: first, that failure of the arch does not take place; and, second, that its length remains constant—a condition which would often be realized in nature for the first six cases, but could hardly persist long after underturning had set in.

Professor Theodore R. Running of the University of Michigan, an expert in the mathematical study of curves, has at the writer's request subjected this series of curves to examination. He has found that to a close approximation the first seven of the series, the only ones which were tested, alike possess an axial line[2] which bisects all horizontal chords, and that the seven may be fitted to the comparatively simple general equation

$$y=y^{0}\left(\frac{a^{2}-x^{2}}{a^{2}}\right)^{m}$$

in which the oblique co-ordinate axes are the base line and the bisecting axial line, in which y° is the length of this axial line from base to crown, and in which a is one-half the base.

Competence of a relatively strong member in an anticline to lift the load from inferior strata.—For the purposes of this discussion, the load which rests upon an anticline in competent strata may be

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[1] Cf. Willis, *op. cit.*, pp. 251–52.

[2] Trace of the axial plane of the anticline. That this axial plane bisects horizontal chords of the anticline in all stages has been often noted by the writer in studying the folded schists of the Berkshire Hills of New England and elsewhere; but this character had not consciously been made a basis of measurement in drawing the curves of Fig. 13, which were made to accord with the *shapes* of anticline sections repeatedly observed in the field.

regarded as uniformly distributed throughout a horizontal plane; since, as already stated, anticline formation is believed to occur at such depths that the altitude of the arch is small by comparison. The discussion of the competence of an anticline differs from that of an arch of masonry, for the reason that the latter receives no external support in a vertical direction except at the abutments. An anticline is, upon the other hand, in part supported by the resistance to compression of the weaker formations which are arched beneath it. It may never alone support the entire load which rests upon it; but since it is stronger than immediately inferior beds, it tends always to lift from them some portion of the load. This portion varies at different parts of the arch, and for any point is roughly proportional to the cosine of the angle which the tangent at that point makes with the vertical (Fig. 14). By a summation of these values for

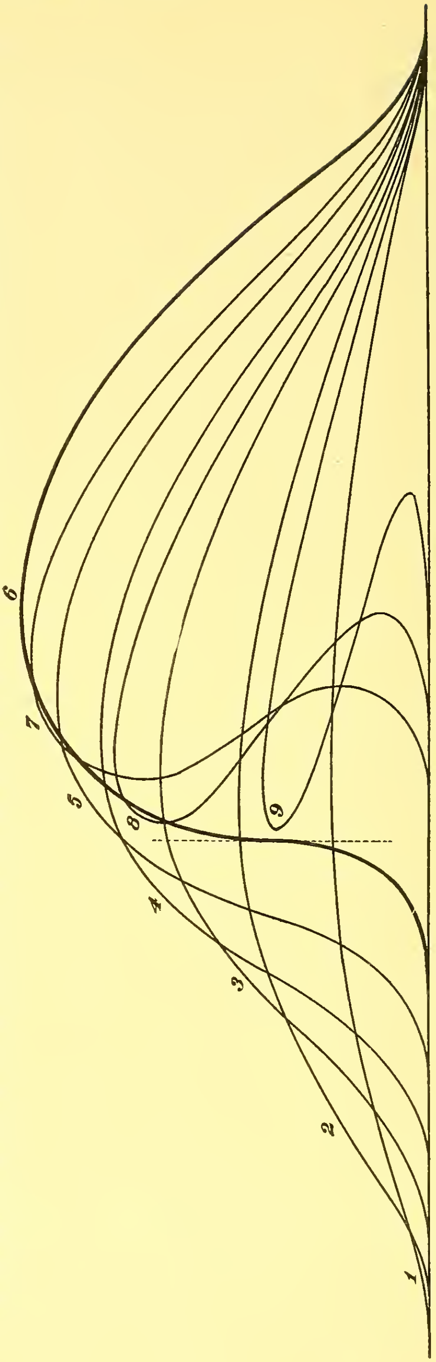

Fig. 13.—Series of successive stages of an anticline developed in a competent member within a folding series. The active force is at the left.

the entire arch a figure is obtained represented by the area *AGOHB*, which for convenience we may refer to as the "cosine area." To this there is probably to be added for the crown region particularly some part of the tangent-normal component of the load which is spent in internal strain within the arch; but since any extensive settling of the crown would bear upon the subjacent formation and transmit this burden to them, the additional amount from this source is probably so small as to be negligible in our discussion. For the different stages which we have selected in the evolution of an anticline, these cosine areas may be derived by graphical methods, and through dividing each by the total load, the percentage which is lifted by the competent member may in each case be roughly estimated.

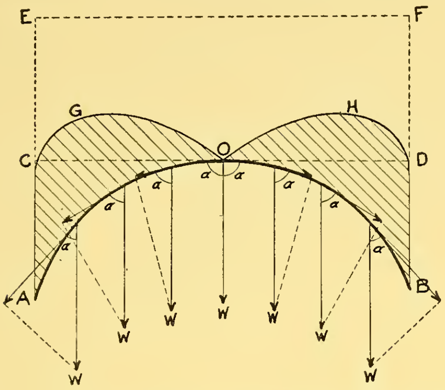

FIG. 14.—Diagram to show the proportion of total load which is lifted from underlying formations by an anticline here assumed for convenience to be the arc of a circle. *AOB*, anticline; *CDEF*, area proportional to the entire load; *AGOHB*, cosine area proportional to the load lifted from interior formation beneath the arch.

Relative competence of a member in successive stages of anticline evolution.—The cosine areas for each of the successive stages of a developing anticline which are represented in our series afford the figures of the following table:

TABLE I

Stage	Ratio of Rise to Span	Competence Figures	Percentage of the Load Lifted	Relative Volume of Anticline
1	0.073	12.6	12.6	8.6
2	.152	25.6	26.9	15.0
3	.223	34.5	37.8	19.0
4	.301	37.2	43.5	21.8
5	.361	37.8	47.9	22.8
6	.441	36.5	51.9	24.5
7	.578	29.6	50.9	18.5
8	.471	22.4	37.2	11.8
9	0.274	3.6	7.9	5.2

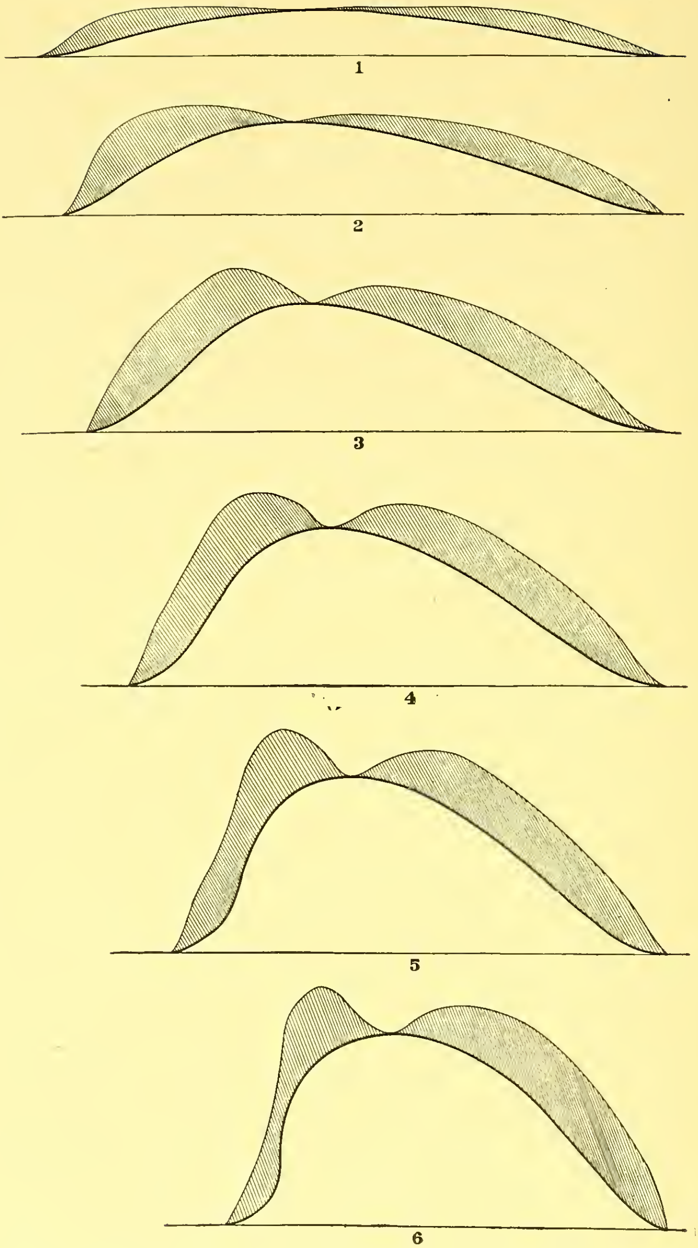

FIG. 15.—Cosine areas of the arbitrary stages 1 to 6 of a growing anticline

The drawings upon which these figures are based have been reproduced on a much reduced scale in Figs. 15 and 16. From examination of them it is learned that an anticline within a competent stratum is able in its early stages, when the ratio of rise to span is relatively small, to lift but a small proportion of its load from the underlying formation; but that this competency increases beyond the arbitrary stage 1, in which the ratio of rise to span

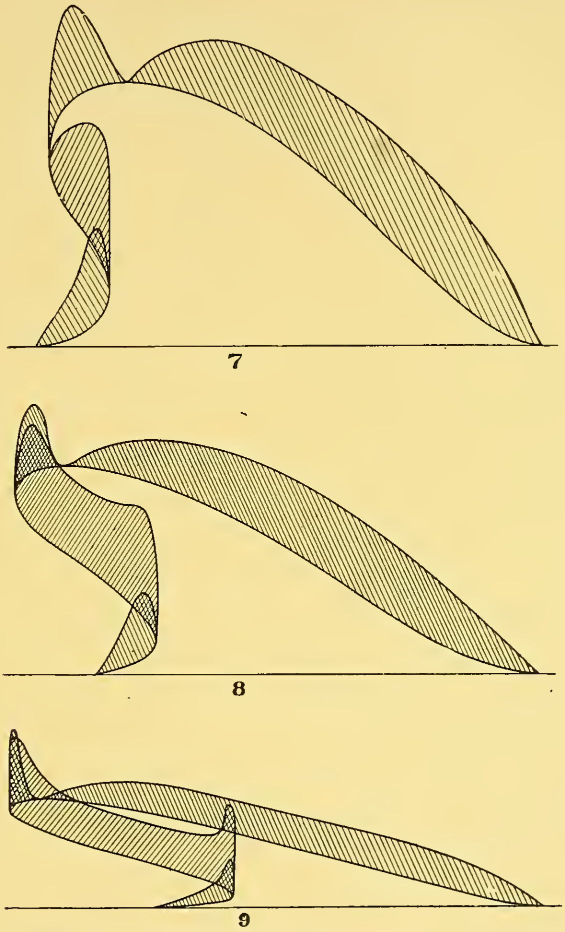

Fig. 16.—Cosine areas of the underturned stages 7 to 9 of a growing anticline (assuming, however, that the length of the arch is not increased).

is about $\frac{1}{10}$. Although the actual load lifted increases but little after this ratio has reached $\frac{1}{4}$, the percentage which is lifted of the total load upon the arch continues to increase up to stage 6, where underturning begins and from which point the competence falls off at a rapid rate. These deductions are graphically reproduced in Fig. 17, where the abscissae are the ratios of rise to span, and the ordinates have a different significance for each curve. The upper curve gives the percentage of total load which is lifted from inferior beds within the arch; the middle curve gives in arbitrary units the relative loads which are lifted; while the lowest curve gives in arbitrary units (not those of the middle curve) the relative volumes inclosed by the anticline.

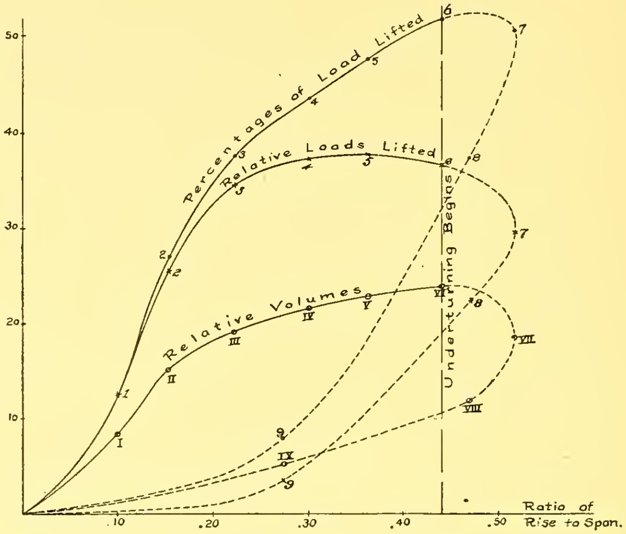

FIG. 17.—The curves of relative competency and of relative volume of an anticline in different stages up to the stage of underturning; and (in dotted lines) the purely hypothetical competence and volume on the assumption that the length of the arch is not increased after extended underturning without failure.

Initiation of new anticlines in series.—The stage marked 6 in our series is where underturning begins, for the steeper limb includes a point at which the tangent to the curve is vertical. The active compressive force, which up to this stage has been deflected upward and hence devoted to lifting the load, can no longer be thus turned out of its original course and is therefore more or less completely transmitted through the anticline to the still unfolded section of the stratum beyond (Fig. 18). At this point, therefore, the anticline has the effect of temporarily at least stiffening the stratum locally and so extending the reach of the deforming stress. Since, however, some energy is lost in the continued deformation of the original anticline, the new reach beyond the farther base will generally be less than that when the first anticline began to rise. A second arch thus tends to form behind the first, but one of somewhat smaller dimensions. This second anticline having in its turn risen to the stage of underturning, conditions for the development of a third enter; and the process may go on until continued diminution of the reach due to imperfect stiffness of the anticline series brings the process to an end.

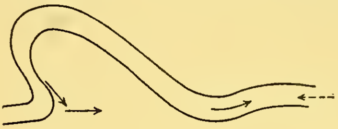

Fig. 18.—Diagram to illustrate the initiation of new anticlines in series.

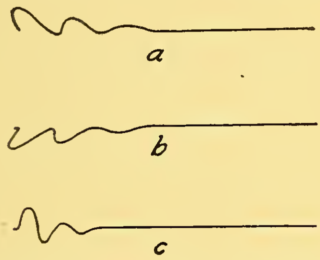

Fig. 19.—Correct (*a*) and two incorrect (*b* and *c*) representations of anticlinoria.

Successive anticlines thus developed in series are characteristic of Willis's experiments so often cited, and may be represented schematically by *a* in Fig. 19, where anticlines and synclines alike are developed *above* the original position of the stratum. Thus it is seen that though *series of arcs* develop in order from the central area of the series outward, the *series of anticlines* within each arc develop in the reverse order, or from without inward toward the central area.

Conditions of formation of plunging crowns and recumbent folds.—The peculiar curves of unsymmetrical anticlines show clearly that the horizontal external forces which produce them are so resolved as to produce rotation, and in such a sense that the base of the arch is pushed backward under the crown. This is equivalent to saying that after the anticline has begun to rise, a couple arm separates the two opposing forces and that the point of application of the active force of compression is below that of the passive force of resistance. So soon, however, as underturning has set in, a new couple enters which involves not the compressive forces in generally horizontal positions, but the vertical external forces; namely, the load and the passive resistance of the mass to depression (Fig. 20). Within the underturned portion of the anticline this passive force may be concentrated near the base of the under limb, while the load upon the underturned section of the arch is centered in front, so that the action of the couple tends to rotate the crown of the arch, not forward as before, but downward. Such sinking of the crown is resisted by any support of the superior strata which have been underfolded beneath the crown. If these are of sufficiently strong material, the crown is not bent; but in the event of their being weak, the crown is sunk as in Fig. 21. Such "plunging crowns" (*tête plongeante*, *sinkende Gewölbe*) are the normal feature in the northern zone of the Alps, where the weak Flysch (Eocene) overlies the competent Helvetian limestones.[1]

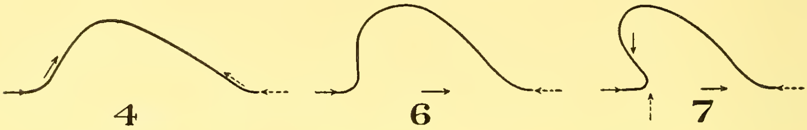

FIG. 20.—Diagrams to show the new couple which enters with the underturning of anticlines.

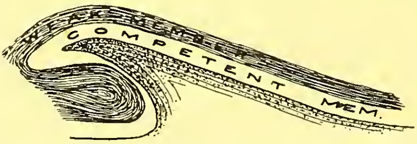

FIG. 21.—Plunging or sinking crown of an underturned anticline due to weak strata above the competent member.

Whether the crown be sunk or not, as the anticline becomes increasingly underturned, it is forced down as a whole by the action of this couple and so becomes a "recumbent fold" (Fig. 13, stage 9).

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[1] For another excellent example of a plunging anticline crown see E. B. Bailey and M. Macgregor, "The Glen Orchy Anticline," *Quar. Jour. Geol. Soc.*, LXVIII (1912), 164–78, Pl. 10, and especially Fig. 3.

Attenuation of under limb of anticline after underturning.—There are still other consequences of the rapid loss of competence of an anticline after underturning has begun. The active force of compression, now no longer deflected upward into the first anticline but transmitted along its original direction, tends to reduce the volume of the included arches of inferior strata. The resistance which they offer to this reduction of volume tends to extend (stretch) the under limb (Fig. 22). It is a very general observation that thinning of the under limb is characteristic of so-called "overturned" anticlines, and emphasis may here be laid upon the point that, were anticlines really overturned, as has been so generally supposed, it is the upper limb which should be attenuated by the process, and not the lower (Fig. 23).[1]

FIG. 22.—Stretched under limb of a recumbent anticline. Drawn from a photograph of the Dent de Morcles as seen from Les Martinets, western Switzerland.

Though closed anticlines with attenuated upper limbs have, so far as known, never been observed in folded rock formations, they are, on the other hand, the characteristic type of close recumbent folds in the ice of glacier snouts, where the action of gravity and the resistance of friction in the lower layers force the upper layers to override the lower in true overturning movements (Fig. 24, p. 182).[2]

Not only may the lower limb of underturned anticlines be attenuated by stretching due to the resistance of the inclosed inferior strata, but the upper limb may in this stage be bulged upward as a result of the same system of forces.

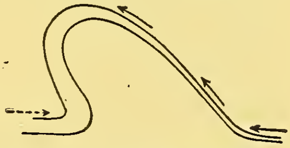

FIG. 23.—Attenuated upper limb of an anticline, a necessary consequence of overturning.

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[1] See also *ante*, p. 82, and Fig. 7. The sinking of the crown in an anticline tends to develop a tension within the upper limb, and it is perhaps conceivable that this tendency might in some stage either equal or overbalance that which normally causes attenuation of the lower limb, yet so far as known no example is furnished by folded strata.

[2] See among other views which show this effect: *Med. om. Gronland*, XLVI (1912), Fig. 24; *The Alpine Journal*, London, XXI, 187; Chamberlin and Salisbury, *Geology* I, 280, Fig. 268.

Possible formation of a magma macula beneath an anticline.—From examination of Fig. 17 and Table I (pp. 178 and 175) it will be seen that a relatively competent member near the top of a series of beds may remove from underlying members as much as one-half of the load which rests upon the arch. Under such conditions the underlying beds may be deformed by failure, even though the competent member is not (Fig. 25), and if at a depth where the isogeotherms are sufficiently high to melt the inferior members when thus partially relieved of load, a macula of magma may develop from the fused sediments. Such fusion is the more likely to occur the lower the fusion interval of these inferior formations. The writer has elsewhere shown that the composition of igneous rocks in general is such that magma must inevitably develop, if at all, from the pelitic sediments, like shale and slate; the great abundance of which, no less than their structural weakness and their normal position in sedimentary series, is in favor of the view.[1]

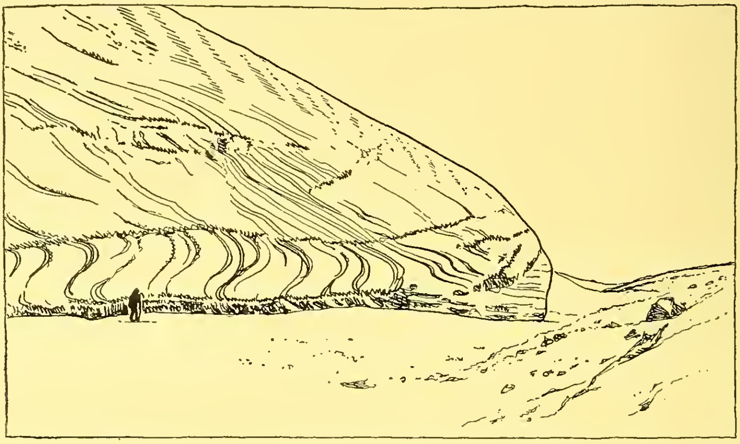

FIG. 24.—View of the front of the ice in northeast Greenland where overturned anticlines with thinned upper limbs are to be seen (after Koch and Wegener).

Reduction of volume of anticline an efficient cause of elevation of magma.—Before the formation of a macula of magma through fusion

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[1] "Some Considerations Concerning the Place and the Origin of Magma Maculae," *Gerland's Beiträge zur Geophysik*, XII (1913), 329–61, Figs. 1–8; see also "Variations in Composition of Pelitic Sediments in Relation to Magmatic Differentiation," *Comptes rendus 12^{me} Congrès Géologique International*, Canada, 1913.

A

B

Fig. 25.—Results of lateral compression of parallel horizontal layers of materials which have varying degrees of rigidity, but are rendered plastic by the loads upon them. The active force is applied at the left (after experiments by Bailey Willis).

A, relatively less rigid beds deformed by failure beneath a competent (more rigid) stratum. There is also to be observed a slide which passes through all members alike.

B, successive anticlines and slides—imbricated structure.

of the roll of sediments beneath a relatively competent member, these inferior sediments support, as we have seen, a considerable portion of the entire superincumbent load. After fusion this support to the competent arch, which has hitherto been in excess of half the load, is now replaced by the molten magma of high incompressibility and perhaps also high viscosity. The compressive stress is now exerted through the under limb of the anticline in such a way as to squeeze or compress the macula. Under this action the under limb may suffer greater or less extension and consequent attenuation, but there must also be a tendency for the mass of magma to find an outlet along the path of least resistance, and it may in consequence fuse a course for itself upward toward the earth's surface (Fig. 26). In the upper levels any fractures that may exist are likely to be followed, and more especially fracture intersections. Recent studies make clear that magmas have the capacity of melting their own way by the process of overhead stoping. If such magma arrives at the surface along essentially vertical paths, its loci of emergence will constitute a series of arcs parallel to, and generally behind, the folded mountain arcs beneath which the maculae were developed. Thus we encounter in a consideration of the mechanics of folded mountain arcs a possible explanation of the position of volcanic arcs, and a possible solution of the vexed problem of the cause of elevation of magma in volcanoes of markedly Pacific type.

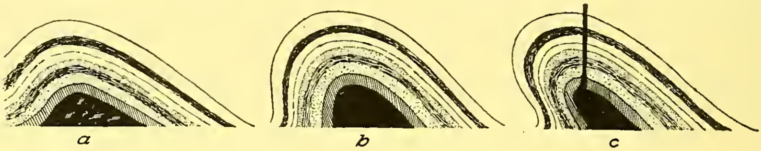

Fig. 26.—Diagrams to illustrate the tendency to reduction in the volume of progressively underturned anticlines and a consequent cause of the elevation of lava toward the earth's surface.

Volcanic vents once secured at the surface, magma should be exuded or ejected, and partial and further temporary relief be secured below from the compressive stress. Broad relationships

—rather than close responses— should therefore be expected to connect the growth of mountains and their attendant seismic disturbances with volcanic manifestations. The variations in the competence of the rising arch particularly after underturning has begun, considered in connection with the incidents of failure and their attendant consequences (hereafter to be discussed), are such as to make probable long-period variations particularly, both in seismic disturbance and in volcanic extravasation.

Backfolding of anticlines.—As yet comparatively little attention has been given by geologists to the effect of the local occurrence of weak or strong facies of a formation or series upon the character of the folds produced in them.[1] The subject is too complex and too little known to be discussed at length, but there are yet some very significant indications of its importance in fixing the location of the rare backfolds which have sometimes been described. In this connection a simple experiment by Daubrée is illuminating.[2] The strip of lead, which in so many of his tests was compressed from the end by a piston, was in one case locally weakened by thinning at some distance from the piston head, and the amplitude of upward deflection was limited by a horizontal beam above. The flexible strip was under these conditions deformed into a true backfold (Fig. 27), although it failed to simulate the Glarus double-fold as had been intended.

FIG. 27.—Backfold induced in a leaden strip above a local zone of weakness (after Daubrée's experiment).

Nature has furnished an even better illustration in the Weissenstein of the Chain Jura, which the series of parallel profiles by

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[1] Paulcke's experiments fail to afford altogether satisfactory results for the reason that his competent member is insufficiently loaded and does not fold.

[2] *Op. cit.*, p. 296, Fig. 85.

Buxtorf displays to the best possible advantage.[1] In these profiles (Fig. 28) the western (lower) ones reveal a slightly underturned anticline with perhaps some late bulging-upward of the upper limb,

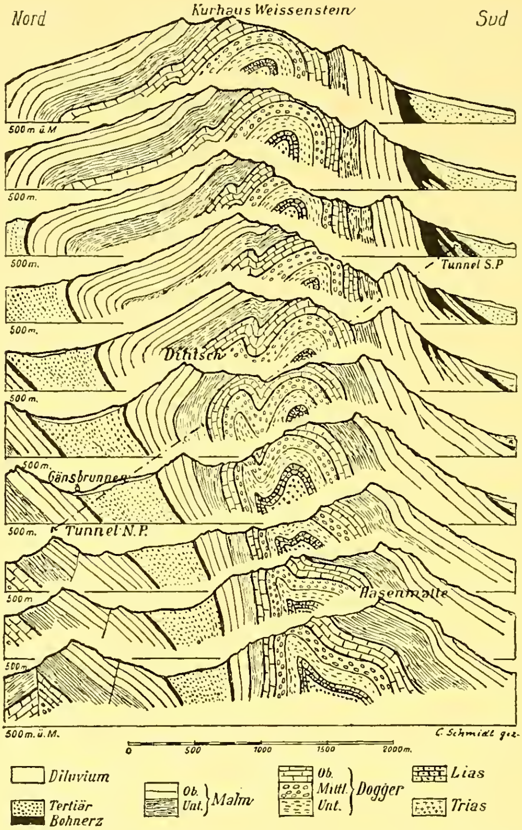

FIG. 28.—Series of geological profiles through the Weissenstein, Chain Jura, showing the development of a backfold above the *Bohnerzformation*, which is represented in black (after Buxtorf).

but with no indication of backfolding. Farther to the eastward, however, where a thin zone of the *Bohnerz formation* in part replaces

---

[1] Aug. Buxtorf, "Geologische Beschreibung des Weissensteintunnels und seine Umgebung," *Beitr. z. Geol. Karte d. Schweiz*, N.F., XXI (1907); C. Schmidt, A. Buxtorf, und H. Preiswerk, *Führer zu den Exkursionen der deutsch. geolog. Gesellschaft im südl. Schwarzwald, im Jura und in den Alpen*, 1907, pp. 21–22.

the strong Malm of the competent arch, the anticline is backfolded and in a degree dependent upon the thickness of the weaker formation.

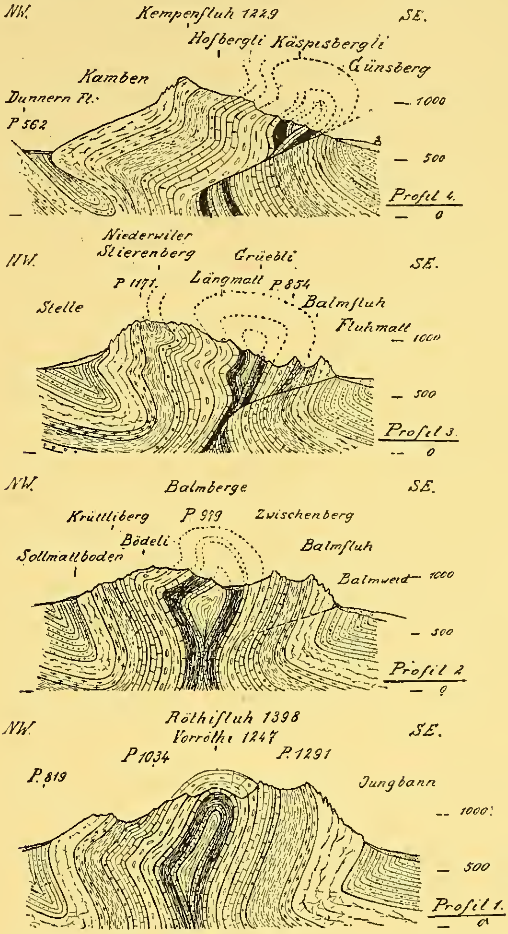

FIG. 29.—Backfolding due to the presence of a disjunctive surface in the folding formations. Series of profiles through the Weissenstein, Chain Jura (after Buxtorf).

The same district of the Weissenstein folds has supplied an equally instructive example of backfolding (near Balmberg-Günsberg), but one where the determining local weakness was a plane of fracture and not a zone of weak rock (Fig. 29).

Fan (carinate) anticlines may thus be a result of backfolding, though they may possibly in other cases be due to compression under the action of equal thrusts from opposite directions. It is, on the other hand, extremely difficult to conceive of conditions which could give rise to a fan or carinate syncline, for the reason that synclines, like anticlines, should develop above the zone of maximum pinch (see Fig. 19, p. 179). It is thus with a certain satisfaction that we may contemplate the abandonment of the conception of the Glarus double-fold, which in an earlier generation was standard doctrine in tectonics and required us to account for supposed fan synclines upon a gigantic scale (see *ante*, Fig. 1, p. 76).

PETROLOGICAL ABSTRACTS AND REVIEWS

EDITED BY ALBERT JOHANNSEN

ALLEN, E. T., and CRENSHAW, J. L. "The Mineral Sulphides of Iron. With Crystallographic Study by Esper S. Larsen," *Amer. Jour. Sci.*, XXXIII (1912), 169–236.

ALLEN, E. T., and CRENSHAW, J. L. "The Sulphides of Zinc, Cadmium, and Mercury; Their Crystalline Forms and Genetic Conditions. Microscopic Study by H. E. Merwin," *Amer. Jour. Sci.*, XXXIV (1912), 341–96.

ARSANDAUX, H. "Sur la présence au Gabon de roches appartenantes à la série de la charnockite," *Comptes rendus de l'Acad. d. Sci., Paris*, CLIV (1912), 896.

In the Como Basin, a part of the French Congo, the author finds hypersthene granites, of a type hitherto found in but few localities; associated with ordinary granites and with amphibolite schists, gabbros, and diabases. Similar rocks of the charnockite family have been found on the Ivory Coast, about 1,000 miles northwest, but in that region the rocks found associated in the Como Basin characterize separate localities.

F. C. CALKINS

ARSCHINOW, W. W. *Ueber zwei Feldspäthe aus dem Ural.* Moskau, 1911. Pp. 12.

An article in the Russian language, with a German résumé, describing a potash-soda feldspar from the Ilmen, and an oligoclase-albite from the South Urals.

ARSCHINOW, W. W. *Zur Geologie der Halbinsel Krym.*, Moskau, 1910. Pp. 16.

An article in the Russian language, with a German résumé, describing a basalt tuff from the neighborhood of Balaklava. The rock consists of a basic feldspar, of which an analysis is given, diopside, green hornblende, magnetite, and rarely brown basaltic hornblende. The cementing material is in part amorphous, in part of fine crystal particles. Secondary minerals are calcite, zeolites, biotite, chlorite, and glauconite. The presence of glauconite, foraminifera, radiolarians, and sponge spicules, and the gradual transition of the tuff to other sedimentary rocks, indicate a submarine origin. A. J.

BOEKE, H. E. "Räumliche ternäre Kristallisationsmodelle für den Unterricht in physikalisch-chemischer Mineralogie," *Centralbl. f. Min., etc.*, 1912, 257–69.

BOEKE, H. E. "Karbonschmelzen unter Kohlensäuredruck. II. Ueber Witherit, Alstonit, Barytokalzit und Strontianit," *Mitth. d. Naturforsch. Gesell. Halle*, III (1913). Pp. 12.

BOEKE, H. E. "Mineral- und Gesteinsbildung aus dem Schmelzfluss (Magma) und durch Pneumatolyse," *Handwörterbuch der Naturwissenschaften*, VI (1912), 919–30.

A general paper on the formation of minerals and rocks from a magma.

BOEKE, H. E. "Die Schmelzerscheinungen und die umkehrbare Umwandlung des Calciumcarbonats," *Neues Jahrb.*, 1912 (I), 91–121.

An apparatus is described for producing temperatures up to 1600° and under pressures to 150 atmospheres. Iceland spar was found to melt, without decomposition, under a pressure of at least 110 atmospheres of CO_2, at 1289°. Mixed melts of calcium carbonate and calcium oxide were found to crystallize as a eutectic of 91 parts by weight of $CaCO_3$ and 9 parts of CaO at 1218°, and without the formation of crystals of intermediate composition. At $970 \pm 5°$ calcium carbonate reaches its inversion point; below this calcite is the stable form. A. J.

BOEKE, H. E. "Ueber die graphische Ermittelung der Krystallelemente und den Zonenverband in der gnomonischen Projection," *Zeitschr. f. Kryst.*, LII (1913), 175–78.

BOWEN, N. L. "The Melting Phenomena of the Plagioclase Feldspars," *Amer. Jour. Sci.*, XXXV (1913), 577–99.

BÜCKING, H. "Die Basalte und Phonolithe der Rhön, ihre Verbreitung und ihre chemische Zusammensetzung," *Sitzb. Akad. Wiss. Berlin.* XXIV (1910), 490–519.

The rocks described are feldspar basalts, nephelite basalts, nephelite basanites, nephelite tephrites, hornblende basalts, basaltites (trachydolerites), limburgites, and phonolites. Analyses are given of 78 rocks and 22 mineral constituents. There is a 2-page bibliography.

A. J.

BÜCKING, H. "Ueber vor- und nachbasaltische Dislokationen und die vorbasaltische Landoberfläche in der Rhön," *Zeitschr. d. deutsch. geol. Gesell.*, LXIV (1912), 109–24.

CRAWFORD, R. D. *Geology and Ore Deposits of the Monarch and Tomichi Districts, Colorado. Bull. 4*, Colo. Geol. Survey, Boulder, 1913. Pp. 317, pl. 25, figs. 15.

While a great part of this report is economic, there are some 87 pages devoted to the igneous rocks of the region, 21 to sedimentary rocks, and 17 to the processes of intrusion, metamorphism, etc. The pre-Cambrian rocks described are granitic gneiss, hornblende gneiss, hornblende schist, mica schist, garnetiferous schist, biotite-sillimanite schist, quartzite, granite, granite porphyry, syenite, hornblendite, and diorite. Post-Carboniferous igneous rocks are quartz diorite, quartz monzonite gneiss, quartz monzonite, granite, quartz monzonite porphyry, andesite, quartz latite, monzonite porphyry, latite, latite porphyry, andesite porphyry, rhyolite, rhyolite porphyry, pitchstone porphyry, and breccias.

A. J.

DALE, T. NELSON, and GREGORY, HERBERT R. *The Granites of Connecticut.* Bull. 484, U.S.G.S., Washington, 1911. Pp. 137, pl. 7, figs. 12.

This bulletin is a companion volume to those on the granites of Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont (Bulls. 313, 354, 404, U.S.G.S.). The granites of the state (the term granite being here made to do service for granites, monzonites, diorites, pegmatites, and gneisses) are very varied in character, ranging in texture from coarse pegmatites to fine quartz monzonites and from equigranular to porphyritic. In color they range from blue-black to light gray and pinkish red. The rocks have been used for building purposes, monuments, bridges, curbing, paving blocks, and road metal; the amount of production in the last ten years averaging $500,000 a year.

A. J.

DALE, T. NELSON. *Supplementary Notes on the Commercial Granites of Massachusetts.* Bull. 470-G, U.S.G.S., 1911. Pp. 6–56.

Supplementary to Bulletin 354, previously reviewed.

DALE, T. NELSON. *The Commercial Marbles of Western Vermont.* Bull. 521, U.S.G.S., 1912. Pp. 170, pl. 17, figs. 25.

In this bulletin, Professor Dale has described the western Vermont marbles in much the same manner as he did the granites in a number of earlier bulletins. After a preliminary description of marbles in general, covering 60 pages and including a 6-page bibliography, the various marble quarries of the area under consideration are described in detail. Professor Dale's bulletins on the building and ornamental stones are greatly appreciated, and it is to be hoped that he will continue issuing them. Similar bulletins from other parts of the country would be of considerable value.

A. J.


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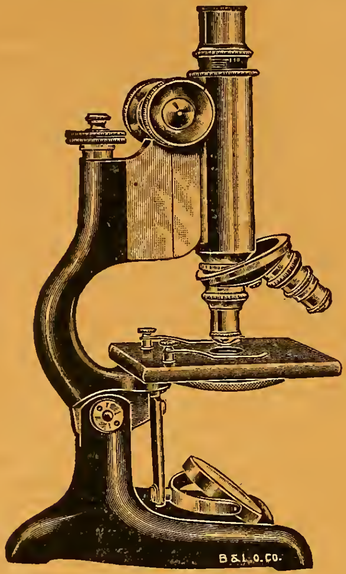
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APRIL-MAY 1914

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MECHANICS OF FORMATION OF ARCUATE MOUNTAINS

WILLIAM H. HOBBS
University of Michigan, Ann Arbor, Michigan

PART III

THE FOLDING PROCESS STUDIED IN THE PROFILE—FORMATION OF SLIDES

Imperfect plasticity of folding strata.—Thus far we have discussed the flexures in rocks as though the plasticity of folding sediments were sufficient in all cases to permit without failure the development of both underturned and recumbent anticlines. Such a condition appears to be realized in nature only in the case of well-laminated rock formations, and it is proper here to consider a little more fully the subject of plasticity within compressed sediments under load and at somewhat elevated temperature.

At the surface of the earth so-called "hard rocks" behave like highly elastic bodies, and the degree to which this property of elasticity is modified by load has prevented a simple mathematical discussion of the subject of folding. Rudzki has stated perhaps as clearly as anyone the reciprocal relations of the properties of elasticity and plasticity in solid bodies.

> The elastic force with which the body resists the deforming force diminishes with time. The time which is necessary for the resisting force to fall to $\frac{1}{e}$ of its original value is called after Maxwell the relaxation time. A body is so much the more plastic the smaller the relaxation time. According to the

kinetic theory one may assume that all bodies are plastic to a certain degree, and that the differences have quantitative value. Obviously for room temperature and atmospheric pressure different bodies possess very different relaxation times. For steel the relaxation time may be some centuries; for wax, paraffine, etc., it is so small that the determination of the elastic constants by the usual static methods is difficult to carry out. Plasticity appears in some cases to be dependent upon the magnitude of the deforming force—it is larger and the relaxation time smaller the greater the force. Temperature has the greatest influence upon plasticity, the plasticity increasing with the temperature. Glass, which is at ordinary temperatures so brittle and breakable, shows distinct plasticity above 300° C. (order of magnitude of the relaxation time about a day).[1]

Quite obviously, where not centuries only but very much larger units of time may be involved in the folding process, the load which is necessary to produce plasticity sufficient for folding may be very much less than that indicated by experiments.[2]

There is, however, a way of looking at the subject of potential plasticity as it relates to folding strata, which will give us an insight into the conditions under which failure may occur. The different parts of a fold are subject to internal strains which in the anticlines of relatively late stage differ by large amounts. It therefore occurs that the period covered by the evolution of a fold may be sufficiently long to permit the resisting forces within the strata to fall, and local strains to occur without failure except at critical points of maximum deformation. In this event failure will occur at the locus of maximum deformation much as it would in a relatively elastic body, even though the remaining portion of the arch adjusts itself to the stress conditions like a truly plastic body. Our problem is, therefore, to discover the locus of maximum strain in a growing anticline.

Contrasted cases of isotropic and anisotropic strata—control of internal strains by lamination.—The problem of representing the system of internal strains within a developing anticline is complicated by the variations in texture which characterize rock formations. There are, on the one hand, formations such as heavy limestone

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[1] *Physik der Erde* (author's German translation), Leipzig, 1911, pp. 232–33.

[2] See in this connection, F. D. Adams, "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *Jour. Geol.*, XX (1912), 97–118; L. V. King, "On the Limiting Strength of Rocks under Conditions of Stress Existing in the Earth's Interior," *ibid.*, pp. 119–38.

or dolomite members which are largely devoid of lamination planes and hence to be regarded as not only nearly homogeneous but approximately isotropic as well. Rather generally, however, sediments are characterized by more or less numerous planes of ready separation (lamination) parallel to the original upper and lower surfaces of the formation, and such formations are to be regarded as essentially anisotropic with a minimum of cohesion at right angles to the lamination planes. The movements of particles due to internal stresses are of necessity guided by these surfaces, since the adjacent thin layers permit of the differential sliding (shearing) motions generally described as accommodation between layers. The more perfect the lamination, the more readily does the stratum rise to form an arch. On the contrary, any tendency toward cross-fractures in the strata, such as are generally to be found in shales, lowers the strength of the arch and brings about its failure. The significance of lamination in this connection may be the better appreciated by considering the bending of two rods, one of wood cut parallel to the grain, and the other shaped from some isotropic substance like glass or wax. The rod cut parallel to the grain possesses large cohesion in the direction necessary to resist strong tension upon the convex surface when bent, but the least cohesion in the direction to facilitate the necessary adjustment by shearing between parallel longitudinal layers within the mass.

Shearing movements within an anticline for the contrasted cases of isotropic and of well-laminated strata.—For the case of laminated strata we may study the internal strains within an anticline by means of a simple experiment. Two exactly similar piles of paper were taken, each some two feet or more in length, two inches in width, and one inch in thickness. Upon the long edges of these piles series of tangent circles were carefully drawn in ink, each with its vertical diameter. The circle was chosen as guide form, both because it is the figure of highest symmetry and favors no one direction more than another, and because conglomerate pebbles, by rudely simulating in some cases this form in section, have sometimes preserved a valuable record of deformations within anticlinal arches.

Thus prepared, one of the piles was bent into the form of an unsymmetrical anticline (Fig. 30), the other being preserved as it was for purposes of comparison and to note the measure of crustal shortening in anticline evolution. Observing now the deformations of the guide circles, it is found that slight deformation only has occurred in the neighborhood of the crest of the anticline and near

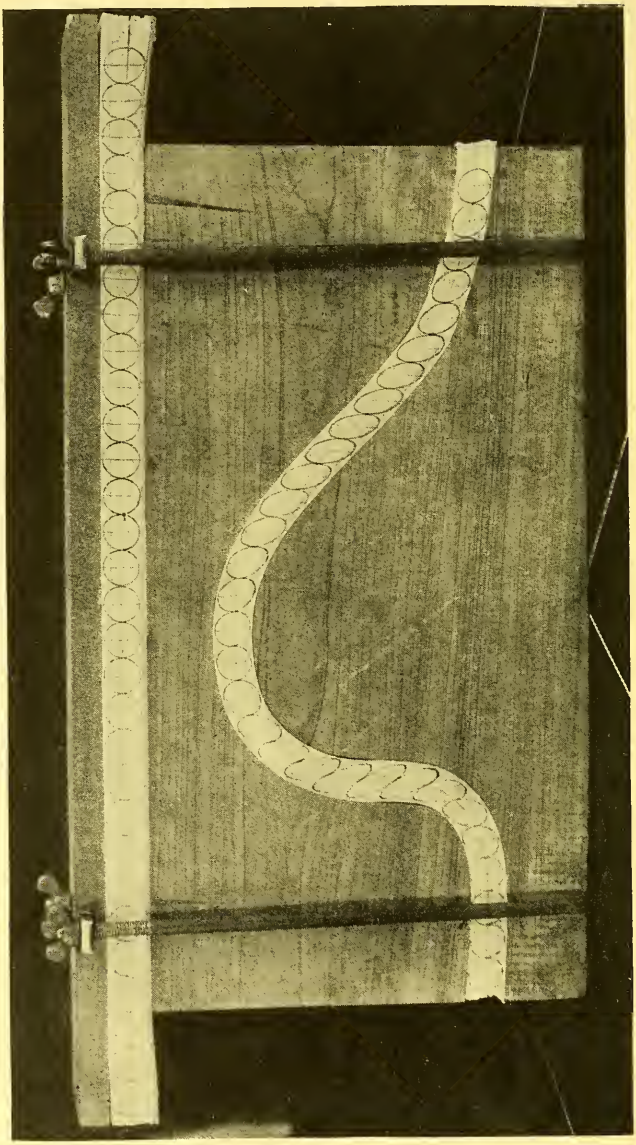

FIG. 30.—Model to illustrate the internal strains which are developed within a stratum in the process of folding

the trough of the neighboring syncline (a slight elongation of the vertical diameter). Elsewhere at all points on either side of the points of inflection of the fold a more complex deformation has taken place, for the circles have been transformed into more or less elongated obovate figures with the greatest elongation at the points of inflection. Comparing the upper and flatter with the lower and steeper limb of the anticline, we find that deformation has been greater in the steeper limb, and since we are seeking the locus of maximum deformation we will examine this limb somewhat more in detail (Fig. 31).

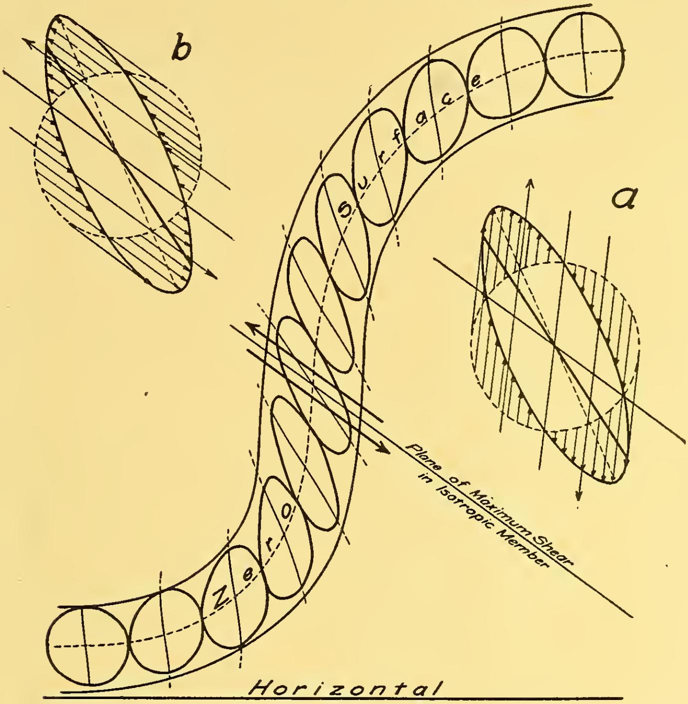

FIG. 31.—Steeper limb of the anticline produced from a pile of paper to show the deformed guide circles (traced): *a*, enlarged diagram at the point of inflection to show the actual migrations of particles by shearing movements parallel to the lamination; *b*, enlarged diagram of the deformations at the point of inflection if the stratum bent had been from isotropic material.

Above the point of inflection of the limb it is to be noted that the originally vertical diameters of the guide circles now diverge upward, thus indicating that there has been tension upon the convex side and compression upon the concave side of the stratum. These relations are reversed in the synclinal portion. The points of inflection of the double curves into which the guide circle diameters have been transformed define a surface within the stratum which has been neither expanded nor contracted and is known as the "zero surface." This surface is in the true anticline section below, and in the syncline section above the median surface of the stratum.[1]

Earlier failure in anticlines of unlaminated or poorly laminated strata.—At the point of inflection in the steeper anticline limb, deformation is clearly at a maximum, and failure, if it is to occur, will be located here. The enlarged diagrams *a* and *b* of Fig. 31, which set forth the original and the deformed conditions of the guide circles at this critical point, show that there are two exactly similar common diameters to the circle and ellipse and that the observed deformations might have taken place through migrations of individual particles either in one or in the other of two ways, dependent upon which offered the minimum of resistance. Obviously the slight cohesion to be overcome by the shear of the paper laminae over each other has determined that in the case of our experiment—a well-laminated (anisotropic) stratum—adjustments shall take place parallel to the laminae, for which reason failure is little likely to result until a late stage of the anticline has been evolved. Had our stratum been, on the other hand, without lamination planes (isotropic), adjustments would have taken place in the sense of diagram *b*, and failure would have occurred parallel to the other common diameter in the figure as an application of the principle of greater weakness on the section of minimum area.

As an application of these considerations we find that unlaminated strong members like limestone fail in the process of anticline

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[1] When well-laminated rock formations lie beneath a competent member of heavy massive rock like limestone, the strong tendency to shear along lamination surfaces may result in a complicated puckering of the laminated inferior formation even though the arch in the competent formation remains comparatively simple. This phenomenon so often observed in folded mountain regions and reproduced by Willis in his experiments (*The Mechanics of Appalachian Structure,* Pl. 90) involves an attenuation of the puckered laminae. It is also to be observed that the puckerings or plications are concentrated in the crown of the anticline where tension in the stratum protected may supply the space necessary for duplication by plication.

formation at an early stage and near the point of inflection of the lower limb; whereas anticlines in tough laminated strata persist until strongly underturned and then fail only after excessive stretching of the under limb and at an angle with the base which would indicate that the adjustments of individual particles were nearly or quite parallel to the laminae. These contrasted examples illustrate respectively Willis' types of "break thrusts" and "stretch thrusts"[1] (Fig. 32).

The second arch within a series of anticlines may in its turn fail in a manner similar to the first, and others of the series in succession; thus yielding a series of slices which in early stages at least dip away from the active force of compression and are described as "imbricated structure" (*Schuppenstruktur*, Fig. 25, *B*).

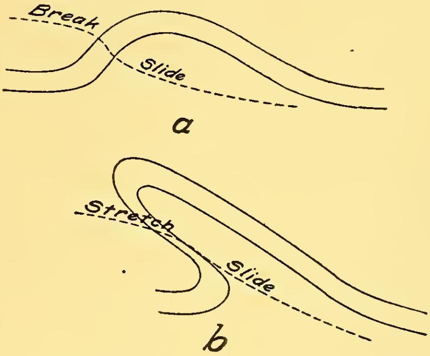

FIG. 32.—Diagrams to illustrate failure in anticlines; *a*, in an isotropic member such as limestone—break slide, or "break thrust"; *b*, in a tough laminated member such as schist—stretch slide, or "stretch thrust."

Slides and their modified direction after leaving the competent member.—The names in most general use, or at least in longest use, for the surface of failure within an anticline are "thrust" and "overthrust." The former is in every way undesirable because so likely to be confused with the same term in general use in mechanics for an active force; while the latter term is further objectionable in that it assumes that the active force responsible for the surface of failure operated from above and behind the anticline. Suess's term "sole" (*Sohle*), now employed by many, is without these objections, but the word "slide" recently suggested by Bailey[2] is perhaps even better.

[1] Willis, *op. cit.*, p. 223.

[2] E. B. Bailey, "Recumbent Folds in the Schists of the Scottish Highlands," *Quart. Jour. Geol. Soc.*, LXVI (1910), 593.

With the advent of failure in an anticline a new resolution of the active force of compression takes place with components parallel and perpendicular to the slide, movement is facilitated, and the potential energy of the system of stresses falls in consequence. The acute angle which the active force makes with the slide, and the reduced resistance opposed to shear along that surface, alike favor the underthrusting of the lower portion of the severed limb of the anticline beneath the upper (Fig. 25, *A*).

In the case of a well-laminated formation where a "stretch slide" has occurred, the slide, being nearly or quite parallel to the lamination, is extended along the lamination planes on either side within the inferior and superior formations of the series. Since the anticline contains the most steeply inclined of the layers, the dip of the slide is progressively flattened as it passes out from the anticline in either direction. For the case of a "break slide" within massive sediments, the entry into these surfaces of least resistance to slide may be less easily made but in either case a local swell of the slide surface may result. Both the low dip angles and the undulations of slides are well established by observation in many districts. The entry of the slides into the bedding planes of the formations tends to make of the severed rock formations a series of flatly disposed and widely extended slices capable of individual lateral migrations in mass, which in view of their position relative to the active force should be described as "underthrusting."

Underthrusting of rock slices separated by slides simulated in experiment.—If we represent the relatively thin slices, which are separated by slides dipping at low angles away from the active force, by a series of overlapping cards resting upon a stretched rubber sheet, and the unfolded neighboring sections on either hand by similar cards laid end to end as essentially continuous and hence relatively rigid sections of strata (Fig. 33), we may illustrate the underthrusting of the strata if we allow the rubber sheet to contract through releasing the tension upon it. With excessive underthrusting the cards are piled into a low dome elevated by the underdriving of the cards in proportion as the contraction of the rubber sheet has been large. It may happen also that the cards above and at the front dip forward and overlap at the forward end those lower in the series. This latter feature is a well-known peculiarity of the *Deckenbau* upon the northern border of the Alps (Fig. 34), and it is clearly favored by the sinking crowns of recumbent anticlines.

Formation of drag folds and listric surfaces at the front of underthrust slices.—The new system of stresses, which is inaugurated with the process of underthrusting, may lead to the formation of secondary folds and eventually to secondary slides within the mass beneath which a slice is driven. This driving-in of one slice after another not only produces friction breccia ("mylonite") at the contacts, but pushes upward and tends to fold under the frontal portion particularly of each underdriven slice. The active force of compression being still directed from in front of the folds and below, the "drag folds" which result (Figs. 34 and 35) should be underturned from the front, attenuated in the underturned lower limb, and eventually underthrust in that limb, much as are the folds of larger order of magnitude upon whose fractured remnants they have been superimposed. Instead, however, of being extended for any long distance on bedding planes, these secondary slides should here converge into the subjacent major slide. The shovel-like curvature which is so generally characteristic of them has suggested the name "listric surfaces" applied to them by Suess[1] (Fig. 35, Rigihochfluh and Mythen, and Fig. 37).

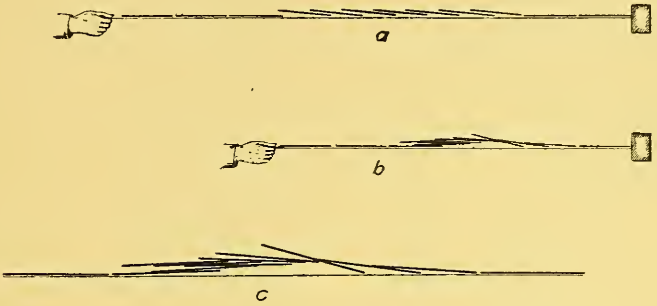

FIG. 33.—Diagram illustrating underthrusting of slices

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[1] *Listrische Flächen* (*Das Antlitz der Erde,* III, Pt. II, p. 612; *The Face of the Earth,* IV, 536).

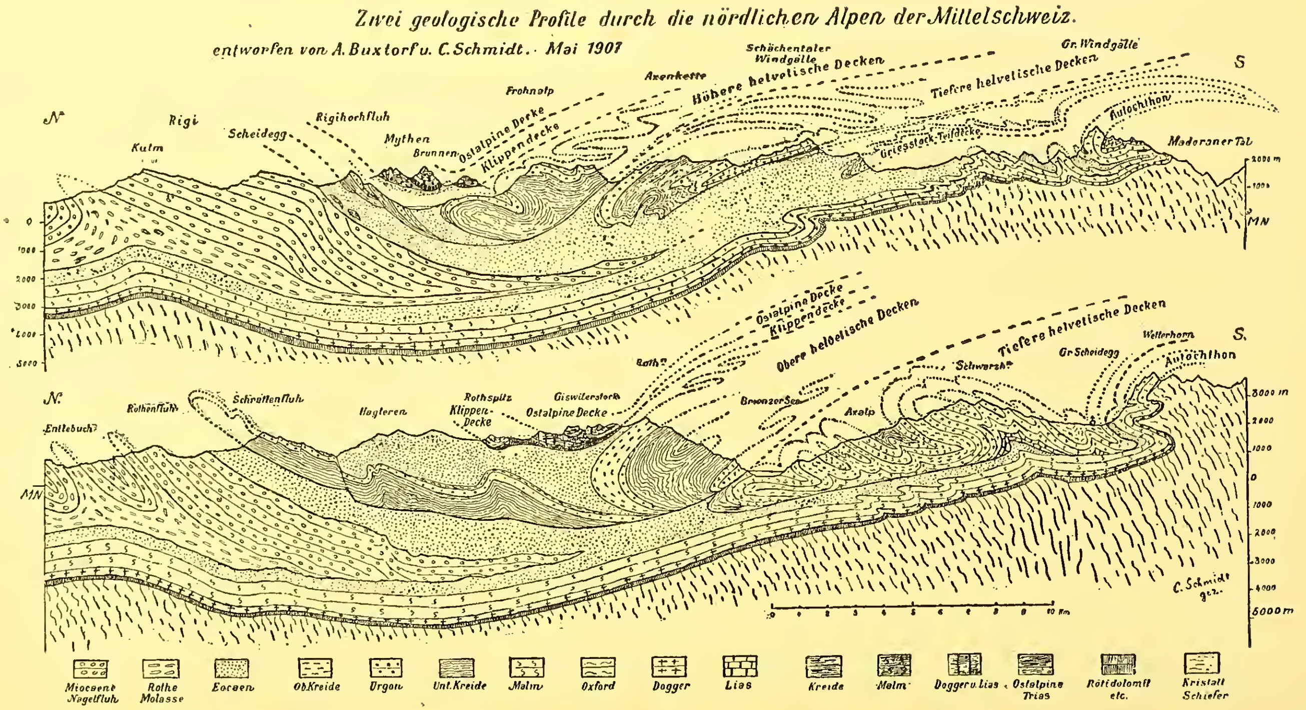

FIG. 34.—Two geological profiles through the northern Alps in middle Switzerland which show the characteristic frontal overlapping of slices and the formation of drag folds and listric surfaces (after Buxtorf and Schmidt).

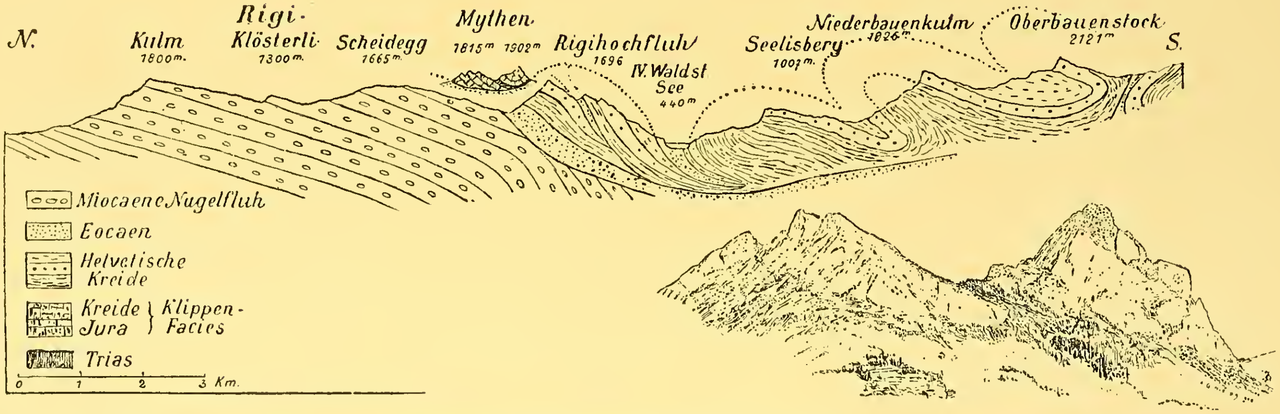

Fig. 35.—Profile of the front of one of the slides in the northern Alps to bring out the relationship of major slides to listric surfaces. At the right a sketch of the Mythen (after Tobler, Buxtorf, and C. Schmidt).

The relationship to each other in position of the listric surfaces which are produced by drag suggests the peculiar shearing surfaces which are seen at the snouts of some glaciers, save only that the distribution of forces is essentially reciprocal. It is the *upper* layers of the glacier which are pushed *forward* and *override* the lower layers held back by friction (Fig. 36). As a consequence, and as already pointed out (*ante*, p. 181), it is the upper limb of each fold rather than the lower that here becomes attenuated.

Extended slides within folded strata of mountains would appear to be greatly favored by the presence of a weak formation immediately above the competent member, this weak formation acting, so to speak, as a lubricant for the slide surface. It is no doubt significant that in the Alps the weak Flysch overlies the Helvetian limestones, for this yielding formation underlies one great slide after another in the series —"*Wildflysch*" (Figs. 34 and 35). It may also be of significance that within the same region the formation against which the slides rise at the front with the greatest development of listric surfaces is the hard *Nagelfluh* conglomerate, which has a local development only upon the northern margin of the Alps, and opposite whose areas rise the largest accumulation of rock slices.

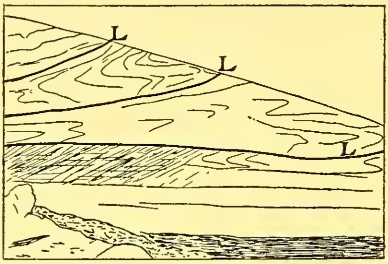

FIG. 36.—Slide surfaces in a glacier snout (after T. C. Chamberlin).

Examination of numerous profiles which include rock slides indicate pretty clearly that portions of the indriven slices have sometimes become involved in the complex of wedges at the front of each overlying slice (Fig. 37). Sections of the Belgian coalfield (Fig. 37, *e* and *f*) and of Buffalo Mountain[1] (Fig. 38) may be cited as examples.

SUMMARY

The Alps represent the type of Asiatic mountain arcs, and hence in explaining their tectonics deductions from Asiatic studies are

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[1] Arthur Keith, "Roan Mountain Folio, Tennessee–North Carolina," *Folio 151*, *U.S. Geol. Surv.*, 1907, p. 9.

to be utilized. Arcuate structure representing a reduplication of strata in recumbent and ruptured folds requires that the duplicated material shall have migrated centripetally from outside the arc and implies that the mass within is relatively the more rigid.

The arcuate ranges of Asia, regarded not individually but as a system, favor the conclusion which we have reached of centripetally distributed thrusts directed toward the center of the system: (1) by their plan of arrangement; (2) by the position of the relatively rigid area (Angara Land); (3) by the greater geological age of the central, and the newer formation of the peripheral arcuate ranges; and (4) by the present locus of intense volcanic and seismic activity along the outer margin.

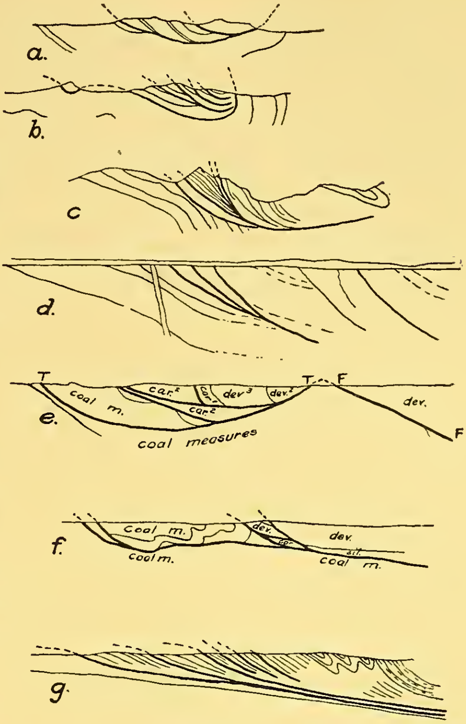

Fig. 37.—Examples of listric surfaces developed at the forward end of major slides: *a* and *b*, Buffalo Mountain, southern Appalachians (Keith); *c*, Rigihochfluh, northern Alps (Tobler and Buxtorf); *d*, Belgian coal-fields from St. Éloi to St. Léon (Briart as reproduced by Suess); *e*, Belgian coal-field at Fontaine-l'Évêque (Briart and Suess); *f*, the same near Denain and Anzin (Bertrand and Suess); *g*, North-central Carpathians (Uhlig). For better comparison all sections have been made to look north, northeast, or east.

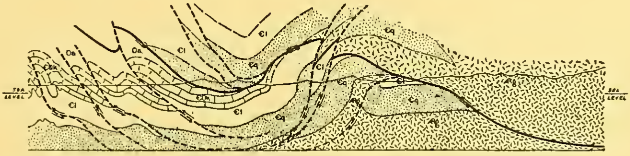

Fig. 38.—One of the sections through Roan Mountain in the southern Appalachians (after Keith).

The ocean floors are today for the most part sinking and represent the great areas of dispersal of thrusts toward the neighboring continents, and mountain arcs should therefore be convex toward oceanic depressions. If in the past during mountain-making periods ocean floors have represented areas of dispersal of thrusts, the position and the orientation of the earlier arcs should be an expression of the former areal relations of the continental pedestals and the ocean floors. For the continent of Asia this theory appears to be borne out by what we know of continental evolution within the principal mountain-making periods.

The active force (thrust) which produces rock folds, instead of operating from behind and above the anticline, as so generally supposed, is applied below and in front. Continuation of the process yields therefore not "overturned" and "overthrust," but *underturned* and *underthrust* flexures. Applied to the Alps, this requires that the main active force concerned in their folding came from the northwest, instead of the southeast, as generally assumed.

Anticlines arise first upon that side of the folding area which is toward the direction from which the force comes. In strong or competent members anticlines lift a portion of the load from arched underlying formations, and this portion, regarded as a percentage of the total load upon the arch, is at first small, but afterward rises steadily and rapidly up to the stage of underturning, after which it rapidly diminishes.

With the underturning of an anticline a new distribution of stresses is inaugurated, as a result of which a second anticline may develop behind the first and subsequently others in succession but of steadily diminishing dimensions until the series comes to an end. Thus it comes about that while the arcs in the order of their age develop from within outward in the series as the continental area becomes extended peripherally, the *folds* (*anticlines*) *within any arc* are developed in order of age from without inward (Fig. 39).

With the stage of underturning a new couple composed of vertical forces enters and tends to rotate the underturned arch, not forward as before, but downward; and if the competent member is overlaid by a weak formation, the crown of the arch will be left without sufficient support and will sink to form a "plunging crown." If supported by a strong formation this will not occur, but it will in any case eventually be rotated as a whole about its base and form a normal recumbent anticline.

Subsequent to the stage of underturning of the anticline, the active force of compression tends to reduce the volume of the included roll of the inferior strata with the effect of stretching and attenuating the under limb of the anticline in the competent member. Attenuated upper limbs of anticlines, though unknown in rock folds, are illustrated by the ice-folds within glacier snouts, where they are due to true overturning movements.

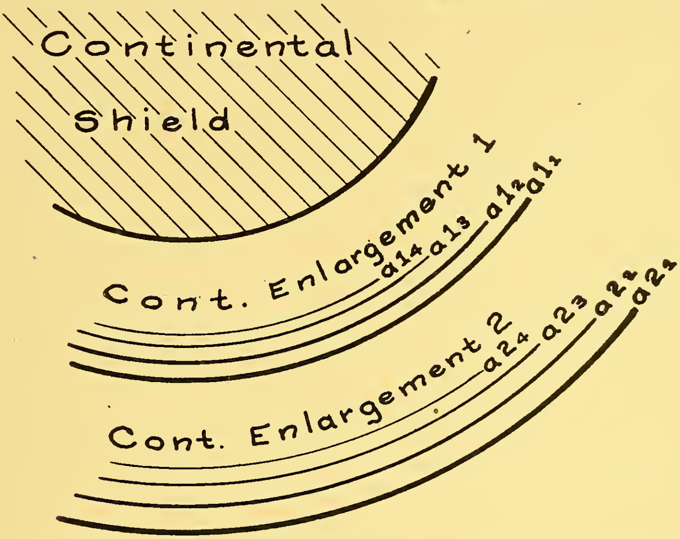

Fig. 39.—Schematic diagram to illustrate the order of development of mountain arcs from within the series outward, and the development of anticlines within each arc from without inward.

The partial relief of load from the inferior formations beneath the competent member in the arch may make possible under suitable conditions of temperature a local development of a magma macula; and the tendency to reduction of volume with continued underturning of the anticline supplies an efficient cause of the elevation of such lava toward the earth's surface. Association both in time and in place of volcanoes of the Pacific type with growing mountain arcs would thus be accounted for.

Backfolding occurs where relatively competent rock formations are locally replaced by weak material, or where a surface of disjunction transects the formation. The backfold develops in front of and eventually above the zone or surface of weakness.

The evolution of an anticline to late stages of underturning is directly determined by the measure of lamination of the competent member and the toughness of the laminae. Relatively strong rocks devoid of lamination fail by cross shear ("break slide") and at a much earlier stage of the anticline than tough well-laminated rocks which, on the contrary, fail on disjunctive surfaces which are nearly or quite parallel to the lamination ("stretch slide").

After failure of an anticline has occurred, a new resolution of the external forces takes place with components parallel and perpendicular respectively to the surface of failure (slide); this surface tends to be extended in either direction along surfaces of least resistance—usually bedding planes—and is thus flattened as it recedes from the competent arch. With the advent of the slides, migrations of the severed parts of the fold are greatly facilitated, and movements of the rock slices take place in such a sense that the lower are driven in beneath the upper—underthrusting.

The large friction on slides incident to underthrusting is reduced by a weak formation superior to the competent member. Friction breccia (mylonite) generally marks the position of the slide which develops special features at its forward end. Here are found secondary folds (drag folds) and secondary slides (listric surfaces), the former being underturned and attenuated in the underlimb, while the latter are concave upward (shovel-shaped) and converge into the major slide below. The lower of two contiguous slices may be ruptured and involved in the complex of curved wedges at the front of the slice immediately above.

September 15, 1913

THE STRENGTH OF THE EARTH'S CRUST

JOSEPH BARRELL
New Haven, Connecticut

PART III. INFLUENCE OF VARIABLE RATE OF ISOSTATIC COMPENSATION

INTRODUCTION AND SUMMARY

The work of Hayford on the deflections of the vertical, and of Hayford and Bowie on the anomalies of gravity, has supplied the geodetic data from which future work must start. As an initial basis to guide their work, it was desirable to assume the hypothesis that isostatic compensation was complete for each topographic irregularity, giving local compensation, and that it was uniformly distributed to a constant depth. The actual results may then be compared to this ideal of local, uniform, and complete isostasy and the degree of departures noted, as given by residuals and anomalies.

In Part II the subject of the regional distribution of compensation was examined and the conclusion was reached that the crust was sufficiently rigid to bear such mountains as Pikes Peak without requiring special compensation below. In general it is thought compensation in mountain regions extends to more than 200 km. and in some regions to more than 400 km. In this part are considered the effects of variations in the vertical distribution of compensation and the degree to which such variability may give rise to anomalies and residuals without signifying incompleteness of compensation in the column as a whole or regional departures from isostasy.

In order to show the limits of variation in density which are to be expected, the specific gravity of rocks is first considered. Figures are computed for the mean specific gravity of igneous rocks and the three types of sediments. It is shown that the range of variation is an important factor. Under the subject of the relations between mass and the distance of mass upon anomalies, the effects are computed of unit masses at various depths and extending various distances.[1] This lays the basis for considering the influence of the specific gravity of the surface geologic formations upon the difference between the mean anomalies for stations on pre-Cambrian and those on Cenozoic areas. It is found that the greater density of the older rocks accounts for a part and another part is accounted for by their resistance to erosion. This still leaves, however, large outstanding regional variations not related to surface geology or topography and requiring some other explanation. To that end criteria are discussed for the recognition and separation of the effects of mere variable vertical distribution of compensation on the one hand, from partial regional absence of isostasy on the other. It is concluded from the application of these criteria that the anomalies are in large part caused by real regional departures from isostasy extending over broad areas. The results are thus

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[1] A paper by Gilbert has recently appeared entitled "Interpretation of Anomalies of Gravity" (*Part C, Professional Paper 85, U.S. Geological Survey*, 1913). This did not reach the present writer until after Parts III and IV of this article were in galley proof, so that his results cannot be as fully interwoven into the discussion as would otherwise have been the case. On pp. 30, 31, Gilbert considers the interpretation of anomalies on the assumption of vertical heterogeneity of the crust and shows clearly that moderate variations of density in a vertical direction could explain them. From this he infers that the anomalies may be due in part to such irregularities. This is the topic which is treated in Part III of the present article under the title "Interpretation of Anomalies in Terms of Mass and Depth." The method of reasoning is somewhat different, but although the conclusion reached is the same, the calculations given here are intended to bring out in addition the limitations of area and mass within which that principle applies. It is concluded as a result of the following examination of the evidence that although vertical variations of density are a real cause they are not the major cause of anomalies.

confirmatory of those reached in Parts I and II. In addition, however, it appears that there is a regional departure from isostasy of two orders of magnitude. Loads under the mean value, giving anomalies below 0.018 to 0.020 dyne and estimated to be equivalent to about 750 feet of rock, can be carried over regions of irregular boundaries ranging up to from 1,000 to 2,000 km. across. Over such a broad region the anomalies are of one sign except for some smaller well-defined sub-areas of high anomaly within them which may or may not have the same sign. These smaller areas give a higher order of stress magnitude and are of more restricted dimensions, being measured in hundreds of kilometers. They range in magnitude of anomaly to several times the value of the mean and the equivalent radii of their areas probably average 100 to 200 km. The deflection residuals show by the limits of the areas of like sign that the regional variations of gravity anomalies of this areal magnitude extend over the whole country, but where the amounts of the local anomalies are less in value than the mean they are largely masked on the contour map of gravity anomalies (Fig. 5), because of their superposition upon the broader areas. Presumably a multiplication of the gravity stations would bring them to light as undulations in the contours which show the regional departures.

A final conclusion on the subject of the variable vertical distribution of mass must, however, be deferred until consideration has been given to a hypothesis advanced by Gilbert in his recent paper, that heterogeneities of mass below the zone of compensation may be the cause in major or minor part of the apparent departures from isostasy. This is a subject too large to be considered in this third part of the present article, but it is planned to investigate it in Part V by a method of graphic analysis devised for determining the depth of excesses or deficiencies of mass.

THE SPECIFIC GRAVITY OF ROCKS

For a knowledge of the variations of density likely to occur in rocks it is important to know the range in specific gravities shown by the common rock types. The following figures, except those for shale, are taken from Pirsson's *Rocks and Rock Minerals:*

TABLE V

Rock	Specific Gravity
Granite	2.63–2.75
Syenite	2.6 –2.8
Diorite	2.8 –3.1
Dolerite	3.0 –3.3
Limestone	2.6 –2.8
Sandstone	2.5 –2.7
Shale	2.4 –2.8
Slate	About 2.8

[The specific gravity of shale, although the most abundant of sedimentary rocks, is not given in any of the manuals of geology, but Professor Hobbs, who has read much of this manuscript and to whom the writer is indebted for a number of suggestions, has called attention to the above figure as given by Trautwine. In general, Trautwine and Kent give a somewhat greater range in specific gravities and they average a little lower than those here given. The figures from Pirsson, however, probably express more closely the relation of the petrologic type and the more compact states of rocks to their density. They are, therefore, thought to be better representative of the lithosphere.]

These figures show that notable departures may occur from the mean density of the outer crust and suggest furthermore that 2.67, the mean density used by Hayford, is lower than the actual mean. A more thorough analysis of the subject is therefore needed.

The abyssal igneous rocks and metamorphic rocks are almost without pore space. The sedimentary rocks, on the other hand, possess abundant pore space in their unconsolidated states, very little in their compact states. The latter is the usual mode of occurrence in the older geological formations. The density is therefore a function of both mineral composition and porosity. The chemical compositions of the several rock types and also of the average sediment and the average igneous rock are well known. The mineral compositions are less well known but may be computed with a fair degree of accuracy; the densities, on the contrary, are least commonly reported and the mean densities of the rock types cannot in consequence be closely determined by averaging numerous determinations, as is done for the chemical compositions. It seems desirable, therefore, to compute the densities of the rock types from the chemical and mineral compositions, combining this with the densities of the individual minerals, making a separate correction for the porosity factor. The data, assembled from various sources[1] and subjected to computation, give the following results:

TABLE VI

COMPOSITION OF AVERAGE IGNEOUS ROCK

Mineral	Percentage
Quartz	12.0
Feldspars	
Orthoclase molecule	22.0
Albite molecule	29.5
Anorthite molecule	8.0
Hornblende and pyroxene	16.8
Mica	3.8
Accessory minerals	7.9
	100.0

TABLE VII

COMPOSITION OF AVERAGE SEDIMENTS

Mineral	Shale	Sandstone	Limestone
Quartz	22.3*	66.8*	2.0
Feldspars			
Orthoclase	18.0	7.0	0.3
Labradorite	12.0	4.5	0.1
Clay	25.0†	6.6†	2.0‡
Limonite	5.6	1.8	0.6
Calcite	5.7	11.1	55.0
Dolomite			35.0
Other minerals	11.4	2.2	5.0
	100.0	100.0	100.0

* The total percentage of free silica.

† Probably sericite in part; in that case the feldspar figure becomes lower.

‡ Two per cent clay takes 0.79 of Al_2O_3. This requires that most of alkalies form non-aluminous hydrous silicates or that 0.81 Al_2O_3 as given by Clarke is too low.

It is thought that the densities without porosity are figures of some value for geodetic computations. The chief error in making the final estimates is in connection with the lack of accurate knowledge regarding the pore space of those sedimentary rocks not used

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[1] For data on the mean chemical and mineral composition of rocks see F. W. Clarke, "Data of Geochemistry," *Bull. 491, U.S. Geol. Surv.*, 1911, pp. 30, 31. For specific gravities of minerals see Pirsson, *Rocks and Rock Minerals*, 1908, p. 31; also Dana, *Mineralogy*. For a discussion of pore space see Fuller, "Total Amount of Free Water in the Earth's Crust," *Water Supply Paper No. 160, U.S. Geol. Surv.*, 1906, pp. 59–72.

as building stones, but this affects appreciably the density of only a superficial layer and chiefly of the youngest deposits.

The ratio of shale, sandstone, and limestone in the average sediment in percentage is, according to Mead,[1] shale 80, sandstone 11, limestone 9. The ratio of average porosities in percentage is, according to Fuller,[2] crystalline rocks 0.2, shales 4, sandstones 15, limestones 5. The figure given by Fuller for shale rests upon a single determination of 7.8 per cent by Delesse, and is averaged in by Fuller with slate. Eight per cent porosity will here be assumed as probably a better estimate. This gives the porosity of the average sedimentary rock as 8.5 per cent. The pore space may be taken, following Fuller's estimate, as half filled with water.

From these data the specific gravities are computed to be as follows:

TABLE VIII

Specific Gravities Computed from Mineral Compositions

Rock	No Pore Space Allowed	Pore Space Half Filled with Water
Average igneous rock..	2.80	2.80*
Shale...............	2.69	2.51
Sandstone...........	2.67	2.35
Limestone...........	2.76	2.64
Average sedimentary rock..............	2.70	2.50

*The same figure as used by Chamberlin and Salisbury, *Geology*, I (1904), 538; also by Pirsson, *Rocks and Rock Minerals;* also by G. H. Darwin as the density of the outer crust.

Where Cenozoic deposits occur in thickness, they are considerably compacted except at the surface, but still the mean specific gravity, owing to the abnormal pore space and deficiency in limestones, is doubtless less than 2.50; 2.45 may be taken. It is probable, on the other hand, that the Paleozoic rocks on the whole have somewhat less pore space than this average, especially as the porosity figure for sandstone rests mainly upon determinations for brownstone, a rather porous type; 2.55 may then be taken as the average for Mesozoic and Paleozoic formations. The pre-Cambrian

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[1] "Redistribution of the Elements in the Formation of Sedimentary Rocks," *Jour. Geol.*, XV (1907), 238–56.

[2] *Loc. cit.*

rocks contain both igneous and sedimentary formations, but the considerable iron ore and metamorphic nature would bring the specific gravity of the sediments somewhat above the average of 2.70 for non-porous sediments. Broad areas of pre-Cambrian probably range therefore between 2.75 and 3.00 in specific gravity. More limited areas, because of a predominance of granite and quartzite, may range as low as 2.70. About 2.67, however, would be a minimum.

As these are merely averages it is better in basing calculations upon them to assume a certain range in density for each figure and to obtain thus a knowledge of the influence of reasonable variations upon the results. The data may then be tabulated as follows:

TABLE IX

ESTIMATED MEAN SPECIFIC GRAVITIES OF GEOLOGIC FORMATIONS

Pre-Cambrian	2.75–2.80
Paleozoic and Mesozoic	2.50–2.60
Cenozoic	2.40–2.50

The range in these specific gravities shows the necessity of considering them in all refined calculations on the anomalies of gravity. In place, however, of using a mean density figure for all stations on formations of a certain geologic age, it would be of much more value to have measurements of the actual surface densities occurring in each area; also estimates by geologists, based on geologic structure and these surface measurements, of the densities extending to the base of the sedimentary rocks of each locality.

It seems probable from the mean density of 2.80 obtained for igneous rocks that the density of 2.67 used by geodesists for the mean density of the zone of compensation is too low. If any variation from the average composition takes place with depth within the limits of 76 miles, it is likely to be a variation toward more basic and heavier rocks. Assuming, however, an average uniformity of chemical composition, the opposing effects of temperature and pressure remain to be considered. Using the coefficient of expansion of the average igneous rock computed by W. H. Emmons,[1] 0.000,019.9 for 1° C., and a temperature gradient of

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[1] Chamberlin and Salisbury, *Geology*, I (1904), 547.

1° F. for 60 ft. in depth, gives an aggregate expansion of 3.6 per cent to the outer 76 miles. Using 6,500,000 as the modulus of cubic compressibility of the average rock in pound-inch units[1] gives a total compression of 3.7 per cent to the outer 76 miles due to pressure; that is, the volume effects of heat and pressure practically offset each other within the zone of isostatic compensation. Therefore 2.80 appears to be the lowest mean figure which should be taken. The use of 2.67 as a mean figure requires for isostatic equilibrium a density of but 2.60 extending to a depth of 76 miles under land 3 km. high, a figure lower than the specific gravity of granite.

INTERPRETATION OF ANOMALIES IN TERMS OF MASS AND DEPTH

Suppose that the zone of isostatic compensation is not of uniform density under any one station, but contains masses of variable density irregularly distributed. Let these masses be of considerable thickness and area as compared to the depth of the zone of compensation. Suppose that the topography is so adjusted to the aggregate density that the pressures are everywhere equal at the bottom of the zone of compensation. Abnormally light masses would then have to be balanced by abnormally heavy masses in the same column. There would still be deflections of the vertical and anomalies of gravity because gravitation varies inversely with the square of the distance, the upper and adjacent masses of abnormal density affecting the station more than those more distant ones of opposite abnormality lying vertically below the upper. The residuals from deflection and gravity measurements would under such an arrangement measure strains within the outer crust but not upon its bottom. The strains, if produced by abnormalities in the upper parts of the crust, would further be proportionately smaller and yet give rise to residuals of a certain magnitude than if produced by abnormalities in the lower parts of the crust. This aspect of the problem must be investigated before any final significance regarding the strength of the crust can be attached to the grouping of residuals discussed under the

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[1] F. D. Adams and E. G. Coker, *An Investigation into the Elastic Constants of Rocks, More Especially with Reference to Cubic Compressibility*, 1906, p. 67.

last part of Part II. It leads to a consideration of the relations between mass, distance, and anomaly.

Under the title of "Interpretation of Anomalies in Terms of Masses"[1] Hayford and Bowie show that the excesses and deficiencies of mass to a great distance have an effect upon the gravity anomalies and that therefore the guarded expression "net effective excess (or deficiency) of mass" is necessary for correctness. They give the following tabulation to show the influence of uncompensated masses in the crust in giving gravity anomalies when the gravity is computed on the assumption of isostasy:[2]

TABLE X

Each tabular value is the vertical attraction in dynes produced at a station by a mass equivalent to a stratum 100 ft. thick, of density 2.67, and of the horizontal extent indicated in the left-hand argument, if that mass is uniformly distributed from the level of the station down to the depth indicated in the top argument and from the station in all directions horizontally to the distance indicated in the left-hand argument.

Radius of Mass	Depth				
	1,000 Ft.	5,000 Ft.	10,000 Ft.	15,000 Ft.	113.7 Km.
1,280 m. (the outer radius of zone E)	0.0029	0.0018	0.0011	0.0008	0.0000
166.7 km. (the outer radius of zone O)	0.0037	0.0034	0.0034	0.0034	0.0024
1,190 km. (or 10°40′, the outer radius of zone 10)	0.0040	0.0037	0.0037	0.0037	0.0034

On p. 111 it is concluded by these authors that the best working hypothesis is to take

> each 0.0030 dyne of anomaly as due to an excess (or deficiency) of mass equivalent to a stratum 100 ft. thick. This working hypothesis is equivalent, as may be seen by inspection of the table just given, either to the assumption that the excess (or deficiency) of mass is uniformly distributed to a depth of 113.7 kilometers and extends to a distance of more than 166.7 kilometers and less than 1,190 kilometers from the station, or that it extends to a distance of 166.7 kilometers from the station and is distributed to an effective mean depth of more than 15,000 feet and less than 113.7 kilometers, or the working hypothesis may be considered to be a combination of these two assumptions.

The mean anomaly of 0.018 dyne, interpreted on this basis of 0.030 dyne being taken as equivalent to 100 ft. of mass, gives a

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[1] Hayford and Bowie, p. 108.

[2] *Ibid.*, 1912, p. 109.

mean departure from isostatic compensation amounting to 600 ft.; given more exactly by Bowie as 630 ft.

It is seen from the quoted statement that the authors accept, first, as one alternative a very widespread regional net excess (or deficiency) of mass uniformly distributed in depth; or, second, a somewhat broad regional distribution but confined to the outer part of the zone of compensation; or, third, some combination of the two assumptions.

The first assumption would throw a real strain upon the bottom of the zone of compensation and signifies regional compensation to limits very far beyond those stated elsewhere by the authors. It is therefore inconsistent from that standpoint, but gives a smaller vertical load and consequently a smaller vertical departure from the level giving isostatic equilibrium than would a more limited area. If, for example, it be assumed that the radius of the zone limiting regional compensation is 58.8 km., which is about the maximum limit for regional compensation which Hayford allows elsewhere; then it may be computed that for uniform distribution of the excess (or deficiency) of mass to a depth of 114 km., a mass equivalent to 100 ft. of density 2.67 corresponds to an anomaly of but 0.0013 dyne instead of 0.0030. This would, for a mean anomaly of 0.018, signify an average departure over the United States of 1,380 ft. from the level giving isostatic equilibrium, instead of 600 ft.

The second assumption, that the excess (or deficiency) is in the outer part of the crust, gives also a much higher anomaly for a unit mass than would an equally permissible assumption that the excesses or deficiencies occurred at various levels and on the average were at a depth of one-third or one-half of the zone of compensation. The relationship of anomalies to geologic formations, to be discussed later, shows certain variations in density in the outer crust, but the greater parts of the anomalies are not due to this cause. From the previous discussion on the limits of regional compensation it would seem that, on the assumption that the excesses or deficiencies of mass are on the whole uniformly distributed, 0.0024 would be an appropriate figure to use as the mean anomaly for unit thickness of mass. The highest anomalies, however, are probably better interpreted by 0.0030 as a divisor, since as a class they must be assumed as due to excesses or deficiencies of mass which are both near and large. This does not mean, however, that the larger masses are not assumed as scattered uniformly, according to the laws of chance, through the crust. It is seen, then, that Hayford and Bowie have favored those interpretations which gave a large anomaly per unit mass and have ascribed the total anomaly as on the average to be interpreted on this basis, obtaining thereby a smaller figure as the mean departure in feet from the level for perfect compensation. They have not discussed, furthermore, in the text the influence of deeper-seated variations of density, which might give considerable residuals, nor the possibility that departures from the mean density in opposite directions might balance each other so as to give equal pressures at the bottom of the zone of compensation. The latter case will not seem improbable to the geologist. The great batholiths of the Archean appear to make a universal floor in the crust. They range in composition from granites to gabbros and have come to rest at various levels. Light and heavy masses may well be irregularly distributed in the same vertical cylinder. If at the time of origin the whole were too heavy, a tendency would have arisen for the column to sink until equilibrium was attained. If the whole, on the contrary, were too light, the column would have tended to rise until a heavier base balanced the lighter mass above. Thus, if irregular distribution of density arose as the result of vertical igneous intrusion, the whole region would tend to seek that level where the irregularities would balance.

In order to gain quantitative ideas as to this possibility of partly explaining the anomalies, the writer has made calculations on the following assumptions. A station is situated upon the axis of a vertical cylinder extending from the station to a depth of 114 km. The radius is taken successively at 58.8, 166.7, and 1,190 km. Let such a cylinder be divided into five equal cylinders by horizontal planes. Let each of the five be equivalent in mass to a cylinder of the same radius but only 100 ft. in depth and of density 2.67; in other words, the unit mass as used by Hayford and Bowie. What will be the attraction in dynes per gram produced at the station by each cylinder respectively?[1] The results are as follows:

TABLE XI

Vertical Attraction in Dynes on One Gram at Station by Cylinder 22.8 Km. Thick, Density 0.00357, Equivalent in Mass to Thickness of 100 Ft. at Density 2.67

No. of Cylinder	Depth in Km. from Station to Top of Cylinder	Attraction for Radius of 58.8 Km.	Attraction for Radius of 166.7 Km.	Attraction for Radius of 1190 Km.
I	0.0	0.0031	0.0032	0.0036
II	22.8	0.0017	0.0028	0.0035
III	45.6	0.0010	0.0024	0.0035
IV	68.4	0.0007	0.0020	0.0035
V	91.2	0.0005	0.0017	0.0034

The results for radius 58.8 km. show that masses of this size situated near the bottom of the zone of compensation exert but a fraction of the influence given by equivalent masses near the surface. A balancing of light and heavy masses in a column of this radius would give isostasy at the base and yet produce notable anomalies. For radius 166.7 km. the importance of depth is much diminished. For radius 1,190 km. it practically disappears. This means that a wide regional variation in depth with plus and minus departures from the uniform density, the light and heavy layers balancing, would not produce anomalies provided, as stated, there was isostatic equilibrium at the base.

To give a somewhat extreme illustration; suppose that the upper cylinder, I, is 2 per cent lighter than the mean density of

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[1] The formula for making these computations was kindly worked out for me by Professor H. S. Uhler, checking it as given by B. O. Pierce, *Newtonian Potential Function*, p. 8. It is as follows:

$$F=2\pi\rho\gamma\left[\sqrt{a^2+c^2}-\sqrt{a^2+(c+h)^2}+h\right].$$

in which

F = force in dynes per gram.
ρ = density, in this case = 0.003,57.
γ = constant of gravitation = 0.000,000,066,58.
a = radius of cylinder.
c = distance on axis from station to top of cylinder.
h = depth of cylinder; in this case 22.8 km.

For radii of 58.8 and 166.7 km. no correction need be made for curvature of the earth's surface. For a = 1190 km. an empirical correction was obtained by comparing the results with Hayford's computations.

The writer overlooked until later the fact that Hayford and Bowie also give this formula with a different notation on p. 17 of their work.

2.67 and the lower cylinder, V, is 2 per cent heavier. Let these abnormalities be limited areally to the cylinder. This is a departure in density of 0.054, 15.1 times the density 0.00357. The anomalies will be as follows:

TABLE XII

ANOMALIES DUE TO IRREGULAR VERTICAL DISTRIBUTION OF DENSITY

No. of Cylinder from Table	Density 2 Per Cent from Mean	Anomalies		
		Radius 58.8 Km.	Radius 166.7 Km.	Radius 1190 Km.
I........................	2.616	−0.047	−0.048	−0.054
V........................	2.724	+0.008	+0.026	+0.051
Resultant anomaly........		−0.039	−0.022	−0.003

It is seen from this tabulation that, first, irregular superposed but balanced positive and negative distributions of density up to distances as large as the radii of the areas of grouped residuals could produce at least a considerable part of the anomalies; or, second, actual departures from isostatic equilibrium with the resultant strain on the crust could produce them; or, third, a combination of the two. In the second case, as Hayford and Bowie show,[1] the anomalies could result from a layer a few miles thick adjacent to the station and of very abnormal density; or from deep and regional masses of great volume, but departing only slightly from the mean density. The choice between these several alternatives, or the degree to which they co-operate, must be investigated under the following topics.

RELATIONS OF ANOMALIES TO EXPOSED GEOLOGIC FORMATIONS

The latest data given by Bowie on this subject are shown in Table XIII (p. 222):[2]

These figures of course are not to be regarded as of high precision, as may be seen by comparing the earlier and later results.

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[1] *Op. cit.*, Pp. 108–11.

[2] "Some Relations between Gravity Anomalies and the Geologic Formations in the United States," *Am. Jour. Sci.* (4), XXXIII (1912), 237–40.

Hayford and Bowie in their successive publications give the following for the pre-Cambrian and Cenozoic stations, the two groups to which the attention will be confined. A few stations of high anomaly must have considerable influence on the result, as most of the stations are used in common in all of the estimates.

TABLE XIII

Geologic Formation	Number of Stations	Mean with Regard to Sign	Mean without Regard to Sign
Pre-Cambrian	10	+0.016	0.026
Paleozoic	31	−0.003	0.019
Mesozoic	20	+0.002	0.015
Cenozoic	29	−0.008	0.021
Intrusive and Effusive	11	−0.007	0.015
Unclassified	22	+0.011	0.020
All stations	123	0.000	0.019

TABLE XIV

	Geologic Formation	Number of Stations	Mean with Regard to Sign	Mean without Regard to Sign
Hayford and Bowie, U.S.C. and G.S.	Pre-Cambrian	7	+0.019	0.026
	Cenozoic	20	−0.011	0.021
Bowie, U.S.C. and G.S.	Pre-Cambrian	9	+0.024	0.024
	Cenozoic	33*	−0.007	0.021
Bowie, *Am. Jour. Sci.*	Pre-Cambrian	10	+0.016	0.026
	Cenozoic	29	−0.008	0.021

*Fifteen stations have plus anomalies, 17 have minus anomalies.

Bowie's figures in the *American Journal of Science* will be used in the following discussion.

Bowie favors the explanation that these relations of anomalies to geologic formations are due to slight changes of density extending more or less through the zone of compensation and leading to departures from perfect isostasy. The writer, however, is led to favor the view that about one-half of the contrasted anomaly for these two groups is due to a lesser density within the outer mile of crust beneath the Cenozoic stations, as contrasted to the outer mile of crust beneath the pre-Cambrian stations. The remainder of the anomaly it is thought is explained by the ease of erosion of Cenozoic formations, the resistance to erosion of the pre-Cambrian rocks. The latter consequently tend to stand above the regional levels. They therefore possess surficial excess both of density and volume.

The average thickness of sedimentary rocks if spread uniformly over the globe is thought to be between 2,000 and 2,500 ft.[1] Over the pre-Cambrian areas it must average much less; over the areas of later formations much more. Under the Cenozoic stations assume:

1,000 ft. of sediments at density	2.40 to 2.50
4,000 ft. of sediments at density	2.50 to 2.60
Giving a total of 5,000 ft. at density	2.48 to 2.58
With a deficiency of density of	0.19 to 0.09

Under the pre-Cambrian stations assume:

5,000 ft. of crystalline rock at density	2.75 to 2.80
An excess of density of	0.08 to 0.13

This does not involve the improbable assumption that below the outer 5,000 feet of crystalline rock of density 2.75 to 2.80 the density suddenly decreases to 2.67 and then remains constant throughout the zone of compensation. The vertical density gradient, *if uniform for all points*, has but little effect, it being the *horizontal* variations of density which enter into the problem of isostasy. To maintain conformity with Hayford's figures, therefore, the density 2.67 will be frequently assumed as the mean density of the lithosphere, although the previous discussion shows that it cannot be assumed as the density of the outer mile of crystalline rocks when comparing these to the mile of sedimentary rocks taken as the mean depth underlying the Cenozoic stations.

In comparison with this thickness of 5,000 ft. the average area of formations is very great. A plane sheet of rock 100 ft. thick and of density 2.67, if of indefinite extent, will produce an anomaly of 0.0034 dyne upon a point outside of it, irrespective of the distance to that point. This theory may be applied without gross error to the relation of surface geologic formations to anomalies. If this unit mass be expanded from 100 to 5,000 ft. thickness, the

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[1] F. W. Clark, "Data of Geochemistry," *Bull. 491, U.S. Geol. Surv.*, 1911, p. 30.

density will be decreased to 0.053 that of water. The data may then be tabulated as follows:

TABLE XV

Computed Anomalies Due to Densities of Surface Formations

	Deficiencies or Excesses of Density	Anomalies in Dynes per Gram Due to Thickness of 5,000 Ft.
Unit mass	0.053	0.0034
Cenozoic	−0.19	−0.012
	−0.09	−0.006
Pre-Cambrian	+0.08	+0.005
	+0.13	+0.008

These mean anomalies of the pre-Cambrian due to the greater density of the outer 5,000 ft. of rock, when compared to the Cenozoic anomalies, are, as shown by this tabulation, at a minimum 0.011 greater, at a maximum 0.020 greater, at a mean 0.0155 greater. The difference of the means shown by geodetic measurement was 0.024. The specific gravities seem to have been taken as far apart in limits as is allowable and the assumed mean thickness of sediments as 5,000 ft. beneath the Cenozoic stations is a generous figure; the mean thickness is more likely to be less, rather than greater. The means for the geodetic anomalies as related to geologic formations are perhaps subject to about the same degree of error as the determinations of the anomalies from the specific gravities and thickness. The result, although not of a high order of accuracy, shows that although the range in specific gravities accounts for a considerable part, perhaps one-half or two-thirds, of the relation of anomalies to geologic formations, it can hardly account for the whole.

To find the cause for the remaining portion of the anomaly, two hypotheses may be considered: first, that it is due to a slight regional excess of density extending to a depth of 114 km., the hypothesis favored by Bowie; or, second, that the Archean areas on the average stand higher than the Cenozoic by virtue of resistance to erosion.

The geologic evidence as it is at present understood is against the first hypothesis and in favor of the second. This statement is based on the view that Archean and Proterozoic areas have tended to be rising elements of the continent. Erosion instead of sedimentation has been dominant in later geologic time, which is the reason why these rocks are now exposed as surface formations. If there is any deep-seated departure of density from the mean this tendency to rise should correspond, however, to a deficiency of density persisting through the geologic ages, extending through much of the zone of compensation and offsetting the more than average surface density. Such a regional deficiency is opposite in character to the excess which is postulated by Bowie as an explanation of the positive anomalies.

Assume then as the next step in the argument that the density of the zone of compensation beneath the pre-Cambrian areas to a depth of 114 km. is the same as under Cenozoic areas except for the outer 5,000 ft., both having a mean density of 2.75 to 2.80, but taken here as 2.67. The outstanding anomaly in that case is due to a longer mean column for the pre-Cambrian areas and consequently greater mass above the level of complete compensation. If the mean radius of these longer pre-Cambrian and shorter Cenozoic columns is as great as 166.7 km., then the unit excess or deficiency of mass of 100 ft. at density 2.67 when spread over these columns will correspond to an anomaly of 0.0024. If the mean effective areas of the pre-Cambrian and Cenozoic formations affecting individual stations are less, the unit mass will give a smaller unit anomaly. If the mean effective areas are greater, the unit anomaly will not, however, rise above 0.0035. Assume then in conclusion a mean radius of 166.7 km., an anomaly of 0.0024 dyne as resulting from 100 ft. of added mass of mean density, and the outstanding anomaly not accounted for by the surficial densities but due to an outstanding difference in volume as between 0.008 and 0.012. These figures correspond to a differential mean elevation of 330 to 500 feet of the pre-Cambrian above the Cenozoic, due to erosion. To physiographers such a conclusion will seem quite in accord with the geologic evidence testifying to the resistance of pre-Cambrian formations.

The character of the Archean and Proterozoic anomalies enters into the problem of crustal rigidity in the following way. If there were local and close compensation, then as erosion removed the softer surrounding rocks there should be isostatic upwarping of such areas of denudation and relative downwarping of the uneroded crystalline areas. Such warping of the Mohawk, St. Lawrence, and Champlain valleys with respect to the Adirondacks has not been noted, though the problem from the standpoint of field evidence has not been fully studied. The physiographic evidence that residual mountain masses known as monadnocks or unakas have not been shown, however, to be marked by local downwarping and, on the contrary, certainly stand in relief due to circumdenudation, combines with the geodetic evidence of the average excess of gravity for the resistant areas of pre-Cambrian formations, to suggest effective rigidity against the stresses produced by erosion. The evidence, however, as developed thus far from the geodetic standpoint shows that there are more important factors than that of the surface geologic formation, since the larger anomalies are much greater than these figures which have been discussed and hold but little relation to either relief or surface geology. In fact Hayford and Bowie do not find any discoverable relation between the anomalies in general and the topography.

It is thought by the writer, however, that if stations were located especially to test the intensity of gravity over various broad plateaus remaining by circumdenudation and the intensity compared with that over adjacent broad areas of lower level, the mean differential anomalies due to the surface excess of mass in the plateau over the lowlands would rise to a larger figure than the 0.008 to 0.012 dyne which has remained to be explained in the present discussion. These figures are low because certain pre-Cambrian areas, like those in the vicinity of Baltimore and Washington, have been lowered by prolonged denudation and do not stand markedly above the level of younger formations. Furthermore, the tendency of broad pre-Cambrian areas to stand above sea-level is very probably of an isostatic nature. This implies under such areas a slightly lower mean density to the whole zone of compensation which would diminish the anomaly due to the surface elevation. In individual areas of 100 to 200 km. radius, however, such a relation of positive anomaly to pre-Cambrian formations and plateaus of circumdenudation may not be found, since it is clear that the anomaly from this cause may be much more than neutralized by other causes. A large number of stations covering broad areas would therefore be required adequately to eliminate these other influences from the means.

LARGE OUTSTANDING ANOMALIES NOT RELATED TO GEOLOGY OR TOPOGRAPHY

In Fig. 5, of Part II, the anomalies are shown for all stations in the United States. It is seen that they possess an areal gradation in magnitude which permits the drawing of anomaly contours. The excessive anomalies of both signs cover oval areas in various parts of the country and show a common disregard of physiographic provinces, structural provinces, and geologic formations. Looking at Fig. 5, one cannot see in either the distribution of anomalies or trends of contours a reflection of Atlantic Coastal Plain, or Appalachian Mountains, or Mississippi Valley.

Typical examples of the lack of necessary relation of the large anomalies to geologic formations are seen in the following tabulation:

TABLE XVI

No.	Station	Geologic Formation	Anomaly
123	Albany, N.Y.	Cambro-Ordovician	−0.043
74	St. Paul, Minn.	Cambro-Ordovician	+0.059
96	Mena, Ark.	Pennsylvanian	−0.052
101	Helenwood, Tenn.	Pennsylvanian	+0.040
53, 56	Seattle, Wash.	Quaternary	−0.093
112	Olympia, Wash.	Quaternary	+0.033

The lack of relation of these anomalies to topography is equally striking. It is clear then that internal conditions in the crust, not expressed on its surface, must be the principal cause of these larger departures from isostasy. The large anomalies show their relationship to internal causes most clearly, but the smaller anomalies may also by analogy be ascribed in part to such hidden causes. The results, however, of surface activities—circumdenudation, sedimentation, tangential pressure, or extravasation—must show in large ratio over regions where the internal variations from uniform density are small; but over the greater part of the United States the distribution of anomalies appears to depend more upon the internal than upon the external departures from regional uniformity and complete isostasy. The internal heterogeneities of mass are therefore presumably greater than the shiftings of mass due to external activities.

CRITERIA FOR SEPARATING VERTICALLY IRREGULAR COMPENSATION FROM REGIONALLY INCOMPLETE COMPENSATION

Suppose the topography smoothed out to a mean level over areas as large as the limits for regional isostasy. The deflection residuals and gravity anomalies would then be due to one or more of three internal causes; first, vertically irregular or laterally displaced compensation; second, regionally incomplete compensation above the bottom of the zone of compensation because of the effective rigidity of the crust above that level; third, regionally incomplete compensation above a certain level because the zone of compensation may be deeper in places, transferring stresses into a deeper rigid earth. The existence of a general approach toward compensation and away from absolute rigidity suggests that the last is not so important as the first two causes. Under this section then will be considered these two causes, their effects upon the deflections of the vertical and the intensity of gravity, with the purpose of drawing criteria by which the action of the two causes may be recognized and separated. To do this it will be necessary to discuss here to some extent the theory of the attraction of underground masses upon stations at the surface of the earth. It has been shown that balanced irregularities in the vertical distribution of densities through the zone of compensation could give pronounced anomalies without disturbing the isostatic equilibrium at the bottom of the zone, since the total weight of the column could still be normal. To show the effect of such balanced irregularities upon a point outside of the column:

Take a vertical line and a horizontal line which intersect. The masses whose effects are to be investigated will be distributed on the vertical line. The effects are to be determined for points on the horizontal line. To express the trigonometric relations between any point on the vertical and any point on the horizontal line, let a point on the vertical line at depth D be defined as at a vertical angle θ below a point on the horizontal line; the latter to be defined as at distance R from the intersection.

Let the gravitative attraction of unit masses along this vertical line upon any other point either in or outside of this line be represented by F. The horizontal component will be the force producing deflection of the vertical and may be represented by Fh. The vertical component will give the acceleration of gravity due to the unit mass and may be represented by Fv. Taking the unit mass such that the constants will have a value of unity, the following relations are deduced:

Attraction of unit mass at depth D, upon a point at R:

$$Fh = \frac{\cos^3 \theta}{R^2}$$

$$Fv = \frac{\tan \theta \cos^3 \theta}{R^2}$$

For the intersection point,

$$R \text{ and } \theta = O \text{ and}$$

$$Fh = 0$$

$$Fv = \frac{1}{D^2}$$

Let the depth of the zone of compensation, 114 km., be taken as unit distance, 1.00, and for purposes of discussion let points I, II, III, IV be located on a vertical line at depth of 0.25, 0.50, 0.75, and 1.00 as shown on Fig. 6. Solving the equations for these points and for various values of R gives the following tabulation:

TABLE XVII

Table of Relative Attractions

(Not in dynes per gram)

Attraction by Unit Masses at			Attraction at Stations for Various Values of R									
No.	Depth	Angle below $R=1.00$	$R=0$		$R=0.25$		$R=0.50$		$R=1.00$		$R=2.00$	
			Fh	Fv	Fh	Fv	Fh	Fv	Fh	Fv	Fh	Fv
0..........	0	0	0	0	16.00	0	4.00	0	1.00	0	0.25	0
I..........	0.25	14°02′	0	16.00	5.60	5.60	2.88	1.44	0.91	0.23	0.24	0.03
II.........	0.50	26°34′	0	4.00	1.44	2.88	1.40	1.40	0.72	0.36	0.23	0.06
III........	0.75	36°52′	0	1.78	0.51	1.52	0.68	1.04	0.51	0.38	0.21	0.08
IV........	1.00	45°00′	0	1.00	0.21	0.91	0.36	0.72	0.35	0.35	0.18	0.09

Fig. 6 shows the curves for $R=1$. For any other value of R the curves would be the same in form, but the scales of ordinates and abscissas would be changed. These curves may be used therefore in a general way.

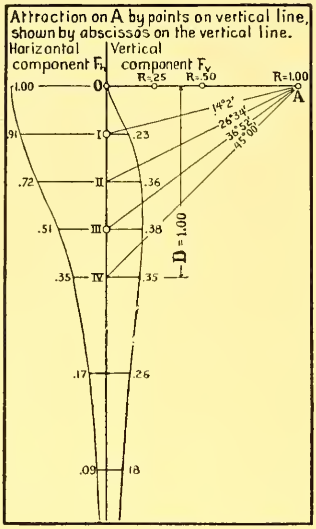

FIG. 6

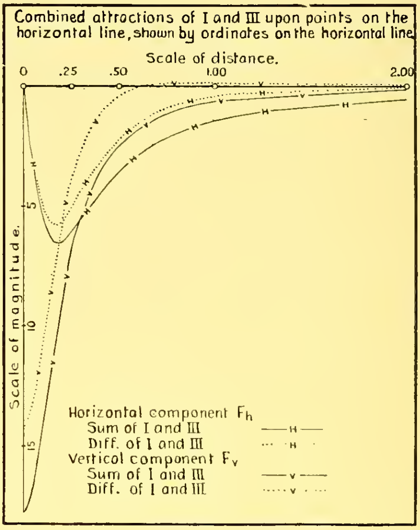

FIG. 7

FIG. 6.—Curves showing relative attraction of all points on the vertical line upon a point at distance $R=1$.

FIG. 7.—Combined attractions upon all points on the surface by unit masses of like and unlike signs at I and III of Fig. 6.

The table shows that if unit masses at II and III have the same sign the *horizontal component*, *Fh*, for the *sum* of their attractions at $0.25R$ will be 1.95, at R it will be 1.23, which is 63 per cent of the value at $0.25R$. If the unit masses have unlike signs the *horizontal component of their difference* at $0.25R$ will be 0.93, at R it will be 0.21, which is but 23 per cent of the value at $0.25R$. The *vertical component*, *Fv*, due to the *sum* of the masses at $0.25R$ is 4.40; at R is 0.74. The *vertical component* due to the *difference* at $0.25R$ is 1.35; at R is 0.02 and of opposite sign. It is noticed that the gravity anomaly diminishes rapidly with increasing horizontal distance from these two masses and passes through zero. The deflection of the vertical first increases sharply and then diminishes, but less rapidly than the gravity anomaly. It is important to notice that in both cases the total influence due to masses of *opposite* sign diminishes much more rapidly, and where their distance apart is 0.25 their influence is small at distance *R* and negligible at 2*R*. This gives a means of determining whether, in the crust, anomalies and deflections are due to regional departures from isostasy or to balanced irregularities in density without absence of isostasy at the base of the zone.

To give a further illustration of balanced departures in density spread over a greater vertical distance, and representing in that way perhaps a more average case, assume that an excess or deficiency equivalent to a unit mass is at depth 0.25 and another at depth 0.75. The following tabulation shows their influence upon the surface of the earth at increasing horizontal distances.

TABLE XVIII

Attraction by Unit Masses at I and III upon Points on the Horizontal Line

Component	Position and Sign of Mass	Horizontal Distance on Surface of Earth from Vertical Line					
		0	0.25	0.50	1.00	2.00	4.00
Fh.....	− I −III	0	−6.11	−3.56	−1.42	−0.55	−0.121
	− I +III	0	−5.09	−2.20	−0.40	−0.03	−0.003
Fv.....	− I −III	−17.78	−7.12	−2.48	−0.61	−0.11	−0.015
	− I +III	−14.22	−4.08	−0.40	+0.15	+0.05	+0.007

The data in this table are represented by the curves of Fig. 7. It shows that for this arrangement of masses the influence on the surface falls off rapidly at a horizontal distance between 0.25 and 0.75, which are also the vertical depths to I and III. When the masses are of opposite sign the anomaly passes through zero at a horizontal distance of about 0.6, and the deflection force for opposite sign decreases to half the value of the sum at about 0.75. The ratio between the effects of like and unlike masses becomes more marked the greater the distance of the point, although the actual magnitudes of the forces decrease.

Now assume the unit masses at I and III to be parts of masses of like density extending to the left of o to a distance N. Consider the aggregate effect upon a given point, as that at 0.50, or in general at point R. The effect of each unit at distance x to the left of o upon the point at 0.50 will be measured by an ordinate at a distance x to the right of 0.50. This will give the same aggregate result as concentrating the masses at o and summing up the area of the curve to the right of the point at 0.50 to a distance of $0.50+N$. Stated in general terms, masses at depths I and III extending linearly to distance N to the left of o will have an aggregate effect upon a point R equal to the area of the curve between R and $R+N$.

As to the aggregate effect on Fv, the gravity anomaly: If the two sheets are of negative density, it is seen that the result will be an increased negative anomaly over the effect of the separate unit masses. If the lower mass is, however, of positive density, the result for ordinarily limited sheets will be a change between 0 and 0.50 from a large negative to a small positive anomaly. This may be compared with the effects of other possible distributions of mass upon the gravity anomaly.

If the anomaly due to the *adjacent* departure from uniform distribution is of the mean value or greater, the *more distant* abnormal masses will have but relatively small influence. This is because the higher anomalies, with the exception of Seattle, are but two or three times the mean. Further, in a zone of large radius there are a greater number of positive and negative departures. Their aggregate effect, according to the laws of chance distribution would increase but slowly and this effect is diminished by distance according to the formula $\dfrac{Fv=\tan\theta\cos^3\theta}{R^2}$.

A reversal from a large anomaly of one sign to a *large* anomaly of opposite sign, rather than a *small* one of opposite sign, marks then in general a passage from an area of excess or deficiency of mass to the opposite. A gradual change in the anomaly is the reflection of a change in the subsurface abnormalities nearly as gradual. If the areal variations show that the passages of the anomaly through zero are not frequent, they go to show that limited notable irregularities of density of opposite sign in the same column are rare. Furthermore, it has been shown under the topic "The Variable Rate of Compensation upon Gravity Anomalies" that a variable distribution of balanced densities has more effect if in areas of between 100 and 200 km. radius and has but little effect on anomalies if the balanced densities extend over much larger areas.

As to the aggregate effects produced upon *Fh*, giving deflection residuals, by these sheets I and III: If the sheets have like sign the deflection force, as shown in Fig. 7, will die out somewhat gradually and extend to considerable distances. If they have unlike sign the deflection force will fall off sharply between 0.25 and 1.00. If, however, the abnormalities of density should disappear gradually, that is, if the sheets did not terminate sharply at 0, this rate of falling off would be slower. Reversals of sign of the *deflection residuals* would require areal, not vertical, irregularities of mass. They could not take place as an effect of distance from a single mass or of two masses of unlike sign and vertically over each other. Where sharp reversals of sign take place in the deflection residuals the presence of areally contiguous areas of unlike departures in mass is shown. A mere difference in magnitude of excess of mass but of the same sign may, however, produce changes in the sign of the deflection residuals. In the irregular areal distribution of abnormal masses not balanced by being over each other, the deflection areas of like sign would thus tend to be smaller than the anomaly areas of like sign. A gradual fading-out of the deflection residuals would be the mark of gradual fading-out of the abnormal mass or the increasing influence of distant masses.

Various special combinations of three or more masses could at any one point simulate the relations indicated, but such special relations would not be of common occurrence and could not give a generality of relation of this sort.

There have thus been drawn up a set of criteria by which balanced irregularities within the zone of compensation may be distinguished from regional departures from isostasy. It remains to apply those to the areal distribution of gravity anomalies and deflection residuals as given by Hayford and Bowie. It must be recognized, however, that the stations, although numerous as compared to previous measurements, are yet very scattered for the precise application of these tests and can at best give but qualitative results. It is thought, nevertheless, that the general nature of the answer is determinative.

GRAVITY ANOMALIES CAUSED LARGELY BY REGIONAL DEPARTURES FROM ISOSTASY

The first question is: To what degree do the areas of excess (or deficiency) of mass as indicated by gravity anomalies coincide with areas of excess (or deficiency) as shown by the deflection residuals? In Fig. 5[1] there are indicated a number of ovals shown in dot-and-dash outline and marked + or −. These are the definitely bounded areas of excess or deficiency of mass indicated by the deflection residuals. The entire surface of the crust must be constituted of such areas, but only a few are surrounded by sufficient observations to permit a boundary to be drawn at present. Even this boundary must not be regarded as sharply definite. Beside these ovals there are shown in illustrations 5 and 6, Hayford, 1909, areas of residuals characterized by like sign, referred to in the present paper as "areas of grouped residuals." They are not definitely bounded on all sides and are not shown in Fig. 5 of this article. The areas of grouped residuals show the intercepts across areas of like sign, but at least two intercepts at an angle to each other are necessary to define well the limits of the area of which they are a part. As the deflection stations are situated largely in lines or zones across the country and not surrounding the areas of like sign, it is seen why the boundaries of relatively few areas are well determined. In so far, however, as the relations of the areas of positive and negative anomaly to positive and negative deflections of the vertical are apparent, Hayford and Bowie state: "The gravity anomalies corroborate the evidence given by the deflections. In no important case are the anomalies and deflections contradictory."[2]

It is seen by inspection of the illustrations by Hayford, and also by the discussion in Part II of this article, that the areas of

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[1] P. 153, Part II.

[2] Hayford and Bowie, 1912, p. 112.

like sign of deflection residuals are more sharply bounded and smaller in size than the areas of like sign of gravity anomalies. The latter occur commonly in areas so broad that a vertically balanced irregularity in the distribution of density would have but little effect. Yet the large gravity anomalies occur in the midst of such large areas, as shown on Fig. 5. There are, furthermore, few sharp reversals of sign of the gravity anomalies save those at different elevations in mountainous regions and these are explained by the presence of regional compensation. There are, on the contrary, many sharp reversals of the deflection residuals.

It is to be concluded, therefore, that, although some degree of balancing of irregularities in the same column no doubt exists, this is not a common or controlling explanation of the anomalies and residuals. They are overshadowed by a distribution which points, on the contrary, to regional departures from isostasy by regional excesses or defects in density.

In the location of stations, the deflection observations are arranged at relatively close intervals and in linear zones, owing to the necessity of triangulation. They give the most information as to the size of areas of relative excess and defect. But two areas of relative excess and defect may both be in absolute excess or absolute defect. The gravity stations are more widely scattered. The local variations are in consequence poorly defined, but the limits of absolute excess and defect of mass are determined with more accuracy. They appear to show that areas as large as 1,000 by 2,000 km., 620 by 1,240 miles, may depart in one direction from isostasy, but only to a moderate amount. It is seen from Fig. 5 that between Florida and a line drawn from Lake Superior to the Rio Grande the broad areas of less than mean anomaly are negative. From this line a great positive area extends to the northwest. The quarter of the United States bordering the Pacific Ocean is, however, another great region of negative anomalies. Upon these broad regions of mean anomaly or less are superposed smaller and better-defined areas of more than mean anomaly, negative and positive areas occurring in the same broad region. These smaller areas are inclosed by the 0.020 anomaly contour. They commonly range from 300 to 400 km. across, 200 to 250 miles, but the maxima which reach above 0.040 are much smaller. The limits of regional isostasy appear then to vary with the amount of the load. Well-defined areas 200 to 250 miles in breadth may stand vertically 800 to 1,600 feet on the average from the level, giving isostatic equilibrium, and their central portions reach still higher values. They represent the limits of regional isostasy discussed in an earlier part. But these are superposed on broader areas which may extend for a thousand miles or more and lie as much as 400 to 800 feet either above or below the level for equilibrium. Stresses given by loads of this order are then not restricted in area to the limits set for higher values.

The size of the areas of intenser stress reveal the capacity to which the earth can carry mountain ranges uncompensated by isostasy. The size of the areas of weaker stress shows the capacity of a considerable portion of a continent to lie quiescent while the surface agencies carry forward their leveling work. This is the present state of this particular continent after a geologic period of world-wide notable vertical movement and adjustment. It is not likely, therefore, that these loads measure the maximum stress-carrying capacity of the earth. They may be more in the nature of residual stresses which the earth can hold through periods of discharge of stress. East of the Cordillera there has been but little local differential movement and these areas have lain in crustal quiet for long geologic ages, being subject only to broad and uniform crustal warping of moderate amount. It is to be presumed, therefore, that the strains which exist in such regions by virtue of the regional departures from isostasy are of ancient date and well within the limits of crustal strength.

It would seem probable for such conditions, from the standpoint of mechanics, that the zone of compensation is not sharply limited, with its implication of marked lowering of rigidity at its base; nor the distribution of compensation uniform to the base. It seems more probable that the abnormalities of density and the resultant strains should fade out through a considerable depth more after the manner suggested by Chamberlin.

[*To be continued*]

ON THE NAMES OF AMERICAN FUSULINAS[1]

GEORGE H. GIRTY
U.S. Geological Survey, Washington, D.C.

Though material both good and abundant is not lacking, our American Fusulinas have never been carefully studied by any American investigator and it has remained for an alien to give us a comprehensive treatment of them. This is done in Schellwien's monograph of the Fusulinidae which since his untimely death has been carried on by other hands, the North American portion by Hans von Staff[2] having recently been published. Of the scientific part of this paper it will suffice to say that it appears to represent much research, yet one cannot but fear that the lack of judgment shown in the proceedings of nomenclature has extended to the scientific portion also.[3] It is to certain points of nomenclature that attention is here directed.

In order not to shock the sensitive reader too violently I will begin with a minor point. Our common Pennsylvanian species of Fusulina was described by Say as *Miliolites secalicus*, the generic reference being later changed to Fusulina. In the monograph by von Staff this is arbitrarily shortened to *Fusulina secalis.* Say's word *seçalicus* was clearly derived from the Latin "*secale, is*," a kind of grain, and while a more appropriate termination might have been chosen in forming the adjective from the noun, *secalicus* is a gem of pure latinity compared with many words in the shady lexicon of paleontology. Von Staff's term *secalis* can be nothing

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[1] Published by permission of the Director of the U.S. Geological Survey.

[2] *Paleontographica*, Band 59, 4te Lieferung, 1912, pp. 157 ff.

[3] One rarely meets nowadays with a work whose presentation is as poor as this. The text is without plate references and the plates without page references. The distribution of the species is given only incidentally, and apparently is not given completely or in detail. The magnification of the figures is not stated either on the plates themselves or on the plate descriptions. I think it is given somewhere in the text but on my last reference to the work, I did not have time to read it through completely, and so am unable to say definitely that the fact is or is not stated.

but the genitive case of the same noun, *secale*, and is even less appropriate than the adjective, besides which there is very little precedent, in paleontologic literature at all events, for making the species name a common noun in the genitive, although proper nouns in the genitive are not rare. It seems clear that the only acceptable form of this name is *secalica*.

The second point which I propose to raise concerns the status of *Fusulina secalica* Say, *Fusulina centralis* Say, and *Fusulina elongata* Shumard of which the first two are retained as valid species in von Staff's monograph, and the last cited as *Fusulina extensa* var. *californica*, *F. extensa* being a manuscript name of Schellwien's and *californica* a new varietal designation. To be more explicit, Shumard's original description of *Fusulina elongata* is listed as a doubtful synonym and my later citation, in 1908, as an undoubted synonym of the manuscript species and new variety. Von Staff points out the indubitable fact that Shumard's description is very meager, so that the only important feature of *F. elongata* given is the great length, in which respect the later specimens described and figured by me are distinctly, though perhaps not greatly, inferior to Shumard's measurement. For this reason Shumard's work is cited with doubt and mine without doubt in the synonymy. Von Staff's treatment of these three species is inconsistent, for if the description of *F. elongata* is meager it is less meager than that of *F. centralis*, and if the description of *F. elongata* assigns a greater length than has actually been found in later collections, that of *F. secalica* assigns a feature which is quite alien to the whole genus Fusulina, a solid axis.

In fact, all three species are too poorly described to be determinable, and since the typical collections are now lost, it is necessary to redefine them in the light of new studies based on other material. The method employed in the case of *F. secalica*[1] and *F. elongata*[2] was to base the later studies on material from about the same locality and horizon as the original, and in this the possibilities of satisfactory results depend largely upon whether one or several species are there present. If more than one are present

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[1] *Am. Jour. Sci.* XVII (1904), 234.

[2] *U.S. Geological Survey, Professional Paper 58*, 1908, p. 62.

the statements of the author are liable to afford but inadequate means for determining which was the authentic species.

Very large, very elongated Fusulinas are found in inconceivable multitudes in the Guadalupe Mountains. It is possible that specimens occur which are one-fourth larger than the largest seen by me, but it does not follow that they necessarily belong to a different species. Even if there is a larger form which is a distinct species, it is, humanly speaking, impossible that Shumard could have obtained specimens from this region without much the greater portion of them belonging to the smaller type. It is also, humanly speaking, absolutely certain that even if he had any of the larger shells at all, the smaller ones were included along with them as *F. elongata*. By implication I restricted the name *F. elongata* to the smaller form, if, indeed, there is any specific difference. By implication von Staff would restrict *F. elongata* to the larger form whose existence is hypothetical. Which restriction has priority, if either is valid at all, is a matter of record. Which is the more conservative and reasonable needs no argument. I have really no doubt that the form which I figured in 1908 is the true *F. elongata* of Shumard, while the status of *F. secalica* is much less certain and *F. centralis* has almost no standing at all. Consequently, *F. elongata* is the proper name for the species; the "new variety" *californica* is a straight synonym; and the European or Asiatic form for which Schellwien intended to use the name *extensa* will be a new variety or species as is subsequently determined.

Furthermore, von Staff has "emended"[1] *F. secalica* so as to make it include a different species from that identified by me and also probably a different species from that originally described by Say. As to the first statement there can be little doubt, since von Staff's *F. secalica* is a much more inflated form with much more strongly folded septal walls, and since von Staff himself identifies my *Triticites secalicus* with his *F. centralis* Say.[2] (Nevertheless, in 1912 he placed my citation in the synonymy of *F. secalica*.)

My *Fusulina* (*Triticites*) *secalica* agrees very closely with Say's description, so that von Staff's *F. secalica* differs from Say's *Fusulina* (*Miliolites*) *secalica* in the same particulars in which it differs from

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[1] *Neues Jahrbuch*, Beilageband XXVII (1909), 494 ff.

[2] *Op. cit.*, 1909, p. 508, description of Fig. 9, Pl. 8.

my *F. secalica*, namely, it is more inflated and has the septal walls more strongly folded. In evidence of this statement Say gives the length of his typical *F. secalica* as 0.3 inch and the breadth as $\frac{1}{12}$ inch, so that the ratio is 3.6:1, whereas von Staff gives the ratio in his form as 2.5:1 or 2:1, with a ratio of 3.2:1 and 1.6:1 in extreme forms only (*op. cit.*, p. 496). As to the folding of the septal walls, Say describes the shell as composed of tubes or siphons placed parallel to one another, a phraseology indicating, I should think, chambers uninterrupted by foldings of the inclosing walls. However, Say probably did not study the form by means of sections, and may have based his statement partly on the appearance of the external suture which is always straight, no matter how much the septal walls are folded within the shell.

Dr. J. W. Beede[1] was the first one to revive Say's *F. secalica* and give figures of it. He figures numerous specimens in side view and also one in thin section (axial). He does not, however, state whether the figures are enlargements, nor does he give the localities from which the originals were obtained. The figure representing the thin section is clearly an enlargement, and I suspect that some of the others are also. The largest has an axial length of 18 mm., much greater than that of any Fusulina which I have seen from Kansas. The proportions vary considerably in these figures, but with few exceptions they range between 3.6:1 and 3.2:1. This then is a more slender shell than von Staff's *F. secalica*, and if the figures are of natural size, a larger. It has much the same proportions as my *F. secalica* and as Say's original *F. secalica*, but it may be much larger.

The figure showing a thin section is considerably less slender than the others, and has more the shape of von Staff's *F. secalica*. Its proportions are almost exactly as 2:1. From this fact and from the bluntness of the ends (the other figures are terminally somewhat attenuated) I infer that this section does not exactly follow the axis but is somewhat oblique to it, though passing through the initial cell. The septal walls are much simpler than in von Staff's *F. secalica* (cf. Fig. 3, Pl. 15, of his 1912 publication), but, on the other hand, they are represented as porous, a feature apparently characteristic of the latter.

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[1] *University Geological Survey of Kansas*, Report, Vol. VI (1900), p. 10.

It is doubtful whether Dr. Beede's *F. secalica* is the same as Say's *F. secalica;* doubtful also whether it is the same as von Staff's, since it is much more slender, possibly larger, and with much less strongly plicated walls, at least as represented in the figure.

My *Triticites* or *Fusulina secalica* came from about the same locality and horizon as the original and agrees with the original description in all the characters mentioned, though this agreement unfortunately is not adequate to establish complete specific identity.

Everyone probably would admit that we do not actually know what true *F. secalica* is, but it might well be argued that the species had been re-established by emendation in the reports of Dr. Beede, or of myself. Dr. Beede's emendation has priority over mine, but mine I believe is more probably the original *F. secalica* of Say. My species is clearly, and Dr. Beede's may well be, distinct from von Staff's. I should not object to seeing Dr. Beede's interpretation or any other supersede my own if it were shown to be the authentic species or more probably the authentic species, but the facts are, if anything, just the opposite, and it would be especially inadvisable to adopt Dr. Beede's interpretation if it entailed the inclusion (as it probably would) of von Staff's also, since his is in all probability distinct from the original.

Until some better evidence comes to light, therefore, it would seem to be necessary to interpret *F. secalica* on the basis of my *Triticites secalicus* of 1904. Von Staff is probably correct in identifying the latter with his *F. centralis*, but as his application of this name is entirely arbitrary, *F. centralis* von Staff must for the present be written in the synonymy of *F. secalica* Say.

On the other hand, *F. secalica* von Staff almost certainly goes out of the synonymy of *F. secalica* Say, together with all the American citations of *F. cylindrica* which agree with it, including possibly *F. secalica* Beede.

The proper name for this species (*F. secalica* von Staff *non* Say) I am unable to suggest. It may be undescribed, but I suspect that it is the authentic *F. ventricosa* (*F. cylindrica* var. *ventricosa*) of Meek and Hayden, and that von Staff's *Girtyina ventricosa* is a still different type. *F. cylindrica* var. *ventricosa* was described (without figures) from Juniata and Manhattan, Kansas, but Meek and Worthen later identified and figured it from a lower horizon (probably) in Illinois. It is the latter form which von Staff cites as *Girtyina ventricosa*, without recognizing the fact that the original variety *ventricosa* was a much larger and less ventricose[1] form and not improbably a different species. This inference, based on intrinsic characters, is verified by the fact that von Staff recognizes *G. ventricosa* only from Illinois, although having a full series of Kansas specimens in his hands for identification. *G. ventricosa* von Staff, therefore, is almost certainly a distinct species from *F. cylindrica* var. *ventricosa* Meek and Hayden, which is, on the other hand, possibly the same as von Staff's *F. secalica*.

The gentle author has considerable to say about my proposed genus Triticites, of which he disapproves in emphatic language and liberal exclamation points, some of which might have been saved if he had fully understood the statements which he was criticizing. The studies of special investigators have, indeed, minimized the differences on which Triticites was separated from Fusulina, but it was regrettably heedless for von Staff, after condemning Triticites, to turn around and propose the new subgenus Schellwienia and at the same time to include in Schellwienia the type species of Triticites, *T. secalicus*. If a new name is needed for the group in question Triticites clearly should be employed.

Even if, however, one adopts the classification proposed by von Staff, which I think few will do, a new name is not needed here. He proposes to include both Fusulina and Schwagerina as subgenera in a single group which he regards as forming one genus and for which he retains the name Fusulina. It is for Fusulina in the old and strict sense that Schellwienia is introduced. This seems to me comparable to Hyatt's course in using Goniatites as a general term and introducing Glyphioceras for Goniatites ss., and it is equally inadmissible. If the author regards Schwagerina as a subgenus of Fusulina, the proper course is to retain Fusulina ss. as the name for the companion group. From the present evidence Schellwienia is a synonym of Triticites, and Triticites of Fusulina ss., a name which must be retained in a subgeneric sense even if von Staff's classification is adopted.

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[1] Meek gives the length as $\frac{1}{2}$ inch (13 mm.) and the diameter as $\frac{2}{10}$ inch. This makes the ratio of course 2.5:1. *Girtyina ventricosa* is described as having an axial length of at most 5 mm. and the ratio as 1.7:1.

THE RED BEDS BETWEEN WICHITA FALLS, TEXAS, AND LAS VEGAS, NEW MEXICO, IN RELATION TO THEIR VERTEBRATE FAUNA

E. C. CASE
University of Michigan, Ann Arbor, Michigan

During the summer of 1912 the author traveled by wagon from the north line of Oklahoma, south along the contact of the Pennsylvanian limestones and the Red Beds, to near Purcell and then west to the Wichita Mountains; from there the party turned south to Wichita Falls, Texas, and then west across the Staked Plains and eastern New Mexico to Las Vegas. It is the portion of the trip from Wichita Falls to Las Vegas that is described in this paper.

Active work during recent years has resulted in abundant collections from the Permian or Permo-Carboniferous beds of Texas and New Mexico, and we have now a fair knowledge of the most common fossil vertebrates. New forms will undoubtedly be found and additional information gained as to the habits and structure of forms already partially known, but enough information is at hand to warrant an attempt to determine the habitat and distribution of the fauna as a whole. The work of the expedition was directed toward determining (1) the limits, both geographical and geological, of the vertebrate-bearing beds in Texas and New Mexico, and (2) the character of the beds as revealing information of the habits and habitat of the creatures.

Vertebrate fossils of Permian or Permo-Carboniferous age have been found in Cowley County, southern Kansas, in a north-south strip through central Oklahoma, in north-central Texas, and in north-central New Mexico. In Kansas, fossils have been found in only one locality and there only in the excavation of a well located at the bottom of a ravine; no exposure of bone-bearing beds has been found. In Oklahoma, fossils have been found in Kay, Grant, Noble, and Logan counties, and south of the Wichita Mountains, all in the Enid formation, but others will undoubtedly be found wherever the Enid occurs. The lack of exposure and the abundant vegetation make their discovery a matter of great difficulty. In Texas, fossils occur in Wichita, Archer, Baylor, and Willbarger counties, and a few fragments of bone have been reported by Cummins as far south as the southern line of Haskell County, all in the Wichita and Clear Fork formations.

The Texas beds have yielded by far the greater number of vertebrate fossils and are regarded as the type locality; the relation of these beds to those of Oklahoma and New Mexico is still uncertain. On the east the Texas beds shade into the Cisco limestone as shown by Cummins and Gordon and on the west they disappear beneath the Dockum beds of Triassic age, on the eastern edge of the Staked Plains. On the western side of the Staked Plains Red Beds again appear and can be traced nearly to the edge of the Rocky Mountains, but for some distance east of the mountains they are covered, in the latitude of Las Vegas, by Cretaceous.

In attempting to answer the first question mentioned above, it was necessary to trace the Red Beds from their easternmost appearance to the edge of the mountains. The route followed was west from Wichita Falls through Seymour, in Baylor County, Haskell, Haskell County, Spur, Dickens County, Crosbyton, Crosby County, north through Floyd, Motley, and Briscoe counties to Clarendon, and then approximately along the line of the Fort Worth & Denver City Railroad to Amarillo and along the Chicago, Rock Island & Gulf Railroad to Tucumcari and Montoya. At Montoya the party left the railroad and headed for Las Vegas along the foot of the high mesa to the head of the Conchas River and then over the mesa to Las Vegas Hot Springs. The return route was across northeastern New Mexico to Clayton and then through the No Man's Land of Oklahoma to Alva where the party broke up.

Near Wichita Falls the surface rocks belong to the Wichita and Clear Fork formations already described in more or less detail by Cummins, Case, and Gordon.[1] On the east the Wichita beds shade into the Pennsylvanian limestone just as the Enid does to

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[1] Cummins, *Second Annual Report, Geological Survey of Texas;* Case, *Bull. American Museum Natural History,* XXIII; Gordon, *Jour. Geol.,* XIX.

the north in Oklahoma;[1] this shows that there was to the east an open sea whose eastern limits cannot be determined as the deposits have been removed by erosion. The Wichita is composed largely of sandstones, sometimes heavily bedded, and red and blue clays sometimes with irregular shaly sandstones and local conglomerates. The Clear Fork to the west is characterized by layers of impure and dolomitic limestone distributed through a considerable thickness of irregular beds of sandstone, shale, and clay, mostly of a red color. The outcrop of the limestone is approximately along the line between Baylor and Archer counties. This formation has less of the blue clay and more of the red, with less heavily bedded sandstones, than the Wichita, but aside from the limestone the beds are so irregular in position and distribution that little can be said concerning their arrangement and, unless the appearance of the limestone be taken as a dividing line, no demarkation between the beds can be described. Farther west the Clear Fork is overlain by a series of dark-red and mottled clays with some blue and gray layers all characterized by the more regular bedding, the darker red of the clay (in general), and the presence of large quantities of gypsum in irregular seams, layers of satin spar, and thick beds of massive and semicrystalline character. Gordon found it difficult to distinguish between the Clear Fork and these beds (the Double Mountain of Cummins) and so mapped the two as undifferentiated Clear Fork and Double Mountain.[2] To the author it is as difficult to distinguish between the Wichita and the Clear Fork as it is between the latter and Double Mountain. In following or crossing the line drawn between the two last by Cummins, approximately through Haskell and Vernon, in Texas, a decided change is noticeable in the sediments. This is not to be readily detected in any limited distance or thickness. As far as Haskell the beds are similar to those found east and north of Seymour, that is, they are typical Clear Fork, with a thin but persistent layer of gray or purple conglomerate composed of small pebbles with a considerable amount of cement. This is the layer which I have previously

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[1] Cummins, *loc. cit.;* Gordon, *loc. cit.;* Adams, *Am. Jour. Sci.*, XII; *Bull. Am. Geol. Soc.*, XIV.

[2] *Loc. cit.*

described as the Wichita conglomerate north of Seymour. Its persistence and peculiar character make it readily recognizable. Just beyond Sagerton, southwest of Haskell, there is a steep bluff of red clay and shales capped by a heavy sandstone just below which is a thin layer of impure limestone with large-sized, irregular ripple marks. A section taken on the east side of this bluff, locally known as Flat Top, is as follows:

Gray sandstone and fine reddish conglomerate	6–7 feet
Impure limestone, gray, ripple marked	1–2
Red clay with local harder layers and thin seams of gypsum	67
Shaly red clay and bluish clay	12

In the lower beds are some nodules of gypsum and thin layers of satin spar.

These beds are evidently above the Clear Fork and are different in color, in the regularity and persistence of the beds, and in the first occurrence of gypsum in any quantity. Moreover, a careful search failed to reveal any bones; not even fragments in the conglomerate. Cummins found fragments of bones on Paint Creek a few miles southeast of Haskell. The country between Haskell and the exposure just described is very flat or rolling, with a smooth surface and few exposures of the rocks; there is no opportunity, therefore, to determine the line of separation between the Clear Fork and the Double Mountain and I doubt very much whether such a line could be detected in the most favorable exposure. The two series shade into each other so gradually that a sharp line of demarkation does not exist. Double Mountain time was initiated by a slow change in the sedimentation and the climate which resulted in a more regular deposition and for short and irregular periods in a great concentration of the waters. Either of these changes would render the occurrence of vertebrate fossils in the beds much less probable. West of Sagerton the surface of the country is more irregular owing to the occasional breaking-down of the capping layer of sandstone. This is especially true of the breaks on the sides of the Double Mountain Fork of the Salt Fork of the Brazos River. Just before the deeper part of the valley is reached there are several layers of impure limestone which must be considerably higher stratigraphically than the limestone seen at

Sagerton. The stream runs between steep walls of clay with abundant gypsum. On the east side of the stream near the crossing is a bluff from 60 to 70 feet high composed very largely of gypsum with thin intervening beds of gypsiferous clay. No pure selenite was found in this bluff but almost every other form of gypsum occurs: layers of splendid satin spar, impure gypsum in thin and bifurcating irregular seams, as described by Cummins, heavy beds of granular gypsum, and equally heavy beds of clusters of imperfectly formed crystals. From the dip of the beds this is evidently higher than the beds at Sagerton but it is very probable that the increase in the amount of gypsum occurs not only in the rise of the beds but also in their western extension.

Beyond the Double Mountain Fork the surface rock is a loose sandstone of considerable thickness which readily breaks down into a poor sandy soil with very few exposures on the sides of the gentle but pronounced swells. There is considerable gypsum in this sandstone, as shown by the frequent efflorescence and beds of pulverent calcium sulphate. True beds of gypsum do not appear again until the hills beyond Aspermont are reached; here at a much higher level than the gypsum on the banks of the Double Mountain Fork, there occur layers, several feet in thickness, of pure granular gypsum, so soft that it is deeply marked by grooves due to rills of rainwater.

At Double Mountain, a few miles southwest of Aspermont, the following section was made by Dumble and Cummins:

Lower Cretaceous	Caprina limestone	40 feet
	Comanche Peak series	55
	Trinity	25
Triassic	3*a*. Dockum	35
Permian	Shaly clay underlaid by red or terra cotta sandstone	105
	Upper gypsum beds	60
	Middle gypsum beds	75
	Lower gypsum beds	135[*]

[*] *Am. Geol.*, 1892, p. 348.

The author's section agrees in only a general way with the portion marked Permian, unless it be understood that the gypsum beds be considered to mean red clay with much interspersed gypsum. Double Mountain is an outlier of the Staked Plains and shows the easternmost appearance of beds which can be referred to the Triassic. The reference is without paleontological evidence, but there is certainly a bed of disturbed sandstone and sands which fill a gap between the Permian and the Cretaceous. West of Double Mountain the comparatively level surface is continued to the breaks of Blanco Canyon west of Spur in Dickens County. Just east of the point where the road from Spur to Crosbyton crosses the Blanco Canyon there is a small tributary of the canyon; the road crosses this tributary on a layer of hard, bluish-green sandstone which is apparently near the dividing line between the Triassic and the Permian (see Fig. 1); above it are the sands and clays of the Dockum, as attested by the plant and vertebrate remains, and below it is a break indicated by a stratum of tilted sandstone which in turn lies upon sandstones and clays of the Double Mountain.

Fig. 1.—Contact between the Dockum (Triassic) and the Double Mountain (Permian) beds near Blanco Canyon. The tilted layer just opposite the figure on the left marks the line of contact.

A general section of the Triassic at this point is as follows:

Fine cross-bedded conglomerate, variable in thickness	5–20 feet
Red clay shading into yellow above	40–60
White, red, and maroon clay	20–40
Light-brown clay shading into a white clay with gypsum, plant remains, Unio and Triassic vertebrates	10–30
Bluish-green sandstone	3–4
Cross-bedded and tilted sandstone and red clay of the Double Mountain formation	10+

The discovery of Triassic vertebrates in the white clay confirms Cummins' location of the Permian-Triassic line at this point. Just below the bluish-green sandstone which is regarded as the base of the Triassic there is a layer of steeply tilted sandstone which marks a decided disturbance, perhaps of only local significance. Beyond Blanco Canyon the Triassic continues to the base of the Staked Plains and is covered by the Tertiary, the lowest portion of which is a gravel containing many water-worn shells of Gryphea and Ostrea. The red is again seen in the Blanco Canyon. Where the party descended into the canyon a few miles southeast of Mount Blanco the white Tertiary is underlain by a pink or reddish deposit of clay which is probably of Tertiary age and composed of reworked Triassic material. Below this there is undisturbed red clay, probably of Triassic age, though no fossils were found in it. Beyond Blanco Canyon, in the vicinity of Lyman in Motley County, the

FIG. 2.—Contact between the Dockum (Triassic) and Double Mountain (Permian) beds on Mott Creek. Above the head of the pick is a light-yellow cross-bedded sandstone; below is a solid red clay.

party worked its way into the valley of Mott Creek and followed down the creek to Conleys Peak near White Flat. This creek heads in the Tertiary, producing a very rough topography of characteristic Tertiary bad lands; below this is a wide terrace of coarse gravel and conglomerate carrying water-worn Cretaceous fossils. Below the terrace is a series of red clays and sandstones, the latter much cross-bedded and disturbed; in certain local layers of limy material Unios and fragments of Phytosaur bones were found in the sandstone, determining the Triassic age of the beds. On descending Mott Creek the disturbed Triassic beds are seen to lie upon a series of red clays, very dark in color and evenly bedded, very similar in appearance to the Double Mountain beds farther east and south. The physical characters are far from being a dependable character for correlation in the Red Beds, but taken in connection with the sudden change in character, the striking unconformity, and the correct stratigraphic position these are very probably the same, Double Mountain, beds as seen east of Spur.

FIG. 3.—Triassic beds on Salavito Creek. Gray clays and sandstones capped by heavy gray and red sandstone.

From Mott Creek the party again ascended to the surface of the

Staked Plains at Quitaque and then made its way to Clarendon across the Red River, or the Prairie Dog Fork of the Red River, as it is marked on the maps. This region has been described by Gould in *Water Supply Papers 154* and *191* and needs no further description. It appears to me from our section and almost continuous tracing of the beds that there can be no doubt that the horizons called Quartermaster and Greer in the eastern and western portions of the Panhandle by Gould are the same as the Double Mountain beds farther south.

FIG. 4.—Triassic beds in the Bad Lands of Trujillo Creek, east of Tucumcari. The capping sandstone and conglomerate is the same as that which forms the surface of the shelf extending north from the foot of the Staked Plains.

From Clarendon the party went to Amarillo and then followed the Chicago, Rock Island & Gulf Railroad across the Staked Plains to the western edge. Here the red again appears in irregular beds of sandstone and varicolored clays extremely irregular in thickness and extent but carrying Phytosaur bones wherever seen. In the breaks of the small Arroya Salavito just beyond Endee in Quay County, New Mexico, the beds are even more than ordinarily complex, massive white and gray sandstones lie above cross-bedded white and gray sandstones and clays, but here again fragments of Phytosaur bones and teeth were found. The main object of the trip from this point west to the mountains was to detect any recurrence of the Permian Red Beds, but, as will be shown, nothing below the Triassic was found.

Farther west the breaks of San Juan Arroya or Trujillo Creek are locally known as the Bad Lands; here there is a very considerable exposure of Red Beds. The beds, as in Salavito Arroya, are considerably below those which are exposed in the bluff forming the western edge of the Staked Plains a few miles to the south. A layer of heavy sandstone and conglomerate, varying rapidly in character, but as a whole very persistent, determines a shelf extending north from the foot of the plains and covered with grass. It is only in the valleys of the streams that it is broken through and the lower part of the section exposed. A short distance to the north the streams run out upon the shelf which is not again broken until the breaks of the Canadian River to the north are reached. A

FIG. 5.—Larger view of the pillar shown in Fig. 4. The light-blue layer of sandy clay is seen just below the conglomerate cap. Below is red clay.

section of the upper portion of the Triassic taken on the west side of the plains just west of Adrian is as follows:

Tertiary marl	6–20 feet
Fine white sandstone	20
Red clay	10
Red sandstone or hard sand	12–15
Dark-red clay containing a layer of variable sandstone and conglomerate	20+

It is the conglomerate at the base of the section which forms the top of the shelf described above; it rises and falls in the layer of clay and changes its character very suddenly, being strongly reminiscent of the conditions in the Clear Fork beds. In the breaks of the streams mentioned above the conglomerate forms the top of the section. A general section in the Bad Lands of Trujillo Creek is as follows:

FIG. 6.—Variegated clays of Triassic age in the Bad Lands of Trujillo Creek. The remnants of the conglomerate cap may be seen. The clays are red, purple, and light orange.

1. Conglomerate (top). Grayish in general, but locally reddish and overlain by red sandstone in places. The pebbles variable in size and character. Some thin layers of clay and shale. In places replaced by sandstone (in one place a true arkose).

2. Thin, blue, sandy clay; very persistent just beneath the conglomerate and frequently much distorted, apparently by local movements due to pressure. From 6 to 12 inches thick.

3. A heavy bed of red clay of varying shades and some blue streaks. Generally very homogeneous but with some layers of calcareous material. Near the bottom some shaly layers with worm casts. Two hundred and fifty feet thick, more or less.

4. A second series of sandstone and shaly layers. Bottom not seen, but Triassic bones to bottom of exposures.

FIG. 7.—A remnant in the Bad Lands of Trujillo Creek. Just below the conglomerate cap may be seen the layer of bluish sandy clay, just over the figure. Below the bluish layer the clay is purple, which shades downward into bright red.

The lower beds may be traced to Tucumcari and Montoya, the road lying upon the shelf described above. At Mount Tucumcari and in the magnificent section seen in Bull Canyon, just south of Montoya, it is the upper portion of the Triassic which is exposed. A slight anticlinal fold at Montoya brings some of the lower beds to the surface, but even here Phytosaur bones were found in the lowest exposures.

From Montoya the route of the party led along the foot of the mesa to the head of the Conchas River. The sandstone or conglomerate followed from farther east forms the floor of the valley; the upper part of the Triassic is exposed in the walls of the mesa beneath the capping of Dakota Cretaceous and the Morrison formation (Lee), and the lower part is seen in the valleys of the streams. Beyond Cabra Spring (a single ranch house located near the middle of the Corazon Topographic Sheet) the Conchas River has cut a deep gorge through the heavy sandstone and conglomerate into a heavy bed of white sandstone (40–50 feet) of a local character. Beneath and partly within this sandstone is a lense of dark-red and mottled clays and shales, much distorted and streaked with greenish clay and a greenish conglomerate of small pebbles. This is the lowest bed of the Triassic that was seen and it so much resembles the Double Mountain that I at first thought that it must be Permian; but the discovery of Unios in the layer of greenish conglomerate revealed its Triassic age. This makes it altogether probable that nothing below the base of the Triassic appears between Montoya and Las Vegas.

Fig. 8.—Red clay in the walls of Bull Canyon just south of Montoya. This is the portion of the Triassic above the conglomerate layer which forms the shelf extending north from the foot of the Staked Plains.

Ascending to the top of the mesa by the difficult road at the head of the Conchas Canyon, the party proceeded to Las Vegas Hot Springs. Here the red again appears in vertical layers on the edge of the mountains. This class of exposures is obviously an exceedingly unfortunate one in which to search for vertebrate fossils. The Red Beds had been lost when we ascended to the top of the mesa from the Conchas Canyon, but the nearly horizontal condition of the beds in the sides of the mesa and the Cretaceous cap leave little possibility of doubt that the beds turned up on the sides of the mountains at Las Vegas Hot Springs are the same as those we left a few miles to the east. On the Geological Map of the United States the Red Beds on the flanks of the mountains are called Permian. Girty examined the beds at Las Vegas Hot Springs but was unable to determine their age. A day's careful search by the author in the vicinity of Las Vegas Hot Springs

FIG. 9.—Clays, sandstones, and impure limestones in the wall of Bull Canyon just south of Montoya. Contrast the horizontal condition of the beds in this the upper portion of the Triassic with the disturbed condition shown in the lower beds (FIG. 3).

resulted in the finding of a single broken tooth in a conglomerate near the middle of the series; as this is a Phytosaur or Dinosaur tooth it shows that the upper half of the beds, at least, is Triassic. Whether any of the beds below this belong in the Permian it is still impossible to say, but when we consider the great thickness of the Triassic not very many miles to the east it is not likely that Red Beds of Permian age have any considerable thickness, if they are present at all. Moreover, it can be shown that the Permian beds north of Santa Fe were laid down in an area of deposition completely separated from that over Texas and Oklahoma. I am inclined to suggest that the sea or area of deposition which covered northern and western Texas and Oklahoma had its western border somewhere east of the present Rockies and that the Red Beds on the eastern flanks of the mountains in northern New Mexico and southern Colorado, at least, have no Permian members.

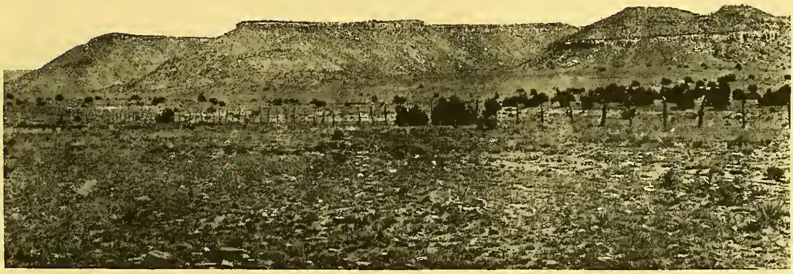

Fig. 10.—Wall of the mesa near the head of the Conchas Canyon. The capping layer is Dakota beneath which lie the beds considered by Lee as Morrison. The lower heavy layer is the uppermost layer of the Triassic.

It will be seen from the foregoing that the evidence from vertebrate fossils bears out in a pretty conclusive manner the conclusions drawn from stratigraphic evidence. The Clear Fork beds, with their vertebrate fauna, disappear beneath a distinct set of beds, the Double Mountain, at about the line of Haskell. Just how much farther west they go it is impossible to say, but it is not far. In western Texas and eastern New Mexico, along the line followed, they are deeply buried beneath the Triassic and most probably do not appear on the flanks of the Rockies. The change from the Clear Fork to the Double Mountain was a very gradual one but sufficiently profound to render the presence of fossils in the beds or of animals in the region during the time of deposition (the two things are very different) almost impossible.

The contact between the Triassic and the Double Mountain is marked in several places by sharp unconformities, but the beds are so irregular above and below that it is impossible to evaluate the unconformity. It is certain that after a period of erosion or exposure conditions of sedimentation closely resembling those of the Clear Fork followed the more uniform conditions of the Double Mountain. That this interval was long is suggested by the totally new fauna contained in the beds, but this is not conclusive. The fauna may have been evolving during the Double Mountain time or may have started even earlier and reached this region by migration at the beginning of the Triassic.

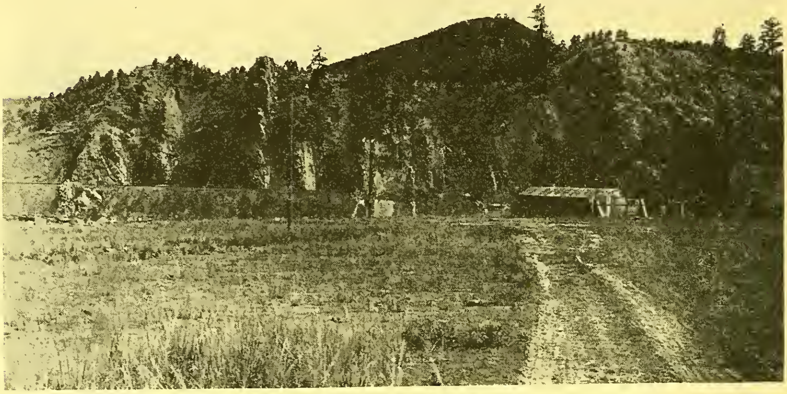

FIG. 11.—Vertical beds of Triassic age on the south side of the small valley at Las Vegas Hot Springs.

The sediments of the upper part of the Permian were undoubtedly derived from some not very remote land mass but the outlines of this cannot as yet be suggested. Undoubtedly the Wichita Mountains furnished much of the sediments of the Texas and Oklahoma beds, but where the western land mass lay and what were its limits are yet uncertain. Many suggestions have risen as to its possible outlines but the discussion of the evidence is beyond the limits of this paper.

PLEISTOCENE VULCANISM OF THE COAST RANGE OF BRITISH COLUMBIA

EDWARD M. BURWASH
Upper Canada College, Toronto

During the present summer the writer had occasion to visit the Mount Garibaldi region of the Coast Range of British Columbia, which lies about forty miles due north of the city of Vancouver, between 49°40′ and 50° north latitude and on the 123d meridian of west longitude. The approach to this district is by way of Howe Sound, a typical fiord, and the valley of the Cheakamous River. The volcanic origin of Mount Garibaldi, the highest peak in the region, had been recognized by members of the British Columbia Mountaineering Club, who made the first ascent of it some six or seven years ago. The region to the north of Garibaldi as far as the Black Tusk Mountain was subsequently penetrated for the first time by Mr. W. J. Gray, in whose company the present writer had the advantage of visiting the locality. The general situation, as far as it could be determined in a few days' study, is as follows:

I. PHYSIOGRAPHIC AND GLACIAL HISTORY

The Cheakamous River flows into the head of Howe Sound through a valley whose general trend is the continuation of that of the sound itself and lies in a north-northeast direction. The mountain-mass known as the Garibaldi Range lies to the eastward of it. At a point about twenty-five miles from tidewater the Cheakamous receives on the eastern side a tributary which is known as Stony Creek whose valley affords a convenient means of access to the higher parts of the range. Commencing with the bottom of the Cheakamous valley, the following features are to be observed as one ascends the range:

1. *Post-Glacial gorge*, in which the Cheakamous at present flows, cut through glacial deposits and in part through the rock to a depth of at least 300 feet.

2. *Main valley of the Cheakamous*, which has a total depth approaching 4,000 feet, and consists of well-marked inner and outer valleys. Both of these are glaciated parallel to their length. The outer valley is represented by a terrace at least a mile wide on the eastern side, and some 3,000 feet below the rim of the valley.

3. On reaching the upper edge of the valley one emerges at about 5,100 feet elevation, on a plateau, which has been dissected into broad, flat-topped spurs by the streams tributary to the Cheakamous. The surface of the plateau slopes upward to the east at an angle of from 7° to 10°, which increases toward the east, and an extension of the plateau surface probably forms the summit level of the range, at an altitude of about 8,000 feet. Incised in its surface are the remains of one or two older valleys which once ran parallel to the Cheakamous, but have since been cut across by the tributaries of that stream, and appear as notches crossing the intervening spurs. The age of this plateau is indicated by the fact that two ridges rise above it whose summits consist of remnants of andesitic lava flows, probably of early Miocene age. These flows originally probably filled valleys. The floor upon which the flow rested is now in one case, the Black Tusk Ridge, at least 1,200 feet above the plateau-surface below, while in another case, near Table Mountain, the columnar andesite itself forms a part of that surface. The end of the erosion-cycle which was responsible for the plateau can therefore hardly be earlier than Pliocene or late Miocene. On the other hand, both the plateau-surface and that of the ridges above it bear striae of the earliest glaciation of which record remains. The ice during this time covered the range up to a height of at least 6,500 feet as a sheet, whose general movement in this locality was S.S.W., or parallel to the trend of the main valleys. The plateau may therefore be assumed to be pre-Pleistocene. It is composed of rocks of Palaeozoic (probably Devono-Carboniferous)[1] age, of the subsequently intruded (Upper Jurassic) granites of the Coast batholith, and, as already explained, in some parts of the Miocene andesites. The tributary valleys which dissect it end in cirques in the upper part of the range, which are for the most part still occupied by glaciers. These valleys are of considerable depth, in one case

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[1] See O. E. LeRoy, G.S.C., *Publication No. 996*, 1908.

over 1,800 feet. Many of them are hanging valleys as regards the Cheakamous valley. They exhibit well-marked evidences of the second epoch of glaciation, which was merely an extension of the existing glaciers which filled the valley-system, including the main valleys, but did not override the range in a continuous icesheet.

II. VULCANISM

Superimposed upon the topographic featues which have been described are the andesitic cones and lava flows, which are unglaciated by the earlier icesheet, and only partially so by the later ice-advance. The volcanic foci which have been visited up to the present are three in number, but other peaks visible to the northward seem to be undoubtedly of similar origin.

Mount Garibaldi, the largest of the group and also the most southerly, is the highest peak in the region. Its summit is 8,700 feet above the sea, from which it is about 12 miles distant. It stands about 3,500 feet above the plateau. It is so surrounded by glaciers and snowfields that a study of its relations to the underlying terranes is impracticable, except possibly on the western face where freshly-cut ravines may expose sections. The walls of the cirques which have been cut into its sides afford admirable sections of the cone itself. The materials of which it is composed are of a light reddish-brown color, and appear to be largely fragmental. Lava streams extended down into the inner Cheakamous valley, where remnants of them may be seen along the Lilooet road. The proximity of the cone to the valley and the somewhat loosely coherent nature of the materials of which it is composed have rendered dissection somewhat rapid, and the conical symmetry has already been lost to a considerable extent, while the crater can only be doubtfully identified.

Situated about 5 miles to the north of Garibaldi, on the western margin of the lake of the same name, is the double volcanic cone known as Red Mountain, which has an elevation of about 1,000 feet above the plateau, or 6,500 feet above sea-level. As this volcano is much more easily accessible than Garibaldi, and practically free from snow, a fairly complete view was obtained of it. The volcanic cone stands within a cirquelike basin cut into the plateau on the south side of the valley of Garibaldi Lake. This basin consists of a wall of granite, inclosing the cone on its west and southwest sides and a summit standing out on the east side of the cone which is composed of the older Miocene andesite. This also appears to form the floor upon which the volcano stands. This basin is probably a glacial cirque. It is now almost completely filled up by the volcano, but some small areas of its floor which are exposed on the north side appear to have been almost certainly glaciated. It might otherwise have been attributed to explosive action in the early stages of the vulcanism, but there are no fragmental materials around its margin which would confirm this. The inner wall of the basin shows no evidence of glacial polishing, while the plateau above is well striated by the first glaciation. The basin seems, therefore, to have originated at a time later than the first glaciation, and is probably a cirque formed during its retreat or during the second period of ice-advance. The beginning of the volcanic activity must therefore also be dated subsequent to the first glaciation and perhaps later than the beginning of the second glaciation, if time must be allowed for the formation of the cirque. Neither of the two cones show any evidence of having been overridden by ice at any time. The older cone lies to the east. It is

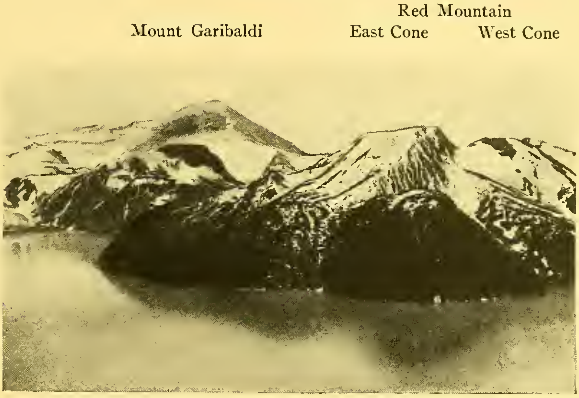

FIG. 1.—Mount Garibaldi and Red Mountain from the north. Garibaldi Lake in the foreground. The lava flow which dams it is to the right, beyond the picture. The old trunkated flow described is in the foreground. The flat-topped mountain in front of Mount Garibaldi is Table Mountain, which is composed of Miocene lavas.

more largely composed of fragmental materials than the western one, which is essentially a lava-cone. The older cone contains much material derived from the underlying rocks, especially fragments of granite and the columnar Miocene andesite which exhibit evidences of the high temperature to which they have been exposed within the vent. In the case of the granite the result is a general softening and tendency to disintegration, while the andesite blocks show cooling cracks which extend some distance from their surfaces inward.

That there was a still earlier cone which has been destroyed is proved by the remnant of a large lava-stream on the nothern side of the older remaining cone, the upper part of which has been cut off so that it presents a precipitous face, inside of which the older of the present cones has been built up. The cones as they now stand are therefore later than that from which this lava was extruded. The lower part of this old flow descended into the valley of Stony Creek, now occupied by Garibaldi Lake, but has been eroded away, probably by the glacier which occupied the valley during the second period of glaciation. This would indicate that the period of activity of this volcano extended back into the later of the two glacial epochs.

There is, on the other hand, abundant evidence that vulcanism continued for some time after the ice had retreated nearly to its present limits. Lava-flows from the western crater of Red Mountain have filled Stony Creek valley for a distance of about a mile and a half, and their surfaces are entirely unglaciated. The resultant damming of the creek has produced Garibaldi Lake, whose waters now find their outlet along a channel between the edge of the lava-flow and the northern wall of the valley until they reach a recess in the lava which forms the basin of Lesser Garibaldi Lake. From this point onward the stream follows a subterranean channel under the lava flow, beneath which it reappears at the foot of the cliff known as "the Barrier," which has been formed by the undercutting of the lower end of the lava-flow. At times of exceptionally high water, a part of the stream flows over the surface to Stony Lake, and thence over the Barrier into the lower valley. The cutting away of the lava here has exposed a section of the flow, which can be seen to rest upon glacial till, and upon rock surfaces which bear striae belonging to both periods of glaciation. These later lava-streams are therefore undoubtedly post-glacial. Their surface is covered with a well-grown forest.

A small cinder-cone, some 500 feet in height, about four miles north-northeast of Red Mountain, is the most northerly volcanic vent examined. It stands in the mouth of a large cirque which faces the north and opens upon a valley known as Desolation Valley. This is an abandoned glacial hanging valley and contains a number of lakes. Its floor is about 5,350 feet above sea-level. The cirque contains a large snow-field, whose lower edge rests against the side of the volcanic cone and discharges by a glacier on each side of it. There is evidence that the ice at one time overrode parts of the cone which are now free from it, and probably filled the valley on the north side of it since the volcano was active. A small lake lying in the valley is rapidly being filled by a delta of outwash from the glacier, most of which consists of volcanic materials. A glacial stream which flowed over the western part of the cone from the snow-field behind it has cut a ravine in the flank of the cone in which a cross-section of the faulted tufaceous strata is well shown. The summit is 5,850 feet above sea-level and the cone has a crater about 70 feet deep, which was partially filled with water at the time of our visit.

FIG. 2.—Cinder Cone in Desolation Valley. The cone is in the middle distance covered with dark bushes. To the right is a snow-field, and one of the glaciers discharging from it beside the cone. In the left foreground are a small lake and the outwash-delta of the glacial stream. The ridge which bounds the snow-field forms the background.

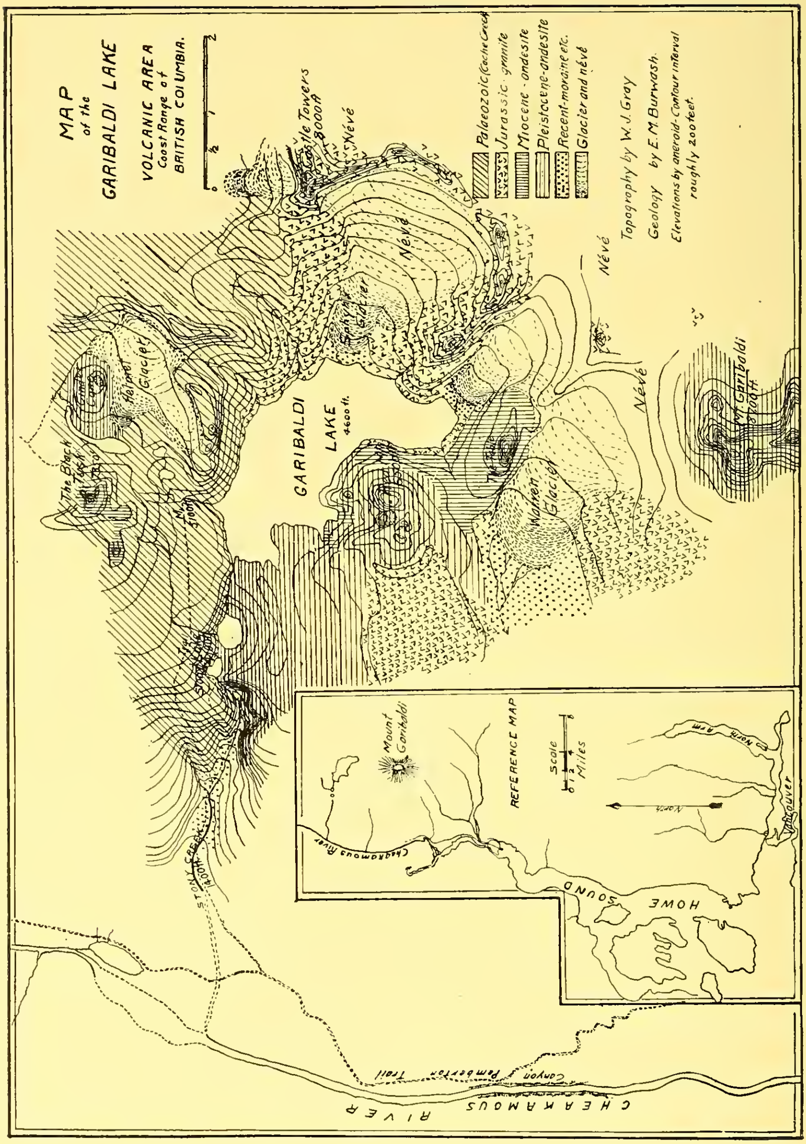
MAP
of the
GARIBALDI LAKE
VOLCANIC AREA
Coast Range of
BRITISH COLUMBIA.
0 ½ 1 2
Palaeozoic (Cache Creek)
Jurassic · granite
Miocene · andesite
Pleistocene-andesite
Recent-moraine etc.
Glacier and névé
Topography by W. J. Gray
Geology by E. M. Burwash.
Elevations by aneroid-Contour interval
roughly 200 feet.
Castle Towers
8000 ft.
Névé
GARIBALDI
LAKE
4600 ft.
Glacier
Helmet
Glacier
The Black Tusk
Warren
Glacier
Mt. Garibaldi
8700 ft.
STONY CREEK
1400 ft.
REFERENCE MAP
Mount
Garibaldi
Scale
Miles
North
Cheakamous River
North Arm
Vancouver
HOWE
SOUND
Canyon
Pemberton
Trail
CHEAKAMOUS
RIVER

FIG. 3

The age of this cone appears to correspond with that of Red Mountain. Neither can be said to have originated as far back as the first glacial period. In the tills, however, which represent the end of that period in the Capilano Valley, near Vancouver, there are blocks of the reddish andesitic lava which is characteristic of this period of vulcanism. This locality lies south of Mount Garibaldi, and could only be reached by ice of a general glaciation, moving over the summits of the higher ridges. It is probable, therefore, that Mount Garibaldi is of considerably earlier date than either of the smaller vents to the northward, and that the lava erratics of the Capilano Valley may be referred to the early eruptions of Mount Garibaldi. This would also agree with the extensively dissected condition of the Garibaldi cone as compared with the others. The total time-range of the vulcanism would therefore extend from early Pleistocene through a considerable part of the Recent, if we suppose the earliest recorded glaciation to have been in fact the earliest of the Pleistocene ice-ages. In any event, we must place the beginning of the vulcanism well back in the Pleistocene.

The nature of the lavas, which are reddish-brown andesites and andesite-porphyries indicates a lithological relationship with the Pleistocene volcanics of the Pacific coast states. The zone of activity is thus extended from Mount Baker in a north-northwest direction for about 100 miles, and into a quite new geological province, that of the Coast Range batholith.

DIASTROPHISM AND THE FORMATIVE PROCESSES. VI

FORESET BEDS AND SLOPE DEPOSITS

T. C. CHAMBERLIN
University of Chicago

Nearly all marine sediments are carried to their resting-places in one or another of three general ways: (1) by rolling or sliding down relatively steep slopes, where gravity is the chief factor and the agitation of the water only an auxiliary agency; (2) by being forced along low slopes where agitation and currents are essential factors; and (3) by flotation, where the relative levity or fineness of the material is an essential factor. These are conveniently called (1) foreset beds, (2) topset beds, and (3) flotation beds. If we may use these terms in a rather free and broad sense, based on the dominant feature, with neglect of intergradations and alternations, it will be convenient to speak of the shelf-sea deposits as topset beds, of the deposits of the abysmal slope as foreset beds, and of the deep-sea deposits as flotation or bottom-set beds, though flotation contributions enter in notable measure into the composition of both the other classes.

The abysmal deposits were the subject of our last discussion, and in earlier articles the shelf-sea deposits were under study. It remains to see, so far as we may, what bearings on diastrophic problems the foreset beds have, taking as our leading type those that lie on the abysmal faces of the continental terraces.

These foreset beds are formed of a coarser and a finer element. The coarser embraces material that has been rolled or pushed by stages over the upper face of the continental shelves until the oceanward edges of these were reached, beyond which the material has descended the steeper slopes under degrees of agitation of milder sorts than those required to move them over the upper face of the shelves. These materials may be said to be the overflow of the topset or shelf-sea beds. As these slope deposits are gradually built out, they serve as a causeway on which the topset beds are advanced seaward.

The finer element embraces those portions of the silts from the land that were light enough or fine enough to be kept in suspension—or to be stirred up frequently into temporary suspension—by the agitated waters of the shelf-seas and so borne oceanward continuously or by stages. They were, however, insufficiently comminuted to float long and so to reach the central ocean areas and find lodgment in the true abysmal depths. This element in general is intermediate between the coarser flotation material which settles and remains on the sea-shelves in spite of considerable agitation, and the extremely fine silt that reaches the heart of the ocean and enters into the deep-sea deposits.

The many obvious qualifications of these broad statements need not detain us here for we are seeking chiefly the relations of these formative processes to problems of diastrophism. The matter of first special interest in this relationship concerns the thicknesses of the foreset, the topset, and the flotation beds respectively and the inferences drawn from these thicknesses. It is common practice to regard the thickness attained by any series of beds prior to a deformation, as a measure of the subsidence of the crust, if evidences of agitated water or shoal life occur at various horizons in the series. This inferred subsidence, when large, is often thought to have invited a deformative movement. Theories of the cause or of the localizing agency of deformations have been hung on such supposed proof of deep subsidence. Appeals have been made to a rise of the geotherms supposed to be consequent upon subsidence. Even softening or melting of the under crust has been deduced from such depression. When the series is thick and shows abundant evidence of shallow-water action at nearly all horizons, these features have been regarded as proof of such deep subsidence, and the proof has been felt to be quite irrefragable. Few tenets of geology have a firmer hold on the convictions of working geologists or have seemed more nearly axiomatic. If the trustworthiness of this tenet is to be called in question, in any sense, or in any degree, the grounds for so doing should be clear.

Flotation beds may be laid down in strict horizontality, and on slopes of various moderate degrees as well. Sediments that come into place only by sliding or rolling usually require a declining gradient. It is admissible to regard the abysmal beds, looked at broadly, as essentially horizontal. Additions to them are made by sheets of flotation sediment falling from above with some approximation to uniformity. The thicknesses that may be attained by such beds in the ocean, so long as the crust maintains a static condition, are strictly limited by the depth of the ocean. This seems a mere truism and falls in with the instinctive inferences that have given rise to the common conviction.

It is, however, admissible, if not imperative, to regard the sea-shelves as sloping from the continents oceanward, and to recognize that in the very nature of their formation, they persist in sloping systematically toward the ocean at all stages of their formation when they are built up normally. The slopes on the present continental shelves vary through a considerable range. The precise slope is not a matter of special moment in this paper, though it is important in special problems. It will serve our present purpose to recognize slopes as being often as low as three feet per mile and often as high as twelve feet per mile, or from 1 in 1,760 to 1 in 440, while both lower and higher slopes are not uncommonly observed. For this discussion let us take the conservative figure of four feet per mile, or 1 in 1,320, as representative. While it is not here important to assume one approximate figure rather than another, it is important to recognize that some such slope is a systematic feature of the shelf-sea deposits in their normal state, that it is inherent in the nature of the case, and that it may safely be presumed to have affected the sea-shelf deposits of all periods.

At the oceanward edge of these slightly sloping shelves, the topset beds join at an angle or curve the foreset beds that form the steeper abysmal slope. While the dips of the foreset beds have large variations, they are usually much higher than the topset beds and this higher dip is a systematic feature. Such higher dips must be presumed to have affected the foreset beds in all stages of shelf growth and to be a persistent feature. Willis generalizes the commoner angles of the present abysmal slopes at 2° to 5°, which may be translated, roundly, into 1 in 30 to 1 in 12, but much higher and much lower slopes occur. These slopes vary with conditions, as in the case of the topset beds, but, in the nature of the case, they persist at some grade so long as there is continental feeding and effective shelf-sea action.

If now the picture of the slopes of the topset and of the foreset beds of the continental shelves, and their relations to one another, are clearly in mind, and it is plainly seen that they are persistent and systematic features, we are prepared for the question: What is the limit of thickness of foreset and topset beds in an ocean of given depth where no subsidence or creep takes place? As thus stated, no determinate answer to the question is possible. The depth of the ocean—beyond a sufficient working depth—is essentially immaterial so far as the theoretical possibilities of thickness are concerned. It is rather the *breadth* of the ocean than its *depth* that controls the possible thickness of such sloping beds. *The growth of the continental shelves oceanward increases the thickness of the topset and foreset strata irrespective of the ocean depth.* The ocean depth merely determines the amount of material required to effect the oceanward growth. While it may thus influence the rate of growth in thickness or the ratio of topset beds to foreset beds, or their slopes, or other details incidental to thickness, it is not vital to the possibilities of thickness.

If all this is not evident from the mere statement of the case, it should become so from an inspection of the accompanying figure in which it is assumed that the crust remains absolutely stationary, that there is a continual supply of material from the land, that the sea surface changes only as it is forced to rise by sea-filling, that the depth of effective shelf-sea action is 100 fathoms, and that a normal distribution of sediment arises from the movements of the sea-water. According to standard methods of finding the thickness of beds, the measurement is taken on lines normal to the deposition planes. This is obviously the correct method, as it sums up the successive increments of sedimentation. It will be seen from the diagram (Fig. 1) that the topset and the foreset beds increase by the addition of layer laid obliquely upon layer in the course of the growth seaward and that these lie in essentially the same horizon and may accumulate quite irrespective of the total depth of ocean.

A growth of the continental shelf seaward to the extent of 1,000 miles would increase the sum of the thicknesses of the topset or sea-shelf strata to the amount of 4,000 feet, if the shelf slope were constant at 1 in 1,320; while the sum of the foreset beds on the abysmal slope would increase to 176,000 feet, if its inclination remained constant at 1 in 30, i.e., constant at a slope of about 2°. The thicknesses of topset beds under the range of slope given above would vary from 3,000 feet to 12,000 feet and of foreset beds from 176,000 feet to 440,000 feet. In all this, it is assumed that there is absolutely no subsidence of the crust, nor creep, nor diastrophism of any kind, nor any change of any kind, except what may be involved in keeping up a supply of terriginous matter and in maintaining normal sea action on the shelf, and so maintaining a systematic growth seaward.

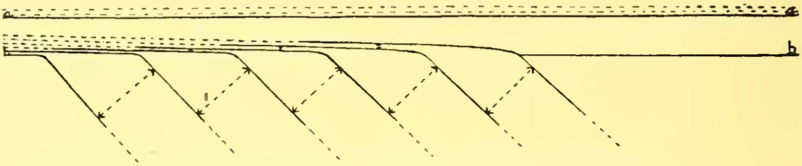

FIG. 1.—*aa*, sea level; *bb*, limit in depth of effective surface action; crust stationary; creep absent; silt supply constant; action strictly normal; slopes exaggerated.

From this it is easy to see that, given a sufficient supply of material and a continuance of normal action and static condition, it would be possible for normal processes to build out into the ocean a series of foreset beds that would sum up a thickness much exceeding the whole geological column, without the slightest subsidence. Even the sea-shelf beds in such a case would attain a very impressive sum of thicknesses.

In these statements, it is assumed that thicknesses are measured in the standard way, bed by bed, at right angles to the bedding planes.

Under the perfectly stable conditions named, and on the assumption that the angle between the topset and foreset beds of the continental shelf was maintained at 100 fathoms below the sea surface, the series of shelf-sea deposits would never have a vertical depth of more than 600 feet plus the rise of the sea-level due to filling, but, *because they lie inclined upon one another*, the sum of their individual thicknesses may have reached the impressive figures indicated. So also, under these conditions, the vertical depth of the foreset beds would never equal the depth of the ocean, but the sum of their individual thicknesses might many times exceed its greatest depth.

Under the conditions named, the shelf-sea or topset deposits should bear abundant evidence of a shallow water origin at all horizons, since none were formed at a greater depth than 600 feet, plus the rise of the sea-level, and yet their stratigraphic thickness measured in the usual way, the correct way, might rise to some thousands of feet without the slightest subsidence.

Under the same conditions, the upper edges of the foreset beds, or beds of the abysmal slope, might show evidences of sea agitation and the special marks of currents actuated by winds and tides, and they might be filled with fossils that lived within a thousand feet or so of the sea surface. These evidences of somewhat shallow water might affect the upper edges of tens of thousands or hundreds of thousands of feet of inclined beds measured in the usual correct way. Farther down on the abysmal slope the beds would of course carry life implying deeper water, and at still greater depths there would be a gradation toward, and finally into, true abysmal deposits.

It is immaterial whether the sediments are inorganic or organic so long as the comminution is such as to permit transportation in one or another of the three usual ways. Coral sand and silt are as susceptible to sloping sedimentation as siliceous or silicate sands and silts, and perhaps as frequently take on sloping attitudes. The depositional dips of corraline limestones are often of a pronounced order. Calcareous sands and silts from any organic source, foraminal, algous, and bacterial included, are susceptible of deposition on either topset or foreset slopes, and so beds of limestone or dolomite may alternate with other topset beds or foreset beds in normal sloping terranes.

The principles of stratification, and of stratigraphic interpretation, thus systematically embodied in the outward growth of the continental shelves, are likewise embodied in the growth of shelves from the borders toward the interiors of the smaller water-filled basins, whether these smaller basins arise from diastrophism or from any other source, and whether they are indentures of the borders of the continents or lie within them as mediterranean basins. In these smaller basins the shelves are usually narrower and the slopes are liable to be higher because the backward distribution of the sediments is less effective since the surface agitation and the circulatory currents are generally feebler, but this difference of slope is not inevitable nor universal.

There is this further difference, that in the intra-continental basins the land surrounds the water bodies and they are, in an areal sense, the minor elements, while the oceans surround the continents and, in an areal sense, are the major elements. In the intra-continental basins, the feeding areas are generally large compared with the depositional areas. The growth of the terraces is centripetal and their borders constantly diminish, while the growth of the circum-continental shelves is centrifugal and their borders constantly increase. While these are only features that have a quantitative bearing, they are worthy of passing notice because by far the larger part of the subaqueous strata that have been studied in detail by geologists are of the intra-continental or epicontinental order. The study of the circum-continental growths is a field to which less ample attention has been directed.

Before the foreset beds are left, some special features may well be considered but they are reserved for a later article.

PETROLOGICAL ABSTRACTS AND REVIEWS

EDITED BY ALBERT JOHANNSEN

DUPARC, LOUIS, et MONNIER, ALFRED. *Traité de technique minéralogique et pétrographique.* Vol. II-1. *Les méthodes chimiques qualitatives.* Leipzig: Veit & Co., 1913. Pp. xii+372, figs. 117, colored plate 1.

This volume, the second of the series, deals with qualitative chemical methods for the determination of minerals. A third volume on quantitative methods is to appear shortly.

The author discusses first the processes of separating the mineral constituents of a rock, or a mineral from its impurities, by means of sliming, heavy solutions, the electro-magnet, and chemicals. The microchemical reactions are next treated. It would have been desirable, from a petrographical standpoint, had the authors discussed these methods more fully than in the 27 pages here given. While much work has been done by Behrens, Streng, Brauns, Haushofer, and others in the determination of the elements, no one, since Boricky, has fully taken up the work from the mineralogist's side.

The methods for blow-pipe determinations are given from the chemical, rather than from the mineralogical side, since the determinations are for the chemical elements. To the preparation of solutions of minerals preparatory to chemical analysis, 19 pages are given. Following this there are 196 pages of chemical reactions of the different elements. This is very complete, all the methods which have ever been employed for the identification or separation of the elements being given. There are also 60 pages of spectroscopic methods and 5 of determinations of radioactivity.

The last chapter is devoted to the rapid determination of minerals by the examination of certain chemical characters. The authors here closely follow von Kobell's tables.

A good index is added, something which was greatly missed from the first part.

The book is an important and needed contribution to the chemical side of mineralogy. It is uniformly bound with the first part, in half leather.

ALBERT JOHANNSEN

ENDELL, K., und RIEKE, R. "Ueber die Bildung des Cristobalits aus Quarzglas und ueber seine reversible Zustandsänderung bei 230," *Tschermaks Min. u. Petr. Mitt.*, XXI (1912), 501–12.

ENDELL, K., und RIEKE, R. "Ueber die Umwandlungen des Kieselsäureanhydrids bei höheren Temperaturen," *Zeitschr. anorgan. Chemie*, LXXIX (1912), 239–59.

The authors show that quartz, amorphous silica, and quartz glass change to cristobalite at high temperatures and in the absence of mineralizers.

A. J.

ENDELL, K., und SMITS, A. "Ueber das System SiO_2," *Zeitschr. anorgan. Chemie*, LXXX (1913), 176–84.

A further contribution to the inversion of quartz glass to β-cristobalite, quartz glass to β-quartz, and β-cristobalite to β-quartz.

A. J.

ENDELL, K. *Ueber die Umwandlungen der Kieselsäure bei höheren Temperaturen.* Leipzig, 1913. Pp. 6.

An address before the eighty-fourth meeting of the Gesellschaft deutscher Naturforscher und Aertzte zu Münster giving a summary of the author's work on the inversion of SiO_2 at high temperatures.

A. J.

ENDELL, K. "Ueber Granatamphibolite und Eklogite von Tromsö und vom Tromsdaltind," *Centralbl. f. Min., etc.*, 1913, 129–33.

Garnet amphibolite and eclogite from northern Norway are described. A chemical analysis of the former, calculated in the Osann system, gives $a_{1.5}c_5f_{13.5}$.

A. J.

FENNER, CLARENCE N. "The Various Forms of Silica and Their Mutual Relations," *Jour. Washington Acad. Sci.*, II (1912), 471–80.

Shows that either tridymite or cristobalite may, under certain conditions, such as those which induce rapid crystallization, form at temperatures below their inversion points. Either mineral will retain its form when the temperature is reduced. Quartz, however, is probably never deposited at temperatures greater than 870°. The inversion point of quartz to tridymite is 870°+10°, and tridymite to cristobalite 1470°+10°. The α–β inversion point of quartz at 575° is not questioned.

A. J.

FLETT, J. S., and HILL, J. B. *The Geology of the Lizard and Meneage*, Mem. Geol. Survey England and Wales, Explanation of Sheet 359. London, 1912. Pp. 280, pl. 15, figs. 10.

The rocks described are serpentines, peridotites, gabbros, dolerites, epidiorites, gneisses, granite gneisses, greenstones, soda granite porphyries, granites, and schists, as well as sedimentary rocks. Many analyses are given, and there are 24 fine heliotypes of rock sections.

A. J.

FOOTE, W. M. "Preliminary Note on the Shower of Meteoric Stones at Aztec, near Holbrook, Navajo County, Arizona," *Amer. Jour. Sci.*, XXXIV (1912), 437–56, figs. 17.

In the meteoric fall at Holbrook, Ariz., July 19, 1912, over 14,000 stones are recorded, with a total weight of 218,310 grams.

A. J.

GALPIN, SYDNEY LONGMAN. "Studies of Flint Clays and Their Associates," *Trans. Amer. Ceramic Soc.*, XIV (1912), 301–46.

From geologic occurrences, dehydration tests, and microscopic examination, the author concludes: (1) Flint clays have been formed by the setting and recrystallization of fine-grained, largely colloidal sediments. The products of recrystallization are mainly kaolinite, with minor amounts of hydrated micas. (2) The semi-flint or soft clays have been derived from the flint clays through metamorphism, resulting in a conversion of much kaolinite into hydro-micas. (3) Plastic fire clays have resulted from long weathering of the soft clays. They contain a high percentage of hydro-mica. (4) The change from muscovite through hydrated or hydro-micas to kaolinite may take place without destruction of the original structure, indicating the possibility of an isomorphous series embracing all of these minerals.

A. J.

GOLDBECK, ALBERT T., and JACKSON, FRANK H. *The Physical Testing of Rock for Road Building.* Bull. 44, Office of Public Roads, U.S. Dept. of Agriculture, Washington, 1912. Pp. 96, figs. 20.

GRATON, L. C., and MURDOCH, JOSEPH. "The Sulphide Ores of Copper. Some Results of Microscopic Study," *Trans. Amer. Inst. Min. Eng.*, New York meeting, Feb., 1913, 741–809.

While this paper is principally of interest to the economic geologist, it is of importance to the petrographer from the authors' work on the determination of ore minerals by means of the microscope. This is a problem which has only recently been attacked, and in the solution of which but little has been done. It opens up a new field to petrographers, and promises to be of great importance in the determination of opaque minerals.

A. J.

GWILLIM, FARIBAULT, and BARLOW. *Report on the Geology and Mineral Resources of the Chibougamau Region, Quebec.* Quebec, 1911. Pp. 216+viii, pl. 78, figs. 19, maps 2.

Numerous rocks and minerals are described and illustrated. A number of analyses is given.

HARDER, E. C. "Structure and Origin of the Magnetite Deposits near Dillsburg, York County, Pennsylvania," *Econ. Geol.*, V (1910), 599–622.

HATCH, F. H., and RASTALL, R. H. *Text Book of Petrology; The Sedimentary Rocks.* London, George Allen & Co. Pp. 525, figs. 60.

While there is a wealth of literature regarding the sedimentary rocks, the processes which produce them, and their metamorphic equivalents, this volume represents the first published attempt, in English, to bring the knowledge of the subject together. About one-third of the book is devoted to the sedimentary rocks, and the balance to the metamorphic processes and the metamorphic derivatives of the sediments. The subjects cementation, metasomatism, contact metamorphism, regional metamorphism, and weathering are included.

Though no classification of the sediments has been generally agreed upon, the authors group deposits as fragmental, chemical, and organic. The various types of these are described, and much space is devoted to their origin. An attempt is made to present criteria by means of which the terrestrial deposits may be distinguished from each other and from marine deposits. These criteria include the form and size of the grains, and the presence or absence of certain minerals, but, as is pointed out by the authors, there are such insufficient data on many of these points and the exceptions are so numerous that safe conclusions can scarcely be drawn. The absence of mica in wind-blown sand is notable, but this criterion could not confidently be applied to cemented deposits where mica might have been developed by slight metamorphism.

The statement is made that because of variations in the chemical composition of coals "they must have originated under widely different conditions." This is hardly a necessary conclusion, since varying amounts of inorganic matter must have been transported by wind and water into the many basins of accumulation. The analyses of different kinds of coals quoted are neither average nor typical analyses of their types.

The authors seem to accept the idea that the fusion of sediments on a large scale is due to the great pressure of accumulated overlying matter, but it is to be greatly doubted whether fusion on a large scale has ever taken place, although there are undoubtedly many places where local fusion has gone on. The thickness given for the Laurentian gneisses as some 50,000 feet may be the result of complex duplication of beds by faulting and folding.

The geology of the Scottish Highlands, which has been so minutely worked out in recent years, is presented in some detail as an illustration of regional metamorphism.

A final chapter on the systematic examination of the loose detrital sediments is given under the authorship of T. Crook.

Field data and abundant references to geological literature enhance the value of the book and it is well adapted to elementary courses. The figures are numerous and clear.

E. A. STEPHENSON

IDDINGS, JOSEPH P. "The Petrography of Some Igneous Rocks of the Philippines," *Philippine Jour. Sci.*, V (1910), 155–70.

Describes both plutonic and eruptive rocks. Andesites make up the great bulk of the volcanic rocks of the island, basalts are next in importance, while dacites and rhyolites, so far as known, are rare and occur in relatively small bodies. Syenite, diorite, quartz diorite, gabbro, peridotite, and granite occur, the latter being rather uncommon. The rocks are given the standard names, no attempt having been made to determine them in the Cross, Iddings, Pirsson, Washington system.

A. J.

Jevons, H. Stanley, Jensen, H. I., Taylor, T. G., and Süssmilch, C. A. "The Geology and Petrography of the Prospect Intrusion," *Jour. and Proc. Roy. Soc. N.S. Wales*, XLV (1911), 445–553.

About 18 miles from Sydney, in the midst of the Wianamatta (Triassic) shales, occurs a massive intrusion of an augite-plagioclase rock. The mass is roughly oval in shape, two miles long by one mile wide, and forms a ring inclosing an isolated area of the shale. Numerous exposures show this shale to be nowhere more than a few feet thick, and the igneous rock is everywhere continuous beneath it. The main rock consists of titaniferous augite 36 per cent, a zonal feldspar 36 per cent, olivine 10 per cent, ilmenite and magnetite 13 per cent, with biotite and apatite as accessories, and analcite secondary. The plagioclase is called an acid labradorite by the authors. Its central portion is labradorite (Ab_3An_4), the rim is oligoclase ($Ab_6 An_1$), and the average composition of the whole, by analysis, Ab_4An_3. The authors believe the analcite to have been derived from the feldspar, and not from a pre-existing nephelite. They regard it as distinctly secondary.

Surrounding the central mass of the intrusion is a shell of a very dark, compact, gray rock, having the appearance of basalt. It not only forms the outer zone, but occurs at the contact with the central mass of shale as well, showing that it is actually a mantle around the entire mass. This rock grades into that of the main mass, the size of grain gradually increasing.

The main mass of the Prospect rock has always been called a dolerite in the sense of Teall, Hatch, *et al.*, and not in the German sense, or a diabase in the sense of Harker. The outer zone has been spoken of as basalt or olivine basalt. On account of the association of the rock with nephelite rocks, and the presence of as much as 18 per cent of orthoclase and a little aegirite-augite in some of the segregation veins, the authors regard the rock as a basic differentiation product of an alkali mother magma, wherefore they give to it the name essexite. To the border they give the name pallio-essexite, the prefex being applied by Mr. Jevons to denote the compact envelope of any rapidly cooled igneous rock. In the Cross, Iddings, Pirsson, Washington system, the rocks are camptonoses; the inner mass a grano-augite-camptonose, the envelope a pitaxi-biaugi-camptonose.

Further, there are described associated pegmatite and aplite veins, and the mode of intrusion is discussed.

ALBERT JOHANNSEN

JEVONS, H. STANLEY, JENSEN, H. I., and SÜSSMILCH, C. A. "The Differentiation Phenomena of the Prospect Intrusion," *Jour. and Proc. Roy. Soc. N.S. Wales*, XLVI (1912), 111–38.

In this paper the origin of the various segregation veins occurring in the Prospect intrusion is discussed. The authors assume that all have originated *in situ* during the cooling and consolidation of a single magma, which may or may not have been homogeneous when intruded. The paper is divided into two parts. In the first Jevons summarizes the various differentiation hypotheses, and in the second, the differentiation phenomena of the Prospect intrusion are discussed by Jensen and Süssmilch.

A. J.

JOHANNSEN, ALBERT. *Manual of Petrographic Methods.* New York: McGraw-Hill Book Co., 1914. Pp. xxviii+649, figs. 770.

This publication fills a long-felt want of a comprehensive book in English on petrographic methods.

After a brief introduction on crystallographic principles and on stereographic projection it gives a full treatment of those parts of optical crystallography of value in petrographic research, and the various means of determining the optical constants. For each of the more important properties, methods are given in historic order. Not only are the present standard methods fully described, but those of historic interest are either described or briefly outlined, with references to the original literature, so that one hoping to improve petrographic technique may be saved much unnecessary labor by having placed before him the various schemes that have been tried and later displaced by apparently more satisfactory methods. The discussions are both geometrical and analytical.

The properties of lenses are discussed and the various types of microscopes and accessories are briefly described and illustrated, thus giving the student an idea of the different characteristics of the designs of instruments produced by the various European and American makers.

Methods of specific gravity determinations and of separation of rock constituents are given, including a description of each of the various heavy solutions and melts used for such purposes. Microchemical tests are briefly presented, the treatment being limited to special methods for distinguishing certain particular minerals and groups.

Methods for the study of opaque minerals are but briefly referred to. Considering the growing importance of this part of the subject, it would seem desirable that this section should be expanded, as the author himself remarked in his preface.

The book ends with a discussion of the preparation of thin sections, collecting, filing, and cataloguing of rock specimens and sections, and an appendix of useful mathematical formulas, recipes, etc.

A special feature of the book is the references to the original literature, which are representative and comprehensive even in those parts of the subject which are but briefly treated in the text.

The illustrations are abundant and excellent. Special mention may be made of the beautiful half-tones (after Hauswaldt) of interference figures. And in this connection it may be noted that much credit is due the publishers for the excellent book work—a feature which adds much to the readability and usefulness of the book.

The multiplicity of methods described would probably be confusing to most beginning students, yet the descriptions are presented as far as possible in a simple and elementary way, taking little for granted, and thus by a judicious selection of the articles to be studied, the book could be made use of in an elementary course. Numerous cross-references are helpful in making rapid reference possible to related or explanatory sections.

For a first edition of a book of this character, dealing with numerous details of description, tables, and formulas, it appears to be remarkably free from infelicities or errors of detail in statement or print. With no attempt at completeness, a few may be noted.

P. 20, throughout discussion, a should read c to agree with Fig. 35.

P. 33, article 25, line 10, "If α is constant," read ω for α.

P. 67, the row of figures 113 to 118 should be inverted, the figure at the right being 113.

It would seem desirable to use some such expression as "normal velocity surface" instead of "wave surface" in the discussions of pp. 75 ff., and also pp. 97 and 98. Light passing from the center point may be ideally conceived as actually passing out in the form of the so-called ray surface, but it cannot be imagined as spreading out in the form of the "wave surface," and this again is confusing to students. The vibration "ellipsoid" of Fig. 131 should of course be "ovaloid."

P. 243, line 1, second paragraph, for "microscope" read "micrometer."

P. 275, next to last line, for figure "370" read "373."

P. 358, α and α' should read θ and θ' (lines 3 and 11).

P. 359, line 2, sin $^2V>K$ should read sin $^2V<K$.

P. 528, in table, fifth column, bottom row "bromoform" should read "iodoform."

It is remarkable, considering recent tendencies, to find so large a general treatise in petrography without an abundance of newly coined terms. The author contents himself with one: melatope, for the spot or "eye" in interference figures representing the emergence of an optic axis.

George D. Louderback

Johnston, John, and Adams L. H. "On the Density of Solid Substances with Especial Reference to Permanent Changes Produced by High Pressures," *Jour. Amer. Chem. Soc.*, XXXIV (1912), 563–84.

Johnston, John, and Adams, L. H. "On the Effect of High Pressures on the Physical and Chemical Behavior of Solids," *Amer. Jour. Sci.*, XXV (1913), 205–53.

Kato, Takeo. "Ueber die Kordieritführenden Einschlüsse in der Lava aus dem Vulkan Komagataké auf Hokkaido, Japan," *Jour. Geol. Soc. Tokyo*, XIX (1912), 27–37.

The volcano of Komagataké is built up of layers of pyroxene andesite and pumice agglomerate. The chief lava streams are three in number, of which the lower is compact, the second less so, and the upper porous and slaggy and filled with inclusions of the same material and fragments of rhyolite, norite, and cordierite-bearing rock. The three lava streams have similar mineral composition and consist of labradorite, hypersthene, and augite, in a glassy or hyalopilitic groundmass. Olivine occurs in the lower part of the middle flow. The underlying rock of Komagataké consists of late Tertiary tuffites, shales, and diatomaceous earths, and the cordierite in the included fragments has been produced by the metamorphism of the sedimentary rock by the andesite.

A. J.

KATO, TAKEO. "The Tourmaline Copper Veins in the Yakuoji Mine, Nagato Province, Japan," *Jour. Geol. Soc. Tokyo*, XIX (1912), 69-88.

The copper veins of the Yakuoji mine occur at the contact between a monzonite stock and Paleozoic sediments, 3 kilometers east of Oda in the province Nagato. Near the contact with the eruptive rock the metamorphosed sandstones and sandy slates are traversed by innumerable minute veinlets consisting chiefly of chlorite and rare tourmaline. The latter mineral occurs in irregular patches and is considered by the author as replacing feldspar grains, partially or entirely.

A. J.

KILLIG, FRANZ. *Das Korund- und Paragonitvorkommen am Ochsenkopf bei Schwarzenberg in Sachsen.* Inaug. Diss., Greifswald, 1912.

The corundum of the Ochsenkopf is a product of regional metamorphism and was derived, contemporaneously with the formation of the surrounding phyllite, from an aluminium rich sediment. The paragonite is not an alteration product of the corundum but has been derived independently from the normal phyllite.

A. J.

KOLDERUP, CARL FRED. "Sogneskollens og Bremangerlandets granodioriter," *Bergens Museums Aarbok*, 1911, Nr. 18, pp. 30.

Describes various granodiorites. The rock from Sogneskollen, in western Norway, is post-Silurian in age. It consists of about 70 per cent feldspar, predominantly oligoclase, with some microperthite, microcline, and orthoclase; 23½ per cent quartz, 6 per cent biotite, and some epidote, garnet, titanite, pyrite, and sericite. The granodiorite of the Island of Svano occurs in the form of a dike. It contains 55⅔ per cent plagioclase (oligoclase-albite and albite), 12 per cent orthoclase and microcline, 23 per cent quartz, 9 per cent muscovite and epidote, and one-third of 1 per cent zircon, apatite, and titanite. The Bremangerland rock consists of 62 per cent feldspar which is entirely andesine, oligoclase, and albite. No orthoclase occurs although a little K_2O is shown by the analysis. Quartz makes up 27¾ per cent of the rock, biotite 9 per cent, magnetite two-thirds of 1 per cent, and pyrite one-third of 1 per cent. This rock cuts the Silurian strata and occurs in fragments in the Devonian. Analyses are given of all of the rocks.

A. J.

KOLDERUP, CARL FRED, og OTTESEN, P. O. "Utsires fjeldbygning og bergarter," *Bergens Museums Aarbok*, 1911, Nr. 17, pp. 21.

Utsire is a small island off the west coast of Norway. About four-fifths of the rock of which it is composed is gabbro, and one-fifth is "granodiorite." A small amount of gneiss was found. An analysis of the "granodiorite" shows but 0.25 per cent of K_2O, and on the mechanical separation of the constituents by means of heavy solutions, no orthoclase was found, the constituents being 50 per cent plagioclase (labradorite 7 per cent and oligoclase 43 per cent), 42 per cent quartz, 8 per cent hornblende, and accessory biotite, iron minerals, and garnet. The rock would better be called a quartz rich quartz diorite. A. J.

KOTO, B. "On nephelite-basalt from Yingé-men, Manchuria," *Jour. Coll. Sci., Imp. Univ. Tokyo*, XXXII (1912), Art. 6, pp. 14, pl. 2.

This is the first recorded occurrence of nephelite basalt in the Japanese-Korean-Chinese region. It is found in the Yingé-men area, forming low hills, and was probably poured out from the junction between the granite country rock and the overlying Cambrian formation. Its age was not determined. The rock is megascopically porphyritic with minute olivine phenocrysts. Under the microscope its texture is nearly holocrystalline, a very small amount of a brownish, granulated, or fibrous base occurring. The minerals, in the order of their abundance, are: titanaugite, magnetite and titaniferous magnetite, nephelite (30 per cent), and olivine (15 per cent). Picotite is an accessory. Neither feldspar nor apatite occurs. According to the quantitative system of Cross, Iddings, Pirsson, and Washington the rock is a shonkinose-monchiquose, the norm giving 45.5 per cent feldspar, 11.9 per cent nephelite, 23 per cent diopside, 1.4 per cent olivine, 7.4 per cent magnetite, 5.5 per cent ilmenite, and 1.0 per cent apatite. A. J.

KRAUS, EDWARD H. "Die Aenderungen des optischen Axenwinkels im Glauberit mit der Temperatur," *Zeitschr. f. Kryst.*, LII (1913), 321–26.

So long ago as 1829 Brewster showed that the optic axial angle of glauberite was changed with change of temperature. Kraus shows that the mineral is uniaxial for sodium light at 42°9 and for lithium light at 51°8. The curves show that, like gypsum, with increasing temperature the angle becomes less and less until the zero value is reached, after which increasing temperature enlarges it. A. J.

REVIEWS

"The Wisconsin Drift Plain in the Region about Sioux Falls, South Dakota." By J. ERNEST CARMAN. *Proc. Iowa Acad. Sci.*, XXVI (1913), 237–49.

It sometimes happens that questions of no great moment in themselves—and these chiefly local—come to play a more conspicuous part in the literature of a science than their real importance warrants simply because someone has seen fit to emphasize them unduly and has made them the ground of unwarranted impressions of the delinquencies of predecessors who kept them more nearly in their proper proportions. This paper of Carman's is an appropriate contribution to the geology of a corner of Iowa and of the adjacent regions, and is fittingly published in the *Proceedings of the Iowa Academy of Sciences.* In addition to this appropriateness and local value, it acquires some general interest as an antidote to impressions less well founded and less appropriately given to the scientific public. The question chiefly discussed has so much of importance as may attach to the precise limits to which the Wisconsin drift extended in the region named and to local phenomena incidental to this. To the general student of geology it is of little moment whether a given ice advance stopped at a particular line or went a few miles farther, if no special significance is attached to the precise extension and localization. In the case in hand, it appears that some three decades ago Chamberlin and Todd, as a part of extensive reconnaissance work intended to outline the essential features of the Wisconsin ice invasion, mapped and described the approximate border of the Wisconsin drift in the Sioux Falls–Canton region of southeast Dakota, that later they introduced slight modifications of the original mapping, and that Wilder, of the Iowa Survey, introduced other variations, as did also some others, none of which had more than local value. Perhaps the only feature of general interest was the slight lobation of the glacier implied by the border of this drift, in which all these were agreed. Shimek, however, in a paper read before the Geological Society of America and printed in *Bull. G.S.A.*, XXIII (1912), 125–54, made it appear that these differences were of a more serious order and summed up his "more important conclusions" with dogmatic impressiveness (p. 154). It now appears from Carman's careful paper that the earlier views were the more nearly correct, and that the earlier authors took views of the value of the features in question more nearly proportionate to their intrinsic importance. Carman seems, therefore, to have performed a distinct service in contributing to the restoration of a more judicious, as well as more judicial, evaluation of the field evidence of the region and of the views that may be best entertained respecting it.

C.

Textbook of Paleontology. Edited by CHARLES R. EASTMAN. Adapted from the German of KARL A. VON ZITTEL. 2d ed. Vol. I.

Since the appearance of the first edition of Eastman's Zittel in 1900, this work has been the standard textbook of invertebrate paleontology in all American colleges and universities, and this new edition will be welcomed enthusiastically by all teachers and students of the subject. In the preparation of the present edition, as was also the case with the earlier one, the editor has had the collaboration of many of the leading American specialists in the field of invertebrate paleontology, as well as several European investigators. The work is not a translation of the latest German edition of Zittel; the several chapters have been thoroughly revised or entirely rewritten, bringing the matter up to date in a most satisfactory manner. Were it not that the same illustrations are used for the most part in both the German and the American editions, large portions of the volume would scarcely be suspected of having any relation whatsoever with the original Zittel, although the scope and general treatment is modeled after the well-known German textbook.

It is not worth while, in this place, to enter upon a discussion of the details of the changes in classification, and the additions which have been incorporated in this edition, but the wonderful progress in our knowledge of the extinct invertebrates which has gone forward since the beginning of the century is all reflected in this book.

S. W.

Petroleum and Natural Gas in Oklahoma. By L. C. SNIDER. Pp. 196, figs. 37, pls. 4. Oklahoma City, 1913.

This book is intended to give to those interested a comprehensive review of the petroleum and natural gas industry in Oklahoma. Methods of prospecting are briefly outlined, the geology of the state is described with special reference to favorable points for the accumulation of oil, and detailed description of the known productive oil fields is given. Supplementing this material are special chapters on the character of the oils, and the methods of transporting and refining them. A review o conditions by counties completes the volume, which should be of much service to those interested in oil, especially in Oklahoma.

A. D. B.

The Examination of Prospect. By C. Godfrey Gunther. New York: McGraw-Hill Book Co., 1913. Pp. 222; 79 figs. $2.00 net.

A small handbook of mining geology. The first chapter is devoted to mining examinations proper, while succeeding chapters deal with the geologic features of ore deposits, with examples drawn from a large number of localities. The book is well illustrated with diagrams taken from geologic reports and with a few photographs. It should prove a valuable book for the geologist in the field, where no access to the original reports is to be had. The subject-matter, though brief, seems to be well organized and carefully condensed. The work is bound uniformly with the publishers' series of field handbooks in flexible leather.

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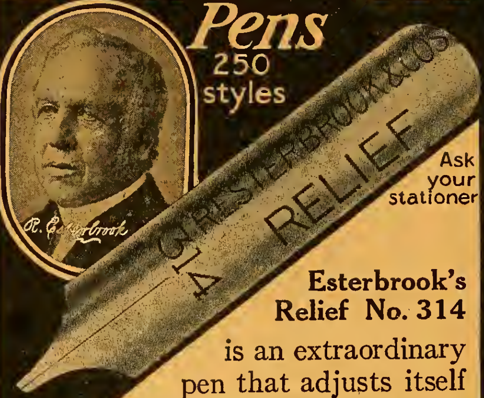

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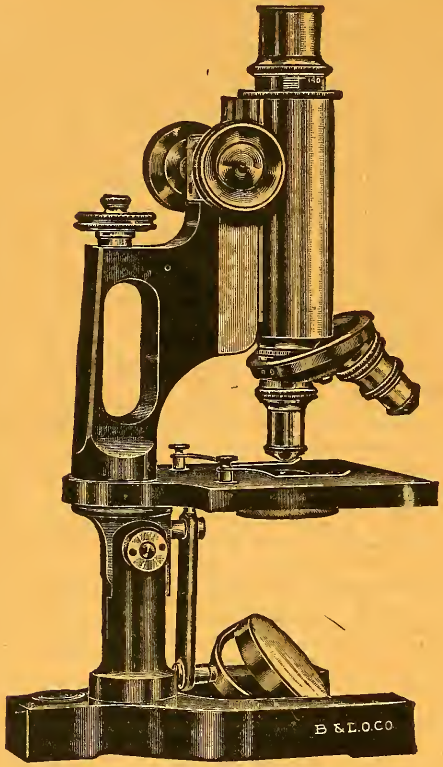

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THE STRENGTH OF THE EARTH'S CRUST

JOSEPH BARRELL
New Haven, Connecticut

PART IV. HETEROGENEITY AND RIGIDITY OF THE CRUST AS MEASURED BY DEPARTURES FROM ISOSTASY

INTRODUCTION AND SUMMARY

In Part I were examined certain geologic tests of the strength of the crust; in Part II the geodetic evidence in regard to the effective areal limits of rigidity; in Part III the influence of variable vertical distribution of density. All three lines of investigation converge toward showing the rigidity of the outer crust—the zone of isostatic compensation—to be such that very considerable stresses can be carried over areas whose radii range between 100 and 300 km. There arise to be considered next the following problems: first, the variability in depth of compensation and its influence; second, whether the stresses represented by the incompleteness of isostasy are carried by the rigidity of the outer crust, or are transferred in some measure to the deeper body of the earth; third, the magnitudes of the stresses, measured in terms of loads, which are indicated by the gravity anomalies and deflection residuals.

It is found in answer that under the hypothesis which forms the basis of Hayford's work, that of uniform compensation, complete at a given depth, there are indications, given by comparing different areas, of a great range in the depth of the bottom. Under an assumption which is probably nearer to nature—that is, the hypothesis of a variable and gradually disappearing compensation—there is room for even a greater heterogeneity of the crust and a greater variability in the depth reached by the zone of compensation. But, on the other hand, it is concluded that the zone of compensation, as an outer rigid crust separated from the rigid inner earth by an intervening zone of lowered rigidity, is a reality in earth structure. The stresses due to the heterogeneities of density and relief within and upon this crust appear to be borne by the crust, not by the inner earth. Under the third subject it appears, upon review of the evidence given by the deflection residuals, that these may be interpreted so as to show departures from equilibrium comparable to the results given by the gravity anomalies, instead of the 250 feet which Hayford thought to exist. The two independent lines of geodetic investigation are thus seen to agree and it may be concluded with some confidence that the individual isostatic regions of the United States are on the average between 600 and 900 feet out of equilibrium. Evidence from other parts of the world appears to show, furthermore, that a number of regions exhibit greater departures from isostasy than those observed within the United States. The strain imposed on the crust by the Niger Delta, though large, is apparently not as large as some made known by geodetic measurements.

Thus from various directions of attack the crust is shown to be an earth shell of high rigidity and consequently high elasticity. Geodetic evidence justifies the view, brought forward by geologic evidence, that the delta of the Niger is to be looked upon as supported by the strength of the crust.

VARIABLE OR CONSTANT DEPTH OF COMPENSATION

The Cordilleran region awoke to an era of great orogenic and igneous activity near the beginning of the Tertiary, and, especially in the Neocene, has become broadly elevated into one of the great plateau regions of the world. Large areas like the Colorado plateaus, which since the beginning of the Paleozoic had rested near sea-level, at times beneath and again slightly above, have been lifted many thousands of feet. Block-faulted structures indicate the dominance of vertical forces rather than surficial compression as the cause of these movements. The uplift has not been of the nature of a broad even upwarp, and adjacent regions show great contrasts in elevation. These different surface results of the interior forces suggest differences in elevatory forces at comparatively shallow depths. The region is known to be in a fair degree of isostatic equilibrium notwithstanding the high relief. Davis has shown why these movements cannot be regarded as differential sinkings toward the center of the earth.[1] These features suggest, then, subcrustal decreases in density during the Tertiary as a cause of the broad movements of elevation.

The rising of great bodies of magma to high levels in the zone of isostatic compensation, their irregular distribution, the great quantities of heat and gases which would invade the roofs are suggested by the observed evidences of regional igneous activity at the surface as the probable causes of the changes in density and regional vertical movements. A consequence of such a cause would be a lessened strength of the crust to resist strain, a lessened depth to the zone of isostatic compensation, and a decreased size of the unit areas departing from equilibrium.

The history of the Cenozoic in the Cordillera has repeated the history of other regions at other times, either in the Archean igneous activity or later. The slow conduction of this excess heat from the outer crust, the solidification of the reservoirs of magma, would, in the course of ages, bring about a new rigidity. Upon disturbances of the equilibrium by erosion or compressive forces there would be found a new and greater depth to the zone of compensation.

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[1] "Bearing of Physiography upon Suess's Theories Abstract," *Intern. Geog. Cong., 8th Report*, 1905, p. 164; *Amer. Jour. Science* (4), XIX (1905), 265–73.

Where ages of uplift and erosion have followed periods of igneous activity there are revealed great bodies of intrusive rock varying in density from granites at 2.65 to gabbros at 3.0. These great batholiths are of irregular distribution in the crust, both vertically and horizontally. Their abundance increases downward so far as erosion has revealed the evidence. The outer crust of the earth has become vertically and areally heterogeneous by such means and should cause variations and irregularities to an appreciable degree in the distribution of isostatic compensation, as noted under the topic of the influence of variable rate of compensation upon gravity anomalies. Here we note in addition the decreased depth of compensation and decreased rigidity at the time of intrusion.

Hayford notes that the stations classified into geographic groups show as a rule as great contradictions in depths of compensation between adjacent groups as in those which are far apart. This variation between adjacent groups is taken by him as weakening the evidence that there is any real variation in the depth of compensation over the whole area investigated.[1] For the reasons outlined previously, the present writer, influenced by the geologic inferences, does not view such irregularity of distribution as proof that the evidence is weak and conflicting. The strength of the evidence must be judged rather by the nature of the residuals. Hayford points out that the depth of compensation in the West seems on the whole to be somewhat less than in other parts of the United States, though he does not regard it as safe to assert that it does exist. On dividing the whole area into four sections, the minimum sum of the squares of the residuals indicates depths as follows as best satisfying the hypothesis of uniform distribution of compensation:

From all residuals of the central group, 174 km.
From all residuals of the northeastern group, 187 km.
From all residuals of the southeastern group, indeterminate.
From all residuals of the western group, 107 km.[2]

In the 1909 paper Hayford gives a tabulation of the residuals for fourteen geographic groups. The results for the United States as a

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[1] 1909, pp. 58, 59.

[2] 1906, pp. 142–46.

whole and for the groups showing the shallowest, deepest, and the most irregular compensation are quoted below.[1] That solution is regarded as nearest the truth which gives the smallest mean value of the squares of the residuals.

TABLE XIX

PROBABLE DEPTHS OF COMPENSATION

GROUP	NO. OF RESIDUALS δ	MEAN VALUES OF THE SQUARES OF THE RESIDUALS IN VARIOUS GROUPS					MOST PROBABLE DEPTH
		Solution B Infinite Depth	Solution E 162.2 Km.	Solution H 120.9 Km.	Solution G 113.7 Km.	Solution A 0.0 Km.	Km.
United States (all observations)...............	733	146.50	14.05	**13.73**	13.75	25.77	**122.2**
Group 12 (parts of Minn., N.Dak., S.Dak., Neb., Kan.)...............	36	196.57	**7.00**	7.47	7.59	11.46	**305**
Group 5 (Mich., Minn., Wis.)	52	34.97	**23.60**	23.64	23.67	27.53	152
Group 8 (parts of Utah, Nev., Cal.)..........	42	128.97	22.27	18.79	**18.25**	35.78	**66**
United States (residuals multiplied by 1.327 to compare with Group 8)	....	194.40	18.65	**18.23**	**18.25**	34.21	....

It is seen that the mean value of the squares of the residuals in group 12 with most probable depth of 305 km. is considerably less than for the United States as a whole, in part no doubt owing to the moderate relief, yet the differences between the residuals in group 12 for the different solutions is much more pronounced than for the United States as a whole. The number of stations, 36, is large enough so that this can hardly be regarded as accidental. On the contrary, it would appear that for the whole United States the group differences are sufficient to mask in part the accuracy of the mean result of 122 km. and that the depth of compensation within certain groups is more reliable than for the United States as a whole.

In group 8 with most probable depth of 66 km. the mean value of the squares of the residuals is nearly 50 per cent higher than for

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[1] 1909, pp. 55–58.

the United States as a whole, a value which may be ascribed to the mountainous relief and the support of individual mountains and ranges by the rigidity of the crust. Nevertheless the residuals for the several solutions fall into a somewhat regular system, and solutions E, H, and G are more sharply differentiated from the most probable one than for the whole United States. They may be compared better with the latter if the residuals for the whole country are multiplied by 1.327 as a factor in order to give the same numerical value under solution G. This is done at the bottom of the table. It would appear from these figures as though the arguments previously given from geologic analysis receive considerable support from the geodetic results and point to a much shallower depth for isostatic compensation in the Great Basin than over certain other portions of the United States. Furthermore, in the examination of the question of local versus regional compensation, it was only the forty mountain stations classified into two groups according to elevation which gave any suggestion that regional compensation to a radial distance of 166.7 km. was not about as probable as more local compensation. In these two lines of geodetic evidence as to limited depth and breadth of compensation there are suggestions therefore which support the geologic inference that the crust of the Cordilleran region may be weaker than over the United States as a whole. On the other hand, the warping or faulting-down of ancient continental areas into marginal sea-bottoms implies an increasing density of the subcrust and therefore possibly an increasing rigidity and strength under such areas. Such a contrast between the Atlantic Ocean bottom and the Great Basin would correspond to the great strength of crust necessary to sustain the delta of the Niger as compared with the moderate rigidity found by Gilbert for the crust beneath extinct Lake Bonneville, located within the limits of group 8.

The regions of shallower compensation in the United States are on the whole marked probably by a higher temperature gradient, the regions of deep compensation by a lower. This is illustrated by the very high gradient of the Comstock mine in Nevada and the very low gradient which is found in the Lake Superior copper mines. The temperature gradient may measure the depth to a zone of low rigidity, determined by a certain relation of temperature and pressure.

Within an overlying zone of high rigidity, even where it is of uniform depth, the geodetic measurements of the depth of compensation may not, however, show uniformity. If the density is unequally distributed, the compensation of a region may be nearly completed at some depth above the base of the rigid zone, the lower part consisting of rock of mean density and therefore not possessing influence. A region of deep and marked rigidity, if characterized by notable irregularities in the distribution of either density or relief, would show large residuals. A region characterized by more uniform distribution of density and gentle relief would show lower residuals even with the same rigidity. A region with deep compensation would show within the limits of the group lower residuals for the same degree of uniform compensation, than where compensation was at lesser depths, since the attracting masses are spread over a greater distance.

As applications and tests of these principles, it is to be noted that group 5, embracing the Lake Superior region with its low-temperature gradients, has the highest residuals of any group in the United States. Further, the mean values of the least squares for the different solutions show less differentiation than in any other group. These facts suggest irregular distribution of density, high rigidity, and the zone of rigidity may extend below the most probable depth, 152 km., indicated for the limits of compensation. The topographic deflections are only 58 per cent compensated. The contiguous group to the southwest, No. 12, shows the lowest residuals of any group, the separate solutions are sharply differentiated and the depth is the greatest in the United States. On the side of this area, the gravity anomaly at St. Paul, 0.059 dyne per gram, is, next to Seattle, the largest found thus far in the United States. It may be concluded, then, that in this part of the continent, undisturbed by igneous activity or mountain-building since the pre-Cambrian, the depth of the zone of rigidity appears to be very great. The irregularities in residuals in group 5 may date from the Keweenawan period, when enormous masses of basic and therefore heavy magmas were intruded and extruded in the Lake

Superior region. If such be the case it shows the long endurance of strains borne by this part of the earth. In the almost universal epeirogenic movements which marked the close of the Tertiary and opening of the Pleistocene, the Lake Superior basin showed notable downwarping, its bottom being now beneath the level of the sea. It formed a trough which directed the flow of glacial ice. The latter must have scoured it clean but can hardly be ascribed as the cause of the existence of the basin. The crust movements have doubtless been in the direction of relief of stress, but the relief has been but partial; geodetic investigation reveals that the age-long load is yet borne.

DEPARTURES FROM ISOSTASY SUSTAINED BY RIGIDITY IN THE ZONE OF COMPENSATION

It was concluded under the last topic that the rigidity over certain parts of the earth probably carries the zone of possible compensation as deep as 300 km. even under the assumption of uniform rate, an assumption which tends to minimize the depth; whereas in other regions under that hypothesis it is less than 100 km. in depth. This raises the question whether the regional departures from isostasy are carried as strains within the zone of compensation or are transferred in part to the deeper body of the earth. There are reasons for believing that the former is the case, pointing by inference to a zone of markedly diminished rigidity between the rigid lithosphere and still more rigid centrosphere.

The geodetic evidence consists in the large values of the squares of the residuals for solution B, the solution which postulates extreme rigidity and compensation at infinite depth. For the whole United States, as shown in the Table XIX, p. 293, the mean value of the squares of the residuals for solution B is 10.7 times the value for solution H. But for group 12, that for which the most probable depth of compensation is 305 km., the distinction is still greater; solution B showing a mean-square residual 28 times greater than for solution E. Dividing in this way the value for solution B by the value for the most probable solution, and taking the mean for all those groups which indicate a depth of compensation greater than the average for the United States, it is found that the ratio is twice as great for the groups with deep compensation as for the United States as a whole. That is, the groups with deep compensation, instead of showing a leaning toward solution B show on the contrary more definitely that it is not true. The hypothesis of uniform compensation complete at a certain depth appears to be more nearly true for regions with deep compensation than for shallow compensation. This does not mean, however, a lesser rigidity of the crust for the regions with deep compensation, their high capacity to carry strain being shown by the large gravity anomalies which are found in places within them.

There seems to be no evidence, however, that the zone of diminished rigidity is sharply bounded or is marked by real liquidity. It is doubtless due to the gradual rise of temperature with depth, overcoming within a certain zone the influence of the increasing pressure. Seismologic and tidal evidences show, furthermore, that under stresses of relatively brief duration the earth acts as a unit and as an elastic rigid body. The physical condition of the zone of low rigidity may approach that of a highly viscous fluid, the time element thus entering within these limits as a fundamental factor. This zone is incapable of bearing pronounced strains for long periods in the manner of the zone above. In geologic operations it thus serves to separate the mode of expression of forces generated below from those originating above this level. The former give rise to the great compressive movements in the outer zone, the latter to the vertical movements not determined by tangential compression.

INTERPRETATION OF DEFLECTION RESIDUALS IN TERMS OF MASSES

On p. 59, paper of 1909, Hayford shows that the actual deflections of the vertical average only one-tenth of what they would be if the continent and the portions of the ocean basins which were included in the calculations were both underlain by matter of the same density and the relief sustained wholly by the rigidity of the crust. The effect of the topography calculated on this assumption —that the density is uniform and the larger as well as the smaller features are sustained by rigidity—gives what is known as the topographic deflections. These, as stated above, average ten times the value of the actually observed deflections. The surface may be regarded, therefore, as nine-tenths compensated by variations of density. The details for the five more significant groups are given below:[1]

TABLE XX

1	2	3	4	5	6	7	8
No.	Area of Group	No. of Stations in the Group	Probable Depth of Uniform Compensation in Kilometers	Mean of Topographic Deflections without Regard to Sign	Mean Residual of Solution H without Regard to Sign	Value in Sixth Column Divided by Value in Fifth Column	Percentage of Completeness of Isostatic Compensation for Solution H
12....	Parts of Minn., N.Dak., S.Dak., Neb., Kan.......	36	305	8.23	2.17	0.26	74
8....	Parts of Utah, Nev., Cal....	42	66	32.23	3.57	.11	89
10....	Cal., southern part........	57	126	65.44	3.91	.06	94
9....	Cal., northern part........	60	176	60.50	2.93	.05	95
14....	Northern Cal., western Ore., and Wash..............	37	84	53.68	3.37	.06	94
	Whole United States......	733	122	30.37	2.91	0.10	90

Group 12 gives the greatest depth for uniform compensation. By using the residual for Solution E, 2.09, the percentage of completeness of compensation would have been 75, a trifle more than for Solution H, but still next to the least perfect in the United States.

Group 8, the Great Basin region, has the lowest depth of compensation but shows about the average approximation to isostatic equilibrium.

Groups 10, 9, 14 comprise the Pacific Coast Ranges. They give the highest topographic deflections of the United States, doubtless on account of the great relief of the ocean basin and continental border, but the actually observed deflections do not differ greatly from group 8 or the mean for the whole United States. The result is that in this mountain region bordering the continent the degree

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[1] Taken from pp. 56, 58, 69, and illustration No. 2, Hayford, 1909.

of completeness of compensation is the highest in the United States.

On the basis of the figures for the whole United States Hayford writes: "The average elevation above mean sea-level being about 2,500 feet, this average departure of less than one-tenth from complete compensation corresponds to excesses or deficiencies of mass represented by a stratum only 250 feet (76 meters) thick on an average."[1] It is this last statement, interpreting the deflection in terms of mass, which has meaning to the geologist. It has been widely quoted as perhaps the chief geologic result of the work and yet the writer believes that it is without basis. By an oversight of the author he misinterprets his results. If the present writer is correct in making this statement it should not be taken, however, as a criticism of the mathematical portion of the work.

The sea-level is from the standpoint of the problem of isostatic compensation but little more than a datum surface. Imagine the ocean water to be converted into rock of density 2.7 of the same mass as the water and resting on the present ocean bottom. Every thousand feet of water would be replaced by 380 ft. of rock. Then the sea-level surface after this transmutation is seen to lose all real significance.[2] To show the fallacy of taking this level as a basis for interpreting the departures from compensation in terms of thicknesses, let attention be given to groups 1, 2, 3, 4, 6, 11,[3] which cover the United States east of the Mississippi River. The average departure of these from compensation is 0.11, which on the basis of Hayford's statement means that the surface on the average departs but 275 ft. from the level which would give complete isostatic equilibrium on the hypothesis of uniform distribution of compensation to a depth of 122 km. If, however, this eastern third of the United States be regarded by itself, its average elevation may be assumed as 1,000 ft. (it is probably less). By the same reasoning as Hayford applied to the whole United States, 11 per cent of this is 110 ft. Therefore although the average deflections are slightly

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[1] 1909, p. 59.

[2] More accurately, the equivalent rock should be imagined as suspended at the mean depth of the water, but the effect of the difference in level is negligible upon the topographic deflection.

[3] 1909, p. 59.

greater than for the United States as a whole, it would be concluded that for the region east of the Mississippi the departure from the levels giving complete compensation averages not more than 110 ft. instead of the 275 ft. previously stated.

Or, again, imagine a rise of ocean-level so that the average elevation of this part of the continent is reduced to 100 ft. without changing the detail of the topography. The deflections would suffer only small alterations due to the added mass of water. Although the crust remained without change, the same reasoning would then lead to the conclusion that the topography departed on the average but 11 ft. from the levels which would give complete compensation.

In computing the influence of the topographic irregularities and their compensation upon the deflection of the vertical, all the topography was taken into account up to a radial distance of 4,125 km. from each station. This radius is approximately the length of 37° of latitude. It embraces the Pacific Ocean out to the Hawaiian Islands and to ten degrees south of the equator, and the Atlantic Ocean out to the Azores. The relief within this region ranges from −8,340 m. north of Porto Rico to +6,220 m. in Mount McKinley, +6,247 in Chimborazo; a total differential relief of about 14,590 m. About one-half of the topography surrounding the coast stations consists of ocean bed. Even for the stations in Minnesota, farthest removed from the sea, about one-third of the surrounding topography within the limits is deep ocean, but lying at a greater distance and carrying lesser influence. The average depth of the oceans influencing the deflection of the station at mean distance inland may be assumed for purposes of illustration to be about 5,000 meters. This depth of water is equivalent in mass to 1,900 m. of rock of density 2.67, leaving an effective ocean depth of 3,100 m. Add the mean continental elevation of 760 m. to this, and 3,800 to 3,900 m. represents about the effective mean relief between continent and ocean. On coast stations this differential relief has greatest influence. For inland stations the several portions of the continent have proportionately more effect. For the United States as a whole it is this relief of between 3,500 and 4,000 m. between continent and ocean, more than the relief between the major features of the continent, which is nine-tenths compensated by the corresponding variations in crustal density, not the 760 m. which is the average elevation of the United States above sea-level.

It is the belt of Pacific coast stations which measures more closely than other groups the degree of compensation accompanying the continental relief above the ocean bottoms. These stations lie in groups 10, 9, and 14, for which the mean residuals are but 0.06, 0.05, and 0.06 of the mean topographic deflections respectively. These residual deflections indicate that for this coastal zone the departures from complete compensation amount to but 5 or 6 per cent. If the mean effective relief which controls this be assumed as 4,000 m., then the mean departure from equilibrium is represented by a mass 200 to 240 m. thick, approximately between 650 and 800 ft. On the other hand, groups 5 and 12 are those farthest removed from the ocean basins and their deflections are controlled most largely by the internal continental relations. For them the departures from complete isostatic compensation as measured by the ratio of the mean residuals to the computed topographic deflections amount to 42 and 26 per cent. The mass to which this is equivalent may be no greater than the 5 per cent departure on the Pacific coast. These estimates fall into the same order of magnitude as that of the masses represented by the gravity anomalies.

This reconnaissance of the problem is sufficient for present purposes. It is readily seen that even greater difficulties stand in the way of a precise statement regarding the equivalence of mass corresponding to deflections of the vertical than arose in the interpretation of the gravity anomalies. The residual for each observed deflection is the sum of the influences of all the excesses and deficiencies of mass as compared to solution H on all sides of a station. The effect of each unit varies inversely with the square of the distance and directly with the sine of the angle which the line of force makes with the horizontal passing through each station. A combination of the data from the measurements of the intensity of gravity with those of the deflections of the vertical would apparently be necessary to state for each region the equivalence in terms of mass which is implied by the residual at each station.

MAXIMUM LOADS INDICATED BY ANOMALIES

Hayford and Bowie consider that 0.0030 dyne of anomaly may be regarded as equivalent to 100 ft. of rock possessing a density of 2.67. From the previous considerations it would seem that this is probably too high for a mean figure, but may apply to certain areas, especially those with extremely broad boundaries. In other regions 0.003 may be far too high, since it is shown under the topic "Variable or Constant Depth of Compensation" that in certain parts of the United States the depth of the zone of compensation probably goes notably deeper than in other parts and the density may be distributed either nearly uniformly or with considerable irregularity. The greatest depth of compensation indicated for any region is 305 km. A unit thickness of mass uniformly distributed to this depth and to a radius of 166.7 km. would give but 0.0014 of anomaly instead of 0.0024 as given by a depth of 114 km., or 0.0030 as taken by Hayford and Bowie. For general use 0.0024 dyne is perhaps the best value, corresponding to a uniform distribution of a unit excess or defect of mass to a depth of 114 km. and to a radial distance of 166.7 km. For the mean anomaly of 0.018 this would give 750 ft. of elevation as the mean departure of the surface of the United States above or below the position giving isostatic equilibrium, instead of 600, or more exactly, 630 ft. as taken by Bowie. The largest known anomaly in the United States is at Seattle, −0.093. This corresponds to a defect in mass equivalent to a stratum 4,000 ft. thick if the divisor is 0.0024, a stratum 3,200 ft. thick if the divisor is 0.0030. At Olympia, but 50 miles or 80 km. distant, the anomaly is +0.033, corresponding to excesses of mass of 1,375 or 1,100 ft., according to the divisor. The difference of regional load between Olympia and Seattle becomes 5,375 or 4,300 ft.

But these relations of unit thickness of mass to the gravity anomaly are based on the assumption that the excess or deficiency of mass extends to as great a radial distance as 166.7 km. radius. This minimizes the thicknesses or densities needed to account for the anomalies above what would be required for a more local concentration of mass. But an inspection of the distribution of gravity and deflection residuals shows that in many cases the masses producing the greater disturbances have much smaller size. This is especially striking in the case of the largest negative anomaly in the United States, that at Seattle, only 50 miles from the large positive anomaly at Olympia. The latter is surrounded on all sides by negative anomalies as follows:

DISTANCES FROM OLYMPIA, WASHINGTON

Astoria, Ore.	76 miles	S.W.	−.013 dyne anomaly
Heppner, Ore.	195 "	S.E.	−.027 " "
Skyhomish, Wash.	84 "	N.E.	−.028 " "
Seattle, Wash.	50 "	N.N.E.	−.093 " "

The excess of mass which exists in the vicinity of Olympia, above that required for compensation under solution G, must therefore be much less than 166.7 km. (102.5 miles) in radius. The same is doubtless true of that excessive deficiency which exists at Seattle, since the anomaly sinks to less than one-third the value at Skyhomish only 45 miles east, and changes to a large positive anomaly at Olympia, 50 miles south-southwest.

The large positive mass in the vicinity of Olympia must diminish appreciably the effect of the still larger negative mass in the vicinity of Seattle. The latter with the other surrounding negative masses must diminish still more the anomaly due to the positive mass at Olympia. Furthermore, it is highly improbable that the observations at Seattle should happen to be made at the point of really maximum anomaly. Let the very moderate assumption be made then that the abnormal Seattle mass as a unit by itself would give a maximum anomaly of −0.100 dyne. It would doubtless give more. Let limiting assumptions be made as to the dimensions and density of this mass such that the actual volume and density are quite probably embraced somewhere within these limits. Tables XXI[1] and XXII show the results of such assump-

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[1] Table XXI is readily derived from Table X, Part III. Take, for example, the cylinder of radius 1,280 meters, depth of 1,000 feet, and density 0.267. Multiply its dimensions by 30 and the volume of each unit portion will be increased by the cube of 30. The attraction of each unit of mass on the given point will vary inversely with the square of the distance and will therefore be diminished by the square of 30. The anomaly will consequently increase directly with the dimensions, provided that the density remains constant. This gives the basis for the calculations in column 2, Table XXI.

tions. In Table XXI the attracting mass is supposed to have the form of a vertical cylinder. With a given anomaly the deficiency

TABLE XXI

VERTICAL CYLINDERS GIVING A NEGATIVE GRAVITY ANOMALY OF 0.100 DYNE AT CENTER OF TOP SURFACE OF CYLINDER

1	2	3	4	5
Diameter	76.8 km.	51.2 km.	102.4 km.	51.2 km.
Depth	9.15 km.	30.5 km.	61.0 km.	61.0 km.
Density	− 0.31	− 0.15	− 0.07	− 0.12
2.80−Density	2.49	2.65	2.73	2.68
Thickness of cylinder of same area and mass, but density 2.67	1,080 m. 3,550 ft.	1,700 m. 5,600 ft.	1,700 m. 5,600 ft.	2,770 m. 9,080 ft.
Anomaly per 100 feet of mass of density 2.67 expanded to depth of cylinder as given in second line	0.0028 dyne	0.0018 dyne	0.0018 dyne	0.0011 dyne

TABLE XXII

SPHERES GIVING A NEGATIVE GRAVITY ANOMALY OF 0.100 DYNE AT POINT VERTICALLY ABOVE ON THE SURFACE OF THE EARTH

1	2	3	4	5
Diameter	50. km.	100. km.	50. km.	100. km.
Depth to center	25. km.	50. km.	32. km.	64. km.
Density	− 0.144	− 0.072	− 0.236	− 0.118
2.80−Density	2.66	2.73	2.56	2.68
Length of polar axis of oblate spheroid of same equatorial section and same mass, but density 2.67	2,700 m. 8,850 ft.	2,700 m. 8,850 ft.	4,420 m. 14,500 ft.	4,420 m. 14,500 ft.
Anomaly per 100 feet of polar axis of mass at density 2.67 if expanded to diameter of sphere	0.0011 dyne	0.0011 dyne	0.0007 dyne	0.0007 dyne

of mass will be least if the cylinder extends from the station downward instead of being at a greater depth. Furthermore, for a given volume and density of cylinder the gravitative force will vary according to the ratio of the depth to the diameter.

Let H = depth
Let $2R$ = diameter
Let F = gravitative force

Then $\pi R^2 H =$ the volume, a constant. To find the ratios of H to R which give maximum attraction for unit mass

Let $R^2 H = 1$ and solve for various values of R the equation

$$F = 2\pi\rho\gamma \left[\frac{(R^3+1) - \sqrt{R^6+1}}{R^2} \right].$$

Several solutions are as follows:

For $H=0.75$, $R=1.15$; $F=(2\pi\rho\gamma)\ 0.523$
$H=1.00$, $R=1.00$; $F=(2\pi\rho\gamma)\ 0.586$
$H=1.50$, $R=0.81$; $F=(2\pi\rho\gamma)\ 0.609$
$H=2.00$, $R=0.71$; $F=(2\pi\rho\gamma)\ 0.586$
$H=4.00$, $R=0.50$; $F=(2\pi\rho\gamma)\ 0.200$

This shows that the gravitative force is a maximum for a cylinder of constant volume and mass in which the depth varies from one-half the diameter to four-thirds the diameter. The force varies but slightly between those limits. The cylinders of columns 3, 5, and 6, of Table XXI, lie within these limits. Thus all the assumptions thus far made favor the minimization of the negative load which produces the Seattle anomaly.

Taking the mean density of the outer part of the lithosphere as 2.80 it is seen that the cylinder of column 2, Table XXI, has a density below that of the lightest rock-making minerals and would require the existence of a molten magma or of abnormal pore space to great depth. It may therefore be eliminated as not probable. Cylinders 3, 4, and 5 show densities within the limits of granite, the lightest of the abyssal igneous rocks. It may be concluded, therefore, that the deficiency of mass, if of approximately cylindrical form, is equivalent to a negative load of between 5,000 and 10,000 feet of rock, extending over a distance of from 50 to 100 km., or a somewhat less local load superposed upon a broad but small regional load of the same sign. The nature of the assumptions has been such that we may conclude with confidence that the Seattle anomaly corresponds to at least 5,000 feet of rock and may reach a considerably higher figure, perhaps 10,000 feet. Furthermore, Hayford's unit mass, extending to the areal limits, 100 feet thick and density 2.67, would here produce an anomaly as low as between 0.0010 and 0.0020 dyne.

Instead of a cylinder suppose the mass which produces the deficiency of gravity to approximate more to the form of a sphere. The results are shown in Table XXII. In columns 2 and 3 the sphere is tangent to the surface, a position diminishing the mass for a given anomaly. In columns 3 and 4 the top of the sphere is 7 and 14 km. deep respectively. The low density of column 4 shows it to be beyond the limiting conditions. The load, though negative in sign, is seen to be equivalent in order of magnitude to the greater volcanic piles; 30 to 60 miles in diameter, 9,000 to 14,000 feet in height for rock of density 2.67. The anomaly produced by the unit mass of 100 feet thickness and density 2.67, considered here as 100 feet of polar diameter for a spheroid of the given horizontal dimensions, ranges between the low values of 0.0007 and 0.0011 dyne.

From a consideration of these two tables it is seen that the large anomalies require either a variation of mass equivalent to as much as 5,000 feet of rock extending over some thousands of square miles or to 10,000 feet of rock, more or less, extending over 1,000 square miles, more or less. These tables determine the order of magnitude, but the data are not sufficient to permit a more accurate solution of the problem.

Thus this detailed examination of the anomalies in the region of Seattle shows that the divisor of 0.0030, as taken by Hayford and Bowie, or 0.0024, as considered here the best for general use, is too high for the more limited areas of high anomaly. The latter may be regarded as made up in part of a regional portion for which the divisor of 0.0024 would be applicable and a local portion for which the divisor is probably not over 0.0015. As a mean value, for the more limited areas of large anomaly the amount due to the unit thickness of 100 feet of rock of density 2.67 should apparently not be taken as over 0.0020 dyne.

In forming conceptions as to the uncompensated vertical stresses existing widely in the earth's crust it is important to know the maximum range of departures from the mean stress as well as the latter. These can be studied well in Fig. 5.[1] The mean of fourteen maxima of defect of gravity is −0.033, the mean for eleven

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[1] Fig. 5, p. 153, Part II; also see Hayford and Bowie, pp. 107–8.

areas of excess of gravity is +0.034. With the exception of the Seattle stations with an anomaly of −0.093, none reach a value of 0.060. It is thus seen that the average notable maximum is not far from twice the mean anomaly. Even by using a uniform divisor of 0.0024 or 0.0030 to convert anomalies, regional departures of load amounting to 1,300 or 1,500 ft. over areas of several square degrees are found to be not uncommon. Over smaller areas the loads rise to about three times the mean, and at Seattle to five times the mean. These figures of course do not measure simply the elevations or depressions of uncompensated erosion features. On the contrary, if the hills and valleys be imagined as smoothed out, then the resulting mean surface would be out of isostatic equilibrium in the same direction over distances amounting frequently to hundreds of kilometers and attaining maximum departures too low or too high over smaller areas by these figures.

But an inspection of the contour map of gravity anomalies (Fig. 5) shows that the large anomalies, those of 0.040 dyne or above, are all located by Hayford and Bowie as centers of maximum anomaly, though the nearest adjacent stations average as much as 100 miles distant. Between the widely spaced stations, the anomaly gradients are gentle. But where the stations form a series closer together, as that from the city of Washington to New York City, the gradients are seen to be steeper and more irregular. It is to be presumed that a further multiplication of stations would show increased complexity over the whole country and reveal maxima higher than those now recorded. The value of the mean anomaly without regard to sign should furthermore increase somewhat through the discovery of additional areas of maximum value. Areas of regional positive or negative anomaly would persist in something of their present size, but within broad areas of anomaly of one sign should be discovered smaller areas of opposite sign which are now unknown. Upon the completion of such a detailed survey the high anomaly of Seattle would not appear so exceptional as it does at present.

The chart of the residuals of Solution H[1] shows within the larger areas of like deflection of the vertical many large and sharp

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[1] Illustration No. 3, Hayford, Supplementary Paper, Bowie, Illustration No. 5.

variations in value and in direction. The resultants of the plotted arrows point toward the centers of exceptional mass and their rapid changes in value and direction point toward the existence of many comparatively shallow masses. The epicentral points above such masses are those where the gravity anomaly, Fv, is at a maximum. If a hidden mass may be regarded as approaching a spherical form and has its center at depth D, the following relations exist between the value of the gravity anomaly and the distance x from the epicenter:

Fv = Maximum for $x=0.00\,D$
Fv = .75 max. " $x=0.46\,D$
Fv = .50 max. " $x=0.77\,D$
Fv = .25 max. " $x=1.23\,D$

If, for example, an approximately spherical mass has its center at a depth of 32 km., .005 of the earth's radius, the anomaly Fv will fall to half-value at a distance of 25 km. from the epicenter. If the center is 64 km. deep, the anomaly will fall to half-value at 50 km. from the epicenter. Between stations located 100 km. apart by far the greater number of real maxima would be missed, and in so far as they depended upon masses in the upper half of the zone of compensation the indicated maxima would at most places be less than one-half the real maxima.

The stresses acting within the crust owing to excesses or deficiencies of mass are not so concentrated and therefore not quite so great as if those abnormalities of mass existed as surface loads of rock of density 2.67 in the manner imagined for the interpretation of anomalies.[1] Nevertheless to gain a conception of the meaning of the gravity anomalies, imagine the present compensated topography to be smoothed out to sea-level and the variations of mass away from isostatic equilibrium to become variations of volume upon its surface. The anomaly contours will then become topography contours, the line of zero anomaly will become the datum plane. The values in mass to be assigned to the successive anomaly contours can only be given in mean figures. It has been shown however in Part III that balanced vertical irregularities of density

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[1] The relations of mass and its distribution to the resulting stresses will be considered in a later part.

do not play a large part in causing gravity anomalies. It will be shown later that neither can nucleal heterogeneity below the 200 to 300 km. level of isostatic compensation account for a large part. The anomalies represent in greater part real departures from isostasy and, as shown in this section, the limited areas of high anomaly are to be interpreted as implying on the whole a local load in higher ratio to anomaly than do the broad areas of anomaly. The average relation thought to exist is shown then in the following table:

TABLE XXIII

AN ESTIMATED AVERAGE RELATION OF ANOMALY CONTOURS TO CONTOURS OF EQUIVALENT ROCK MASSES OF DENSITY 2.67

Anomaly Contour, Positive or Negative	Assumed Divisor for 100 Feet of Rock upon a Level Surface	Equivalent Contour in Feet, Positive or Negative
.020	.0025	800
.040	.0023	1700
.060	.0020	3000
.080	.0018	4500
.100	.0016	6300

Upon conversion of a detailed anomaly map, if such existed, into the equivalent topographic contour map by means of such ratios as those given in Table XXIII, the whole United States with its compensated topography previously smoothed out to sea-level would be reconverted into a roughly mountainous country with no notable distinction between what are now the central plains and mountainous border regions of the continent. On to broad plateaus or basins upward of 1,000 feet from the mean elevation would be added higher elevations and depressions. The extreme differential relief would probably be in the neighborhood of two miles though the average departure without respect to sign from the mean surface of the geoid would probably be between 800 and 1,000 feet. Though everywhere as irregular as a mountainous country, there would be little or no relief of the mean level of this hypothetical surface above the ocean bottoms and no such broad and high masses as the Cordilleran plateaus would remain within its limits. The major relief of the continent above the ocean bottoms would be about nine-tenths eliminated and the mean elevation of all areas as great as several hundred miles in width would be reduced to a small figure. This is the effect of isostasy. But within these unit areas which measure the limits of regional compensation would everywhere rise a rolling mountainous surface.

Imagine the hypothetical surface as broad as the United States, concealed from view by an impenetrable envelope of cloud, and aerial explorers to sink a sounding line to this invisible land at 124 places chosen at random. The resulting contour map compiled from these soundings would yield a much smoothed and flattened surface such as is shown in the contour map of gravity anomalies. Many of the soundings taken really on mountain slopes, because they were the highest of those made, might be casually interpreted as located on mountain peaks. The latter, standing sharp and high, would be missed save for an occassional lucky chance of the sounding line.

Interpreted in terms of weights and stresses, it is seen that even the parts of the continent appearing to the eye as plains long in geologic quietude really conceal within them strains as great as those imposed by the weight of mountains. That these great strains have been born for geologic ages, in many localities probably from the Archeozoic, gives a surprising conception of an enduring rigidity and elasticity of the crust wholly at variance with certain current doctrines regarding the weakness of this zone. It is not here found to be a failing structure.

On p. 81 Hayford and Bowie give the new-method anomalies for sixteen stations not in the United States. An abstract is given below of the greater anomalies from that table with the addition of Seattle. The thickness of stratum taken as corresponding to the anomaly is also added. This thickness, if the compensation is uniform with depth, measures the distance by which the earth's surface is out of isostatic equilibrium at those points. A plus sign indicates an excess of mass and a consequent tendency to sink, resisted by rigidity; a minus sign a defect of mass and therefore the existence of an upward strain.

The divisor 0.003 dyne of anomaly, taken as the equivalent of 100 feet of abnormal mass of density 2.67, is Hayford's figure. As previously discussed it is thought to minimize too much the thickness of equivalent rock. It is given, however, for comparison with the column derived from the use of 0.0024 as a divisor. This is regarded as a better average figure, but for some cases at least, as shown for Seattle, this also may give too low a result.

TABLE XXIV

Number and Name of Station	Elevation in Meters	New-Method Anomaly	Thickness of Equivalent Stratum on Land in Feet	
			0.003 Anomaly =100 feet	0.0024 Anomaly =100 feet
2. Tonga plateau, Hecker, at sea	−2,700	+0.255	+8,500	+10,625
4. Tonga deep, Hecker, at sea	−6,500	− .184	−6,130	− 7,660
9. Mauna Kea, Hawaiian Islands	+3,981	+ .183	+6,130	+ 7,660
10. Hachinohe, Japan	+ 21	+ .110	+3,670	+ 4,590
13. Sorvaagen, Norway	+ 19	+ .146	+4,870	+ 6,090
Seattle, United States	....	−0.095	−3,170	− 3,960

It is seen that the excesses of mass indicated for Mauna Kea and at Sorvaagen are each comparable in equivalent thickness and extent to the maximum thickness of the Niger Delta if measured by rock upon land, 5,450 feet. The departures from equilibrium at Hachinohe, Japan, and Seattle, United States, are comparable in thickness and area to the burden of the Nile Delta, the weight in air of 3,600 to 4,200 ft. of rock. In weight as in area, therefore, these deltas are seen to impose burdens on the crust no greater than are found, by means of geodetic observations, to exist in certain other regions where geologic evidence had not revealed them. The accuracy of Hecker's method for determining the intensity of gravity at sea has been called into question by Bauer[1] so that, until

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[1] "On Gravity Determinations at Sea," *Amer. Jour. Science* (4), XXXI (1911), 1–18. "Hecker's Remarks on Ocean Gravity," *Amer. Jour. Science* (4), XXXIII (1912), 245, 248.

this question is settled by geodesists, equal weight should perhaps not be attached to the figures given for the departures from isostasy shown over the Tonga plateau and Tonga deep. Neither is the area of these departures known, though the areas of the plateau and deep are large. These regions are seen, however, to indicate considerably higher departures from isostasy than the measurements determined from the deltas of the Nile and Niger. The latter, therefore, perhaps do not measure the full strength of the crust.

Major H. L. Crosthwait has applied Hayford's methods to the investigation of isostasy in India.[1] The residuals of the deflections of the vertical serve as a measure of the degree of compensation existing in the United States as compared in India and are as follows:

United States of America

Group S.E., mean residual	− 0″.74
Group N.E., mean residual	− 1.04
Group Central, mean residual	− 1.66
Group W., mean residual	− 4.02

India

Region No. 1, Himalaya Mountains, mean residual	−16″.
Region No. 2, Plains at foot of Himalaya Mts., mean residual	− 2.
Region No. 3, N.E., mean residual	+ 8.
Region No. 4, Central, mean residual	+ 5.
Region No. 5, N.W., mean residual	+ 4.
Region No. 7, W., mean residual	− 3.
Region No. 8, E., mean residual	− 2.
Region No. 9, S., mean residual	+ 1.

It is seen that the residuals average several times as great in India as in the United States, which leads him to conclude that "Speaking generally it would appear that isostatic conditions are much more nearly realized in America than in India, i.e., if we are to take the smallness of the residuals as an indication of the completeness of isostatic compensation."[2] Colonel Burrard, utilizing the Hayfordian computations, points out the existence of zones

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[1] *Professional Paper No. 13, Survey of India*, 1912.

[2] *Op. cit.*, p. 4.

in India where the deflections of the plumb-line are actually in opposition to the directions called for by isostasy.[1] The major elements of the relief, the Himalayas, the plateau of India, and the surrounding ocean basins are of course largely compensated, but these figures show that in detail the hypothesis of complete isostasy is very far from the truth. Crosthwait suggests that the explanation for the difference between the United States and India probably lies in the magnitude of the recent upheavals of the crust in that part of the globe. Nevertheless such upheavals cannot exceed the strength of the crust, and in India, therefore, perhaps may be better observed than in the United States the maximum strains which the earth is competent to endure.

It may be concluded, therefore, that the convergence of geodetic evidence shows the crust to be competent to sustain loads measured by the weight of several thousand feet of rock extending over circular areas some tens of thousands of square miles in area. This is a measure of crustal strength twenty, fifty, or even a hundred fold greater than that advanced in recent years by the leading champions of high isostasy.

FURTHER GEODETIC WORK NEEDED FOR GEOLOGIC PROBLEMS

It has been the intention in the preceding analysis to show two things: first, that the data set forth by Hayford and Bowie are of great value to geology and establish new methods of research, but, second, that the difficulties inherent in the observations and their mathematical treatment, and the fewness of the stations in comparison with the heterogeneity of the earth, are such that the conclusions from the geologic study of deltas in the first part of this paper are as convincing and perhaps as accurate as the present results of the geodetic studies. The latter, however, opens for the whole earth a field of investigation which the geologic evidence covers very locally and imperfectly, a world-wide field which should be pursued for the geologic as much as for the geodetic bearings.

By means of the divining rods of pendulum and plumb-line the heterogeneities of mass and the loci of strain in the outer crust of

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[1] "On the Origin of the Himalaya Mountains," *Professional Paper No. 12, Survey of India*, 1912.

the earth should be sought out and measured in detail. For this work it would seem that many new stations would have to be established; in groups so as to reduce the errors of each locality; in sets so as to attack particular phases of the problems. For example, it would appear that gravity stations should be located in pairs close together and of as great a difference in elevation as possible. Certain stations should be located within areas of plateaus spared by circumdenudation, such as the Cumberland and Allegheny plateaus; others should be located in the broad erosion basins. Deflection stations should be located on the lines separating regions of erosion from those of circumdenudation, and also on the lines separating areas of upwarp from those of downwarp. A network should inclose, finally, all centers of marked gravity anomaly or topographic deflection. Such an increase in the number of stations would permit the introduction of simple hypotheses of variable depth and rate and regional limits of compensation. But such an extensive program is within the reach only of some research institution. It needs the co-operation of geologists and geodesists. The location of stations with respect to surface features and their geologic history should be controlled by the geologist. The density of the rocks to the limits exposed by the structure should also be determined by him. The geodesist, on the other hand, should seek out the hidden heterogeneities in the crust and guide the details of the work.

[*To be continued*]

DIASTROPHISM AND THE FORMATIVE PROCESSES. VII

PERIODICITY OF PALEOZOIC OROGENIC MOVEMENTS

ROLLIN T. CHAMBERLIN
University of Chicago

INTRODUCTION

Within the last few years there has been a growing belief among American geologists that diastrophism, in its greater manifestations, has been periodic, rather than continuous. According to this view the earth has passed through periods of diastrophic activity alternating with periods of relative quiescence.[1] During the more protracted of the periods of quiescence the earth's surface is believed to have remained stable sufficiently long to allow base-leveling to reach an advanced stage, and this is held to imply stability, for, without stability in the outer portion of the earth, mature base-leveling is scarcely possible. During such a time of base-leveling, stresses within the body of the earth must be accumulating steadily, but because of the high rigidity now apparently demonstrated these stresses show little outward manifestation of their presence for a long time, until finally, according to this view, the increasing internal stresses reach such an intensity that the mass of the earth can resist no longer but yields, and a period of active deformation succeeds the state of crustal inactivity. The deformation once inaugurated continues till the stresses are essentially eased. Then another period of quiescence sets in, to be followed in turn, after a long interval during which new stresses have developed, by another deformative outbreak.

Such diastrophic movements are held to be in themselves major events in the earth's history; and, in addition, they are the direct

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[1] T. C. Chamberlin and R. D. Salisbury, *Geology*, III (1906), 192, 193; T. C. Chamberlin, "Diastrophism as the Ultimate Basis of Correlation," *Jour. Geol.*, XVII (1909), 685–93; Charles Schuchert, "Paleogeography of North America," *Bull. Geol. Soc. Am.* XX (1910), 427–606; Bailey Willis, "Principles of Paleogeography," *Science*, XXI, No. 790 (1910), 246–49; E. O. Ulrich, "Revision of the Paleozoic System," *Bull. Geol. Soc. Am.*, XXII (1911), 281–680.

cause of extensive changes in sedimentation; and these, together with climatic and other effects that follow, influence profoundly the life-development. Thus, back of both stratigraphy and paleontology lies diastrophism, which furnishes the conditions upon which they depend.[1] If periods of diastrophism are thus truly the ultimate basis of correlation, they form a subject of inquiry of prime importance.

The chief purpose of the study upon which this paper is based is to determine to what extent past diastrophic movements of the higher order actually have taken place—simultaneously in different parts of the globe and periodically in the same region—with a view to the bearing of the facts on the determination of systems and periods, and on the broader correlations of geologic events. It is an attempt to test the hypothesis that the geologic periods represent, in the main, periods of relative quiescence, during which there were sea-transgressions and widespread sedimentation, and that they were separated one from another by diastrophic disturbances of shorter duration. The study is an attempt to discover whether the principal manifestations of diastrophic activity in one portion of the globe can be correlated approximately with corresponding disturbances in other parts of the globe, and whether the synchronous disturbances have been sufficiently widespread and effective in their manifestations to constitute a satisfactory basis for dividing geologic time into periods.

There can be little doubt that there are various grades of deformation and that most or all of these are serviceable as markers of time divisions of some order, but in the present discussion I shall try to limit the deformations recognized to those that involve some notable folding, or at least to unconformities so marked as to imply notable warping somewhere. This paper will be further limited in that it offers merely a preliminary selection of data relative to earth movements of the Paleozoic era that have been gathered from various accessible sources but not yet fully traced to their original sources and critically examined. The data are a part of a more general collection which includes the Mesozoic and Cenozoic eras. The present paper is but a modification of one read at the Twelfth

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[1] T. C. Chamberlin, "Diastrophism as the Ultimate Basis of Correlation," *Jour. Geol.*, XVII (1909), 692.

International Geological Congress at Toronto in August, 1913, and is presented here because it was undertaken as a part of the series of studies now appearing under the title "Diastrophism and the Formative Processes."

For brevity in designating the various diastrophic disturbances, my father has found it convenient in his lectures to use such terms as the following: Ordovicides for foldings or strong diastrophic movements which took place either at or near the close of the Ordovician period; Silurides for like movements at or near the close of the Silurian period; and similarly, Devonides, Carbonides, and Permides for movements connected with the closing stages of the Devonian, Carboniferous, and Permian periods. For movements near the close of the Mississippian, or Lower Carboniferous period, the term Culmides is used in place of a more cumbersome derivative from the name Mississippian. These terms will be used in this paper.

CAMBRIDES ?

The Proterozoic era seems to have closed with profound diastrophic movements in most parts of the world where satisfactory identifications have been made. At the close of the era the sea was quite generally withdrawn into the deep basins. The Paleozoic era which followed commenced with advancing seas in which the Cambrian sediments were laid down unconformably, for the most part, upon eroded and trunkated Proterozoic strata. During the Cambrian period there appears to have been a general, but more or less fluctuating, advance of the sea up to the close of what is usually classed as Upper Cambrian. Following this, in the debatable ground that lies between the well-recognized Upper Cambrian and the undoubted Ordovician, evidence of some diastrophic movements appears, but, so far as present data go, these movements do not seem to be of the decided class to which this paper chiefly relates. Rather widespread unconformities occur near this horizon in various parts of the Mississippi and St. Lawrence basins, but they are not of such a nature as seriously to affect the general parallelism of the Cambrian and Ordovician systems.[1] There are discordances be-

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[1] Chamberlin and Salisbury, *Geology*, II (1906), 311–12; Ulrich, "Revision of the Paleozoic System," *Bull. Geol. Soc. Am.*, XXII (1911), 614–16, 626–28; Schuchert, "Paleogeography of North America," *ibid.*, XX (1910), 522–29.

tween the Cambrian and Ordovician in Bohemia, in certain parts of the Armorican massif,[1] in the north of Wales,[2] in Norway,[3] and at Spiti in the Himalayas,[4] but no clear evidence of important folding appears. It is not clear that any one of these unconformities is of the higher order; they seem rather to be intercurrent movements of the minor order in what was, in general, a time of crustal quiescence. In general much hesitation and indecision has been shown by geologists in determining where to draw the dividing line in the transition series between the Cambrian and the Ordovician. In this study it is the periods of pronounced crustal crumpling, or of marked differential movement, that are especially sought as unequivocal representatives of events of the first order of importance; for unconformities of the simpler order are liable to represent events of a minor order of importance. Judged by this rather severe standard, the transition from the Cambrian to the Ordovician was relatively quiet; it does not now appear that there were pronounced crustal movements, and hence, on the basis chosen, it does not seem clear that the two were sharply separated periods in the earth's history. Throughout most of the globe where evidence is available, there was no radical change in the areas or the attitudes of sedimentation. This indecisiveness in the character of the diastrophic movements associated with the close of the Cambrian and the opening of the Ordovician leaves the question of the separateness of the two as distinct periods a somewhat open one considered from the diastrophic basis simply.

ORDOVICIDES

The greater part of the Ordovician period seems to have been a time of crustal quiescence, in the sense of the term used in this discussion, but its closing stages were marked by pronounced disturbances in various portions of the globe. These are the first crustal deformations of the higher order for which I have found clear evidence since the close of the Proterozoic.

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[1] Emile Haug, *Traité de géologie*, II (1911), 634–35.

[2] A. J. Jukes-Browne, *The Building of the British Isles* (1911), p. 78.

[3] Eduard Suess, *The Face of the Earth*, Sollas trans., II (1906), 52.

[4] A. de Lapparent, *Traité de géologie*, 5th ed., II (1906), 808.

In North America the disturbances occurred principally on the eastern side. A portion of the Atlantic border was strongly folded. According to Campbell, the general region lying eastward from what is now the Appalachian Valley, throughout much of its extent, was subject to disturbing influences at several periods during the Paleozoic.[1] This is in accord with the view that the source of the vast quantity of clastic sediment which was laid down in the Appalachian geosyncline in the course of the Paleozoic was the old land of Appalachia lying between the present mountains and the edge of the continental shelf. So great a volume of the sediments derived from this not very extensive land area is thought to imply a repeated renewal of the land by uplift.

Definite evidence of one such disturbance is found in the Taconic Mountains of western New England and the adjacent portions of New York and Canada. In this region the Cambrian and Ordovician strata are sharply folded and faulted while the Silurian strata rest unconformably upon the flanks of these folds and are not incorporated in them.[2] Today only the obscure stumps of these ancient mountains are visible, but they seem once to have constituted a great range. Thrust faulting, not unlike that of the southern Appalachians, was prominent but perhaps on a somewhat smaller scale.[3]

This ancient chain of mountains extended far to the northeast, paralleling the present coast. A large tract in northeastern Maine, northwestern New Brunswick, and the Gaspé Peninsula is occupied by a broad synclinorium of Silurian strata which appear to lie unconformably upon folded and eroded Cambrian rocks.[4] From Maine the eastern margin of the Silurian extends northeastward across New Brunswick to the Bay of Chaleur. In surveying the line between the Cambro-Ordovician and the Silurian, Bailey found

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[1] M. R. Campbell, "Paleozoic Overlaps in Montgomery and Pulaski Counties, Virginia," *Bull. Geol. Soc. Am.*, V (1894), 178–79.

[2] James D. Dana, *Manual of Geology*, 4th ed. (1895), p. 386.

[3] C. D. Walcott, "The Taconic System of Emmons," *Am. Jour. Sci.*, 3d Ser., XXXV (1888), 315–20; James D. Dana, *op. cit.*, p. 528.

[4] L. W. Bailey and William McInnes, "Explorations in New Brunswick, Quebec and Maine," *Ann. Rept. Geol. Surv. Canada*, New Ser., III (1889), 29–31 M.

"incontestable evidence of discordance along its whole length."[1] The fossiliferous Silurian slates are marked by a heavy basal conglomerate whose pebbles have been derived from the Cambro-Ordovician strata, but it is not clear how much time is represented by the unconformity.

The width of the belt affected by the movement may have been considerable. In southern Quebec, southeast of the St. Lawrence River, isolated areas of Silurian strata, largely limestones, occur in some of the synclines, and these Silurian beds are found to lie unconformably upon Ordovician strata, indicating that this region also was affected by the movement.[2] But the effects of the uplift were not felt upon the north side of the Gulf of St. Lawrence, for on Anticosti Island the accumulation of the great limestone formation which commenced in Ordovician times continued without a break into the Silurian.[3]

From the region of the Taconic Mountains of New England and New York evidences of this uplift may be traced southwestward. What appear to be evidences of the same disturbance have been noted on the east side of the Appalachian Mountains as far south as Virginia.[4] In 1892, N. H. Darton found some crinoids, which Walcott has assigned to the Upper Ordovician, in the slate quarries at Arvon, in the Piedmont region of Virginia.[5] While the age of the deformation and metamorphism of these rocks is not established, Dana nevertheless regarded this strip as possibly a part of a long Westchester Taconic range which passed just west of Philadelphia and Baltimore.[6] Very possibly also a portion of the folding of early Paleozoics in New Jersey may belong to the Taconic movement. But here again the age of the folding has not been definitely placed.

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[1] L. W. Bailey, in G. M. Dawson's *Summary Rept., Geol. Survey of Canada*, XIII (1900), 146–48 A.

[2] R. W. Ells, cited by Willis, "Index to the Stratigraphy of North America," *Prof. Paper 71, U.S. Geol. Survey* (1912), p. 250.

[3] W. B. Scott, *An Introduction to Geology* (1907), p. 567.

[4] M. R. Campbell, "Paleozoic Overlaps in Montgomery and Pulaski Counties, Virginia," *Bull. Geol. Soc. Am.*, V (1894), 189.

[5] N. H. Darton, "Fossils in the 'Archean' Rocks of Central Piedmont Virginia," *Am. Jour. Sci.*, 3d Ser., XLIV (1892), 50–52.

[6] J. D. Dana, *op. cit.*, p. 532.

In the northwestern portion of the state, where the Silurian strata are present to aid in correlation, this critical time period is represented by an extensive unconformity, but there has been no folding there. But that is distinctly west of the Taconic belt.[1] Kümmel discusses the matter thus:

> Contrary to long-prevalent and apparently well-established belief, the lower and middle portions of the Silurian system are not represented in New Jersey. Their absence in this and adjoining regions is indicative of somewhat widespread earth movements, unaccompanied in this region by folding, which closed the period of deposition indicated by the Martinsburg sediments, or possibly overlying beds afterward removed by erosion, and raised the region above the zone of sedimentation. When deposition began again, late in Silurian time, beds of coarse conglomerate were laid down. . . . .

This is the Shawangunk formation between which and the Martinsburg shale there is a gap representing the upper part of the Ordovician and all of the Silurian below the Salina of the full New York section, but there is no marked divergence of dip and strike where the two formations outcrop in proximity.[2]

In general, throughout most of the Appalachian province the youngest Ordovician (Richmond) beds are lacking, and an angular discordance between the Ordovician and Silurian at many points implies an emergence corresponding to the Taconic folding to the northeast. Ulrich states that at this time the whole Appalachian region was considerably elevated and the middle and eastern parts of Appalachia itself most probably subjected to profound orogenic movements.[3] Dana in particular has urged the magnitude and importance of this early mountain development. Because evidences of this movement, which was so intense in New England and New York, have been recognized over a much wider area, he regarded the Taconic Range of western New York as only one in a great Taconic system of mountains.[4] This great system lay entirely

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[1] Stuart Weller, "The Paleozoic Faunas of New Jersey," *Geol. Survey of New Jersey, Rept. on Paleontology*, III (1902), 54.

[2] H. B. Kümmel, "Geological Section of New Jersey," *Jour. Geol.*, XVII (1909), 356–57.

[3] E. O. Ulrich, "Revision of the Paleozoic System," *Bull. Geol. Soc. Am.*, XXII (1911), 436–37.

[4] James D. Dana, *Manual of Geology*, 4th ed. (1895), pp. 531–32.

to the east of the present Appalachians, more or less paralleling that later system as it does the coast. This Ordovician system may be regarded as a forerunner of the late Paleozoic Appalachians.

The local stratigraphic details in various portions of this general region, and the great extent of the emergence at this time are clearly pictured in the time scale for eastern North America given by Ulrich and Schuchert in their paper on Paleozoic seas and barriers in eastern North America.[1] It is the view of these authors that the disturbance was felt first in the southern portion of the Appalachian region and progressed thence northeastward along the axis of folding and westward toward the Mississippi basin, and so they believe it was not quite synchronous throughout the entire region affected. In the Lenoir basin (comprising the Athens and Knoxville troughs) the emergence followed the deposition of the Sevier shale, while in the Mississippi basin they regard the main emergence as having followed the Richmond, the time of the maximum uplift. The movement appears to have commenced with several minor pulsations in the closing stages of the Ordovician (Lorraine and Richmond) which quickly led to the great Taconic revolution which terminated the Ordovician, and which was one of the greatest movements in North American Paleozoic history. According to Ulrich and Schuchert, this revolution affected all North America, there being perhaps land throughout from Richmond to Oneida time. But the length of this land interval they believe cannot be satisfactorily ascertained as there are no Mississippi basin sea deposits by which its duration may be measured.

It appears quite widely in the literature that the Cincinnati Arch and Nashville Dome, in Ohio, Indiana, Kentucky, and Tennessee, originated also at this time. The basis for this view has been the widespread unconformity at the base of the Silurian. The Clinton follows the Ordovician and contains in its basal member rounded fragments of the Ordovician rocks[2] which suggests that the primary uplift of these domes may have been a feature of the Ordovicide movement. Foerste, however, regards the evidence for

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[1] E. O. Ulrich and Charles Schuchert, "Paleozoic Seas and Barriers in Eastern North America," *Bull. LII, New York State Museum* (1901), p. 658.

[2] Bailey Willis, *op. cit.*, p. 232.

the origin of the Cincinnati geanticline at this time as inconclusive, and, instead, places its inception between the Niagaran and the Middle Devonian, while it is recognized that the geanticline owes its present proportions to later upwarping which occurred probably in post-Mississippian times.[1] Minor oscillations and tilting, according to Ulrich, occurred in the region of the Cincinnati and Nashville domes much earlier (during the Ordovician period) but these movements were not of the more pronounced type.[2]

In North America the principal orogenic disturbances of the early Paleozoic thus occurred near the close of the Ordovician and were located near the Atlantic border where thick sediments had been accumulating. Europe seems to have behaved similarly. Throughout much of continental Europe the relatively quiescent conditions of the Ordovician continued with little interruption into the Silurian. But in the British Isles, where the Cambro-Ordovician strata are very thick, there were pronounced orogenic movements which were approximately contemporaneous with the Taconic revolution of North America. Over large areas the Lower Silurian rocks were upheaved, more or less contorted, and in many places suffered a great amount of denudation before the deposition of the Upper Silurian strata began.[3] A large portion of the British Isles became land, and Jukes-Browne believes that this continental land included also a large part of the North Sea and nearly the whole of Norway.[4] The results of this disturbance are conspicuous in the original tract of Siluria (western England and the adjacent portion of Wales) where a decided unconformity separates the Ordovician from the Silurian. In some places the latter extends across the trunkated edges of the former, group after group, till they rest directly upon the Cambrian beds. Ramsay's diagram of the section between Church Stretton and Chirbury in Shropshire shows nearly horizontal Llandovery (basal Upper Silurian) beds cutting across nearly

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[1] A. F. Foerste, "The Ordovician-Silurian Contact in the Ripley Island Area of Southern Indiana, with Notes on the Age of the Cincinnati Geanticline," *Am. Jour. Sci.*, 4th Ser., XVIII (1904), 321–42.

[2] E. O. Ulrich, *Bull. Geol. Soc. Am.*, XXII (1911), 416–19.

[3] A. C. Ramsay, *The Physical Geology and Geography of Great Britain*, 6th ed (1894), p. 74.

[4] A. J. Jukes-Browne, *The Building of the British Isles* (1911), pp. 94, 97.

vertical Cambrian and Ordovician strata.[1] It is evident, therefore, that in this region considerable disturbance and extensive denudation followed the Ordovician and preceded the commencement of the Silurian sedimentation.[2]

Of the events in Asia at this time much less is known. But it is known that in the eastern portion of that continent the Ordovician seas withdrew late in the period, leaving large areas emerged in Mongolia and Manchuria[3] and probably also in northern China where the Ordovician is terminated by unfossiliferous dolomites which were probably lagoon deposits. The Silurian has not yet been recognized above them and very likely was never laid down there.[4] But we have as yet no good evidence of any pronounced mountain-making movements in Asia at this time.

In the Andine region of South America there is a suggestion of diastrophic movements following the Ordovician, for the Silurian is often lacking there, the Devonian resting directly upon the Ordovician.[5]

The eastern portion of the Australian continent was the locus of mountain-making movements at several periods during the Paleozoic. In New South Wales, the close of the Ordovician was attended by both volcanic and diastrophic disturbances. Süssmilch states that at Tallong, the one place where a junction between the Ordovician sediments and those of the next period has been observed, a well-marked unconformity occurs. The evidences of this region are interpreted by Süssmilch as showing that at the close of the Ordovician period there occurred extensive earth movements by which the marine sediments and volcanic ash, which had accumulated to a thickness of many thousands of feet, were pressed into a series of folds trending approximately north and south, and that these suffered denudation so that when the sea readvanced upon these land areas in Silurian time, the new sediments were deposited unconformably upon the trunkated edges of the Ordovician strata.[6]

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[1] A. C. Ramsay, *op. cit.*, p. 77.

[2] Sir Archibald Geikie, *Textbook of Geology*, 4th ed., II (1903), 953.

[3] A. de Lapparent, *Traité de géologie*, 5th ed., II (1906), 807.

[4] Emile Haug, *Traité de géologie*, II (1911), 653.

[5] *Ibid.*, p. 657.

[6] C. A. Süssmilch, *Geology of New South Wales* (1911), p. 18.

These evidences of pronounced folding movements in different quarters of the globe at the close of the Ordovician are supported by the extensive withdrawals of the sea from the line of maximum transgression in the mid-Ordovician, to the shore lines implied by the early Silurian beds in many other regions which were not affected by the more violent disturbances. This was a time of general disturbance; but it remains for future study to establish just how nearly synchronous these widespread disturbances were.

SILURIDES

During the greater part of the Silurian period there was a relative freedom from diastrophic disturbances of the major sort. But toward the close marked disturbances set in and may be said to have terminated the epicontinental phase of the Silurian sedimentation in various parts of the globe. North America was affected chiefly by movements of the milder sort but certain portions of Europe suffered from intense orogenic deformation. In North America a comparatively rapid emergence of the continent began with the Guelph and continued until the Silurian period closed with the land nearly as extensive as it was at the beginning of the period, when most of the North American continent stood above water.[1] While the very widespread unconformities indicate a general epeirogenic movement at this time, or else a withdrawal of the sea, or both, very little evidence of pronounced folding has as yet been found on the mainland of this continent. Some slight folding, however, has been recognized on the Atlantic border. Campbell, in a summary of the periods of Appalachian folding in Virginia, has described a deformative movement which, preceding the deposition of the Walker black shale, has folded the limestones and marks the division line between the Silurian and Devonian. It is the principal period of deformation in the region before the great Appalachian revolution which came at the close of the Paleozoic.[2]

Siluride movements following the extensive Silurian sedimentation were especially prominent in the higher northern latitudes.

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[1] Charles Schuchert, "Paleogeography of North America," *Bull. Geol. Soc. Am.*, XX (1910), 491, 540.

[2] M. R. Campbell, *Bull. Geol. Soc. Am.*, V (1894), 189–90.

In the Yukon region of Alaska, according to Brooks and Kindle, it seems probable that one of the recurrent epochs of crustal disturbances took place in early Devonian or late Silurian times, for all the rocks laid down before this period appear to fall into the metamorphic class, though they have suffered a varying amount of alteration. Granitic intrusions are associated with this folding and it is probable that this epoch was closed by an uplift followed by erosion.[1]

In northeast Greenland, what appears to be an orogenic movement at the close of the Silurian has been recognized and described by Nathorst as follows:

> The Silurian strata, as we have seen, are folded and compressed and partly metamorphosed. If this bears any relation to the formation of a mountain range, the folding took place before the deposition of the Devonian strata, for the latter show only a relatively slight amount of disturbance. Otherwise it must be surmised that the folding was the result of a depression of the Silurian strata along a fault at their eastern border, or perhaps between such a fault and another which can be imagined as passing west of the present boundary of the Archean.[2]

This folding in northeast Greenland parallels and may perhaps be related to the great Caledonian folding of Scotland and Scandinavia.

In Europe the close of the Silurian was a time of much greater disturbance. Flexing and faulting of the crust at this time developed a chain of stupendous mountains in northwestern Europe. The present stumps of these great mountains run throughout the length of Scandinavia; reappear in the northwest highlands of Scotland, and extend onward into Ireland, Wales, and England. Evidences of these ancient mountains are to be recognized as far south as Devonshire. To this chain Suess has applied the name Caledonian, recognizing it as one of the greatest ranges of the past.[3] Both in Scandinavia[4] and in the Scottish Highlands[5] the formation

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[1] A. H. Brooks and E. M. Kindle, "Paleozoic and Associated Rocks of the Upper Yukon, Alaska," *Bull Geol. Soc. Am.*, XIX (1908), 312–13.

[2] A. G. Nathorst, cited by Willis, *op. cit.*, p. 341.

[3] Eduard Suess, *The Face of the Earth*, Sollas trans., II (1906), 82–86; III (1908), 386–99.

[4] A. E. Törnebohm, "Grunddragen af det Centrala Skandinaviens Bergbyggnad," *K. Svenska Vetensk Akad. Handl.*, XXVIII (1896), 212.

[5] B. N. Peach, J. Horne, and others, "The Geological Structure of the Northwest Highlands of Scotland," *Mem. Geol. Survey of Great Britain* (1907), 463–594.

of this range was characterized, not only by sharp folding, but by some of the most remarkable overthrust faulting of which we have any record. The horizontal thrusting amounts to many miles.

According to Lake and Rastall this folding occurred during the Devonian,[1] since it followed the deposition of a portion of the Old Red Sandstone. In Wales this portion passes downward conformably into the Silurian. Sir Archibald Geikie likewise stated that the Old Red Sandstone of Britain consists of two divisions, the lower of which passes down conformably into the Upper Silurian deposits, while the two divisions are separated one from another by an unconformity which makes a great physical and paleontological break.[2] This break presumably corresponds to the mountain-building.

But Jukes-Browne, writing in 1911, states that some beds which were formerly called Old Red Sandstone are now placed in the Silurian, while the mass which was formerly called "Middle Old Red Sandstone" is now admitted to be the true Lower Old Red, and known from its fish fauna to belong to the Lower Devonian.[3] The movement in Wales he places at the beginning of the Devonian,[4] while the principal physical features of Scotland had been developed between the close of the Ordovician and the opening of the Devonian period. In the southern uplands, where the time limits are more closely drawn, the plication follows the Silurian, for that system is included in the crumpling. The time of deformation is finally summed up by Jukes-Browne: "Thus the first uplift of the outer ranges may have taken place in Silurian time; the date of the central axis we know [apparently close of Silurian] and the final intense development of the pressures in the outer ranges may have occurred either at the same time or even during the actual formation of the lowest Old Red Sandstone."[5]

The Scandinavian portion of this great mountain system apparently affords less definite evidence of the precise time of this disturbance, but Haug concludes that although we cannot, in the

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[1] Philip Lake and R. H. Rastall, *Textbook of Geology* (1910), pp. 342–43.

[2] Sir Archibald Geikie, *Textbook of Geology*, 4th ed., II (1903), 1006–7.

[3] A. J. Jukes-Browne, *The Building of the British Isles* (1911), p. 114.

[4] *Ibid.*, p. 119.

[5] *Op. cit.*, p. 126.

absence of incontestable Devonian deposits, determine in a precise manner the age of the folding in Scandinavia, we can place it, from the analogy with Scotland, at the junction of the Silurian and Devonian.[1]

Holtedahl has noted a northward continuation of the Caledonian mountain-folding in Spitzbergen, but as he found beds which he believes to belong to the uppermost Silurian resting unconformably upon the Silurian strata which are incorporated in the folds, he would place the date of the folding late in the Silurian instead of at its close, which, if correct, would seem to indicate that the disturbance commenced in the northern portion of the Caledonian chain somewhat earlier than it did farther south.[2]

While there was intense crumpling in the Grampian geosyncline and in Scandinavia along this northeast-southwest Caledonian axis at the beginning of the Devonian, folding also took place, in central Europe, at approximately the same time, along a northwest-southeast axis. The folded belt extends from the Ardennes of France through the Taunus and Thüringerwald into Moravia, where this system of folds disappears under the great overthrusts of the Carpathians, which are of much more recent origin.[3] Farther west than the Ardennes, in the Cotentin region of northwestern France, Lecornu has described Siluride folding which may be a westward continuation of this mountain system of central Europe.[4]

In the Sahara Desert recent explorations by Gautier have shown the existence of folding during the Caledonian epoch. The early Devonian strata in the Oran Sahara rest in horizontal or slightly undulating beds upon folded Silurian strata.[5]

According to Hauthal, South America also suffered from deformative movements at this time. In the Sierra de la Ventana, of Argentina, Hauthal found that the older Paleozoic sedimentaries

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[1] Emile Haug, *Traité de géologie*, II (1911), 730.

[2] Olaf Holtedahl, personal communication.

[3] Emile Haug, *op. cit.*, p. 732.

[4] L. Lecornu, cited by Suess, *op. cit.*, IV, 48.

[5] R. Chudeau and E. F. Gautier, "Sur le structure géologique du Sahara central," *Comptes rendus*, CLXI (1905), 374–76.

were affected by folding which took place between the Silurian and Devonian.[1]

Over considerable areas in southeastern Brazil horizontal beds of Devonian age rest unconformably upon folded and metamorphic rocks for the most part of probable pre-Cambrian age, but possibly including some strata representing the Cambrian or Lower Silurian.[2] This is the most conspicuous period of deformation to which the eastern half of the continent of South America has been subjected since Archean times. It resulted in a great chain of mountains, of which the present Serra do Espinhaço, or Backbone Range of Brazil, represents the roots. The time of the crumpling and faulting has not yet been closely determined, and this cannot yet be classed as a Siluride movement, though Hauthal believes that the Sierra de la Ventana, in which he found evidence of a Siluride movement, are related in origin to the Brazilian Highlands.

In New South Wales, according to Süssmilch, the Silurian period was brought to a close after a long period of sedimentation, by a pronounced deformative movement which folded and elevated the Silurian strata to such an extent that much of the country was raised above sea-level. Incomplete knowledge of the nature and distribution of the succeeding Devonian sediments makes it impossible to form any definite opinion as to the extent of this movement.[3] But farther north, in the Narrigundah Gold Field of Queensland, Devonian strata are again found resting horizontally upon folded Silurian beds.[4]

Like the closing stage of the Ordovician, the end of the Silurian period was a time of rather general crustal disturbance which reached extreme intensity in certain regions. Present knowledge is not adequate, and correlations are not sufficiently exact, to determine how nearly simultaneously the disturbances appeared in the

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[1] R. Hauthal, "Excursion à la Sierra de la Ventana," *Publicaciones de la Universidad de La Plata*, 1901, pp. 30.

[2] Hartt, cited by Suess, *op. cit.*, I, 508. J. C. Branner, *Geologia Elementar, Rio de Janeiro* (1906), p. 217.

[3] C. A. Süssmilch, *An Introduction to the Geology of New South Wales* (1911), p. 33.

[4] H. I. Jensen, "The Building of Eastern Australia," *Roy. Soc. Queensland*, XXIII (1911), 165.

different regions; and that is a crucial point. But from available data it would seem that the deformation was in progress at some points as early as the latter part of what has been classed as Silurian, while it persisted at other points into what has been classed as early Devonian. Even if the identifications are strictly decisive, such a range of time for a major deformative movement would not seem more than is to be expected under the hypothesis of a genetic relationship between the movements in widely separated quarters of the globe, for absolute simultaneity is improbable. The critical question, however, lies between the weight that is to be given to the identifications of the dividing line that has been fixed by geologists in their local studies in the cases cited, and that which may properly be given to the diastrophic movements when they shall have received the critical attention that has been given to the stratigraphic and paleontologic criteria. If a real discrepancy is found ultimately, which class of evidence shall give way to the other?

DEVONIDES

In North America the most noteworthy orogenic disturbances connected with the Devonian period occurred near its close in eastern Quebec, New Brunswick, Maine, and perhaps also southwestward through the tract of Appalachia which was rather disposed toward upward movements during the Paleozoic. In the Gaspé Peninsula of Quebec the Bonaventure conglomerate of late Devonian, or early Mississippian, age was laid down unconformably upon the vertical edges of the Silurian and Devonian strata about Percé.[1] The Devonian and older strata have been thrown into pronounced folds of the Appalachian or Jura type, indicating that a conspicuous mountain range was developed here after the deposition of these Devonian strata. The youngest formation included in the folded mountains is the Gaspé sandstone, which has been correlated by Clarke with the Hamilton of New York.[2] The great folds of Gaspé therefore arose some time between the late Hamilton and the beginning of the Mississippian, with the evidence tending

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[1] J. M. Clarke, "Early Devonic History of New York and Eastern North America," *Mem. New York Mus.*, No. 9 (1908), 92–102.

[2] J. M. Clarke, *op. cit.*, pp. 86–88.

to show that the disturbance came within the later Devonian rather than at its close.[1]

These movements apparently also affected a portion of Nova Scotia, for in the MacArras Brook region, according to Ami, the Lower Carboniferous strata rest unconformably upon the upturned edges of the Lower Devonian of that region.[2] Though the folding is here less definitely located than in Gaspé, both foldings would seem to be manifestations of the same diastrophic disturbance.

Evidences of the same uplift and folding are to be looked for in Appalachia. Following the black Hamilton shales from New York to southern Virginia there occurs a great volume of sandy shale and argillaceous sandstone comprising the Jennings and Hampshire formations of Maryland, or the Chemung and Catskill of New York. Willis has estimated that if this mass of sediment could be restored upon a sea-level plain corresponding in shape and size to Appalachia, it would produce a mountain range closely resembling in height, extent, and mass the Sierra Nevada of California.[3] These he calls the Devonian Highlands. Their elevation would follow the Hamilton and thus correspond closely in time with the folding period in Gaspé.

At the close of the Devonian much of the continent of South America stood out of water.[4] In northeastern Argentina, to the west of the Cerro del Agua Negra, Bodenbender found the thick Devonian formations unconformably overlain by red Permo-Carboniferous sandstones.[5] The time of this movement has not been as yet closely determined.

But the greatest Devonide movements which have yet been recognized are those of Australia. The close of the Devonian was one of the greatest mountain-making epochs of New South Wales, according to Süssmilch—of such importance, indeed, that the name

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[1] *Ibid.*, pp. 14–15.

[2] H. M. Ami, "Meso-Carboniferous Age of the Union and Riversdale Formations, Nova Scotia," *Bull. Geol. Soc. Am.*, XIII (1902), 533.

[3] Bailey Willis, "Paleozoic Appalachia or the History of Maryland during Paleozoic Time," *Maryland Geol. Survey*, IV (1902), 61–62.

[4] Charles Schuchert, *Jour. Geol.*, XIV (1906), 738.

[5] G. W. Bodenbender, *Boletin de la Academia Nacional de Ciencias de Cordova*, XV (1897), 201.

Kanimbla epoch has been suggested for this mountain-making period.[1] Süssmilch states that the folding must have taken place either at the close of the Devonian, for the Devonian beds are infolded, or, at the latest, early in the Caboniferous, for the Devonian strata had been greatly eroded before the horizontal Permo-Carboniferous strata were laid down. The general movements were on such an extensive scale as to convert the greater part of New South Wales into land. The folding was accompanied by batholithic intrusions.

In northwestern Europe, where accumulated strains had been relieved by such an extensive and remarkably vigorous crustal deformation at the close of the Silurian, the Devonian and early Carboniferous periods were a time of comparative quiescence. Devonide movements, however, have been recognized along a belt which, beginning in Brittany, includes the Armorican massif, the basin of Saarbrück, the Vosges, Black Forest, Thüringerwald, and continues into lower Silesia. These movements occurred either at the dividing line between the Devonian and the Lower Carboniferous, or very early in the latter period.[2]

Suess also implies that this chain may be related to one in the southern Tian Shan Range in central Asia, where an unconformity with folding at the base of the Lower Carboniferous represents an east-and-west line of Devonide wrinkling.[3] A possible connecting link between these widely separated wrinklings is suggested by Boutscheff's observations in the Balkans, northeast of Sophia, where steeply overfolded Upper Silurian graptolite beds are covered unconformably by the Culm.[4] But the age of this folding is not closely limited.

CULMIDES

The Lower Carboniferous or Mississippian period seems to have been one of comparative quiescence, as implied by the extensive formation of limestone which characterizes this portion of the

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[1] C. A. Süssmilch, *An Introduction to the Geology of New South Wales* (1911), pp. 51–52.

[2] Emile Haug, *op. cit.*, p. 831.

[3] Eduard Suess, *The Face of the Earth*, Sollas trans., IV (1909), 2.

[4] S. Boutscheff, cited by Suess, *op. cit.*, p. 16.

earth's history in so many parts of the globe. But at the close of the period there was a widespread withdrawal of the sea. In North America the seas retired from a large part of the United States, New Brunswick, and Nova Scotia, to such an extent that when the sea again advanced in the Pennsylvanian or Upper Carboniferous period, the new sediments were laid down unconformably upon the eroded Mississippian beds over wide areas. This unconformity at the top of the Mississippian, or at the base of the Millstone Grit, is continued very widely throughout most of the interior and western states and an unconformity at about this same horizon appears also at various points in Alaska.[1] It was chiefly because of the unconformity which occurs at this horizon over such wide areas, not only in North America, but in other continents as well, that the portion of the Carboniferous below the unconformity was urged as a separate period under the name Mississippian.

Distinct folding movements occurred in the Arbuckle region of Oklahoma. Near the close of the Mississippian or beginning of the Pennsylvanian, the rocks of the Arbuckle region were folded and the western part thrown into mountains. Faulting also occurred on a large scale.[2] As a result of the elevation of these mountains at this time, with the attendant acceleration of erosion and rapid clastic sedimentation, the sediments of the succeeding Pennsylvanian period have reached a thickness in the adjacent portion of Arkansas of 18,000 feet.[3] These Arkansas Coal Measures correspond to only a lower part of the Pennsylvanian.[4]

In Europe conditions were somewhat similar. De Lapparent states that there was considerable volcanic activity from the Armorican region to the Vosges together with a complete withdrawal of the sea from the region, at the close of the Dinantian, or Lower Carboniferous. At this time there was energetic folding in the Vosges on the eastern frontier of France, while evidences of

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[1] A. H. Brooks and E. M. Kindle, "The Paleozoic Section of the Upper Yukon, Alaska," *Science*, XXV (1907), 182.

[2] J. A. Taff, "Geology of the Arbuckle and Wichita Mountains in Indian Territory and Oklahoma," *Prof. Paper 31, U.S. Geol. Survey* (1904), p. 37.

[3] T. C. Chamberlin and R. D. Salisbury, *Geology*, II (1906), 562.

[4] A. J. Collier, "The Arkansas Coal Field," *Bull. 326, U.S. Geol. Survey* (1907), p. 24.

similar orogenic disturbances are seen in the Laval coal basin on the borders of Brittany[1] and also in the Sudetes.[2] The Culm occupies a large area in southern Portugal. But the Upper Carboniferous of that country is very restricted in area and rests unconformably upon the rocks below, probably indicating a Culmide movement.[3]

Asia also shows evidences of mild disturbances, at least, following the Culm. In Hseng King, the southern province of Manchuria, Inouye states that the Upper Carboniferous is unconformable upon the Lower.[4] In the southern portion of the Tian Shan range in central Asia the Lower Carboniferous, according to Suess, is marked by unconformities with orogenic movements both above and below it.[5] The Lower Carboniferous shows folding which took place before the basal beds of the Carboniferous were laid down. The inference naturally drawn from Suess is that this folding occurred before the beginning of the Pennsylvanian, but from Keidel's original description the first beds to be deposited upon the trunkated folds are to be correlated with the uppermost Carboniferous of Europe.[6] Hence the folding may have taken place either at the close of the Culm or before the Stephanian of the Pennsylvanian period. From the fact that strong folding was so general a phenomenon in many of the neighboring ranges of central Asia in the middle of the Carboniferous period, it is possible that this folding in the Tian Shan occurred also at that time, and so would be a Westphalo-Carbonide movement.

WESTPHALO-CARBONIDES

The closing of the Paleozoic era was accompanied by much diastrophism. Though sometimes referred to as a more or less continuous period of disturbance from mid-Carboniferous times till the close of the Paleozoic, a closer analysis seems to show that

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[1] A. de Lapparent, *Traité de géologie*, 5th ed., II, 906.

[2] Eduard Suess, *op. cit.*, II, 69.

[3] K. G. Jane, *Encyc. Brit.*, 11th ed., XXII (1911), 135.

[4] K. Inouye, cited by Suess, *The Face of the Earth.*

[5] Eduard Suess, *op. cit.*, IV (1909), 2.

[6] Hans Keidel, "Geologische Untersuchungen im südlichen Tian Schan nebst Beschreibung einer obercarbonischen Brachiopodenfauna aus dem Kukurtuk-Tal," *N. Jahrb. f. Min.*, XXII, Beilage Bd. (1906), pp. 266–384.

there were at least two distinct periods of deformation, separated by a period of comparative quiescence. The first stage of disturbance falls at the close of the Westphalian epoch, and hence may take the name of Westphalo-Carbonide movement. At this time extensive warpings and folding affected large portions of central and southern Europe and gave rise to a notable series of mountains which are grouped under the names Armorican and Variscan chains,[1] or collectively the Hercynian system,[2] and sometimes designated the Paleozoic Alps.[3]

The area of Armorican folds has a breadth reaching from Bristol, England, on the north, to La Vendée on the south, a distance of 330 miles across the strike.[4] This broad belt was crumpled into a succession of parallel folds trending east and west. They extend from the Atlantic shores of South Ireland, Cornwall, and Brittany eastward through the Ardennes, Vosges, Schwartzwald, Taunus, Harz, Thüringerwald, Frankenwald, Erzgebirge, and on into the Sudetes and Carpathians and are probably continuous, beneath younger formations, with the Carboniferous chains among the Balkans, and with the folds of the same age in Dobrudja, near the Black Sea,[5] a really great range of mountains of which we have today only the stumps remaining.

It is generally agreed that the chief episode in the formation of this great mountain system occurred between the deposition of the Westphalian and that of the Stephanian series. On the north side of the chain—in the south of England, in the Ardennes, in the Harz, and in Westphalia—the folding follows the Westphalian, but as the Stephanian is absent from this belt the date of the folding cannot be closely determined, though it is certainly before the Saxonian which inaugurates the Permian transgression.[6] But in the central plateau, the principal orogenic movements antedate the Stephanian which rests directly upon the Dinantian and older

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[1] Eduard Suess, *The Face of the Earth*, Sollas trans., II (1906), 86–111.

[2] Marcel Bertrand, "La chaîne des Alpes, et la formation du continent Européen," *Bull. Soc. Géol. France*, 3d Ser., XV (1887), 435–40.

[3] Emanuel Kayser, *Geologische Formationskunde*, 2d ed. (1902), p. 174.

[4] A. J. Jukes-Browne, *op. cit.*, pp. 178–88.

[5] Emile Haug, *op. cit.*, p. 830.

[6] *Ibid.*, p. 831.

rocks which are generally metamorphosed. In the basin of Laval (Mayenne) the Stephanian Coal Measures with a conglomeratic base lie unconformably upon overfolded Westphalian beds.[1]

Contemporaneously there occurred several belts of disturbance in England somewhat apart from the main range. Here are included the Lancastrian flexures and the folding of the Pennine range, sometimes called the backbone of England. The folding is pre-Permian and appears to have come rather late in the Carboniferous period. From the immense amount of rock material which must have been removed from the broad arch of the Lake District before the Permian sandstones were laid upon it, Jukes-Browne suggests that this erosion possibly occupied the whole of Stephanian time, thus making this folding of the same date as the Armorican flexures.[2]

The Malvern and Abberley Hills are but the worn-down remnants of a mountain chain which was formed in the limited interval between the deposition of the Lower and Upper Coal Measures.[3] According to Groom, this folding and faulting was essentially contemporaneous with that of the Hercynian system. This would seem to be so if the Upper Coal Measures of Britain are equivalent to the Stephanian, as they are given by Geikie.[4] But according to Jukes-Browne, the Stephanian is absent from England and the Hercynian disturbance came after the English Upper Coal Measures.[5] If this be the correct correlation, the formation of the Malvern and Abberley Hills would seem to have been accomplished slightly earlier than that of the main Hercynian system.

On the border line between Italy and Austria the Carnic Alps result from east-and-west plications which are referred to Carboniferous times, but the precise stage remains doubtful. The principal Paleozoic movements in the exterior chains of the western Alps as well as in the eastern Alps are referred to this period with similar qualification.[6]

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[1] A. J. Jukes-Browne, *op. cit.*, p. 188. [2] *Ibid.*, pp. 189–92.

[3] T. T. Groom, "On the Geological Structure of Portions of the Malvern and Abberley Hills," *Quart. Jour. Geol. Soc.*, LVI (1900), 176–95.

[4] Sir Archibald Geikie, *Textbook of Geology*, II (1903), 1051.

[5] A. J. Jukes-Browne, *op. cit.*, p. 171. [6] Emile Haug, *op. cit.*, pp. 830–31

Also in the Pyrenees there was a stage of folding at about this time. In the Asturias, and doubtless in the greater part of the Iberian Peninsula, folding movements followed the Westphalian, coming probably before the Stephanian, but in any case before the Permian. From Galicia in the extreme northwest corner of the peninsula and from the north of Portugal, a number of nearly parallel folded ranges, closely packed, run southeastward into the great Meseta and continue as far as the valley of the Guadalquivir in southern Spain.[1] This intensely folded mountain system includes much of the Carboniferous together with much granite which, for the most part, was intruded during the Carboniferous period. As in the Asturias, here also the upper beds of the Carboniferous rest unconformably on the folded region, and the general structure of these mountains thus dates, like that of the Armorican and Variscan systems, from late in the Carboniferous period.

South of the Mediterranean there are evidences of Hercynian movements as far as the African Caledonian fold zone.[2] In the Atlas Mountains of Morocco the age of the closing Paleozoic folding has not been fixed more closely than between the close of the Lower Carboniferous and the beginning of the Permian. But in eastern Morocco and in south Oranais, the Devonian, Dinantian, and Moscovian (Westphalian) are found in concordance just as in Spain, which has led Haug to conclude that they belong to the same geosynclinal and to the same zone of folding.

In South Africa the most definite bench mark for correlation is afforded by the base of the Karroo System—the Ecca series, and especially its basal formation, the Dwyka conglomerate. Its widespread occurrence, its distinctive petrographical characteristics, and the fact that, while conformable in the south of Cape Colony with the uppermost member of the Cape System, it shows a varying degree of unconformity elsewhere, make the Dwyka conglomerate an excellent datum level.[3] In the north of Cape Colony, according to Hatch and Corstorphine, in Natal, Zululand, Rhodesia,

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[1] Eduard Suess, *The Face of the Earth*, Sollas trans., II (1906), 126.

[2] G. B. Flamand and E. F. Gautier, cited by Haug, *op. cit.*, p. 831.

[3] F. H. Hatch and G. S. Corstorphine, *The Geology of South Africa*, 2d ed. (1909), p. 335.

Orange River Colony, and in the Transvaal, the Dwyka conglomerate rests unconformably upon the older rocks, generally upon the strata of the Cape System.[1]

The age of the Cape System is still somewhat uncertain; the middle member (Bokkeveld series) is of Devonian age, but the age of the upper member (Witteberg series) is more in doubt, as these beds have as yet yielded no remains of animals, and only rather poor specimens of plants. While little value can be placed upon the determinations, it is to be noted that all the genera found occur in the Carboniferous rocks of Europe.[2] Hatch and Corstorphine are also inclined to correlate the Witteberg series with the Carboniferous of the Northern Hemisphere.[3] The Ecca series is of Permo-Carboniferous age, but until more is known about the age of the strata involved in the folding this widespread break in South Africa cannot well be correlated with movements elsewhere. But it would be most natural to suppose that the glaciation (represented by the Permo-Carboniferous Dwyka conglomerate) followed closely upon the deformation.

In North America movements which appear to be contemporaneous with the Hercynian folding of Europe at the close of the Westphalian have been recognized at a number of points. Very pronounced movements affected portions of Oklahoma. The Arbuckle Mountains, which had suffered Culmide folding, were again subjected to strong folding before the close of the Pennsylvanian. Taff states that this deformation commenced near the beginning of Upper Carboniferous time and ended before its close.[4] Hutchison describes the major portion of the present structure of the region of the Arbuckle and Criner Hills as formed in early mid-Carboniferous times.[5] The date of the folding, while occurring some time within the Pennsylvanian period, cannot as

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[1] F. H. Hatch and G. S. Corstorphine, *op. cit.*, pp. 335–38; also Plate I, opposite p. 33.

[2] A. W. Rogers and A. L. DuToit, *An Introduction to the Geology of Cape Colony*, 2d ed. (1909), pp. 159–60.

[3] Hatch and Corstorphine, *op. cit.*, p. 344.

[4] J. A. Taff, "Geology of the Arbuckle and Wichita Mountains in Indian Territory and Oklahoma," *Prof. Paper 31, U.S. Geol. Survey* (1904), p. 38.

[5] L. L. Hutchison, *Bull. 2, Oklahoma Geol. Survey* (1911), p. 7.

yet be closely located. But rocks of very late Pennsylvanian or early Permian age have been deposited across the western end of the Arbuckle uplift. They lie in a nearly flat position across the eroded edges of several thousand feet of the Pennsylvanian, all of the Mississippian, Devonian, Silurian, and a large part of the Ordovician rocks.[1] The folding of the Wichita Mountains is thought by Taff to have occurred simultaneously with that of the Arbuckle uplift.[2]

Some movements, though they do not appear to have been very pronounced, affected the extreme eastern border of the continent. In the southeastern part of New Brunswick the strata of the Upper Carboniferous[3] (or Permo-Carboniferous)[4] rest unconformably upon the Millstone Grit at various points. These movements may possibly have affected also the eastern side of the Appalachians farther south, but the intense deformation which developed the Appalachian Mountains, as now known, came later.

In the Appalachian region, according to David White, there is distinct evidence of a shift in the region of sedimentation or, in other words, a change in the direction of warping of the Appalachian trough at the close of the Westphalian time; for during the Westphalian the maximum subsidence and loading was toward the south, in which region no Stephanian was ever deposited, while in the northern Appalachian region, the greater part of which was exposed during most of the Westphalian time, there occurred the maximum deposition of Stephanian with possibly lack of interruption in its passage into the Permian.[5]

In addition to the better-known cases of mountain development, there are several movements of this general age which cannot be placed very closely with the data now at hand. According to Evans, the eastern Andes of Bolivia, which had been folded in very early times and had again been brought beneath the sea, received

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[1] J. A. Taff, *op. cit.*, pp. 35–36.

[2] *Ibid.*, p. 80.

[3] R. W. Ells, *Geol. Survey of Canada, Ann. Rept.*, I (1885), 7, 29 E.

[4] L. W. Bailey, "Report upon the Carboniferous System of New Brunswick," *Geol. Survey of Canada*, XIII (1902), 19 M.

[5] David White, personal communication.

renewed elevation late in the Carboniferous period.[1] Kayser is authority for the statement that the folding of the Urals began late in the Carboniferous and reached its height in the Permian, and, even as far as Armenia and central Asia, evidences of folding and mountain-building movements at about this time have been recognized.[2] Farther east, in the southern Tian Shan range, Keidel has recognized pronounced foldings which occurred within the Carboniferous period. The Lower Carboniferous sandstones and shales had been greatly folded and considerably eroded before the Schwagerina-bearing limestone was laid down upon the trunkated folds. The Schwagerina limestone, which is correlated with a similar formation in the Urals, belongs to the uppermost part of the Pennsylvanian.[3] Whether this movement is a Culmide or a Westphalo-Carbonide is therefore not yet determined, but because movements of the latter class were so widespread along this general east-and-west axis it may not improbably prove to belong to this group.

Further studies in the heart of the continent should add much to the subject of Carboniferous diastrophism, for the broad mountainous zone between central Siberia and the Tertiary chains in south Asia is made up of ranges whose principal folding appears to date from about the middle of the Carboniferous period, which suggests that they may be the homologues of the Armorican and Variscan chains of Europe.[4] The Altai and the chains of Trans-Baikalia make up one series so assigned; another begins in the Kuen Lun and follows the Nan Shan to the chain of northern China; and another is the Tsing Ling Shan and the mountains of northern Szechuan where Baron von Richthofen found folding at

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[1] J. W. Evans, "Expedition to Caupolican Bolivia, 1901–1902," *Geog. Jour.*, XXII (1903), 633–34.

Isaiah Bowman, "The Physiography of the Central Andes," *Am. Jour. Sci.*, 4th Ser., XXVIII (1909), 376.

[2] Emanuel Kayser, *Geologische Formationskunde*, 2d ed. (1902), p. 174.

[3] Hans Keidel, "Geologische Untersuchungen im südlichen Tian Schan nebst Beschreibung einer obercarbonischen Brachiopodenfauna aus dem Kukurtuk-Tal," *N. Jahrb. f. Min.*, XXII, Beilage Bd. (1906), pp. 282–83.

[4] Emile Haug, *op. cit.*, p. 834.

the close of the Carboniferous, together with great eruptions of igneous rock which were presumably associated with the movements.[1]

PERMO-CARBONIDES

In the two preceding sections an endeavor has been made to separate the Culmides and Westphalo-Carbonides out of the great group of diastrophic movements that marked the close of the Paleozoic. It remains to assemble the movements that took place following the Permo-Carboniferous sedimentation. But here the time of the diastrophism can be less definitely located, and the correlations less closely made than in the case of the Westphalo-Carbonides. Recognizing this difficulty the term Permo-Carboniferous is quite widely in use in various parts of the world, and as this is in reality a period of transition from the Paleozoic to the Mesozoic, this terminology has its advantages, and the name Permo-Carbonides will be used to designate the final set of disturbances which mark the break between the two eras.

One of the most familiar as well as one of the most pronounced of the Permo-Carbonide movements was the folding of the Appalachian Mountains of North America. The principal folding of the Appalachians followed the laying-down of the Dunkard sediments, which are the youngest strata involved in the folds. The age of the Dunkard beds was identified as Permian by Fontaine and White in 1880,[2] and this has been very commonly accepted since. But David White states that the flora of the Dunkard shows it to be transitional between Carboniferous and Permian, and that its uppermost portion corresponds approximately to the lowest member of the Rothliegende of Europe.[3] This reference of the greater part of the Dunkard to the Lower Rothliegende he believes to be well founded. This would bring the main folding of the Appala-

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[1] Bailey Willis, *Research in China*, I, Pt. I (1907), 297.

[2] W. M. Fontaine and I. C. White, "The Permian or Upper Carboniferous Flora of West Viriginia and Southwestern Pennsylvania," *Second Geol. Surv. of Pennsylvania, Report of Progress, PP.* (1880), pp. 105–20.

[3] David White, "Permian Elements in the Dunkard Flora," *Bull. Geol. Soc. Am.*, XIV (1903), 538–42.

chians after the Carboniferous and after a portion, at least, of the Permian, and it may not have followed immediately after the deposition of the Dunkard.

The time of the Appalachian folding seems to have been also an epoch of general epeirogenic movements. At this time much of the eastern half and of the interior of North America was uplifted and aqueous sedimentation largely stopped. Much of this region was never again the site of notable sedimentation.

In South America also a general movement of emergence seems to have been in progress at this time. Katzer places the withdrawal of the sea from the lower Amazon region within the Permian. Schuchert states that the sea retreated from this region "at the close of Neo-Carbonic time," and that thereafter the interior of this extended land, as far as observations will permit judging, was not again subjected to marine deposits.[1]

In Australia minor deformative movements are said to have occurred in New South Wales during the Permo-Carboniferous period, while Süssmilch states that at its close renewed orogenic movements of a more pronounced sort took place in the same region.[2] At this time the folding extended sufficiently far southward to develop a series of broad anticlinal and synclinal folds in the Permo-Carboniferous strata along the northern edge of the Maitland coal field where the folding is believed to have produced an elevation of at least 7,000 to 8,000 feet.[3] The axis of the folding is north and south, parallel to the present coast. This was the last folding in New South Wales; subsequent movements have been of the epeirogenic sort.

In eastern Europe it was not until late in the Permian that folding is said to have taken place on the site of the Russian geosynclinal. All members of the Carboniferous, and some of the Permian, thus form a thick concordant series. In the Donetz basin, the Upper Permian was affected by the folding.[4]

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[1] Charles Schuchert, "Geology of the Lower Amazon Region," *Jour. Geol.*, XIV (1906), 725.

[2] C. A. Süssmilch, *op. cit.*, p. 102.

[3] *Ibid.*, p. 121.

[4] Emile Haug, *op. cit.*, p. 834.

The close of the Permian in western Europe seems to have been accompanied by a general uplift. In most parts of England there is a certain amount of unconformity between the Permian and the Bunter, or Lower Triassic, but it does not indicate any great tectonic disturbance, though in the northern and central portions of England there was some tilting of the Permian beds as well as some faulting in the interval.[1] In the Hercynian chain, the last movements took place at the close of the Permian, according to Haug. From them arises the discordance observed in the southern Vosges and in the central plateau of France between the Upper Permian and the Lower Triassic.[2] In the southern portion of the central plateau, especially in the basin of Gard, the most intense foldings of the Hercynian system came after the Stephanian, and in the Alps of Savoy the Permian also is often found to have been included in the pre-Triassic folding.[3]

A Permo-Carbonide movement also affected the southern Tian Shan range in central Asia. The youngest member of the Paleozoic sedimentary series in this region, according to Keidel, is a conglomerate containing pebbles from the Schwagerina (Permo-Carboniferous) limestone formation.[4] This conglomerate has resulted from an upbowing of the range, and associated with it is a discordance. Resting upon the conglomerate are the Angara beds which are classed as Triassic, though Keidel is inclined to believe that their lowest layers should be placed in the Paleozoic. But if diastrophism be followed as the basis of correlation the break between Paleozoic and Mesozoic would naturally come somewhat lower—at the discordance.

GENERAL

From this brief assemblage of data bearing upon the periodicity of the diastrophism during the Paleozoic era, it appears that the orogenic disturbances of the more pronounced type fall quite generally into distinct groups; that these groups are well separated from one another; and that the disturbances of each group were more or less widely distributed over the globe, and that they had their

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[1] A. J. Jukes-Browne, *op. cit.*, p. 215.

[2] Emile Haug, *op. cit.*, pp. 917–18.

[3] *Ibid.*, p. 831.

[4] Hans Keidel, *op, cit.*, pp. 356–57.

active stages at about the same time, so far as correlations now permit one to judge. It appears also from this study, that the current divisions into periods which represent the general judgment of geologists as to what are natural divisions, and which are based on various considerations largely stratigraphic and paleontologic, are in fair accord with the divisions that would be made if diastrophism were chosen as the primary basis of division. Such general accord was to have been expected if diastrophism is a true and fundamental basis for such division, but some divergencies in detail were also naturally to be anticipated.

The chief divergencies that have been found are the debatable division line between the Cambrian and the Ordovician, and the partially accepted separation of the old Carboniferous group into Mississippian, and Pennsylvanian. It is notable that these division lines are those that have been regarded as the least satisfactorily established. Since the famous controversy of Murchison and Sedgwick the Cambro-Ordovician dividing line has been a subject of debate, and of uncertainty and oscillation of judgment. The breaking-up of the old Carboniferous period and the recognition of the lower portion as a distinct period under the name Mississippian is a matter of recent date and is only partially accepted. There is evidence of distinct diastrophism at the close of the Mississippian, but from present data it does not seem to be of the same order of magnitude and prevalence as the deformations that mark off the other periods, with the exception of the mooted Cambro-Ordovician diastrophism.

The Westphalo-Carbonide movement is brought by diastrophic studies into more prominence than was given it under the criteria that have been in common use.[1] It appears to have been unusually widespread and pronounced. On account of its magnitude, dynamically and geographically, it seems entitled, under the diastrophic view, to be made to mark the beginning of the closing scenes of the Paleozoic era. Shortly following it, and perhaps in

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[1] De Lapparent, however, states that while formerly it was thought proper to put the coal beds all in one undivided period, one is now forced to observe that the coal formations are traversed, between the Westphalian and the Stephanian, by an orogenic phenomenon of such importance that it should be of greater weight than all else in determining the limit of the systems (*Traité de géologie*, 5th ed., II [1906], pp. 889–90).

consequence of it, came the extraordinary Permo-Carboniferous glaciation, attended by biological changes of so pronounced a nature that they have generally been regarded as the initiation of the distinctive types of life of the Mesozoic era. The Permo-Carboniferous events that followed the Westphalo-Carbonide movement have been growing into recognition in recent years as indicating a time of transition from the Paleozoic to the Mesozoic. These studies give support and definiteness to that idea.

Thus it appears that the division of Paleozoic time on the basis of diastrophism, so far as present data go, does little violence to the systems and time divisions already formed on stratigraphic and paleontologic and other grounds, while it seems to throw distinct light on the remarkable phenomena that closed the era, phenomena over which not a little obscurity long has hung.

ON THE RELATIONS OF THE GREAT MARLBOROUGH CONGLOMERATE TO THE UNDERLYING FORMATIONS IN THE MIDDLE CLARENCE VALLEY, NEW ZEALAND

C. A. COTTON
Victoria College, Wellington

CONTENTS

INTRODUCTION

McKay, in describing the geology of the Cape Campbell district in 1877, mentioned "conglomerates, composed in chief part of well-rounded bowlders, but having a large percentage of angular blocks of great size, so that on the surface they often present the appearance of old Morainic accumulations." His description continues as follows: "A great variety of rocks are represented in these conglomerates—old slates and sandstones, and even crystalline rocks from the inland ranges; volcanic rocks from the Amuri group; green sandstone from the Saurian beds; and great masses of Amuri limestone—as before mentioned large bowlders of conglomerate from the Awatere beds, as well as limestones, sandstones, and shell conglomerates belonging to the same."[1] In the section accompanying McKay's report[2] the deposit is represented as superficial, lying on the upturned edges of the "Saurian beds"

[1] A. McKay, *Geol. Surv. of N.Z., Rep. Geol. Expl. during 1874–76*, p. 190, 1877.

[2] *Op. cit.*, BB, opp. p. 188.

(Cretaceous), and its correlation is suggested with "the high-level shelly conglomerates at Amuri Bluff,"[1] which are probably Pleistocene.

Some years later the same geologist found deposits of similar type, which he regarded as parts of the same formation, at various places in Eastern Marlborough. The most conspicuous and characteristic of these are several outcrops in the neighborhood of Kekerangu,[2] that forming Deadman's Hill,[3] and a long strip in the Middle Clarence Valley.[4]

The beds exposed in Heaver's Creek, Kekerangu, are described by McKay in the following terms:

> They are rudely stratified, at places showing that the beds are standing nearly vertical; in the lower part are enormous blocks of Amuri limestone and masses of soft marly strata, which it seems impossible to convey any distance and deposit in the position in which they are found. Saurian concretions from the Amuri beds, and bowlders containing Awatere fossils, are also plentiful. . . . . It is impossible to give any description which will convey a correct idea of the pellmell manner in which the various materials of this conglomerate breccia are mixed together. Well-rounded sandstone conglomerates are confusedly mixed with angular blocks of all sizes up to 12 ft. or 15 ft. in diameter, divided into thick beds by thin beds of sandy and clay beds, which themselves are not evenly bedded, but twist and wind among the coarser materials as though the beds had been thrown into undulations prior to their being upheaved and subsequently brought into their present position by faulting."[5]

Hector[6] mentions, in the same section, the most finely laminated silts with fossil plants in the midst of the coarse conglomerate.

Both Hector[7] and McKay always regarded the conglomerate as unconformable to the beds on which it rests, and it is thus represented in all their sections illustrating structure in the Clarence Valley and also at Deadman's Hill.[8] In all these cases, it is repre-

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[1] *Op. cit.*, p. 191.

[2] A. McKay, *Geol. Surv. of N.Z.*, *Rep. Geol. Expl. during 1885*, pp. 114–16, 1886; *ibid.* (*1888–89*), pp. 169–71, 1890.

[3] *Op. cit.* (*1886*), pp. 116–17; *ibid.* (*1890*), pp. 171–72.

[4] *Ibid.* (*1886*), pp. 118–22; *ibid.* (*1890*), pp. 174–78.

[5] A. McKay, *op. cit.* (*1886*), p. 115.

[6] Sir James Hector, *Geol. Surv. of N.Z.*, *Progr. Rep. for 1885*, p. xxxvi, 1886.

[7] *Ibid.*, p. xvi.

[8] See, for example, Hector, *op. cit.*, p. xxxv; McKay, *op. cit.* (*1886*), pp. 94, 95, 116.

sented as following the Grey Marl, a formation which, in the classification adopted by Hector's Survey, was classed as Cretaceo-Tertiary, i.e., older than Upper Eocene. Since the conglomerate contains bowlders of fossiliferous rock, which McKay regarded as derived from the Awatere beds (believed to be of Miocene age), the reason for regarding it as unconformable to the underlying series is apparent.

It was recognized that the accumulation of the conglomerate took place prior to the earth movements that gave rise to the Kaikoura and Seaward Kaikoura ranges,[1] but one of the lines of argument on which McKay relied to prove his contention was undoubtedly a mistaken one. He argued that, since no beds had been discovered in place in the neighborhood from which the fossiliferous Tertiary blocks in the conglomerate could have been derived, these bowlders had been transported across the site of the Kaikoura Ranges, before their uplift, from a known outcrop of similar rocks far to the southwest.[2]

Recently, however, Thomson[3] has discovered a bed of marine, fossiliferous, Tertiary sandstone, apparently interstratified between two coarse bands of the conglomerate forming Deadman's Hill, which is identical with the material of the blocks in the conglomerate in that locality formerly regarded as exotic. The large bowlders, moreover, in Deadman's Creek (or Shades Creek), the presence of which has been noted by various observers, come in reality from this outcrop of rock in place, and not, as has been supposed, from the conglomerate. The writer has also examined the locality in company with Dr. Thomson. The junction of the sandstone with the underlying band of conglomerate is not clear, and there is a bare possibility that the beds are separated by a fault (or thrust plane). If this is so, the sandstone may be the source of the fossiliferous bowlders in the underlying as well as in the overlying conglomerate beds. Whether this is the case or not, the discovery indicates the danger of assuming that any of the constituents

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[1] Hector, *op. cit.*, p. xxxvi; McKay, *Geol. Surv. of N.Z., Rep. Geol. Expl. during 1890–91*, p. 95, 1892.

[2] A. McKay, *op. cit.* (*1892*), p. 4.

[3] J. Allan Thomson, *N.Z. Geol. Surv.*, *7th Ann. Rep.*, 1913, p. 123.

of the conglomerate are not of local origin because local outcrops of similar rock in place have not yet been found.

The same conglomerates have been described as glacial moraines by Park,[1] who assumes extensive glaciation in Eastern Marlborough in the Pleistocene period.

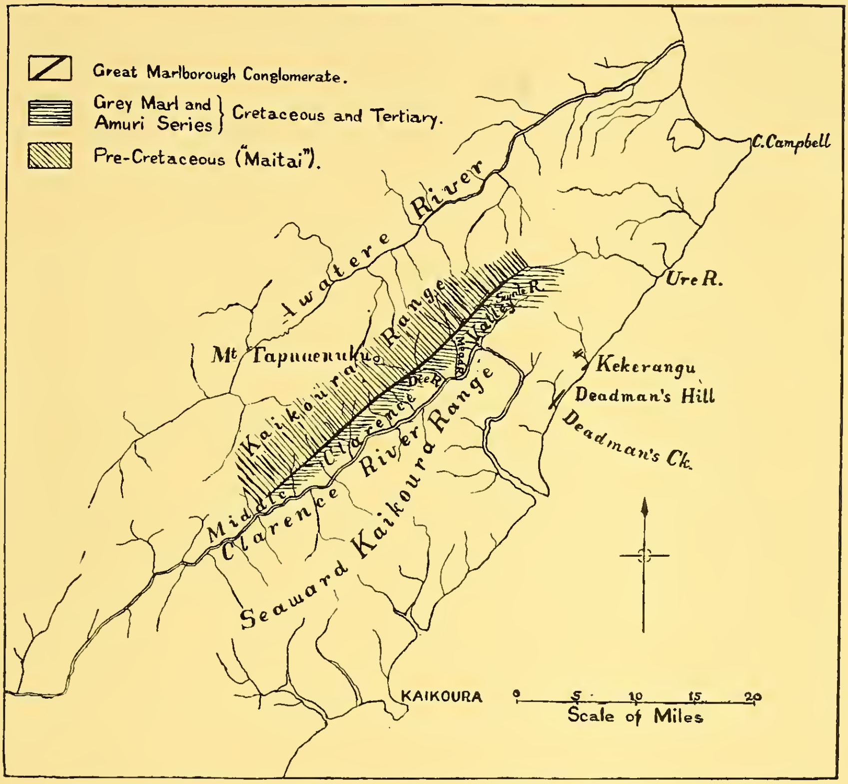

FIG. 1.—Locality map of Eastern Marlborough, New Zealand. Geology after McKay.

The writer has examined several outcrops in the neighborhood of Kekerangu, that forming Deadman's Hill, and also, at a number of points, the strip which follows the line of the Middle Clarence Valley. The outcrop near Cape Campbell was, however, in the limited time available, not found, although a great part of the

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[1] J. Park, *Trans. N.Z. Inst.*, XLIII, 520–24, 1910; *Geology of New Zealand*, pp. 201–5, 1910.

area mapped by McKay[1] as conglomerate was traversed, and it therefore appears that the outcrop is much smaller than is indicated by McKay's map. The stratigraphy at Kekerangu and Deadman's Hill is much involved, and, if Dr. Thomson's discovery at Deadman's, already referred to, is excepted, the sections of the conglomerate there exposed throw little light on its stratigraphical relations.

The writer has, therefore, studied in greater detail the strip in the Middle Clarence Valley where, especially in the Dee and Mead gorges, the sections are clearer; and the results are presented in the following pages.

From what has been already said it is clear that our knowledge of the age of the beds is insufficient to warrant the use of the name "Great Post-Miocene Conglomerate" applied by McKay and the formation will therefore be referred to in this paper by the name "Great Marlborough Conglomerate" adopted by Thomson.[2]

CONCLUSIONS AS TO THE NATURE AND RELATIONS OF THE CONGLOMERATE

Briefly stated, the conclusions as to the nature and relations of the Great Marlborough Conglomerate reached by the writer are as follows:

1. It exhibits fairly regular stratification, always more or less parallel to that of the underlying series.
2. Its relation to the underlying series, wherever the junction has been examined, appears to be one of conformity.
3. It contains, in abundance, masses of rock derived from the underlying formations.
4. It is, in the main, a fluviatile deposit.

The second and third statements, which appear, at first sight, contradictory, may be otherwise stated thus: The conglomerate forms a "superposed series" with the beds on which it rests, but, with an adjoining area of the same beds, which has since been entirely removed by erosion, but which supplied much of the material of the conglomerate, it formed, when first laid down, an

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[1] *Op. cit.* (*1877*), map, p. 188.

[2] J. Allan Thomson, *N.Z. Geol. Surv.*, *7th Ann. Rep.*, 1913, p. 123.

"apposed series."[1] The evidence in favor of these conclusions is set out in the following pages, and also a hypothesis to account for the peculiar features of the formation.

CONFORMABLE RELATION TO THE UNDERLYING BEDS

In the Middle Clarence Valley the conglomerate overlies the bluish-gray mudstone to which the name Grey Marl is generally applied, and this, in turn, conformably overlies the Amuri Limestone. Wherever examined the Amuri Limestone, Grey Marl, and Great Marlborough Conglomerate have the same strike and dip, striking approximately northeast and dipping at high angles to the northwest, while the conglomerate is terminated upward by a reversed fault which runs for many miles, parallel to the strike of the above-mentioned beds, along the front of the Kaikoura Range, and brings the conglomerate against the old rocks of the range as indicated in Figs. 1 and 2.

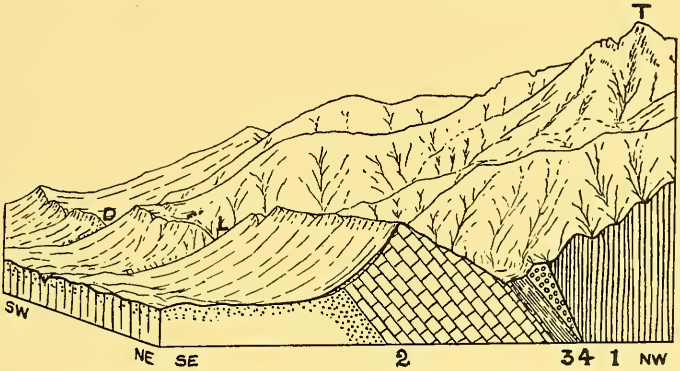

Fig. 2.—Diagram illustrating the occurrence of the Great Marlborough Conglomerate with the underlying Grey Marl and Amuri series in the Middle Clarence Valley, along the base of the Kaikoura Range.

The front of the diagram is a generalized section along the southwest side of the Mead River. (The dip of the fault plane in this section is hypothetical.)

D, Dee River; *L*, Limburne Stream; *T*, Mount Tapuaenuku
4, Great Marlborough Conglomerate
3, Grey Marl Series } Cretaceous and Tertiary
2, Amuri Series }
1, Pre-Cretaceous ("Maitai") Rocks. (Structure obscure)

In the gorge of the Mead River clear sections are exposed showing the relation of the conglomerate to the Grey Marl. The

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[1] Cf. E. Suess, *The Face of the Earth*, I, 378–79 (Oxford, 1904).

junction plane, at the point examined, strikes N. 25° E., and dips at an angle of 47° to the west-northwest. The irregular bedding in the conglomerate is roughly parallel to the junction and apparently the junction is parallel to the bedding of the Gray Marl. In the latter, however, the only indication of stratification is given by discontinuous bands of concretions.

The upper layer of the Grey Marl is, lithologically, very similar to the Grey Marl as a whole except that it contains some broken shells and a few small pebbles or perhaps concretions of material similar to the Grey Marl but more indurated and containing shells in a bad state of preservation. These resemble larger masses, found close at hand, at a somewhat lower horizon, but still near the top of the Grey Marl series, which contain well-preserved fossils.[1] It is not quite clear whether they are derived bowlders or concretions. Thomson regards them as the former and considers that they indicate a certain amount of contemporaneous erosion.

Immediately overlying the upper layer of Grey Marl is a layer, 2 ins. in thickness, of conglomerate formed of various-sized rolled pebbles of graywacke (from the pre-Cretaceous formations). Next follows 2 ft. 6 ins. of bedded sandstone, covered by 1 ft. of mudstone, and that again is followed by many feet of fairly coarse conglomerate interbedded with sandstone and mudstone bands 1 ft. to 3 ft. in thickness, and with bands of very coarse conglomerate.

A distant view of the junction in the Mead gorge gives a false appearance of unconformity with discordance of dip, and led McKay to make the statement: "The overlying conglomerates are quite unconformable."[2]

This appearance of unconformity is due mainly to two causes:

1. Owing to the fact that the Grey Marl is a weak stratum, while both the underlying Amuri Limestone and the overlying conglomerate are very resistant, the valley of the Mead River is contracted into narrow, vertical-walled gorges where it crosses the conglomerate and limestone, but, between the two gorges, it opens out, with broadly flaring sides and a floor of considerable breadth, to form a nearly circular hollow on the outcrop of the

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[1] J. Allan Thomson, *N.Z. Geol. Surv., 7th Ann. Rep.*, p. 123, 1913.

[2] A. McKay, *op. cit.* (*1886*), p. 95 and section p. 94.

weaker rock. The junction between the Grey Marl and the conglomerate passes as a conspicuous line up the sides of this basin, and, since the face on which the section is exposed runs for some distance more nearly parallel to the strike than to the dip, the effect is to make the dip of the junction, when viewed from downstream, or from the center of the hollow, appear much more nearly horizontal than it really is. The apparent dip is, owing to the absence of a hard line of division between the Grey Marl and Amuri Limestone, compared by the eye with the true dip of the limestone outcropping in the monoclinal ridge (see Fig. 2), and there is thus produced the effect which was sketched by McKay as shown in Fig. 3.[1] Fig. 4, however, which is a photograph looking along the strike of the junction, shows that there is no appreciable discordance of dip.

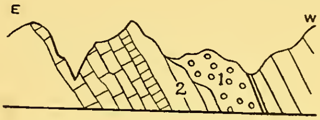

FIG. 3.—Part of McKay's section in the Mead River, showing the junction between the Grey Marl (2), and the Great Marlborough Conglomerate (1).

FIG. 4.—View of the junction between the Grey Marl and Great Marlborough Conglomerate, looking south-southwest across the Mead River.

2. Although the surface of junction between the Grey Marl and the conglomerate was originally plane, it is now broken by a number of small faults, each with a downthrow of only a few feet, which appear to be tension faults formed while the conglomerate and the underlying strata were in their original horizontal position. These, collectively, have let down, by trough-faulting, a wedge of conglomerate into the Grey Marl, giving the surface of junction a somewhat undulating form shown in Fig. 4, in which the faults can be seen.

[1] After McKay, *op. cit.* (*1886*), section p. 94; see also Hector, *op. cit.*, p. xxxvi.

A false appearance of bedding in the Grey Marl, nearly at right angles to the real stratification, is produced by the downward continuation of the faults, veins having been formed along the fault planes, which stand out a little from the bare, denuded surface of the weak marl.

In the Dee River (north branch) there is also a clear section showing the conformable relation between the Grey Marl and the conglomerate, in which the upper part of the Grey Marl is sandy, and contains near the top small pebbles of "Maitai" (pre-Cretaceous) graywacke, up to $\frac{1}{2}$ in. in diameter. Next follow lenticular masses of conglomerate composed of "Maitai" pebbles the largest of which are the size of a hen's egg, and from this there is a gradual passage to the typical conglomerate with sandstone bands.

COMPOSITION

The writer can confirm, in a general way, the descriptions of the conglomerate, at the various localities visited, as given by McKay, some of which were quoted on an earlier page.[1] McKay, however, in almost every description, reports the occurrence of coarse-grained igneous rocks resembling the intrusives of the Kaikoura Range, which have recently been described by Thomson.[2] These are referred to in the description of the Deadman's Hill conglomerate as follows: "Hornblendic and syenitic rocks brought from the central part of the Inland Kaikoura Range are very abundant."[3] In the Clarence Valley, on the watershed between the Ure and Swale, "abundance of crystalline dyke-rocks derived from the higher part of the Tapuaenuka Range" are reported in the conglomerate,[4] and McKay concluded that the abundant bowlders of igneous rock in the lower Ure River were derived from this source. The writer was unfortunately unable to examine the conglomerate closely at the source of the Ure, but a reconnaissance in the lower

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[1] See also, for descriptions of the conglomerate at Deadman's Hill, McKay, *op. cit.* (*1886*), p. 116; (*1890*), p. 171; and for the Clarence Valley, McKay, *op. cit.* (*1886*), pp. 118–22; (*1890*), pp. 174–78.

[2] J. Allan Thomson, "On the Igneous Intrusions of Mt. Tapuaenuka," *Trans. N.Z. Inst.*, XLV, 308–15, 1913.

[3] McKay, *op. cit.* (*1886*), p. 116.

[4] *Ibid.* (*1886*), p. 119.

Ure valley showed that the great majority, at least, of the bowlders of igneous rock in the bed of that river were brought in by tributaries from the northeastern end of the Kaikoura Range where they are present in place. McKay states definitely that these rocks are present throughout a great part of the length of the outcrop in the Middle Clarence Valley[1] and notes their absence only at the southwest end of the strip.[2]

The writer, however, has been forced to conclude, from the results of his own examinations, in which Dr. J. A. Thomson kindly assisted, that igneous rocks of the Tapuaenuku type are absent from the conglomerate at all the points in the Clarence Valley at which it was examined. No such statement can, of course, be made with reference to the conglomerate at the source of the Ure.

The absence of these rocks from the conglomerate in the Dee gorge is especially significant since the intrusions are now exposed in the immediate vicinity and supply the bulk of the bowlders in the bed of the Dee.

The constituents of the conglomerate in the Dee and Mead gorges, as noted by the writer, are as follows:

In the gorge of the Dee.—Small well-rolled pebbles of pre-Cretaceous or "Maitai" rocks, both graywacke and jasperoid, are very abundant. Much rarer are lumps of Amuri Limestone of irregular, angular shape, up to the size of a man's head, and there are some pieces of flint, apparently derived from the flint beds which replace the basal part of the Amuri Limestone. Still more rare are lumps of very fossiliferous Tertiary sandstone, and of Cretaceous sandstone containing fragments of *Inoceramus;* these range up to 1 ft. in diameter. The largest blocks, generally several feet in diameter, are of crumbling, sandy marl or mudstone exactly agreeing, lithologically, with the upper beds of the Grey Marl present in place immediately below the conglomerate. All the larger blocks are arranged with their largest flat surfaces parallel to the stratification. There are present also some spherical concretions, 1 ft. to 2 ft. in diameter, resembling those in the Grey Marl. Igneous rocks are represented by bowlders of coarse-grained

[1] A. McKay, *op. cit.* (*1892*), p. 4.

[2] *Ibid.* (*1886*), p. 121.

basic, volcanic rock varying in size, the largest noted being 4 ft. in diameter, and by very rare, small pebbles of a fine-grained, porphyritic rock with small felspar phenocrysts.

Successive bands of conglomerate vary in coarseness, but there is no definite alternation or succession of coarser and finer strata. One conspicuously coarse band which occurs about 40 ft. from the base of the section in the main branch of the Dee is shown in Fig. 5. The large bowlders of which it is mainly composed are derived principally from the younger rocks, but large "Maitai" pebbles, up to 6 ins. in diameter, are present, and there are some rounded bowlders up to 6 ft. in diameter which may be either Cretaceous or pre-Cretaceous.

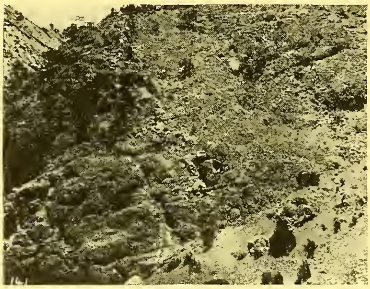

Fig. 5.—Coarse band in the Great Marlborough Conglomerate in the Dee gorge. View looking southwest.

In the gorge of the Mead.—In the Mead gorge the conglomerate is, on the whole, coarser than in the Dee, and here, more than anywhere else where it was examined by the writer, there is a mixture of fragments of all sizes. The very largest are rare, but blocks up to 2 ft. in diameter are common, and about one-third of the bulk is composed of bowlders over 6 ins. in diameter. All of them are water worn and most are fairly well rounded. Small pebbles are very abundant throughout, the majority of them being as small as or smaller than a hen's egg. They are fragments of the hardest of the pre-Cretaceous or "Maitai" rocks, smooth and well rounded, frequently almost spherical. There is in addition, both here and in the Dee, a large proportion of fine, sandy material filling the interstices, and the conglomerate is cemented into a very hard rock. The rocks represented are: large bowlders of the same coarse-grained, basic, volcanic rock that occurs in the Dee section; smaller and much rarer fragments of the fine-grained porphyritic rock also sparingly represented in the Dee; blocks of fine, Tertiary sandstone up to 2 ft. in diameter, crowded with shells and water worn (these are the bowlders regarded by McKay as exotic, but Thomson[1] refers them to the same source as the possibly derived masses in the Grey Marl in this locality); Amuri Limestone, not very abundant, in blocks up to 6 ins. in diameter, but rarely larger; sandstone blocks of all sizes, some resembling the sandstones of the Cretaceous, others possibly pre-Cretaceous; pre-Cretaceous or "Maitai" pebbles, both graywacke and jasperoid, forming, as already mentioned, the bulk of the finer material. Fig. 6 is a photograph showing the general appearance of the conglomerate in the Mead section. In the Mead and Dee sections, as well as elsewhere, thin bands of sandstone occur throughout the conglomerate. They are referred to in the next paragraph.

FIG. 6.—The conglomerate in the gorge of the Mead. (The hammer handle is 10 inches long.)

FLUVIATILE ORIGIN

From the foregoing descriptions and from those quoted, as well as from the photographs of the conglomerate outcrops at Heaver's Creek, Kekerangu, and Kekerangu South Head published by Park,[2] it will be gathered that superficially the material resembles glacial morainic accumulations. Park[3] lays stress on the angular nature of some of the bowlders, but no polished or striated bowlders have as yet been described. "Large angular blocks" are certainly present, but it is also true that everywhere the bulk of the conglomerate consists of medium-sized to small pebbles of hard rocks, exceptionally well rounded. This fact was noted by McKay.[4] There is, moreover, almost everywhere a rough sorting into coarser

[1] J. Allan Thomson, *N.Z. Geol. Surv., 7th Ann. Rep.*, p. 123, 1913.

[2] J. Park, *Trans. N.Z. Inst.*, XLIII, Pls. 20, 22, 1910; *Geology of New Zealand*, Fig. 93, 1910.

[3] J. Park, "Marlborough Coastal Moraines," *Trans. N.Z. Inst.*, XLIII, 522, 1910.

[4] See, for example, *op. cit.* (*1886*), p. 115; *ibid.* (*1892*), p. 4.

and finer bands in the conglomerate itself, and fairly regular sandstone bands are universally present. These are clearly exposed in the gorge of the Dee, where the series is well stratified, with bands of coarse conglomerate and fine conglomerate, and thin bands of sandstone. In the Mead gorge a similar stratification is well marked, especially in the higher beds, and here the beds are seen to be lenticular, many of the sandstone beds especially thinning out to a feather edge.

In no case, on the other hand, has a distinct false bedding been noted, nor an arrangement of foreset beds that would indicate beach or delta conditions of subaqueous deposition. The beds were evidently laid down nearly horizontally and such deposition of coarse material appears to be impossible in standing water. It is practically certain, therefore, that the shallowing water of the Grey Marl sea was immediately filled when deposition of the conglomerate began, and that subsequently accumulation went on under subaerial conditions.

The character of the conglomerate supports the view that it accumulated under fluviatile conditions, and it presents many striking analogies with the terrestrial deposits in Owen's Valley, California, described by Trowbridge,[1] who has set out a list of criteria for the recognition of such deposits. Of these criteria the following, which appear to be the most valuable, are satisfied by the conglomerate:

1. In alluvial fans coarse material has a wide distribution as against confinement to a narrow zone near shore in standing-water deposits.
2. Textural range in single exposures is large in fan materials.
3. Fan materials are not in general so well sorted as deposits in standing water.
6. Fan material has a lens and pocket stratification, as against a sorting into more or less uniformly thick horizontal layers, as in lakes or seas.
7. Huge bowlders widely distributed vertically and horizontally in a deposit indicate that it was deposited by running water, and with a large proportion of fine material; that is, they indicate that the material is part of an alluvial fan deposit, except in cases where glaciers have affected it, or where standing waters could have received icebergs, or where basal conglomerates are formed near shore.

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[1] A. C. Trowbridge, *Jour. Geol.*, XIX (1911), 706–47.

The continuity of the conglomerate in the Middle Clarence Valley throughout a line of outcrop thirty miles in length indicates that it was there deposited as a piedmont alluvial plain and not as isolated fans. A somewhat similar feature now in course of formation by several rivers, between the Seaward Kaikoura Mountains and the sea, in the vicinity of Kaikoura, constitutes the Kaikoura Plain.[1]

It may be noted that both Hector[2] and McKay[3] expressed their conviction that the conglomerate was of fluviatile origin, but both regarded it as the work of a single river system.

HYPOTHESIS TO ACCOUNT FOR THE PECULIAR FEATURES OF THE CONGLOMERATE

From the description in the preceding pages it is apparent that the Great Marlborough Conglomerate, in the Middle Clarence Valley, rests conformably on the Grey Marl, and yet is largely made up of material derived from that series and the beds conformably underlying it. Much of the material, moreover, agrees exactly in facies with the beds upon which it rests, and undoubtedly has been transported only a comparatively short distance.

In order to account for the supply of this material it is necessary to assume that a neighboring area was differentially elevated to the extent of perhaps as much as twelve thousand feet (the maximum thickness of the Amuri and Grey Marl series, as exposed in the neighboring Coverham section being estimated by McKay[4] at that amount), without seriously disturbing the horizontal attitude of that portion of the Amuri[5] and Grey Marl series, which, a little later, had the conglomerate deposited upon it, and which, as shown in Fig. 2, is, in part, still preserved.

Of the exact nature of this uplift no information is to be obtained, at least in the present state of our knowledge, from the pre-Cretaceous rocks in the vicinity, for their structure is obscure, nor

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[1] See McKay, *op. cit.* (*1886*), p. 126.

[2] Sir James Hector, *op. cit.* (*1886*), p. xxxvi.

[3] A. McKay, *op. cit.* (*1892*), pp. 4–5.

[4] A. McKay, *op. cit.* (*1886*), p. 90.

[5] The Amuri Series as here understood includes the whole of the "Lower Greensand" and "Cretaceo-Tertiary" of Hector's Survey.

from the topography, for the main lines of the relief were determined by an orogenic uplift which took place after the deposition of the conglomerate.[1]

Of the three possible ways in which differential uplift might take place, namely, folding, warping, and block-faulting, the first two seem to be out of the question since the surface of the Grey Marl, in the area where it is preserved, was not appreciably tilted by the movement, and appears to have been neither elevated nor depressed to any extent by it. There remains the hypothesis of block-faulting with the restriction that the uplifted block alone moved.

Significance of faults in the conglomerate.—Movement of the nature of block-faulting, giving rise to mountains of the Basin Range type, usually takes place along normal faults,[2] and, for a long period after the main faulting, the formation of small normal faults continues, the younger faults so formed dislocating the fan deposits resulting from the erosion of the earlier fault scarp.[3] The occurrence of numerous small faults dislocating the Great Marlborough Conglomerate and the underlying series is, therefore, of some importance. In the Mead and Dee gorges, and in the gorge of the Limburne, a stream between the Mead and the Dee, the conglomerate, wherever examined, was found to be traversed by a number of faults with small throw. The fault planes are now in some cases nearly horizontal, and in others highly inclined, and the downthrow is fairly often found to be on the opposite side from the hade of the fault plane. If, however, the hade be measured from a normal to the plane of bedding, instead of from the vertical,

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[1] C. A. Cotton, "Physiography of the Middle Clarence Valley," *Geographical Journal*, XLII (1913), 228.

[2] The advocates of lateral crustal extension and of some phase of crustal compression as the active agency in the formation of block mountains appear to agree that in most though not all cases the boundary faults hade toward the downthrow direction and that the planes of later movements on approximately the same lines are similarly normal fault planes.

[3] See G. K. Gilbert, *U.S. Geol. Surv., 2d Ann. Rep.*, p. 200, 1882; and *Monograph I*, pp. 340–57, 1890; I. C. Russell, *U.S. Geol. Surv., 4th Ann. Rep.*, pp. 451, 453, 1884; and *Monograph XI*, pp. 274–83, Pl. XXVIIIB, 1885; W. M. Davis, *Bull. Mus. Comp. Zoöl.*, XLII, 129–73, 1903; G. D. Louderback, *Bull. Geol. Soc. Am.*, XV, 322, 1904; A. C. Lawson, *Bull. Seismol. Soc. Am.*, II, 193–200, 1912.

the angle of hade is in no case great and the faults are all normal. There are, therefore, good grounds for the assumption that the faults were formed while the beds still lay in their original position.

One fault on the southwest side of the Dee gorge, which may be taken as an example, is illustrated in Fig. 7*a*. The line of fault, in the section exposed, slopes down to the east-southeast and makes an angle of 75° with the vertical, and a sandstone band in the conglomerate is displaced a distance of 4 ft. toward the east.

In the gorge of the Mead, as noted in an earlier paragraph, the faults are numerous, the fault planes striking about east and west. Fig. 7*b* is a sketch of one of them in the conglomerate gorge, which has a downthrow of 1 ft. 6 ins. to the south, and others are shown in Fig. 4. Very numerous faults can be seen in the Mead gorge passing down through the Grey Marl into the Amuri Limestone, but owing to the nature of these strata, the faults are less conspicuous in them than in the conglomerate.

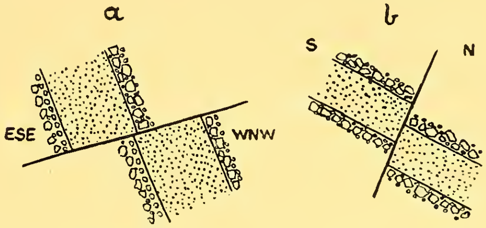

FIG. 7.—Faults in the Great Marlborough Conglomerate.

GEOLOGICAL HISTORY

During a long period extending from some time in the Cretaceous to well on in the Tertiary, deposition had been going on in the Middle Clarence Valley area under geosynclinal conditions, that is, upon a sea floor that sank gradually during the greater part of the period. Toward the end of the period of deposition of the Amuri Limestone subsidence ceased, and the character of the deposits became more and more argillaceous as the water shallowed. There is thus a gradual passage from the typical Amuri Limestone to the typical Grey Marl. The upper portion of the latter becomes somewhat sandy and contains layers of small pebbles from the old land. The presence of these does not necessarily imply uplift, but slight regional uplift, if it had occurred, would have sufficed to revive slightly the streams of the old land and so to increase the supply of coarser waste. It is probable that the old land had previously been reduced to senile relief. Slight regional uplift would account for some contemporaneous erosion of the Grey Marl,[1] as it would bring the landward margin of the deposits into the zone of erosion, but it is possible that this is to be explained by slight differential uplift heralding the somewhat later uplift that supplied the material of the Great Marlborough Conglomerate. At this stage the maximum thickness of the accumulations in the geosyncline had reached about twelve thousand feet.[2]

According to the writer's hypothesis, a normal fault was next initiated approximately along or parallel to the line of the great reversed fault previously referred to (see Fig. 2), that was formed during a later period of folding, and now bounds the Clarence Valley on the northwest side, separating the conglomerate from the pre-Cretaceous rocks of the Kaikoura Range. The earlier normal fault, being a line of weakness, may have determined the position of the later reversed fault.

Uplift of the block northwest of the fault plane took place, initiating a period of active denudation along the fault scarp. Some portion of the old land appears to have participated in the uplift, and its revived streams no doubt kept up the supply of well-rolled "Maitai" pebbles which are common in the conglomerate. Some of these, however, may be a rewash of the basal conglomerate of the Amuri Series.[3] The streams from the old land, in their lower courses, crossed the uplifted younger rocks, and, as they emerged from young gorges in the fault scarp, built

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[1] Thomson, *op. cit.*

[2] McKay, *op. cit.*

[3] Since the above was written the writer has had an opportunity of reading a paper by A. C. Lawson entitled "The Petrographic Designation of Alluvial Fan Formations" (*Bull. Dep. Geol., Univ. Cal.*, VII, No. 15, 1913), in which the name *fanglomerate* is proposed for the class of deposit to which the Great Marlborough Conglomerate belongs. Lawson regards all rounded pebbles in fanglomerate as derived from older conglomerates, and, if it were possible in this case to regard them all as a rewash, both the amount of uplift and the area of the uplifted block that it is necessary to assume would be considerably less than on the hypothesis that they are derived from pre-Cretaceous rocks in place. The writer is not, however, prepared to admit that *all* the small well-rounded material is so derived, although a possible source of supply is the Cretaceous conglomerate (McKay, *op. cit.* [*1886*], p. 90), which locally, at

fans, the material of which was a mixture of angular blocks from near at hand and well-rolled pebbles brought from a distance. The presence of blocks with the facies of the underlying series is thus explained. The bowlders of volcanic rock, while they have not their equivalent in the immediately underlying series, are of the same type as the known volcanics of the Amuri Series which occur a few miles to the northwest in the Awatere Valley,[1] and it is quite possible that they were present in that portion of the Amuri Series that has been denuded off the site of the Kaikoura Range. The absence of the coarse-grained intrusive rocks of the Kaikoura Range, even if these should prove to be absent everywhere from the conglomerate, is not remarkable, and does not necessarily indicate that the date of their intrusion was later than that of the accumulation of the conglomerate. It indicates rather that the rocks of the present Kaikoura Range, which, it must be remembered, owes its present elevation to later folding, had not then suffered the enormous denudation which has exposed the intrusions. It is possible that the bowlders of volcanic rock in the conglomerate represent the more superficial equivalents of the deep-seated intrusions now exposed in the range.

The foregoing hypothetical explanation refers only to the strip of Great Marlborough Conglomerate following the line of the Middle Clarence Valley. The writer believes that the outcrops near the coast may be similarly explained, but further study of them is required, and an extension of the hypothesis to cover all occurrences of the conglomerate is beyond the scope of this paper.

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several places in the northeast end of the Middle Clarence Valley, attains a considerable thickness, but is thin as a rule. The pebbles in the fanglomerate, on the other hand, seem to be uniformly abundant, indicating a uniform source of supply. The necessity arises also of accounting for the presence of the rounded pebbles in the transition beds from the Grey Marl to the fanglomerate, the deposition of which must have been contemporaneous with the beginning of movement on the fault plane, that is to say, must have preceded the exposure in the fault scarp of the deeply buried Cretaceous conglomerate. These pebbles at least must have come from the old land.

[1] McKay, *op. cit.* (*1890*), pp. 184–85.

THE OSTEOLOGY OF SOME AMERICAN PERMIAN VERTEBRATES[1]

S. W. WILLISTON
University of Chicago

ARAEOSCELIS

A few days before the close of the field trip of the University of Chicago paleontological expedition of 1909, Mr. C. L. Baker, a member of the party, discovered in a ravine near the west line of Craddock's Ranch, near Seymour, Texas, a large lot of loose bones lying on the surface. The spot where they lay was within a hundred yards of the road which probably every collector in the Texas Permian region had traveled many times, but had neglected to investigate, because of its unpromising appearance. The bones lay strewn over a considerable area, and included numerous forms, a list of which, so far as they have been determined, I have given in my *American Permian Vertebrates.* About a bushel of bones and fragments of bones were collected from the surface at this time, including some of the forms under discussion. Early the next season Mr. Paul C. Miller extensively excavated the bone-bed with most interesting and valuable results. At one end of the deposit, a little distance from other bones, though on the same level, he discovered a "nest" of small bones. Occurring in the moist clay and isolated, the bones were first disclosed by the plow, which naturally had a rather disastrous effect upon them, small and delicate as they are. As soon as the deposit was recognized, the pieces of clay containing the loose bones, and the various nodules in which others were inclosed were carefully collected. The closely associated bones of the skeletons were more or less cemented together by a hard-clay nodular matrix, which has been removed with difficulty, the more so because much of the preparation had necessarily to be done under a dissecting microscope. Many of the bones protruded freely from the nodules into the soft clay;

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[1] *Contribution from the Walker Museum,* Vol. I, No. 8.

others were wholly free; such bones or parts of bones are in most exquisite preservation. Doubtless had the deposit been discovered sooner and the whole mass brought to the laboratory in a large block, carefully bandaged, there would have been many more bones recovered—bones more or less anatomically associated. As it was, notwithstanding the greatest care, many bones and parts of bones were lost, and others were broken, and their restoration has been especially difficult, since the fragments must be adjusted under a microscope, for the greater part.

The whole collection of skeletons covered only a few square feet, and probably represents a dozen individuals in various stages of growth. It is not improbable that the student intent upon the naming of species and genera would have described these specimens as belonging not only to different species but to different genera as well, had he not known the conditions under which they were found. I think, however, that the remains are all conspecific, notwithstanding the different sizes and degrees of growth which they show. Especially do the smaller, long bones show a lack of ossification at the ends. I have figured parts of the skeleton of several of these specimens, but have not attempted to reduce them all to one scale, which could easily have been done, since the various more or less articulated skeletons give the relations between the different parts of the skeletons. I have made no figures, however, of the bones of the young animals, save of the clavicle, which I cannot find among the more adult bones. In case the future "species splitter" reaches the conclusion that I have lumped several allied species under one name, I may say that the larger specimens of humerus and femur, originally figured, may be considered as the type of both species and genus.

One can only conjecture the reason why so many skeletons of animals of one species in various stages of growth should have been fossilized so closely together. Possibly a group of hibernating animals were suddenly overwhelmed and drowned, or suffocated and afterward covered by water.

I may add, that in the hope of acquiring material for the more complete elucidation of the form, and baffled at first in the interpretation of the skull, I have delayed the full description until

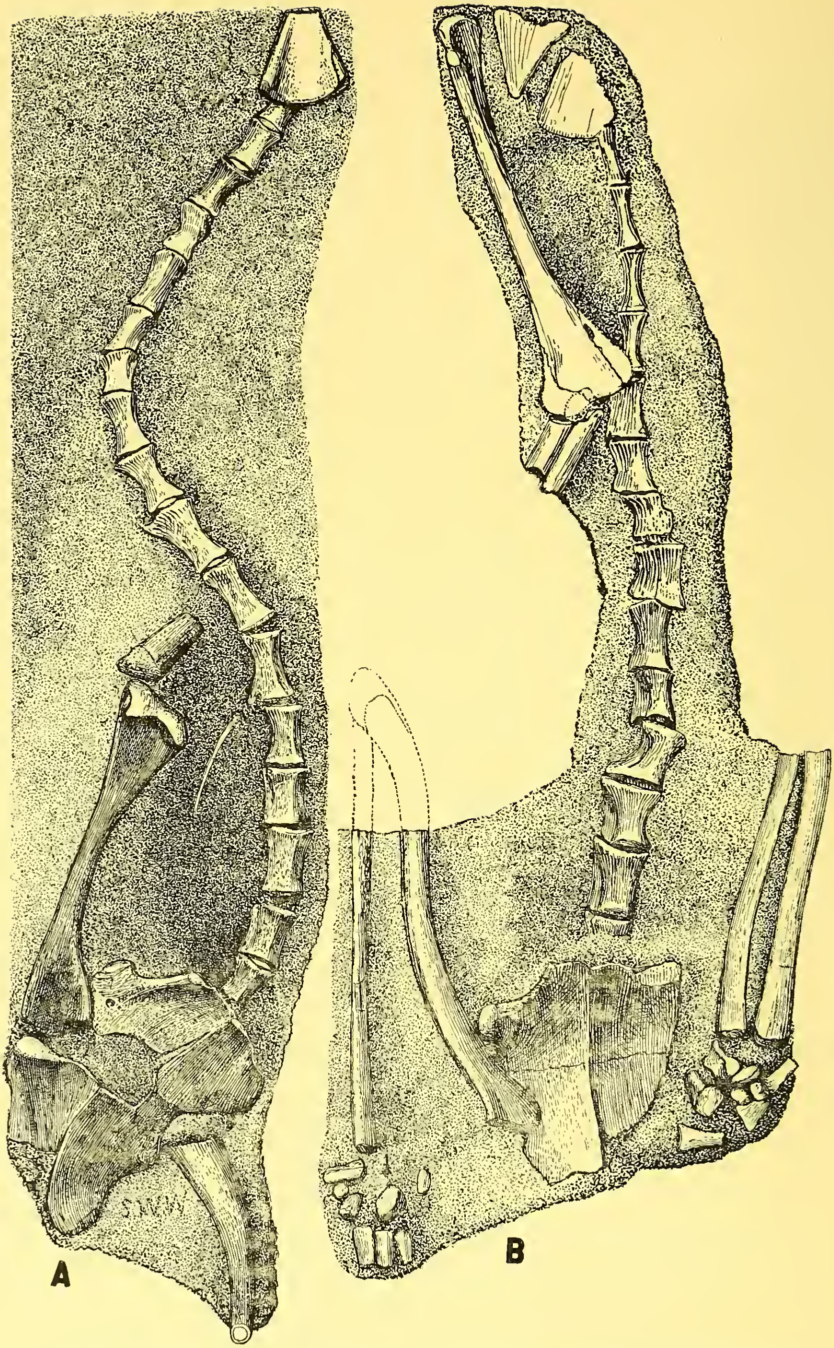

FIG. 1.—*Araeoscelis gracilis* Williston: *A*, part of nearly adult skeleton, as preserved in matrix; *B*, part of adult skeleton, as preserved in matrix. Natural size.

further excavation of the original deposit could be made. Unfortunately, explorations the past year have brought to light only a few more bones, including, however, the skull which has served as the key to the solution of its structure. This delay is the more to be regretted as it has caused Dr. Broom to misinterpret the genus and redescribe it under another name.[1]

SKULL

The material studied consists of seven skulls, none complete. They are all more or less distorted, with the different elements more or less separated, and in some misplaced and broken. They also differ in size; two preserved in blocks of matrix in association with cervical vertebrae are of adults; the loose ones are all more or less immature, though none is of a quite young animal.

The first specimen studied, at the time I gave the preliminary description of the genus, had the right temporal region exposed, showing conspicuously what seemed to be the smooth border of an entirely open temporal region. Within the depression, however, there is a large flat bone, and the fragment of another, which seemed to be misplaced elements that had been crowded into the cavity. On the opposite side the same free border was visible with the inclosed space filled more or less by matrix. It was because of this apparent structure that I stated in my preliminary description of the genus that "almost certainly there is a large temporal vacuity" and that "nothing definite can be said about *Araeoscelis* till the skulls have been cleaned and studied, and possibly not even then, save the presence of a temporal vacuity."

Unfortunately for my first belief, when the matrix was removed from the left temporal region of the above-mentioned skull it too was found to have a broad expanse of bone at its bottom, filling out nearly the whole space, definitely proving that the bone of the opposite side belonged where it was found. Nevertheless, distinct evidence of a free border above, and the whole structure of the skeleton so definitely uncotylosaurian, made it difficult for me to

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[1] *Araeoscelis gracilis* Williston, *Jour. Geol.*, XVIII (1910), 518; *American Permian Vertebrates* (1911), p. 6; *Jour. Geol.* (1913), p. 743; *Science*, November 9, 1913; Huene, *Morph. Jahrb.*, 1912 (not *Araeoscelis* Schultz, 1911); *Ophiodeirus casei* Broom, *Bull. Amer. Mus. Nat. Hist.* (1913).

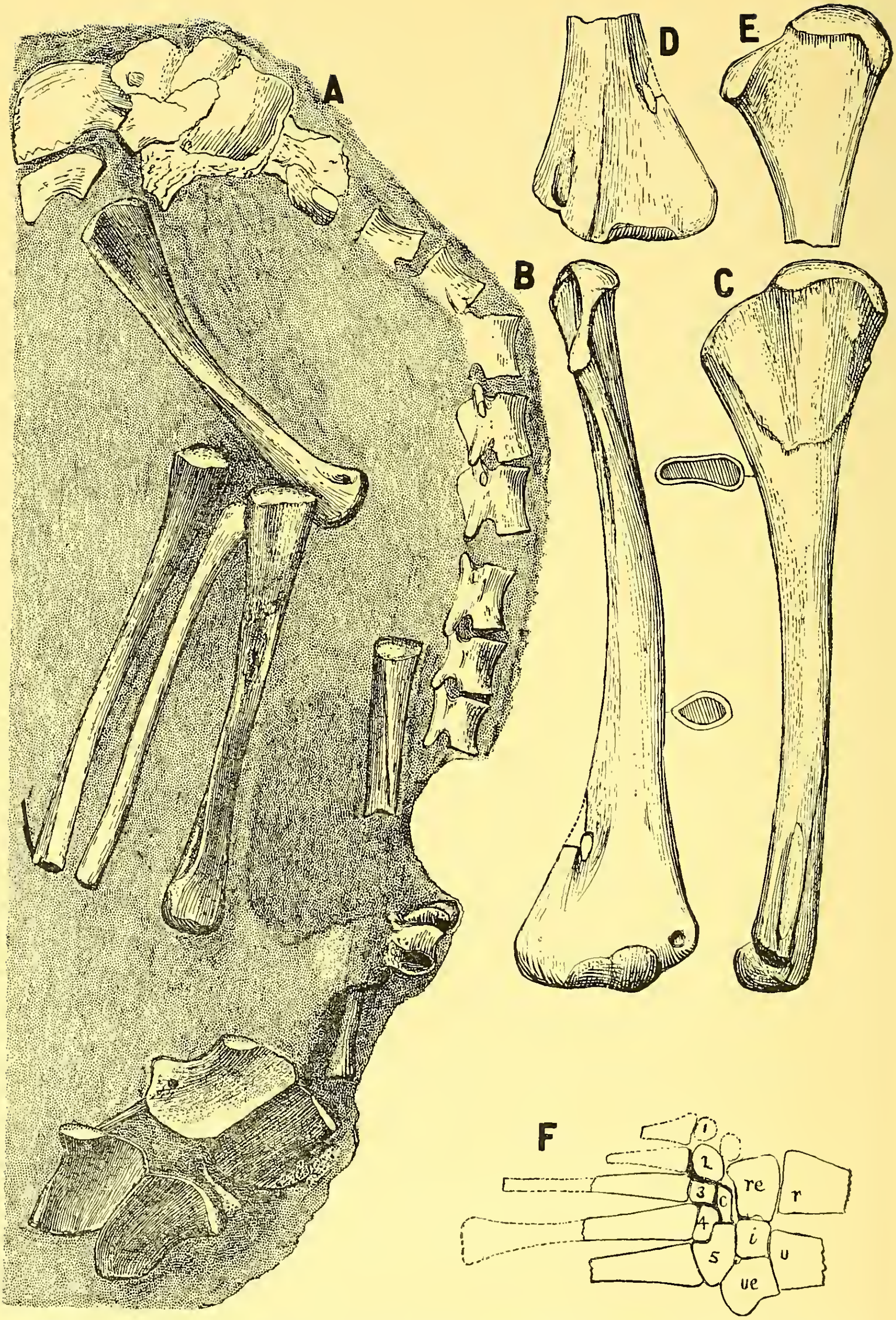

Fig. 2.—*Araeoscelis gracilis:* *A*, part of young skeleton, as preserved in matrix; *B*, left humerus, adult, ventral side; *C*, the same, radial side; *D*, distal end of another left humerus, ventral side; *E*, proximal end of smaller humerus, ulnar side; *F*, part of left front foot. All except *A* enlarged one-half.

believe that the temporal region was closed in. I spent many hours in the endeavor to reach an understanding of the temporal structure, which appeared to be so inconsistent with that of the remainder of the skeleton. That there was only an upper temporal vacuity did not at this time occur to me, since we know of no other paleozoic reptile having such a structure. I had almost despaired of the solution of the riddle when an additional skull was found which shows on the left side the temporal region in an almost perfect condition. With this specimen as a key, the structure of the skull was readily and completely unlocked.

The drawings of the skull herewith given (Fig. 3, *A*, *B*) are composites derived from all the different specimens, though chiefly based on one of about two-thirds adult size. Nearly every character shown or described has been corroborated by several specimens; in the palate only, less corroborative material is available.

In only one specimen is there anything of the premaxillae preserved. In the reconstruction of the general form of the skull I believe that the figures are tolerably accurate, though I cannot be sure that the skull may not have been a little wider or narrower or higher than I have shown it. It is difficult to make exact measurements of such small bones. The preparation of the specimens has required very patient work with a fine needle under a dissecting microscope, for the most part, but the bones, when carefully prepared, come out clean and smooth.

The *parietals* are longer than broad. In one excellent specimen found later, the distinguishing suture in front is clearly shown. The parietal foramen is large, as shown in three skulls; it is situated toward the front part of the parietals, just a little behind the posterior margins of the orbits. Posteriorly, the parietals are produced into an acute angle in the middle, projecting slightly over the supraoccipitals. I can find in no specimen the slightest indication of a distinct dermosupraoccipital, on the upper surface of the skull at least. On the posterior outer angle each parietal is produced into a slender process, as in lizards. In two specimens, the articulating tabulare was cleanly removed, showing a striated sutural surface near the angle. The arch thus formed, of parietal

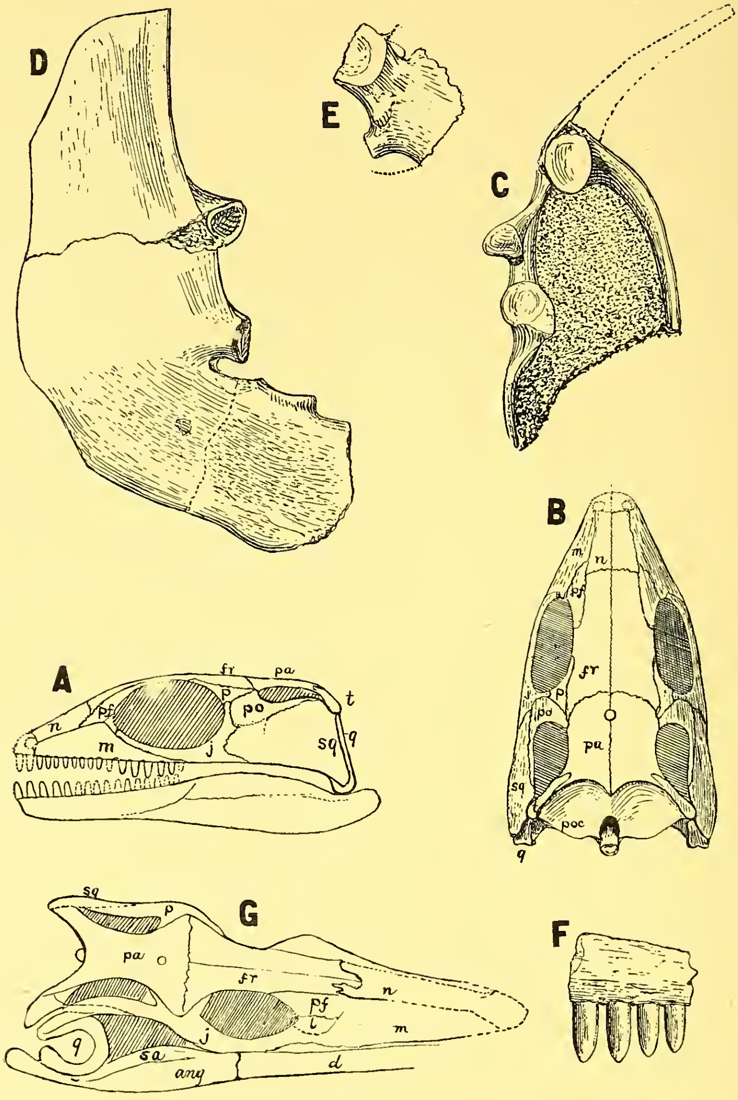

FIG. 3.—*Araeoscelis gracilis: A*, skull, about adult size, from the side; *B*, the same, dorsal side; *m*, maxilla; *n*, nasal; *pf*, prefrontal; *pa*, parietal; *poc*, paroccipital; *t*, tabulare; *sq*, squamosal; *q*, quadrate; *po*, postorbital; *p*, postfrontal, *j*, jugal; *C*, left scapulacoracoid, from behind, as preserved in matrix, enlarged one-half; *D*, the same, from the side, the upper end extended in same plane; *E*, part of another scapula; *F*, first four maxillary teeth, much enlarged; *G*, *Opetiosaurus* Kramberger, skull, from above.

and tabulare, is slender throughout, slightly dilated at its extremity, and is directed outward and backward at an angle of about 45 degrees with the long axis of the skull; it is gently curved downward at its extremity to articulate with the squamosal, quadrate, and paroccipital. There can be no doubt of the separation of the element forming the chief part of the arch; I identify it as the *tabulare.* I think that my reasons for so doing are valid. The tabulare in the early reptiles and amphibians is always associated with the outer end of the paroccipital. The only other element that could possibly be in this position is the so-called supratemporal or suprasquamosal. That the present bone is the supratemporal of contemporary authors is, I think, very improbable. This bone is never known to be in relation with the paroccipital and quadrate, relations that the tabulare invariably has; it always articulates with the postfrontal or postorbital when present. I think that doubt of its identity may be dismissed here; it is indisputably the tabulare or "epiotic."

It is now nearly ten years since I wrote the following:

> I prefer to call the bone articulating with the postorbital [in the lizards] the squamosal, the bone which in other reptiles articulates with the postorbital behind. Of course if this is the real squamosal, the posterior element cannot be the squamosal. . . . . The inner part of the so-called squamosal in the mosasaurs [the posterior bone of the arch] corresponds quite well with the outer part of the paroccipital or opisthotic element, which was not found by Parker in the lizard embryo. Referring now to the figures it will be seen that the outer part corresponds fairly well with the bone called the "epiotic." . . . . It may be objected that the presence of an epiotic bone [tabulare] in the lizards is a far too primitive character, but we are now quite certain that the lizards are an exceedingly old group, probably dating from the Permian, and that they have not a few primitive characters,"[1] etc.

The condition of this bone in the mosasaurs is such that one might easily conceive that it is a compound bone formed by the outer part of the paroccipital and the tabulare fused together, though I no longer believe that any part of it is the paroccipital. It was Cope who insisted that the bone in the mosasaurs is the paroccipital only, a view that was vigorously combated by Baur. This view, that the bone is the tabulare, I have consistently held

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[1] Williston, *Biol. Bull.* (1904), p. 190.

ever since, though it is only very recently that any other writer has accepted my contention. Three years ago I again expressed my opinion as follows: "I have long believed that the small element intercalated between the paroccipital and the so called squamosal of the lizards corresponds to the epiotics of the stegocephs,"[1] etc.

In front of the parieto-tabulare arch the side of the parietal is concave and free, forming the upper, inner margin of a typical supratemporal vacuity. It was this free border, seen in two specimens, which convinced me originally of the presence of a temporal vacuity in the skull of *Araeoscelis*.

The relations of the *postfrontals* and *postorbitals* are shown in four specimens. The postfrontal is a small bone which forms the upper, posterior border of the orbit, extending forward on the frontal margin not quite to the middle. Below, near the middle of the postorbital, it unites by a slender squamous underlap with the slender postfrontal process of the jugal. In five different specimens this suture is seen, but more positive evidence is furnished by another in which the jugal had been separated a little distance from the postfrontal, showing the delicate striated sutural surface for their union. The postorbital unites with both postfrontal and jugal by a convex suture, which approaches near its middle very near the orbital margin. Above, the postorbital reaches narrowly to the parietal, back of the postfrontal. In one specimen these bones have been separated from the frontal and parietal, leaving the striate sutural surface free. Below, the somewhat thinned anterior part of the postorbital extends downward between the jugal and squamosal at least a third of the way to the lower margin of the arch. Although in one specimen the lower border seems to be complete, I cannot be quite sure of its extent. From this expanded anterior part the bone contracts to extend more and more slenderly very nearly to the tabulare, thus forming nearly the whole of the outer border of the temporal vacuity. Along its whole lower border it is suturally united with the squamosal. These relations are corroborated in so many specimens that there cannot be the slightest doubt on the subject.

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[1] Williston, *Amer. Jour. Anat.* (1910), p. 82.

The *squamosal* is a flat and thin bone which fills out the broad expanse of the sides of the skull back of the jugal. It has a very slender connection with the outer border of the quadrate above, and extends downward very nearly to the cotylar margin. At its upper angle, just back of the hind end of the postorbital, it has a facet for union with the tabulare. Below, the bone forms nearly the whole of the lower margin of the arcade. I can find no evidence of a distinct quadratojugal; if such a bone was present it is so firmly fused with the squamosal as to be indistinguishable in any one of the four sides in which the squamosal is preserved nearly entire. In front the bone reaches forward to the hind border of the jugal in one case; in others the anterior part is deficient, so that I cannot be quite sure of the relations here of postorbital and squamosal. It is not impossible that my identification of tabulare and squamosal may be contested—there has been such a vast deal of speculation about the temporal arches that one must expect more—and that what I call the tabulare may be declared to be the squamosal and my squamosal the quadratojugal. But, inasmuch as such an interpretation will be speculation purely and impossible of proof, I am not disturbed by the possibility.

The *quadrate* is more or less exposed in three cases; in one it is nearly wholly exposed on the front side. It is expanded, somewhat fan shaped above, and is thinned. It is visible on the outer side narrowly behind the squamosal attachment. It articulates with the end of the tabulare above, with the paroccipital on the inner side, and with the squamosal on the outer side, as described for that bone. Just above the cotylar margin there is a free, concave surface, bridged over possibly by the lower part of the squamosal. If so, there would seem to be a small quadrate foramen here, arguing the presence of a quadratojugal bone. But I do not think that the evidence is conclusive. The quadrate stands somewhat obliquely, with the outer, gently curved, and thicker margin forming the posterior border of the temporal region; its anterior border is directed forward and inward, and is continuous with the posterior process of the pterygoid. Just how much of this part is pterygoid and how much quadrate I cannot say.

The *jugal* is well preserved in two specimens, completely so in one, with the postfrontal process broken away in the other; a third specimen shows the posterior process. It is a long, narrow bone, which borders the whole lower side of the orbit. It sends a short, pointed process backward to articulate below the front part of the squamosal. The process which is directed upward to meet the postfrontal and postorbital is broader, ending in a slender projection on the front side which overlaps narrowly the postfrontal in front of the postorbital. Posteriorly above it also meets the lower part of the anterior expansion of the postorbital. The anterior end extends nearly to the extreme front end of the orbit, bordering for a long distance the upper side of the maxilla. The bone forms the free margin of the arch back of the maxilla for only a short distance.

The *frontals* are moderately broad and rather long bones, evidently flat or gently concave between the orbits. In most specimens they are pressed more or less together, but, by excavating one of them, I have determined its precise shape. It forms the orbital margin for only a short distance between the ends of the postfrontal and prefrontal. The frontonasal suture is a little before the front end of the prefrontal.

The *prefrontals* are visible in part or wholly on four sides. They are large, triangular bones, projecting outward somewhat in front of the orbit. They extend back narrowly along the frontal margin to within a short distance of the anterior end of the postfrontals.

The *maxillae* are unusually broad bones for a Permian reptile. Each articulates with the nasal in front, excluding the lacrimal from the nares. It is more or less complete in four cases. It terminates posteriorly in an acute point a little before the hind border of the orbit, and is bordered to its highest elevation by the slender jugal. A small space is left between the end of the jugal and the prefrontal in which there may have been a small *lacrimal*, but this bone cannot be distinguished with certainty in any specimen.

Of the *premaxillae* I can say but little. In only one of the specimens can I detect any vestige of it. In one skull, however, the mandibles are preserved in position with the maxillae entire, showing that the premaxillae must have been small, with not more than two teeth in each.

The *occiput* is clearly distinguishable in two skulls, and partially so in a third. It has a smooth declivity on each side between the angular median projection and the foramen magnum on the inner side, and the parietal arch on the outer side. The surface, descending nearly to the lower border of the foramen magnum, is clearly distinguishable from the dorsal surface and the tabulare, although no distinct post-temporal vacuity is visible; probably in life there was a small vacuity here, which has been obliterated by the depression of the arch. At the outer side the thin bone abuts against the distal end of the tabulare, and thus must come in contact with the upper end of the quadrate. I can distinguish no sutural divisions on this surface, though doubtless it must be formed by the supraoccipital, paroccipital, and exoccipital. I am very skeptical of some of the recent interpretations of the structure of the occipital region of certain American Permian reptiles. It cannot be said too emphatically that only under the most exceptional circumstances can sutures be determined with any degree of certainty from single specimens. The foramen magnum is large; the occipital condyle is hemispherical.

The details of the palate are less certainly determinable. There is an interpterygoidal vacuity, with low, conical teeth along the pterygoids and vomers in front. One specimen shows an indication of a median parasphenoid. The downwardly prominent portion corresponding to the transverse bone—if it be distinct—is armed with five conical teeth of a size nearly as large as those on the anterior part of the maxilla; this elevation joins the maxilla just back of the teeth. Back of these transverse rows of teeth there is an elongated basisphenoid, with a shallow cavity in the middle and a low basisphenoid tuberosity on each side at the end of a lateral elevation.

The teeth of *Araeoscelis* either are variable or the material that I have assumed to belong to a single species comprises more than one. Without better evidence to the contrary, however, I shall assume that the differences which they present, like those of the skeletal bones, are merely ontogenetic or individual. Typically—that is, those adult skulls associated with the largest vertebrae, and doubtless belonging with the largest humeri and femora—there are fourteen teeth in the maxilla, with the shapes as shown in the illustrations (Fig. 3, *F*, *A*), that is, with the first four rather slender and of nearly equal length; the next four are a little broader at the base, though but little longer; with the ninth they increase in size, both in length and breadth, reaching the maximum in the twelfth; the thirteenth and fourteenth decrease a little in length. Possibly there is a smaller one beyond these, but if so, I cannot distinguish it. This is the condition in both maxillae in one specimen lying in the matrix, in which the teeth have not been injured in preparation. In another skull the number of teeth is the same, but the ninth to the eleventh are not noticeably larger than the preceding ones. In a third specimen, one of the larger ones, I count fourteen teeth in the maxilla, but the last three are small. Finally, in still another specimen, comprising only the maxilla, mandible, face, and anterior palatal bones, fifteen teeth are preserved in the maxilla, with an alveolus for at least one more, and probably alveoli for two more. These teeth, moreover are all smaller than in the other specimens and are of uniform size throughout. The teeth are all simple, without accessory cusps of any kind. They are somewhat wider at the base than long anteroposteriorly and are beveled on the inner side. They are somewhat flattened on the outer side and are obtusely pointed. They are thecodont or protothecodont.

This description in the main seems to agree with that given by Broom[1] of *Ophiodeirus*, though some effort is required to understand his description. One does not feel sure, for instance, what the antecedent of "it" is in the twentieth line of his description of the teeth, but I assume that it refers to *Ophiodeirus*. In the typical *Araeoscelis* it is the last or sixteenth tooth of the series which is smaller, while in *Ophiodeirus*, if I understand the description correctly, the fourteenth, fifteenth, and sixteenth teeth are smaller. He also described the teeth of *Ophiodeirus* as cuspidate; they are not at all so in *Araeoscelis*.

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[1] *Bull. Amer. Mus. Nat. Hist.* (1913).

The question of the relationship of *Araeoscelis* to *Bolosaurus* has been raised by Broom in the paper cited. He believes that all three genera, *Bolosaurus*, *Ophiodeirus*, and *Araeoscelis*, are closely related members of the Bolosauridae of Cope. The genus *Bolosaurus* was originally described by Cope from a fragmentary skull, of which the only distinguishable character is found in the teeth These are remarkable, formed as they are of a low crown, with a sharp principal and a low accessory cusp. The type specimens were later studied by Case who referred them to the Cotylosauria, as had Cope, and as did Huene also later. With these typical specimens Case later associated other imperfect ones discovered by himself, describing them, so far as his material sufficed, as *Bolosaurus striatus* Cope. With these later skulls Case provisionally associated a number of vertebrae and fragments of limb bones, but with no assurance, as he expressly stated, of their actual identity—they were merely found in the same bone-bed and he could refer them to no other known form. Had he followed the more usual rule of paleontologists he would have described them as new and left to others the problem of their identity! This caution, however, was not imitated by Broom, who referred all these remains to one species without question of possible distinction, notwithstanding Case's warning.

He distinguishes very properly the skeletal bones from *Bolosaurus*, of which nothing is known with certainty, under the name *Ophiodeirus casei* Broom, but recognized their relationship and possible identity with *Araeoscelis*. I had hoped that the time was past in vertebrate paleontology when genera and species were named on the mere possibility of validity. There can be scarcely a doubt that, aside from the skull, the bones described by Dr. Broom as of *Ophiodeirus casei* are those of *Araeoscelis gracilis*, and in much probability the discrepancy of the skull is due to error.

VERTEBRAE

The precise number of cervical vertebrae (Fig. 4, *A*, *C*, *E*) cannot be determined. The probability is seven, though there is the possibility of a larger number. The atlas has not been recognized, nor is its loss surprising, since the bones composing it must

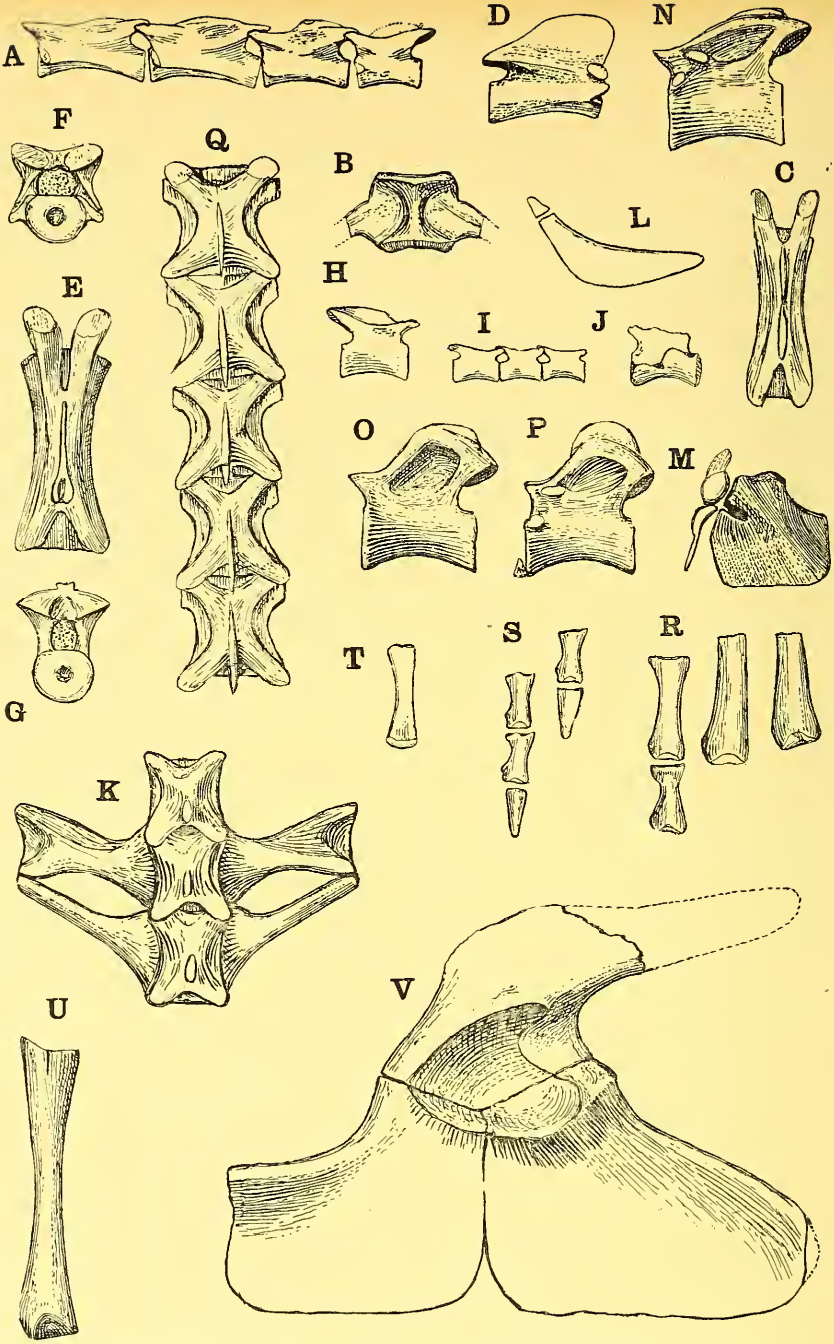

FIG. 4.—*Araeoscelis gracilis: A*, posterior cervical vertebrae of young, as connected in matrix; *B*, second caudal vertebra, from below; *C*, fourth or fifth cervical vertebra, from above; *D*, axis, from the side; *E*, median cervical, adult, from above; *F*, proximal end of same; *G*, distal end of same; *H*, median caudal, from the side; *I*, distal caudals, from the side; *J*, median caudal, from the side; *K*, first presacral and sacral vertebrae, not quite adult, from above; *L*, clavicle of half-grown animal; *M*, calcaneum, adult; *N*, dorsal vertebra, adult; *O*, lumbar vertebra, adult; *P*, anterior dorsal, adult; *Q*, series of anterior dorsals, adult, from above; *R*, metacarpals and phalanges of third, fourth, and fifth digits, as preserved in matrix; *S*, phalanges in positions as preserved; *T*, metacarpal or phalange; *U*, fourth metatarsal, adult; *V*, pelvis, adult, from the side. All enlarged one-half.

have been almost microscopical in size, and in none of the specimens has the neck been preserved complete.

A very perfect axis has been found among the loose material. It is shown in Fig. 4, *D*. It doubtless belongs with one of the larger, but not largest, skeletons; probably with the vertebrae shown in Fig. 4, *C*. It measures just 8 mm. in length, and differs markedly from any axis hitherto found in the American Permo-Carboniferous deposits. It has a rather high, thin spine of more than half the length of the centrum, its border sloping downward from above the middle of the centrum to divide into the two postzygapophysial processes. The anterior zygapophyses are unusually large, indicating a large atlantal arch. They are oval and are situated one on each side of the base of the spine, their faces looking upward and outward. The anterior end of the centrum is concave; it is rather narrow, and has an obtuse, keel-like process below; on each side there is a winglike process continuous with the front surface for the attachment of the cervical rib. The plane of the front end is at a considerable angle with the long axis of the centrum. The postzygapophyses are strong, but do not project far beyond the centrum. The centrum has a strong keel below in front, becoming linear posteriorly. The posterior surface of the centrum is nearly circular in outline, and is at right angles with the long axis. In the middle is a deep pit, which doubtless extends through the centrum.

Four posterior cervicals are associated in one specimen, belonging with one of the smaller skeletons. They are shown in Fig. 4, *A*. The first two of these are of nearly equal length; they are elongate and slender. On the side of the centrum in front there is a winglike projection with a facet, as shown in Fig. 4, *A*, for the articulation of a small, single-headed, cervical rib. Leading backward and downward from this facet there is a distinct ridge, which becomes obsolete before reaching the hind end of the centrum. In the middle of the centrum below there is a sharp, narrow keel. The prezygapophyses are more prominent than the posterior ones; their articular surface looks almost directly dorsad. The third vertebra of this series is not only shorter but it lacks the oblique ridge from the costal facet. The fourth is still shorter, and has a tuberculiform parapophysis, but does not have a diapophysis on the side of the prezygapophysis, and hence must be considered a true cervical.

A second connected series of cervicals, of somewhat larger size, includes three elongated vertebrae, of nearly equal length. I cannot distinguish the posterior two from the anterior two of the preceding series, and the first of this series is scarcely different, save in having a little more pronounced spine on the posterior half of the arch rising directly above the level of the zygapophyses. The two series thus fix the number at not less than seven, four of which are much elongated, and the fifth only a little less so. This, however, does not preclude the possibility of a larger number of vertebrae in the neck. Among the free cervical vertebrae are four elongated ones of adult size, one of which is shown in Fig. 4, *E*, *F*, *G*. There are also several others like these, but of smaller size, one of which is shown in Fig. 4, *C*. They all have rudimentary spines, very thin, short, and low. In some, there is a very small cartilaginous surface on the upper margin. The cervical vertebrae were originally described by me as caudals, but the error was immediately recognized when the connected series were prepared.

Dorsals.—In the three specimens shown in Figs. 1 and 2 the dorsal series of vertebrae are complete and connected except that a few have been dislodged in the specimen presented in Fig. 2, *A*. Unfortunately in all three specimens the matrix has been removed from the ventral side, and it would be a matter of much difficulty now to clean the dorsal side and thus to determine the transition from the cervicals to the dorsals. Inasmuch as in two of these specimens the scapulae lie in relation to the nineteenth or twentieth presacrals, that number may be accepted as almost certain for the dorsal series.

Several other series of dorsal vertebrae showing the dorsal side have been prepared. A part of one of these series is shown in Fig. 4, *Q*, from above; and two isolated dorsal vertebrae are shown in Fig. 4, *N*, *P*, together with a more posterior one, a lumbar, in Fig. 4, *O*. The dorsals, as seen from below, are all rather slender; from above they appear less so, because of the overhanging arch. The centra are all more or less obtusely keeled below. An anterior dorsal is shown in Fig. 4, *P*. In this vertebra the spine is more elevated than it is farther back; in much probability the spine is yet higher in the more anterior dorsals. The spine is thin, and has no tubercular projections of any kind. Another rib-bearing vertebra is shown in Fig. 4, *N*, with a less pronounced spine. The posterior zygapophyses overhang the centrum at a considerable elevation and there is, as in all, an excavation in the sides above. The articular processes for the rib form two surfaces separated by a distinct interval. The diapophysis is on the arch just back of the anterior zygapophysis; it projects but little or not at all beyond the margin of the zygapophysis. The facet for the capitulum is shown in several specimens as a small surface near the front end of the centrum, high up; whether it is on the arch or the centrum cannot be said, but it appears to be on the former. A series of five lumbar vertebrae, in all probability a part of the same skeleton as that to which the figured dorsals belong, differ in their somewhat greater stoutness, and in the entire absence of any diapophysial process or facet; the spine is also vestigial. One of these vertebrae is shown in Fig. 4, *O*.

Sacrum (Fig. 4, *K*).—The two sacral vertebrae and a connected lumbar were found in one specimen closely attached to the inner side of the left ischium. The sacral ribs on one side have been worked out fully, and on the other partly. The dorsal arch unfortunately had been injured somewhat. The sacral ribs are long, and those of the second vertebra very slender. They resemble so closely those of some lizards that it is needless to describe them further. As is seen, the first one has an expanded extremity and bore nearly the whole support of the ilium; the posterior one projects markedly forward.

Caudals.—Numerous caudal vertebrae are preserved isolated. One of a series of three proximal vertebrae is shown in Fig. 4, *B*, from below. The co-ossified ribs or transverse processes are elongate; none is preserved entire; they turn backward, as usual. More posterior caudals have tubercles on the sides for the posterior ribs. A yet more posterior caudal is shown in Fig. 4, *H;* it has a slight, thin spine on the posterior half, scarcely rising above the level of the zygapophyses. Three found attached in the clay matrix are shown in Fig. 4, *I*. They are quite like the usual distal caudals of other reptiles. Although the entire number of caudal vertebrae cannot be determined, even approximately, the structure of the numerous isolated vertebrae preserved indicates decisively a long and slender tail. A median caudal of a young animal, shown in Fig. 4, *J*, is of interest because it is the only vertebra in the collection which shows any indication of the suture between arch and centrum.

PECTORAL GIRDLE AND EXTREMITY

Of the pectoral girdle nothing has been detected of the *interclavicle* in any specimen, and of the *clavicle* only one specimen has been discovered, that of a young animal not more than half adult size, as indicated by the associated long bones in the matrix. This bone is shown in Fig. 4, *L*, as it lies on the matrix in one plane. Its concave border is a little thickened, the convex thin; its scapular extremity is a little thickened, as shown by the section at the broken end. The bone has an unusual shape for a Permian reptile, as might be expected from the unusual shape of the scapula.

The *coraco-scapula* (Fig. 3, *C*, *D*) is of remarkable structure, so unlike anything I am acquainted with among reptiles that I was puzzled at first to interpret it. One complete specimen was found in an isolated nodule, overlapped on its coracoid border by a fragment of the opposite side. In order that the complete structure may be seen, this fragment has been sacrificed. The specimen seems to be quite perfect and undistorted, save that the upper part was smoothly broken and turned over the lower, as shown in Fig. 3, *A*, from behind. In Fig. 3, *C*, I have shown the whole bone as in one plane, though doubtless the upper part was curved strongly inward in life, perhaps more than I have indicated in the dotted line. The postglenoid facet is smooth, rounded, and gently concave; its face looks directly outward from the plane of the coracoid. The preglenoid facet of other Permian reptiles is divided into two very distinct processes, separated by a considerable space, in which there is a smooth, rounded border. There can be no possibility of error in this, since two other fragments, one of which is illustrated in Fig. 3, *E*, show the same peculiarities. Nor can

I find any trace of a supracoracoid foramen; a notch below the lower preglenoid process may represent the vacuity for the passage of the artery. An opening corresponding to the supraglenoid foramen seems to be present just above the supraglenoid articular surface. Apparently the suture distinguishing the coracoid in front is seen in a division across the bone, which I have indicated by a dotted line; but I cannot find the least trace of an anterior suture.

Doubtless the scapula proper must include all that part above the upper facet; possibly the lower preglenoid process is on the anterior coracoid, if there be such a bone in this scapula. At the upper end the scapula is rather narrow, with a thin front border, and a thickened posterior border. If the two coracoids met along the middle line, the blade of the scapula must have projected strongly forward. But that is improbable. Probably the two sides approximated each other only at the posterior end, leaving a large V-shaped interval between the anterior borders, partially filled out by the clavicles and interclavicle.

Humerus.—Three complete humeri are preserved free (Fig. 2). Two other complete ones, of a somewhat smaller size, are preserved in the matrix, associated with skeletal bones; and there are various other parts of juvenile humeri that were found in the clay matrix, portions of which have been lost. The articular head in the best-preserved specimen (Fig. 2, *E*) is oval in shape, and is not widely separated from the lateral process, which is much nearer the head than is usual in Permian reptiles. The bicipital fossa is rather shallow. The distal extremity is thin and flat, and is only moderately expanded on the ulnar side. The entepicondylar foramen is small, and is bridged over by a very delicate bar of bone, so delicate that it has been lost in all our specimens. Indeed, so thin is the broken edge left above the foramen that for a time I was in doubt as to whether it was not merely a notch. I am now convinced that the foramen was closed in; nevertheless it seems to be obsolescent. On the radial side there is an ectepicondylar foramen, quite as in modern lizards, formed by a slight bridge over the end of the ectepicondylar groove in the adult humerus, but wholly wanting in the juvenile specimens. The capitellum is well formed, as is also the trochlear surface for the ulna. Both are small, but the joint here was evidently unusually compact and strong.

The planes of the two extremities of the humerus are turned nearly at right angles with one another. One would not recognize the figure given by Broom of the humerus of *Ophiodeirus* as that of an allied animal even, much less as that of *Araeoscelis*, were it not for the statement in the text that the two ends of the specimen, as figured, did not connect with each other. He thought that little was missing and figures the two ends in the same plane, though an examination of the humerus of *Araeoscelis*, as figured by me, should have convinced him of his error. As a matter of fact, taking as indices the two ends as figured, a slender cylindrical piece of the shaft 12 mm. in length was missing, giving a total length of about 50 mm. for the whole humerus, a trifle less than that of the adult humeri here figured. With these corrections his figured humerus may well be that of *Araeoscelis*.

There are no complete specimens of *radii* or *ulnae* preserved, though there are several partly complete. There can be scarcely a doubt that they were as long as the humerus. In two specimens the proximal ends are preserved in relation with the humerus, and two others have the distal ends preserved in relation with the carpus. Both bones are of equal size and are nearly straight. The radius has a cupped surface at the proximal end and a moderately expanded distal end. The ulna has a moderately produced olecranon; the distal end is a little less broad than that of the radius; there is no articular surface for a pisiform.

Carpus (Fig. 2, *F*).—The carpus and hand of *Araeoscelis* are so unlike those of other known contemporary reptiles that careful study was necessary for their interpretation. Fortunately, however, the material is good, and pretty nearly complete, consisting chiefly of two specimens, both with the carpals nearly all in position, together with the distal ends of the epipodials and the proximal ends of some of the metacarpals. The better of these specimens has the bones cemented together in a nodule that was inclosed in clay, which was cleanly washed away, leaving the bones visible. The wrist was compressed a little and flexed, so that the radius and ulna had slipped backward and downward, carrying the radiale with them. Nor is there anything left in this specimen of the first and second metacarpals and the first carpale. The second specimen includes the epipodial and mesopodial bones and the proximal ends of the first and second metacarpals; the intermedium is not visible, possibly it is lost. There is also much more of the metapodials than in the other specimen, though none is complete. In a separate piece of clay at least three fingers were lying in position, but only the three metacarpals and some of their phalanges were preserved in place. These have been added to the figure made from the first specimen in dotted lines. The three specimens are the same or nearly the same size.

The *ulnare* is a stout, thick bone, which forms half of the articular surface for the ulna. It rests only slightly on the fifth carpale, though more than is shown in the figure, since it underlaps it to a small extent. At its lower, outer angle there is a small notch, all that seems to represent the perforating foramen. Its outer border is straight, and joins the inner border of the intermedium closely. The *intermedium* is a cuboid bone, a little wider below than above, with a considerable concave articular surface at each end, that of the proximal end continuing smoothly the ulnar articular surface. The *radiale* is seen only from the proximal side, as it lies back of the other carpal bones at the ends of the radius and ulna, the ulna partly rotated on its long axis. This surface shows an excavation where it partly covered the centrale. On the ulnar border there is a distinct notch between it and the intermedium that is puzzling. Lying by the side of the radiale there is a small nodular bone which must be either the first carpale or the first centrale; I have dotted it as the centrale. The *centrale* is a narrow bone with peculiar relations. At its inner side it articulates with the outer angle of the fifth carpale. The fifth carpale is also unlike that of any other Permian reptile that I know in its large size and relations with the fourth carpale, which it excludes from the proximal bones. The fourth carpale is small. It interlocks with both the centrale and the fifth carpale. The third carpale has a flat, rectangular anterior surface, a little longer than wide. It articulates above with the outer end of the centrale, and on each side with an adjacent carpale. The first carpale is a small bone.

The *fingers* are remarkable, so far as they are preserved. The great size of the ulnar ones over the radials suggested at first the possibility of error in their determination. As shown in the illustration, the unbroken lines represent bones of the more complete specimen, while those shown in dotted lines are taken from the other two specimens as they lie in place. There can be no legitimate doubt of the phalangeal formula, 2, 3, 4, 5, 3. Not a few slender phalanges are preserved loosely, belonging in the fingers. The claws are elongated and sharply pointed.

PELVIC GIRDLE AND EXTREMITY

Pelvis (Fig. 4, *V*).—The more or less complete pelvis is preserved in three different specimens. In addition, there are two isolated ischia preserved in small nodules; one of these is of a young animal, the other of a nearly full-grown one, though a trifle smaller than the largest. These two small ischia have been used to complete the drawings made from an adult specimen. The pubes in the three associated skeletons shown in the figures are determinable in all details. The ilia are concealed in the pelves associated with the vertebrae, but there are two incomplete ones that were found free in the clay, in perfect preservation, save for the loss of the greater part of the posterior process.

The ilium, so far as it is determinable, shows no peculiarities of note to distinguish it from the common pelycosaur type, especially that of the poliosaurids. It has a rather slender posterior process, like that of *Varanosaurus*. Nor is the ischium at all peculiar; it is, indeed, of the form of all the ischia known of the American Permian, meeting its mate in a broad symphysis, and doubtless forming a more or less spout-shaped orifice to the pelvis. The pubis, however, departs markedly from the universal pelycosaur type, that observed in *Dimetrodon*, *Sphenacodon*, *Varanosaurus*, etc., agreeing rather better with that of *Casea*. In the fully adult specimens it meets the ischium in a nearly complete sutural union, leaving no puboischiadic vacuity, or a very small one, such as is always found in the true pelycosaurs. It is subquadrate in shape, with its superior outer margin somewhat thickened and emarginate, but not forming a spout-like anterior projection. Broom compares the pelvis of *Ophiodeirus*, or his so-called *Bolosaurus*, with that of *Poecilospondylus*, but restores the latter wrongly. All the Poliosauridae, as indeed all of the Pelycosauria in the narrower sense, have a very characteristic pubis, standing horizontally far in advance of the true pelvic brim. I have seen the type specimen of *Poecilospondylus* and know that it is intimately allied to the genus I have described as *Varanosaurus*[1] but which is not congeneric with the genotype. Indeed, there is no more characteristic bone in the true Pelycosauria than the pubis, an element that I have relied upon, perhaps unduly, as a determinant of the relationships between the Sphenacodontidae and Poliosauridae.

Numerous juvenile or incomplete *femora* (Fig. 5, *A–D*) are represented among the free material found in the clay, but there is only one complete femur of an adult, with parts of three others. It is the longest bone in the skeleton, measuring about 2½ inches in length. In front view the bone is nearly straight, with a long, cylindrical shaft and only moderately expanded extremities. In side view the bone is shaped much like the italic letter *f*, with the concavity above, the convexity below, on the front side. The head is stout and rounded, with its articular surface almost wholly at the extremity. The trochanter, a rather thin plate, springs inward and backward nearly at right angles, a little below the head, and continues as a thin edge, winding about the shaft till it reaches the middle, a little above the middle of the bone, and then continues as a linea aspera to the lower third, where it becomes obsolete. The tibial condyle juts inward, forming a right angle. The tibial surface is narrow, but connects broadly with the fibular surface. The two surfaces together make an angle of nearly 45 degrees with the long axis of the bone.

Tibia and fibula.—The tibia and fibula (Fig. 5, *E–I*), like the radius and ulna, are remarkably slender bones, fully as long as the femur. No free specimen of either bone is preserved entire, though one of each, in all probability those belonging with the femur

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[1] The recent descriptions by Broili and Watson of the genotype of *Varanosaurus*, *V. acutirostris*, disclose, as I suspected, generic differences from the species *V. brevirostris* Williston. I therefore propose the generic name *Varanoops* for the latter.

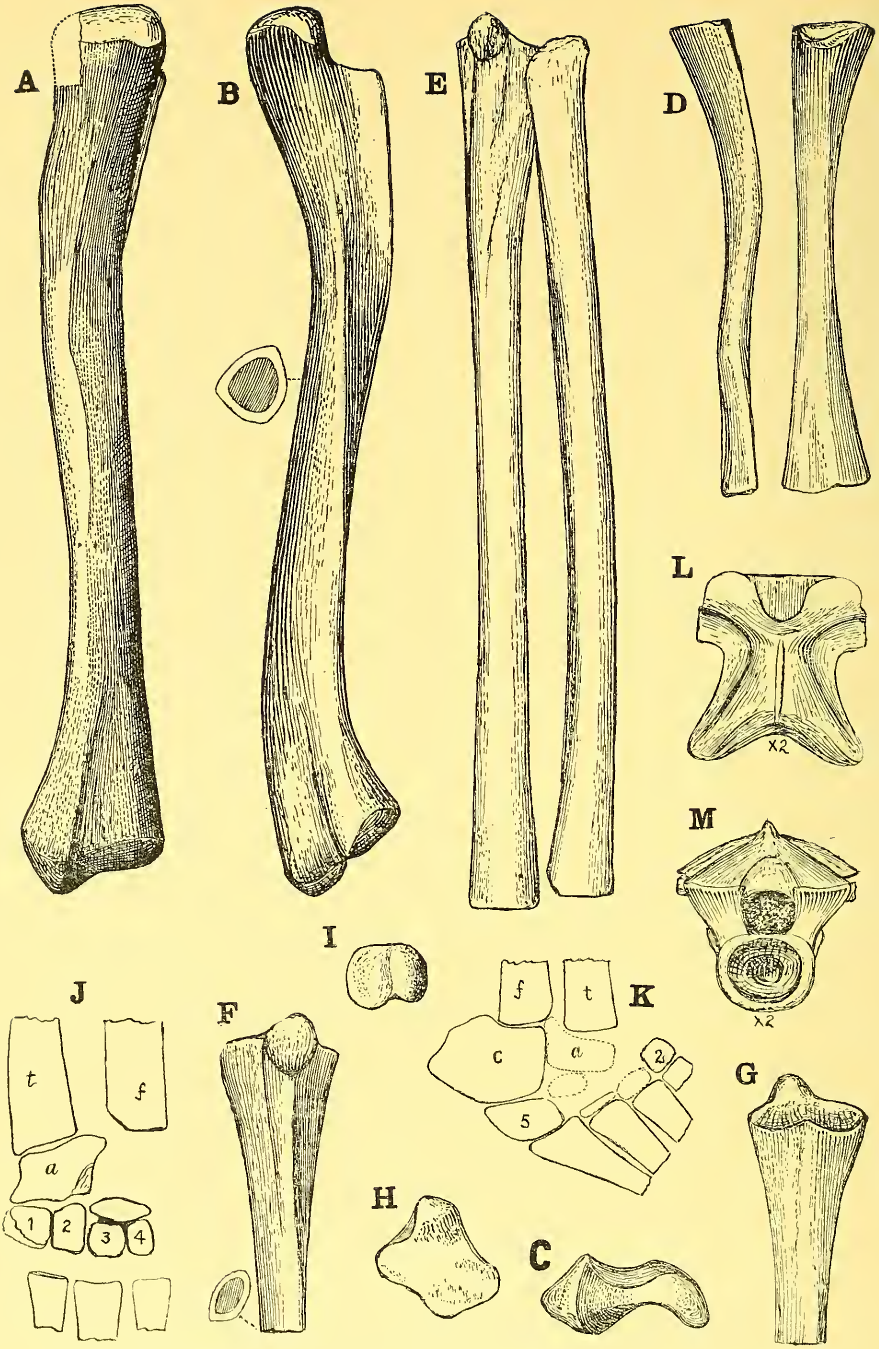

FIG. 5.—*Araeoscelis gracilis: A*, right femur, obliquely from above, adult; *B*, the same, obliquely from tibial side; *C*, distal end of same; *D*, femur of half-grown specimen, from side and front; E, tibia and fibula, adult, from the front; *F*, right tibia, proximal end, from the front, adult; *G*, the same, from behind; *H*, the same, from above; *I*, fibula, distal end; *J*, part of tarsus of Fig. 1, *B; K*, part of tarsus, immature; *L*, dorsal vertebra, from above; *M*, the same, from the front. All except *L* and *M* enlarged one-half.

that I have figured, are very nearly complete. In Fig. 5, *E*, the two bones are shown as completed from these and other specimens, aided by the complete specimens of a little smaller size shown in the associated skeleton of Figs. 1 and 2. The tibia (Fig. 5, *E–H*) is considerably expanded above, and has a prominent cnemial ridge ending in a rounded, rugose, cnemial crest above, for the attachment of what was evidently a strong quadriceps extensor ligament. Its upper surface is gently concave and fits very perfectly the distal articular surface of the femur. Its shaft is nearly straight and nearly cylindrical, or a little flattened. Its lower extremity is but little dilated, and its end is squarely truncate. The fibula is a little more curved, but scarcely differs in size from the tibia. Its upper end is moderately dilated on an oblique plane. Its lower extremity, as shown in Fig. 5, *A*, is nearly cylindrical, its articular surface distinctly divided into two facets, the one on the tibial side for articulation with the astragalus, a little narrower than the calcaneal, and rounded.

Foot.—The *tarsus* (Fig. 5, *J*, *K*), more or less complete, is preserved in two specimens, and in part in a third. Of one of these the bones are shown as they lie at the ends of the tibia and fibula in Fig. 5, *B*, and as brought as nearly as possible into their articular relations in Fig. 5, *J*. The tibia in this illustration is shown partly from the side and has apparently undergone a slight external curvature, though it is possible that this curvature is natural, and that I have represented the shaft in Fig. 5, *E*, too straight on the lower part. The astragalus is a small cuboid bone, very different in form from that of other known Permian reptiles, in that I can detect no surface on the inner side for the arthrodial articulation of the tibia. Its articulation with the tibia seems to have been firm and close, with not much motion. Lying at the outer side of this bone is a smaller one which can be interpreted only as a centrale of small size, articulating with the third and fourth tarsalia and probably somewhat with the astragalus. This is a rather unusual position for the centrale, but it seems certain that such were its relations. The first two tarsalia are relatively large, the third and fourth small. The fifth tarsale and the calcaneum are missing in this specimen.

A second specimen, in a small block of matrix belonging with a smaller animal, has the bones in the positions shown in Fig. 5, *K*. The distal ends of the epipodals, the calcaneum, fifth tarsale, and first tarsale are shown very clearly in the outline, but in their excavation from the hard matrix the surface of the tarsal bones has been somewhat injured. Crowded in the space below the tibia the bones of the external side of the tarsus are more confused and injured; but they confirm, so far as they can be deciphered, the arrangement shown in Fig. 5, *J*. The calcaneum (Fig. 4, *M*) is shown very perfectly and undistorted in a free specimen found in the clay. The heel is distinctly produced and has a slight cartilaginous thickening on its border for the Achilles tendon. The tibial surface shows very distinctly the notch for the perforating foramen. Elsewhere the borders are rather thin, save that for the articulation with the fibula. The fifth tarsale is shown very completely. It is of unusually large size, filling out the space between the calcaneum and the fifth metatarsal. All these bones in this specimen lie evidently in a natural position, the bones closely articulated.

Only four metatarsals are preserved together in any specimen, though the presence of the first tarsale would seem definitely to indicate the presence of the full five. It is also evident from these that the bones of the fibular side were stronger than those of the tibial, corresponding to those of the front feet, though the difference is not so great. Parts of three digits are shown in Fig. 4, *R*, as they were preserved in a small mass of clay. Doubtless the whole foot or the greater part of it had been present, but only these were recovered, though it is probable that the bones shown in Fig. 4, *S*, belong with the same specimen. The single metatarsal of adult size shown in Fig. 4, *U*, seems to correspond in its proximal and distal ends with the fourth; and it is evident that the digit showing the two phalanges of Fig. 4, *R*, is the fifth. The phalanges shown in Fig. 4, *S*, are in all probability the distal ones belonging with the two metatarsals shown in Fig. 4, *R*, that is, of the third and fourth digits, and that two proximal ones of each digit were ones probably corresponding in size pretty well with those of the fifth toe of Fig. 4, *R*. On these assumptions the feet may be restored with much probability.

RELATIONSHIPS

Araeoscelis is the first paleozoic reptile in which a typical upper temporal vacuity has been definitely recognized. The Proganosauria, only, from an approximately equivalent age, have been accredited by Huene with a single, upper temporal vacuity, and doubtless correctly, but its boundaries and position have not yet been certainly determined. Inasmuch as great importance has been attributed to the number and boundaries of these openings in the relationships of reptiles, it will be well to discuss briefly all those forms in which only an upper opening is known or supposed to be present. Various theories have been proposed concerning their origin and relationships, but in my opinion they are as yet for the most part speculations, or at the most hypotheses. Attempts to base a primary classification of the order chiefly on the number of temporal openings so far have not been very successful. The most meritorious of these attempts is that of Professor Osborn, which, though it can no longer be accepted as the true solution of the reptilian phylogeny, did much to place the classification of reptiles on a more secure basis; notwithstanding its faults, its merits are obvious. All students of the order are in practical accord as regards the phyletic relationships of the double-arched forms. It is only concerning those groups in which there is but a single opening that grave doubt and uncertainty yet remain. The single vacuity, when present, is so inconstant in its position and in its boundaries that one is seldom certain whether it is the upper, or lower, either or both; or, indeed, as Watson thinks, in some cases neither!

The following groups of reptiles, more generally considered to be orders, have a single temporal vacuity on each side: Ichthyosauria, Sauropterygia, "Pelycosauria," Placodontia, Therapsida, Squamata and, if Huene is correct, the Proganosauria. Of these the Pelycosauria and Therapsida may at once be dismissed in any discussion of the relationships of *Araeoscelis*, since the opening, whether upper or lower or neither, has such different relations and boundaries as to preclude any immediate phyletic relationships. And, of the others, the Sauropterygia can have only a remote relationship and may be dismissed from the discussion. In addition to these, some poorly known forms that have long been classed with the rhynchocephalian reptiles, under the assumption that any primitive reptile in which the temporal region was unknown probably was allied to *Sphenodon*, show such possible or probable resemblances to *Araeoscelis* as to merit consideration.

Squamata.—I have no hesitation in saying that the skull and skeleton of *Araeoscelis* present distinctively primitive characters of the *Squamata*, to such an extent indeed that I believe the genus has a definite phylogenetic relationship with the order. In fact, as far as the skull is concerned, all that seems necessary to convert *Araeoscelis* into a primitive lizard is the erosion of the lower part of the squamosal bone until only a slender rod is left along the under side of the postorbital, and the development of streptostyly in the quadrate, which would necessarily ensue with the loss of the support of the squamosal. The quadrate is supported quite as in the lizards by the tabulare and paroccipital, in conjunction with the squamosal. The quadrate itself retains some of its primitive characters in its moderately expanded upper end, which, however, is much less in extent than in other known contemporary reptiles. It is visible in part from the side, and fully so from behind. The postorbital is peculiar and unlike that of other known reptiles in that it takes no part in the formation of the posterior border of the orbit. In conjunction with the postfrontal it is quite like that of the mosasaurs and lizards in its extension backward nearly to the tabulare. Among mosasaurs I have seen indications of a sutural division of the "postfronto-orbital," and I have little doubt that the bone is really composed of the two elements. If it be really only a single bone, it must be the postorbital, not the postfrontal. In the reduction of the lacrimal to a small or vestigial bone we have another pronounced lacertilian character, never before observed in the earliest reptiles.

Unfortunately I have been unable to determine all the details of the palate. Although teeth are not known on the vomers[1] of

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[1] For some years I was inclined to accept the conclusions of Broom that the so-called vomers of most reptiles were not homologous with the vomer of mammals, which represented the parasphenoid; and to adopt the name he proposed for them, prevomers. The more recent studies of Gaupp, Fuchs, Versluys, and Terry throw grave doubt, to say the least, over these conclusions. I therefore return to the use of the term "vomer."

squamate reptiles, their presence in *Araeoscelis* is only what would be expected in a primitive lizard. Nor is the presence of teeth on the transverse bone (if it be distinct) a character to which any weight can be attached. Though no lizards have such teeth we may be sure that their ancestors had them.

In the structure of the skeleton of *Araeoscelis* there is very little that would not confidently be expected in the primitive lizard. The ribs of the neck and lumbar region are single-headed in the strictest sense, not holocephalous, as in the cotylosaurs, and they articulate exclusively with the centrum. In the dorsal region they are dichocephalous, but the head and tubercle are close together, separated only by a short emargination. The head is articulated, unlike the condition in contemporary reptiles, high up on the side of the centrum near the front end, the tubercle to a short diapophysis on a level with and just back of the anterior zygapophyses. The fusion of these two articulations, or, what is more probable, a loss of the diapophysis, which actually occurs in the lumbar region, would make the rib attachment typically lacertilian. I am quite sure that the primitive lizards had dichocephalous or holocephalous ribs, that is, capitular and tubercular articulations. *Araeoscelis* offers a rational explanation of the way the very peculiar rib attachment of the Squamata arose.

The pectoral girdle shows certain peculiarities not known among the Squamata, especially the separate articular facets in front of the glenoid facet, and the possible absence of the supracoracoid foramen. The distinction of the coracoid is not quite certain, though the dotted line of the figure represents what seems to be a real sutural division. I have urged that the posterior coracoid bone has been lost in all modern reptiles; that such a bone was present in the ancestral lizard is quite certain.

In the anterior extremity the presence of a distinct ectepicondylar foramen, quite as in the lizards, is suggestive, at least, of genetic relationships; and there is also a suggestion that the entepicondylar foramen was obsolescent. The structure of the feet is unlike that of the contemporary reptiles in the elongated calcaneum and reduced astragalus. The pelvis is plate-like, without a decided pubo-ischiadic vacuity; but no other kind of a pelvis could be expected in the primitive lizards.

The elongation of the cervical vertebrae was clearly a specialization and not an ancestral character; but aside from this and the peculiar scapula, I can see nothing in the entire skeleton that might not have been confidently predicted in the ancestral lizard. It may be objected that the thecodont, or more properly protothecodont, teeth were an aberrant character; that the lizard ancestor must have had, like the living ones, acrodont or pleurodont teeth. On the contrary, I believe that the teeth primitively in the Squamata were protothecodont, which, by the loss of the parapet of bone on the inner side of the maxillae, and the anterior part of the coronoid, became pleurodont. Moreover, the teeth in the mosasaurs are attached in shallow cavities. In Fig. 3, *G*, I give a sketch drawing of the skull of *Opetiosaurus* Kramb., the earliest known skull of a squamate reptile, from the uppermost part of the Lower Cretaceous. The figure was made by me from the type specimen in the Munich museum, and differs somewhat from previous ones by Kramberger and Nopsca.

Proterosaurus.—There are certain marked resemblances between *Araeoscelis* and *Protorosaurus* which may, and probably do, indicate genetic relationships. Unfortunately much doubt remains as to the structure of the skull in this genus, notwithstanding the numerous specimens which have been studied during the past two centuries. Seeley's interpretation of the skull structure of *P. speneri* has been received with considerable doubt by later students. I have examined the specimen on which he based his results chiefly, preserved in the collection of the Royal College of Surgeons, but could make little of it; my examination, however, was brief, and without the aid of Seeley's paper. Nevertheless, I am inclined to the belief that his interpretation of the elements will eventually be found to be approximately correct. He figures the temporal region as open at the sides of the narrow parietals. If it should be found that the side was largely covered below by the squamosal, leaving a vacuity above, the structure would be essentially like that of *Araeoscelis*.

There is certainly as much justification for this hypothesis as there is for the one usually accepted, the presence of two temporal arches, for which I can see no evidence whatever. Nevertheless, it was on this assumption and the equally unjustified assumption of a superior temporal vacuity in *Paleohatteria*, that these two genera and others even more indeterminate have been almost unreservedly classed either among the Rhynchocephalia or as a group of the Diaptosauria, of which the true Rhynchocephalia are another member. As I have elsewhere said, *Sphenodon* and the Rhynchocephalia have been, in the past, a cloak which has covered a multitude of taxonomic and phylogenetic sins. We have tried to trace all reptiles back to a primitive double-arched condition, on the assumption that *Sphenodon* is a very primitive reptile. It now seems more than probable that a single perforation of the temporal roof was the more primitive condition among reptiles, and that the Squamata are, in this respect, more primitive than the Rhynchocephalia. It has been assumed, indeed, that the Squamata themselves were derived from a primitive double-arched condition by the loss of the lower arcade, an assumption that in itself would seem to be improbable. Is it reasonable to suppose that the quadrate lost its fixity and became streptostylic suddenly, which would necessarily have been the case by the final loss of the quadratojugal arch? It would be far more reasonable to suppose that the gradual loss of a large squamosal, such as is found in *Araeoscelis*, permitted the gradual acquisition of streptostyly.

Seeley also figures a small antorbital vacuity in *Protorosaurus*, but with doubt; there is certainly none such in *Araeoscelis*. The lacrimal, according to Seeley, is small in *Protorosaurus*. So far, then, as I can see, there is nothing known in the skull of *Protorosaurus* that would prevent the immediate association of the genus with *Araeoscelis*.

In the skeletal structure *Protorosaurus* shows some remarkable resemblances to *Araeoscelis:* in the elongated cervical vertebrae, in the attachment of cervical and dorsal ribs, and in the general hollowness of the bones of the skeleton. These characters, in connection with the probable, or at least possible, resemblances of the skull, are, I believe, more than coincidences; they are genetic, not homoplastic.

Unfortunately little is known of the structure of the girdles in *Protorosaurus*. The vertebrae show distinct differences in the elongation of the spines and in the reduced number of dorsals, though I think that the last-mentioned character is doubtful. The limb bones are not so much curved as in *Araeoscelis* but the epipodials are nearly as long as the propodials. Von Meyer also states that there are no epicondylar foramina in the humerus, and Seeley does not figure or mention any. The presence of a small ectepicondylar foramen, however, might easily have been overlooked, and I suspect that a close examination of adult specimens will disclose its presence. The bones are all very hollow as in *Araeoscelis*.

Kadaliosaurus.—There also seems to be much probability of a close genetic relationship between *Araeoscelis* and *Kadaliosaurus*, as shown in the skeletal bones in the absence of all knowledge of the skull. I had the pleasure of studying the type specimen of *Kadaliosaurus* the past year at Leipzig, thanks to the kindness of Drs. Stille and Krenkel. So far as the shapes of the limb bones and vertebrae are concerned, they seem almost identical with those of *Araeoscelis*. There is, I am convinced, an ectepicondylar foramen in the humerus, as Credner thought; there was probably also an entepicondylar foramen, though its existence cannot be proved, because of the loss of the ulnar border in the impression of the humerus, where the foramen should be. That the two genera are closely related I have little doubt, though it is hazardous to express a very decided conviction in the absence of any knowledge of the skull. *Kadaliosaurus*, however, differs generically in the structure of the long bones. I convinced myself thoroughly of the statement of Credner that the bones are not hollow, but are composed of cancellous tissue; the ribs, however, like those of *Araeoscelis*, are hollow. There is, also, a strong armature of ventral ribs, not the slightest indications of which have been observed in *Araeoscelis*. Further speculations as to the relationships of the two genera will be idle until the skull of *Kadaliosaurus* is discovered; the characters, so far as they are known, ally the two genera closely.

Paleohatteria.—This genus has long been associated with *Protorosaurus* as a member of the Protorosauria, or Rhynchocephalia, on the assumption of two temporal arches. We have seen how small was the justification for the assumption in *Protorosaurus* and *Kadaliosaurus;* there is even less for *Paleohatteria.* We have tried to make every doubtful form in the past related to *Sphenodon;* even *Procolophon*, a true cotylosaur, has been placed in the same group, as a member of the Diaptosauria. As a matter of fact, *Paleohatteria* is not intimately related to the primitive rhynchocephalian stem, but is more closely allied to the so-called Pelycosauria, or even to the Proganosauria, as Baur first located it. I had the privilege, also, the past year, of studying the type specimens of *Paleohatteria* in Leipzig. Unfortunately some of the specimens had been loaned at the time of my visit to the museum, but the ones showing most conclusively the skull and skeletal structure were available. The results of my observations it will be worth while to reproduce here, though not immediately pertinent to the present subject. The skull, as shown in Credner's Plate XXIV, Fig. 3, is in my opinion preserved in a more natural profile than is any of the others, and is, I believe, more complete. The outline as I traced it is more complete and perfect than Credner figured it. The lower temporal opening is definitely shown, as are also the relations of the bone marked *sq* (quadratojugal?). Under the most careful scrutiny with a lens I could find no evidence of an upper vacuity. Neither do I believe that there is evidence of sclerotic plates in the orbits, though I did not see all the specimens.[1] The skull is rounded posteriorly, not projecting, as Jaekel has figured it. There is nothing in this specimen to suggest an upper temporal vacuity, nor could I find such evidences in any other specimen available for study. I could not distinguish the sutures between the prefrontal and lacrimal in any specimen; the lacrimal is certainly longer than Credner figured it, and it may have reached the nares. The upper surface of the skull, as stated by Credner, is distinctly rugose.

Credner's figures (Plate XXIV) of the scapula and coracoid are erroneous. The two are in close relation, but with the division visible (Fig. 6). The scapula seems to be somewhat longer than is visible, the upper end hidden below the humerus. The lower

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[1] It has generally been assumed that the presence of sclerotic plates means aquatic habits, the fact being overlooked that there are not a few purely terrestrial lizards in which the sclerals are highly developed.

end is expanded, as in the allied American reptiles. The coracoid lies over the stem of the clavicle, and in all probability is composed of the anterior element only, which is the case with the numerous known scapulae coracoids of *Varanoops brevirostris*. The clavicle was represented by Credner as a slender rod, without designation; its shape is like that of *Ophiacodon*, and it lies in articulation with the interclavicle and the upper front margin of the scapula. I thought that I recognized the usual supracoracoid foramen in the impression of the coracoid, but in this I may have been mistaken. The outline of the coracoid is clearly shown on both sides of this specimen. The outline of the front border of the scapula is also clearly apparent, broadly convex below, gently emarginate above. In fact, the structure throughout of the pectoral girdle is like that of *Varanoops brevirostris*, or as it would be in an immature specimen of that species. The ribs are holocephalous, like those of *Ophiacodon*. The humerus in this specimen is turned outward, not inward, and only an entepicondylar foramen is present. There are not more than three pairs of sacral ribs. In much probability the number of presacral vertebrae is twenty-seven, the constant number in the Pelycosauria in the more restricted sense. In brief, *Paleohatteria* is in every respect a member of the Pelycosauria (*sensu latiore*), of which it represents a family, Paleohatteriidae (Baur), of co-ordinate value with the Poliosauridae or Sphenacodontidae.

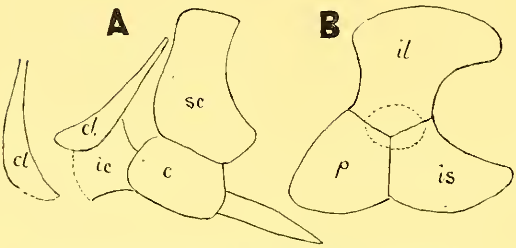

FIG. 6.—*Paleohatteria longicaudata* Credner: *A*, pectoral girdle, in part; *B*, left pelvic bones: *sc*, scapula; *c*, coracoid; *ic*, interclavicle; *cl*, clavicle; *il*, ilium; *is*, ischium; *p*, pubis.

Pleurosaurus (*Acrosaurus*).—This genus has generally been classed with the Rhynchocephalia in the narrow sense, notwithstanding the fact that it has but a single temporal opening, a fact that has previously been known and definitely confirmed by Watson. I had the pleasure of studying the excellent material of this genus preserved in the Munich museum, for which my thanks are due to Dr. Broili. I reached the decided conviction that *Acrosaurus* is merely the young of *Pleurosaurus.* Of course the presence of a single upper temporal vacuity excludes the form decisively and absolutely from the Rhynchocephalia or Diaptosauria, even. Whether or not it is intimately allied to *Araeoscelis* and *Protorosaurus* I shall not presume to say; but certainly its claims to such relations are vastly greater than those with the rhynchocephalian forms.

Proganosauria.—If Huene is correct in the attribution of a single upper temporal vacuity to *Mesosaurus* (and I believe that he is, notwithstanding the imperfect material that is in the collections of the skull of this genus), there may arise a question of the relationships between it and some of the forms I have briefly discussed. So far as the skeleton of the proganosaurs is concerned, it is simply an aquatic modification of the primitive cotylosaurian, or better, pelycosaurian type. Here, also, until the more precise structure of the skull is known, speculation is idle. The order Proganosauria may be accepted until it is proved that it has no claim for independent existence.

Ichthyosauria.—The origin and relationships of the Ichthyosauria have long been an unsolved problem, but little nearer solution today than it was a score of years ago, notwithstanding the brilliant discoveries of Dr. Merriam. On the strength of its generalized characters it has been associated with the rhynchocephalian type, as a member of the double-arched division of reptiles, under the hypothesis that the lower vacuity was secondarily closed by the encroachment of the orbit. More recently Huene has urged that its relationships are nearest with the Proganosauria, and with much reason. This much can be said: If all the known reptiles having a distinctive upper temporal opening have arisen from a single ancestral type, that is, are monophyletic, then the ichthyosaurs must be more closely related to the Squamata, *Protorosaurus*, and Proganosauria, than to any other known reptiles This much I believe: The Ichthyosauria are of very primitive origin; they have never possessed a lower temporal vacuity; the two bones of the temporal region, variously known as supratemporal and squamosal, point to a direct origin from the stegocrotaphous reptiles, provided these bones are not both identical with those I call the tabulare and squamosal in the lacertilians and *Araeoscelis*. If they are identical, then the two phyla may have originated together.

The problem remains, What shall be done with *Araeoscelis?* To throw it into a common receptacle with *Dimetrodon*, *Edaphosaurus*, and *Casea* may be an easy way to dispose of the genus, but it is hardly scientific. Some classification, even the most conservative, it must have; and while I am vigorously opposed to the still more reprehensible practice of giving every form that is hard to understand a new group name, it is evident that to place *Araeoscelis* with the Pelycosauria is to increase the confusion.

I have urged that the resemblances of *Araeoscelis* to the Squamata would justify its inclusion in that order as a suborder, under the name Araeoscelidia, co-ordinate with the Lacertilia and the Ophidia. And I believe that will be its final disposition under some subordinal designation. But it seems to me that the relations with *Protorosaurus* and *Kadaliosaurus* are too definite, too pronounced, to warrant their dissociation. I would therefore propose to unite these three genera, together with, provisionally, *Haptodus* and *Callibrachion*, under the order Protorosauria of Seeley, and place the order immediately before the Squamata in any serial classification of reptiles.

RESTORATION

The restoration of the skeleton shown in Fig. 7 is based upon the material described in the foregoing pages. I have omitted the tail because, while there are a sufficient number of caudal vertebrae preserved to show conclusively that it was long and slender, there are not enough preserved in connection to determine its length. I have little doubt that the number of vertebrae exceeded sixty. The precise lengths of the digits are also in a measure conjectural, since in no specimen is a digit preserved complete. Sufficient phalanges, however, have been recovered to enable one to reconstruct the fingers and toes with little chance of error, following the arrangement determined in other contemporary reptiles. The first digit of the hand is purely conjectural. It must have been small, and may have been absent; the hand upon the whole seems to have been much like that of *Varanosaurus brevirostris*. The lengths of the anterior ribs are determined from one specimen in which they are preserved nearly completely in relation with the vertebrae. The lengths of the posterior ribs are conjectural. It is also assumed that there are not more than seven cervical vertebrae; there is a strong possibility, however, that the neck was longer.

In the life restoration (Fig. 8) I have added the tail in like proportion to that of slender living lizards. That it was as long as the head, neck, and trunk together there can be scarcely a doubt, for it is not often shorter in swift-crawling reptiles; it may have been longer. In much probability the living animal was covered with corneous scales; one can hardly conceive of a reptile with habits such as *Araeoscelis* must have had as having a bare skin, and it is quite certain that the body was not protected with bony scutes.

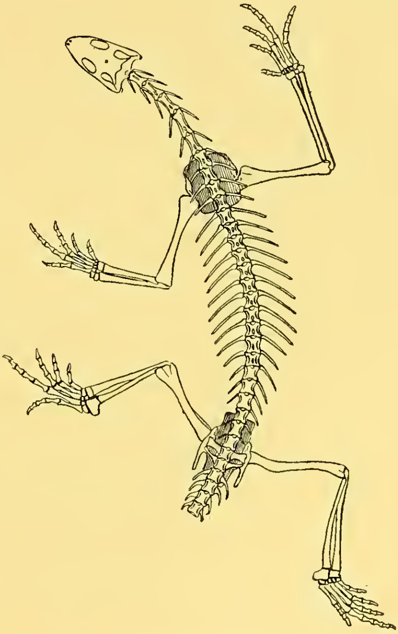

FIG. 7.—*Araeoscelis gracilis* Williston: Restoration of skeleton, about one-fourth natural size.

HABITS

Just what is the significance of some of the peculiar characters possessed by *Araeoscelis* I am at a loss to conjecture. That the creature was a swift-moving, crawling reptile there can be no doubt. That it was arboricolous I also believe; the pointed and curved ungual phalanges determine the presence of sharp claws in the living animal. The unusual development of the calcaneum and outer toes seems to indicate springing habits, and the curved femora and elongated epipodials resemble those of *Scleromochlus*, of whose leaping powers there can be little doubt. The extremely hollow bones also suggest arboricolous habits. Why the creature had such elongated cervicals I do not see. At one time the idea was entertained that *Araeoscelis* possessed more or less of a *Flughaut*, because of the development of the outer fingers and the possible loss of the first. And the cervical vertebrae certainly suggest those of the pterodactyls or birds, as Seeley has suggested of *Protorosaurus*. The presence of similar cervical vertebrae and hollow bones suggests somewhat similar habits for both these reptiles, but the vertebrae of *Protorosaurus* are clearly more like those of the crawling lizards, while those of *Araeoscelis* resemble more those

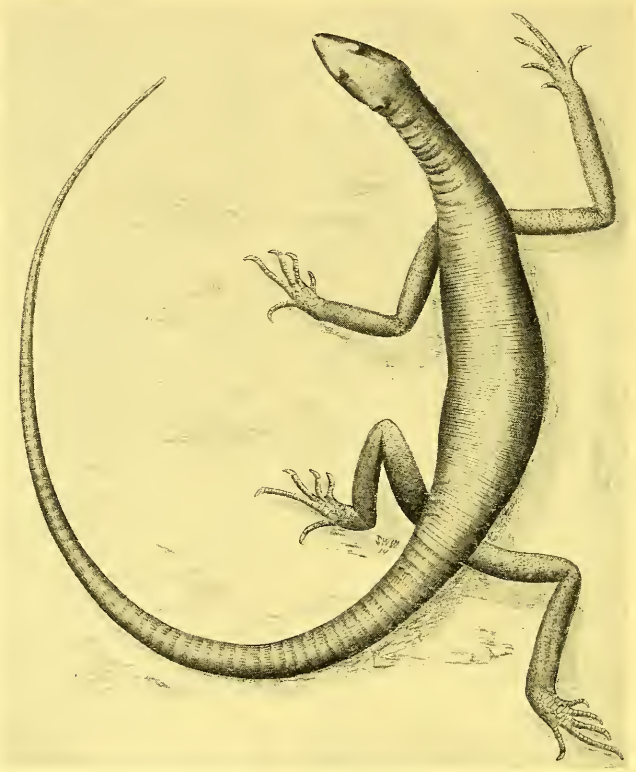

FIG. 8.—*Araeoscelis gracilis* Williston: Life restoration, about one-fourth natural size.

of snakes. The hind legs of *Protorosaurus* are longer than the front ones, and this is the case also with *Araeoscelis*, though not to the same extent. One can say with assurance that *Araeoscelis* was an extremely light and slender, terrestrial and arboreal reptile, with springing powers, and possibly with a parachute development of the body membrane. Its length, when adult, was about 2 feet.

THE SKULL OF *CASEA*[1]

A preliminary description of the skull of *Casea*, as based on a single, not quite complete, specimen, has been given by me in my *American Permian Vertebrates*, with a promise of a further discussion whenever the additional material of the University collections should be worked out. One other skull has, so far, been discovered and prepared, though there is still a probability of others turning up in the future. This skull, unfortunately, had been somewhat injured in the collection of the material by the loss of much of the upper part in front of the parietal foramen. The right orbit is nearly complete and the lower part of the left, as also the lower part of the nares. The quadrates are somewhat displaced, but otherwise the skull is more perfect than the one previously described. The specimen is a part of a nearly complete skeleton which has not yet been worked out of its nodular matrix; it is of precisely the same size as the skeleton previously described. The premaxillae are complete, or nearly complete, and are in position with respect to each other and the maxillae. They project farther forward than did the incomplete ones of the previous specimen, terminating above in slender processes, which separate the nares narrowly. In the first-described specimen the nares had been somewhat injured, with the roof depressed, especially on the right side. The present specimen gives the lower side complete and quite undistorted, enabling me to restore the orifice with the aid of the other specimen, accurately, I think. It is possible that the orifice may have been a little higher than I have figured it (Figs. 9, 10). The nares, it is seen, are of enormous size, communicating immediately with the very large internal openings below

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[1] Williston, *Jour. Geol.*, XVIII (1910); *American Permian Vertebrates* (1911).

them. Lying just within the orifice there is a thin, plate-like bone, evidently forming a turbinated structure, the sphenomaxillary.

Not much can be added to my description of the temporal vacuity. On the right side the orbital bar and inferior arcade are nearly complete, but on the left side they have been injured by the displacement of the quadrate. I think, however, as I suspected, that the vacuity is a little smaller than I figured it. Nothing definite can be said as to the presence of a distinct quadratojugal bone.

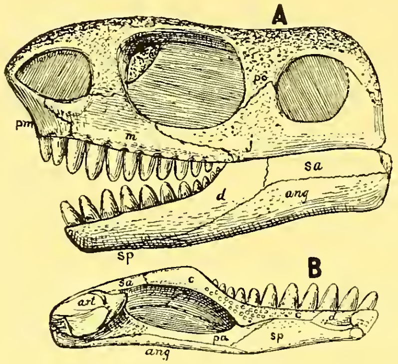

FIG. 9.—*Casea broilii* Williston: *A*, skull from the side; *B*, left mandible of same, from inner side, three-fifths natural size; *pm*, premaxilla; *m*, maxilla; *po*, postorbital; *j*, jugal; *d*, dentary; *sa*, surangular; *ang*, angular; *sp*, splenial; *art*, articular; *pa*, prearticular; *c*, coronoid.

The palate, fortunately, is in such preservation that its structure, save in details, is very clear. The whole surface is closed, as in *Pantylus*, and is covered with small, but pointed, conical teeth. Large orifices in front, corresponding with those shown in the former figure, are the nares, situated immediately below the external openings. The two sides of the palate show divisions so alike that one cannot resist the conviction that some of them, at least, are sutural separations. Especially do the divisions running backward from the nares, which are not only alike on the two sides, but which agree with those of the former skull, indicate the sutures between palatines and pterygoids. One cannot be sure of the division between the pterygoids and vomers, covered, as the surface is, with numerous small teeth, which cannot be entirely freed from the matrix; but a symmetrical depression on the two sides seems to indicate the sutures, as shown by dotted lines in the figure. On either side behind, there are two divisions, which seem to be exactly alike on the two sides, one running forward and outward from the inner extremity of what would be the transverse bones if present; the other forward and inward to near the front end of the interpterygoidal space. That all of these should be fractures, so exactly alike on the two sides, seems strange, but there can hardly be any other interpretation of the inner divisions, at least. They all bear teeth forming a continuous dentigerous surface between the mandibles, back of the nares. The two inner pieces are crowded nearly in contact over what is probably a slender parasphenoid in this specimen; in the other specimen, however, the base of a narrow parasphenoid is seen between the two sides.

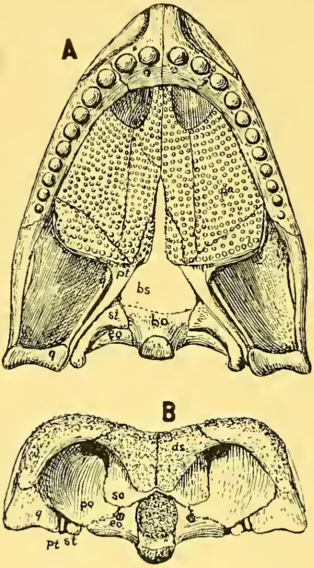

FIG. 10.—*Casea broilii: A*, skull from below; *B*, the same, from behind, three-fifths natural size; *po*, paroccipital; *pa*, palatine; *bs*, basisphenoid; *bo*, basioccipital; *pt*, pterygoid; *q*, quadrate; *st*, stapes; *eo*, exocciptal; *so*, supraoccipital *ds*, dermosupraoccipital.

In one or the other of the two skulls the structure of the posterior palatine region is definitely shown. The basisphenoid is a broad, flat, or gently concave bone, lying contiguous with the posterior processes of the pterygoids in front, and terminating in front, as I have figured it, apparently in a slender parasphenoid. Posteriorly the very stout stapes fits closely into an interval between the posterior angle of the basisphenoid and the exoccipitals. It is directed outward and backward, as a heavy, somewhat curved, cylindrical rod, to near the lower end of the quadrate, lying in close relation to the posterior process of the pterygoid.

The basioccipital forms the whole of the gently curved, cordate-shaped condyle, with a short, broad surface below in front. On either side the exoccipital is distinctly separated from the basioccipital, extending up on either side of the foramen magnum to near the top, as in *Dimetrodon*. These sutures are clearly shown; that between the exoccipital and paroccipital is less certain, though, from the agreement of lines on both sides in both specimens, I believe that the suture is situated as I have figured it in dotted lines. A small foramen for the posterior cranial nerves is visible as I have figured it. The broad, outer concave surface of the occiput is formed chiefly by the paroccipital—I can detect nothing of the petrosal—leaving a small post-temporal vacuity above as an emargination of the upper side of the bone. At what seems evidently the junction of the paroccipital and supraoccipital there is a distinct notch, from which what seems to be a sutural line passes downward to join the exoccipital suture. The supraoccipitals form together a plate, somewhat convex in the middle above the foramen magnum, which extends upward to the under side of the parietals, as in lizards, but are covered, for the most part, by the loosely applied bones of the cranial roof, which descend to, or nearly to, the upper margin of the foramen magnum, with a slight notch in the middle. In one specimen they come quite to the margin, in the other they terminate some little distance above, owing to the greater depression of the skull roof in the former. These bones are rugose on the upper surface, forming a continuation of the cranial table. I suppose that they are the dermosupraoccipitals, joining the true supraoccipitals quite as in the cotylosaur *Labidosaurus;* but no certain line of distinction can be seen above. On the sides in each specimen a sutural line seems distinct, separating the bones from the lateral element, whatever it may be, of the suspensorial arch. As these lines agree in the two specimens, there would seem to be little doubt of their sutural character.

I cannot be sure of the structure of the process that curves downward on either side behind to cover the upper end of the quadrate. Since they join broadly the outer end of the paroccipitals behind, one would expect to find a distinct tabulare here; but if so, it cannot be demonstrated from these specimens.

With the exception of the loosely applied dermosupraoccipitals it will be seen that the whole structure of the occipital region, as I interpret it, resembles that of *Varanus,* except that the post-temporal vacuity is smaller, and that the exoccipitals take no part in the formation of the occipital condyle.

The sutures of the mandible are shown very satisfactorily in the two specimens, and doubtless I should have detected them in my previous study of them, had I then known what to expect.

The coronoid reaches posteriorly on the upper side of the meckelian orifice nearly to the anterior extremity of the articular; anteriorly this bone borders the alveolar margin as far forward as the third tooth. It is covered, for the most part, with small, conical teeth, like those of the opposite palatal surface. These teeth had been smoothly removed with the investing matrix in the first specimen described, but their attachments are clearly visible under a hand-lens; they are visible in the investing matrix of the second skull. The splenial enters into the mandibular symphysis below, as usual among the early vertebrates. The boundaries of the prearticular are less distinct posteriorly, though certain evidences of sutural lines are visible as I have figured them.

The teeth in the second specimen are somewhat better preserved than in the first; they are of somewhat larger size, but their number and characters are quite the same.

Any comparison of the skull of *Casea* with that of other reptiles will be more or less speculative. It shares with *Diadectes*, *Pantylus*, and *Edaphosaurus* the short, broad skull and more or less elevated narial region. In all these the palatal region is practically closed in front and covered with more or less thickly set teeth, indicating similar food habits. From the nature of the obtuse mandibular and maxillary teeth, I had inferred herbivorous habits; but it is quite possible that the food may have consisted chiefly of the softer invertebrates. Against this assumption, however, is the very large abdominal capacity that suggests plant food. The skull, as I have before suggested, has a strange resemblance to that of *Amblyrhynchus*, the subaquatic Galapagos lizard, in the great development of the narial region.

The single large temporal vacuity reminds one of *Edaphosaurus*, but the intimate resemblances end there. Nor is there a very intimate relationship between *Casea*, the poliosaurids, as represented by *Varanoops*, or the ophiacodontids as represented by *Theropleura* or *Ophiacodon*. That the genus represents a distinct family there can be no doubt; its higher relationships must await further discoveries—I have little faith in phylogenetic speculations based on our present ignorance of the early reptilian faunas.

ARRIBASAURUS, A NEW GENUS OF THEROMORPH REPTILES FROM NEW MEXICO

Among the collections made by Mr. David Baldwin for Professor Marsh more than thirty years ago, there is a considerable quantity of more or less broken and fragmentary bones of a small reptile from El Cobre Cañon, New Mexico. All of this material, or at least the greater part of it, was evidently collected from the surface at one spot where it had been washed from some bone-bed. The material consists, apparently, of the remains of a single species, represented by the bones of adults and young. Among the collections made by the University of Chicago expedition to the same region in the summer of 1911, there are a number of bones and fragments of bones collected from the surface near the west part of the same cañon, that evidently are of the same species as some if not all the remains of the Yale collection, if not also of the American Museum collection made by Baldwin for Professor Cope from El Cobre, which includes the type of the species *Dimetrodon navajoicus* Case. I should feel quite confident that the Chicago collection came from the same bone-bed deposit as the remains preserved at Yale University, were it not that the bones all seem to belong to a single individual, save for a small femur of a yet unnamed cotylosaur of very small size. Of the Yale material the larger part consists of the remains of immature animals, as shown by their smaller size and incomplete ossification of the ends of the long bones. There are, however, portions of the skeletons of at least two adults among the collection. The lower end of one of these adult specimens agrees so well with the humerus figured and described by Case under the name *Dimetrodon navajoicus*, that I feel fairly confident of their specific identity, notwithstanding the apparent absence of an ectepicondylar process in the specimen as figured by Case. That all this material at Yale and at Chicago belongs in a single genus there can be no reasonable doubt. If the adult specimens are later shown to belong to a distinct species it will be time enough to give a new name when the facts are known. The genus may therefore be defined as follows:

Arribasaurus, genus new. Teeth slender, conical, more elongate anteriorly, short and closely placed posteriorly. Spines of verte-

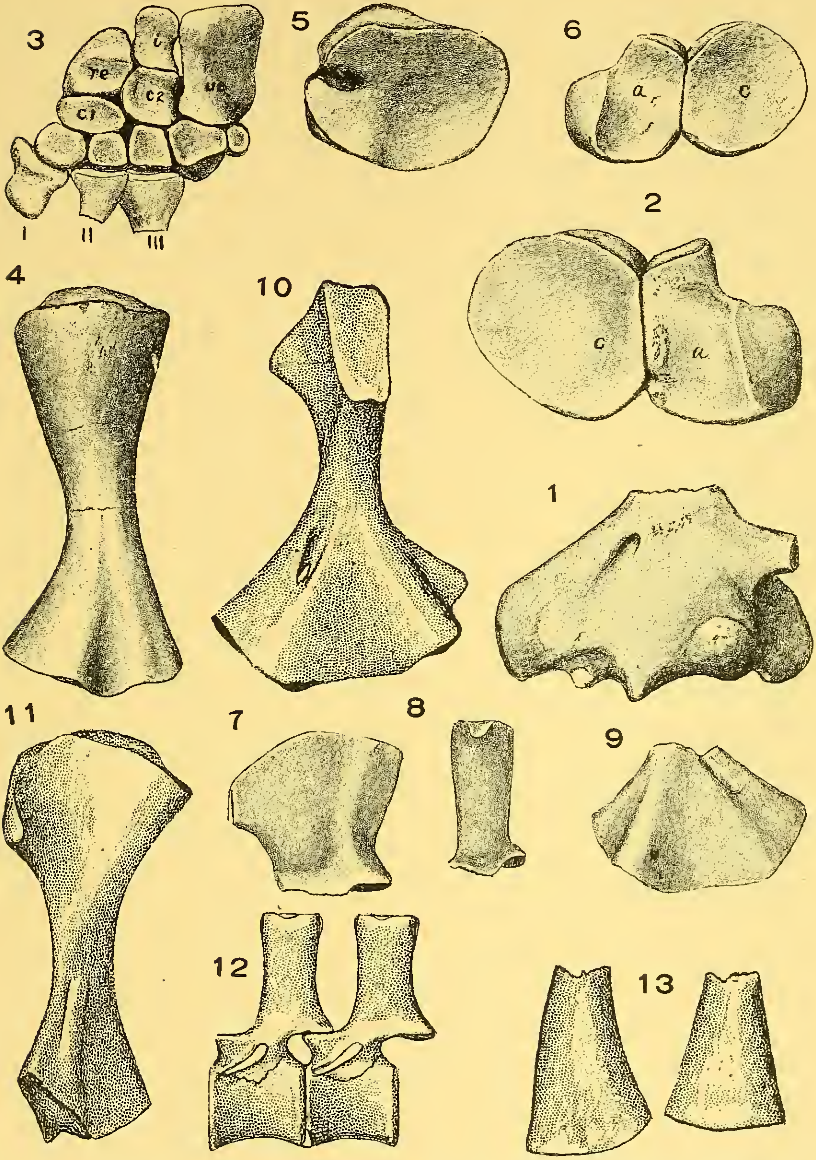

FIG. 11.—*Arribasaurus navajoicus* Case: *1*, distal end of left humerus, ventral side; *2*, calcaneum and astragalus, from the front; *3*, left carpus, from the front; *4*, left femur, dorsal side; *5*, pubis; *6*, right calcaneum and astragalus of young, from the front; *7*, spine of axis; *8*, spine of dorsal vertebra; *9*, distal end of young humerus; *10*, right immature humerus, dorsal side; *11*, the same, ulnar side; *12*, two dorsal vertebrae, from the side; *13*, distal end of tibia; *14*, distal end of fibula. All natural size.

brae (Fig. 11, *8*, *12*) short and flattened, with the upper extremity flattened ovate in section; axis with a broad spine, as in the Poliosauridae; diapophyses with a continuous articular surface, directed downward and forward, showing holocephalous ribs, as in *Ophiacodon*. Humerus (Fig. 11, *1*, *10*, *11*) with the lateral process high up on the shaft; distal extremity much expanded, its plane nearly at a right angle with that of the proximal end; carpus (Fig. 11, 3) very much as in *Ophiacodon;* the first centrale and inner carpalia larger. Pubis (Fig. 11, *5*) subcircular or subquadrate in outline, with the obturator foramen more or less notched (in the young at least); ischium and proximal tarsal bones (Fig. 11, *2*, *6*) as in *Ophiacodon;* femur with a rather slender shaft (Fig. 11, *4*). Length of animal probably about 5 feet.

So far as the skeletal bones and teeth are concerned, the genus seems to be related to *Ophiacodon*, but the pubis shows very distinctive characters, and the spines of the vertebrae are relatively much shorter; the humerus is also much more elongated. On the strength of the pubis alone, a very characteristic bone in the Pelycosauria, the genus is, I think, eliminated from the Poliosauridae or Ophiacodontidae; and the teeth will exclude it from the Sphenacodontidae. The pubis has a distinct resemblance to one which I figured erroneously as a calcaneum in my *American Permian Vertebrates* (Plate XXXI, Fig. 10, and Plate XXXII, Fig. 11), from the Craddock bone-bed, Texas; and it is possible that the femur, also figured in this work on Plate XXX, Fig. 4, may belong with this pubis, a yet unnamed genus, that may prove to be related to the present one.

THE PRIMITIVE STRUCTURE OF THE MANDIBLE IN REPTILES AND AMPHIBIANS

Until within recent years the mandible of reptiles was thought to be composed of not more than six bones, originally named by Cuvier and Owen the articular, angular, surangular, coronoid, splenial, and dentary. In *Sphenodon* only was it known that one of these bones, the splenial, was absent. The bone long known as the splenial in the turtles occupies an anomalous position for that bone, overlying the inner side of the articular and remote from the position of the splenial in other reptiles. Baur,[1] in 1895, discovered in the extinct *Toxochelys* a bone that corresponds to the true splenial of other reptiles, and recognized for the first time that the so-called splenial of other turtles really is homologous with a dermal element which is either wholly wanting or is indistinguishably fused with the articular in all other reptiles then known. Unfortunately, assuming that the bone so called in the Chelonia was the true splenial, he changed the names of the elements in other reptiles to correspond, naming that originally called the splenial by Owen the presplenial, causing thereby much confusion in nomenclature. In 1903 I recognized[2] for the first time in an another reptile this dermogenous element, in the plesiosaurs, and corrected Baur's error by naming it the prearticular, retaining the names of all the other elements as originally applied by Cuvier and Owen. Soon afterward Case recognized the prearticular in the Pelycosauria, and Branson in the Stegocephalia. Since then the name has come into general use, though other names were later proposed for the same bone (dermarticular Kingsley, goniale Gaupp). Five years ago I expressed the conviction that a separate prearticular would be found characteristic of all early reptiles; we now know that to be the fact. Typically the bone overlies the inner side of the articular, forming the inner margin of the suprameckelian orifice, and the posterior and superior margin of the posterior inframeckelian foramen, when it is present, its anterior end intercalated between the splenial and the coronoid. In other words, it has precisely the same relations as has the anterior inner part of the angular in the crocodiles (Fig. 12), in which no evidence has so far been adduced of a prearticular ossification. One wonders whether embryological investigation may not show a fused condition of prearticular and angular in these reptiles; in which case the so-called angular would properly be called the angular-prearticular, just as the so-called articular of lizards is really the articular-prearticular.

In all later reptiles the coronoid is a small element occupying the eminence of the mandible back of the teeth, articulating with

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[1] Baur, *Anat. Anzeiger* (1895), p. 412.

[2] Williston, *Field Columb. Mus. Publ.*, No. 73, p. 30.

the dentary, surangular, and prearticular or angular, and also the splenial when present. It never extends farther forward than the posterior part of the dental series. In the same plesiosaurian mandible in which I recognized a separate prearticular, there was "a long, slender, flattened, trihedral bone, extending far forward along the alveolar margin, meeting its mate in the median symphysis" (Fig. 16), which I was forced to call the coronoid, though it was utterly unlike anything that had previously been recognized as the coronoid. Only within recent years has this peculiar structure of the coronoid been recognized in other plesiosaurs, by Andrews and Linder; doubtless it is characteristic of the order, testifying to its primitive origin. This elongate form of the coronoid is now known to be characteristic of all primitive reptiles. In these reptiles it lies along the inner alveolar margin of the mandible, extending toward the symphysis, but entering into union with its mate only in those reptiles having a long mandibular symphysis. Its posterior end occupies the position of the coronoid of later reptiles, that is, articulating with the anterior superior part of the surangular, chiefly on the inner side of the mandible, and forming the anterior margin of the meckelian orifice. It articulates with the prearticular below; it is always narrow.

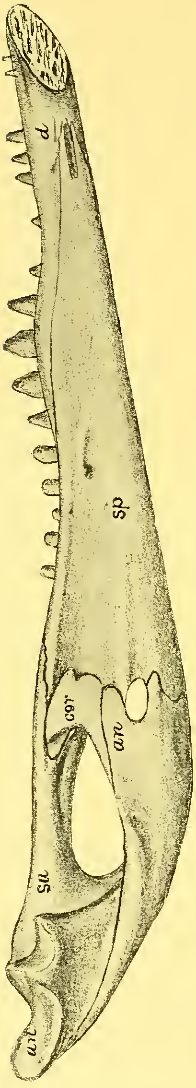

Fig. 12.—*Alligator mississippiensis:* Left mandible, inner side. Explanations as in Fig. 13.

The splenial in all modern reptiles, when present, is a thin bone covering more or less the inner side of the mandible anteriorly and the meckelian groove, extending rarely as far forward as the symphysis; it is not visible on the outer side of the mandible, or, if so, only to a very slight extent. As I stated some years ago,[1] "in all or nearly all reptiles having a greatly elongated

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[1] Williston, *Jour. Geol.*, XVI (1906), 6.

mandibular symphysis, the splenial takes part in its union." But, this symphyseal union of the splenials in such forms is doubtless due to the recession of the symphysis, rather than to the retention of a primitive character, since in the alligator and crocodile, with a short symphysis, the splenials do not meet, while in the gavial, with a long symphysis, they do.

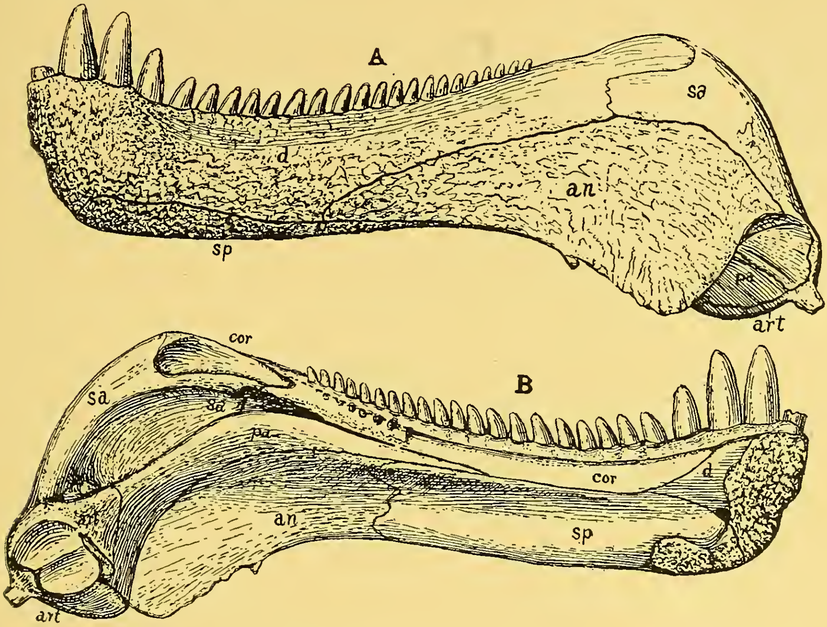

FIG. 13.—*Dimetrodon incisivus* Cope: *A*, left mandible, outer side; *B*, inner side of same; *cor*, coronoid; *d*, dentary; *sa*, surangular; *an*, angular; *art*, articular; *pa*, prearticular; *sp*, splenial.

Not only is the symphyseal union of the splenials a primitive character, as was first stated by me in 1911[1] and reaffirmed the following year, but, unlike modern reptiles, it enters more or less into the outer surface of the mandible, as I have figured it in various cotylosaurs (*Limnoscelis*, *Labidosaurus*, *Captorhinus*). These primitive characters may be summarized as follows:

The primitive mandible of reptiles is composed of seven distinct bones, the articular, prearticular, angular, surangular, coronoid, splenial, and dentary. The coronoid is elongated, extending along

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[1] Williston, *American Permian Vertebrates*, p. 30.

the alveolar margin of the teeth toward the symphysis, and often bearing teeth. The prearticular forms the inner border of the meckelian orifice and is intercalated between the coronoid and splenial anteriorly. The splenial takes part in the mandibular symphysis, and is more or less visible on the outer side of the mandible. A posterior inframeckelian foramen is present in the most primitive reptiles.

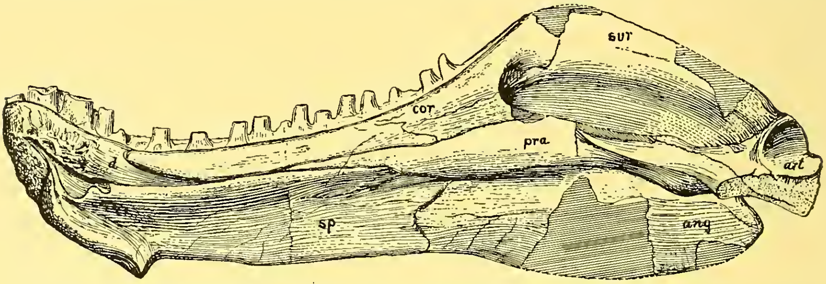

Fig. 14.—*Dimetrodon*, sp.: Right mandible, from inner side. Explanations as in Fig. 13.

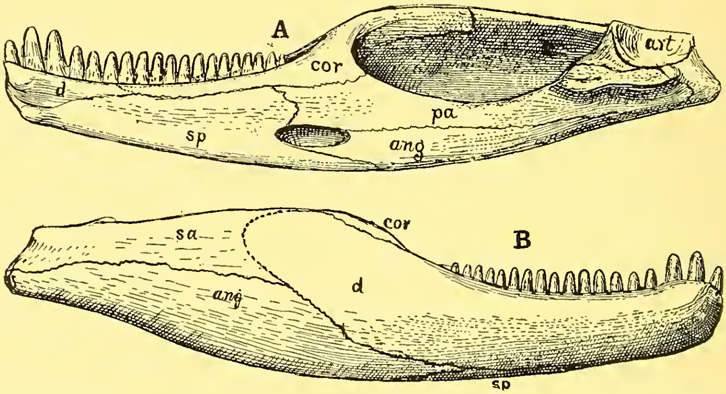

Fig. 15.—*Labidosaurus hamatus* Cope: *A*, right mandible, inner side; *B*, the same, outer side. Explanations as in Fig. 13.

These characters I have determined in six different genera of Permian reptiles, and I doubt not that they will be found in all, from the Lower Permian at least. Figures of the mandibles of four of these are given herewith, and do not need detailed description (*Dimetrodon*, Figs. 13, 14; *Casea*, Fig. 9; *Labidosaurus*,

Fig. 15; and *Captorhinus*, Fig. 16). Photographic copies of the mandible of *Dimetrodon*, precisely as here figured (Fig. 13), were distributed to some of my correspondents in August of 1913. I was not then confident of the continuity of the coronoid bone throughout, and so briefly described it in *Science* of October 10, 1913, as possibly, though not probably, composed of two bones, the anterior one of which I called the alveolar. Later material satisfied me that there is but a single bone. Dr. Broom[1] refers to this description as of a distinct alveolar bone; doubtless it was an oversight, since he received a copy of Fig. 13 in August, as also my figures of the mandibles of *Trimerorhachis* and *Labidosaurus*, before he wrote his paper.

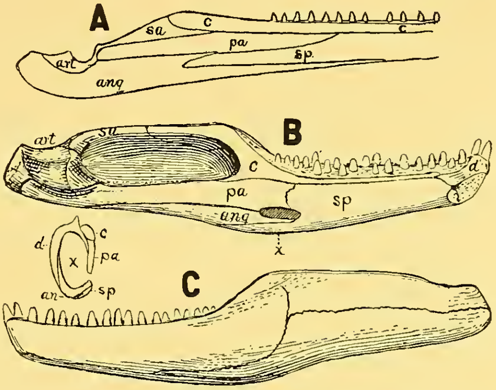

Fig. 16.—*Trinacromerum osborni* Williston: Left mandible to symphysis, inner side, after Williston, 1903; *B*, *Captorhinus aguti* Cope, left mandible, from within; *C*, the same, outer side. Explanations as in Fig. 13.

Since the foregoing went to the printer I have received from Dr. Broom another paper, published February 24, 1914, containing a description and figure of a mandible of a pelycosaur preserved in the National Museum, which he doubtfully referred to either *Dimetrodon* or "*Naosaurus*" (*Edaphosaurus*)! The only addition this paper makes to our knowledge is the precise connection between the coronoid and prearticular. He determines, however, without hesitation or doubt a suture separating the coronoid into two bones, the anterior of which he calls the precoronoid. At my request, Mr. Gilmore kindly sent me the specimen upon which Broom's studies were based. It is very clearly a species of *Dimetrodon*. I give herewith a more accurate figure of the specimen (Fig. 14). All the sutures, aside from the one in question, are

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[1] Broom, *Bull. Amer. Mus. Nat. Hist.* (November, 1913).

clearly shown, especially in connection with my previous figure which Dr. Broom had at the time of his studies. That there is a real suture dividing the coronoid is not impossible, but there is nothing in the specimen to prove that it is not a crack, and not until it is corroborated by additional material should his figure be accepted as certain. Dr. Broom has made mistakes before in his hasty identification of cracks as sutures, and this may be another one. Dr. Broom states that he has "recently" seen a copy of my figure of the *Dimetrodon* jaw as here given (Fig. 13). "Recently" is evidently here used in a relative sense, since he first saw the figure before he began his study of the American mandibles, in August, more than three months before he studied the specimen in the National Museum.

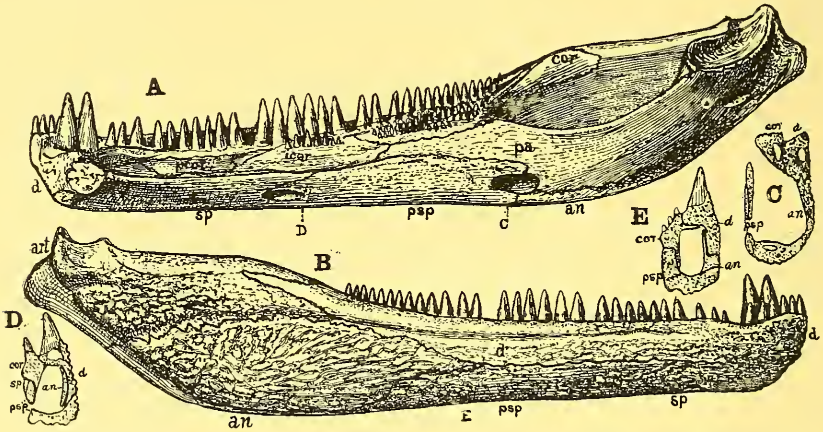

FIG. 17.—*Trimerorhachis alleni* Case: *A*, right mandible, inner side; *B*, the same, outer side; *C*, *D*, *E*, sections of mandible as designated; *psp*, postsplenial; *cor*, coronoid; *icor*, intercoronoid; *pcor*, precoronoid. Other explanations as in Fig. 13.

AMPHIBIANS

In the structure of the mandible the amphibians are remarkably intermediate between the early reptiles and the contemporary crossopterygian fishes, differing from the latter chiefly in the reduced number of coronoids, and from the former chiefly in the possession of two additional coronoids and a splenial.

Until very recently our knowledge of the stegocephalian mandibular structure has been imperfect and more or less erroneous. Branson for the first time recognized in an amphibian the presence of a distinct prearticular, and correctly homologized what is now known as the true splenial with the infradentary of fishes. He erred in uniting the postsplenial with the angular, and in calling the intercoronoid and precoronoid the splenial. He also identified the true coronoid correctly. Watson very recently correctly homologized the true splenial with the infradentary of Branson,

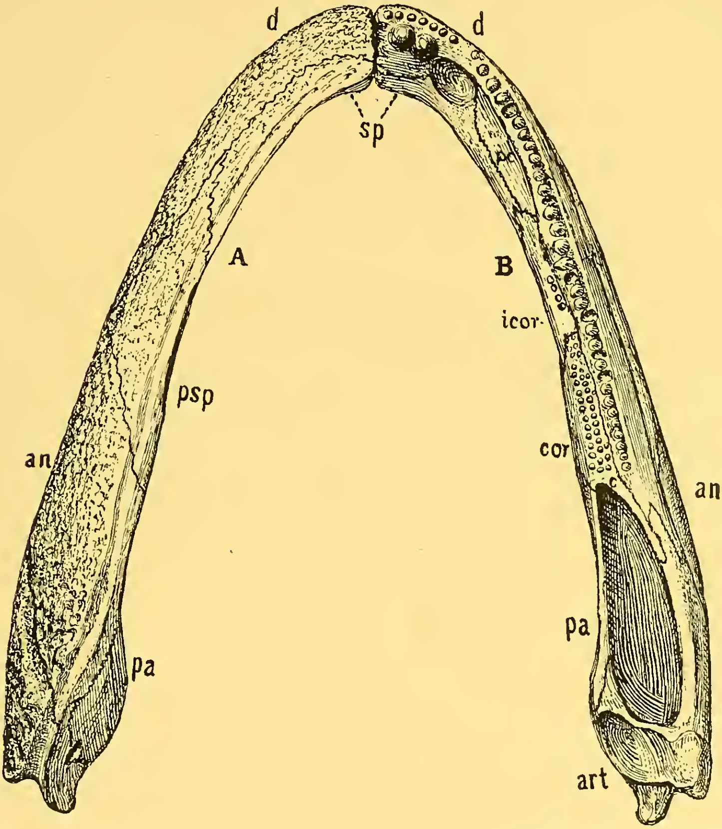

FIG. 18.—*Trimerorhachis insignis; A*, right mandible, from below; *B*, the same, from above. Explanations as in Figs. 13 and 17.

and correctly identified the anterior coronoid. He erred in distinguishing the limits of the prearticular and in giving to the true coronoid the name epicoronoid as an element peculiar to amphibians.

The posterior splenial (Fig. 17, *psp*) was, I believe, for the first time recognized in any amphibian by me in the early part of last August, and its discovery communicated to several correspondents, as was also the structure throughout of the mandible of *Trimerorhachis*, with the exception of the sutures separating the anterior coronoids. Photographic copies of the figures of the mandible of this genus, as published by me in a preliminary paper in the October-November (1913) number of the *Journal of Geology*, were distributed to various correspondents in September and October. That figure differs from the ones here shown only in the less precise sutural line between the coronoid and prearticular, and in the absence of the sutures between the anterior coronoids. All these corrections were definitely and positively recognized by me in a later collection of material sent me by Mr. Lawrence Baker in October a short time before the publication of the paper by Dr. Broom. From this it results that I had discovered the postsplenial and had suggested that name for it before Dr. Broom began his studies of the mandible; and that Dr. Broom discovered the two anterior coronoid elements before I did. The names then, postsplenial, intercoronoid, and precoronoid, may properly be retained for the new elements, provided that nowhere

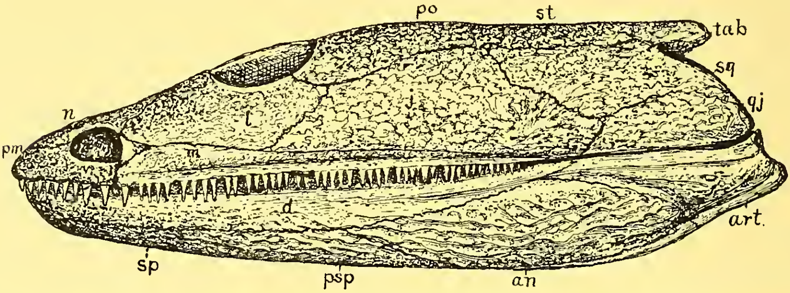

FIG. 19.—*Trimerorhachis insignis* Cope: Skull, from the side, one-half natural size. Explanations as in previous illustrations.

in the ichthyological literature there are prior names for these elements in the crossopterygian fishes.

Although there has been an unnecessary duplication of studies which might have been avoided, the results are fortunate in their independent corroboration, placing at rest any doubts as to the real structure of the stegocephalian mandible. Dr. Broom's figures are inaccurate in detail, as will be seen by comparing them with those herewith given.

A detailed description of the elements is unnecessary; the illustrations will explain them better. In none of the many specimens have the sutures between articular and surangular been distinguished. I have spent much time in making sections of the articular end and in corroding with acid many specimens, but wholly in vain. There are certain variations in different specimens which it may be well to notice. The posterior inframeckelian foramen is sometimes situated farther in advance, and is almost wholly bordered above and below by the postsplenial. The splenial usually enters very distinctly into the mandibular symphysis; in some specimens it takes only a slight part. A structure like that of *Trimerorhachis* I have observed in *Eryops*, *Diplocaulus*, and other stegocephalians. I also find the postsplenial in *Anaschisma*, but have not distinguished the anterior coronoids.

SUMMARY

The mandible of the primitive amphibians differs chiefly from that of the early reptiles in the division of the coronoid into three elements, or possibly four, and in the division of the splenial into two. The surangular cannot be distinguished, if present.

STUDIES FOR STUDENTS

A CLASSIFICATION OF COMMON SEDIMENTS AND SOME CRITERIA FOR IDENTIFICATION OF THE VARIOUS CLASSES

ARTHUR C. TROWBRIDGE
State University of Iowa

Sedimentary rocks are useful to the geologist chiefly through the record of the history of the earth which they contain, and it is desirable that classifications of these rocks should be so arranged as to bring out as much of that history as possible. The common classification of sedimentary rocks, on the basis of texture and mineral composition, into conglomerates, sandstones, shales, and limestones is hardly adequate, because the origin of the rock is only slightly implied, if at all, in the definition. For instance, under the present classification, sandstone is sand cemented; but the discovery of sandstone in a locality may record either a shallow sea not far from shore, dry, windy conditions and the piling-up of sand by wind, the previous existence of lakes receiving sand from near-by lands, or fluvial conditions under which the sand was deposited by streams. Similarly, conglomerate may be marine, fluvial, pluvial, glacial, or lacustrine in its origin. Even limestone is being laid in inland lakes today, as well as in the sea, and by wind in the Bermuda Islands.

If sedimentary rocks are to perform their function as true recorders of past events, their classification must be based on the origin of those rocks. The agents and processes by which sedimentary rocks are made lie chiefly in the realm of physiographic geology. This paper places a physiographic interpretation on the origin of sedimentary rocks.

It is of course understood that there is a wide gap between sediments and sedimentary rocks, but it is also believed that a classification of the various sorts of sediments will be at least a step toward a more effective classification of sedimentary rocks, and that many of the criteria for distinguishing various sorts of sediments are also applicable to rocks resulting from sediments after cementation.

The classification and lists of characters which follow are not presented with the idea that they contain matter which is new, but merely to bring together, in a way intended to be helpful, certain things which have been well known to geologists. Much of it has been published in one place and another in standard works, and these sources have been drawn upon freely in the preparation of the present paper.

The various sorts of common sediments are as follows:

Eolian
Fluvial
Pluvial
Talus
Glacial
  a) Till
  b) Fluvio-glacial deposits
Lacustrine
  a) Near-shore phase
  b) Still-water phase
Marine
  a) Shallow-water deposits
    (1) Zone of major agitation
    (2) Zone of minor agitation
  b) Deep-water deposits

By pluvial deposits are meant those transported by rain water or immediate run-off, without the agency of permanent streams. Talus deposits are those whose constituents are rolled down steep slopes by the action of gravity, not necessarily aided by water. Near-shore lacustrine deposits are those laid in lakes between high-water mark and the surf line. Shallow-water marine deposits are those laid in the sea between high-water mark and the 100-fathom line, and deep-water deposits are laid in the deep sea beyond the 100-fathom line. The shallow-water deposits of the sea have been generally divided into (*a*) littoral deposits (those laid between high- and low-water marks) and (*b*) non-littoral deposits (between low-water mark and the 100-fathom line).[1] For present purposes

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[1] See Murray, *Report of the H.M.S. Challenger, Deep Sea Deposits*, p. 186; and Chamberlin and Salisbury, *Geology*, I, 368, 369, and 379.

at least this is not a happy division, for after analysis it is clear that the differences between deposits above low-water mark and those below low-water mark are slight, and that the differences between deposits in greatly agitated waters and those in quieter waters are great. In spite of infelicities of expression, it seems best here to divide the shallow-water deposits of the sea into two groups, (*a*) those of the zone of major agitation, and (*b*) those of the zone of minor agitation. The deposits of the zone of major agitation include beach deposits, bars, spits, hooks, barrier reefs, etc., for the most part materials laid within the surf line, and the deposits of minor agitation are those laid in quieter water in general beyond the surf line. None of the other terms needs definition here.

The lists of characters of these various sorts of deposits, given below, are the results of (1) a study of the processes and agents by which they are deposited, and (2) observation of undoubted types of the various sorts of deposits in the field. Sand dunes have been studied at the south end of Lake Michigan and loess in Iowa, Illinois, and Wisconsin. Fluvial deposits were examined particularly in Owens Valley, California. Pluvial deposits were noted in Owens Valley, and in the southern Appalachians; talus slopes in Wisconsin, California, and Wyoming; glacial materials in Wisconsin and Illinois; lacustrine deposits in extinct lake bottoms in Wisconsin, and in the Pliocene lake deposits of the Inyo Mountains; and marine deposits in the Paleozoic rocks of the Mississippi Valley.

CHARACTERS OF EOLIAN DEPOSITS

Eolian deposits have the following characteristics. For the sake of brevity they are listed.

1. Low textural range.
2. Material all finely divided.
3. Sorted into irregular beds and lenses.
4. Stratification-planes dip in all directions.
5. Stratification-planes have dips varying in amount up to 30° ±.
6. Material porous.
7. Distributed in irregular areas, not continuous.
8. Vary greatly in thickness within short distances.
9. May be ripple-marked.
10. Grains of sand are rounded.
11. Fossils, if any, are of terrestrial forms.

Most of the foregoing statements need no explanation. No. 4 is due to the constant shifting of the wind and to the irregular surfaces on which dust and sand are laid. In No. 5, the 30° dip is the angle of the lee-sides of sand dunes, as read with the clinometer, and is the angle of rest for sand. These are the characters of eolian sand, but, with the possible exception of 5, 7, 9, and 10, they also characterize loess. A typical section of dune sand is shown in Fig. 1.

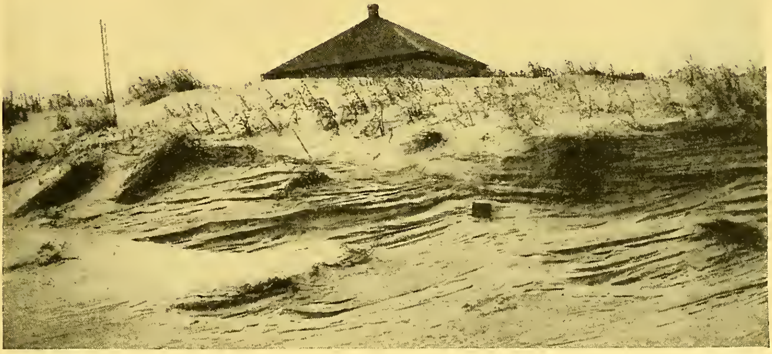

FIG. 1.—A section of sand deposited by the wind near Cape Henry, Virginia (photograph by Dr. T. W. Vaughan).

CHARACTERS OF FLUVIAL DEPOSITS

The conditions under which streams deposit are so various that it is difficult and perhaps unwise to list any one set of characters which will fit all fluvial materials. Swift streams deposit their coarse loads at the bases of mountains under conditions quite different from those of larger and sluggish streams depositing on their flood plains, and yet both distribute, both flow in one general direction, both sort their materials at least roughly, and, after all, the results differ chiefly in degree rather than in principle. Fluvial deposits have the following characteristics:

1. Relatively fine material, though some fans include large bowlders.
2. High textural range (fans), and low textural range (some flood-plain deposits).
3. Only roughly sorted.
4. Lens and pocket structure.

5. Distributed in belts (river flats and piedmont alluvial plains).
6. Bedding planes dip in one general direction, though slightly divergent in the direction of general dip.
7. Beds dip at angles varying up to 18°±.
8. Deposit diminishes uniformly in thickness in the direction of the divergence of dips.
9. Material likely to be heterogeneous, lithologically.
10. Pieces angular or rounded.
11. Fossils rare, and of terrestrial forms.

FIG. 2.—A typical fluvial deposit, showing lens and pocket structure. A section of a stream terrace in Jo Daviess County, Ill.

The lens and pocket structure seems to be especially characteristic of fluvial deposits. In Owens Valley no textural division in the fans could be traced more than fifty feet in any direction. This structure is quite unlike the layered character of still-water deposits such as those laid in lakes or in the sea, and somewhat different from the structure of materials deposited by ocean or lake waves and currents. The 18° of No. 7 above is the highest angle read on the surface of the fans. The slight divergence of dips as stated in No. 6 is due to distribution of the streams. Fig. 2

shows a fluvial deposit of one type in a stream terrace in northwestern Illinois. Lens and pocket structure is visible here. A somewhat different type is shown in Fig. 3, this being a photograph of a section of an alluvial fan at the foot of the Sierra Nevada Mountains in California. While these two deposits are quite different, the differences are those of degree rather than of principle.

Fig. 3.—A fluvial deposit at the foot of the Sierra Nevada Mountains in California.

CHARACTERS OF PLUVIAL DEPOSITS

Pluvial deposits are similar to those deposited under fluvial conditions, except that (1) the material is not so well sorted, (2) it is more restricted in distribution, (3) the beds, if any, dip at higher angles, (4) the material is more likely to be homogeneous lithologically, for it has not been transported so far from the parent ledges, and (5), because not transported so far, the constituent pieces are likely to be more angular. For the sake of easy reference, the list of characters follows:

1. Material coarse.
2. High textural range.

FIG. 4.—A pluvial deposit in North Carolina.

FIG. 5.—A pluvial deposit at the foot of the Inyo Mountains in California. The crude sorting and the angularity of the pieces are the features of the section.

3. Very crude sorting.
4. Distributed in restricted areas, on or near steep slopes.
5. Beds, if any are visible, dip in one general direction, though diverging.
6. Beds, if any, may dip at high angles.
7. Deposit varies in thickness, decreasing uniformly in direction of divergence of dips.
8. Material local and homogeneous lithologically.
9. Pieces, angular.
10. Fossils, if any, of terrestrial forms.
11. Surface and base of formation may have steep slopes.

Figs. 4 and 5 show types of pluvial deposits, one in North Carolina and the other at the foot of the Inyo Mountains in California.

CHARACTERS OF TALUS DEPOSITS

Talus deposits are not abundant among sedimentary materials, and yet they exist. At Ableman, Wis., a talus slope of Huronian quartzite is included in Potsdam sandstone, and it is possible that other conglomerates belong to this type of deposits. The characters of these deposits are listed below. Fig. 6 shows a talus slope of quartzite at Devils Lake, Wis.

1. Coarse material greatly predominates over fine.
2. Pieces are the result of mechanical disintegration.
3. Pieces angular.
4. No stratification.
5. Distributed in restricted and isolated areas, or in very narrow belts near high lands.
6. Base and surface of formation have steep slopes.
7. Pieces touch one another.
8. Very porous.

CHARACTERS OF GLACIAL TILL

The characters of glacial till are so well known as to need no discussion here. For the sake of getting the criteria together the list is given.

1. Heterogeneous in composition.
2. High textural range (rock flour to enormous bowlders).
3. Coarse material generally subordinate in amount to fine.
4. No stratification.
5. Constituents, largely subangular.
6. Great variation in thickness within short distances.

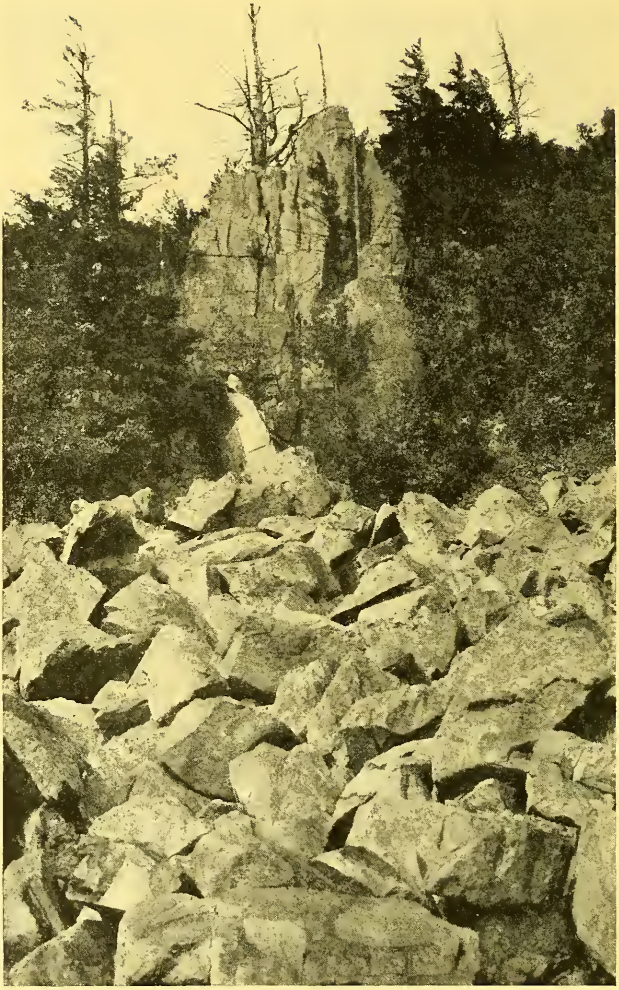

FIG. 6.—A talus slope of blocks of quartzite at Devils Lake, Wis. (photograph by J. J. Runner).

7. Appreciable part of material foreign to location in which deposit is found (does not hold for all glacial deposits in high mountains).
8. Some of the stony matter striated.
9. Lies on unweathered bed (in general).
10. Sharp plane between drift and underlying formation.
11. Beds striated, grooved, bruised, etc.
12. Fossils, if any, show evidences of wear by transportation.

This type of deposit is illustrated in Fig. 7.

Fig. 7.—A section of glacial till in Wisconsin.

CHARACTERS OF FLUVIO-GLACIAL DEPOSITS

Corresponding with the characters of the depositing agents, fluvio-glacial deposits are closely allied to fluvial deposits on the one hand and to glacial till on the other; in general they resemble the former in texture and the latter in lithologic constitution. In shape the constituents of these deposits are a combination of form due to glacial wear and that given to pieces rolled along the bottoms of streams. The list follows:

1. Heterogeneous in constitution.
2. Moderate textural range.
3. All material stratified.

4. Sorted into lenses and pockets rather than into definite, uniform, continuous layers.

5. Constituents have a roundness superimposed on subangularity.

6. Striae rare or lacking on pebbles.

7. Thickness varies with irregularities in bed and shows a general tendency to thin in one direction.

8. Appreciable part of material foreign.

9. Generally does not lie on bed rock, and contact below is not necessarily sharp.

10. Fossils worn, but may include unworn terrestrial forms.

11. Likely to be found in the vicinity of glacial till.

Fig. 8.—A fluvio-glacial deposit in Wisconsin (photograph by L. E. Wells).

Fluvio-glacial deposits bear all relations in position to glacial till. They lie over, under, or within the till, though they may also lie out beyond the till in the form of outwash plains or valley trains. Fluvio-glacial deposits are shown photographically in Fig. 8.

LACUSTRINE DEPOSITS (NEAR-SHORE PHASE)

In these deposits are the materials brought to lakes by streams, cut from the shores by waves, carried and deposited by feeble littoral currents, etc. The zone of deposition is one of frequently changing conditions, due to changes in volume of streams, strength of wind, direction of shore currents, shape of spits, bars, deltas, etc. These deposits may be distinguished by the following characters:

1. Material likely to be coarse.
2. High textural range (bowlders to silt).
3. Well sorted into lenses and pockets and arranged in linear areas.
4. Textural divisions grade out in all directions.
5. Fossils from running-water, surf-water, and still-water habitats.
6. Constituents well or poorly flattened.
7. Cross-bedded.
8. Special markings; ripple-, wave-, rill-marks, mud-cracks.
9. Rather abrupt variations in thickness.
10. Bedding planes dip in all directions, predominantly from shore.
11. Bedding planes dip at angles varying up to angle of rest for the materials (edges of deltas, ends of spits, etc.).
12. Distributed in narrow belt parallel with lake shore.

Fig. 9.—A near-shore phase of lacustrine deposit in Wisconsin.

Fig 9 shows some lacustrine sand and gravel exposed in the margin of the bottom of an extinct lake in Wisconsin.

LACUSTRINE DEPOSITS (STILL-WATER PHASE)

1. Material fine in texture.
2. Low textural range (sand to silt).
3. Well sorted into definite layers.
4. Rather uniform in thickness.
5. Beds likely to be finely laminated (in some cases 20 to the inch).
6. Distributed continuously over large or small areas, according to size of depositing lake.

7. Surrounded by near-shore lacustrine deposits.
8. Textural divisions grade into one another vertically, but not laterally.
9. Fossils of still-water types of life.
10. Bedding planes essentially horizontal.
11. May be ripple-marked.

Fig. 10 shows a section of laminated lake clays which were found less than half a mile from the section in Fig. 9. Fig. 10 illustrates the still-water phase of lacustrine deposits as contrasted with the near-shore phase deposited in the same lake. Another contrast of this sort may be seen in Figs. 14 and 15, *Jour. Geol.*, XIX, 724.

SHALLOW-WATER MARINE DEPOSITS

ZONE OF MAJOR AGITATION

1. In general coarse material.
2. Rather high textural range (bowlders to mud).
3. Sorted into lenses, pockets, irregular linear areas.
4. Contain marine fossils with possible mixture of land forms.
5. Distributed in rather narrow belt parallel with coast.
6. Different textural divisions grade out laterally and vertically.
7. Special markings; ripple-, rill-, wave-marks, mud-cracks.
8. Sorted texturally and to some extent mineralogically.
9. Considerable range in thickness within short distances.
10. Cross-bedded.
11. Constituents likely to be flattened.
12. Bedding planes dip in all directions, but chiefly from shore.
13. Bedding planes have dips varying up to angle of rest for the materials (edges of deltas, ends of spits, etc.).

By comparing these characters with those of the near-shore phase of the lacustrine deposits, these two sorts of deposits are found to have the same characters, with the exception of fossils and a slight difference in distribution. There would also be a difference in degree; that is, the marine deposits might contain coarser material, have a higher textural range, thicker textural divisions, etc. This type of sediment after cementation is illustrated in Fig. 11 which shows a section in the Potsdam sandstone at the Dells of the Wisconsin River near Kilbourn, Wis.

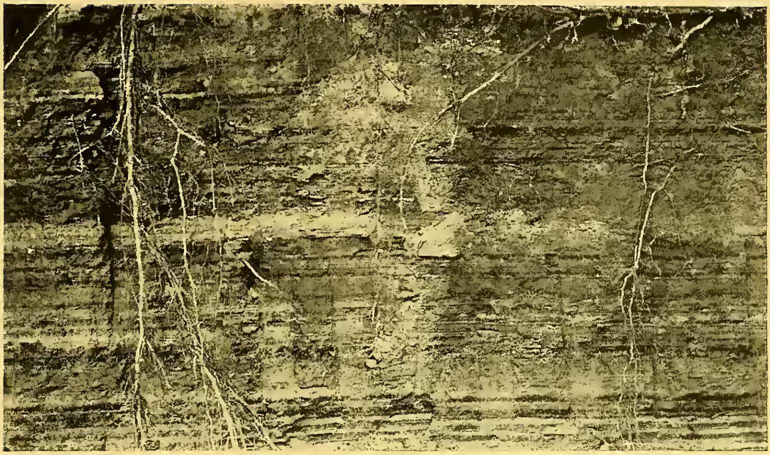

Fig. 10.—Some laminated lake clays deposited in the still water of the same lake which received the near-shore deposits of Fig. 9.

Fig. 11.—The Potsdam sandstone, a type of deposits in the sea in the zone of major agitation.

SHALLOW-WATER MARINE DEPOSITS

ZONE OF MINOR AGITATION

There is no great difference between these materials and the still-water lacustrine deposits, though there are differences in distribution, fossils, textural range, texture, etc. The list follows:

1. Average materials fine in texture.
2. Rather low textural range (sand to silt and limestone).
3. Sorted into definite continuous layers.

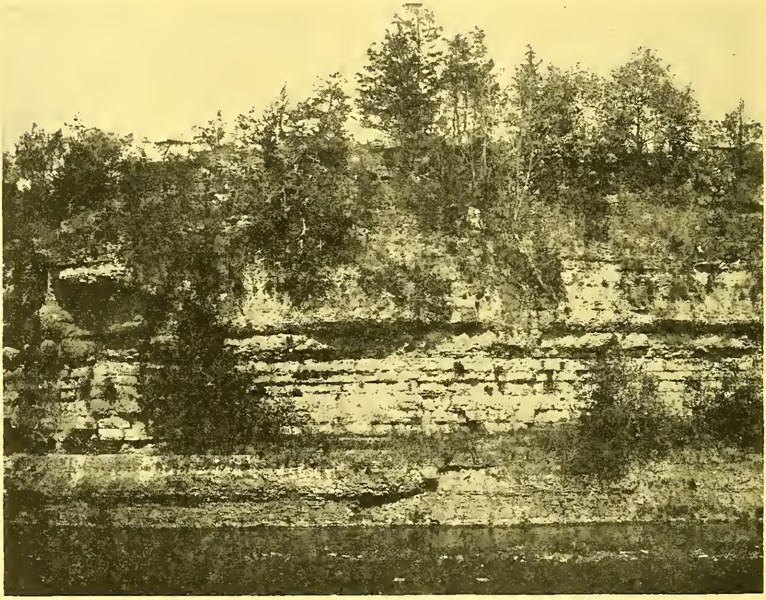

FIG. 12.—A section in the Galena dolomite of northwestern Illinois. This is a shallow-water marine deposit in the zone of minor agitation.

4. Marine fossils.
5. Distributed continuously over wide areas.
6. Does not vary greatly in thickness within short distances.
7. Special markings; ripple-marks (not rill- or wave-marks, or mud-cracks).
8. Include chemical and organic deposits.
9. Bedding planes essentially horizontal.

This deposit is well illustrated by the Galena dolomite of northwestern Illinois, which is shown in Fig. 12. All the essential

KEY TABLE FOR IDENTIFICATION OF VARIOUS CLASSES OF SEDIMENTS

	Eolian	Fluvial	Pluvial	Talus	Glacial Till
Texture...........	Fine	Variable	Coarse	Coarse	Variable
Textural range.....	Low	High	High	Medium	Very high
Stratification.......	Irregular beds and lenses	Lenses and pockets	Lacking	Lacking	None
Constitution.......	Homogeneous or heterogeneous	Heterogeneous	Fairly homogeneous	Homogeneous	Heterogeneous including foreign matter
Distribution......	Irregular areas, not continuous	In narrow, linear areas	Restricted, isolated areas	Restricted, isolated areas	Broad areas
Amount of dip......	Variable within limits (0–30°)	Variable within limits (0-18°)	....	....	....
Direction of dip....	In all directions	Diverge in one general direction	....	....	....
Thickness.........	Varies greatly in short distances	Decrease uniformly in one direction	Increases in one direction	Variable	Exceedingly variable
Shape of pieces.....	Rounded, pitted	Angular or rounded	Angular	Angular	Subangular, striated
Fossils............	Land forms suggesting aridity	Fresh-water and land forms (scarce)	Terrestrial forms, if any	....	Terrestrial or marine forms but worn
Characters not included above.....	May be ripple-marked	May include large bowlders	Found only near highlands	Very porous	Lie on unweathered, striated bed. Large bowlders

	Fluvio-glacial	Lacustrine (Near-Shore Phase)	Lacustrine (Still-Water Phase)	Shallow-Water Marine (Zone of Major Agitation)	Shallow-Water Marine (Zone of Minor Agitation)
Texture	Medium	Variable	Fine	Coarse	Fine
Textural range.....	Rather low	Rather high	Low	High	Low
Stratification	Lenses and pockets	Lenses, pockets, belts	Layered, laminated	Lenses, pockets, belts	Definite, continuous layers
Constitution........	Heterogeneous	....	....	Heterogeneous	Mechanical, chemical, and organic deposits
Distribution	In belts	Belts	Over more or less wide areas	Long, continuous belts	Continuous over wide areas
Amount of dip	Cross-beds may have high dips	Variable within limits	Essentially horizontal	Variable within limits	Essentially horizontal
Direction of dip....	Diverge in one direction	In all directions, chiefly from shore	....	In all directions, especially from shore	....
Thickness..........	Decrease in one direction	Variable	Uniform	Variable	Uniform
Shape of pieces.....	Roundness on subangularity	Flattened or rounded	....	Flattened or rounded	....
Fossils.............	Terrestrial, worn if marine	Fresh-water forms (running-, surf-, and still-water)	Fresh-water forms (still-water)	Marine, with possible land forms	Marine forms
Characters not included above.....	Occur near till	Cross-bedding, ripple-, wave-, rill-marks, mud-cracks	Laminae	Cross-bedding, ripple-, wave-, rill-marks, mud-cracks	Possible ripple-marks

characters have been retained even after cementation and partial metamorphism.

DEEP-WATER MARINE DEPOSITS

Deposits of the deep sea, that is, those materials laid in the sea beyond the edge of the continental shelf, are not here described, partly because their position of deposition makes their study in place almost impossible and partly because they are not commonly represented on the lands either in cemented or unconsolidated rocks. They are known, however, to consist of the finest terrigenous material, remains of pelagic life, submarine volcanic materials, atmospheric dust, extra-terrestrial materials, and the results of chemical alteration of the above-mentioned substances. Presumably most of it is finely divided, has a low textural range, and lies in horizontal strata. The fossils are doubtless pelagic in character.

An attempt is made to condense all the important characters in the foregoing lists into a single table which may be used as a key to the identification of the various common sediments.

PETROLOGICAL ABSTRACTS AND REVIEWS

EDITED BY ALBERT JOHANNSEN

LACROIX, A. "Les roches grenues, intrusives dans les brèches basaltiques de la Réunion: leur importance pour l'interprétation de l'origine des enclaves homéogènes des roches volcaniques," *Comptes rendus*, CLIV, No. 10 (1912), pp. 630–35.

Basaltic breccias on the island of Reunion, about 300 miles east of Madagascar, are cut by dikes and sills of syenite, gabbro, and peridotite, clearly exposed in mountain amphitheaters.

The prevailing type of syenite consists for the most part of various alkali-feldspars, accompanied by alkaline pyroxenes and amphiboles. A scarcer variety contains biotite and a little plagioclase. The gabbros vary in composition: some contain both augite and olivine; those with olivine alone pass to a variety with very basic plagioclase and finally to peridotite; some of the gabbro is essexitic in character. The peridotite is chiefly dunite, but this passes to wehrlite by addition of diopside. The most basic of the intrusives are the oldest. Their chemical relation to the volcanic rocks is not known, except that some of the gabbro is almost identical in composition with some of the basalt.

This occurrence affords a striking proof that coarsely granular rocks have solidified at a depth of only a few hundred meters, in volcanic rocks of Tertiary—probably late Tertiary—age. The author infers that the influence of depth on crystallization has been greatly exaggerated, and that, while a thick cover may be favorable, it is by no means essential to the development of granular texture. He believes that granular rocks may be crystallizing at the present time in the flanks of active volcanoes. In the Reunion locality, he sees no confirmation of Harker's hypothesis that the normal order of igneous manifestations is: (1) volcanic action, (2) plutonic intrusions, (3) small intrusions. He considers the volcanic rocks and the small intrusions contemporaneous.

The author also sees in this locality a demonstration that certain "homogeneous inclusions" in volcanic rocks have been formed by differentiation of the magma prior to eruption, with the result that distinct geologic bodies are formed, fragments of which are loosened and brought to the surface by the ascending lava.

F. C. CALKINS

LACROIX, A. *Discours prononcé a la séance de clôture du congrès.* Congrès des Sociétés Savantes à Paris, 1912. Pp. 20.

A study of the volcanoes of Madagascar.

LACROIX, A. "Sur la constitution minéralogique des volcans de l'île de la Réunion," *Comptes rendus*, CLV (1912), 538–44.

From a single volcano and a single magma there have been erupted subalkaline and alkaline rocks, rocks which had long been considered as necessarily having independent origins and localized in distinct regions of the world (Atlantic and Pacific provinces). Nineteen analyses are given.

A. J.

LACROIX, A. "Un voyage au pays des Béryls (Madagascar). La Géographie," *Bull. Soc. Geog.*, XXVI (1912), 285–96.

A popular account of the minerals of Madagascar.

LACROIX, A. *Les richesses minérales de Madagascar.* Conférence faite à l'Ecole Coloniale le 22 Déc., 1912. Paris, 1913. Pp. 10.

LEISS, C. "Ueber zwei neue Mikroskope für petrographische und krystalloptische Studien," *Zeitschr. f. Kryst.*, XLIX (1911).

Describes two new microscopes with nicol prisms connected by a rigid bar. The first is after de Souza-Brandão and was originally described and illustrated in 1903 in the report of the geological survey of Portugal. Besides the attachments usual in a large petrographic microscope, this instrument has a stage which may be tilted to any angle, and an Abbe illuminating apparatus. The second, with a similar bar connection, is after Wright, and was first described in 1910. In this, likewise, the illuminating apparatus is after Abbe. A compensator ocular is permanently attached to the tube.

A. J.

LEISS, C. "Neues petrographisches Mikroskop für die Theodolit-Methode," *Centralbl. f. Min., etc.*, 1912, 733–36.

Describes a microscope which combines in itself a von Fedorow stage and a petrographic microscope with simultaneously rotating nicols.

The universal stage in this instrument, however, is considerably larger than in the detachable stage, being capable of taking sections 28×48 mm., thus doing away with the necessity of using circular sections.

A. J.

LOEWINSON-LESSING, F. "Beiträge zur Systematik der Eruptivgesteine, I." *Tiré d. Ann. d. Inst. Polyt. Pierre le Grand a St. Pétersbourg*, XV (1911), 229–43.

After a period of ten years, the author resumes his critical studies on the nomenclature and classification of igneous rocks, and proposes to issue a continuation of his former series of papers which was published in *Tschermak's Mittheilungen* in 1889–1902. The paper here reviewed is the first of the new series, unfortunately printed in the Russian language and consequently unavailable, except so far as the short résumé in German goes, to the majority of the petrologists in this country.

The writer discusses first the transition members of the effusive rocks between those from the alkali and from the alkali-earth magmas, and second, the absence of mono-mineral rocks among the effusives. He believes this absence to be a proof that the formation of eutectic and mono-mineral differentiation rocks takes place only in deep-seated magmas. That they do not reach the surface as effusives he thinks may be due to their viscosity and high melting-point, or that they are more active in assimilating the country rocks and, therefore, in the course of their eruption, always become changed in composition.

ALBERT JOHANNSEN

LOUDERBACK, GEORGE DAVIS. "The Monterey Series in California," *Bull. Dept. Geol. Univ. Cal.*, VII (1913), 177–241.

LOUGHLIN, G. F. "Contribution to the Geology of the Boston and Norfolk Basins, Massachusetts. I. The Structural Relations between the Quincy Granite and the Adjacent Sedimentary Formations," *Amer. Jour. Sci.*, XXXII (1911), 17–32.

The igneous rocks in the area studied include an altered biotite granite series, an older felsite series, the Quincy alkaline granite series, and alkaline felsite. The sediments are much folded and include the conglomerates, sandstones, and slates of the Boston and Norfolk basins.

A. J.

REVIEWS

"The Stability Relations of the Silica Minerals." By CLARENCE N. FENNER. *Am. Jour. Sci.*, Ser. IV, Vol. XXXVI (1913), pp. 331–84, fig. 9.

A report of the results of a rigorous study of the various polymorphous modifications of silica. The work shows conclusively that the relations between quartz, tridymite, and cristobalite are enantiotropic. New determinations of the inversion points, including those between α and β phases of quartz, tridymite, and cristobalite, are given. The paper represents by far the most exact work upon the subject to date, and is made especially valuable by carefully constructed diagrams showing the relations between the various phases.

A. D. B.

The Mount Grainger Goldfield. By R. LOCKHART JACK. Report No. 2, Geol. Surv. of So. Australia. Adelaide, 1913. Pp. 24, figs. 10, pl. 1.

Describes very briefly the chief structural features of the region and the more important workings.

A. D. B.


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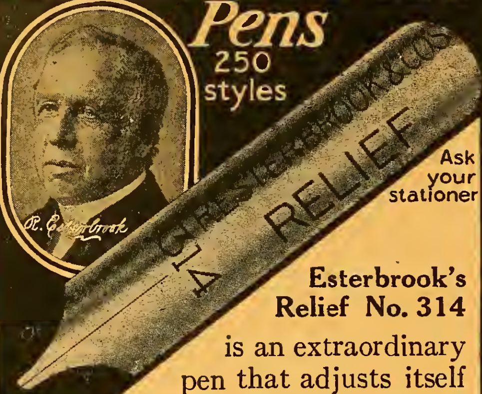

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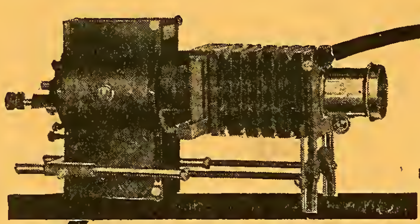

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THE STRENGTH OF THE EARTH'S CRUST

JOSEPH BARRELL
New Haven, Connecticut

PART V. THE DEPTH OF MASSES PRODUCING GRAVITY ANOMALIES AND DEFLECTION RESIDUALS

INTRODUCTION AND SUMMARY

The fact that the observed deflections of the vertical are on the average only one-tenth as large as the computed effects of the topographic relief, computed on the assumption of uniform density throughout each earth shell, shows that the densities of the crust

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[1] Section B of Part V, on the applications of the criteria to determine the limiting depths, forms, and masses of the excesses and defects of density, will be published in the following number of this *Journal*.

are not uniform, but in a broad way are balanced against the relief. This is the proof that a condition prevails of approximate regional isostasy. As the relief of the globe is highly variable, the densities in the lithosphere are therefore within certain limits also highly variable. But on the other hand, the existence of gravity anomalies and deflection residuals indicates that the variations in density are not completely in accord with the demands of the hypothesis which postulates local compensation of the topography uniformly distributed to a uniform depth, nor apparently with any other simple hypothesis. These quantities measure the differences between the hypothesis and the facts of nature. Let the density variations beyond those required to balance the topography vertically above them be called the outstanding excesses or defects of density and the masses which they represent be called the outstanding masses.

It is fundamental to the problems of the strength of the crust, and a system of geologic dynamics in accord with that strength, to determine the depth, form, and weight of these outstanding masses. Do they belong to the centrosphere or to the lithosphere? As Gilbert has noted, if they are to be referred to the centrosphere they do not imply any imperfection of isostasy nor any competence for stress within the crust. Or, if they exist in the lithosphere, the zone of compensation, but are balanced vertically in the same column by other masses of opposite sign, this arrangement will produce local strains within the crust but not tend to flex the crust as a whole. Neither in this case, therefore, would they measure departures from perfect isostasy. As following questions, are the imperfections of isostasy small and local, and the residuals and anomalies the summation of many scattered effects? Or, on the contrary, are there notable regional departures from the conditions of solid flotation which measure a very appreciable rigidity of the crust? If so, to what extent are these regional outstanding masses related to the mountains, valleys, and deltas in process of evolution under the present cycle of surface activities; producing a progressive unbalancing possibly being slowly restored toward balance by a viscous undertow? To what extent are the departures from isostasy due to variable composition and density of igneous intrusions dating back to earlier geologic ages, perhaps never in isostatic balance, and supported permanently and rigidly by the strength of the crust?

These problems have been studied in the last three parts of this article by means of the evidence presented by Hayford and Bowie, but that evidence has not been used to solve the depth of the outstanding masses. Yet it is seen that all of the aspects just enumerated are bound up in that factor. It is especially this problem of the depth and the consequent areal extent and mass of the units which produce the residuals of the deflection and gravity observations which is attacked in this part. It is necessary for this investigation to enter into a study of the complex relations between the anomalies and residuals which depend upon the depth and form of masses. It is a subject upon which, so far as the writer is aware, but little has been done, so that about half of this chapter, published as Section A, consists of a study of these relations preliminary to their application.

For facility of mathematical treatment the individual outstanding masses must be regarded as equivalent to spheres, spheroids, or cylindrical disks, either as units or as aggregates. If only the epicenter (the point on the surface vertically above the center) of the disturbing mass is determinable and the deflections at two or three points on one side of it, then the mass may be most simply interpreted as a sphere; since the mass of a sphere acts as if concentrated at its center. With fuller observations a close approximation to the depth of the mass and a less close approximation to its form and density may be made. The first problem then is to determine the epicenter of the outstanding mass and its depth, using for this purpose the nature of the anomalies and residuals. For a sphere beneath a plane surface it is shown that the value of the maximum gravity anomaly at the surface is 2.6 times the value of the maximum deflection residual, both being measured in the same units of force. The former occurs vertically over the abnormal spherical mass, that is, at the epicenter. The latter occurs at a horizontal distance from the epicenter equal to 70 per cent of the vertical depth to the center of mass. Oblate spheroids and broad cylindrical disks with vertical axes and the same depth of center as the sphere give maximum deflections at greater distances from the epicenter. The curves of the deflection force for these forms, especially the spheroidal forms, resemble somewhat closely those given by deeper spheres of greater mass. If the outstanding masses are in reality horizontally extended the interpretation of the deflection residuals as due to spherical masses assigns to their centers in consequence too great a depth. If, however, the masses have the forms of vertical prolate spheroids or vertical elongate cylinders, the interpretation as spheres will give too shallow a depth. The ratios of the maximum anomalies to the maximum deflections constitute a criterion to show whether the masses depart from spheres by the spreading-out of their substance in a horizontal plane or along a vertical axis.

In Section B the outstanding masses are shown in some cases to be horizontally extended in form and this is thought for the larger masses to be a rather general relationship; that is, the vertical thickness is much less than the length or breadth. Consequently the interpretation as spheres gives maximum limits to the depth.

A general inspection of the geodetic data as well as a detailed study of a certain test region shows that the smaller disturbing masses have their centers in the outer third of the zone of compensation; that is, within 40 km. of the surface. This result is to be expected, since similar small masses at greater depth would not exert a notable effect because their gravitative force varies inversely with the square of the distance. But evidence of more significance is found in regard to the larger centers of outstanding mass not related to topography. These also are found, in so far as they have been investigated, to be situated in the outer third of the zone of compensation. Yet these masses are capable of showing notable effects to distances of from 100 to 150 km. If they were situated at any depth within the zone of compensation they would, therefore, betray both their existence and their depth. The greater departures from isostasy appear, therefore, to be really absent from the deeper parts of the lithosphere.

Centrospheric heterogeneity, if present, would require greater masses in order to show surface effects. But no such effects are noted. In so far as they may be existent, they are largely masked by the more important attractions of superficial masses and hidden by the indeterminate nature of much of the present data. Therefore centrospheric heterogeneity is not a hypothesis which can be used to account for the apparent departures from isostasy. It can be at most only a very secondary factor.

In the last topic of Section B is discussed the relation of the depth of outstanding masses to the various hypotheses regarding the distribution of compensation. The hypothesis of local compensation, as is perceived to a certain extent by those who have used it, is in error in supposing that variations in density correspond to every topographic feature and extend uniformly to the bottom of the zone. But these errors, whether they be small or great, are so spread out in depth and their centers of attraction are consequently so far removed from the surface that they have little effect on the geodetic observations. Especially is this true in comparison with those large and concentrated outstanding masses due to batholithic invasion or other causes which are found to exist at moderate depths in the outer crust. The reasons then why the deflection residuals and gravity anomalies appear to show so little relation to local surface relief and larger physiographic provinces are threefold: in part because of a regional compensation; in part because the hypothesis of local compensation as here shown masks the error contained in the assumption of perfect and local isostasy; in part because for many regions the ancient heterogeneities of mass hidden within the crust seem in reality to be greater than the heterogeneities of mass visible at the surface in topographic form and created by present gradational actions.

The results of this chapter converge with the lines of evidence previously considered and confirm them in showing considerable defects from isostasy for areas which are 100 km. or more in radius. This confirmation is to be expected, since it would be indeed remarkable if a crust, competent to carry such loads as the *geologic* evidence from erosion and sedimentation shows to be imposed, should give *geodetic* evidence of fairly local and nearly perfect adjustment between the topographic forms, developed by present external processes, and the variations in density imposed by past internal forces.

SECTION A

DEVELOPMENT OF CRITERIA FOR SPHEROIDAL MASSES

Separation of lithospheric from centrospheric outstanding masses.—Let the zone of compensation be regarded as the boundary of the lithosphere. At its bottom consider to exist a zone in which that lateral flowage takes place which is necessary for movements of isostatic readjustment and the maintenance through geologic time of a condition of more or less complete isostasy. Below it is the inner and more rigid core of the earth, the centrosphere. Let those excesses or defects of density above the zone of isostatic flow which are not in accord with the isostatic compensation of the topography be designated for convenience as lithospheric outstanding masses. Let all heterogeneities of density within any earth shell below the zone of isostatic flow be called centrospheric outstanding masses.

In his recent paper on the "Interpretation of Anomalies of Gravity,"[1] Gilbert calls attention to the fact that if abnormalities of density exist below the zone of compensation they will produce anomalies of gravity without these signifying real departures from isostasy. This is a very necessary addition to the theory of the cause of gravity anomalies and deflection residuals. As a test, Gilbert has calculated the influence of a right cylinder with vertical axis, of density ±0.025, with height and radius each equal to 122 km., whose upper surface is at a depth of 122 km., thus reaching up to the bottom of the zone of compensation as given by Solution H. Such a cylinder would give a maximum anomaly of ±0.023 dyne at the epicenter, a quantity of the same order of magnitude as the mean anomaly for the United States, 0.018 or 0.020 dyne.

In the application of this test to the earth it would appear, however, that two things should be noted. First, to account for the *mean* anomaly of 0.020 dyne the centrospheric masses would have to be several times as great as this cylinder, even for this depth of 122 km. to the top surface, since the maximum value of the anomaly occurs at the epicenter of the mass, and for a cylinder of

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[1] *Professional Paper 85C, U.S. Geol. Survey*, 1913, pp. 35, 36.

the form postulated falls off rapidly with increasing horizontal distance from the epicenter. Second, the test mass has been taken as contiguous to the zone of compensation above and with that limited depth given by the hypothesis of uniform compensation. This gives it greater effect according to the law of inverse squares, but postulates either an indefinitely thin zone of isostatic flow at the bottom of the zone of compensation or a capacity in a thicker zone of weakness to maintain within itself heterogeneities of density similar to those of the lithosphere above and the centrosphere beneath. It is thought by the present writer that a more probable presumption is that the centrospheric heterogeneities which may exist are distinctly deeper than 122 km. and separated from the lithospheric outstanding masses by a thick zone which yields to broad inequalities of pressure either upon it or within it and therefore is incapable of maintaining notable inequalities of mass in this shell.

The reasons for this preliminary hypothesis are briefly as follows: The depth of compensation seems to be variable and to extend in some regions to as much as 300 km., even under the assumption of compensation uniformly distributed and complete at the bottom. Under a more natural assumption that isostatic compensation gradually disappears, those heterogeneities of density which give isostatic compensation would gradually diminish with depth and this diminution would extend to a considerably greater depth than 122 km. If heterogeneities which act isostatically gradually disappear, the heterogeneities which can be borne in excess should also be expected to diminish.

As to the nature of the shell immediately below the zone of compensation, Schweydar has recently analyzed mathematically the results of the measurements of earth tides by means of the horizontal pendulum.

The calculations were designed to test the presence or absence of a viscous zone between an elastic crust and elastic interior. It is concluded that even a magma bed with a viscosity as high as that of sealing wax at house temperatures and a thickness of but 100 km. cannot be present. The assumption in best agreement with observations is that of the presence of a layer about 600 km. thick, slightly ductile (coefficient 10^{13} to 10^{14}), existing beneath an outer crust 120 km. thick.[1]

By postulating such a thick zone for isostatic flow, the viscous resistances are reduced and solid flow is made easier. It also is in conformity with the probability of a gradual change of physical state from the rigidity above into a less rigid and less stable tract and this in turn into a more rigid interior. Now if such a thick viscous zone is incapable of supporting over broad areas loads imposed by abnormalities of density above, it should also be incapable of supporting such horizontal inequalities of mass within it, provided these are sufficiently large. But in order to produce the same gravitative surface effects as more superficial masses, the heterogeneities of this zone of viscous flow would in fact have to be much larger. A cylinder of the dimensions postulated by Gilbert, if of negative density and adjacent to another at the same depth but of positive departure from the mean density, would tend to be underthrust by the latter, and the denser would in turn tend to be overflowed by the lighter.

For these reasons it is not to be expected that the same departures from those densities giving isostatic equilibrium which could exist in a rigid shell above would extend immediately below.

Influence of centrospheric heterogeneity.—To test the question of the influence of heterogeneity below the zone of compensation a sphere will be considered. First, one whose center is at a depth of 319 km., 0.05 of the radius of the earth. As a second test, the influence will be determined of a sphere whose center is at a depth of 637 km., 0.10 of the earth's radius. For considering the attraction of a mass at points on the surface other than at the epicenter it is more convenient to take the mass as having the form of a sphere rather than a cylinder, since the mass of the sphere acts in all directions as if concentrated at its center. This favors, furthermore, the accentuation of the effects upon the surface over what they would be if the outstanding mass had a stratiform extension.

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[1] Dr. Wilhelm Schweydar, "Untersuchungen über die Gezeiten der festen Erde und die hypothetische Magmaschicht," *Veröffentlichung des k.k. Preusz. geodät. Institutes,* Neue Folge No. 54, Leipzig, 1912 (B. G. Teubner).

The sphere having the same volume as a cylinder 122 km. in radius and 122 km. in depth will have a radius of 111 km. Let a radius of 100 km. and a density of ±0.025 be assumed as the dimensions and mass of a standard sphere in this deep zone. If the center of such a sphere is at a depth of 183 km., the same depth as the center of Gilbert's postulated cylinder, the anomaly at the epicenter will be 0.021 dyne, whereas the cylinder gave an anomaly of 0.023 dyne. They are therefore nearly equal in effect. If the center of the sphere is placed at a depth of 319 km., making the top at 219 km., the anomaly at the epicenter becomes 0.0068 dyne. Consequently the variation in density or volume of the sphere would have to become three times as great in order that its maximum anomaly should equal the mean observed anomaly. But as the average anomaly is not measured at the epicenter, and the maximum anomalies, occurring at the epicenters, are several times the observed mean anomalies, this figure would have to be still further multiplied. To account, therefore, for the magnitude of surface anomalies, the disturbing spheres, if with centers at a depth of 319 km. and if of 100 km. radius, would have to have abnormalities of densities ranging up to 0.25 in order of magnitude. If the centers of the spheres were at twice this depth the abnormalities, to produce the same effect, would have to be four times as great in mass. In a region of which there is no precise knowledge such variations of density might well occur. The problem must therefore be investigated by means of the gradients which would result in the gravity anomalies and deflection residuals and a comparison of these with the gradients actually observed and plotted.

Distribution of surface forces for centrospheric spheres.—For masses as deep as these the curvature of the earth becomes of importance, but the complications which it introduces into the analytic treatment have been avoided by means of a graphic solution.

In Fig. 8A, the anomaly is calculated for the epicenter. Then the gravitative force at any other point on the surface, such as that having a dip angle θ, can be determined by squaring the inverse ratio of distance. Multiplying the force at the epicenter by this

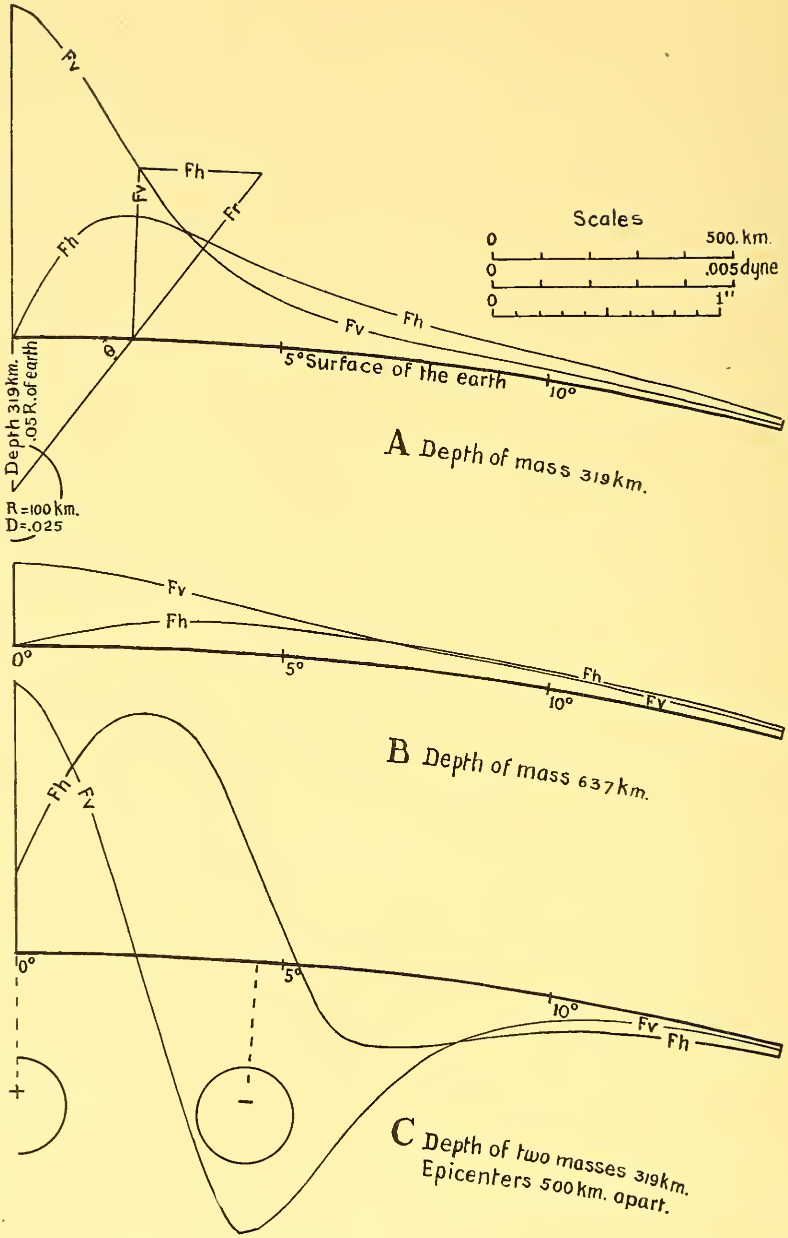

FIG. 8.—Curves showing values for the gravity anomalies *Fv*, and deflection residuals *Fh*, on the surface of the earth, for spherical masses situated at depths of 319 and 637 km., respectively. Ordinates measured at right angles to earth's surface.

factor gives the force at the second point acting in the direction of the radius of the attracting sphere. This value is laid off as *Fr* and then resolved into two components *Fv* and *Fh*, vertical and parallel respectively to the surface of the earth. The ratio of *Fv* to *Fh* is tan θ. With increasing distance from the epicenter θ becomes increasingly greater than it would be if the earth's surface were regarded as a plane. Therefore for distances of 5 to 10 degrees and more from the epicenter *Fv* begins to hold an appreciably higher ratio over *Fh* than it would if curvature were neglected. It is seen that $Fv=Fh$ for $\theta=45^\circ$. Nearer the epicenter *Fv* is in excess; at greater distances *Fh* is the greater. *Fv* is a maximum for $\theta=90^\circ$. *Fh* is a maximum for $\theta=55^\circ$ if curvature be neglected. For the earth's curvature and a depth of 319 km. to the center of mass, θ is a maximum for $53^\circ\pm$. The point giving this is at a distance from the epicenter of 0.75 the depth. The ratio of maximum *Fv* divided by maximum *Fh* is approximately 2.7. In Fig. 8C are shown the effects of two spheres of opposite sign but of equal mass. If these two spheres were superposed they would of course completely neutralize each other. Upon moving them horizontally apart to 1.5 times the depth, the maximum value of *Fh* becomes twice the value for a single sphere. This occurs halfway between them, and the value of *Fv* for this point is zero. The ratio of maximum *Fv* over maximum *Fh* becomes 1.1. Two equal masses of like sign would, on the contrary, give a maximum value of *Fv* and a zero value of *Fh* at a point halfway between them. These represent the extreme departures from the case of a single spherical disturbing mass. More distant masses show less overlapping of their fields of force and tend to have their individual effect upon a point between them neutralized by the larger number of masses acting from various directions. The values of *Fv* are much more under the control of the individual masses than are the values of *Fh*.

Returning to the single dominating mass of spherical form as shown in Fig. 8A, let the values of *Fv* and *Fh* be represented by ordinates as shown in the figure; then the surface representing the gravity anomalies, *Fv*, would be a dome of double curvature, like a craterless volcano; the surface representing the deflection force, *Fh*, would be in the form of a caldera or crater ring. According as the attracting mass departed in its nature from a sphere these shapes of the force surfaces would be modified, but the general character of volcanic cone and caldera would remain. Negative masses would have the forms reversed. If the disturbing masses are at distances apart which average several times their depth, then a relief map of the resultant forces would resemble a volcanic field with the volcanoes isolated from each other. If the centers are much closer, the relief map would come more to resemble those lunar craters which show all degrees of superposition upon older craters. The deeper the masses the broader the volcano-like curves of forces upon the surface, but the lower will be the relief, unless the disturbing spheres increase in mass with the square of the depth. Stratiform-like masses, such as oblate spheroids or cylindrical disks, will show less pronounced effects than the equivalent spheres and will simulate somewhat the effects of spheres at a greater depth. The attempt to apply these principles as criteria to the published data must be deferred until the influence of abnormal masses in the zone of compensation has been considered and also in somewhat more detail the influence of masses in other forms than spheres.

Influence of spheres within the zone of compensation.—The forces produced by spheres within this zone are more readily treated analytically, since it will be seen that the curvature of the earth may be neglected. Otherwise this topic is to a considerable degree an extension of the last. The unit mass which it is convenient to adopt for this discussion is that of a sphere whose radius is 50 km. and density 0.100, one-half the mass of the sphere previously considered. Its center is taken at a depth of 64 km., 0.01 of the earth's radius, and approximately at the middle of the zone of compensation as given by Solution H. This gives the greatest abnormality of mass in the middle of the zone of compensation and will approximate to the mean effect of an outstanding density distributed uniformly throughout that zone. At the epicenter the attraction is wholly effective in producing gravity anomaly and is measured by the formula

$$F=\frac{dc(\frac{4}{3}\pi R^3)}{D^2}$$

In this d=density, c=constant of gravitation, R=radius, D=depth. Solving this equation for the values chosen gives

$$F = .0853 \text{ dyne}$$

Take the earth's surface as a plane and any point on it as located by the dip angle θ, made by a line from the point to the center of the sphere of outstanding mass. Then the vertical component Fv and the horizontal component Fh are given by the following equations:

$$Fv \text{ (dynes)} = 0.0853 \sin^3 \theta$$

$$Fh \text{ (dynes)} = 0.0853 \sin^2 \theta \cos \theta$$

To convert Fh into seconds of arc divide by 0.00475 and

$$Fh \text{ (seconds)} = 17.94 \sin^2 \theta \cos \theta$$

The maximum value of Fh occurs for $\theta = 55°$ and is 0.0328 dyne or 6.9 seconds. The curves for Fv and Fh are shown in the unbroken lines of Figs. 9 and 10. They are seen to be quite close in character to the curves of Fig. 8. Changes in the mass or depth of the sphere will serve to change only the scales of forces and distances so that these curves may be adapted readily to apply to all spherical masses situated within the lithosphere.

Influence of sum of intersecting spheres approximately equivalent to spheroids.—The analysis of the gravitative forces which a sphere exerts upon points in an external plane serves as a starting-point for the consideration of the problem of the influence of those unit masses of excess or defect of density which exist in the crust. As a further step, any one mass may be considered as approximating in form either to some oblate or prolate spheroid or to some ellipsoid of three unequal axes. But the equations for the forces exerted by spheroids upon an external plane are complicated and laborious to solve. A sufficient approximation to the influence of a spheroid may be made, however, by employing several intersecting spheres which together give an approximation to the right quantity and distribution of mass. The influence of the composite mass is readily attained by summing up the curves given by the modifications for the several spheres.

In Fig. 9 the unbroken lines, as previously noted, are the curves of force due to the single unit sphere. The broken lines show the

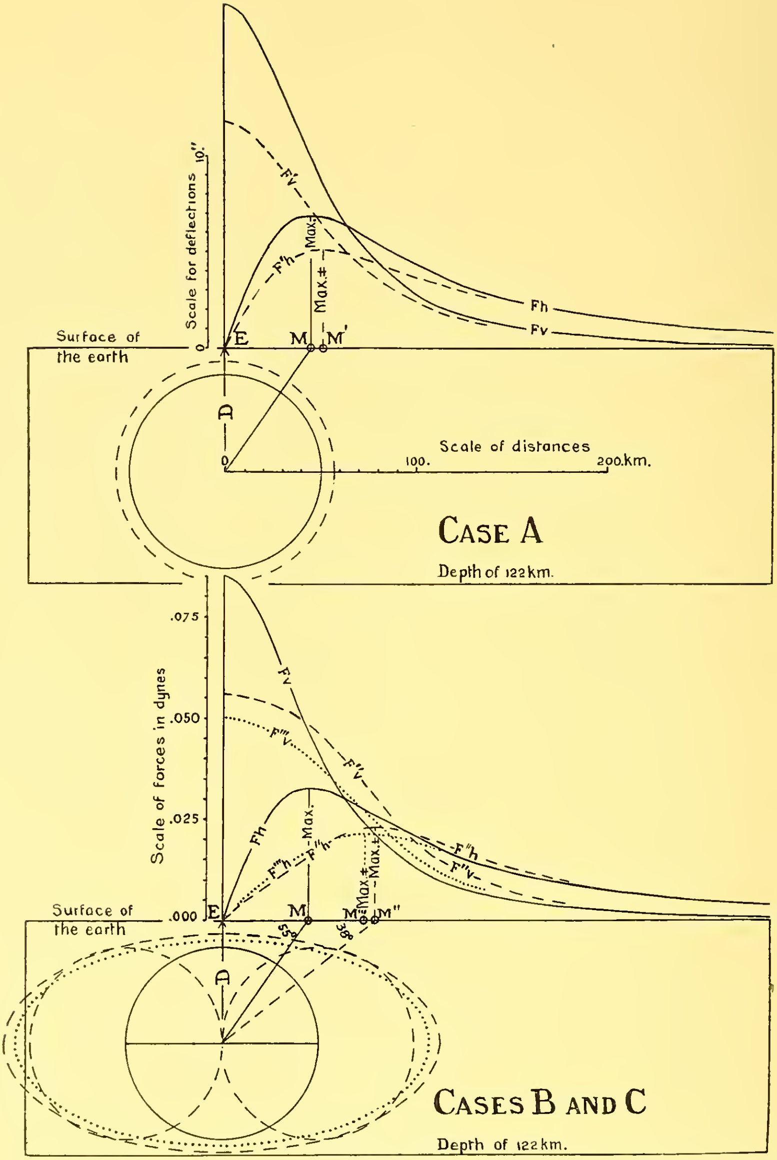

FIG. 9.—Various cases of horizontal and vertical components of the gravitative force due to a unit mass concentrated into a single sphere and expanded into several intersecting spheres. Cases A and B, three spheres in line. Case C, five spheres made by combining A and B and omitting one central sphere.

curves of force due to the same unit mass expanded into three spheres of the original dimensions and with centers 50 km. apart on a horizontal line. One-third of the mass is therefore in each sphere and the density of each is 0.033. In Case A the line joining the centers is at right angles to the vertical section plane. In Case B the line joining the centers lies in the section plane. The dotted lines show Case C. In this the unit mass is expanded into five spheres of the original size, each sphere possessing, therefore, one-fifth of a unit mass, and consequently a density of 0.020. In this case the five centers are arranged in a horizontal plane, the four outer spheres having their centers 50 km. from the center of the inner sphere.

The single sphere has a volume given by the formula $V=\frac{4}{3}\pi R^3$, in which $R=50$ km., and a density of 0.100. The three spheres have a volume therefore of $4\pi R^3$ and a density of 0.333. The three spheres make a solid of revolution whose semipolar axis is equal to $2R$, equatorial radius equal to R. Upon comparing this aggregate to a spheroid it is seen that the double density 0.667 of the intersecting portions compensates roughly for the two re-entrant zones on each side of the equator. To what regular spheroid does it approximate in its proportions? Let E be the equatorial radius of the spheroid and $2E$ the semipolar axis. The volume will be $\frac{8}{3}\pi E^3$, equal to the three spheres whose volume is $4\pi R^3$, or a single sphere of radius $1.44R$. Solving gives $E=1.14R$, $2E=2.28R$. The spheroid with these semiaxes is shown in broken lines in Fig. 9. This, then, is a spheroid which, if the density be taken as 0.033, is of exactly the same mass as the original unit sphere, or the three intersecting spheres, and which approximates in distribution of mass and in gravitative effect to these three spheres as shown in Fig. 9. The nature of the differences will be discussed later.

Case C shows five spheres of unit volume and of density 0.020 whose intersecting portions would consequently have densities of 0.040 and 0.060. In comparing the compound mass to an oblate spheroid these intersecting portions compensate roughly for the re-entrants between the spheres. The limiting dimensions of the whole in the directions of the three principal axes are R and $2R$. Let it be required to find the value of the equatorial radius $2P$ and semipolar axis P of the oblate spheroid of equal volume in which the axes have these proportions. Then

$$\frac{16}{3}\pi P^3 = \frac{20}{3}\pi R^3$$

$$P = 1.08R$$

It is seen that the five spheres of density 0.020 have the same mass as a sphere whose radius is $1.71R$ and density 0.020; the same mass also as the unit sphere of density 0.100 and radius R and the oblate spheroid of density 0.020 and semipolar axis $1.08R$, equatorial radius $2.16R$. The vertical section of this spheriod is shown in dotted outline in Fig. 9. The distribution of mass and gravitative effect of the five spheres will be nearly the same as for such a spheroid. The nature of the differences, as in cases A and B, will be discussed later.

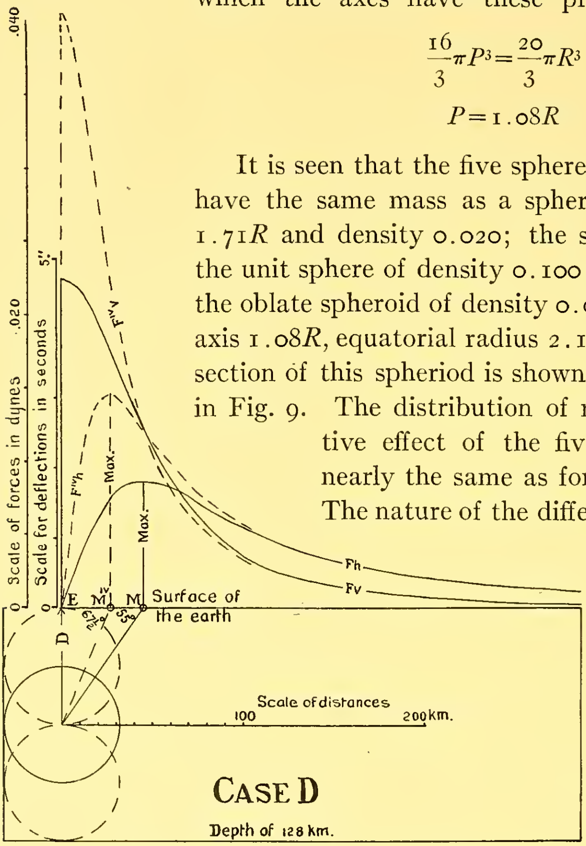

FIG. 10.—Horizontal and vertical components of the gravitative force due, first, to a sphere of 32 km. radius, density 0.100, depth to center 64 km., and second, to the same mass expanded into three such spheres with centers on a vertical line at depths of 32, 64, and 96 km.

The effect of the distribution of mass along a horizontal line and in a plane has been considered in cases A, B, C. There remains to be considered the effect of the distribution along a vertical line and in a vertical plane. Case D, Fig. 10, is given to show the effect of the distribution along a vertical line. The unbroken-line curves show the values of *Fv* and *Fh* for a sphere with density and depth corresponding to the unit sphere previously used, but with radius of 32 km. instead of 50 km. The mass is consequently but 26 per cent of that of the unit sphere. Let this be expanded into three intersecting spheres with centers 32 km. apart and arranged in a vertical line. The composite mass will then extend from the surface to a depth of 128 km. and correspond closely in effect to a prolate spheroid with vertical axis.

The resulting values of the components of the gravitative force for these four cases which are of importance for the development of criteria may be tabulated as follows:

TABLE XXV

	Unit Mass		Ratio of Maximum *Fv* Divided by Maximum *Fh*	Value of θ for Maximum *Fh*
	Maximum *Fv*	Maximum *Fh*		
Sphere	0.085	0.033	2.6	55°
Case A	0.056	0.024	2.3	51±
Case B	0.056	0.023	2.4	38±
Case C	0.050	0.022	2.4	41±
	0.26 Unit Mass			
	Maximum *Fv*	Maximum *Fh*		
Sphere	0.023	0.009	2.6	55
Case D	0.041	0.015	2.8	67.5

To complete the series the curves should be drawn for five intersecting spheres arranged in a vertical plane analogous to Case V, first parallel and then at right angles to the plane of the section, making cases E and F, but the general character of the resulting curves may be inferred from the cases already given. Therefore, in order to abbreviate the discussion, an additional figure for cases E and F has been omitted.

It is seen from inspection of Figs. 9 and 10 and Table XXV that even for a constant mass and center of gravity the values of *Fv* and *Fh* change rapidly with the changing form of the mass. Upon the linear extension of a sphere into a form such as cases A and B the maximum value of *Fv* falls to two-thirds of its original value. For Case C it is still less. The ratio of the maximum value of *Fv* divided by the maximum value of *Fh* is also seen to change, but more slowly, decreasing for the spreading-out of the mass in a horizontal direction, increasing for a linear vertical extension. For the spheroids whose axes are in the relation of 1 to 2 and to which the spheres are equivalent in volume, the changes would be still more marked. This is because the duplications of mass due to the intersecting spheres are near the center and in Case C a top view would show considerable deficiencies of mass in the equatorial zone between the spheres and the spheroid. These intersecting spheres are consequently more effective in producing gravity anomaly and somewhat more effective in producing deflection of the vertical in the zone of maximum deflection. For cylindrical disks of the same mass and proportions as the spheroids the changes away from the values for a sphere would be still greater, since a greater proportion of the mass would be removed from the center to the edges of the body.

Distinctive effects of individual spheres and spheroids.—In the subjection of deflection measurements to the hypothesis of isostasy Hayford found it necessary to consider the effects of topography to a distance of 4,125 km. and in the determination of gravity anomalies the topography of the whole earth and its compensation were considered. To what extent then do distant masses affect the local residuals and vitiate any attempt to analyze the effects of local masses? In answer, it is seen that the effects of distant masses are negligible. It is the great topographic contrast of ocean basins and continental platforms, to a lesser extent the large variations of relief within these areas, which require their effects to be considered to such a great distance. But it is found that this larger relief of the crust is nine-tenths compensated and the outstanding masses so far as known do not show any marked segregation as to sign within the continental areas as opposed to the oceanic areas. Furthermore, the unit areas departing markedly from isostatic equilibrium are much smaller than these major segments of the crust. Therefore where it is the effect of the outstanding masses which is under consideration they are seen to be individually small in comparison with the greater relief features of the globe, and further, they mutually cancel their effects. The local outstanding masses are furthermore of the same order of magnitude as the more distant ones and therefore the effects of the distant masses sink to negligible quantities in comparison, in accordance with the law of inverse squares. The general agreement in the magnitude of the departures from isostasy, as shown by deflection residuals and gravity anomalies, shows, furthermore, that deep nucleal heterogeneities can have no large and broad regional effects, since such would affect the gravity measurements within a broad central circle to a greater degree than they would the deflections of the vertical. Therefore each region is seen to offer its local problems and the dominating centers of outstanding masses may be readily determined save where several such masses are contiguous, especially if of opposite sign. Let attention be given then to those features in the influence of outstanding masses which are indicative of the form and depth of the attracting mass.

Let the depth to the center of mass be D. Then it is seen that for ellipsoids near the surface in which the major axes are twice the minor axes the influence of form has mostly disappeared at horizontal distances from the epicenter or from $2D$ to $3D$, and at greater distances the curves become practically coincident. For greater departures from the spherical form the distances before the curves approach those given by a spherical mass are still greater. At these distances where the curves approach those of spheres, the effects of the form of the mass could not be distinguished, but the curves are so flat that neither could the effects of depth be readily evaluated. For instance, the curves of force at $4D$ to $6D$ for a sphere of mass M at depth D would be approximately the same as for a sphere of mass $4M$ at a depth of $2D$. Furthermore, at these distances from the epicenter the forces are so small in proportion to the maxima for the same mass that other outstanding masses would greatly change their value and prevent a correct analysis. Therefore, to be determinative, observations must be made at a number of points between the epicenter E and a distance not more than double that which at the point M gives the maximum value to Fh. It is seen that if a mass symmetrical about a vertical axis departs widely from the spherical form, this will be detected by noting the ratio of maximum Fv to maximum Fh, the latter being measured along any line radiating from the epicenter. If the mass is unsymmetrical about a vertical axis, observations must be made along at least two lines at right angles to each other.

A minimum number of observations will define an isolated outstanding mass, but if several masses have their fields of force notably overlapping, a larger number of observations becomes necessary in order to differentiate their effects. An inspection of Figs. 9 and 10 shows that the shape of the curve of Fv between the epicenter and a distance where it falls to one-tenth the maximum value has more distinctive relation to the form of the immediately adjacent mass than has the curve for Fh. But the available geodetic data supply less information regarding the gradients of the gravity anomalies than for the deflection residuals. The latter are given along a certain belt of triangulation stations, whereas the gravity stations are located at long distances apart. Furthermore, but few of the gravity stations coincide with deflection stations. The present analysis will therefore rest upon the data giving the curve for Fh. This curve is flat at the top, so that the data will readily give the approximate value of the maximum but will not determine closely its distance from the epicenter. The value of θ will, however, be determined ordinarily on two sides of the epicenter by means of the deflection residuals and the mean will give a more reliable figure than either alone. But according to the form of the mass within those limits shown in Figs. 9 and 10 the value of θ may range from 38° to $67\frac{1}{2}°$. If the abnormal mass is assumed to have a spherical form, its center will lie at an angle of 55° below the maximum value of Fh and at a depth 1.4 the distance to the epicenter. The error in locating the points of epicenter and maximum Fh may cause the estimate of depth to be in error 20 per cent and yet this figure will show definitely whether the sphere lies within the zone of compensation or in the centrosphere. If the mass, however, is in reality a horizontally elongate mass, the change in the distance EM from the epicenter to the point of maximum Fh in two directions at right angles to the epicenter will show that fact. A check on the form of the mass may be obtained if the value of the deflection curve is known with fair accuracy to a distance from the epicenter of three times the distance of the maximum. Let the distance to the point of maximum value be M. The ratios of the value of Fh at M to the value at $3M$ are given below as measured from the curves.

RATIOS OF Fh AT M TO Fh AT $3M$

Sphere	2.4
Case A	2.1
Case B	4.3
Case C	3.4
Case D	2.0

It is seen that, from the difficulty in the precise location of M and hence the difficulty in locating a point as at $2M$ or $3M$, and furthermore the probability that other masses may influence to a degree not readily determinable the value at $3M$, this test cannot ordinarily be determinative. However, for spheroids with polar axes vertical, markedly prolate masses give a ratio distinctly smaller than for a sphere, the curve of deflections falling off more abruptly; markedly oblate masses, on the other hand, give a ratio distinctly larger than that for a sphere, the curve of deflection beyond the point of maximum being flatter.

If the outstanding mass approximates to an oblate spheroid with polar axis vertical, then the assumption of a spherical nature will locate the center of mass too deep and imply a greater mass than really exists. If, on the contrary, the form of the outstanding mass approaches the form of a vertical prolate spheroid, the interpretation of the deflections as caused by a sphere would locate the center of figure too high and give it too small a mass.

Suppose the curves for Fh shown in cases C and D have their maxima well determined in position and in magnitude, but that the values of the curves at distances two or three times beyond are not accurately known. Let these maxima be interpreted as produced by spheres. The depth and masses of the spheres which give these maximum deflections will be too great by the amounts shown in the following tabulation (Table XXVI, p. 462).

Where the data are sufficiently complete the form and depth of mass may both be determined, though a high precision is not to be expected. But in most cases with the present geodetic data the form of the mass will not be determinable and all that can be done is to interpret the deflections as produced by spherical masses. What then are the geological suggestions as to whether vertical prolate or oblate forms may be expected to characterize the larger outstanding masses? In the one case the error of interpretation will be to make the masses appear too small and shallow; in the other case, to make them appear too great and deep.

TABLE XXVI

ERRORS DUE TO INTERPRETATION AS SPHERES OF UNIT MASSES AT DEPTH *D*

FORM	DATA		ASSUMPTION	RESULTING INTERPRETATION	
	Fh Max.	*EM.*	θ	Depth to Center	Mass
Case C (True)	4″.5	74 km.	41°	1.0*D*	1.0*M*
Interpretation as a sphere	4.5	74 km.	55	1.6*D*	1.8*M*
Case D (True)	3.05	27 km.	67.5	1.0*D*	1.0*M*
Interpretation as a sphere	3.05	27 km.	55	0.6*D*	0.6*M*

Stocks, and especially volcanic pipes, approach in form to vertical cylinders, but these are merely connecting structures. On the other hand, mountain ranges and geosynclines, although linearly extended, are of breadth which is great in comparison with the depth of excess or defect of density. Laccoliths and regional extrusions are also broad in comparison with depth. The relations as regards the great intrusive masses are not so clear, but erosion exposes batholiths over progressively greater areas; and whole provinces which exhibit regional metamorphism give suggestions that they are underlain by widespread igneous bodies. The hydrostatics of the magmas and their differentiation into masses of unlike density would also give tendencies to layers and horizontal extensions of the larger masses of abnormal density. These would depart, then, from the form of spherical masses in the direction of oblate spheroids with their equators in a horizontal plane. Narrower belts of disturbance like that which passes through Washington, D.C., may, on the other hand, tend to have the form of vertical plates. Therefore in none but the smaller and connecting structures are there geological suggestions of vertical prolate form.

The summation of this discussion shows that if in the first assumption as to the form of abnormal masses they be taken as spheres, then the determination of the depth of the center of mass by means of the curve for *Fh* and the location of the point of maximum value is more likely to overestimate than underestimate the depths and masses. As the object of this investigation is especially to find the depth of masses and to test the hypothesis of centrospheric heterogeneity as a cause of deflection residuals and gravity anomalies, it is desirable to have the error of interpretation in the direction of indicating a depth too great rather than too small. Therefore the initial assumption that the outstanding masses are spheres is justified by the geologic probabilities and is found in Section B to be justified by the geodetic evidence. The next topic will therefore develop further the subject of the interpretation as spheres with the view to utilizing the geodetic data.

Depths of spheres whose epicenters are not on the line of traverse.— If the primary purpose of a geodetic investigation were the determination of the location of the epicenters of abnormal masses and then the measurement of their form, size, and depth, a series of gravity and deflection measurements could be made in a line passing above the mass and near the epicenter. The preceding discussion would then directly apply. In only a few localities, however, will a line of triangulation stations, located in connection with the measurement of the earth's surface, pass approximately over the center of a large outstanding mass. How then, from the locations and values of the deflection force along any linear belt of measurements, shall the location of the epicenter and depth to the center of an abnormal mass to one side of the line of traverse be determined?

In Fig. 11 is developed a method for the solution of this problem. In accordance with the preceding discussion and the reconnaissance nature of a first investigation, let it be assumed that isolated abnormal masses approach a spherical form; that is, that a mass may be regarded as concentrated at a point. Take the center of the mass as the center of co-ordinates and the axis *X–X* as lying parallel to the line of traverse. The epicenter is at *E*. Then the vertical distance from the center to the epicenter is *D*. The

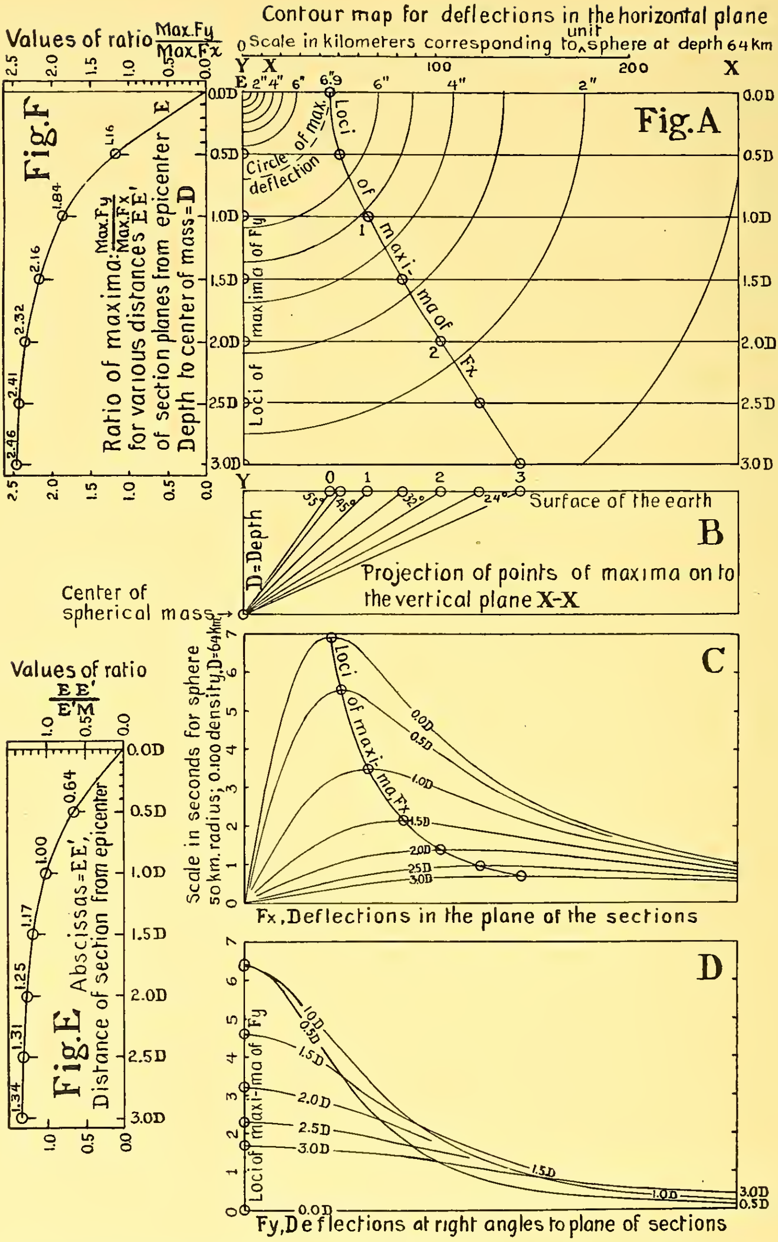

FIG. 11.—Values of the components of *Fh* on traverse lines which pass at various distances *EE'* from the epicenter *E* of a spherical mass at depth *D*; *EE'* being measured in terms of *D*.

distance EE' from epicenter to the traverse line is y. Then the co-ordinates of any point on the surface are x, y, and D. At any such point the component in the horizontal plane of the gravitative force due to the outstanding mass is Fh. But Fh is directed radially from all points to the epicenter. Fh, consequently, is subdivided into two components at right angles. Let that acting in the line of the section be called Fx, that at right angles be called Fy, parallel respectively to the X and Y axes.

The value of Fx for any point is given by the equation

$$Fx = dc\frac{4}{3}\pi R^3 \frac{x}{(x^2+y^2+D^2)^{\frac{3}{2}}}$$

and the value of Fy is given by the equation

$$Fy = dc\frac{4}{3}\pi R^3 \frac{y}{(x^2+y^2+D^2)^{\frac{3}{2}}}$$

Fig. 11 shows the results of the solution of these equations. In Fig. 11A is drawn a contour map of the deflection force produced by the unit sphere. The deflection force Fh at any point is measured by the contour map and is directed toward the epicenter. The lines of equal deflection are seen to be circles with center at E. They show in plan the values which were shown in section by the full lines for Fh in Figs. 9 and 10. The contours, as previously discussed, are seen to give the form of a volcano whose crater has a rounded rim and a conical interior reaching to the epicenter.

Now let a number of parallel sections be taken at horizontal distances from the epicenter equal to $0.0D$, $0.5D$, etc. The curves for Fx for each section are shown in Fig. 11C and for Fy in Fig. 11D. The points of maximum value for each section are indicated in A, B, C, and D and through these points are drawn the curves which are loci of maxima. For Fy there is a single maximum for each section and this is situated at $x=0$. For Fx there are in each section two equal maxima but of opposite sign, one for a plus, the other for an equal minus value of x. In Fig. 11C only one side of the curve is shown, that for plus values of x.

Fig. 11B shows the points giving maximum values of Fx projected onto the vertical plane passing through X–X. The dip angle θ measures the slope from the point of maximum value to the center of mass. Here is shown its value when projected onto the plane X–X. This projected angle is seen to grow smaller with each more eccentric position of the section plane.

For section 0.0D the real value of θ is 55°
For section 1.0D the projection of θ' is 45°
For section 2.0D the projection of θ'' is 32°
For section 3.0D the projection of θ''' is 24°

Therefore it is seen that if the traverse line were assumed to pass through the epicenter of all disturbing masses, the error introduced would be to show the center of mass deeper than it really is. The nature, however, of the geodetic data permits this assumption to be eliminated and the distance EE' to the section plane to be approximately determined. An error up to 0.5D will not involve much error in the resultant depth as determined by the projection of θ. At each station along a line of triangulation[1] both Fx and Fy are determined and their resultant points toward the center of gravitative control. Each station gives an independent determination of this resultant and the intersection of two resultants if accurately determined and due to the gravitative force of a single symmetrical mass would give an accurate location of the epicenter, measuring its distance and direction from the traverse line. The data in many cases permit as many as three or four resultants to be drawn, the size of the triangle of their mutual intersections showing to what degree the forces may be ascribed to a single center. The relative positions of the line of section and epicenter of mass are thus in many cases approximately established.

But although the relative position of epicenters and traverse line are thus ascertained, the depth of the masses remains to be solved. In Fig. 11 the distance of the traverse line from the epicenter is given in terms of D, but this is the unknown. Two independent methods lead up to the solution of D.

First, on any line of section occurs a zero point for Fx. Let this be called E'. On each side of the zero point for Fx occurs a

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[1] As shown in illustration No. 3, Hayford, *Supplementary Paper.*

maximum value for Fx. Let the point of this maximum be called M. These two values are given by the geodetic data. Then for any spherical mass the ratio of $\frac{EE'}{E'M}$ increases with increase in the ratio of $\frac{EE'}{D}$ but not as a rectilinear function. This relation of ratios is shown graphically in Fig. 11E, in which the abscissas are the values of $\frac{EE'}{D}$ and the ordinates are the corresponding ratios of $\frac{EE'}{E'M}$. This ratio may be determined from the geodetic data but *from the location of the maxima, not their amount.*

The second method for determining the depth depends upon the ratio of the maximum value of Fy for any traverse line to the maximum value of Fx for the same traverse line, thus being dependent upon the *relative values of the maxima and not their location.* This ratio also increases with increase in the ratio of $\frac{EE'}{D}$ but not as a rectilinear function. The maximum Fx for a section at any distance from E is shown in Fig. 11C. For example, if $E'E=0.5D$ the maximum Fx for the unit sphere is $5.52''$. The maximum Fy is shown in Fig. 11D, and for $E'E=0.5D$ is $6.42''$. The ratio of 5.52 to 6.42 is 1.16. These ratios are shown in Fig. 11F for all traverse lines up to a distance of $3.0D$ from the epicenter. The value of this ratio is given by the geodetic data for any traverse line and hence the distance to the epicenter is given in terms of D.

In conclusion on this topic it may be said that the curves shown in Figs. 11E and 11F are independent of the mass or volume of the sphere, depending only upon its depth, and are adapted to use with the geodetic data. It is seen from both curves that the significant ratios change in value rapidly with increasing distance of the traverse line from epicenter up to a distance $E'E=D$, but beyond this point the change in the value of the ratios becomes progressively small as compared to a change in the distance of the section plane. The method is therefore well adapted for determining the depth of the outstanding masses assumed as spheres, provided the section line is not farther from the epicenter than the latter is above the center of mass. The method may be used, however, with less precision for distances of the traverse line $E'E$ up to $2D$. Beyond this distance, however, influences of other masses or errors in the geodetic data would be likely to give wholly erroneous results, not distinguishing between a large excess of mass at a great depth or a smaller one at a much less depth.

[*To be continued*]

CERTAIN TYPES OF STREAM VALLEYS AND THEIR MEANING

JOHN LYON RICH
University of Illinois, Urbana, Ill.

A recent study of the "thalwegs" or immediate valleys of a number of streams, with particular reference to their ground-plan and their form as revealed in cross-section, has brought to my attention a wide difference in form of valleys produced by different streams and even by a single stream in different parts of its course. A subsequent failure to find in the literature any approximately complete explanation of these differences in form leads me to attempt the following analysis of the work of a river in carving its valley, in the hope that it will lead to a clearer understanding of the meaning of these marked morphological differences and will pave the way for the use of these distinctive valley forms as criteria for the interpretation of the physical history of a region where they occur.

An examination of a large number of valleys, as delineated on the contour maps published by the United States Geological Survey and by the French and German Surveys, led to their classification under three types which seem fundamental. For each type there is a further series of stages marking the development of the valley from its initial to its final form. For the three types I suggest the following names:

1. The Open Valley.
2. The Intrenched Meander Valley.
3. The In-grown Meander Valley.

The *Open Valley* is one which is either straight, as valleys go, or winding in broad, open curves. The valley sides are relatively straight and may be smoothly trimmed. The stream swings from side to side in broad, open curves which, except in the very earliest stages, do not necessarily correspond with the curves of the valley as a whole.

The *Intrenched Meander Valley*[1] is one whose stream, having inherited a meandering course from a previous erosion cycle, has sunk itself into the rock with little modification of its original course.

The *In-grown Meander Valley* is one whose stream, which may or may not have inherited a meandering course from a previous cycle, has developed such a course or expanded its inherited one as it cut down. Thus, as the stream sunk its channel lower and lower into the bed-rock, the meanders were continually *growing* or expanding. The term "in-grown" has been chosen to express this idea.

Three valleys illustrating the above types have been selected from the United States Topographic Atlas. A brief description of each should bring out the most essential characteristics of its type:

1. Typical of the first group, the *open valley*, is that of the Kanawha River as depicted on the Charleston (W.Va.) special sheet; U.S. Geol. Survey (see Fig. 1). The valley of Elk River, entering the Kanawha at Charleston, also illustrates this type as developed by a smaller stream.

The "thalweg," or immediate trough of the Kanawha River, is sunk some six or seven hundred feet below the general level of the neighboring upland, which it traverses in broad, open curves. The valley bottom is flat and about two-thirds of a mile wide, or about six times as wide as the stream. The sides are steep and trimmed to remarkable regularity—being, in fact, practically parallel. There is a slight tendency to greater steepness of the concave bank on the sharper bends. In this open, flat-bottomed valley the stream swings in broad, free curves, now hugging one bank, now the other. A space of something like six miles intervenes between successive points of impingement against the same bank. The curves of the stream in its swinging do not everywhere correspond with those of the valley trough.

The flat bottom, so conspicuous in the valley of the Kanawha, is not considered an essential feature of the open valley. A non-meandering valley with a V-shaped cross-section would, in the sense

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[1] The term "incised meander" has, apparently, been used synonymously with intrenched meander in previous writings. Would it not be well to use "incised meander" as a generic term covering both the above-described cases, and to restrict the meaning of intrenched meander as indicated above?

in which the writer proposes to apply the term, be as truly an "open valley" as the flat-bottomed one described above.

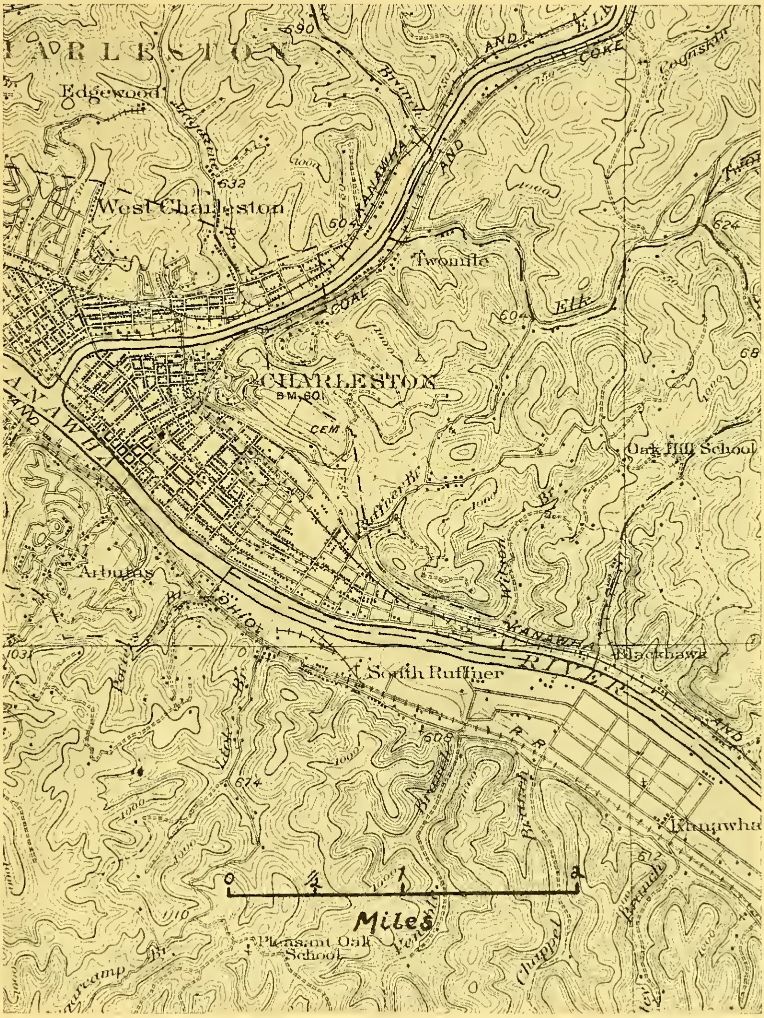

FIG. 1.—Part of the Charleston (W.Va.) special topographic sheet showing typical "open" valleys. Contour interval 20 feet.

2. The second type, or *intrenched meander valley*, is finely illustrated by that of the Kentucky River and its tributary the Dix,

as shown on the Harrodsburg (Ky.) topographic sheet. A part of this is reproduced as Fig. 2.

Fig. 2.—Part of Harrodsburg (Ky.) topographic sheet showing typical intrenched meander valleys. Contour interval 50 feet.

These rivers follow remarkably sinuous meandering courses. The meanders, however, are sunk sharply into the upland, and show no evidence of having been widened appreciably during the time of their incision. The windings of the valley correspond with those of the stream. Lack of flats along the stream indicates that incision is still in progress.

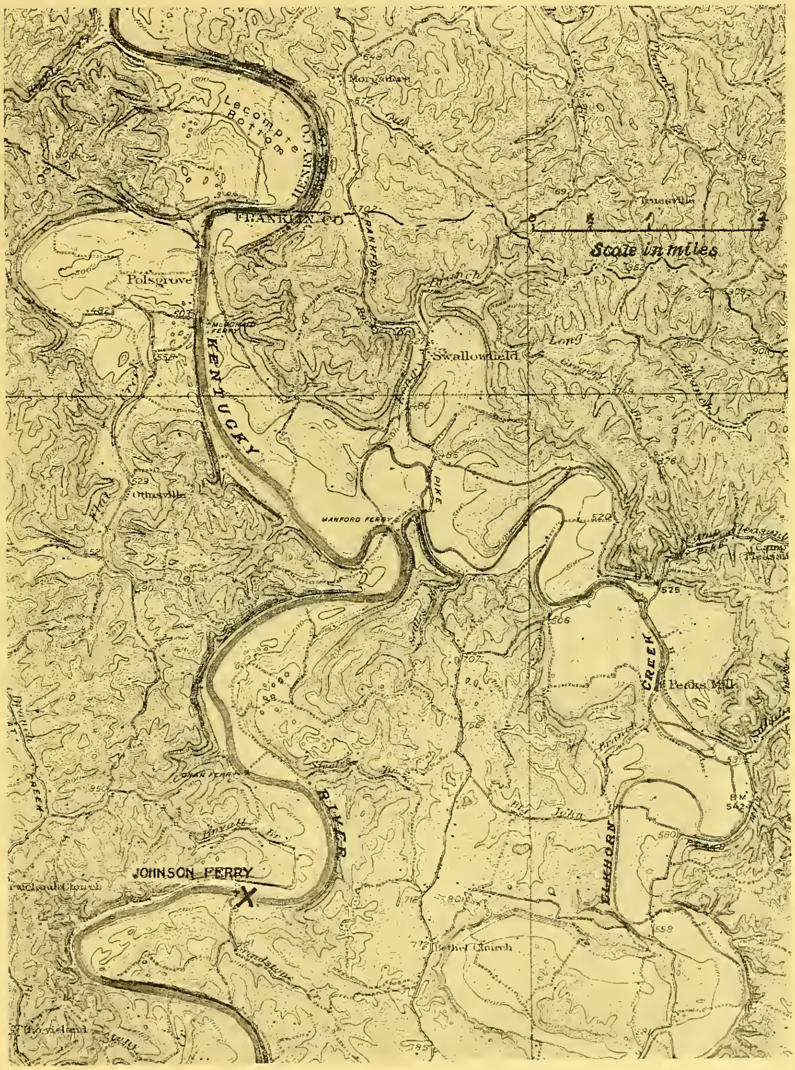

FIG. 3.—Part of Lockport (Ky.) topographic sheet showing typical in-grown meander valleys. Contour interval 20 feet.

It is especially characteristic of this type that the portion of the upland between the meander loops keeps its full height and flat surface almost to the inside end of the loops. The valley, in cross-section through the end of one of the loops in a direction transverse to the general direction of the stream, is practically symmetrical. There is a slight tendency to the development of "slip-off slopes" and undercut bluffs, but it is subordinate.

3. The *in-grown meander valley* is well shown on many of the United States topographic maps. One of the most beautiful which has come to my notice is portrayed on the southern part of the Lockport (Ky.) sheet, where the valleys of the Kentucky River and Elkhorn Creek display with great clearness the characteristics of the type (Fig. 3). The concave and the down-valley banks are marked by steep bluffs, while on the insides of the loops are well-marked slip-off slopes descending gently to the river. This characteristic feature is clearly shown on the inside of the loop just above Johnson Ferry (**X** on the map, Fig. 3).

Such a valley presents clear evidence that whatever may have been the course of the river in a previous cycle, the meanders have been much widened and enlarged during the present cycle.

All three of the valleys described above are the products of comparatively young and decidedly vigorous streams. All three, moreover, are in approximately the same stage of development in the erosion cycle—namely, youth to maturity. All are, or have recently been, degrading streams. We cannot, therefore, ascribe the differences in valley form to differences in the stage of development of the valleys. The differences are more fundamental than that. Nor are we dealing with old-age streams in which the meanders are features of the flood plain. Such old-age streams and valleys may be looked upon as *end products* of the development of any one of the types of valley described above.

Having recognized these distinctive valley types we are confronted with the problem: What conditions determine the type of valley which a stream will develop? A satisfactory solution of that problem calls for a brief review of some of the basic principles of river work.

ANALYSIS OF THE WORK OF A RIVER IN CARVING ITS VALLEY

The development of the immediate valley or thalweg of a river is accomplished mainly by a combination of three well-known processes—vertical down-cutting, lateral cutting, and down-valley migration of the curves or meanders, to which Davis has applied the excellent term "sweep." Of these, vertical cutting, when the conditions are favorable, is much the most rapid, because it has gravity as its direct and powerful ally.

In a normal degrading stream, all three processes are active in shaping the valley, but vertical cutting may be so much more rapid than the others as to mask their effects. When, however, a stream approaches grade and vertical cutting diminishes, one or the other of the two remaining processes advances to prime importance.

Any one of these processes, if dominant, is capable of impressing upon the valley, which it is helping to shape, certain characteristics of form which are distinctive. An acquaintance with these distinctive forms should enable one, on examining a valley, to determine which process took the leading part in its sculpture. If, carrying the analysis back a step farther, we can determine the controlling factors which lead to dominance of a given process, we shall be in a position to read much of the physical history of a region from the form of its valleys.

DISTINCTIVE FORMS ASSOCIATED WITH EACH OF THE THREE VALLEY-CUTTING PROCESSES

Dominant down-cutting implies that a stream is sinking its bed vertically at a greater rate than it is cutting laterally or down-valleyward on the bends. The necessary result of such a process is the development of a *gorge-valley* with narrow bottom, not, as a rule, much wider than the stream at flood, and with sides whose steepness, while usually great, depends largely on the nature of the rock and on the activity of weathering agents. The stream tends to sink itself vertically in whatever course, whether straight or meandering, it may hold at the beginning of down-cutting. Lateral cutting and sweep will modify this original pattern somewhat, but not to the extent of destroying the characteristic gorge form.

Dominant lateral cutting.—The well-known tendency of a stream to swing from side to side of its valley results in very unequal wear on its channel—active under-cutting on the outsides of the bends being accompanied by deposition on the insides.

An inspection of Fig. 5 will make clear that lateral cutting alone, a result of the force due to inertia, should result in *symmetrical* enlargement of the meanders without their displacement. The resulting topographic feature would be the symmetrical undercut bluff or meander scaur combined, if the stream were cutting down meanwhile, with symmetrical slip-off slopes. A thalweg, therefore, shaped by dominant lateral cutting should present a pronounced scalloped outline—the greater the dominance of lateral cutting the more symmetrical and the more nearly circular the scallops. That we do not find these symmetrical forms in normal valleys is sufficient evidence that with lateral cutting there is combined another process which destroys the symmetry. That process is *sweep*.

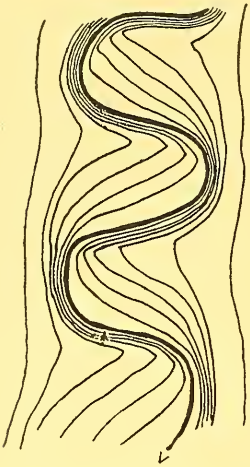

Fig. 4.—Contour sketch showing typical features of an in-grown meander valley, and the effect of sweep in producing assymmetry. Note the unsymmetrical necks of land on the insides of the loops; the sharp undercut bluffs on the outside and down-valley sides of the bends, and the gently inclined slip-off slopes opposite.

Dominant sweep.—The down-valley migration, or sweep, of meanders brings the stream successively over all parts of its valley flat. Any obstructions in the valley, opposing the orderly march of the meanders across and down the valley, is attacked. Thus the whole tendency of sweep is toward a *clearing-out* of the valley by the removal of spurs or other obstructions. It follows, therefore that, where sweep dominates, only the open type of valley (type 1 above) is "stable." In the case of a valley of the meandering type, the tendency of the meanders to sweep down-valley leads to more active erosion on the down-valley sides of the meander bends than on the up-valley sides. This results in asymmetry of both undercut bluffs and slip-off slopes with resulting forms like those illustrated in contours in Fig. 4.[1]

Combinations of processes.—As already stated, all three of the above processes are normally in operation at the same time along a stream valley. The analysis of the form produced when any one is dominant is a necessary preliminary to an understanding of the more complex forms resulting when two or more of these processes act in combination. Where down-cutting is vigorous the effects of the other two are, as a rule, masked to a greater or less degree. A gorge-like valley is the result. When, in the history of a stream, down-cutting ceases or becomes very slow, lateral cutting continues to widen the valley[2] while sweep tends to clear it out if it is not already relatively straight. Once a valley assumes the open form, whether as a result of initial conditions or as a consequence of the clearing effect of sweep, the constant down-valley procession of meanders tends, throughout the remainder of the cycle, to maintain this form by shifting continually the locus of attack of the stream, and to produce a valley with fairly uniform width and with relatively straight walls.

Between the stage marked by predominant down-cutting and that marked by predominant sweep there must be an intermediate stage when sweep, down-cutting, and lateral cutting bear such a relation to one another that whatever width of meander is gained by the stream in its lateral cutting is retained because of the contemporaneous down-cutting, while the spurs between the meanders, with their characteristic slip-off slopes, are not cleared out by sweep. In valleys developed under such conditions, the slip-off slopes would be conspicuous and the undercut bluffs well developed. The form would be that of the in-grown meander valley (type 3 above). Sweep, in this case, would be subordinate because, as will be explained more fully in a subsequent paragraph, in the interval between the sweep of successive meanders past a given point,

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[1] W. M. Davis, "Incised Meandering Valleys," *Bull. Geog. Soc. Philadelphia*, IV (1906), 182–92.

[2] A. Penck, *Morphologie der Erdoberfläche*, II. Buch, I. Abschnitt, S. 350: "Langsame Vertiefung ist das Erforderniss zum gleichseitigen Verschieben der Flussbetten. Sobald erstere rasch geschieht und auch letztere erfolgt, so wird eine ungeheuere Trummermasse dem Flusse zugeführt werden, die er nicht zu bewältigen vermag."

the stream would have lowered its bed so that each succeeding meander in its sweep would be opposed by rock.

CONTROLLING FACTORS DETERMINING THE DOMINANT PROCESS

Down-cutting will dominate whenever a stream finds its bed well above its local profile of equilibrium. After a stream reaches grade it may still lower its bed as the general level of the country is lowered, but the process must be gradual—too gradual for the continued dominance of down-cutting over lateral cutting or sweep.

Lateral cutting.—The tendency toward lateral cutting, which, it appears, is dependent upon a balance between two opposing forces[1]—(1) that due to inertia, tending to displace the thread of fastest current tangentially from one bank to the other, thereby favoring lateral cutting, and (2) the down-stream component of gravity, tending to make the current follow parallel to the walls of the channel—is controlled largely by the gradient of the stream, which determines the latter of these two forces. The lower the gradient the greater the proportion of the stream's energy used in lateral as distinguished from down-valleyward corrasion.

Volume also must play a part, for increased volume, by decreasing friction and thereby increasing velocity, would augment the value of the force due to inertia, and would therefore favor lateral cutting.

Sweep, it appears, particularly the ratio of the rate of sweep to that of down-cutting, plays a most fundamental part in determining the form of the valley. It deserves, therefore, a more detailed study.

Three factors suggest themselves as determining the rate of down-valley migration of meanders, or sweep. These are: the gradient of the stream, its volume, and the character of the material against which it impinges at the bends.

The importance of gradient and volume will be apparent from a study of Fig. 5, which illustrates the forces acting in a meandering stream. In a bend such as that shown in the diagram, inertia, if acting alone, would throw the current from *A* diagonally across the channel to *B* in the direction of the tangent to the curve

[1] See Fig. 5.

of the bank at *A*. If only inertia were acting, the meanders would be enlarged symmetrically; but there are two other factors to be taken into account. These are the down-stream component of gravity and the tendency of the thread of the current to follow the shortest course round the insides of the bends.[1] The former of these acting on a particle of water at any point, *X*, would tend to make the particle move in a direction *X-Y*, parallel to the median line of the stream at that point. The latter would tend to lead the current along the inner bank, *A-C*. The resultant course of the thread of fastest current would be along some line such as *A-D*, intermediate between *A-B* and *A-C*, giving greatest erosion at and below *D* rather than at *B*. The current, on account of a combination of the two latter forces, would hug the down-valley bank *A-C* more closely than would otherwise be the case, while it would draw away from the up-valley bank near *B*. Thus would the meander migrate down-valley.

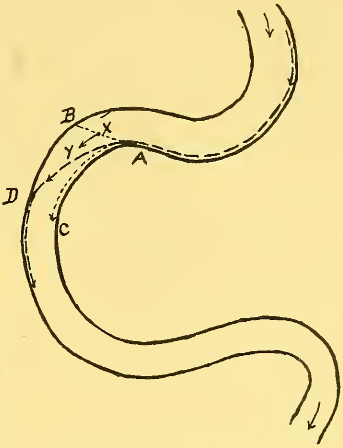

FIG. 5.—Diagram of a stream meander to show the explanation of the down-valley migration or sweep of meanders and the effects of gradient on the forces concerned. The dashed line represents the thread of fastest current; the dotted lines the courses this thread of fastest current would take if the various forces were acting alone. The line from *A* to *B* represents its course if inertia alone were active; *A* to *C* that if inertia were inoperative.

It is at once evident that an increase in gradient of the stream would increase this tendency to down-valley migration because it would increase the down-valley component of gravity at a greater rate than it would increase the force due to inertia, since the latter, dependent as it is on velocity, would be cut down by friction.

Increase in volume without change in gradient would tend toward greater symmetry and relatively slower down-valley migration, for greater velocity, due to lessened frictional resistance,

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[1] J. Thompson, *Proceedings of the Royal Society of London*, XXV (1876), 5–8.

would increase the inertia component without altering either of the other two.

In respect to the third of the factors determining the rate of sweep, it is of course evident that this rate will, other things being equal, depend directly on the resistance of the material against which the stream is working. If this material is the soft alluvium of a flood plain, the meanders will sweep past rapidly; if it is resistant rock they will go much more slowly. If the banks are low, less material must be moved than if they are high, consequently the meanders will tend to move more rapidly.

Where the meanders are intrenched, lateral, vertical, and down-valley erosion will be equally affected by the character of the rock, but where a stream is flowing on a flood-plain-floored valley with rock bluffs on the sides, lateral cutting into the valley walls is opposed by rock, while sweep is opposed only by soft flood plain alluvium of moderate thickness. The result must be a relatively rapid down-valley migration of the curves of the river.

Conditions under which sweep becomes dominant.—The ratio between the rate of sweep and that of down-cutting is one of the fundamental factors in determining the form of a valley. Three common conditions lead to dominance of sweep. These are: (1) a stream at grade in a relatively straight valley; (2) a stream which for any reason, for instance a decrease in gradient, has ceased down-cutting altogether; and (3) a stream carrying *coarse material.*

In the first of these cases a stream, having cut down to its profile of equilibrium in a relatively straight valley, still continues to deepen this valley, but only slowly, as the region as a whole becomes lower. The stream swings from side to side in ever-broadening, open curves. The tendency to down-valley migration of these curves is opposed only by the resistance of the thin coating of relatively weak flood-plain material on the valley flat, plus that of the thickness of rock which represents the amount of down-cutting in the interval between the passage of successive meanders. The tendency toward lateral cutting is opposed by the *rock* of the valley walls. The result is that when the stream is turned against the valley side, the flood-plain material on the lower side of the bends yields rapidly and the locus of attack on the rock of the valley side is shifted down stream before any great impression on the valley walls can be made. A repetition of this process with its constant down-stream migration of the locus of attack must produce relatively straight valley walls.

In a stream of constant volume, as the gradient gradually decreases with advancing age, the tendency to sweep (dependent on the gradient) decreases, while the tendency toward lateral expansion of the meander loops increases (since the latter becomes relatively more effective as the gradient becomes less). The stream, therefore, remains against its rock banks at any given place longer than before with the result that the straight valley wall characteristic of its earlier stages gradually gives way to a series of crescentic scaurs marking the successive points of impingement—the older ones, perhaps, considerably modified by general weathering since their formation.[1]

In the second case, when a stream has ceased down-cutting altogether or has so nearly ceased that the amount of such cutting is at a minimum, down-valley sweep, combined, of course, with lateral cutting, will take first place and will work out its characteristic results whatever may have been the original form of the valley. In valleys of either the intrenched or the in-grown meander type the stream will develop a flat flood plain, first on the up-valley sides of the bends and on the convex banks of the loops; gradually it will cut off any spoon-shaped necks of land between the loops, perhaps producing "rock islands" as a by-product, and finally it will remove all spurs or isolated rock masses.[2]

The third case, streams carrying coarse material, is best illustrated by the small headwater tributaries of many streams, particularly those in regions of resistant rocks. A plentiful load of coarse material means a high gradient, for only a swift stream is "competent" to the coarse débris.[3] The high gradient gives high values to the forces responsible for down-valley sweep while the

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[1] This feature is well shown on the Williamstown (N.C.) topographic sheet.

[2] See W. M. Davis, "River Terraces in New England," *Bull. Mus. Comp. Zoöl.*, XXXVIII (1902), 281–346.

[3] Gilbert, *Henry Mountains*, chapter on "Land Sculpture."

heavy load of coarse débris prevents rapid down-cutting. Sweep therefore dominates.

Conditions unfavorable for rapid sweep.—The following conditions are unfavorable for rapid sweep: low gradient, as explained above; relatively rapid down-cutting; and an original meandering course sunk into bed-rock (the latter not, of course, affecting the tendency to sweep, but only its absolute rapidity in a given case).

Under the second of these, relatively rapid down-cutting, the stream is continually cutting deeper into bed-rock and thus constantly increasing the amount of material to be moved by a meander in sweeping down-valley; not only so, but in the interval between the passage of successive meanders, the stream, at a given point has deepened its bed and there is still *rock*, not flood-plain material, to be removed by each succeeding meander as it sweeps down the valley.

In cases where down-cutting is long continued, but slow enough so that lateral cutting is conspicuous, there may result a peculiar type of valley with its bottom section exhibiting fine specimens of in-grown meanders, but with the upper part of its walls relatively straight. Such a condition would be the necessary result of a passage down-valley of a series of meanders during a slow uplift or its equivalent. What may be a valley of this sort is illustrated by the Chaquaqua Canyon as depicted on the Mesa de Maya (Colo.) sheet (Fig. 9).

The influence of load.—A full load of sediment, by occupying all the stream's available energy in its transportation, is an effective check to down-cutting. This does not, however, interfere with the process of sweep on the flood plain, for the sediment derived from cutting on a concave bank may be redeposited on the convex bank next below without in any way increasing the permanent load of the stream. It is a question also if it entirely prevents lateral cutting on the valley walls at the point of impingement of the meander bends. In a fully loaded stream, at any rate, sweep is dominant and the straight-walled valleys are to be expected.

DEDUCTIVE STUDY OF THE EFFECTS OF THE RATE OF UPLIFT OF A DRAINAGE BASIN ON THE FORM OF ITS VALLEYS

We have already seen what a fundamental rôle in the determination of valley form is played by the *rate of down-cutting.* A deductive study of the effects of differing rates of uplift, with their correlated differing rates of down-cutting, on streams of varying characters should enable us to evaluate properly this important factor.

Rapid uplift of a relatively straight stream.—Assume a region of perfectly homogeneous rocks, drained directly to the sea by a master stream and its tributaries. Let the region have advanced to the old-age stage in the erosion cycle, with all the streams thoroughly graded and with the master stream swinging in long, open curves on its way to the sea. Now, considering only the master stream, assume an uplift of the land uniform in amount throughout the drainage area, and so rapid that the stream in its down-cutting cannot keep pace with it. What will be the result?

In the first place, a wave of down-cutting, beginning at the mouth of the stream, will progress up the valley. Since, by assumption, the stream is a large one, down-cutting will be rapid and will greatly outstrip lateral cutting and sweep. The stream will quickly intrench itself in whatever course it happens to be following. Until grade is reached on the cessation of the uplift, deepening of the lower course of the stream will greatly exceed lateral cutting. As soon, however, as grade is attained, lateral swinging and sweep will increase in relative importance. The latter, as explained above, will dominate and the constant downstream procession of more or less open meander loops will widen the valley and at the same time tend to produce relatively straight valley walls. Further widening and further decrease in gradient will, as already explained, result in the scalloping of the bluffs. Finally, as the flood plain comes to exceed the width of the meander belt, the further widening will be more irregular, and the older of the meander scaurs will lose their original sharpness, though not their characteristic ground-plan.

The valley resulting from such a series of events would correspond to our "open valley" (type 1) and the series of stages through which it would pass in its development ought to be matched in actual valleys subjected to similar conditions.

Rapid uplift of a meandering stream.—Assume all initial conditions the same as before except that the master stream instead of flowing relatively straight, writhes in closely looped meanders along its lower course toward the sea. Assume, as before, a rapid uplift terminating after a moderate interval.

Down-cutting, as before, will greatly exceed lateral cutting and sweep and the stream will intrench itself with little modification into the bed-rock. On the sharper bends the accentuated lateral cutting may succeed in producing under-cut bluffs and slip-off slopes of moderate extent, but as a whole the stream will merely intrench itself in its inherited course. The cross-section of the valley, except at the sharpest bends, will approximate symmetry, and the upland marking the original plain will extend unbroken into the inside of the meander loops, in sharp contrast to the gently decending slip-off slopes which mark the insides of the bends when the meander has *developed* as uplift proceeds.

As uplift and down-cutting continue, some of the narrowest necks between meanders are likely to be cut off by under-cutting as has happened at the Frying Pan Bend, and as may eventually happen just above Handy's Bend in the Kentucky River (Fig. 2).

Just so long, however, as the gradient of the stream remains so great that down-cutting dominates, will the meanders continue to intrench themselves deeper and deeper, still holding nearly their original courses.

When the uplift ceases, the master stream will quickly cut down to grade. Thereafter deepening will be slow. Lateral cutting combined with sweep will at once advance to the dominant place, and the bottom of the valley will become widened. The outside and down-valley sides of the meander bends will feel the effects of the changed régime first and most strongly; flats will develop; narrow necks like that at Handy's Bend (Fig. 2) will be quickly cut through, making "rock islands" of the cut-off remnants. Down-valley sweep will continue active and will tend to remove, gradually, the spurs and rock islands from the valley and to transform it into a flat-bottomed, crescent-bordered trough. In

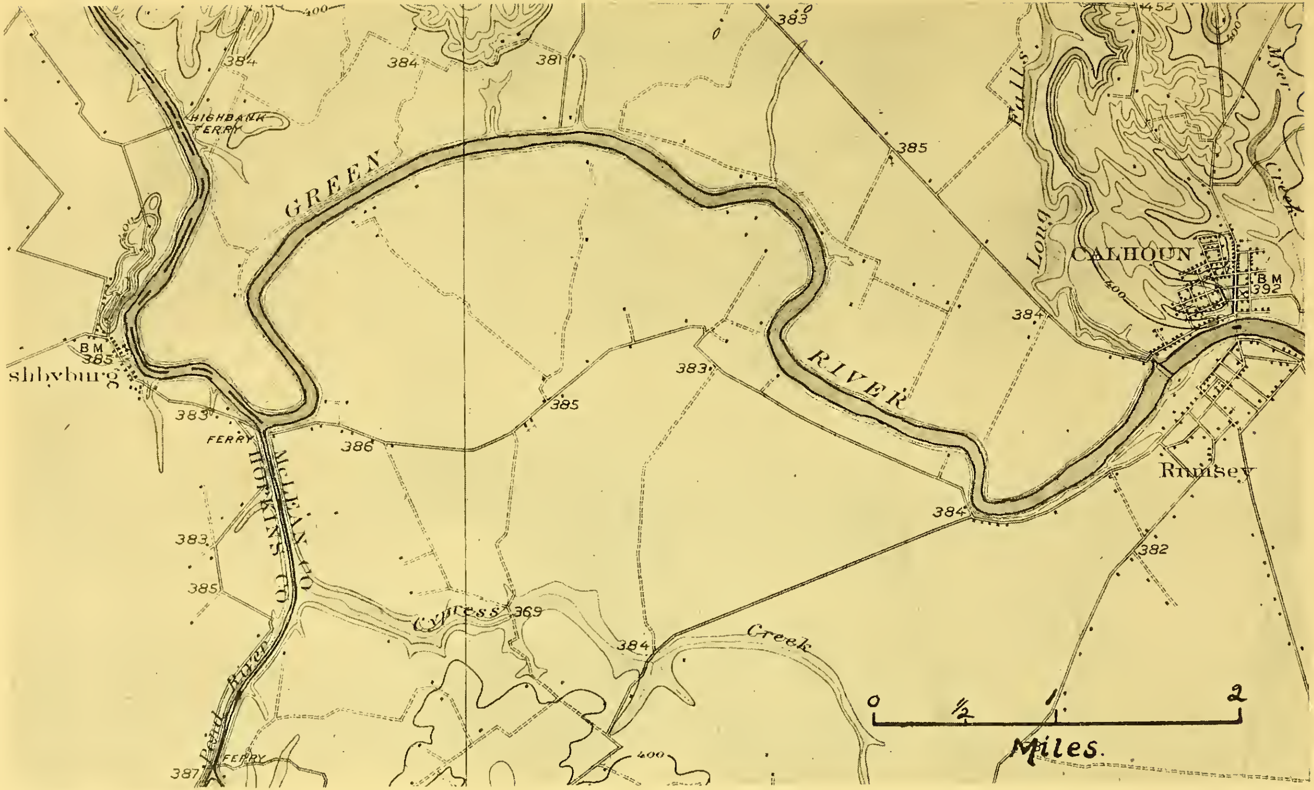

FIG. 6.—The earliest stages of the formation of an intrenched meander valley. Note the almost complete absence of evidence of lateral shifting of the meanders. From the Calhoun (Ky.) topographic sheet. Contour interval 20 feet.

the valleys of swift streams the latter process will be relatively rapid; in those of streams of low gradient, such as the master stream we have postulated, the river may flow for long ages before removing all signs of its former stages.

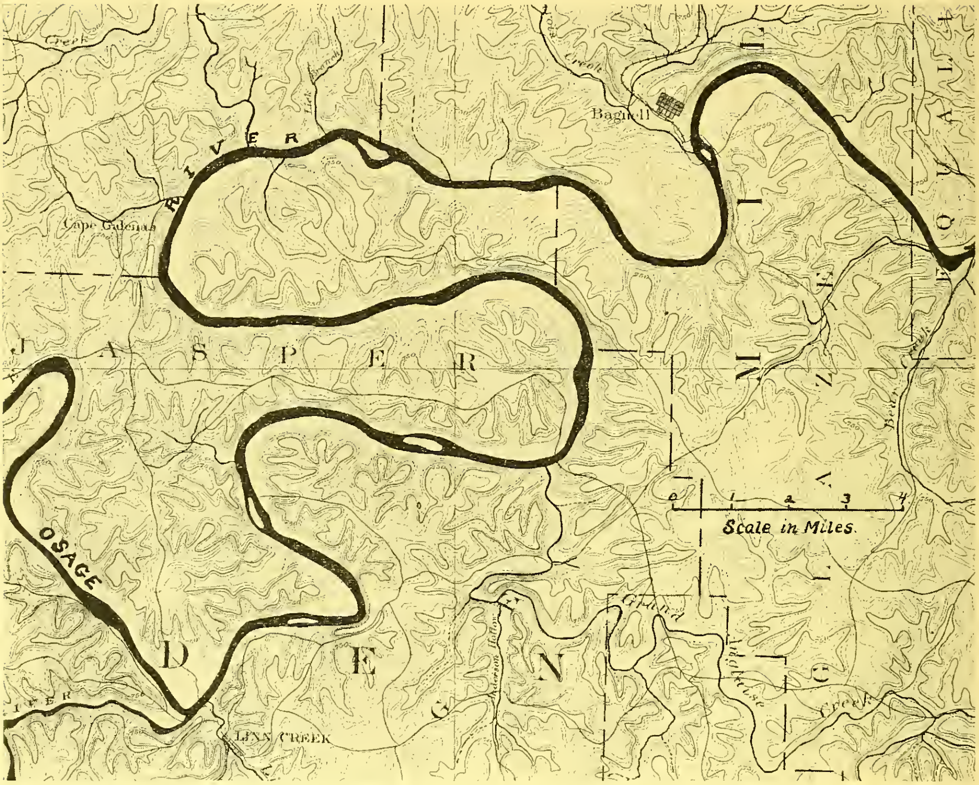

FIG. 7.—An intrenched meander valley in which the stream, having reached grade is beginning to widen the valley. Note that the upland between the loops keeps practically its full height almost to the end. From the Versailles (Mo.) topographic sheet. Contour interval 50 feet.

Examples of streams which show features corresponding to those just deduced are very numerous. For the earliest stage, when intrenchment is just beginning, the Green River in Kentucky (Fig. 6, Calhoun sheet, U.S. Geol. Surv.) is instructive. Here the predominance of down-cutting over lateral cutting in the determination of the valley form is very evident. Later stages, where the trenching is deeper but where the down-cutting is still active, are shown by such streams as the Kentucky and the Dix (Fig. 2). A still later stage, when grade has been reached and the formation of a flat valley-bottom has begun, is excellently shown on the Versailles (Mo.) sheet of the Geological Survey (Fig. 7). A still more advanced stage in a stream which seems to have had a history somewhat like that just outlined is shown by the Black River on the Oberlin (Ohio) sheet (Fig. 8). At the beginning, the stream, in its lower reaches, seems to have had a distinctly meandering course in which it cut down quickly to grade. It is at present changing the form of its meander bends and opening out its valley on account of a relatively rapid down-valley sweep. At the town of Elyria, where the stream has evidently encountered rock of considerable resistance, it is still cutting down and holds its original meandering course only slightly modified. The valley here is a typical intrenched meander in its youthful stage of development. Further down, in the softer rocks, a more advanced stage has been reached.

Slow uplift of a straight stream.—The results of another type of uplift may be deduced by assuming, as before, an ideal drainage system with the stream flowing in broad, open curves, to be subjected to an uplift so slow and continuous that the stream, while forced to continued down-cutting, is, nevertheless, able to maintain itself continuously near grade.

Under such conditions lateral cutting will assume an important rôle from the very first, and the stream, though its original course may have been comparatively straight, will come to swing in ever-broadening curves. Continued slow lowering of the stream bed will insure the retention of all width of meander gained by lateral cutting. Sweep will, for reasons already set forth—namely low gradient and continuous cutting in rock—take a subordinate place and will not hinder the further development of the meanders in the bed-rock. As the process continues the stream will sink its bed deeper and deeper into the rock; the meanders will become wider and wider, and the form of the resulting valley will be characteristic—the outsides of the meander bends marked by steep undercut bluffs and the insides by more or less gently inclined

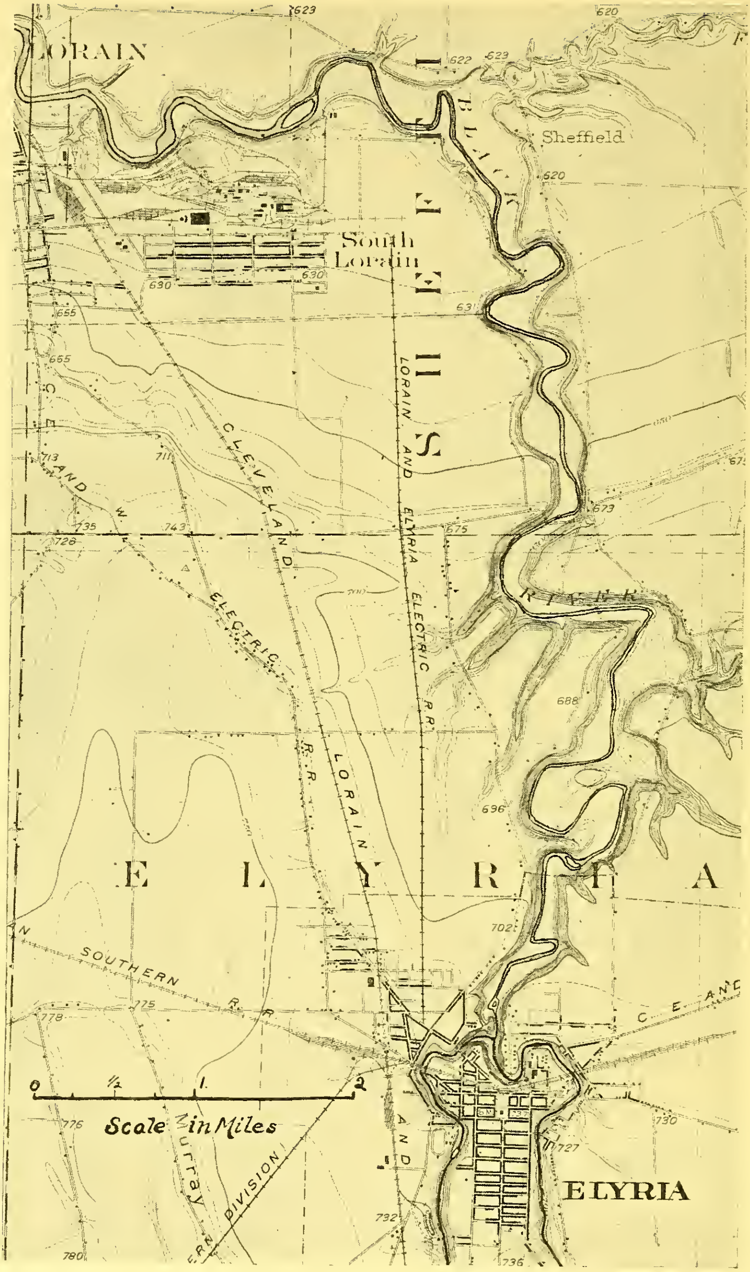

FIG. 8.—Part of the Oberlin (Ohio) topographic sheet, showing a meandering stream of the intrenched type in two different stages of development in different parts of its course. At Elyria it is in the earliest stage of intrenchment; farther down, grade has been reached and sweep is clearing out the valley.

slip-off slopes. Sweep will lead to asymmetry of the necks of land between the loops.[1] In time, if the uplift is continued, a single meander may sweep more than its width down stream, but before the next one arrives the stream bed will have been so lowered that the characteristic valley form will still be preserved. In time cut-offs may develop in solid rock. As uplift continues and the valley becomes deeper, the amount of material to be removed by lateral cutting, or as a result of lateral cutting, will become so great that further increase in the width of the meander belt may be checked. The valley form may then approximate that shown by the Chaquaqua Canyon, Mesa de Maya sheet, Colo. (Fig. 9).

FIG. 9.—A deep valley of the in-grown meander type at the bottom; upper walls noncommittal. From the Mesa de Maya sheet, Colorado.

The reader has, doubtless, ere this discovered the correspondence between these deduced consequences and the features of the ingrown meander type of valley as described above (see also Fig. 3).

After such a slow uplift, with its consequences as just described, has progressed until the stream is incised to a considerable depth below its

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[1] W. M. Davis, "Incised Meandering Valleys," *Bull. Geog. Soc. Philadelphia,* IV (1906), 182–92.

original level, what will be the consequences of a cessation of uplift?

The stream, which as we have assumed has kept an approximately graded condition throughout the uplift, will soon cease active down-cutting. Lateral cutting and sweep will, however, continue. A flat flood-plain will begin to develop. All meanders will be pushed down stream, some probably being cut off in the process, leaving rock islands standing isolated on the flats. The tell-tale slip-off slopes and undercut bluffs might, nevertheless, remain in protected spots, and, at least until the new régime became far advanced, would tell the story of the mode of development of the valley, and, incidentally, of the slow and continuous character of the down-cutting. Should the land remain long enough at one level all traces of the undercut bluffs and slip-off slopes would finally be obliterated, and the stream would swing in its meanders across a flat, open flood plain bordered by meander-scalloped valley walls, or bluffs.

Thus we see that the *end product* in this case is similar to that in the others and that the distinctive valley types are characteristic only of the youthful and mature stages of development, while all tend to become alike in the old age stage.

Slow uplift of a meandering stream.—If, with initial conditions as in the last case, we assume, instead of a straight stream, a meandering one with uplift slow enough to keep the master stream cutting down, but never to its full capacity, we should expect lateral cutting, as before, to play a relatively important part from the first. The original meanders would increase in width as they intrenched themselves into the rock. Cut-offs would probably occur. The form of the valley would be that of the *in-grown meander valley* with undercut bluffs on the outsides of the meander bends, or concave banks, and slip-off slopes on the insides or convex banks. There would probably, however, be some of the features of the intrenched meander such as the flat upland between the original meander bends. In the earlier stages of the development of such a valley it might be possible to determine definitely whether the original stream was meandering before the uplift by noting whether or not slip-off slopes occupy the greater part of the width of the necks of land between the loops.[1]

Conclusions from deductive study.—From the foregoing considerations it becomes apparent that a *slow* uplift, of such a master stream, unless it be so slow that sweep dominates, will tend toward the formation of the *in-grown* type of meander, whether or not the stream meandered widely in the cycle preceding the uplift, and that a *rapid* uplift will result in the intrenchment of the stream in whatever course it may happen to be holding at the time. If this original course happens to be relatively straight, a valley of the open type will develop; if it is meandering, the meanders will be intrenched but will present characteristics sufficient to distinguish them from the *in-grown* meanders resulting from *slow* uplift.

It appears also—and this fact should be emphasized—that, for each of the hypothetical cases studied, the form of the valley goes through a definite and characteristic evolution as it advances in the erosion cycle, but that the end product, namely the open valley, wider than the meander belt and with meander-scalloped sides, is the same in all cases.

New terms might, perhaps with advantage, be invented to designate the different stages in this evolution, or it might, perhaps, be wise to apply the familiar, though somewhat overworked terms, "youthful," "mature," and "old." If this were done "youth" might be made to cover the period up to the time when active down-cutting ceases; "maturity" the period from the latter until wide, meander-scalloped flood plains develop and until the spurs of incised meanders have been cleared away by sweep, and "old age" the remainder of the cycle.

Significance of uplift.—In the preceding discussion we have assumed rapid or slow uplift of the basin of a master stream flowing directly to the sea. We concluded that rapid uplift should result in one type of valley form; slow uplift in another. If this proposition holds true, we have a valuable criterion for determining from the form of the river valleys or thalwegs the rate of the uplift to

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[1] C. F. Marbut, *Physical Features of Missouri*, p. 104; "Meanders," *Missouri Geological Survey Bull.*, X, 94–109. This is a very excellent discussion of meanders; both the flood plain and incised types.

which a region may have been subjected. In applying this criterion in practice, however, we immediately encounter the difficulty that not all regions have master streams flowing directly to the sea. The region we are studying may be located in the interior of a continent and on a relatively small stream. In such cases, can we use the form of the valley in arriving at conclusions as to the rate of uplift of the region? Obviously not without qualification.

In order to put this criterion on a basis where it may be applied in practice it is only necessary to bear in mind that the equivalent of *uplift* as used in this connection, is *any condition which will cause a stream or any section of a stream to behave as it would if it were independent and subjected to uplift.* In other words the equivalent of uplift may be thought of as any condition which lowers the local base level of a stream. Thus a lowering of the lake level in the case of a stream flowing into a lake or the deepening of a master stream, in the case of a tributary, is equivalent to uplift in an independent stream.

VARYING TYPES OF VALLEY FORM IN DIFFERENT PARTS OF A SINGLE DRAINAGE SYSTEM

Turning our attention once more to our hypothetical drainage system uplifted after having reached the old-age stage of development, we may readily see that, even in this simple case, the same type of valley will not, as a rule, develop in all parts of a drainage system. Take, for example, the case of rapid uplift. We have seen that the master stream would trench rapidly and would form an open valley of type 1 or, where the original course was meandering, the intrenched meander valley of type 2. What would happen meanwhile in the distant headwater branches?

Let the profile of the stream before uplift be represented by the line *a* of Fig. 10. The final profile of equilibrium after uplift may be represented by the line *c*. The trenching resulting from uplift would proceed upstream in such a way that at some time between uplift and final grading the profile would take a form somewhat like the line *b*. Now at a point *W* in its lower course the master stream, at the time represented by the profile *b*, would have cut down a distance represented by the length of the line *V-W*. At another point, *Y*, farther up the valley the stream would, in the same time, have cut down a much shorter distance, represented by the line *X-Y*. The effect at the latter point, particularly on tributaries entering there, would be equivalent to that of a *slow* uplift. We should expect, therefore, to find valleys normal for such an uplift—namely, in-grown meander valleys—developing at that point.

Thus in the lower course of the master stream, valleys typical of a rapid uplift would be found, while in its upper or middle course, and in many of the tributaries, valleys typical of a slow uplift would be encountered.[1]

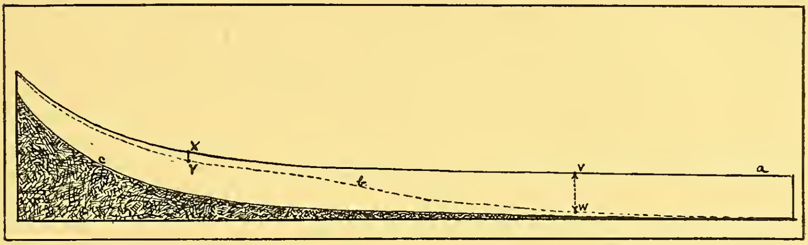

FIG. 10—Diagram to illustrate the explanation of the different types of valleys in different parts of a drainage system. Vertical scale greatly exaggerated.

Valleys of the *in-grown* type are especially likely to develop on the upstream side of resistant rock masses. These resistant masses retard the progress of a wave of trenching following an uplift and the stream above them, which must wait upon their down-cutting, is affected as by a *slow* uplift.

It follows, from considerations outlined above, that, for the *direct* determination of the rate of uplift by means of the form of the stream valleys, only the master streams, or those emptying directly into the sea may be successfully used. In other cases the character of the rocks and the distance from the sea may play a more important part than the rate of uplift. This fact does not, however, destroy the usefulness of the criterion, for it still indicates the rate of lowering of the *local* base-level of any particular stream in question.

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[1] A. Penck, in *Morphologie der Erdoberfläche*, Buch II, S. 348, calls attention to the tendency to the formation of meanders in the middle course of a stream; also to the fact that meanders are characteristic of an underloaded stream when it is so placed that it cannot work downward.

Effects of a tilting uplift.—In the above analysis we have considered the drainage system as being uplifted bodily—the mouth of the stream as much as its headwaters. We were led to the conclusion that under those conditions the type of valley in the upper course of a stream would normally be different from that in the lower course.

If the uplift were of a tilting nature with the axis at the mouth of the master stream and with the headwaters receiving the greatest uplift, the upper reaches of the stream would feel the effects of the uplift as soon as any other part of its course, and, if the uplift were rapid, it would seem that the type of valley associated with rapid uplift would prevail throughout.

If we may safely reason from the deductions outlined above, we may conclude that, where rock textures do not complicate matters too much, a drainage system with valleys of the type representing rapid uplift in its lower part, and with types representing slow uplift in its upper branches indicates, though, on account of other complicating factors, it may not prove, a rapid bodily uplift of both headwaters and lower course, while one displaying the forms associated with rapid uplift throughout its course indicates a rapid *tilting* uplift, with maximum elevation in the upper parts of the drainage system. Effects of tilting in the opposite direction need not be considered here: the reader may readily work them out for himself.

If this criterion of tilting is found to hold good it might be possible, in the case of a fairly extensive dendritic drainage system, to determine the axis of tilting by noting the types of valleys in streams coming in from different directions and therefore affected differently by the tilting.

SPECIFIC APPLICATION OF THE CRITERIA.

As an example of the application of the criteria outlined in preceding paragraphs we may take the case of the Mississippi River as illustrated on the Waukon (Iowa-Wis.) sheet. The river here is flowing in a flat-bottomed valley of the open type some two miles wide and with steep, smoothly trimmed and parallel valley walls some 400 feet in height. The river swings from side to side of the valley in broad, open curves which could scarcely be dignified by the name of meanders.

According to our deductions, an open valley of this type indicates a great predominance of *sweep* over the other processes at work in the formation of the valley. Such a valley might, as we have seen, be brought about by either one of two conditions: (*a*) a rapid deepening of the valley to grade, with subsequent widening, or (*b*) a deepening so slow—perhaps on account of a heavy sediment load—that sweep predominated from the beginning, continually shifting the locus of lateral cutting and thereby widening the valley uniformly as down-cutting proceeded.

In the valley of the Mississippi itself there appears to be nothing to indicate which of these is the correct interpretation, but when the tributary valleys are examined a clue presents itself. They are found (so far as can be judged from the contour maps, which are not so clear as could be desired) to enter through incised meander valleys, most of the larger of them clearly of the *intrenched* type. This form of valley indicates that the local base-level was lowered quickly (the equivalent of rapid uplift), and that the first of the two possible explanations mentioned is more probably the correct one. Such a conclusion should be tested further by the examination of other tributary valleys entering the Mississippi above and below this point. If all the larger tributaries are found to agree in their testimony, the hypothesis of rapid down-cutting by the main stream is strengthened.

The possibility that the valley of the Mississippi, at the point referred to, may, at one time, have carried a glacial stream much larger than the present river, and the fact that the valley is now silted up to a depth of from one to two hundred feet must be taken into consideration, but it does not seem to me to alter essentially the interpretation. Glacial waters may, however, be partly responsible for the remarkable sharpness of the features of the valley walls. In all essential particulars, aside from this sharpness, the valley is similar to that of the Kanawha at Charleston (Fig. 1).

SUMMARY

A study of the form of the immediate valley or thalweg of a large number of streams leads to the recognition of three distinct valley types. These are: (1) the open, comparatively straight and straight-walled valley through which the stream swings in more or less open curves, but in which the curves of the stream do not, except in the very earliest stages, correspond, necessarily, with the curves of the valley as a whole; (2) that form of the incised meander which we may call the intrenched meander, in which the meandering stream has sunk itself with little modification into bed-rock. (In this type undercut bluffs and slip-off slopes are not well developed, though they may be present to some extent. The greater part of the land within the loops retains the original height of the upland); (3) the form of the incised meander which we may designate the *in-grown* meander from the fact that as it sinks itself into the rock it is continually growing so that its final form and size may be very different from that at the beginning of incision. This type of incised meander does not necessitate a particularly meandering course of the stream in the cycle preceding the incision—the meandering course may *develop* as down-cutting proceeds. The valley is characterized by marked undercut bluffs and slip-off slopes. The evidences of growth or expansion during incision are very clearly expressed in the form of the valley.

A valley belonging to any one of these types exhibits a series of characteristic valley forms as it advances in the erosion cycle from the youthful to the mature and old-age stages of development, but there is a strong tendency for the final stages of all the types to become alike.

A large factor in determining the form of the valley, it seems, is the relative rate of down-valley sweep of the river curves. Only when this sweep is subordinate to down-cutting may any form of the incised meander valley be developed.

In a large drainage system rapidly and bodily uplifted, the master streams will normally develop valleys or thalwegs of type 1, the open valley, while in many of the headwater branches valleys of type 3, the in-grown meander, may be the common form.

Any barrier of hard rock in the course of a stream may, by retarding down-cutting, allow the development of valleys of type 3 above the barrier at the same time that below it type 1 is the prevailing form.

In conclusion, it appears that it is the ratio of the rate of vertical down-cutting to that of lateral cutting and sweep which determines the form of the thalwegs. When down-cutting predominates, valleys of types 1 or 2 are formed; when sweep is dominant the open valley, type 1, is the result. It is only when conditions lead to continuous down-cutting so slow that it is equaled or exceeded by lateral cutting, yet rapid enough to make sweep subordinate, that the in-grown meander type of valley may be produced.

These conclusions, if correct, establish valuable criteria for the interpretation of the physical history of a region from the form of its valleys.

STREAM PIRACY AND NATURAL BRIDGES IN THE LOESS OF SOUTHEAST MISSOURI

C. L. DAKE
Missouri School of Mines

In Perry and Cape Girardeau counties, in southeastern Missouri, are loess deposits locally deeply gullied into a sort of rather mild badland topography. During the field season of 1913, the writer observed in this gullied loess an unusual combination of erosion phenomena, which illustrates in miniature one process of formation of natural bridges.[1]

Along a roadside a gully had cut into the loess to a depth of over six feet, and, owing to a filling of bowlders and débris at its lower end, had established a temporary base level. The tributary gullies were also near this base level, and during a recent storm had actively widened their valleys.

At a distance of perhaps ten feet from the junction of the main gully and a tributary, undercutting of the banks in opposing directions had reduced the divide at that point to a wall of loess not more than fifteen inches thick, the upper grassy portion of which had crumbled away, lowering the divide a foot or two, at the narrowest place, and forming a sort of saddle.

The bed of the larger ditch was ten or twelve inches lower than that of its neighbor, and, in continually wearing against the loess wall, had completely undercut the divide, opening a gap about a foot high by eighteen inches long, leaving a natural bridge of loess, with an open arch between the two gullies.

The further undercutting of the larger channel had so encroached upon its smaller and higher neighbor as completely to divert the drainage of the latter through the arch, over a low rapids, leaving the lower course of the beheaded gully several inches higher than its former upper course, with a distinct step between them. The

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[1] H. F. Cleland, "North American Natural Bridges, with a Discussion of Their Origin," *Bull. Geol. Soc. America*, XXI (1910), 313–38.

increased gradient of the diverted portion had caused it to intrench itself slightly in the bed of its old course.

The case illustrates both stream piracy and the formation of natural bridges by lateral erosion. The writer observed two other smaller bridges formed in the same way. In the two latter cases, however, drainage was not diverted. Several cases were noted in which the undercutting was nearly complete.

FIG. 1

At the time the writer observed the foregoing features all the gullies were dry. One living in a region of loess or badland formations subject to rapid local erosion could doubtless study these features in actual process of formation during any heavy shower.

Fig. 1 is a rough sketch, showing the general features described in the foregoing material.

CRYSTALLOBLASTIC ORDER AND MINERAL DEVELOPMENT IN METAMORPHISM

FREDERIC H. LAHEE
Massachusetts Institute of Technology

CONTENTS

VARIATIONS IN DEGREE OF METAMORPHISM

Metamorphic rocks often exhibit, within the same region, considerable variation in the kind and especially in the amount of metamorphism to which they have been subjected. This is particularly true of intrusive contact zones where a more or less uniform decrease in metamorphism may be observed away from the intrusive body.[1] In regional metamorphism, too, gradations may be found in the degree of alteration of the crystalline schists; but the variations here are much less regular than in the former case.

Recognizing the fact that long duration of time is an essential requisite for the course of metamorphism,[2] we may assume that a metamorphic rock, whatever may have been the forces concerned in its origin, must have passed through a sequence of stages of

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[1] See A. Geikie, *Textbook of Geology*, 4th ed. (1903), p. 773; G. Barrow, "On an Intrusion of Muscovite-biotite Gneiss in the Southeastern Highlands of Scotland, and Its Accompanying Metamorphism," *Quar. Jour. Geol. Soc. Lond.*, XLIX (1893), 330.

[2] Grubenmann lays emphasis on the great importance of time. He writes, "Die Temperatur darf wohl als der bedeutendste Faktor der Metamorphose betrachtet werden."—*Die Kristallinen Schiefer*, 2d ed. (1910), p. 51.

development leading up to its present form; and we may assume further that, in any given region, provided we consider only rocks which were once of similar nature, this sequence of stages is represented, in a general way, by a graded series from the least altered to the most altered specimens. Within the writer's personal observation the best area illustrating such variations, in the case of regional metamorphism, is the Narragansett Basin in southern Rhode Island.

STAGES OF METAMORPHISM IN SCHISTS OF THE NARRAGANSETT BASIN

The Narragansett Basin is a structural basin consisting of a downfolded and downfaulted block of Carboniferous mudstones, sandstones, and conglomerates of fresh water deposition. These strata were folded and were altered by dynamic and static metamorphism during the Appalachian Revolution. They appear to have been near enough alike in their original state to justify a comparison of them now.

The characters of these rocks, as investigated by the writer,[1] led him to group them, according to their degree of metamorphism, in four stages, designated A, B, C, and D. "The metamorphism is incipient in Stage A; distinct, but rather low, in Stage B; considerable to high in Stage C; and at a maximum in Stage D."[2]

The criteria used in distinguishing between these stages were: amount of granulation or distortion of clastic components; deformation of pebbles, fossils, and such original structures as cross-bedding, ripple-mark, etc.; proportion of new or metamorphic minerals; proportion of recrystallized components; shape of mineral grains; mode of aggregation of constituents; degree of parallelism of minerals with unequal dimensions and of elongate mineral aggregates; perfection of rock cleavage (fracture); and gloss on fracture surfaces of the rock.

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[1] F. H. Lahee, "Relations of the Degree of Metamorphism to Geological Structure and to Acid Igneous Intrusion in the Narragansett Basin, R.I.," *Am. Jour. Sci.*, (4), XXXIII, 249, 354, 447.

[2] *Ibid.*, p. 355.

Briefly the characters of the four stages may be summarized as follows:

Stage A:

Megascopic.—Fracture of rock irregular, or there may be a tendency to break parallel to the bedding. The fracture surfaces are dull. Original structures, fossils, and pebbles are not deformed.

Microscopic.—Nearly all the constituents are of clastic origin, with clastic outlines. Sericite, the first metamorphic mineral to appear, may be present in small quantity. There is no parallel alignment of elongate or flat minerals, unless parallel to the bedding, and then this arrangement is primary.

Stage B:

Megascopic.—There is a fair secondary cleavage. The cleavage surfaces have a faint gloss due to the parallel orientation of microscopic blades of sericite. Original structures, fossils, and pebbles may be somewhat distorted.

Microscopic.—Clastic grains are bent, strained, or crushed. Quartz grains may be granulated about their edges, or in bands that cross them, or entirely, and in the latter case the aggregates of grains may have been pressed out into lenticular form. Sericite is more abundant than in Stage A and a large proportion of it has parallel orientation. It is the principal cleavage-maker. Pebbles in conglomerate are thinly coated with this mica.

Stage C:

Megascopic.—The secondary cleavage is very good and the fracture surfaces have a brighter gloss. Fossils are usually unrecognizable. Pebbles may be much flattened or elongated. Original structures have been obscured or destroyed. Metacrysts[1] begin to be of marked importance.

Microscopic.—Much of the crushed clastic quartz has been recrystallized, the new grains being somewhat elongate parallel to the schistosity. Feldspar of secondary origin is occasionally seen. Sericite is very abundant and may show signs of growing coarser, to muscovite.[2] Its plates and laths lie approximately parallel. In the conglomerates sericite may be observed developed within the pebbles, but most other new minerals occur in the paste only. The mica coatings of the pebbles are thicker.

Stage D:

Megascopic.—A thin, perfect cleavage characterizes the rock. There may be a false cleavage. Fracture surfaces have a high sheen. Original structures are much deformed. Pebbles are either sheet-like or spindle-shaped, much longer than they are thick. No sign of fossils can be discovered.

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[1] The name "metacrystals" was proposed by Lane for phenocrysts in metamorphic rocks, these crystals being of later origin than the groundmass (A. C. Lane, "Studies of the Grain of Igneous Intrusives," *Bull. Geol. Soc. Am.*, XIV [1903], 369).

[2] Grubenmann, *op. cit.*, p. 86.

Microscopic.—All the quartz is secondary. It often occurs in long thin blades and in thin plates parallel to the schistosity. Sericite has given place largely to muscovite. There is extreme parallelism of the constituents which are clear and free from indications of strain. The metamorphic (secondary) minerals are as abundant in the pebbles as in the paste. Recrystallization in pebbles and paste is at a maximum.

STUDY OF THE METACRYSTS

Many of the fine-grained schists of the last three stages contain metacrysts, or pseudophenocrysts, of ilmenite, biotite, garnet, and ottrelite, named in order of decreasing frequency. The same minerals are found in some of the coarser rocks, but in these they are no longer conspicuous for their relatively large size. The relations of these four minerals to one another and to the schistosity in the different stages of metamorphism will be described herein in greater detail than was possible in the earlier paper on this subject.[1]

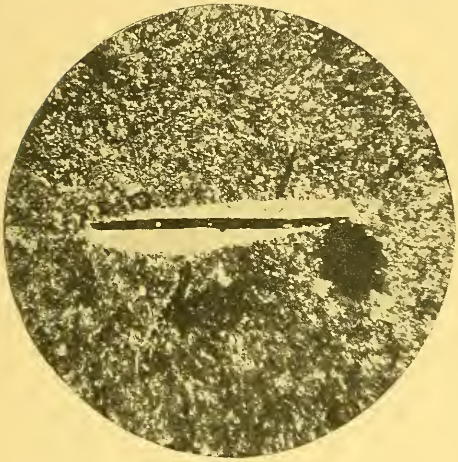

FIG. 1.—Crystal of ilmenite sandwiched between layers of secondary quartz. 15 diameters.

FIG. 2.—Metacrysts of biotite and ilmenite in a rock with poor flow cleavage. (See Fig. 3.) 15 diameters.

Ilmenite.—In rocks of Stage B metacrysts of ilmenite occur as tabular crystals, thin or thick as the case may be (see Figs. 1, 2,

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[1] F. H. Lahee, *op. cit.*

and 3).[1] When examined under the microscope they are quite opaque. Occasionally they contain small inclosures of quartz and sericite, the principal constituents of the groundmass, and their edges are more or less serrate where they have grown against these minerals. Since ilmenite is not a silicate, it evidently made room for itself by replacing the minerals of the groundmass and not by absorbing them. Its efficiency of replacement must be high for it contains relatively few inclusions.[2]

Where the groundmass has no parallel arrangement of its constituents and even where it does possess a flow cleavage that is not too well marked, the ilmenite plates lack definite orientation. Fig. 2 illustrates a portion of a rock slide in which the ilmenite crystals were scattered at random and the schistosity curved round them. It is evident here either (1) that they developed before the flow cleavage and that, in this case, the shearing of the rock was not sufficiently rapid or strong to bend or break them; or (2) that they grew *pari passu* with the schistosity, but that the shearing force was not enough to prevent their random orientation, that is, that their molecular forces were greater than the exterior stress. In either event they may have suffered some rotation.

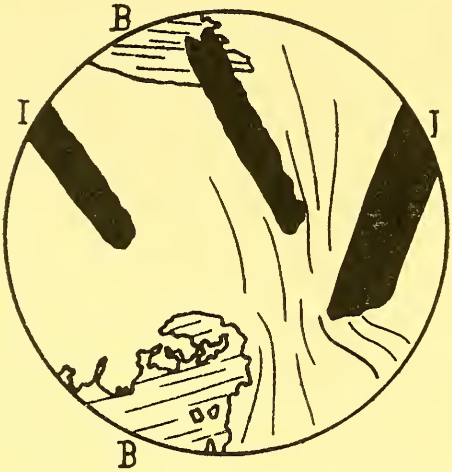

FIG. 3.—Outline sketch of Fig. 2. Ilmenite crystal partly inclosed in biotite. Note curving of the schistosity. I, ilmenite. B, biotite.

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[1] The photomicrographs used for this article were taken by Professor E. C. Jeffrey of Harvard University. The writer is happy to express his deep gratitude to Professor Jeffrey for this compliment and for valuable suggestions in preparing the illustrations.

[2] Cf. Van Hise, "In proportion as minerals are unable to absorb, they are able to enclose."—Treatise on Metamorphism, *U.S.G.S. Monog.*, XLVII (1904), 700.

In many of the finer mud schists the plates of ilmenite are coated with quartz[1] (see Fig. 1). The correct explanation for this phenomenon is not certain. The suggestion has been made that the quartz-ilmenite aggregate occupies a space which was formerly an actual cavity or a potential one. This does not seem to be true, for the space has not the shape of a rent, and neither the ilmenite nor the quartz granules of the rim reveal any evidence of having grown inward from the walls of a cavity. The form of the present quartz-ilmenite aggregate indicates that it is a replacement of an earlier larger crystal of ilmenite or of some other flat mineral.

In rocks with a good flow cleavage, produced both by thin plates of recrystallized quartz and by sericite (Stages C and D), the ilmenite crystals are parallel to the schistosity (see Figs. 4 to 8). It is not at all likely that the ilmenite here originated before shearing, for rotation could not account for the nearly exact parallelism of all the plates in the rock. Two possibilities remain, then: that the building of its crystals was either contemporaneous with, or subsequent to, the origin of the schistosity. If the first condition was the actual one, the ilmenite as well as the quartz and sericite contributed to the accommodation of the rock to the stress, the accommodation being brought about by crystallization and recrystallization, i.e., by chemical processes. If, on the other hand, the second condition was the real one, the ilmenite plates did not contribute toward the accommodation, but acquired their parallelism on account of a property of the groundmass constituents (principally quartz and sericite) to dissolve more readily parallel to the schistosity than in any other direction. Now, it is known that

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[1] Ilmenite has been described by Wolff and Pumpelly as bordered by chlorite; by Renard as bordered with sericite; and by Williams as coated by biotite. See the following:

A. Renard, "Recherches sur la composition et la structure des phyllades ardennais," *Bull. Mus. R. His. Nat. Belg.*, I, 212; II, 127; III, 84, 230 (1884).

G. H. Williams, "The Greenstone Schist Areas of the Menominee and Marquette Districts," *Michigan U.S.G.S., Bull. 61* (1890), 200.

J. E. Wolff, "On Some Occurrences of Ottrelite and Ilmenite Schists in New England," *Bull. Harv. Mus. Comp. Zoöl.*, XVI, 8 (1890), 162.

R. Pumpelly, J. E. Wolff, and T. N. Dale, "Geology of the Green Mountains in Massachusetts," *U.S.G.S. Monog.*, XXIII (1894), 183.

FIG. 4.—Ilmenite and biotite metacrysts in a rock having good flow cleavage. 15 diameters.

FIG. 5.—Outline sketch of Fig. 4. The ilmenite crystals lie parallel to the schistosity. One of them and the biotite contain inclusions of quartz. The irregularities of both ilmenite and biotite are due to growth of these minerals against the constituents of the groundmass.

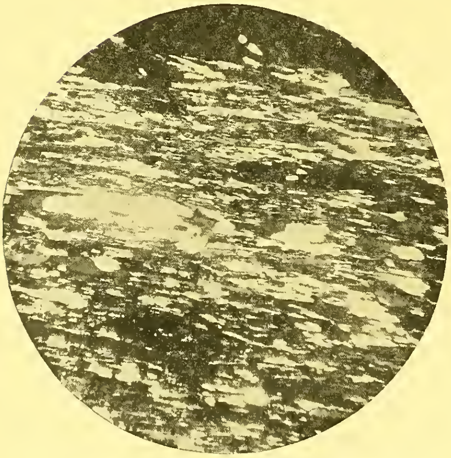

FIG. 6.—Photomicrograph of a rock belonging to "Stage D." The quartz is all secondary. The schistosity is well developed. An ilmenite lath with two quartz inclusions lies parallel to the schistosity. (See Fig. 7.) 10 diameters.

FIG. 7.—Outline sketch of Fig. 6. Shows position of the ilmenite crystal, and its relation to the flow cleavage.

the facility of solution and crystallization varies in different crystallographic directions and for different crystal forms of the same substance;[1] but, while this property might be suggested to explain the replacement of sericite, it could not account for the replacement of quartz, because quartz does not have crystallographic parallelism. Quartz plates would not tend to dissolve more readily at their edges than on their broad surfaces. If the rule applied to sericite only, and not to quartz, we should expect to find evidence of selective replacement by the ilmenite—substitution of sericite and not of quartz. However, no such evidence is apparent. The necessary conclusion is that the ilmenite plates, like the sericite and quartz, were formed during the operation of the shearing stress.[2]

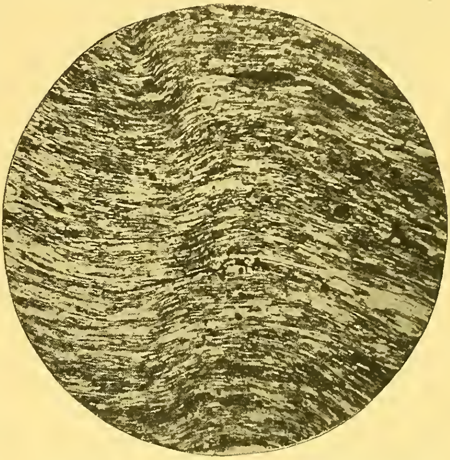

FIG. 8.—Similar to Fig. 6. An ilmenite lath may be seen near the top of the figure. The flow cleavage has been somewhat folded, thus showing a tendency toward the formation of a false cleavage. 20 diameters.

The relations of the growth of ilmenite to the development of the schistosity are brought out in Figs. 9 to 12. Figure 9 exhibits a garnet grain (about 1/16 inch in diameter) which partly inclosed an ilmenite crystal. The portion of the ilmenite outside the garnet is about half as thick as that inside and lies parallel to the schistosity which wraps round the garnet. The events illustrated by the photograph seem to have been as follows: (1) growth of a relatively thick plate of ilmenite; (2) inclosure of part of this plate by a crystal of garnet; (3) shearing of the rock, which produced, in the groundmass, a schistose structure that curves round the garnet, and

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[1] See writings by Goldschmidt and others.

[2] Van Hise states that no minerals show crystallographic orientation under mass-static conditions (*op. cit.*, p. 689). When minerals are crystallographically, as well as dimensionally, oriented, the suggestion derived from Goldschmidt's work should receive careful consideration.

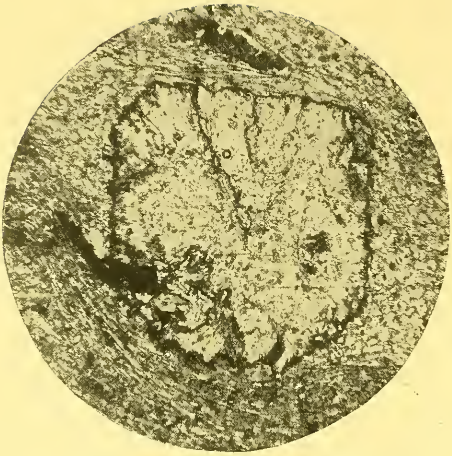

Fig. 9.—A large garnet grain partly inclosing an ilmenite lath which has been bent into parallelism with the schistosity. (See Fig. 10.) 15 diameters.

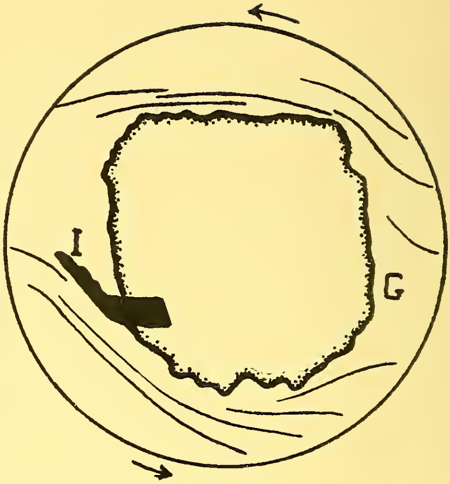

Fig. 10.—Outline sketch of Fig. 9. The schistosity, shown by curving lines, wraps round the garnet grain. The position and shape of these curves indicates that the garnet was rotated (arrows). G, garnet. I, ilmenite.

Fig. 11.—Ilmenite bent and inclosed in garnet. (See Fig. 12.) 25 diameters.

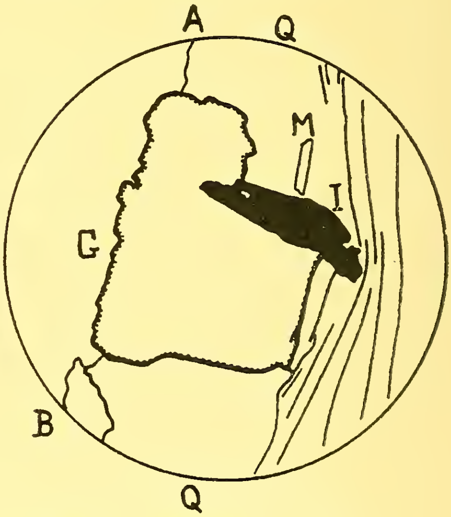

Fig. 12.—Outline sketch of Fig. 11. M, muscovite. Q, quartz. Between A and B is the edge of the rock section, under the cover glass.

resulted in the thinning of the protruded part of the ilmenite and in its being bent into parallelism with the adjacent schistosity. Since the ilmenite reveals no sign of fracture at its "elbow of deformation," its distortion was probably accomplished by gliding or by less regular molecular readjustment. In either case the facility of adjustment in the ilmenite must have been at least as great as the ease of accommodation of the groundmass; i.e., deformation of the ilmenite must have kept pace with development of the schistosity.

Fig. 11 shows a similar instance of an ilmenite crystal partly inclosed by garnet, but here the projecting portion of the ilmenite is less bent and less thinned than in the preceding example. A small re-entrant at the elbow of deformation, now filled with secondary quartz, suggests that the shearing produced a small fracture, subsequently perhaps more or less restored, or—and this is more probable—that it locally increased the tendency toward molecular readjustment at that place, making the ilmenite susceptible to replacement by quartz.[1]

Garnet.—Garnet metacrysts are found in rocks assigned to Stages C and D. In all cases there is clear evidence that this mineral originated before shearing entirely ceased.[2] Figs. 9 to 12 bring out this feature very well. The structure of the groundmass, particularly in Figs. 9 and 10, indicates rotation of the garnet crystal, and a similar relation appears in Figs. 13 and 14. Fig. 13 shows also the so-called "tails" of quartz, light areas that extend in opposite directions a short distance out from the metacryst, parallel to the schistosity. Such "tails" are without doubt in process of formation during the shearing of the rock. Consequently, their peculiar association with the garnet metacrysts is another fact pointing to the conclusion that the garnet was formed before the cessation of mechanical deformation.

Biotite.—As would naturally be expected, in rocks with no flow cleavage, biotite plates, if present, have no definite orientation.

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[1] "The experimental work of Barus and Hambeuchen together has completely demonstrated that a state of strain in substances is favorable to chemical action."—Van Hise, *Treatise on Metamorphism*, p. 691.

[2] Cf. this statement by Leith: Garnet, staurolite, andalusite, etc., "in many if not in most cases crystallized out later than the principal cleavage-making minerals. . . ."—C. K. Leith, "Rock Cleavage," *U.S.G.S., Bull. 239* (1905), 93–94.

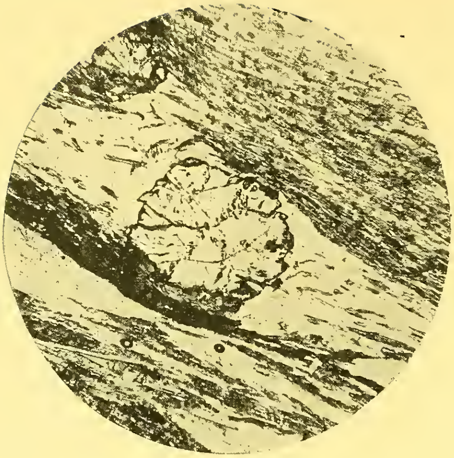

Fig. 13.—Garnet crystal in schist. (See Fig. 14.) 15 diameters.

Fig. 14.—Outline sketch of Fig. 13. C, chlorite. A and B, the poles of minimum compression. The quartz "tails" extend out from the garnet (G) from these poles in opposite directions. The curves of the schistosity indicate rotation of the garnet (arrows).

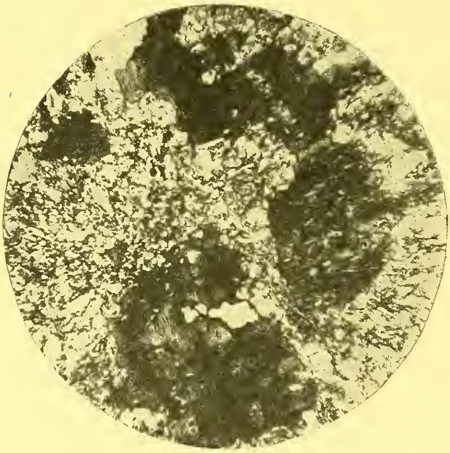

Fig. 15.—Metacrysts of biotite in a rock having no flow cleavage. The irregular outlines of the metacrysts are determined by the adjacent quartz grains. The biotite has neither dimensional nor crystallographic orientation. 12 diameters.

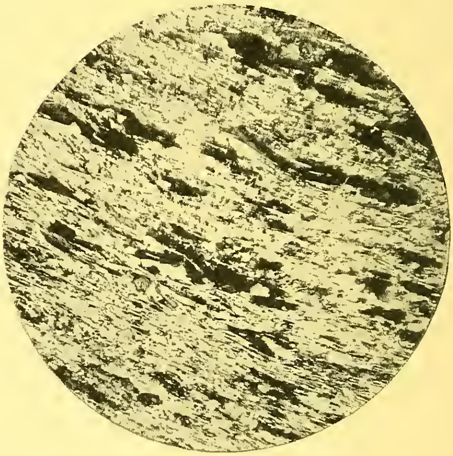

Fig. 16.—Photomicrograph of a rock with a well-developed flow cleavage. The biotite plates (dark) have dimensional parallelism and many of them have crystallographic parallelism. 10 diameters.

This is illustrated in Fig. 15. The biotite is here mottled lighter and darker. The light portions were once quartz grains of the groundmass, which were absorbed or replaced by the mica in its growth. The dark areas contain a large proportion of opaque carbonaceous matter which was also a part of the groundmass and which was included, but not absorbed nor replaced. For this reason the structure of the groundmass is nearly as distinct within these biotite crystals as it is outside. Their edges, like those of the ilmenite plates, are irregular because of their growth against constitutents of the groundmass, and the white inclusions and reentrants are unabsorbed quartz grains.

In schists belonging to Stage C, in which ilmenite has already acquired parallel orientation and much of the quartz of the groundmass bears evidence of recrystallization, biotite still lacks dimensional and crystallographic parallelism. The biotite crystal photographed in Fig. 4 was cut where a quartz band passes quite through it. Its cleavage is nearly perpendicular to the schistosity and its length is only very little greater than its width.

Under conditions of extreme metamorphism (Stage D), biotite acquires dimensional parallelism (Fig. 16). At this stage the quartz of the rock is of secondary origin and the sericite, the earliest new mineral to appear at the inception of metamorphism, has given place to muscovite. .Crystals of these three minerals are roughly of the same size. The quartz and white mica have become relatively larger, and the biotite has become relatively smaller.

Several slides show that the biotite was subsequent to the ilmenite in respect to its origin. In Figs. 2 and 17 biotite crystals have partly inclosed adjacent plates of ilmenite. The projecting ends of the ilmenite in Fig. 17 (see also Fig. 18) have quartz borders like those illustrated in Fig. 1. This quartz border, once entirely surrounding the ilmenite, was absorbed or replaced by the biotite in just the same way as the quartz grains of the groundmass, as shown in Fig. 15. This is the explanation of the light halo that encircles the included portion of the ilmenite.[1]

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[1] Professor Wolff describes a rock in which ilmenite plates are coated with chlorite except where they are included in ottrelite (J. E. Wolff, "On Some Occurrences of Ottrelite and Ilmenite Schist in New England, *Bull., Harv. Mus. Comp. Zoöl.*, XVI, 8 [1890], p. 162).

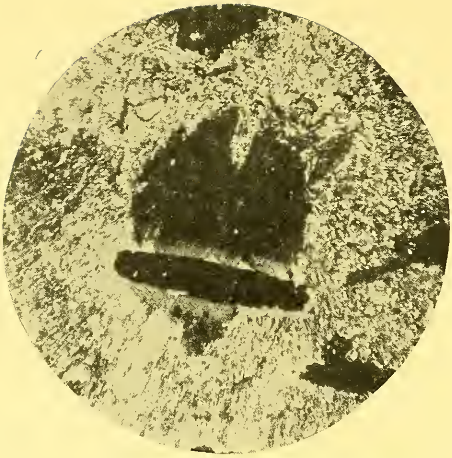

FIG. 17.—Ilmenite crystal nearly inclosed in biotite. (See Fig. 18.) 12 diameters.

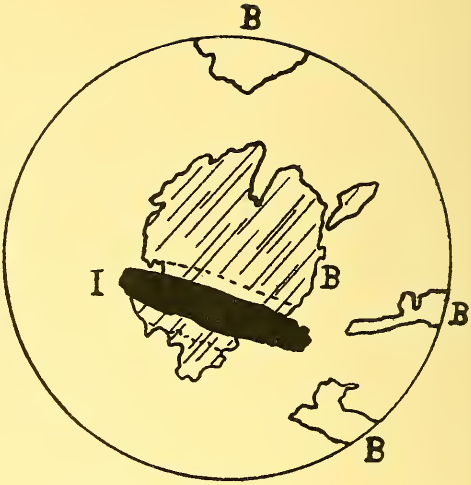

FIG. 18.—Outline sketch of Fig. 17. B, biotite. I, ilmenite. The dotted lines represent the edge of what used to be a quartz coating on the ilmenite. Cf. Fig. 1.

FIG. 19.—Biotite and garnet metacrysts. (See Fig. 20.) 25 diameters.

FIG. 20.—Outline sketch of Fig. 19. B, biotite. G, garnet. The dotted lines represent the edges of the garnet crystals before replacement by biotite.

Fig. 19 shows a large biotite plate which has replaced a portion of a garnet crystal. The hexagonal outline of the cross-section of the latter is plainly visible in the mica. Between the biotite and the outlying strip of garnet (Fig. 20) is a clear space occupied chiefly by secondary quartz and muscovite. Two or three minute grains of garnet in this space suggest that this mineral once existed as a complete crystal which was replaced partly by biotite and partly by the quartz-muscovite aggregate.[1] Obviously, biotite developed after garnet.

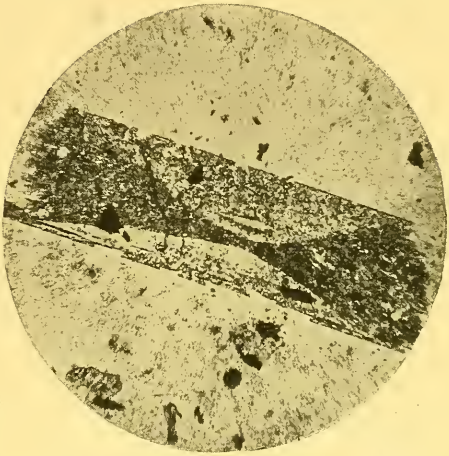

FIG. 21.—Metacryst of ottrelite showing hour-glass twin. 25 diameters.

Ottrelite.—Although ottrelite (Fig. 21) was seen only in rocks with a good flow cleavage, its crystals were never observed to have dimensional parallelism. Leith states, however, that it may occasionally show a definite orientation.[2] Plates of this mineral sometimes wholly or partly include metacrysts of ilmenite and biotite. Ottrelite, then, originates later than ilmenite, garnet, and biotite, and as a rule subsequent to the development of the schistosity.

SUMMARY AND CONCLUSIONS

The facts presented in the foregoing description of microscopic structures in the Narragansett Basin schists may be summarized as follows:

1. The commonest minerals in these rocks are sericite, muscovite, quartz, ilmenite, garnet, biotite, and ottrelite. Quartz and sericite or muscovite form a large percentage of the composition of

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[1] Cf. B. K. Emerson on "skeleton crystals" of garnet: "Note on Corundum and a Graphite Essonite from Barkhamsted, Connecticut," *Am. Jour. Sci.* (4), XIV (1902), p. 234.

[2] "Rock Cleavage," *U.S.G.S., Bull. 239* (1905), p. 44.

each rock. They may occur as a relatively fine groundmass in which ilmenite, biotite, garnet, and ottrelite may be present as metacrysts.

2. Minerals that crystallize or recrystallize with parallel orientation promote the accommodation of the rock to the stress.[1]

3. A mineral that is shown to acquire parallel orientation at an *early* stage of dynamic metamorphism will grow with parallel orientation in later stages, provided shearing continues.

4. A mineral that acquires parallel arrangement at a *late* stage of dynamic metamorphism may develop at an earlier stage, but in this case it originates after shearing has ceased and then has no definite orientation.

5. In the Narragansett Basin schists sericite is the first metamorphic mineral to appear and is the first to acquire definite orientation of its crystals under conditions of stress. In Stage D it may give place to muscovite.

6. Quartz is chiefly clastic in the early stages of metamorphism and secondary (recrystallized) in the later stages. In the accommodation of the rock to stress it assists first by granulation and later by recrystallization. It acquires dimensional, but not crystallographic, parallelism in Stages C and D.

7. The order in which the minerals acquire both dimensional and crystallographic parallelism, beginning with the earliest, is as follows: sericite, ilmenite, biotite, ottrelite. Secondary quartz, having only dimensional parallelism, would come between ilmenite and biotite.[2]

8. The order of origin of the metacrysts, as shown by their relations to one another, is: ilmenite (first), garnet, biotite, and ottrelite. Grubenmann calls this a crystalloblastic order (Reihe).[3] He gives the following succession for minerals of metamorphic origin: titanite, rutile, hematite, ilmenite, garnet, tourmaline,

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[1] Cf. Leith: "Minerals showing the best evidence of recrystallization are those best adapted by their shape and dimensions to conditions of unequal pressure," *op. cit.*, p. 95.

[2] Leith places quartz after the micas in respect to its cleavage-making capacity. Commencing with the best cleavage-maker, his order is: micas, hornblende, quartz, and feldspar (*op. cit.*, p. 64).

[3] *Die kristallinen Schiefer*, p. 91.

staurolite, cyanite—epidote, zoisite—pyroxene, hornblende—magnesite, dolomite, albite, mica, chlorite, talc—calcite—quartz, plagioclase—orthoclase, microcline. In general the series is one of decreasing specific gravity and of increasing molecular volume.[1] It is interesting to compare Grubenmann's values for specific gravity and molecular volume[2] for the four minerals under dicussion. They are:

	Sp. gr.	Mol. vol.
Ilmenite	4.70	31.7
Garnet (almandite)	4.11	119.8
Biotite	3.06	152.2
Ottrelite (chloritoid)	3.50	69.6

Ottrelite is an exception to Grubenmann's generalization.

Mention may be made here of other references to crystalloblastic order. Wolff[3] has shown that ottrelite may crystallize out before ilmenite. According to F. W. Clarke,[4] andalusite, sillimanite, and kyanite originate in the order named, with increasing metamorphism. This has been recorded by several observers. Van Hise[5] states that garnet represents a less advanced stage of alteration than staurolite. Where both of these minerals occur in the same schist garnet is frequently inclosed in staurolite. The present writer has seen this in many of the New Hampshire schists. Leith[6] writes: "We know definitely that quartz generally crystallizes before feldspar, and mica and hornblende before quartz and feldspar. . . . . Muscovite and biotite, when they occur together, usually develop simultaneously. . . . . Exceptionally the muscovite evidently crystallizes before the biotite." Garnet and staurolite are listed by Leith with the minerals that crystallize out after the cleavage-making minerals.

October 18, 1913

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[1] *Op. cit.*, pp. 91–92.

[2] *Op. cit.*, pp. 54–55.

[3] J. E. Wolff, "On some Occurrences of Ottrelite and Ilmenite Schist in New England," *Bull. Harv. Mus. Comp. Zoöl.*, XVI, 8 (1890), p. 163.

[4] "Data of Geochemistry," *U.S.G.S., Bull. 330* (1908), p. 528.

[5] C. R. Van Hise, *Treatise on Metamorphism*, p. 903.

[6] *Rock Cleavage*, pp. 93–94.

DIASTROPHISM AND THE FORMATIVE PROCESSES. VIII

THE QUANTITATIVE ELEMENT IN CIRCUM-CONTINENTAL GROWTH

T. C. CHAMBERLIN
University of Chicago

In a previous article of this series (VI, p. 271) we endeavored to show that the depth of the ocean does not, in itself, set limits to the thickness of the strata laid down in it—when these are measured in the usual way—though it does determine the amount of material required to build the continental terraces oceanward to given distances and thus indirectly affects the thickness of strata actually attained by a given amount of material. As a quantitative factor, then, ocean depth has its importance in determining the amount of peripheral growth that may arise from a given amount of sediment; or, if the peripheral growth be given, the amount of sediment required to accomplish it and, by interpretation, the time. The unit of such quantitative measurement is found in terms of radial extension rather than stratigraphic thickness. This distinction of terms and methods arises from the fact that the ocean depth affects the *area* of each stratum because of its inclined attitude. The quantity of sediment in the circum-continental terraces is one of the elements by which the denudation of tributary land is measured; or, the rate of denudation being roughly known or assumed, the amount of sediment in the terraces is a measure of the time occupied in the formation of the terraces. It thus becomes not only an index of the antiquity of the terraces but gives some incidental testimony as to their history.

In such rough approximations as alone are possible in studies of secular denudation and accumulation, we may assume that the surface movements of the ocean waters were effective in the same way and to the same extent in all ages, though this assumption was probably not strictly true and perhaps not approximately true in some cases. On this assumption the topset deposits of the continental shelves were of the same order of vertical depth as those recently formed. These we commonly agree to limit to the work of the upper 100 fathoms of water, though the sum of the thicknesses of the topset *strata* is not limited to 100 fathoms. The variable effects due to variable ocean depths are hence manifested almost solely in the foreset beds formed on the terrace faces overlooking the abysmal deeps.

Now if we assume, for a concrete example, that the slope of these foreset beds is 1 in 12, and that the mean depth of the abysmal part of the ocean adjoining is 5,000 meters, a symmetrical stratum of such an order as to advance the terrace horizontally one meter oceanward will be 1/12 meter thick, and will have a radial width of 60 kilometers. This stratum is equivalent to a vertical stratum one meter wide and 5,000 meters deep. If any other slope than 1 to 12 be taken as representative, a similar result follows; that is, a stratum that measures one meter horizontally at the surface, may be reduced to a vertical stratum one meter wide and 5,000 meters deep. The measure of *horizontal* advance and the measure of ocean depth thus appear to be the true factors in measuring sedimentary growth about the continents and to be conveniently simple in use. The *slopes* and the *stratigraphic* thicknesses may in many cases be neglected. They must of course be duly taken into account in their own appropriate fields but these are not precisely this field.

Notwithstanding the simplicity of the method thus deduced, all determinations of the quantitative values of the sediments of the circum-continental terraces are embarrassed by several serious difficulties. In spite of these, however, some working concepts may be formed that have value, even though they do not rise above very rough approximations.

In any specific attempt to deal with the sediments of the terrace shelf it is of course necessary to select the epoch or the formation from which the beginning of terrace growth is to be reckoned. It is idle in the present state of knowledge to go back of the Cambrian period and in many problems a much later date is best taken as the starting-point.

When this datum point is chosen there arise at once special difficulties in determining what were the landward and bottom boundaries at the start, for even the landward edge at the surface is largely concealed by later deposits, or has been cut away, while its lower parts and the bottom are generally inaccessible except as diastrophism has forced them into view. In few cases—probably in no case—has a terrace shelf throughout its history been built oceanward solely. In most cases the sea has advanced upon the land and the topset deposits have crept out upon the continent as well as oceanward. The landward advance has in many cases been interrupted by diastrophic movements and the shore line forced seaward, sometimes even beyond the initial line. Later a new advance has taken place from this line of retreat and so the oscillation has gone on. As a result of this the innermost edge of sedimentary deposits is liable to lie farther landward than the line from which growth began at the opening of the epoch chosen. The border sediments that thus lap upon the continent—defined as it stood at the outset—must of course be taken into account but not as extensions of the continent; they are rather superficial replacements or over-placements and, so far as determinable, are usually limited in depth and relatively small in quantitative value.

When pre-Paleozoic formations come out to the present coastline the location of the inner border of the terrace formed after the initial epoch is little better than conjectural. Some suggestions of value may spring from the trend of the border line in adjacent regions and from the consistency of value of any assigned configuration.

Probably the best approximation to the initial line of growth may be reached by setting aside for compensation purposes all sediments that are known to lap upon the continent as it stood at the outset, while such border sediments as are known to be deep and to show no signs of overlap are regarded as belonging to the continental outgrowth. In this it is assumed that any overestimates in the volume of the basal parts will be made good by the sediments of the overlap set aside for this purpose. It will be shown presently why the basal parts are not as likely to lead to overestimates as their apparent uncertainty may lead one to think. They are not wholly uncertain.

Where notable folding or faulting has taken place—and this is common near the coasts—it may be possible to determine more directly how far landward thicknesses of sediment of the order of the ocean depth have once extended, for the upturned beds may reveal them. Such observations must, however, usually give only a minimum extension; the evidences of the maximum extension have usually been cut away by erosion. An additional minimizing effect usually arises from the compression and distortion of the sediments under diastrophic thrusts. Their observed horizontal breadth may be much short of their original depositional breadth.

Students of terrestrial dynamics of all schools will probably agree that the borders of the continents have been the seats of exceptional folding and faulting. Observation and most theories, however diverse otherwise, lend support to this view. It is probably safe, and even ultra-conservative, to take the innermost line of continuous, thick, folded sediments as the landward border of the outward-built terrace, if, of course, these sediments are later than the time fixed upon as the beginning of the terrace-building epoch.

As already remarked, it is useless at present to consider circum-continental terraces older than the Paleozoic, for the metamorphisms and distortions of the earlier terranes and their wide concealment forbid their treatment in any satisfactory way. None the less, there is no good ground to doubt that the oceanward borders of the Proterozoic lands were affected for long periods by the process of terrace-building. The clastics form a notable factor in the Proterozoic terranes; they form a factor, though a less notable one, of the Archean also, and, under the planetesimal view, of terranes below the visible Archean. Whatever, therefore, may have been the original oceanward slopes of the submerged borders of the continental nuclei during the very earliest eras, normal topset and foreset slopes encircling these should have been acquired during the progress of the Proterozoic era. Except, therefore, as modified by diastrophism late in Proterozoic time or at its close, the oceanward face of the continental masses should have borne the normal sedimentary configurations.

Regarding the effects of diastrophism, I think it will be agreed quite generally that the mean results of long stretches of time tend rather to steepen the seaward gradients of the coasts than to flatten them; tend rather also to deepen the adjacent ocean than to shallow it. Theoretically this would seem quite certainly true if any tenable form of isostasy is effectual in diastrophism, and of this there seems less ground for doubt as inquiry goes on. On the observational side, the frequency of fore-deeps and of notable depressions off the continental edge not definitely shaped as fore-deeps seems to support this. It may be assumed, therefore, with much probability, that from Cambrian time onward topset and foreset action kept rebuilding the form of the circum-continental terraces into slopes that lay within their own normal range of variation—diastrophism aside—and that the mean ocean depth bordering the continents was not less than the normal mean depth. It may further be assumed with high probability that the mean effect of diastrophism, when it intervened, was to increase the border slope and the border depth, while it compacted, folded, and shortened the previous terrace outgrowth.

It appears, therefore, that if the upper edge of the landward border of the oceanic basin can be fixed approximately at the epoch from which the terrace growth is to be estimated, the slope of the terrace front and the depth of the adjacent ocean may be assumed to be of the present order, with some likelihood that this assumption is in reality conservative. These considerations relieve very appreciably the embarrassments that would otherwise affect the lower and landward configurations of the circum-continental terraces when we attempt to restore them, by interpretation, for any particular post-Proterozoic epoch.

The surface area of the present continental shelf between the shore line and the 100-fathom line is usually taken at 10,000,000 square miles, following Murray. The additions to be made to this to give the full area of the built terrace when its true border lies on the landward side of the present shore line, and the subtractions that are to be made when it lies on the seaward side, can only be roughly guessed at until the geological determinations of the coastal terranes of the several continents have reached a more advanced state, for any close estimate requires data not now available. None the less, it is worth while to make rough guesses of their values on such data as we have, if only to see what would be their meaning if the facts were as they are guessed to be. Without any pretention to accuracy, permit me to assume, on the basis of rough inspections, that for the total post-Proterozoic outgrowth the landward additions to be made to the present shelf are of the order of 40 per cent of its area, and that the subtractions are of the order of 20 per cent. My real judgment inclines to make the former more nearly 50 per cent and the latter more nearly 10 per cent; but, proceeding on what seems to me a conservative assumption, the total area of outgrowth of the post-Proterozoic circum-continental terrace, neglecting the crumpling, compacting, and shortening that have arisen at times from lateral thrusts, amounts to 12,000,000 square miles.

The coast line of the present continent is sometimes taken as 125,000 miles. For our present purposes a measurement on less curved lines such as to represent the middle of the shelf belt encircling the continents is more suitable, and an estimate on this basis gives about 100,000 miles. The mean breadth of the constructive terrace will then stand at 120 miles. Checked by direct measurements in some of the best determined representative cases this seems conservative.

Let us now turn to the sources of sedimentary supply. It would lead to large errors if each unit of the sea border were assumed to be fed with sediment from the whole area of a strip of land abutting on it and reaching back to the heart of the continent, for in the first place, much of the drainage runs away from the coast, and, in the second place, there is more or less coastwise drift that denudes some tracts and builds out others disproportionately. These factors have no doubt varied from age to age, and perhaps varied greatly, but our immediate purpose is to secure a rough concept of processes as they now are and as they are related to the present accumulation of sediments. These may be qualified later to fit the mean secular conditions or the specific conditions of any particular problem.

At present the continental surfaces may be divided into three classes in respect to the transportation and lodgment of sediments: (1) transportation into interior undrained basins which contribute nothing immediately to circum-continental growth; (2) transportation toward the continental interiors, with a possibility or probability that more or less of the sediment will at length reach the coast by a long and circuitous route but with a liability also of lodgment in lake basins, on low plains, in estuaries, embayments, gulfs, or other dependencies of the ocean, in consequence of which the sediments are consumed in building up depressions in the interiors of continents rather than building out their borders; and (3) direct transportation to the ocean down the border slopes of the continents; or in briefer terms: (1) internal drainage with no oceanic connection, (2) internal drainage with indirect oceanic connection, and (3) direct oceanic drainage. Murray places the area of the first class at 11.5 million square miles out of a total of 55.7 million, or a little more than 20 per cent. Leaving out the circumpolar region that cannot now be treated, there remain about 40 million square miles to be placed under classes two and three. I know of no authoritative division of this area between these classes, nor do I see how any but a somewhat arbitrary division can be made, for the two classes grade into one another in a very intricate way. If we put into class three only the drainage from the coastward sides of the mountains and other elevated tracts that so generally border the continents and add the drainage from the coastal flats where elevations are absent, the resulting area will be inferior to that of the great interior basins. So likewise if, for another line of approach, we turn to the geological record, as now known, the amount of clastic sediments embraced in the coastal slopes seems much inferior to that which is embraced in the great interior terranes. But, as a portion of the sediment that goes inward at first, later reaches the exterior of the continent, let the 40 million square miles be divided equally between the class which contributes to building up the interior and the class that contributes to building the continents outward. We have already taken the length of the circum-continental shelf belt as 100,000 miles. The assigned 20 million square miles tributary to it gives a working mean of 200 square miles tributary to every mile of length of the shelf.

Much study has been given to the determination of the average rate of denudation of land surfaces under present conditions in the endeavor to establish a mean rate serviceable for computing the age of the earth. The more recent representative treatments dealing with specific data may be found in the papers of Walcott,[1] Sollas,[2] Dole and Stabler,[3] Joly,[4] Becker,[5] Clarke,[6] Arthur Holmes,[7] in which may also be found references to earlier studies. The data of the United States Geological Survey, as organized and tabulated by Dole and Stabler, and discussed by Clarke, furnish the most definite and best determined material available, as well as that most suited to our purpose. It is not the rate of the complete denudation of the land which we wish to use in this discussion but only that part of it which found lodgment on the continental terraces. This embraced chiefly materials of certain degrees of coarseness or gravity and a certain portion of the dissolved material.

Clarke has pointed out the wide differences in the data obtained from different regions and has assigned reasons for these. It appears in particular that the average denudation of the basins of the Amazon and Uruguay rivers is but a trifle over one-half that of the Mississippi and St. Lawrence basins, though the precipitation on the tropical basins is nearly double that on the temperate basins. The difference is assigned to the forest clothing of the tropical basins. It appears from such data as Clarke found available that the mean denudation of the river basins of Europe is 100 tons per square mile, of Asia 84 tons, of North America 79 tons, of South

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[1] C. D. Walcott, "Geologic Time, as Indicated by the Sedimentary Rocks of North America," *Jour. Geol.*, I (1893), 639–76.

[2] Sollas, Brit. Assoc. Rept., Address to Sect. C, 1900, quoted by Joly in *Radioactivity and Geology* (1909), p. 246; Presidential Address, *Quar. Jour. Geol. Soc.*, May, 1909.

[3] R. B. Dole and H. Stabler, "Denudation," *U.S. Water Supply Paper 234* (1909), pp. 78–93.

[4] J. Joly, *Radioactivity and Geology* (1909), chap. xi; *Phil. Mag.*, 6th ser., XXII (1911), 358; *Trans. R. S. Dublin*, VII (1899), 23.

[5] George F. Becker, "The Age of the Earth," *Smith. Misc. Coll.*, LVI, No. 6 (1910). "Halley on the Age of the Ocean," *Science*, N.S., XXXI (1910), No. 795, pp. 459–61.

[6] F. W. Clarke, "A Preliminary Study of Chemical Denudation," *Smith Misc. Coll.*, LVI, No. 5 (1910); "The Data of Geochemistry," *U.S. Geol. Surv. Bull. 491*. 2d ed. (1911), p. 60 f., 137–42, 466–67.

[7] Arthur Holmes, *The Age of the Earth* (1913), chaps. iv–vi.

America 50 tons, and of Africa 44 tons.[1] Of course the data for Africa, South America, and Asia are particularly imperfect, but probably the general import of the figures is essentially true. We may push the essence of Clarke's interpretation a step farther and point to the general correspondence of these figures with the degrees of surface cultivation that obtain in these continents. These stand in essentially the same order, viz., Europe, Asia, North America, South America, and Africa. Of course other factors than soil cultivation enter into the results, but it is obvious that a much cultivated surface, softened by soil-tilth and left naked in its softened state for at least a portion of the year and perhaps for all the year, will suffer much more rapid denudation, other things being equal, than surfaces that are constantly mantled with vegetation and whose soils are knit into coherence by a mat of roots. The distinction between the resistance to denudation of native surfaces in humid areas under temperate and tropical conditions, on the one hand, and well-cultivated surfaces, on the other, seems to find peculiar exemplification in the data of Dole and Stabler—the best now available from which to draw tentative generalizations for working purposes. The measurements on which their results are based have been made in very recent years, in the main, and represent the rate of denudation incident to the present state of surface culture. Soil wastage is now notably high. The raising of corn, tobacco, cotton, and potatoes is peculiarly tributary to the leaching and wash of soils. In a somewhat different way, roads are also specially tributary to wash. In very marked contrast to the present state of the surface was its condition just previous to settlement by the whites. The soil of the forested regions was not only protected by a permanent overgrowth of trees and a tangled undergrowth of bushes and herbaceous plants and by a mat of leaves, twigs, and fallen timber, but by a network of roots and rootlets which bound the soil together. The flow of surface drainage was delayed and equalized by the one group of agencies while the soil was rendered resistant to the relatively gentle water action thus insured by the other. On the prairies, the dense mat of native

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[1] F. W. Clarke, "A Preliminary Study of Chemical Denudation," *Smith Misc. Coll.*, LVI, No. 5, (1910), p. 7.

grass was abetted by an even denser mat of root fibers to which it adhered tenaciously at its base, and these together made the native sod peculiarly resistant to erosion. In the ravines and meadows the rank "slew" grass, attached even more tenaciously to a tough mass of fibrous roots, was an especially effective defense against the action of floods and freshets where they were liable to do their most effective work. In those early days, as I distinctly remember, the ravines and upland valleys in times of freshets usually ran clear save that their waters were amber-tinged from vegetal extract. The banks of the brooks were then not only close-sodded to the very water's edge, but by their gradual growth closed in on the narrow, pellucid stream between them. The same brooks now, under close pasturage and the feebler turfing of the exotic grasses that have replaced the native sod, have cut open ditches, several times as wide and these are being further widened anually. Under the native conditions even the floods of spring time were but slightly turbid, whereas now the flush of every shower runs black with sediment. Comparing earlier and later impressions of identical areas in the Mississippi Valley, where cultivation has followed native conditions, whether of forest, plain, or meadow, the rate of denudation under culture seems clearly to be some appreciable multiple of the earlier rate, perhaps a very notable multiple. The matter should be determined by direct trials where either the conditions are under complete control or the data for comparing areas not under control are complete and well in hand.

The statistics of Dole and Stabler[1] give for the surface denudation of the United States taken as a whole a mean rate of 1 foot in 9,120 years. For our purpose it is important to know whether this and other large averages are suited for use in the study of circum-continental shelves when these are dependent for their growth chiefly on sediment brought from the drainage slopes of the sea borders. It might seem a natural inference that the coastal slopes should receive a larger rainfall, in general, than the average surface of the continent and so perhaps be denuded more rapidly. But rainfall commonly increases the vegetal clothing and this tends

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[1] *Water Supply and Irrigation Papers 231–236*, "Denudation," p. 83.

the other way. To see whether the rates of denudation of the coastal border tracts are essentially the same or essentially different from those of the general continental surfaces, the rates given by Dole and Stabler for the districts of the North Atlantic (1 foot in 13,200 years), the South Atlantic (1 foot in 8,520 years), the North Pacific (1 foot in 19,200 years), and the South Pacific (1 foot in 9,320 years), including in each case only the area within the United States, were combined and compared. The rates, averaged without weighting, were found to give a common rate of 1 foot in 12,180 years. If the Laurentian basin (1 foot in 19,320 years) is reckoned in, the unweighted mean rate rises to 1 foot in 13,476 years. If the Colorado River basin (1 foot in 5,280 years) is also reckoned in, the mean falls back to 1 foot in 12,110 years.

The data for some of the sub-districts are very suggestive. For example, the basins of the Penobscot (1 foot in 24,000 years), the Kennebec (1 foot in 25,200 years); the Androscoggin (1 foot in 21,600 years), the Presumpscot (1 foot in 25,200 years), the Saco (1 foot in 25,200 years), the Merrimac (1 foot in 32,400 years), and the Connecticut (1 foot in 24,000 years) are averaged without weighting, the mean rate is 1 foot in 25,371 years. These notably low rates are probably due in part to the numerous catchment basins on the morainic surfaces of these New England basins, but in no small part also are they probably due to the fact that large portions of New England once under plow have been permitted in recent years to return to a wooded or grassy state. It is of interest to note here that the drainage area of Lake Superior, so far as it lies in the United States, which has only been brought partially under culture, has a denudation rate of 1 foot in 37,200 years.

The erosion of the South Atlantic district (1 foot in 8,520 years) is 2⅗ times as fast as that of the North Atlantic district (1 foot in 13,200 years), though the gradient of the former is below rather than above that of the latter. Of like import is the erosion rate of the North Pacific slope (1 foot in 19,200 years) when compared with that of the South Pacific slope (1 foot in 9,320 years) more than twice as fast, though the rainfall of the former is much the higher and its gradients certainly not less steep. One of the most vital factors, probably the most vital factor, in these strong contrasts is with little doubt the different degrees of protection afforded by their vegetal mantles.

It appears then that a review of the best data that we have relative to the present rate of denudation of the coastal slopes gives a mean rate of about 1 foot in 12,000 years. It is to be noted that this embraces tracts that reach to the border of the 30° belt where humidity is low, as well as tracts in the fairly humid mid-latitudes, and that the denudation rate of the latter is scarcely a half of that of the former in spite of the theoretical presumption that denudation should rise and fall with the precipitation. The fact that the efficiency of the vegetal mantle as a protection against erosion also rises and falls with precipitation seems to much more than offset the direct effects of increased drainage flow.

Returning to the broader question, it appears that the best available data relative to the rate of denudation on American coastal slopes at present gives a mean rate of 1 foot in 12,000 years. This is but half the higher rate usually employed in the past, based on the rate for the Mississippi Valley as a whole, 1 foot in 6,000 years. The rate 1 foot in 12,000 years still needs to be corrected for (1) the effect of the present conditions in accelerating denudation, (2) the portions of the sediments lost to the abysmal basins, (3) the portions of the solutions that are held permanently in the oceans as part of the saline element of sea water, and (4) the portions of the solutions that are precipitated to the ocean depths as the hard parts of pelagic animals and plants.

But to curtail this discussion, let us leave these corrections in abeyance and proceed on the basis of the present denudation rate, keeping in mind that it must be corrected to give true results.

Recalling that we had previously fixed upon a belt 200 miles in width as representative of the area directly tributary to the shelf, upon 100,000 miles as its length, and upon 120 miles as the mean width of the shelf, and using the denudation rate 1 foot in 12,000 years, without correction, the formation of the post-Proterozoic terrace would take approximately 108,000,000 years. This is of about the same order of magnitude as the periods usually reached for post-Proterozoic time by employing data based on general denudation in which the present rate is taken as the secular rate. While our results must be corrected for the difference between present rates of denudation and the mean secular rate—and this correction is quite certainly large, involving other factors than the cultural one—comparisons with other modes of attack must be made previous to such corrections if these have not similarly entered into the results of these other studies.

This general concurrence in results seems to imply that the continents have made peripheral growths of the same order as their other forms of growth. This in turn implies that the continental borders have had a permanency and stability of the same order as the continents themselves.

PETROLOGICAL ABSTRACTS AND REVIEWS

EDITED BY ALBERT JOHANNSEN

McLINTOCK, W. F. P. *Guide to the Collection of Gemstones in the Museum of Practical Geology.* London, 1912. Pp. 92.

This pamphlet is much more than a guidebook, the first thirty-four pages being devoted to a general discussion of the properties of gemstones, the manner of cutting, etc. The remaining pages are devoted to descriptions of the different gems found in the collection, information being given in regard to crystal form, occurrence, methods of cutting, coloring, etc. American museums might well follow the plan of those of Scotland and England in issuing these useful guides. A. J.

MEAD, W. J. "Some Geological Short-Cuts," *Econ. Geol.*, VII (1912), 136–44.

The author gives some ingenious methods for shortening the labor of various computations. The first of these is a graphical method for the determination of the composition of a rock from its mineral constituents. It consists in reading directly from diagrams the component oxides of the minerals. Unfortunately for the majority of petrographers, the author reproduces only one table from a set of fifty-four of rock-forming and thirty-seven of ore minerals, prepared in blue print form for his students at the University of Wisconsin. For the same purpose, but in much more convenient form, is the author's "geologist's slide rule." This consists of a circular diagram, based on logarithmic principles. The percentages are read by means of an inner rotating disk and a celluloid arm. In the present slide rule, thirty-six common rock-forming minerals are included, and the author has in preparation a similar one for thirty-eight of the principal ore minerals. A third short-cut is the "straight-line method" by which direct comparison may be made, without recalculation, of analyses of fresh and altered rocks to show the change in composition due to alteration. A. J.

MENNELL, F. P. *A Manual of Petrology.* Chapman & Hall, London, 1913. Pp. 256, figs. 124. 7*s.* 6*d.* net.

This work, originally planned as the third edition of Mennell's *Introduction to Petrology*, was so much changed during revision, that a new title was used. The book is designed for the working geologist while "the more elementary portions are chiefly intended for the student"! As has been the case with many recently issued petrological textbooks, the first portion is given up to the rock-forming minerals, 80 pages being here so employed. Chapters are devoted to the classification, structure, origin, metamorphism, and weathering of rocks, and various rock types are discussed. The author bases his classification of the igneous rocks upon their chemical composition, and divides them, in a very simple manner, by their silica content, thus:

	Plutonic	Intrusive	Effusive
Acid, over 65 per cent silica............	Granite	Granophyre	Rhyolite
Sub-acid, 60 to 65 per cent............	Syenite	Orthophyre	Trachyte
Sub-basic, 55 to 60 per cent............	Diorite	Porphyrite	Andesite
Basic, 45 to 55 per cent................	Gabbro	Dolerite	Basalt
Ultrabasic, less than 45 per cent........	....	Picrite	Limburgite

This classification is simple enough, but it does not show genetic relationships. It would be impossible, by the use of the microscope, to classify rocks according to this system. Chemical analyses would have to be made of every rock, a prerequisite entirely out of the question in practical work. Furthermore, the names thus limited by the silica content have already been used for rocks of certain mineralogical composition, and the new definitions for the old terms cause further confusion in an already almost hopelessly confused nomenclature.

ALBERT JOHANNSEN

MERRILL, GEORGE P. "On the Supposed Origin of the Moldavites and Like Sporadic Glasses from Various Sources," *Proc. U.S. National Museum*, XL (1911), 481–86.

The greenish, chrysolite-like glass pebbles found in many regions and called moldavite, billitonite, australite, obsidianite, or obsidian bombs, are all included by Suess under the name tektites, and are regarded by him as being of ultra-terrestrial origin, the markings being a consequence of their mode of origin. To this Merrill takes exception, regarding the Bohemian and Moravian specimens as water-worn pebbles of weathered glass, originally etched by corroding vapors or solutions, and the Australian forms as pebbles, water-worn or abraded by wind-blown sands. He does not wish to controvert the theory of an original cosmic origin, but thinks until they have been seen to fall, that their source is to be found only in the conditions under which they occur.

A. J.

MERWIN, H. E. "A Method of Determining the Density of Minerals by Means of Rohrbach's Solution Having a Standard Refractive Index," *Amer. Jour. Sci.*, XXXII (1911), 425–28.

After making specific-gravity determinations by means of Rohrbach's heavy solution, the writer determines the density of the latter by means of its refractive index. A comparative table of values of density at 20° C. and corresponding refractive indices is given.

A. J.

MERWIN, H. E. "Quartz and Fluorite as Standards of Density and Refractive Index," *Amer. Jour. Sci.*, XXXII (1911), 429–32.

Quartz and fluorite from different parts of the world were compared and it was found that at ordinary room temperature the density of pure quartz is 2.6495± .0010 and of pure fluorite 3.180± .001. By sodium light the refractive index (ϵ) of quartz was found to be 1.5443−1.5442, and of fluorite, 1.4338+ and 1.4338−.

A. J.

MERWIN, H. E. "Media of High Refraction for Refractive Index Determinations with the Microscope; Also a Set of Permanent Standard Media of Lower Refraction," *Jour. Wash. Acad. Sci.*, III (1913), 35–40.

To fill the gap between fluids having refractive indices from 1.33 to 1.80 and from 2.1 to 2.4, Merwin proposes solutions of iodoform, tri-iodide of arsenic, tri-iodide of antimony, tetra-iodide of tin, and sulphur in methylene iodide. With various proportions dissolved in 100 parts of methylene iodide, fluids of refractive indices between 1.764 and 1.868 are obtained. Fluids from 1.74 to 2.28 were obtained by dissolving arsenic trisulphide in methylene iodide near its boiling-point. Merwin also prepared resin-like substances with indices between 1.68 and 2.10 by dissolving tri-iodides of arsenic and antimony in piperine. For media between 2.1 and 2.6, he used mixtures of amorphous sulphur and arsenic trisulphide. Other media were mixtures of piperine and rosin for indices between 1.546 and 1.682, and mixtures of rosin and camphor for 1.510 to 1.546.

A. J.

MERWIN and LARSEN. "Mixtures of Amorphous Sulphur and Selenium as Immersion Media for the Determination of High Refractive Indices with the Microscope," *Amer. Jour. Sci.*, XXXIV (1912), 42–47.

For minerals having very high refractive indices, Merwin and Larsen propose using molten sulphur, molten selenium, and mixtures of the two, these substances being miscible in all proportions when in a molten condition. The mixtures are prepared by placing the required weight of powdered selenium in a three-inch test tube, heating it until the mineral is thoroughly fused, and allowing it to cool. The proper amount of pure flowers of sulphur is now added and the mixture heated just enough to allow thorough mixing with a glass rod. As the material cools it is gathered on the rod and is cut into small fragments. These may now be returned to the tube, which should be corked, and preserved for use.

To determine refractive indices with this preparation, a small piece of it and a little of the mineral, finely pulverized, are heated together on an object-glass and under a cover-glass, over a small flame, until the preparation is liquid, when the two are mixed and pressed into a thin film. The film is again heated for half a minute until bubbles begin to appear, when it is again pressed thin and cooled, after which the determination is made in the usual manner.

A. J.

MILCH, L. "Grundzüge der Kristallographie," *Taschenbuch f. Math. u. Phys.*, Leipzig u. Berlin, 1913, 359–81.

MILCH, L., and RENZ, CARL, "Ueber griechische Quarzkeratophyre," *Neues Jahrb.*, XXXI (1911), 496–534.

In Argolis and on Hydra, quartz keratophyres and keratophyre tuffs appear, probably of Devonian age. Seven analyses are given.

A. J.

MILCH, L. "Ueber die Beziehungen des Riesengebirgsgranits, (Granitit) zu dem ihn im Süden begleitenden Granitzuge," *Centralbl. f. Min., etc.*, 1911, 197–205.

In an earlier paper Milch had asserted that the two granite areas in question form a single intrusion, the two-mica granite being simply an altered phase of the granitite. Rimann maintained that the two areas represented distinct intrusions. The present paper is a reply to Rimann, and reasons are given for the contention that the mass is a unit.

A. J.

MILCH, L. "Die Systematik der Eruptivgesteine. Erster Teil," *Fortschr. d. Min. Kristallog. u. Petrog.*, III (1913), 189–227.

A history of the development of mineralogical classifications of rocks. Chemical classifications are to be treated in the volume for 1914.

A. J.

MILLER, BENJAMIN L. "The Geology of the Graphite Deposits of Pennsylvania," *Econ. Geol.*, VII (1912), 762–77.

MILLER, WILLIAM J. "The Garnet Deposits of Warren County, New York," *Econ. Geol.*, VII (1912), 493–501.

The author believes the garnets to be due to the assimilation of the Grenville sediments by the intruded igneous rocks.

A. J.

MILLER, WILLIAM I. "Contact Action of Gabbro on Granite in Warren County, New York," *Science*, XXXVI (1912), 490–92.

The author distinguishes nine zones, passing from the typical gabbro to the typical granite country rock. He gives the mineralogical composition of each zone.

A. J.

MOORE, ELWOOD S. "Hydrothermal Alteration of Granite and the Source of Vein-Quartz at the St. Anthony Mine," *Econ. Geol.*, VII (1912), 751–61.

PAIGE, SIDNEY. "The Geologic and Structural Relations at Santa Rita (Chino), New Mexico," *Econ. Geol.*, VII (1912), 547–59.

PAIGE, SIDNEY. "The Origin of Turquoise in the Burro Mountains, New Mexico," *Econ. Geol.* VII (1912), 382–92.

The author gives arguments both for the deep-seated origin of turquoise and for its origin in the zone of weathering. He apparently inclines to the latter belief.

A. J.

RAMSAY, WILHELM. "Beiträge zur Geologie der Halbinsel Kanin," *Fennia*, XXXI (1911), No. 4, pp. 45.

A geologic history of the Kanin Peninsula. An analysis of diabase is given.

A. J.

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—American Geographical Society, Bulletin of the. Vol. XLIV, No. 12, December, 1912. Vol. XLV, No. 12, December, 1913. [New York: Broadway at 156th St., 1913.]

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—BAGG, R. M. Pliocene and Pleistocene Foraminifera from Southern California. [U.S. Geological Survey Bulletin 513. Washington, 1912.]

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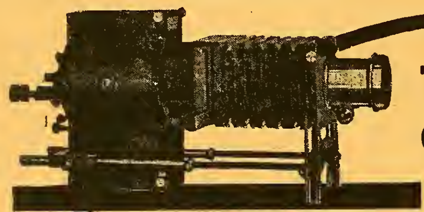

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THE STRENGTH OF THE EARTH'S CRUST

JOSEPH BARRELL
New Haven, Connecticut

PART V. THE DEPTH OF MASSES PRODUCING GRAVITY ANOMALIES AND DEFLECTION RESIDUALS

SECTION B

APPLICATIONS OF CRITERIA TO DETERMINE THE LIMITS OF DEPTH, FORM, AND MASS

DEPTHS INDICATED BY THE MAP OF DEFLECTION RESIDUALS

General relations shown by deflections.—Hayford gives a plate[1] which shows all the residuals of Solution H. These are laid off as arrows and show graphically the magnitude and direction of the portions of the deflections which are outstanding after allowance is made for the deflections calculated according to Solution H. They therefore show the excesses or deficiencies of mass in the crust

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[1] *Supplementary Paper*, illustration No. 3; also Bowie, 1912, illustration No. 5.

as measured against the demands of the hypotheses made in that solution. In Fig. 12A is reproduced a portion of Hayford's chart. A general inspection of the map of the residuals of Solution H shows that many of the large deflections of opposite sign lie comparatively close together. On a line connecting two stations, *Fx* is the component of the deflection which lies in that line, *Fy* is the component at right angles to that line. In most cases not enough stations are located on an approximately straight line to permit well-defined curves to be drawn for *Fx* and *Fy*. But it has been shown that for spheres and other concentrated masses the curve for *Fx* rises steeply from zero to maximum value and sinks away more gently beyond. Even for flat disks the outer part of the deflection curve will be flatter than for the inner part. Random locations on the curve are therefore more likely to give the maximum measurement at some point beyond the real maximum rather than at some point between the epicenter and the real maximum. Using these stations giving maxima for *Fx* as if they were at the points of real maxima will therefore give on the average too great a distance from the center to the point of real maximum *Fx* and consequently too great a depth to the centers of attraction. Interpreting the disturbing masses as spheres is also an assumption likely to give too great a depth, as is indicated later. Minor centers of outstanding mass will affect the positions of the points of maximum value, but in a sufficient number of examples this effect will largely cancel out. The tabulation of the distances measured from Hayford's map between ten pairs of notable *Fx* maxima is given in Table XXVII.

It is seen that the distance between these maxima is more largely dependent upon the length of the sides of the geodetic triangles than upon the depth to center of mass, since in less than half of these illustrations did a station fall between the two maxima. The distance between the real maxima is then probably somewhat greater than 86 km., the average of the six distances without intervening stations, but is probably somewhat under the general mean of 110 km. This mean distance of 110 km. between ten notable maxima of *Fx* corresponds to a mean depth of spheres of 79 km. Considering the various assumptions made, it is seen that the mean depth of masses producing these deflections is probably much less than 79 km. They belong, therefore, to the outer half of the zone of compensation.

TABLE XXVII

DISTANCES BETWEEN ADJACENT LARGE DEFLECTIONS OF OPPOSITE SIGN

Locality of Mass	Sign of Mass	Numbers of Stations	Stations between	Distances between in Km.
New Jersey	+	255–142	0	110
Kentucky–Ohio	+	85–84	0	100
Georgia–Florida	+	292–294	1	160
Florida	+	299–300	0	145
Michigan–Indiana	+	344–346	1	165
Illinois	+	75–74	0	90
Nebraska	+	327–329	1	170
Colorado	−	59–57	1	100
California	−	238–236	0	50
California	−	245–246	0	22
			Mean	110

There are other areas, however, as in the Adirondacks, Maine, Michigan, and the Great Basin, where the distance between the large deflections of opposite sign is considerably greater. So far as this relation goes they could be due either to broad outstanding masses in the zone of compensation or to much greater but more concentrated masses in the nucleus beneath. But the general relations to the magnitude and location of the gravity anomalies as discussed later under that subject suggest that in so far as the evidence is determinative these broader areas are also due to broad excesses or deficiencies in the outer crust, not to masses in the centrosphere. The data are not, however, in all areas of a sufficiently complete nature to give determinate solutions. In other areas, however, detailed study following the lines of criteria previously developed can bring out very definite results in regard to the location and depth of masses in spite of the interference of the fields of force from various centers. An example of what may be done by a detailed examination is shown under the next topic.

Detailed study of the Texas–Kansas region.—Fig. 12A shows the deflections as given on a north-south line of triangulation 1,000 km. in length. The gravity anomalies are shown for distances of 200 km. on each side of the traverse. The stations are sufficient in

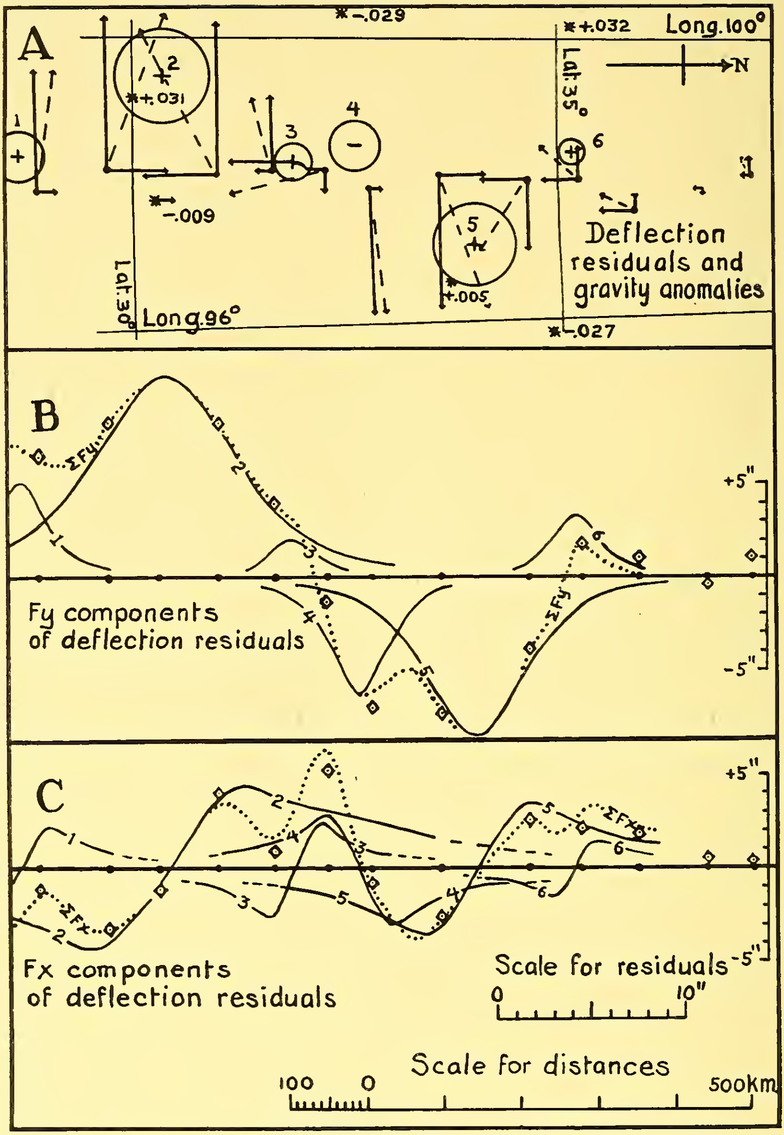

FIG. 12.—Residuals of Solution H and gravity anomalies in Texas, Oklahoma, and Kansas, with the interpretation of the outstanding masses in terms of equivalent spheres.

number and sufficiently close to a straight line to permit the application of the principles previously discussed.

The residuals are given in the north-south and east-west directions. The broken lines give the resultants. Their convergence indicates that there are two large and controlling positive masses marked on the map as 2 and 5. To account for the local variations shown by the resultants from station to station it is necessary, however, to locate smaller masses of positive or negative nature approximately as shown at 1, 3, 4, and 6. There must be of course many other centers of moderate disturbance within the area of 400,000 km. which is shown, but such as exist are far enough from the line of section not to exert an appreciable influence. It is noteworthy that gravity stations only 200 km. from the line of the traverse can show anomalies as large as −0.029, +0.032, and −0.027 dyne without the masses which give these anomalies showing appreciable control over the deflections on the line of traverse. Their areas of influence are therefore restricted. The limited influence of these masses giving anomalies somewhat above the average and at a moderate distance, and the small masses locally modifying the deflections both serve to show the importance of nearness of location. This limitation of control over the deflections, restricted to distances of less than 100 to 200 km., is itself an indication that these outstanding masses lie within the zone of compensation, otherwise their effects would be more far-reaching.

The residuals permit, however, a much more detailed solution to be made. As a first approximation assume the outstanding masses to be spheres. Figs. 12B and 12C. show the results. This is not merely an arbitrary adjustment of curves and one of a number which might be devised. On the contrary, it has been shown in the discussion of Section A and especially in Fig. 11 that the ratio of the two maxima of the deflection components, Fy and Fx, and the ratio of EE' to $E'M$ hold a definite relation to the distance and depth of the center of the sphere. Therefore if curve 2 be drawn in proper proportion and as shown in B in order to satisfy the demands of the y component, then the maximum value of Fx must not be over 40 per cent of the maximum value for Fy, even if the center of mass is close to the surface. It may be any value less than 40 per cent of maximum *Fy*, according to the depth of the center. But having chosen that ratio which appears to fit the demands of the data, the distance of the point of maximum *Fx* from the point of zero value becomes also fixed. The curves numbered 2 in Figs. 12B and C must therefore satisfy between them the demands of the ratios shown in Figs. 11E and F. The value of EE' as deduced from either curve must be the same.

The sum of all the *Fy* curves in 12B is marked $\Sigma\ Fy$ and must pass through, or close to, the points which measure the values given by the deflection residuals. These points are shown as small rectangles in B and C and give ordinates which correspond with the size of the components of the residuals as shown in A. In drawing B and C the adjustment of the curves to give the proper values to $\Sigma\ Fy$ and $\Sigma\ Fx$ resulted in a slight readjustment of the centers of mass as shown in A. The positions as shown in Fig. 12A have been determined from the curves below, and their approximate agreement with the initial indications of the resultants is a check on the validity of the solution. It is seen that the epicenter of a mass should not lie on the exact intersection of any two resultants, since at the point of measurement several masses have an appreciable influence upon the direction of the resultant. The adjustment of the curves is therefore the best way of determining finally the best location of the epicenters.

The measurement of these curves gives the tabulation of data shown in Table XXVIII.

The depth to the centers of the equivalent spheres having been solved by means of the ratios given in Figs. 11E and 11F, the masses of these spheres are ascertained as follows. In Fig. 11 the value of the maximum deflections for *Fy* and *Fx* due to the unit sphere are shown for various distances of the section line from the epicenter. For example, for $EE'=1.5D$, max. *Fy* is 4.6″. Now for sphere No. 4, Fig. 12A, $EE'=1.5D_4$ and the max. *Fy* is 6.2″. But D for the unit sphere is 64 km. whereas D_4 is 31 km. Now the magnitude of the deflections for points similarly situated in two fields of gravitative force will vary directly as the respective masses and inversely with the squares of the distances. This may be put into a formula as follows: Let there be two masses M and M_n with centers at depths D and D_n; below a horizontal plane. For points on the plane similarly situated with respect to their respective centers let the components of the deflection force be Fy and Fx for the one, Fy_n and Fx_n for the other. Then

$$M_n = \frac{Fy_n D_n^2}{Fy D^2} M; \quad \text{also } M_n = \frac{Fx_n D_n^2}{Fx D^2} M$$

The results of the application of this formula are shown in the last column of Table XXVIII. They have been carried out to two significant figures, but the second is not to be regarded as accurate,

TABLE XXVIII

INTERPRETATION OF RESIDUALS IN TERMS OF EQUIVALENT SPHERES

No. of Sphere	Data								Results	
	From Fig. 12			Fig. 11F	From Fig. 12			Fig. 11E		
	Max. Fy	Max. Fx	$\frac{\text{Max. } Fy}{\text{Max. } Fx}$	EE' in Terms of D	EE'	$E'M$	$\frac{EE'}{E'M}$	EE' in Terms of D	Depth in Km.	Mass in Terms of Unit Sphere Whose $R=50$ km. $d=0.1$.
1	5.1	2.3	2.20	$1.7D_1$	42	35	1.20	$1.7D_1$	25	$+0.20M$
2	10.8	4.4	2.46	$3.0D_2$	125	95	1.31	$2.5D_2$	40 to 50	$+2.5$ to $2.9M$
3	2.0	2.5	0.80	$0.3D_3$	13	33	0.40	$0.3D_3$	43	$+0.17M$
4	6.2	2.9	2.13	$1.5D_4$	47	40	1.17	$1.5D_4$	31	$-0.32M$
5	8.4	3.5	2.40	$2.5D_5$	88	67	1.31	$2.5D_5$	35	$+1.10M$
6	3.3	1.4	2.35	$2.2D_6$	34	27	1.27	$2.2D_6$	16	$+0.07M$

even if the original data are accurate to the second place. This is because the error of the square of a quantity is approximately twice as great as the original error, and for values EE' above $1.0D$ the error in even the first power of D is appreciably greater than the error in the measured quantities. This of course is a consideration of the error in the determination of the depth and mass of the hypothetical spheres, not a consideration of the errors in the deflections themselves, nor related to the fact that the masses are in reality not spheres.

It has been shown previously that the interpretation of the outstanding masses in terms of spheres will give depths too great unless the real masses have their greatest dimension vertical. For the same reasons the hypothetical spheres will be of greater mass than the real horizontally extended bodies in order to produce the same deflections as those observed.

The question arises then as to the real form and mass of the bodies interpreted here as spheres. The supplemental data at hand yield evidence only in regard to No. 2. This, however, is the greatest of the six outstanding masses in this series. The supplemental data consist of observations on gravity anomalies at three localities whose distances from the epicenter of No. 2 are as follows:

Relations of Gravity Anomalies to the Epicenter of Mass No. 2

a,	47 km. S. E.	+0.031
b,	163 km. E.	−0.009
c,	250 km. N.N.W.	−0.029

Now the curves for *Fv* and also for the *Fy* component of *Fh* show with increasing distance from the epicenter a rapid fall from the maximum value. These effects of the gravitative force due to outstanding masses are consequently markedly local and the nature of the mass No. 2 must have a distribution such as to account for the anomaly of +0.031 at 47 km. from the epicenter. The interpretation must not give a form which will exert marked influence upon those points distant 163 and 250 km. The dominating influence of mass No. 2 on the value of *Fv* appears therefore to be confined to distances within 125 or 150 km. of the epicenter. But the two limiting spheres of mass 2.5*M* and 2.9*M* respectively give the relations shown in the first two lines of Table XXIX.

TABLE XXIX

Interpretation of Mass No. 2

Form	Mass in Terms of Unit Sphere	Depth to Center in Km.	Radius in Km.	Height in Km.	Excess Density Above Mean	*Fv* at Epicenter in Dynes	*Fv* at 47 Km. in Dynes
A. Sphere.....	2.5	40	40	80	0.5	0.542	0.148
B. Sphere.....	2.9	50	50	100	0.3	0.405	0.157
C. Cylinder....	2.5	40	200	10.4	0.1	0.035	....
D. Cylinder....	0.6	20	100	5.2	0.2	0.035	....

The interpretation of the deflections as due to spheres gives a gravity anomaly at the epicenter of the sphere between four and six times larger than the largest yet observed in the United States.

At the distance of 47 km. the anomaly would be from 0.148 to 0.157 dyne, five times the observed value of 0.031. Clearly then the initial interpretation as a sphere, although it satisfies the deflection residuals of the line of traverse, is far from the truth. The mass must have horizontal dimensions much greater than the vertical. Assume for trial that the mass has the form of a vertical cylinder with the same mass and depth to center as the sphere, but of a proportion of height to breadth which shall satisfy approximately the gravity anomaly. The result is shown in the third line of Table XXIX. The gravity anomaly of 0.035 at the epicenter would correspond in a cylinder of these proportions to a value only slightly less at 47 km. But the radius of the cylinder, 200 km., is now far too great. Other cylinders of similar form will, however, give the same anomaly at the epicenter if the depth and dimensions are all divided by any number, *n*, and the density multiplied by the same number. This gives a series of similar cylinders in which the density varies inversely with the dimensions. Of such a series that shown in the fourth line, obtained by giving *n* a value of 2, comes fairly close to satisfying all the requirements. The exact degree of adjustment which would be needed to satisfy both the gravity anomaly at 47 km. and the deflections on the line of traverse has not been calculated. If this were done and the dimensions adjusted accordingly, it would complete a second approximation to the real form and mass of No. 2. Such an extended treatment of the subject would, however, be beyond the immediate purposes of this article and beyond the limits of space which it should occupy. The data also are at present hardly of a sort which would justify further computations. It should be emphasized, however, that such a complete investigation is not difficult and would require but little further data, properly chosen, to check the conclusions.

In the first approximation, the mass was assumed to have a uniform distribution about a center, giving a sphere. In the second approximation, the vertical axis is assumed to be different from the horizontal axes, but the latter being kept alike, the horizontal section would still be a circle. A single observation of the gravity anomaly near the epicenter suffices to give this second approximation. The third approximation would be to consider the three co-ordinate axes of the mass unlike. This would require some observations in two directions at right angles from the epicenter. More complete data consisting of both deflection and gravity observations would of course give still closer approximations toward the real form and depth of the mass. What it is desired to show here, however, is that the interpretation of this large mass as a sphere gave a depth to the center of mass about twice too great and a mass perhaps four times too great. This result is in line with the general deduction previously made in regard to the direction of the error involved in the interpretation of deflection residuals as due to spheres. It contributes its individual testimony to show that the masses producing the notable gravity anomalies and deflection residuals are situated within the zone of isostatic compensation and more especially in the upper part of that zone.

In regard to the large positive mass No. 5 the data are less determinative. At a distance of 60 km. southeast from the epicenter the anomaly is only +0.005 dyne. At 150 km. northeast it is −0.027 dyne. It thus appears that there are some large negative masses easterly of No. 5. As this, however, is on the side away from the line of traverse the problem of the real form and mass of No. 5 is at present indeterminate.

The adjustment between the deflection curves due to spherical masses and the values of the deflection residuals has been made closer, perhaps, than the probable values of the residuals. Furthermore, the residuals of Solution G, if they had been given for this region, would have required a somewhat different distribution of masses. A solution for that depth of compensation which would reduce to the smallest quantity the sum of the least squares of the residuals of this area 1,000 km. long and 400 km. wide would be still somewhat different. That local solution which would give the smallest residuals would be such as would make small the algebraic sum of the positive and negative masses, but the difference in mass between positive and negative centers would not be much reduced. The depth to the centers of mass would be the quantity most affected by a change in the hypothesis regarding the depth of compensation. These epicenters then, in so far as the accidental errors do not vitiate the values of the residuals, are realities in nature.

In view of this analysis of the data given in Fig. 12 and in Table XXVIII, it is to be concluded that for this region even the larger outstanding masses from Solution H, capable of exerting a notable influence on the *Fx* component of the deflections to a distance of 400 km. or more, appear to have their centers not deeper than 20–25 km. Their mass is consequently within the outer half or even the other third of the zone of isostatic compensation as given by Solution H. There is further no evidence of centrospheric heterogeneity.

OTHER INDICATIONS REGARDING DEPTH OF OUTSTANDING MASSES

Deflections by linear or dike-like masses.—The resultants of the deflection residuals are shown by broken lines in Fig. 12. They show a tendency to converge toward centers. This is true in general for the whole United States, as shown in Hayford's illustration. This tendency to convergence indicates that the dominating outstanding masses may usually be regarded in a first or second approximation as symmetrical with respect to a vertical axis. In contrast, however, to this rule the residuals of Solution H in the vicinity of Washington[1] indicate an outstanding mass with a northeast-southwest extension of at least 120 km., whereas the breadth is probably not more than 20 km. This narrowness is shown by the limited distance between the large residuals of opposite sign in a northwest-southeast direction. The linear extension is shown by the parallel rather than radial arrangement of the resultants. The mass gives rise to large deflections for a distance of as great as 100 km. from the sides, but its influence dies out somewhat beyond.

It is clear from these relations that the assumption of a form of the mass symmetrical about a vertical axis for the purpose of determining the depth of the center would not be justifiable. Other assumptions which might be made in order to subject the mass to mathematical investigation would be to consider it as a horizontal prolate spheroid, or as a horizontal linear mass at a certain depth, cylindriform, or as a vertical plate. The latter would be preferable. For a quantitative solution of its dimensions and mass it would be desirable to have some observations farther to the northwest.

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[1] Hayford, Supplementary Paper, illustration No. 4.

The following qualitative conclusions may, however, be drawn from an inspection of the residuals.

Maximum deflections are found on each side of the axial line not more than 40 km. distant. The deflections continue large for at least twice this distance but not for three times this distance. The existence of large residuals so close to the axial line shows conclusively that the outstanding mass is within the zone of compensation and apparently within its outer half, but the maintenance of the size of the deflections without much change for a considerably greater distance shows also that it is not merely a surficial and linear mass. It must have considerable extension in depth. In these indications it agrees therefore with the more precise solution of limiting depth given for the Texas-Kansas region.

Indeterminate evidence from anomaly contours.—The map of anomaly contours shown in Fig. 5, Part II, and reduced from Bowie, does not in general throw positive light on the depth of the masses which produce the anomalies of gravity. The necessarily generalized and smoothed-out character of this map has been discussed previously, especially in Part IV. A map based upon more numerous observations would show higher values of maximum anomaly and more of them. The centers of outstanding mass and the anomaly gradients would become better defined, and the distances from epicenter to half value of *Fv* would average smaller than shown at present. However, notwithstanding the defects, thirty-two measurements were made on this map of the distances from fifteen pronounced maxima to the anomaly contour of half value, and in directions not toward other adjacent maxima. This distance was chiefly controlled therefore by the single dominating mass. The measurements gave an average distance of 120 km.

If the outstanding masses which gave these anomalies were assumed to have the form of spheres, this would give their centers a depth of 160 km. and imply the existence of marked heterogeneity extending below the zone of compensation as given by Solution H. If the average form were assumed, however, to be that oblate mass shown in Fig. 9C, this distance to the contour of half value would correspond to a depth of 100 km. But such assumptions as to form are hypothetical and justifiable only as a step in successive approximations, not as a conclusion. The anomalies can be accounted for just as readily by an assumption of much shallower depths. The outstanding masses would then possess marked thinness in comparison with their breadth. They would be horizontally extended masses or the algebraic sum of many masses; in either case they could lie within a quarter of the depth indicated by the assumption of spherical form. The mere measurement of the mean distance from epicenter to half value of Fv is therefore wholly indeterminate except as regards the limits of regional compensation. In some respects, however, the present map does give suggestions. Let the attention be turned to these individual features.

A line of stations extends along the margin of the Coastal Plain from Washington, D.C., to Hoboken, New Jersey. The anomalies at the stations and their distances apart as measured on the map are as follows:

No. 22. Washington, D.C., +0.039 dyne
58 km.
No. 23. Baltimore, Md., −0.011
138 km.
No. 24. Philadelphia, Pa., +0.022
61 km.
No. 25. Princeton, N.J., −0.019
69 km.
No. 26. Hoboken, N.J., +0.024

This line of stations extends in the direction of the trend of the foundation rocks, yet the sign is reversed at every station, showing marked heterogeneity even in the direction of the strike. The average anomaly without regard to sign is 0.023, a little larger than the average for the whole United States. The average with respect to sign is +0.011. As there is only one station for each of the positive and negative masses the positions and magnitudes of the real maxima and the curves of changing anomaly are unknown. Masses in the upper half of the zone of compensation could produce these effects at these horizontal distances with but little mutual neutralization. Masses below the zone of compensation would, however, have to be very great, not only because the force decreases inversely with the square of the distance, but because masses of opposite sign whose centers are more than 120 km. deep and situated but from 60 to 70 km. apart would largely neutralize each other in their surface effects. Furthermore, there is no notable extension of the anomaly contours shown in any direction, and more especially at right angles to the line of stations, such as would suggest the wider fields of force due to deep-seated masses. If the masses were at great depth this limitation of attraction to regions near the epicenters could be produced only by a special checkerboard arrangement of opposite masses in all directions. It may be rather firmly concluded, therefore that the anomalies of this chain of stations along a line of low topographic relief are due to heterogeneities of density within the zone of compensation.

In certain regions, as in Florida, in western New York and Pennsylvania, and in the Great Basin, occur broad areas of anomaly showing no central maximum. To some extent this is doubtless due to incompleteness of observations, but in the areas mentioned the stations are so spaced as to show that even if the map were complete there would not exist marked domes of anomaly, such as those central at Minneapolis, Minnesota, and at Lead, South Dakota. This absence of domal form of anomaly curves suggests that the disturbing masses cannot be below the zone of compensation, but should be interpreted as due to the effects of masses widely distributed in the zone of compensation. This relation is especially striking in southern Nevada. The deflection residuals in northern Utah and Nevada all turn away from this southern area of defective mass, shown in Fig. 5, Part II, of this article, as located by Hayford and Bowie. Yet within this broad area of defective mass Station No. 67 shows an anomaly of only −0.013 and some of the surrounding anomalies have actually a larger negative value. There is here then an entire absence of a broad domal form. This is the region which indicates from the least-square equations of the deflections of the vertical the shallowest compensation within the United States; and the combination of the evidence from deflection residuals and anomaly contours goes to show that the anomalies are due to departures from isostasy within that shallow zone.

An inspection of Fig. 5, Part II, shows furthermore that the centers of plus and minus attraction as located by Hayford and Bowie from the deflections of the vertical, although in general agreement with the measurements of gravity anomalies, so far as the positive or negative sign of the center of mass is concerned, yet are not closely related to the large maxima. They are, in fact, in most cases decidedly eccentric to the anomaly contours. The scarcity of these areas is a result of incompleteness of observations, but their eccentric position and association with areas of moderate anomaly is not an error due to the reconnaissance nature of the studies. These relations indicate that the neighboring regions giving broad domal areas of anomaly are in such cases not due to the dominating control of centrospheric heterogeneity, for in that case the resultants of the deflection residuals would point over broad areas in the general direction of the epicenter of the mass. The degree of discordance between the centers of dominant anomaly and centers of dominant deflection indicates that fuller observations, would produce agreement by adding to the number of such centers. The present data suggest therefore that the areas of broad excess or defect of mass as shown by the anomaly map are due to aggregates more or less composite and shallow, so that each part influences individually to some extent the direction of the deflection residuals about it. Special combinations of masses of shallow depth with other masses below the zone of compensation could, however, also account for the effects. The data of the present map of gravity anomalies are therefore largely indeterminate, but the probabilities point toward at least the greater part of the outstanding masses lying well within the zone of compensation. In this conclusion the data agree with the other lines of evidence.

RELATION OF DEPTH OF OUTSTANDING MASSES TO HYPOTHESES REGARDING DISTRIBUTION OF COMPENSATION

The measurements of the deflection residuals are very much more detailed than are those of gravity anomalies. The evidence from them is rather conclusive that, for the regions investigated, the excesses or defects of mass which cause those residuals are situated within the zone of compensation and more especially in its outer half or third. Even if centers of outstanding mass were uniformly distributed, however, with respect to depth, they would lose influence in proportion to the square of their depth. Smaller masses which would exert a very appreciable effect if near the surface would, in consequence, not betray their existence if situated near the base of the zone of compensation. But the larger masses which are found to exist would exert a very visible control upon the deflections of the vertical, even if their centers were at a depth of 100–200 km. The fact that such depths have not been found suggests that the larger variations from the mean density within any one earth shell tend to occur in the outer half of the zone of compensation rather than in its deeper parts or immediately below it.

As a step toward the interpretation of the evidence, let the conclusion reached in Part II of this article be accepted: that regional isostasy for ordinary relief certainly extends to a radius of 100 and probably to 150 or 200 km. Even these limits do not reach the capacity of crustal strength. Such regional limits would not in reality be subject to sharp boundaries. This agrees with the evidence of geology in showing that mountain groups of circumdenudation—those whose relief is due to erosion and not to original differential vertical movement—are upheld by the rigidity of the crust. This applies to many of the mountain groups of the Appalachians; such, for example, as the Catskills.

The fairest initial hypothesis of isostatic compensation would be then to calculate for each station the average elevation of the country within a radius of 99 km., being the outer radius of zone N, and to assume a uniform density to these limits such as is needed to compensate this area. A second trial hypothesis would be to use as the radius of regional compensation the outer limits of zone O, 166.7 km. Under these two calculations for regional compensation the Catskills would be regarded as producing deflections which should show an excess of mass at the surface of the earth. Such an erosion basin as the Nashville basin should show, on the other hand, by its deflections a surface deficiency of mass. For the hypothesis which approaches nearest to the truth, the residuals of the deflections should be small and the outstanding masses would be determined by variations of density within the crust and not of the topography upon its surface.

Under the hypothesis of local compensation as given in Solution H the excess of mass in the Catskills would show, on the contrary, as a slightly excessive density throughout the whole zone of compensation; the Nashville basin as a slightly deficient density through the same depth. The residuals should indicate an outstanding excess and deficiency of mass respectively with the centers at a depth near the middle of the zone of compensation. But masses with centers at this depth and distance would have a very diminished maximum effect upon the residuals of the deflections of the vertical, and one largely modified by the effects of contiguous regions. Heterogeneities of density nearer the surface and not related to compensation would tend also to overshadow the error involved in the hypothesis of local compensation. It would appear then that the nature of the deflections is not very sensitive for testing the relative probability of the hypotheses of local versus regional compensation. The assistance of a computing office for trying out several hypotheses would probably bring to light, however, conclusions which would be more determinative. These statements must be regarded, therefore, as forecasts not yet subjected to the tests of computation.

In view of the preceding discussion it would seem that the deflection residuals of Solution H are chiefly of value for measuring the heterogeneities of density not related to topography, nor to the mantle of sedimentary rocks. This is especially true of the Texas–Kansas region studied in detail, for there the region is one of plains with an average elevation of about a thousand feet, and the demands of local isostasy as postulated in Solution H would call for a nearly uniform density under all this region. The outstanding masses represent in large part, therefore, real and local variations from a mean density of the continental crust.

But if masses of excess or defect of density similar to those numbered 2 and 5 of Fig. 12 were widely extended, say to a radius of 500 rather than 100 km., they would tend much more strongly to make for a local or intracontinental isostatic adjustment. They would become then not outstanding masses but in large part compensating masses. The outstanding masses represent the same kind of variations, therefore, which if more broadly extended would be in accord with an isostatic adjustment of topography to a different level. They suggest that if the zone of compensation of the continental crust be divided into three shells of 40 km. each in thickness, the greatest variations in density take place in the outer shell. This conclusion should be regarded as tentative, however, until confirmed by wider detailed studies and more numerous examples.

Accepting for the present this tentative conclusion, how does it agree with that previously reached—that isostatic compensation in some regions appears to go notably deeper than 122 km. and that, where deep, the residuals average smaller than for the continent in general? The answer would appear to be that moderate variations of density are sufficient to account for the isostatic relations of different parts of the continent to each other and that these moderate variations may go very deep.

If the actual distribution of compensation gradually disappears with depth, the hypothesis of uniform compensation complete at a certain depth corresponds to two outstanding masses, one just above the limiting surface, 122 km. in Solution H, the other just below that surface. But these masses would largely balance each other, having opposite signs; so that they would give at the surface of the earth but little evidence of their existence. Imperfections of the hypothesis in regard to the bottom of the zone of compensation would in consequence not readily be detected by methods for determining the depth of outstanding masses.

The isostatic balance of continental crust against oceanic crust is a somewhat different problem from that of the different segments of the continent with respect to each other. Solution H requires a mean difference in specific gravity of about 0.1 to a depth of 122 km. between the crust of the average continental and average oceanic segments. The contrasts in density are therefore pronounced and go very deep. Within the continent, on the other hand, the variations in density related to isostatic compensation are comparatively small and this investigation suggests that those variations may be more largely in the higher levels of the crust.

In conclusion, the depths of the outstanding masses are seen to be related to many problems in crustal statics and dynamics. The depth determines the magnitude of the masses involved and if known will serve as a test of various hypotheses. The excesses and defects of mass departing from that mean which is demanded by the best hypothesis will be a more accurate measure of the capacity of the rigid crust to carry without viscous yielding loads which have been borne through geologic time, hidden loads whose magnitudes in many regions appear to mask by contrast the present relief between mountains and valleys.

The measure and the meaning of the variable distribution of mass within the lithosphere constitutes an inviting field of geology, discernible in the present, but whose real exploration is a work of the future.

[*To be continued*]

NOTES ON THE GEOLOGY OF THE SUN RIVER DISTRICT, MONTANA

SIDNEY POWERS and HERVEY W. SHIMER
Massachusetts Institute of Technology, Boston

While making a geological examination last fall for the location of an irrigation dam on the North Fork of the Sun River, Montana, Professor W. O. Crosby made a careful collection of some fossils. The latter have been identified by the writers and they form the basis of these notes.

The Sun River has its origin in the Livingston Range and flows eastward to Great Falls. The district in which the fossils were collected, lies in the southern half of the Saypo atlas sheet, about 65 miles west of Great Falls. Owing to the paucity of names in this region, the Sun River is divided into a North Fork and a South Fork. These forks are in turn subdivided into North and South Forks. As only the North Fork of the Sun River is shown on the Saypo sheet, references will be made directly to the Sun River, implying the North Fork of this stream.

In the region near Milk River, about 70 miles northwest of the Sun River, Willis found one large overthrust of the Algonkian upon the Cretaceous.[1] It is probable that this overthrust divides into several smaller thrusts before reaching the Sun River.

There are nine N-S. "reefs" or ridges from the junction of the Sun River with its South Fork east to the Cretaceous plains. The indications are that each of these parallel ridges represents an overthrust to the east. Besides the field evidence of this structure is the evidence furnished by the stratigraphic position of the fossils. These were collected at too few points to show the existence of more than five faults. The fossils indicate a fault both east and west of the Dam Site. There is evidence also of a fault to the east of Arsenic Reef and of another separating the two ridges of Arsenic

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[1] G. S. A. Bull. 13, 1902, p. 305-52.

Reef. The fifth is an overthrust of the easternmost reef, the Carboniferous being found to overlie the Cretaceous. The reef west of the Dam Site—Black Reef—consists of monzonite. So far as known nothing has previously been published bearing on the geology of the Saypo quadrangle.

The fossils were collected from five localities which are numbered from west to east as on the accompanying map.

Locality 1.—At the big bend in the South Fork of the Sun River just north of the junction of Goat Creek with this stream. Embedded in a dark arenaceous shale were found:

Inoceramus labiatus Schlotheim, c.[1]
Lingula sp. c.

The horizon is probably Coloradoan Cretaceous.

Locality 2.—Immediately northwest of the junction of the Sun River with its South Fork. The rock here is a shaly, fine-grained sandstone.

Pleuromya subcompressa Meek C.
P. subcompressa webberensis M. and H., r.
Gryphaea calceola nebrascensis M. and H., r.
Pteria sp. R.
Ammonite, R.

The horizon is Ellis (Jurassic).

Locality 3.—At the Dam Site, just east of the junction of the Sun River with its South Fork. The rock is a dense brownish-gray limestone. The fossils are quite thoroughly silicified.

Syringopora surcularia Girty, c.
Lithostrotion whitneyi Meek, c.
Zaphrentis sp., c.
Productus semireticulatus (Martin), R.
Spirifer centronatus A. Winchell, C.

The horizon is Madison (Mississippian).

Locality 4.—Arsenic Reef lies west of Big George Gulch. At the Sun River valley it divides into two parallel ridges. On the western ridge Professor Crosby noted *Syringopora* and *Zaphrentis* in a hard limestone. It is therefore probably Madison in age.

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[1] C. indicates that the fossils collected are very abundant; c, abundant; r, rare; and R, very rare.

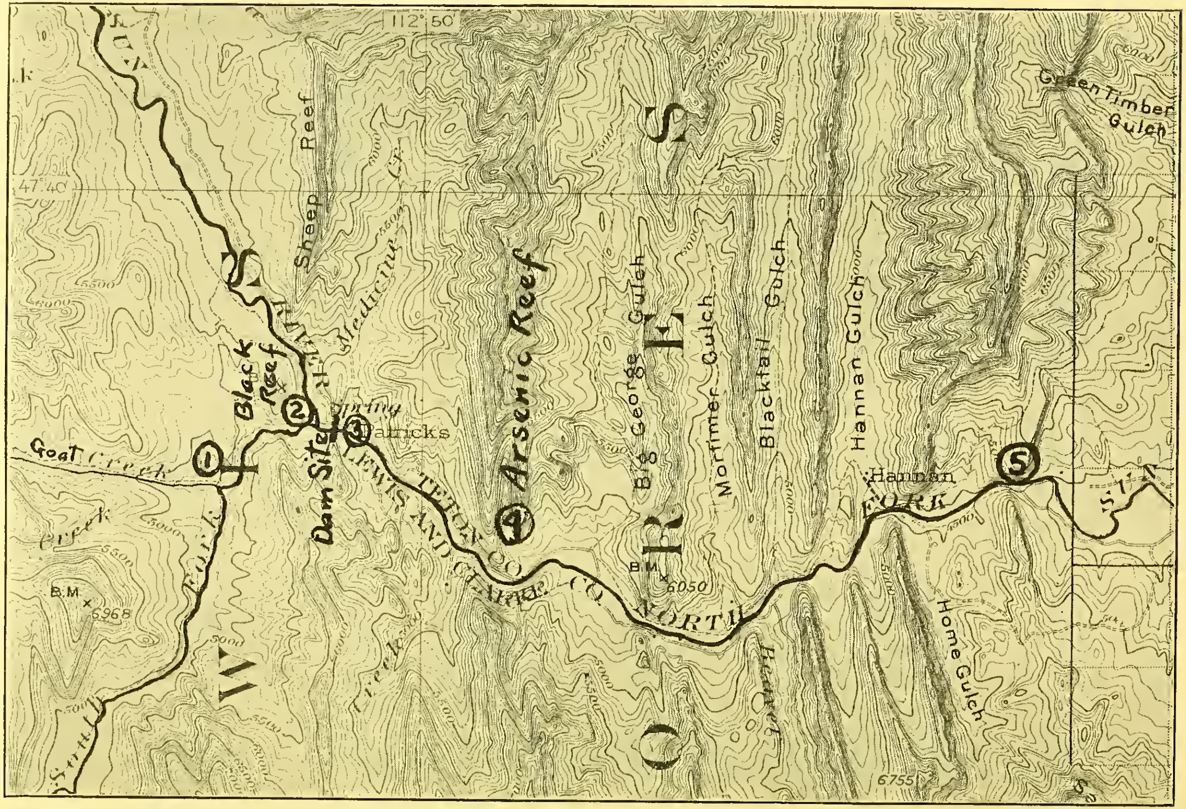

FIG. 1.—Map of a portion of the Saypo Quadrangle showing the fossil localities described in this paper. The localities are numbered 1 to 5.

On the eastern ridge is a softer, brownish limestone containing:

Atrypa missouriensis Miller, C.
Spirifer coniculus Girty, C.

The *Spirifer* indicates an Ouray (Devonian) age.

The *Atrypa* has been reported from the Three Forks (Devonian) shale in which it is abundant in the Yellowstone National Park area. It occurs in a finer-grained and slightly browner limestone than does the *Spirifer*. These two fossils have not been noted on the same piece of rock.

Locality 5.—The easternmost reef consists, according to Professor Crosby, of limestone containing the same corals—*Zaphrentis*, *Syringopora*, etc.—as are present at locality 3 and at the western ridge of Arsenic Reef, locality 4.

This limestone reef is, according to Professor Crosby, overthrust upon the Cretaceous beds to the east. One-fourth of a mile from the eastern edge of the reef a vertical drill core showed the Cretaceous shale beneath the limestone. The Cretaceous near the limestone is slightly folded, but farther east it is approximately horizontal.

CORRELATION AND STRUCTURE OF THE PRE-CAMBRIAN FORMATIONS OF THE GWINN IRON-BEARING DISTRICT OF MICHIGAN

R. C. ALLEN
Director, Michigan Geological Survey

Published information regarding the geology of the Gwinn district is very meager. In 1873, Major J. B. Brooks published[1] a brief description of the locality now occupied by the Princeton and Stegmiller mines, then known as the S. C. Smith mine, in sections 17, 18, and 20, T. 45, R. 25. In speaking of the occurrence of iron ore there he says: "The geographical position is less remarkable than what might be called its geological isolation, for it appears to be in a small patch of Huronian rocks, in the midst of a great area of barren territory, underlain by the Laurentian and Silurian systems." Brooks observed the black slate adjacent to the ore on the northeast in sections 17 and 18 and in "section 20, west of the river, a talcky schist, holding grains of quartz," but was unable to determine the stratigraphic relation of these rocks to the iron formation.

About ten years later this locality was again examined by Dr. Carl Rominger,[2] who writes as follows: "The Cheshire mine, formerly known as the S. C. Smith mine . . . . is working a strip of slaty and quartzose rock beds, known to extend along the valley of the Escanaba River for a distance of nine miles from the northwest corner of section 19, T. 46, R. 26, to the center of T. 45, R. 25." Rominger describes the rocks shown in the mining pits in sections 18 and 20, T. 45, R. 25, in considerable detail. He recognizes an iron formation underlain and overlain by slate. Owing to his misunderstanding of the structure his succession is reversed.

In 1911 the United States Geological Survey published a brief account of the geology of the Gwinn (Swanzy) district by C. R.

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[1] *Michigan Geological Survey*, I, 150–51.

[2] *Ibid.*, V, (1894), Part I, pp. 70–73.

Van Hise and C. K. Leith.[1] These authors had made no detailed survey of this district and attempted merely a summary of the information from other sources available to them at the time their monograph was written. They describe the Gwinn district as a southeastern-pitching synclinorium about two miles long and from one-half to two miles wide, the structure being unknown toward the southeast because of the deep overburden. They correlate the pre-Cambrian sedimentary rocks with the Upper Huronian (Animikee) series and describe them as (1) a basal "quartz slate and quartzite grading down into arkose or decomposed granite" which is overlain by (2) the Michigamme slate carrying the Bijiki iron-bearing formation in "lenses and layers" near its base.

Recent studies by the writer for the Michigan Geological Survey based on field mapping and an examination of the records of several hundred diamond drill holes show clearly that the Gwinn district contains *at least two* unconformable series of sedimentary rocks. It seems probable that the upper series, which will be described as the Princeton series, is equivalent to the Upper Huronian of the Marquette district, that the lower series, which will be described as the Gwinn series, is equivalent to the Middle Huronian of the Marquette district, and that the Lower Huronian series, while not present in the Gwinn synclinorium, is represented by certain fragments of quartzite and cherty slate in the conglomerate at the base of the lower or Gwinn series.

Without the information afforded by records of drill holes and other exploratory operations, any statement of the geology of the Gwinn district would probably be misleading and in any event necessarily fragmentary and incomplete. Outcrops are not plentiful except in certain restricted localities and are limited to the north two-fifths of the district. The records of drill holes, carefully compiled by geologists of the Cleveland Cliffs Iron Co. and the Oliver Iron Mining Co., are the main reliance for mapping the formations. Only a few of the drill samples were seen by the writer, but each of the formations is somewhere exposed either in outcrops or in excavations and was studied on the ground. It will be seen on the

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[1] C. R. Van Hise and C. K. Leith, *Monograph 52, U.S. Geological Survey,* pp. 283–86.

TABLE I

Table of Correlations. Marquette and Gwinn Districts

	Marquette District—United States Geological Survey	Gwinn District—U.S. Geol. Survey, 1911	Gwinn District—Mich. Geol. Survey, 1913
Quaternary system	Pleistocene series—glacial drift	Pleistocene series—glacial deposits	Pleistocene series—glacial deposits
Ordovician system Cambrian system	Unconformity Upper Cambrian (Potsdam sandstone)	Unconformity Limestone Sandstone	Unconformity Limestone and sandstone
Algonkian system—Keweenawan series	Unconformity Not identified but probably represented by part of intrusives in Upper Huronian	Unconformity	Unconformity Not identified but probably represented by basic dikes which intrude all of the pre-Cambrian formations
Huronian series Upper Huronian	Greenstone intrusives and extrusives Michigamme slate (slate and mica schist) locally represented by Clarksburg (volcanic) formation Bijiki schist (iron-bearing) Goodrich quartzite	Michigamme slate Bijiki iron-bearing member in lenses and layers near base of Michigamme slate Goodrich quartzite. Quartz slate and quartzite grading down into arkose or recomposed granite	Michigamme slate, carrying beds of ferruginous slate and chert, quartzite, and graywacke Conglomerate and graywacke (Goodrich)
Middle Huronian	Unconformity Negaunee formation (iron-bearing) Siamo slate Ajibik quartzite		Unconformity Iron-bearing formation and associated overlying and underlying slate (Negaunee-Siamo) Arkose conglomerate, arkose and quartz-slate conglomerate (Ajibik)

Lower Huronian	Unconformity Wewe slate Kona dolomite Mesnard quartzite		
Archean system Laurentian series Keewatin series	Unconformity Granite, syenite, peridotite Palmer gneiss Kitchi schist and Mona schist	Unconformity Granite	Unconformity Granite and greenstone, mainly granite

accompanying map that information is entirely wanting in some parts of the synclinorium and in other parts is insufficient for accurate mapping. Only a few of the many faults, which certainly occur, particularly in the north end of the district, have been mapped and the exact location and character of even those is not apparent.

The lithology of the various formations will be considered only so far as essential to an understanding of the succession and the correlations, but the discussion necessarily will be more in detail than the account published in *Monograph 52*, to which reference has been made.

Preliminary to the statement of the geology, there is given in parallel columns for comparison the succession and correlation of the United States Geological Survey and of the writer.

LOCATION AND TOPOGRAPHY, ETC.

The Gwinn synclinorium occupies an area about six miles long and from one to two miles wide, mainly in T. 45 N., R. 25 W., but extending a short distance into T. 44 N., R. 25 W. The trend of the major structure is about N. 45° W. or almost exactly parallel to the Republic trough, the southern end of which is 22 miles west and 6 miles north of the north end of the Gwinn fold. Gwinn, the principal village, is 16 miles south of the city of Marquette.

The southeast three-fifths of the Gwinn fold is buried beneath a featureless and almost flat sand plain which extends north and east to the hills of the Marquette range. In the opposite direction the surface is broken and hilly with occasional rock exposures. Granite hills encircle the northwest and north sides of the synclinorium. The district is drained by the Escanaba River, which follows the northeast side of the trough to Gwinn and then turns south across the sand plains. On the plains the water table is within a few feet of the surface and the ore bodies are deeply buried under water-saturated sand and gravel, a condition which is a serious menace to mining operations.

The first shipment of ore was made in 1872 from the Cheshire mine, now known as the Princeton No. 1 pit. About 1902 the Cleveland Cliffs Iron Co. purchased the Princeton (Swanzy, Cheshire) mine and during the time which has since elapsed has extended its holdings by purchase and lease until it now controls all of the known workable ore bodies with the exception of the Stegmiller, which is mined by the American (Oliver) Mining Co. Since the building of the beautiful and principal village of Gwinn by the Cleveland Cliffs Iron Co. the name of the district has been changed by common usage from Swanzy to Gwinn. There are five producing mines in the district. This number will be six in 1914, and probably eight in 1915. Concrete shafts have been sunk to two additional ore bodies but it is not known when these will be equipped for mining operations.

NOTES ON THE STRUCTURE OF THE GWINN SYNCLINORIUM

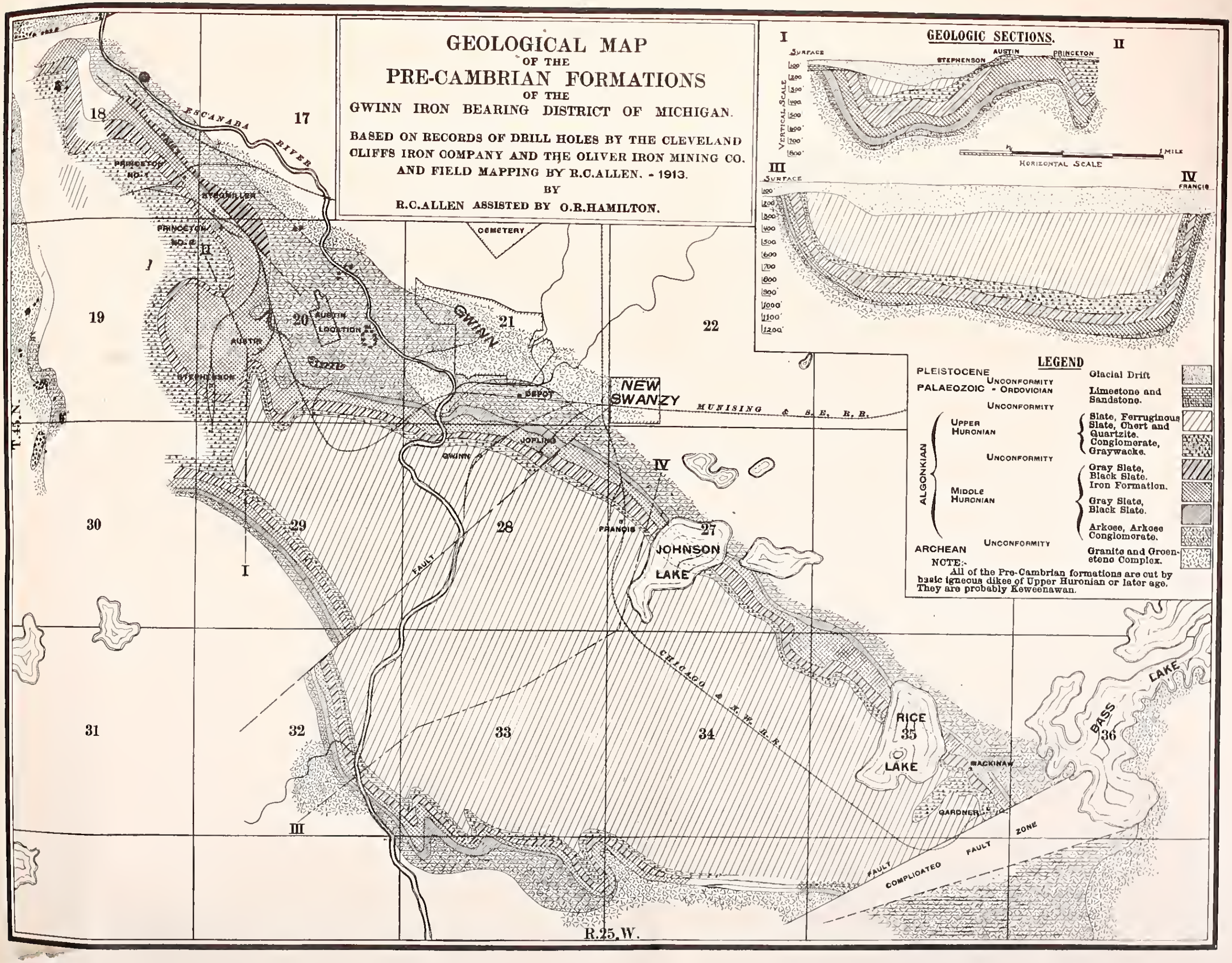
The Gwinn synclinorium contains two unconformable series of sedimentary rocks, having a combined thickness of from 800 to 1,000 ft. Outliers of flat-lying Paleozoic (Cambrian or Ordovician) sandstone and limestone occur throughout this area. The pre-Cambrian beds are remnants of formations, originally much more extensive, which have escaped erosion by downfolding or depression in the Archean basement.

The synclinorium is constricted to not more than three-fourths of a mile in width in the vicinity of the N.W. $\frac{1}{4}$ of section 29, T. 45, R. 25. North of the constricted portion, the rocks are folded and faulted in a complex manner but south of it the structure is apparently somewhat less complicated.

The southern three-fifths of the synclinorium is a spoon-shaped basin four miles long with a maximum width of about two miles. The deepest part of the fold is adjacent to the northeast limb where the Archean granite is reached in many drill holes at depths of from 1,000 to 1,200 ft. (see cross-section III–IV). Drilling along the southwest limb indicates a number of sharp drag folds pitching northwest. The folds on the opposite limb are not so sharp and are apparently simple cross-folds. The most prominent one appears in the S.E. $\frac{1}{4}$ of section 35. The synclinorium practically terminates against a faulted zone on the southeast. It is not possible to determine from present information the full extent of this zone nor the character of the faulting. The rocks in the faulted area are largely slate, chert, conglomerate, and breccia resembling lithologically the succession in the upper or Princeton series, but the regular succession of formations shown on both limbs of the fold terminates abruptly at the line indicated as a fault on the map. Another cross-fault probably trends diagonally northeast through section 28, producing a horizontal displacement of not less than 700 or 800 ft. in the N.E. $\frac{1}{4}$ of section 32 and from 150 to 200 ft. in the N. $\frac{1}{2}$ of the N.W. $\frac{1}{4}$ of section 28. The offset in the latter locality may be explained by folding, but the sharpness of the break in the former locality strongly suggests faulting. In any case, the extension and direction of the fault as indicated on the map is to a considerable degree hypothetical.

Knowledge of the structure of the northeast two-fifths of the Gwinn synclinorium pertains chiefly to the northeast limb. The most conspicuous structural feature of this limb is the broad cross-anticline responsible for the extraordinary surface exposure of the iron formation in the vicinity of the Austin and Stephenson mines, giving rise to two prominent synclines, the northern one carrying the Princeton No. 2 ore body and the southern one the Austin-Stephenson deposit (see cross-section I–II). Northward from Princeton No. 2 mine the east limb is overturned and dips at an angle of about 80° to the northeast, about parallel to a faulted contact with black slate extending from somewhere north of the Old Swanzy pit in the S.W. $\frac{1}{4}$ of the N.E. $\frac{1}{4}$ of section 18 southeast for a distance of probably more than a mile. Where observed in the Swanzy pit and in the Princeton No. 1 pit in the S.E. $\frac{1}{4}$ of section 18, the dip of the fault plane is northeast about 75° or 80°. Both the iron formation and the adjacent slate are intensely sheared along the zone of faulting. The belt of slates adjacent to the fault on the northeast may be stratigraphically either above or below the iron formation so far as the writer has proof. The upper and the lower slate members of the Gwinn series are lithologically very similar. Drill holes and the mine workings show that the iron formation in this vicinity lies directly on the basal arkose member of the Gwinn series with here and there a few feet of black slate lying between them. This makes it very probable that the slate belt northeast of the fault belongs to the upper slate member of


T.45.N.



GEOLOGICAL MAP
OF THE
PRE-CAMBRIAN FORMATIONS
OF THE
GWINN IRON BEARING DISTRICT OF MICHIGAN.

BASED ON RECORDS OF DRILL HOLES BY THE CLEVELAND CLIFFS IRON COMPANY AND THE OLIVER IRON MINING CO. AND FIELD MAPPING BY R.C.ALLEN. - 1913.

BY
R.C.ALLEN ASSISTED BY O.R.HAMILTON.

the Gwinn series. North of the middle of section 18, details of the structure are unknown but the distribution of formations indicated by the few exposures and drill holes suggests deformation by both folding and faulting of a complex character.

ARCHEAN SYSTEM

The Archean system comprises both acid and basic plutonic rocks, granite greatly predominating. These rocks inclose the synclinorium on the west, north, and east sides, encircling the north and northwest sides in bold hills and protruding through the drift in low knobs on the east side from New Swanzy northward. Numerous drill holes reach the system after penetrating the overlying sedimentaries within the borders of the synclinorium.

ALGONKIAN SYSTEM

The Algonkian system is represented by two unconformable series of Huronian sedimentary rocks, the Princeton (upper) and the Gwinn (lower) series. Both series are intruded by basic dikes, probably of Keweenawan age. The basal conglomerate of the Gwinn series contains pebbles and bowlders of quartzite, quartz slate, and siliceous, cherty, slightly dolomitic slate derived from a third sedimentary series unconformably below the Gwinn series but not present so far as known in the Gwinn synclinorium.

MIDDLE HURONIAN

GWINN SERIES

There are four members of the Gwinn series, viz., from the base upward, (1) conglomerate and arkose, (2) black slate and gray slate, (3) iron formation, and (4) black slate, gray slate, and graywacke.

1. *Conglomerate-arkose.*—The basal member of the Gwinn series is mainly arkose and arkose conglomerate. It lies on an uneven surface of Archean granite and is reported to occur in isolated patches over a considerable area outside of the Gwinn synclinorium. Within the fold its thickness varies from practically nothing to above 60 ft. The dominant phase of the member is arkose or decomposed granite. It is evident that the arkose has its origin

in the disintegration and subsequent sedimentation of the disintegrated particles of the underlying granite which in many places it resembles so closely that distinction is difficult. There are phases of the arkose in which the feldspar crystals show little perceptible wear, much less the quartz grains. It is particularly difficult to separate from granite in places near the contact where secondary mica has developed and veins of quartz and pegmatite occur like those in the granite. Phases in which there has been perceptible or conspicuous rounding of the quartz and feldspar particles are commonest and these may be either massive or schistose. The schistosity in the arkose is the result of mashing of the feldspars, by which process the quartz grains are generally not greatly affected. Where the arkose is overlain by the iron formation and particularly by iron ore, as in the mines north and west of Gwinn, it is in many places highly decomposed, soft, and iron stained, the feldspars being largely kaolinized.

The conglomerate is much less abundant than the arkose and according to drill records is not present in most localities. Its occurrence seems to be erratic and, curiously enough, where exposed in the S.E. $\frac{1}{4}$ of the S.W. $\frac{1}{4}$ of section 19, T. 45, R. 25, it lies some distance above the base of the formation. Drift bowlders of the conglomerate are rather plentiful but the only exposures known to the writer are in the S.W. $\frac{1}{4}$ of section 19. Here there are 12–15 ft. of it exposed in layers from 1 to 2 ft. thick dipping about 16° E. and striking N. 15° W. At this locality the contact with the granite is about 150 paces west. The matrix of the conglomerate is chiefly arkose but in one exposure it is siliceous, gray slate interbedded with the arkose. The pebbles are up to several inches in diameter and are mainly vein quartz which is abundant in the underlying granite. There are also many fragments of green schist, dense, vitreous, gray quartzite and siliceous, cherty, slightly dolomitic slate of grayish-green color. The composition of the conglomerate may also be studied to advantage on the waste dump of the Gwinn mine in the N.E. $\frac{1}{4}$ of the N.W. $\frac{1}{4}$ of section 28 where a bowlder bed was encountered in cutting the pumping-station in the shaft. All of the bowlders are well rounded and vary up to 6 to 7 inches in diameter. The matrix is arkose so decomposed that many of the bowlders are lying free on the dump. In addition to the rocks represented in the exposures in section 19 there are many bowlders of granite and greenstone.

The origin of the quartzite and slate pebbles is of great interest in its bearing on the correlation of the Gwinn series. Near Little Lake, about five miles east, in a range of hills on the north side of section 19, T. 45, R. 24, there are numerous outcrops of quartzite, quartz slate, and arkose. Van Hise and Leith considered these rocks to be the base (Goodrich quartzite) of the Gwinn series which we have described. In fact, their description seems to apply mainly to these exposures and not to the basal member of the Gwinn series as it actually exists in the Gwinn synclinorium. There is an arkose and arkose conglomerate in these exposures exactly similar even to the pebbles in its associated conglomerate, to the basal member of the Gwinn series. This formation, however, is plainly uncomformably below the quartzites and quartz slates, as proven by the occurrence of a coarse conglomerate at the base of the quartzite carrying numerous bowlders of the arkose some of which are as much as 2 ft. in diameter. The exposures at Little Lake are not in the Gwinn synclinorium but will be described in a later paper. The point is emphasized, however, that the presence of quartzite and cherty, quartz-slate pebbles in the basal member of the Gwinn series proves that there is at least one unconformable series of sediments between the Archean and the Gwinn series. The writer believes that this series is the Lower Huronian as represented in the Marquette district a short distance north.

2. *The lower slate.*—In the southeastern three-fifths of the district a black, graphitic, and gray slate formation intervenes between the basal arkose member and the iron formation. It is less generally present from the Stephenson mine northward, in this area never exceeding a few feet in thickness, but south of the Stephenson mine it varies up to above 60 ft. thick. Were it not for lithologic dissimilarity this slate would be included in the basal member, but inasmuch as it represents a distinct change in conditions of sedimentation and moreover seems to maintain a definite stratigraphic relation to the overlying and underlying formations, it should perhaps be described as a distinct member of the series.

3. *The iron-bearing member.*—Like the other formations in the Gwinn series the iron-bearing member varies markedly in thickness but is nevertheless persistent, occupying a constant and definite stratigraphic position in the series. The description of the occurrence of this member in "lenses and layers" in slate by Van Hise and Leith is misleading in so far as this implies that the member is discontinuous within the synclinorium. The thickness of the iron formation is ordinarily 50–100 ft. with a maximum of probably less than 125 ft. and a minimum of only a few feet as shown in some drill holes toward the center of the basin west of the Princeton and Stegmiller mines. Some sections show a greater thickness than 125 ft., which is accounted for by folding. The formation is thinner and at the same time leaner toward the west side of the synclinorium. All of the known ore bodies are on the east limb of the fold.

The iron formation is mainly banded, ferruginous chert similar to the "soft ore jasper" of the other Michigan ranges. The original or unaltered phase is cherty iron carbonate. North of the Swanzy pit in section 18, the base of the formation, as shown by drilling, seems to be mainly grünerite schist. This part of the district shows evidence of greater deformation by folding and faulting than areas farther south.

The upper part of the iron-bearing member is slaty in many places and the base of the overlying slate is here and there so ferruginous that it is a matter of choice as to whether it should be mapped as slate or iron formation. On the map these phases are included in the overlying slates.

The iron ores are both Bessemer and non-Bessemer grades, the latter greatly predominating, very soft and fine textured in the main and generally high in moisture. A purplish satin luster is a peculiar characteristic of the Gwinn ores. There are some pits in the upper part of the formation west of the Austin mine that show hard jasper and hard, blue hematite. Localization of the ores is largely coincident with synclinal troughs and faulted zones but is not limited to these structures. An inclined position of the iron formation between the overlying slate and underlying slate or arkose satisfies the structural requirements for ore concentration.

4. *The upper slate.*—The upper slate member is from 30 to 100 ft. thick. It is unconformably overlain by the basal conglomerate of the Princeton series. Its relation to the underlying iron-bearing member is largely gradational. It comprises an interbedded series of black slate, gray slate, and dark graywacke-quartzite. The black graphitic phase is more commonly directly above the iron formation than the gray slate, and the graywacke-quartzite phase seems to be in upper and middle horizons.

PRINCETON SERIES

The Princeton series consists of an interbedded series of slates, ferruginous slates, and cherts, quartzites, ferruginous quartzites, and graywacke with a basal conglomerate. The series is 400–500 ft. thick. Probably the entire thickness is not represented in the Gwinn fold. It is rarely seen in outcrops but it has been penetrated by numerous drill holes and some open pits. For the purpose of this article the interesting member is the basal conglomerate.

The basal conglomerate varies from 30 to 50 ft. to more than 100 ft. in thickness. Nearly all of the many drill holes which cross its horizon show its presence but here and there it is represented by a coarse graywacke. So far as known, the only exposures are in the S.E. $\frac{1}{4}$ of the N.E. $\frac{1}{4}$ of section 18, T. 45, R. 25, where a number of exposures occur on a low brush-covered ridge. Adjacent to them on the east the upper slate member of the Gwinn series is exposed in pits. The strike of the conglomerate is N. 70° W. and the dip 80° N.

The matrix of the conglomerate is coarse, dark graywacke-quartzite, the pebbles are chert and siliceous black slate, quartz, and arkose, derived from the underlying Gwinn series, and quartzite. The matrix carries a good deal of disseminated ferruginous material and some very small fragments of iron ore. There are also a good many small irregular cavities in the rock which are lined with hematite and limonite produced by weathering-out of iron-bearing fragments of some kind. The largest chert fragments are two to three inches long and one-half to an inch wide. All of them show wear by attrition, the smaller ones being generally lens shaped.

So far as can be ascertained, the Princeton and Gwinn series are structurally almost accordant. The strike of the conglomerate where exposed in section 18 indicates discordance in trend with the Gwinn series, but too little is known of the structure in that vicinity to place any importance on this observation.

KEWEENAWAN SERIES (?)

Basic dikes have been cut in a few drill holes and may be observed in section 20, T. 45, R. 25, cutting the basal arkose member of the Gwinn series. These dikes intrude both the Princeton and the Gwinn series. They are younger than Palaeozoic and older than the Princeton series. Their age is therefore probably Keweenawan.

PALEOZOIC

Isolated remnants of limestone and sandstone of Cambrian or Ordovician age, or possibly both, occur throughout the district. Some of these are in excess of 50 ft. thick. No fossils or other means of determining the exact age of these outliers is available at the present time.

CORRELATION OF THE GWINN AND THE PRINCETON SERIES

It has been shown that the pre-Cambrian sedimentary rocks of the Gwinn synclinorium consist of two unconformable series. The unconformity between them is marked by a basal conglomerate the position, extent, and thickness of which imply an important erosion interval which intervened between the periods of deposition of the two series.

Concerning the respective ages of these two series, it may be said that probably no geologist familiar with the pre-Cambrian formations of the Lake Superior region would correlate the Gwinn (lower) series with the Lower Huronian. It contains an important iron formation associated with graphitic slates, an assemblage of rocks not known in the Lower Huronian. Moreover, the basal conglomerate carries fragments of quartzite and quartz slate dissimilar to any known Archean sediments in Michigan but exactly similar to certain Lower Huronian rocks in the adjacent Marquette district. This evidence considered in connection with the unconformity separating the Princeton and the Gwinn series is a sufficient basis for the correlation suggested in this paper, but an additional consideration tending to show that the Gwinn series is

Middle Huronian appears in the absence from its basal conglomerate of jasper fragments from the Negaunee formation so strongly developed in the adjacent Marquette district.

Escape from the correlations suggested in this paper involves a disregard or subordination of the importance of the unconformity separating the Gwinn and the Princeton series. There is no certain evidence in this synclinorium of great structural discordance between these two series but it may be and probably is as great as that separating the Upper Huronian and the Middle Huronian series of the Marquette district. Great structural discordance could hardly be expected inasmuch as the main deformation took place after the deposition of the Princeton series. Some structural discordance is implied in the consideration that although the upper slate member of the Gwinn series was probably not cut through in this district, there was sufficient erosion in adjacent territory to uncover the different members of the entire Gwinn series prior to the deposition of the basal conglomerate of the Princeton series.

EVIDENCE OF THE MIDDLE-UPPER HURONIAN UNCONFORMITY IN THE QUARTZITE HILLS AT LITTLE LAKE, MICHIGAN

R. C. ALLEN AND L. P. BARRETT

A critical examination of the exposures of quartzite, quartz slate, and arkose in the hills near Little Lake in T. 45 N., R. 24 W., Marquette County, Michigan, was inspired by the results of recent studies by the senior writer in the Gwinn synclinorium, which lies between five and seven miles west.

The Gwinn synclinorium contains two series of Huronian sedimentary rocks, separated by an unconformity which is characterized by a conglomerate at the base of the upper (Princeton) series containing fragments derived from the various formations (including a productive iron-bearing member) of the lower (Gwinn) series and also from a third sedimentary series not represented in the synclinorium. The work at Little Lake resulted in the identification of an unconformity which, in connection with other data to be described, establishes a basis for correlation of the formations at Little Lake with certain of those in the Gwinn synclinorium.

So far as the writers are aware, no previous mapping and careful study of the rocks at Little Lake has been made. Rominger barely mentions the locality in 1894 in the statement that "iron-bearing rock beds occur in the vicinity of Little Lake."[1] Reference was again made to this locality in 1911 by Van Hise and Leith[2] who correlated the quartzite, quartz slate and arkose in the hills at Little Lake with the Goodrich quartzite or basal member of the Upper Huronian as developed in the Marquette district and the arkose and arkose conglomerate at the base of the Gwinn series in the adjacent Gwinn (Swanzy) synclinorium.

The succession and correlation of the formations in the Gwinn synclinorium and those at Little Lake are given below:

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[1] *Michigan Geological Survey*, 1894, Vol. V, Part I, p. 71.

[2] C. R. Van Hise and C. K. Leith, *Monograph 52, U. S. G. S.*, pp. 283-86.

CORRELATION TABLES

Gwinn Synclinorium and Little Lake Hills

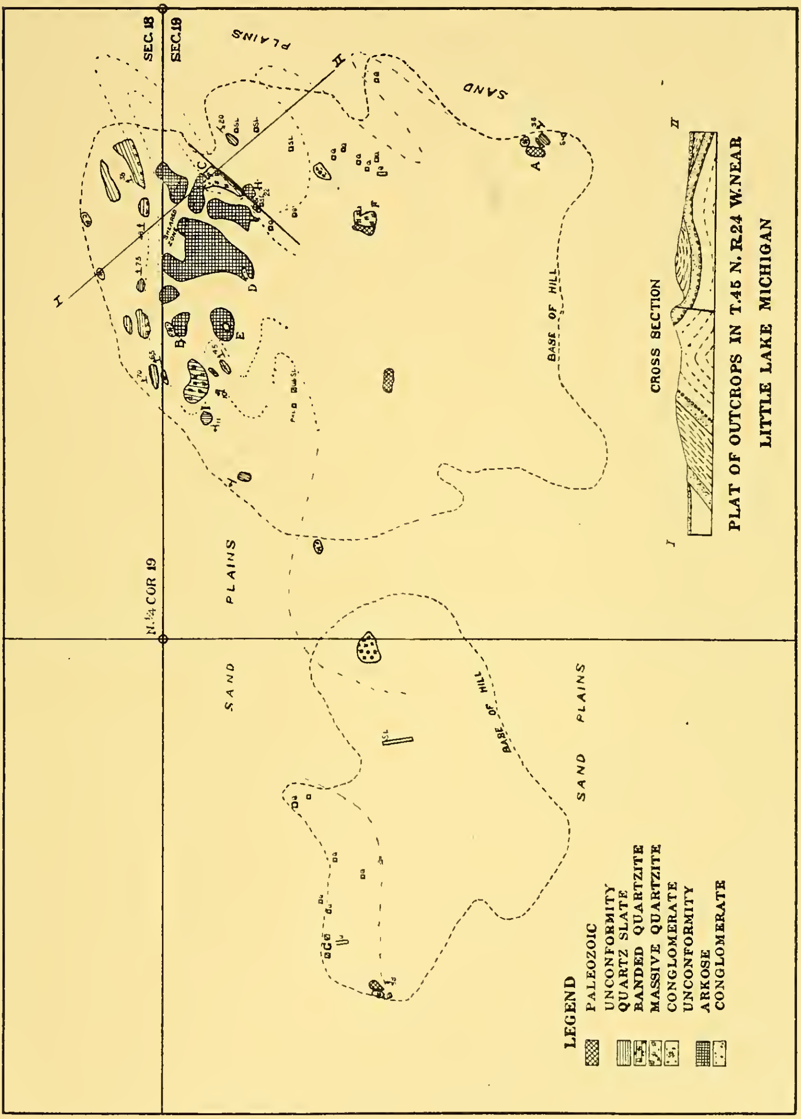
	Gwinn-Little Lake District, U.S. Geol. Survey, 1911.	Gwinn District, Mich. Geol. Survey, 1913.	Little Lake Hills, Michigan Geol. Survey, 1913.
Quaternary System	Pleistocene Series—Glacial Deposits.	Pleistocene Series—Glacial Deposits.	Pleistocene Series—Glacial Deposits.
Ordovician System? or Cambrian System?	Unconformity Limestone Sandstone	Unconformity Limestone and sandstone	Unconformity Limestone
Algonkian System—Keweenawan Series	Unconformity	Unconformity Not identified but probably represented by basic dikes which intrude all of the pre-Cambrian formations.	
Huronian Series Upper Huronian	Michigamme slate Bijiki iron bearing member in lenses and layers near base of Michigamme slate. Goodrich quartzite. Quartz slate and quartzite grading down into arkose or recomposed granite.	Michigamme slate, carrying beds of ferruginous slate and chert, quartzite, and graywacke. Conglomerate and graywacke (Goodrich).	Quartz slate and quartzite Conglomerate
Middle Huronian		Unconformity Iron-bearing formation and associated overlying and underlying slate (Negaunee-Siamo). Arkose conglomerate, arkose and quartz slate conglomerate (Ajibik).	Unconformity Conglomerate, arkose, and quartzite
Lower Huronian			
Archean System Laurentian Series Keewatin Series	Unconformity Granite	Unconformity Granite and greenstone, mainly granite	Not exposed near Little Lake Hills. Probably granite

STRUCTURE OF THE LITTLE LAKE HILLS

Rising to a height of possibly 100 feet above a featureless flat sand plain near the station of Little Lake are two hills on which there are many exposures of pre-Cambrian arkose, quartzite, and quartz slate with associated conglomerates. These hills present today, in reference to the fluvio-glacial sand plains in which their bases are buried, somewhat the same appearance that they seem to have had near the close of pre-Cambrian time, when they were monadnocks on a pre-Cambrian peneplain, for remnants of flat lying Paleozoic (Cambrian or Ordivician) limestone still cling to their sides and summits.

The eastern and larger hill is nearly a half-mile in diameter; the western and smaller one is about three-eighths of a mile long in an E.–W. direction with a basal width of about one-eighth of a mile. The exposures are most abundant on the north half of the east hill, but on both hills there are a large number of pits and trenches which were dug many years ago by prospectors whose diligence deserved a better reward than this locality seems to have offered. Aside from the red color of some of the quartz slate beds in the upper series, iron-stained shear zones in the quartzite and arkose, and an exposure at locality *F* (see figure) of about eighteen inches of hematite occupying a lens-shaped cavity along a zone of thrust faulting in massive quartzite, there appears no present evidence of the attractiveness which these hills seem to have presented to the early prospector for iron ore.

The structure of the north side of the east hill is apparently an anticline, the crest of which has been cut away by erosion, thus exposing the arkose and associated conglomerate of the lower (Gwinn) series flanked on the north, east, and west sides by conglomerate, quartzite, and quartz slate of the upper (Princeton) series. This is the only complete structural feature which can be determined from the available data. There is evidence in the development of cleavage and schistose structures, shear zones and faults of both normal and thrust type, that general deformation has been severe. Further evidence of the intensity of deformation is afforded in the overturning of the formations, with consequent apparent reversal in succession, in exposures at locality *A* at the southeast extremity of the east hill. While evidence of minor faulting is abundant in outcrops and pits, it is found impossible with information available to trace the course or measure the throw of any of these faults. The fault at locality *C-H* is a partial



PLAT OF OUTCROPS IN T.45 N. R.24 W. NEAR LITTLE LAKE MICHIGAN exception but the only thing known about this fault is its direction and the fact that its vertical displacement is inconsiderable. In reference to the structure of the west hill perhaps no inferences are warranted. So far as known, the arkose of the lower series is not exposed but the distribution of the lower and higher members of the upper series together with the topographic expression faintly suggests a shallow syncline trending across the hill in a N.E.–S.W. direction carrying the quartz slate member in the trough and exposing the underlying quartzite on its opposite flanks. But the structure is probably not so simple as this for there is evidence of faulting in some of the pits.

THE LOWER (GWINN) SERIES

Arkose and conglomerate.—The major portion of the arkose formation is in reality now an abundantly sericitic quartzite, the sericite being a metamorphic derivative of the original feldspar. The abundance of sericite affords on cleavage surfaces, a characteristic pearly luster. From the dominant phase there are gradations through intermediate phases to typical arkose with feldspar practically unaltered. Of subordinate importance are interstratified lenses of conglomerate varying from a foot or two up to eight feet in thickness. The pebbles are mainly vein quartz well rounded and of various sizes under four inches in diameter. Other pebbles of dense, vitreous, gray quartzite, black chert, and siliceous dolomitic slate are much less abundant. The matrix of the conglomerate beds has the composition of quartzite rather than arkose and is usually dark, dense, vitreous, and slightly sericitic.

Bedding structure is not observable in any of the various phases of the formation, except as it may be represented by an occasional thin layer of gray chert. The deposition of these cherty layers probably heralded the approach of a change in conditions of sedimentation represented by an iron-bearing member in the adjacent Gwinn synclinorium which lies in part directly on a similar arkose-conglomerate formation. At Little Lake the iron-bearing member appears to have been removed by erosion prior to the deposition of the overlying conglomerate and quartzites. The similarity of the arkose-conglomerate of Little Lake to that at the base of the Gwinn series extends to the pebble content. Rounded fragments of dolomitic siliceous slate, and gray quartzite are common to both localities, but the bowlders of granite and green schist which occur in the conglomerate of the Gwinn district were not observed in the exposures at Little Lake.

UPPER (PRINCETON) SERIES

The upper series, so far as represented at Little Lake, comprises a higher horizon of red- and gray-banded quartz slate and slaty quartzite grading down through banded quartzite and massive non-bedded quartzite into a basal conglomerate.

Conglomerate.—The contact of the upper and the lower series is exposed at localities *B* and *C* (see figure). At locality *B* this contact is distinguishable only on careful examination. The base of the upper series on weathered exposures is not conspicuously dissimilar to the underlying arkose except on freshly fractured surfaces which reveal, in contradistinction to the underlying sericitic, quartz-feldspar rock, a dense, hard matrix of quartzite holding pebbles of vein quartz of sizes less than an inch in diameter. At locality *C*, however, all doubt of the unconformable relations of the arkose-conglomerate and the overlying series is dispelled. The change from arkose to dense, black, vitreous quartzite is abrupt at a wavy contact of knife-like sharpness. In addition to the quartz pebbles observed at locality *C* there are pebbles of chert and large bowlders of the underlying arkose above one foot in diameter. The arkose bowlders are much softer than the embedding matrix of quartzite and weather out to form characteristic pit-like depressions. The full thickness of the basal conglomerate is not exposed at locality *C*, but at locality *B* it is apparently only six feet. At *C* only about four feet are observable.

Quartzite and quartz slate.—There are three distinct main phases of this series, viz., (1) a massive phase associated with the basal conglomerate, grading upward into (2) a banded phase which in turn is over-lain rather sharply by (3) beds of gray- and red-banded quartz slate. Although these three phases correspond to definite stratigraphic horizons, considerable difficulty is experienced in correlating the various exposures of the different members of this series. The chief difficulties refer to the relation of the quartzite on the west hill to that exposed on the east hill and to the determination of the stratigraphic position of the two outcrops of quartzite north of the slate at the base of the east hill. The outcrops of gray quartz slate and red-banded quartz slate on the north slope of the west hill are apparently stratigraphically above the exposures of quartzite in outcrops and pits on its northwest and northeast sides. Whether the quartzite at the base of the north slope of the east hill is stratigraphically above the quartz slate or represents the underlying massive quartzite brought up by faulting cannot be determined.

Extended description of the different phases of the quartz rocks in the upper series has little interest for present purposes. The dissimilarities of the different members refer mainly to texture and bedding structures rather than to composition. The red color of certain layers in the quartz slates is caused by the presence of small particles of finely disseminated hematite.

Notes on the correlation.—In a former paper the senior writer discussed the importance of the unconformity separating the Princeton (upper) and Gwinn (lower) series in the Gwinn synclinorium and adduced evidence in support of the correlation of these two series with the Upper and Middle Huronian. The lithologic similarity of the arkose-conglomerate formation at Little Lake to the basal member of the Gwinn series, only a few miles distant, considered in connection with the unconformity separating it from the overlying quartzites and quartz slates is a sufficient basis for extending the arguments for the correlations in the Gwinn district to cover the two unconformable series at Little Lake. The geology of each area accounts for three unconformable series of sedimentary rocks corresponding to the Lower, Middle, and Upper Huronian of the adjacent Marquette district. The upper two series are present while the lower one is represented in both areas by fragments of some of its formations in the base of the middle series.

The absence in the lower series at Little Lake of the slate and iron formation members developed in the Gwinn synclinorium strengthens the evidence of the importance of the erosion interval which intervened between the deposition of the Princeton and Gwinn series. Incidentally it has a practical bearing on the possibilities for success attendant on drilling for iron ore in the immediate vicinity of the Little Lake Hills. Some drilling, of which the writers have no records, has already been done and we understand that additional drilling is contemplated by parties who are likewise ignorant of the results of the former explorations.

PHYSIOGRAPHIC RELATIONS OF SERPENTINE, WITH SPECIAL REFERENCE TO THE SERPENTINE STOCK OF STATEN ISLAND, N.Y.

W. O. CROSBY
Massachusetts Institute of Technology

The serpentine highland of Staten Island is one of the most anomalous physiographic features of the Cretaceous peneplain of the Atlantic seaboard. This ancient and widespread base-level slopes southeastward and seaward from the highlands of Southern New York and Northern New Jersey; and from the latter district it has been designated, locally, the Schooley Plain. In its approach to the coast it is most continuously and perfectly preserved in the long, straight crest of the Palisade trap ridge. This approach is, in fact, unbroken to Kill Van Kull; and the peneplain passes below sea-level in the northwestern quarter of Staten Island. The normal seaward gradient of the peneplain, in the vicinity of the coast, as proved by numerous deep borings, ranges from 75 to 100 feet per mile; and nowhere else is it so perfect and so perfectly preserved as where it is still covered and protected by the Cretaceous sediments beneath which it was progressively buried as it slowly sank below sea-level, and in so sinking received its finishing touches in the addition of marine planation to terrestrial peneplanation.

Beneath the southeastern and southern plain or lowland of Staten Island, the peneplain, developed here on the Manhattan schists, has been found by the drill at depths (increasing seaward) of 200 to 400 feet, or just where its normal gradient would have led us to expect it. But between the northwestern and southeastern lowlands the continuity of the buried peneplain is interrupted by the great lenticular stock of serpentine nearly eight miles long from northeast to southwest and fully three miles in maximum breadth, and rising to an extreme height of nearly 400 feet above the sea, or 400 to fully 800 feet above the encircling peneplain. The southeastern slope, especially, of this relief is very abrupt and in part almost precipitous, the boldness of the ridge being, in general, one of its most impressive aspects. It is noteworthy, also, that it consists entirely of serpentine and embraces the entire known area of the serpentine. The Manhattan schist on the southeast side of the ridge and the Triassic trap and sandstone on the northwest side, are wholly outside of the highland area, being strictly confined to the lowland or, rather, to the underlying peneplain, although the trap, at least is far more resistant than the serpentine.

The serpentine relief clearly holds the general or formal relation of a monadnock to the Cretaceous peneplain above which it towers;

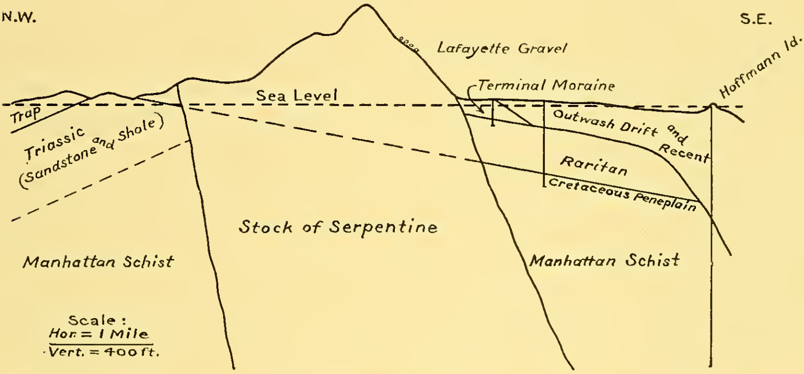


FIG. 1.—Cross-section of Staten Island, showing the geologic and topographic relations of the stock of serpentine.

and this most obvious interpretation of the Staten Island bedrock relief demands the first consideration. In this connection it may be noted that serpentine, owing to its insolubility and general chemical stability, imperviousness, massive structure, and tight joints offers greater resistance to erosion than its inferior hardness would indicate; and it is not improbable that in the relatively inert nature of the stone we have an adequate explanation of some of its topographic reliefs, especially where the surrounding formations are of a weak and yielding character. A general survey of serpentine occurrences, the world over, shows, however, that, almost regardless of the geologic environment, they are, if of a massive character (stocks, dikes, etc.), characterized by topographic relief.

Evidently, some other factor than differential erosion is required for a full and satisfactory explanation, especially in the case of such an ancient and pronounced serpentine relief as the Staten Island highland, standing, as it does, in close proximity to the coast and to the mouth of a large river. It is simply inconceivable that with its more complete exposure to the agents of erosion—subaerial, fluvial, and marine—the Staten Island serpentine stock should have been able successfully to resist erosion and maintain its high relief throughout the period during which the far harder and more resistant diabase of the nearby Palisade ridge was completely base-leveled.

The obvious inadequacy of the monadnock or residuary-relief explanation of the serpentine heights of Staten Island has led Willis and Dodge[1] to explain the relief of the serpentine by faulting. According to this explanation, Staten Island Heights would seem to stand as a solitary instance on our entire Atlantic seaboard of important post-Cretaceous faulting not due to glacial agency; and glacial drag and thrust must be powerless to elevate the bedrock *en masse*, especially at the extreme limit of the ice invasion. It is, however, further suggested by Willis and Dodge that this supposed faulting may be correlated with that traversing the Newark (Triassic) rocks of New Jersey; although it is commonly conceived that the faults of the Triassic strata date from Triassic time. Were they post-Cretaceous, they could not fail to break the continuity of the Cretaceous peneplain elsewhere than on Staten Island. The suggested faults would be rather unique, also, in closely circumscribing the serpentine area without traversing or breaking the inclosing schist or the Triassic sandstone and trap. Evidently, this explanation is not altogether satisfactory; and it appears advisable to seek further. In fact, we seem forced to the conclusion that the serpentine possesses an inherent power of growth or self-assertion that has enabled it, progressively, to lift its head above the base-level to which it may have been at least approximately reduced in Cretaceous time.

Assuming, as we must, that this great stock of massive and essentially structureless serpentine has been derived from some massive, basic, and highly magnesian igneous rock, such as peri-

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[1] *U.S. Geol. Survey, Folio 83; Science*, February 20, 1903.

dotite, we find in the process of serpentinization and the consequent inevitable expansion the requisite innate power of growth and topographic rejuvenation. This alteration, of which hydration is now the most important phase, and which is simplest, most direct, and most important for the mineral olivine, involves in every case a notable diminution of density and increase of volume, the volumetric gain, according to Van Hise,[1] ranging, with different species and varying conditions, approximately from 15 to 40 per cent. It is, of course, to this notable expansion that we owe the tightness of the joints and the internal slickensides and slip-fiber veins so characteristic of massive serpentine.

Under the conditions surrounding an approximately vertical plug or stock, at a great depth in the earth, the expansion due to serpentinization cannot be, to any large extent, isometric (cubic), but must take place chiefly or wholly upward, that is, in the direction to give it the maximum topographic value. This means that for the maximum ratio of expansion, 40 per cent, and ignoring contemporaneous erosion, the surface exposure of the serpentine stock would be elevated nearly 40 feet for every 100 feet in depth of peridotite altered to serpentine; or one-half as much for an assumed mean expansion of 20 per cent. These relief or topographic values may, however, be exceeded in the cases, probably numerous, where the diameter of the stock increases downward, the sepentine then reaching the surface by accelerated flow through a more or less contracted vent.

If we assume, with Van Hise,[2] that serpentinization is limited to the zone of katamorphism, the estimated depths of which range from 30,000 to 40,000 feet, the total vertical expansion in this zone, even for the minimum ratio, would still account many times over for the relief of the pseudo-monadnock of Staten Island Heights—a monadnock developed, in the main at least, subsequently to the peneplanation and in a manner suggesting comparison, rather, with the growth of the spine of Mont Pelé.

We have here, apparently, a new physiographic type, a variety of auto-relief not heretofore clearly recognized; and comparison with the spine or obelisk (pelélith) of Mont Pelé is inevitable The pelélith, we may suppose, resulted from the extrusion (or protrusion)

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[1] *U.S. Geol. Survey, Monograph 47.* [2] *Ibid.*

of a solid, and in the lower part merely a highly viscous, plug of lava by the vertical expansion of less viscous lava beneath, through the separation, due to cooling and relief of pressure, of aqueous and other vapors and various gases. The serpentine relief of Staten Island, on the other hand, is believed to be due to the extrusion (or protrusion) of a plug or stock of serpentine by the vertical expansion resulting from the progressive downward growth of the serpentine through the hydration and consequent swelling of the anhydrous magnesian rock in the alteration of which it has its origin. Reliefs formed after the manner of the Mont Pelé obelisk are now known as *pelêliths;* and parity of usage suggests *statenliths* as an appropriate designation for serpentine reliefs formed on the plan or after the manner of Staten Island Heights. It is, of course, conceivable that a rock formation, antecedent or subsequent, covering a serpentine stock may, by continued upward growth of the latter, be lifted into a dome; and such a dome, somewhat comparable with a laccolithic dome, may be called a statenlithic dome.

For proof that the statenlith of Staten Island is not unique, a solitary instance, we need look no farther than Castle Point, in Hoboken, between 7 and 8 miles north of Staten Island and approximately on the line of strike of the Staten Island serpentine stock. This point forms a hill about half a mile long and 100 feet high, consisting exclusively of serpentine. It holds the formal relation of a monadnock, not to the Cretaceous peneplain, but to the topographically lower Miocene base-level or partial peneplain very perfectly developed on the Manhattan schist and Triassic sandstone and shale of Hoboken and Jersey City. That this relatively small serpentine relief, standing on the very brink of the deep, buried gorge of the Hudson, post-dates the base-leveling of the inclosing formations is most probable. It is, thus, essentially similar in its geologic and physiographic relations to the Staten Island serpentine, a parallel instance, and unquestionably a true statenlith.

The question naturally arises at this point as to whether or not statenliths include only serpentine reliefs; and the answer must be that, on theoretic grounds, at least, various other secondary, hydrous silicates are entitled to recognition, notably the chlorites and probably talc. The chlorites are chiefly derived from augite, hornblende, and biotite; and the total expansion, including accessory epidote, quartz, iron oxide, etc., ranges approximately, according to Van Hise,[1] from 10 to 25 per cent. We are not restricted here to bodies of pure or approximately pure chlorite, such as chlorite schist; but may properly take account, also, of the vastly more extensive chloritic rocks known collectively as greenstones—massive, basic, igneous rocks (diabase, diorite, gabbro, etc.)—which have, in the zone of katamorphism, undergone the greenstone alteration, of which chloritization is the principal phase. The outcrops of dikes, stocks, etc., of greenstone are commonly protuberant; and if more salient than the relatively resistant nature of the rock would lead us to expect, we may find in the expansion, of which the chloritization is a reliable index, an entirely adequate explanation. Furthermore, the differential movement resulting from the expansion is very generally attested by internal slickensides.

Again, if the question be raised as to whether statenliths are necessarily limited to silicate rocks, the answer, on theoretic grounds at least, must be in the negative; for the hydration of anhydrite to form gypsum involves, in the absence of solution, the very notable expansion of 60.3 per cent; and the resultant deformation, it is well known, may be very severe. Also, it is matter of common knowledge that gypsum, in spite of its extreme softness and ready solubility, is not infrequently characterized by decided relief, and may be classed as to some extent a hill-forming rock. Occurring mainly or normally as a sedimentary deposit, it must, however, lack the power of persistent topographic rejuvenation, save where the strata have exceptional thickness or are highly inclined.

The dynamic and structural relations of the statenliths to the various other types of relief are expressed in the following systematic outline:

Outline of a Genetic Classification of Reliefs

Superficial Agencies
    Destruction (erosion) reliefs
        Youth = continuous, lobate plateaus
        Maturity = connected, dendritic ridges
        Senility = isolated hills—monadnocks

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[1] *U.S. Geol. Survey, Monograph 47.*

- Construction (accretion) reliefs
    - Littoral and fluvial = spits, bars, deltas
    - Eolian = dunes
    - Glacial = drumlins, moraines, eskers, kames

Subterranean Agencies

- Construction (accretion) reliefs
    - Igneous extrusion = volcanoes and peléliths
    - Igneous intrusion = laccoliths and laccolithic domes
    - Aqueous extrusion = tufa cones and terraces
    - Aqueous intrusion = crystosphenes and saline domes[1]
- Deformation reliefs
    - Plication = anticlinal and monoclinal ridges, domes and plateaus
    - Dislocation = block mountains and plateaus
    - Hydration and vertical swelling = statenliths and statenlithic domes

Serpentine is a rock of rather restricted distribution. In Eastern North America it is chiefly confined to the narrow and discontinuous Appalachian belt of peridotite and other basic magnesian rocks (to the alteration of which the serpentine owes its origin) in the western margin of the seaboard zone of crystalline rocks (igneous and metamorphic). In this belt, extending from Newfoundland and Gaspé Peninsula to Central Alabama, the basic magnesian rocks tend to occur in a series of isolated lenses (lenticular stocks and dikes) the axes of which coincide with the strike of the enclosing gneiss and schist.[2] The Staten Island and Hoboken stocks of serpentine are thus seen to be entirely typical in their structural relations; and it is a legitimate inference from these that all of the stocks in which serpentinization is well advanced are, theoretically at least, statenliths. Many of the serpentine stocks exhibit actual relief, notwithstanding the resistant nature of the inclosing formations; but rarely, probably, is the relief so marked or so sharply defined as in the type example.

[1] A crystosphene, as defined by Tyrell (*Journal of Geology*, XII, 232–36), is a lens of ice formed in or beneath the tundra of high latitudes and arching up or doming the overlying materials. It is here proposed to broaden the definition to include the saline domes of the Gulf Coastal Plain and, in general, all instances where the surface has been domed by mineral (ice, salt, sulphur, gypsum, etc.) segregation and crystallization. This appears permissible, since crystosphene may equally well be translated ice-wedge or crystal-wedge.

[2] *North Carolina Geological Survey*, Vol. I, Plate 4.

In Central Alabama the basic magnesian and serpentine belt passes beneath the Coastal Plain and the conditions become favorable to the occurrence of statenlithic domes. It is interesting, therefore, to find directly on this line 90 miles and 120 miles respectively, from the border, the Lower Peach Tree anticline and the Hatchetigbee anticline, the one intersected by the Alabama River and the other by the Tombigbee River. These deformations of the Coastal Plain sediments are essentially unique east of the Mississippi. That they are normal folds, due to horizontal compressive stress, is sufficiently improbable to suggest that they may be either saline domes or statenlithic domes; and it is hoped that the testimony of the drill will decide the matter in the near future.

Although these anticlines have marked geologic relief, the upward arching of the Eocene, and, presumably, of the Cretaceous strata amounting to hundreds of feet, they are devoid of topographic relief, the Pliocene (Lafayètte) strata crossing them without deviation. In other words, they were base-leveled in Pliocene time and have suffered no subsequent deformation, the power of growth, whatever its source, seeming to be quiescent or exhausted. A further distinct indication that they are not true statenlithic domes is found in the fact that their axes, trending with the strike of the Coastal Plain formations, are directly transverse to the course of the basic magnesian or serpentine belt.

It appears, then, that an unquestionable statenlithic dome remains to be identified; although it may be suggested in passing that in so far as the saline domes are due to the derivation *in situ* of gypsum from anhydrite they belong to this new type of relief.

The contact of the statenlith with the bordering formations is a true fault; and to this extent Willis and Dodge are right in their interpretation of Staten Island geology. But they err, as I believe, in correlating the obvious displacement with ordinary fracture and slip faults and with the extended, rectilinear displacements of the Triassic strata. The latter originated in a profound crustal readjustment involving the entire depth of the katamorphic zone and tapping, in some cases, reservoirs of the most truly abyssal magmas. The statenlith displacement, on the other hand, strictly limited to the periphery of the serpentine stock and to the katamorphic zone, finds its origin in the quiet and unobtrusive chemical reactions of that zone involved in the secular absorption and downward penetration of meteoric water, and the displacement must, obviously, die out downward.

Apparently, then, we have in the statenlith not only a new physiographic type, but also, in its periphery, a hitherto unrecognized type of fault, a type finding its origin in the localized, deep-seated expansion, through hydration, of the base of the upthrow block. Assuming that the horizontal dimensions of the statenlith increase downward, the encircling fault would be, structurally at least, of the normal or gravity type.

Pursuing this subject a step further, and recognizing that reversed or thrust faults are due to horizontal compression, that normal or gravity faults are due to vertical compression, and that vertical compression can yield only normal faults, we may, on genetic grounds, distinguish two types of normal faults: first, those due to the gravitative settling of the hanging wall block; and, second, those due to the upward expansion of the footwall block. The expansion of the footwall may be, in varying proportions, both thermal and aqueous, that is, due to the absorption of heat and of water, the normal fault of this type being the precise geologic concomitant of the statenlith.

On passing now to the consideration of the relations of the Staten Island statenlith to the history of the Coastal Plain, of which it is one of the most commanding relief features, we are confronted at the outset with the question as to whether or not the statenlith's innate power of topographic rejuvenation has enabled it to keep its head above water throughout Cretaceous and Tertiary times, thus making it a perpetual watch tower guarding the mouth of the Hudson. Although continuity of relief through geologic ages, a sort of physiographic immortality, is conceivable, it is, nevertheless, highly improbable. The clearest disproof of topographic perpetuity would, of course, be afforded by overlying Coastal Plain sediments; but this evidence, unfortunately, is almost wholly wanting; although its absence proves nothing to the contrary.

The only sediment referable to the Coastal Plain series now resting upon the Staten Island serpentine is the yellow gravel

(Lafayette) scantily preserved on a bench or terrace above the steep southeast slope of the serpentine ridge, at elevations of 180 to 220 feet above the sea. Since this gravel is identical in character with the Lafayette (Beacon Hill) of New Jersey, and the elevation is that normal for the Lafayette in the latitude of Staten Island, this correlation appears inevitable; although it involves the conclusion that the elevation of the marginal part of the serpentine, relatively to the Cretaceous peneplain, has remained unchanged since Pliocene time; with the further suggestion that the central and higher part of the serpentine (180 to 360+ feet) has experienced a differential elevation of nearly 200 feet in post-Pliocene time. An alternative but not very probable view is that the serpentine was not completely base-leveled in Pliocene time. That the central part of the stock should rise most rapidly or should continue to rise after the elevation of the periphery has virtually ceased is not difficult to understand, especially if the stock becomes larger downward, since in that case serpentinization of the central part may be conceived as lagging behind the serpentinization of the peripheral part.

As the surface of the ground is lowered by erosion, the lower limit of the zone of katamorphism and of serpentinization must be correspondingly depressed; although it is probable that the latter effect tends to lag behind the former. Downward extension of serpentinization means a 15 to 40 per cent or greater upward extension of the summit of the serpentine, the topographic relief of the serpentine being, thus, constantly renewed and increased. It is probable, however, that when erosion was sufficiently long continued with reference to a definite base-level, as during the Jurassic and early Cretaceous subaerial peneplanation and marine planation of the site of Staten Island, the process of serpentinization, overtaking the slowly receding and finally stationary lower limit of the zone of katamorphism, was, for the time being, virtually exhausted. The upward growth of the serpentine then ceased; and it was, at least approximately, base levelled with the surrounding formations, and, in due course, covered by the conformable series of Upper Cretaceous and Eocene sediments.

The marked elevation and consequent extensive erosion of the land in early Miocene, substantially repeated in early Pliocene time, probably depressed the lower limit of the zone of katamorphism and thus renewed serpentinization and the topographic relief of the serpentine stock. The meager data do not permit a more detailed or definite statement; but the best general conclusion appears to be that throughout the Coastal Plain history the downward extension of serpentinization and upward extension of the serpentine stock have been active during periods of elevation and rapid erosion and quiescent during periods of base-leveling and sedimentation; and that, in spite of the present strong relief of the serpentine, developed in large part, presumably, during the great Pleistocene elevation, the successive Coastal Plain formations have been, in general, deposited across the serpentine area.

The uniformity and virtual continuity of the narrow Appalachian belt of basic magnesian stocks and possible statenliths suggests uniformity of age or practical synchronism, the indicated age being, roughly, Mid-Paleozóic, and the argument being approximately as cogent as for the Triassic age of the similarly homogeneous belt of basic eruptive and irruptive rocks associated with the sediments of that formation. The purpose now, however, is not to insist upon the precise age of the stocks of peridotite and allied rocks of the ultra basic magnesian belt, but, rather, to point out that in spite of similarity of composition, structure, and age, they present strong contrasts in the degree or extent of serpentinization and hence, presumably, of the statenlithic development.

Recognizing that the process of serpentinization (and the same is true of chloritization) belongs, in the zone of katamorphism, not to the superficial and shallow belt of weathering, but to the deeper and vastly more extensive belt of cementation, we realize that climatic conditions must be eliminated as possible factors in the differentiation of the stocks. Hence the fact that in the northern half of the ultra-basic magnesian belt serpentinization is, superficially at least, more general, and, as a rule, more complete than in the southern half, is without climatic significance. The meaning of this contrast, which is to a large degree regional, is not readily apparent. But, whatever the initial cause of serpentinization, even though we tacitly assume its beginning, in any case, as essentially fortuitous or accidental, once begun this becomes a determining cause of its continuance; and the change spreads through the mass as a veritable mineral contagion.

Of more special interest now, however, is the fact that in Western North Carolina and elsewhere stocks of peridotite and of other rocks susceptible of the serpentine alteration are unaltered at least near the surface. This suggests that when the serpentinization of these masses begins, if not already begun, in the deep zone of cementation, the resultant statenlith must be, for a time, crowned with the unaltered peridotite or other original rock. We should, therefore, be prepared to recognize serpentine statenliths where no serpentine is exposed to observation. The relief of certain stocks of peridotite in Western North Carolina has been attributed to the supposed superior resistance to erosion of the peridotite as compared with the inclosing gneiss; but it is here suggested that deep-seated serpentinization, attested by peripheral slickensides, is an explanation worthy of some consideration.

THE MODE OF FORMATION OF CERTAIN GNEISSES IN THE HIGHLANDS OF NEW JERSEY

CLARENCE N. FENNER
Geophysical Laboratory, Carnegie Institution of Washington

PART I. OBSERVATION OF FIELD PHENOMENA

In Northwestern New Jersey a broad belt of pre-Cambrian crystalline rocks extends across the state and is prolonged northeasterly into New York, forming there the Highlands of the Hudson. On the southwestern side it is continued into Pennsylvania. The rocks which compose this belt are of considerable variety. Gneissic rocks of several types predominate, but beds of crystalline limestone are associated with them, and masses of rock of granitic and dioritic character, showing at times almost no foliation, are also present. The general trend is northeast and southwest, with steep dips, usually toward the southeast.

The geological character of the region as a whole and of various portions of it has been frequently described. As in other areas of similar foliated gneisses in various parts of the world, the question of origin of the various types has been a most puzzling one. Certain observers have held them to be highly metamorphosed sediments; others have favored the view that they represent the partial differentiation of a still fluid magma, which by continued movement has pressed out the differentiated portions into broad sheets; and a third view would attribute their structure to the shearing and recrystallization of an already solidified mass.

In a number of visits which the writer has made to various portions of the area, certain features have been observed in several places which were believed to be of considerable significance in the interpretation of the mode of origin of the rocks in which they occurred, and during the past summer (1913) especially favorable conditions for observation were found at a quarry which is being newly opened up at Pompton Junction. The quarrying operations and the stripping-off of the soil from a large area have disclosed the structural features in a very plain manner, and the relations thus revealed afford evidence toward an explanation of the processes by which the structures of the rock in question have originated. In this article it is proposed to give some description of the features found in this locality and to present the evidence regarding the mode of origin which they suggest. It has seemed desirable also to consider certain of the general properties of magmas with the purpose of finding an explanation for some of the phenomena observed in the field. It is believed that rock-types of a similar character are to be found in other portions of the area and indicate a similar origin, but at the same time it is recognized that the region as a whole is most complex and that this description and explanation do not apply to all parts of it.

In recent publications of the United States Geological Survey, W. S. Bayley and A. C. Spencer[1] have described in somewhat general terms certain features of the gneisses in a manner which indicates that a theory of origin similar in some respects to that which will be presented here was held in view, and others[2] appear to have favored similar explanations. Thus far, however, descriptions of the mode of action of the processes concerned, as illustrated by the resultant rock structures, and a discussion of the conditions under which they operated, appear to be lacking.

The quarry in question is that of the Pompton Pink Granite Company,[3] and is situated at the intersection of the New York, Susquehanna & Western Railroad and the Greenwood Lake Branch of the Erie Railroad, near the southeastern front of the Highlands.

A number of years ago a quarry was in operation at this point and a considerable amount of granite for building-purposes was obtained from it. The dressed stone was of a very pleasing appearance and was quite widely used, but difficulty was found in obtaining

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[1] W. S. Bayley and A. C. Spencer, *Franklin Furnace Folio* (1908), and *Passaic Folio* (1908).

[2] J. V. Lewis, *Annual Report of the State Geologist of New Jersey for 1908*, p. 64.

[3] I wish to express my appreciation of the courtesy of the general manager of the company, Mr. Charles H. McIntyre, for the opportunity which was afforded to visit the quarry workings and all parts of the property.

large blocks free from streaks and bands of dark-colored minerals. This objectionable feature probably led to the abandonment of the workings. Recently another company has taken hold of the property and without attempting to do much work at the old site they have gone several hundred feet up the ridge, at the base of which the old quarry lies, and have exposed great masses of granite of the same composition as before, nearly free from inclusions. Extensive operations are now being undertaken at this point.

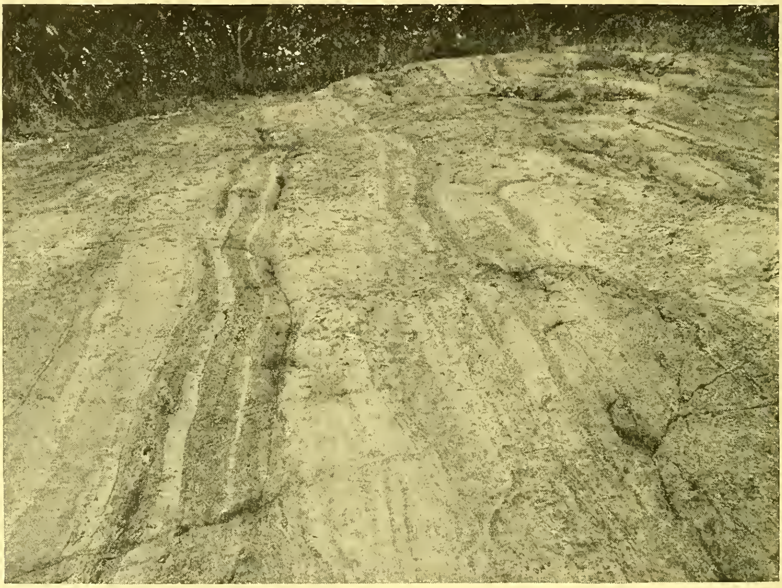

Fig. 1

In the *Annual Report of the State Geologist of New Jersey for 1908*, in an article on the building-stones of the state, J. V. Lewis gives an excellent description of the macroscopic and microscopic characteristics of the rock and some information regarding the field relations. It is evident that he recognized the intrusive nature of the granite into the gneisses of the region, but he does not enter into any extended description of the details and results of the process.

At the quarry itself and in the immediate vicinity two rock types are found, differing greatly from each other structurally.

The first is a very coarse-grained granite, almost a pegmatite in texture, in which crystals of microcline, or crystalline aggregates of the same mineral, occasionally attain a diameter of four or five inches. Where found in the largest masses it is almost free from dark minerals and consists essentially of quartz and two kinds of feldspar. In such places it is very massive and shows little or no indication of parallelism in the disposition of its constituent minerals. At the other extreme from this type is a finely banded gneiss, such as is shown in Fig. 1. This photograph was taken at an exposure of a large surface of glaciated rock about one-fourth mile (0.4 kilometer) north of the quarry, and the relations shown are typical of much of the rock in the vicinity. The light bands consist principally of quartz and feldspar, while the dark bands and streaks are characterized especially by large amounts of biotite, hornblende, or chlorite mixed with the quartz and feldspar. When developed in the manner shown in this photograph, either the dark or the light bands may individually have any thickness up

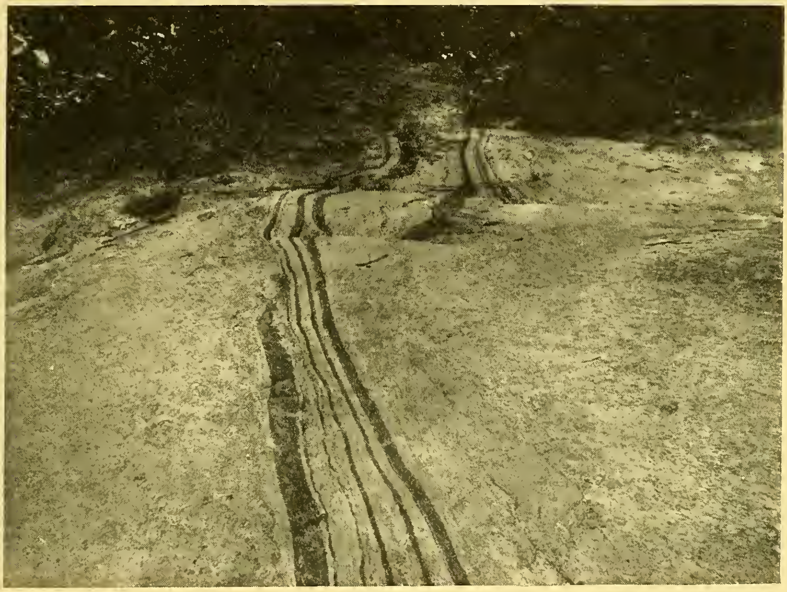

FIG. 2

to several inches, and show remarkable continuity and parallelism. The relations shown at this point, however, are by no means universal. It is found frequently that the lighter bands swell and pinch in an irregular manner and that the darker bands are interrupted or fade out in places and may be continued after an interval. By a further development of such features and by an increasing predominance of the light-colored bands, we arrive at such results as are shown in Figs. 2 and 3. These views show another portion of the glaciated surface at the same locality as Fig. 1 and represent dark bands separated by the light-colored granitic rock and bordered on both sides by large masses of granite. These two photographs illustrate very well the persistence and continuity sometimes shown by the bands of basic rock through masses of granite, and also the manner in which they may suddenly lose their identity and fade out within a few feet or inches. Fig. 4 is a sketch of the details at the termination of one of the bands of Fig. 3. Fig. 5 shows somewhat similar features.

FIG. 3

Microscopic examination of thin sections of the various types shows that the purest granite is made up almost entirely of microcline (having always a little microperthitic intergrowth) an acid plagioclase very near albite, and quartz. In such a type dark minerals may be almost lacking but when present they consist of aggregates of chlorite and epidote whose character bears evidence of a derivation from original biotite. Indications of a slight amount of deformation are often shown by strain shadows in the quartz and the curving of twinning lamellae in the feldspars, and in some cases this has gone so far as to produce cracks, along which epidote, chlorite, quartz, and calcite have been deposited. It is very evident, however, that nothing resembling granulation or mashing has occurred. In the darker bands the distinctive feature is the large amount of biotite or hornblende present. In addition quartz is an important constituent, as well as microcline and acid plagioclase. Magnetite is also quite common, together with such secondary products as chlorite, epidote, and sericite in rather minor

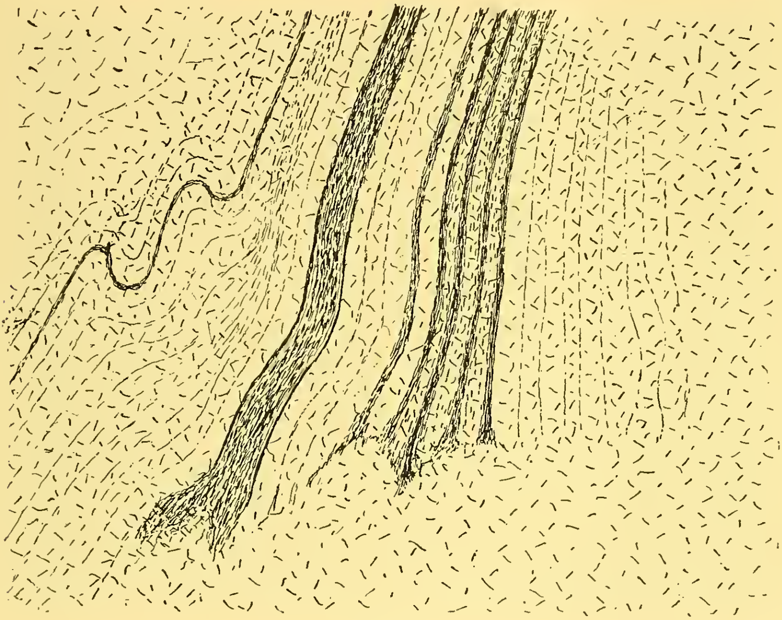

FIG. 4

amount. As in the massive granite, some indications of strain and deformation are apparent, but evidences of granulation to any important degree are lacking.

At the old quarry and at natural exposures in the neighborhood the rock masses exhibit features similar to those which have been described. Fig. 6 shows a portion of a glaciated surface adjacent to the old workings. The bands appearing in the foreground are composed of very dark hornblende-biotite gneiss, having a collective width of 2–3 feet, which are exposed for a length of about 25 feet and are cut off at both ends by granite. At their terminations the individual layers become considerably separated by an increase in the width of the dividing bands of granite. This is a feature which was noted in a number of instances. At each side there are large masses of coarse granite in which traces of dark minerals arranged in parallel lines are just visible.

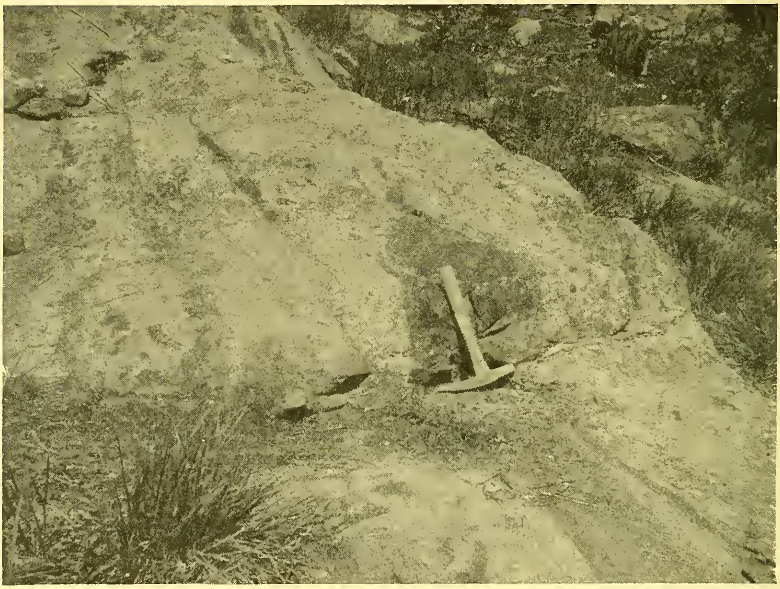

Fig. 5

In the old quarry, where dark inclusions are fairly plentiful, the quarry-faces, which are still perfectly fresh and clean, exhibit the finer details of the relations between the granite and the basic streaks more plainly than do natural surfaces. Figs. 7–11 represent such exposures. In the vicinity of the quarries the coarsely granitic material is far in excess of the banded rock, but occasionally the latter is very plentiful, especially in the older opening. In places there is probably as much of the finely foliated rock as of the massive material; in other places there are great masses of granite almost free from inclusions (Fig. 12). Between these two extremes there are all degrees of transition in relative proportions of the two. Quite frequently the contact between granite and inclusions is sharp, although the minerals at the border always interlock; elsewhere the minerals characteristic of the inclusion become more and more infrequent at the sides until only faint parallel lines can be seen in the granite. The manner of transition shows several interesting features. It appears in some cases that the basic minerals at the immediate contact have become involved in the granitic magma without losing their identity or parallelism, so that a perfect

FIG. 6

transition is produced from the hornblendic or biotitic gneiss or schist, in which foliation is prominent, through gradations in which the dark minerals become less and less noticeable and the proportion of granite increases, up to a type in which little or no parallelism of structure can be perceived. In other places the dark minerals appear to have been taken up or digested by the magma and to have crystallized out again in large blades. Even in the latter case it is not always certain that perfect solution has been effected at any one time. The process may have been rather in the nature of a chemical reaction with the original minerals or the solution and redeposition of a portion of the material at a time, leaving the general relations undisturbed. This possibility is

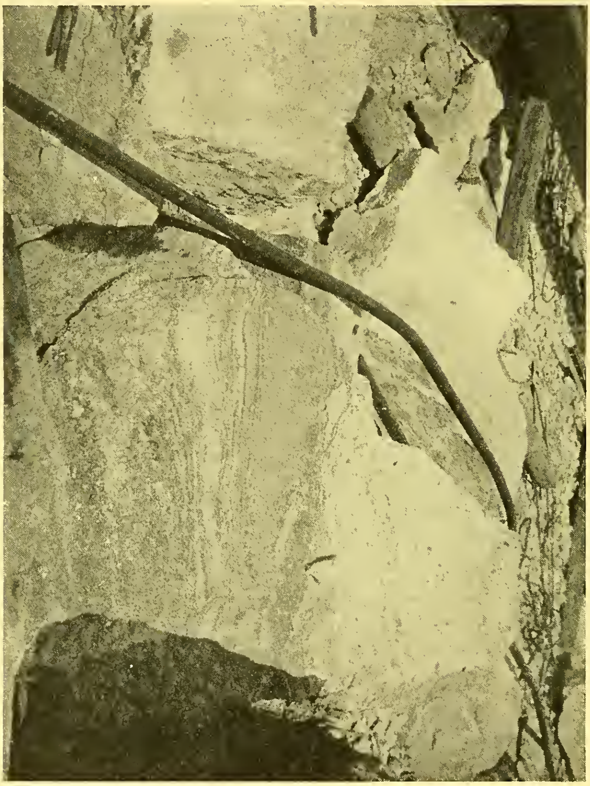

Fig. 7

suggested by the fact that frequently even the coarser micaceous blades or aggregates of dark minerals show evidence of parallelism, and this would be difficult to account for under the supposition that solution was so perfect that the original structure was completely wiped out. In Fig. 9 some of these features may be seen. The band of dark inclusions appearing in the middle of the quarry-face has a boundary with the granite on the left-hand side which is quite sharply defined and persistent. On the right there is more scattering of the dark minerals and an irregular, ill-defined marginal portion. Still farther to the right the original bands have been pretty well replaced by coarse granite and show only as scarcely traceable lines of coarse mica or chlorite. The block shown in Fig. 11 would by itself be considered a fairly normal massive granite, but even here a suggestion of parallel arrangement of the dark minerals may be perceived, surviving as a slight evidence of the process by which it has been produced. Frequently, however, in the largest masses of granite all indications of a parallel structure are absent.

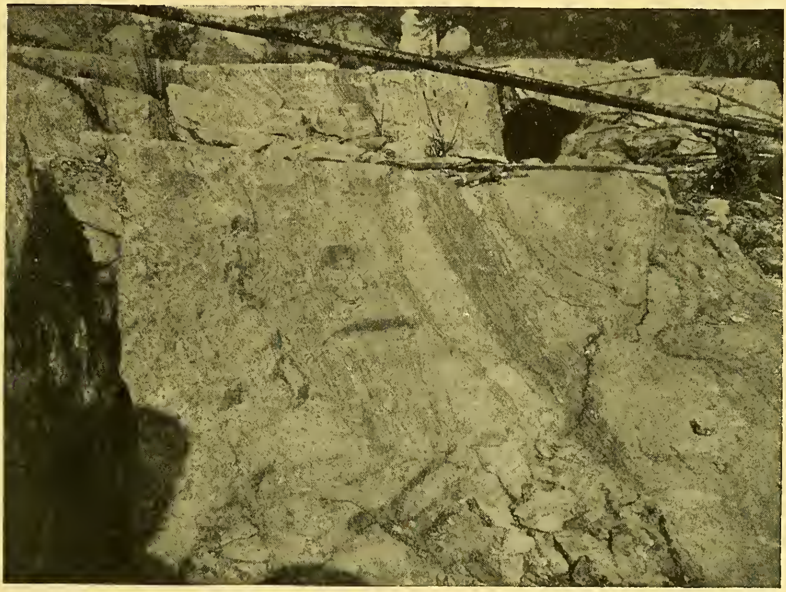

FIG. 8

It was observed in many instances that in such occurrences as show bands of basic rock in largest amount the adjacent granite contains the greatest quantity of dark silicates, and where inclusions are rare the granite is very light colored and nearly free from ferromagnesian minerals, and it seems probable that the invading magma was composed essentially of quartz and feldspars, and that the dark minerals, even in massive granite, were derived to a large degree from the rocks which were invaded.

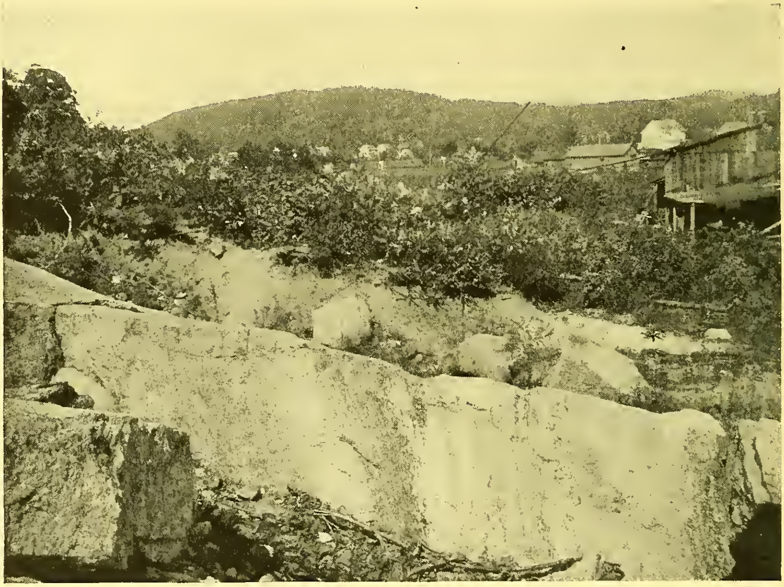

Fig. 9

In the foliated gneisses the light bands are frequently of the same composition and appearance as the granite of the large masses, and their relations to such bodies and their general characteristics are such as to point strongly to their being essentially portions of the same magma which have traveled long distances along parallel layers of inclosing rock. The mechanism of injection appears to have involved a progressive movement of a rather thin magma between the layers of a foliated rock, in some cases spreading them apart by the force of injection, elsewhere being transfused into the original layers and crystallizing these, or digesting and carrying away certain constituents, or entering into reactions with the component minerals. The variations found may be readily explained by the greater predominance of one or the other of these factors. The manner of action will be considered in more detail in Part II of this article. The fluidity of the magma is manifested by the narrowness and persistence of some of the injected layers. The question of the actual degree of fluidity will also be considered in the later discussion.

FIG. 10

Certain phenomena suggest that a force of crystallization may at times have been an effective factor in separating the layers. Aggregates of microcline and quartz crystals in the form of augen are seen, inclosed by curving bands of schist as in Fig. 13. Such augen may have suffered a small amount of deformation and granulation of the solid material by shearing movements subsequent to crystallization, but obviously not to such a degree as to drag out the crushed fragments into a band, as has occurred in some augen-gneisses.

Inasmuch as quarrying operations have exposed the rock masses in three dimensions, it is possible to arrive at a very clear conception of the form of the gneissic inclusions. It is seen that they dip very steeply and have an extension in depth comparable to their prolongation along the strike. Their form is therefore that of thinly tabular sheets.

FIG. 11

In general the strike of the bands is almost straight and conforms to the general northeast-southwest strike of the region, but in places the layers are more or less curved and occasionally so much contorted as to suggest a "kneading" of the material. In Fig. 10 one of the abrupt bends which are often visible is depicted. The movements in the magma by which such features were produced may perhaps be ascribed to the antagonism of forces brought into play by the up-welling of liquid magma into strata subjected to a tangential compression due to the weight of overlying rock. In all cases, however, the appearance of the contorted strata was such as to imply that the flexures were of a minor order, not involving large masses of rock but suggesting considerable freedom of movement among the component layers. The contortions appear to have originated during the period of injection and not during subsequent movements of solidified rock. Frequently individual bands are sharply bent, while others lying at either side, but separated by intervening granite, are nearly straight. An instance of this may be seen in Fig. 3. On the whole the general parallelism of the basic bands lying in the midst of masses of granite and the agreement of their strike with the general strike of the region was a noticeable feature and was considered important in its implication regarding the mechanism of the process by which the granite was injected. It implies that the granitic magma entered among the layers of a previously schistose or foliated rock without causing great disturbance in their position. Some of the layers appear to have become incorporated in the magma, others were forced

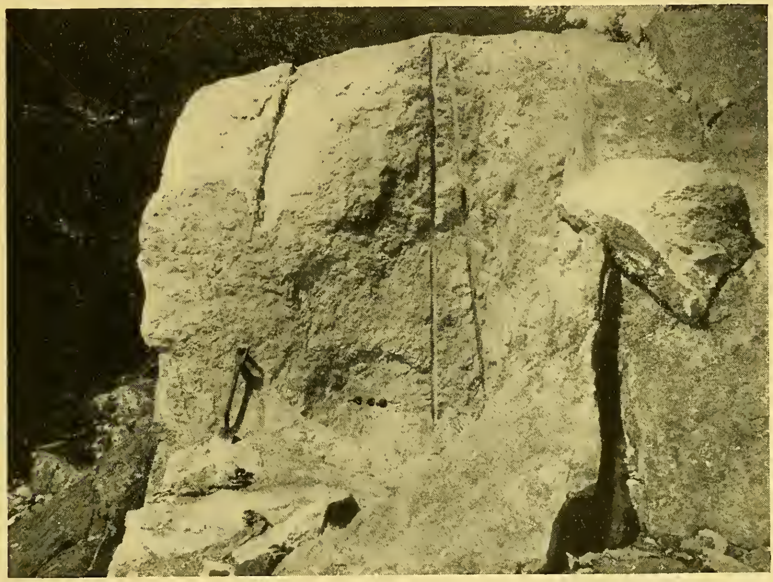

FIG. 12

apart and even sharply contorted in minor folds, but brecciation, or large disturbances of any sort appear to have been lacking. Where the invading magma entered in large quantity, movements of considerable amount within its mass appear to have occurred. One body having a width of nearly 200 feet was observed, in which the infrequent inclusions had a somewhat more blocklike form than in general and a variable strike, approaching at times a right angle to that which generally prevails, implying differential movements within this large mass of liquid. The dark bands shown in Fig. 14 lie somewhat to the northeast of this main mass of granite and trend directly toward it, and are bordered on either side by tongues or offshoots from it. As they approach the granite mass in their prolongation beyond the lower left-hand side of the photograph they curve much more toward the left and are finally cut off or dissolved by the granite.

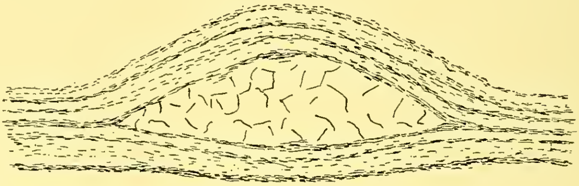

FIG. 13

In the process of igneous intrusion illustrated at this locality it is quite certain that nothing in the nature of "stoping" was a factor of importance. It is not intended to imply, however, that such a process may not have been the effective means of intrusion in other instances. It is assuredly true that in different localities and under varying conditions the mechanics of intrusion have been radically unlike.

Several of the features which have been described argue against the probability that the dark bands represent squeezed-out differentiates in a mass of magma. Probably the most impressive evidence in this connection is the sudden termination of certain sharply defined bands, with indications of corrosion at the end, which was frequently observed. The same phenomenon is opposed to the idea that the elongated structure of the bands of schist is essentially due to a plastic flow. Certain features of rupturing likewise suggest that the attributes of a rigid body were retained to some degree in such cases. Elsewhere, however, the phenomena are more consistent with the idea of softening. The abrupt flexures and general appearance of kneading of the material, as well as the manner in which certain bands gradually fade out along the strike, imply a partial fusion of the original material or a penetration of the magmatic liquor among the grains to such a degree that their mutual adhesion was diminished and some freedom of movement thus permitted.

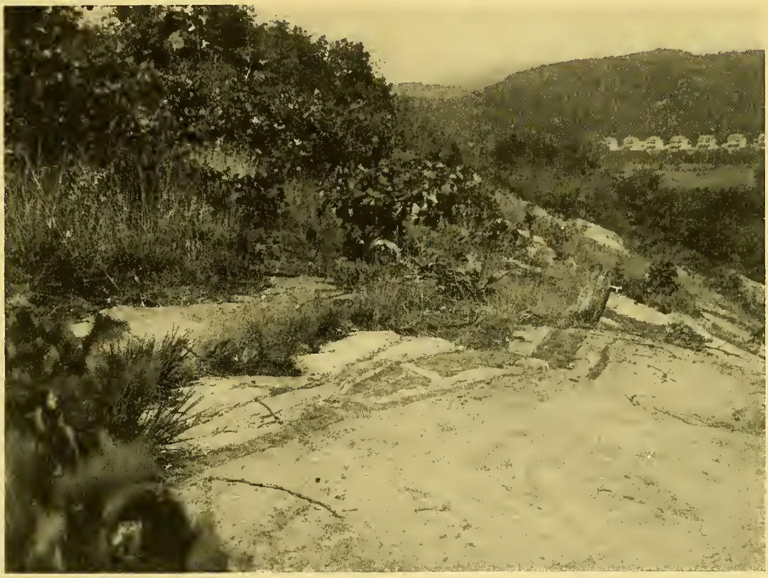

FIG. 14

There can be little doubt that during the period of intrusion the masses of rock now exposed were buried within the crust of the earth to a depth at which the increase of temperature due to the rise of the geotherms was considerable. In seeking an explanation of the phenomena of intrusion the question arises whether the conception which Sederholm[1] has advocated to account for the relations

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[1] J. J. Sederholm, *Bulletin de la Commis. Géol. de Finlande No. 23* (1907).

observed in certain areas of pre-Cambrian rocks of Fenno-Scandia may be applicable. He urges that in certain cases the strata have been buried to such a depth that the rocks as a whole have become plastic, and the more fusible portions have actually formed a magma at the horizon observed or at a comparatively small depth below. We are hardly warranted from the evidence at hand in accepting this explanation here. The general parallelism and straightness of the bands indicate that prior to the injection of magma the dominant characteristic of the rock was fissility rather than plasticity. The phenomena of softening must therefore be attributed to the injection itself, but the evidence shows that while the magma was still in movement softening had ensued, and we are led to conclude that the process of injection was long continued. It appears, however, that in the New Jersey Highlands large areas show evidences of granitic injection of the type which has been described, suggesting that beneath such areas the conditions necessary for the softening and flow of masses of rock may have been realized.

The process by which the granite and gneisses have assumed the relations described in the foregoing pages appears to be similar in many respects to that which French geologists, notably Michel-Lévy and Lacroix,[1] have termed *lit-par-lit* injection. In their typical examples the phenomena are attendant upon the intrusion of batholiths of igneous rock into areas of Paleozoic sediments, and the contact phenomena may be plainly seen. In the New Jersey example the appearances imply rather the presence of a reservoir of magma at some lower level, from which offshoots in large and small apophyses were injected into the roof and are now exposed for observation. In many respects, however, the mode of injection appears so similar that the same term may be applied.

It will readily be seen that the resultant gneisses are believed to be composite rocks, made up of material of different sorts, derived from different sources. An older, sheared or bedded rock is postulated, to which magmatic material has been contributed; first, by

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[1] The publications of these two authors which bear upon the subject are quite numerous. Special mention may be made of Michel-Lévy's *Bull. No. 36, Carte géol. fran.* (1893), and Lacroix's *Bull. No. 64* (1898) and *Bull. No. 71* (1900), *Carte géol. fran.*

injection along parallel layers, and second, by a process of absorption exerted by the original rock upon the injected magma. The latter process will be discussed a little later.

The nature of the original rock does not appear at all certain. The laminated character might as well be considered as representing bedding planes in a sedimentary series or shear planes in a schist of either sedimentary or igneous origin. The prevalence of ferromagnesian minerals in many of the bands might be supposed to imply a derivation from a basic igneous rock, but there is a question as to how far the present composition represents that of the original material. The French geologists mentioned have directed special attention to the profound changes wrought in the composition of the original sediments by "imbibition" of material derived from the igneous mass. Sederholm also has described similar phenomena accompanying the process of granitization, and the work of Adams and Barlow[1] in the Haliburton and Bancroft areas of Ontario is of great importance in this connection. The last-named geologists present evidence of the metamorphism over large areas of the pure, non-magnesian limestones of the Hastings-Grenville series into amphibolites and pyroxene-gneisses by transfusion of material from invading batholiths of granite.

There is some evidence not far distant from the quarries described that not all of the original rocks of the region could have been of a basic igneous character. About two miles ($3\frac{1}{4}$ kilometers) to the north, a little west of the railway station at Haskell, a bed of crystalline limestone or dolomite occurs in the gneissic series. The thickness is somewhat uncertain but appears to be 20 feet or more. In places the amount of carbonate minerals is large, though tremolite, phlogopite, and a pale-green pyroxene are extensively developed, as well as secondary serpentine. Elsewhere along the same belt carbonates appear to be wholly absent and the rock consists almost entirely of the greenish pyroxene or a mixture of pyroxene and quartz. The belt can be traced by occasional outcrops for several hundred feet. In one place a gneiss composed of feldspar, quartz, biotite, and much garnet occupies a

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[1] Adams and Barlow, "Geology of the Haliburton and Bancroft Areas," *Memoir No. 6, Canadian Geological Survey* (1910); see especially pp. 87 and 157.

position either on the strike of the limestone or closely adjacent. The strike of the limestone bed is parallel to that of the associated gneisses—an indication that part at least of the foliation is to be attributed to an original bedding. The manner in which minerals from the magma may have been introduced into the limestone and other sedimentary beds will be considered in the discussion which follows.

[*To be continued*]

THE MISSISSIPPIAN ROCKS OF NORTHEASTERN OKLAHOMA[1]

L. C. SNIDER
Norman, Oklahoma

At a recent conference of the state geologists of the states of the Mississippi Valley it was decided to have prepared a brief tabular statement showing the present state of knowledge of the Mississippian rocks in each state, for use of those interested. This tabular statement for Oklahoma has been prepared by the writer. However, such a table is necessarily greatly condensed, and this paper has been prepared to give a somewhat more detailed statement of our present knowledge of these rocks.

The brief outline presented herewith is the result of a rather thorough examination of the literature on the region, and of about five months of field work by the writer, assisted by J. B. Newby. The field work has not been completed, and there are still several points of stratigraphy and correlation on which definite statements cannot be made. The paleontological collections have been studied in only a preliminary way and the faunal lists are necessarily incomplete.

LOCATION AND AREA

The Mississippian area in Northeastern Oklahoma is the southwestward extension of the Ozark Uplift of Missouri and Arkansas. It occupies the extreme northeastern part of the state, including all of Delaware and parts of Ottawa, Craig, Mayes, Wagoner, Cherokee, Adair, and Sequoyah counties. Portions of the Wyandotte, Vinita, Pryor, Siloam Springs, Tahlequah, and Muskogee quadrangles of the United States Geological Survey are included in the area. The region considered, and the relative position of the quadrangles are shown in the sketch map (Fig. 1). The Tahlequah and Muskogee quadrangles were surveyed by Joseph A. Taff for the United States Geological Survey, and the folios

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[1] By permission of the Director of the Oklahoma Geological Survey.

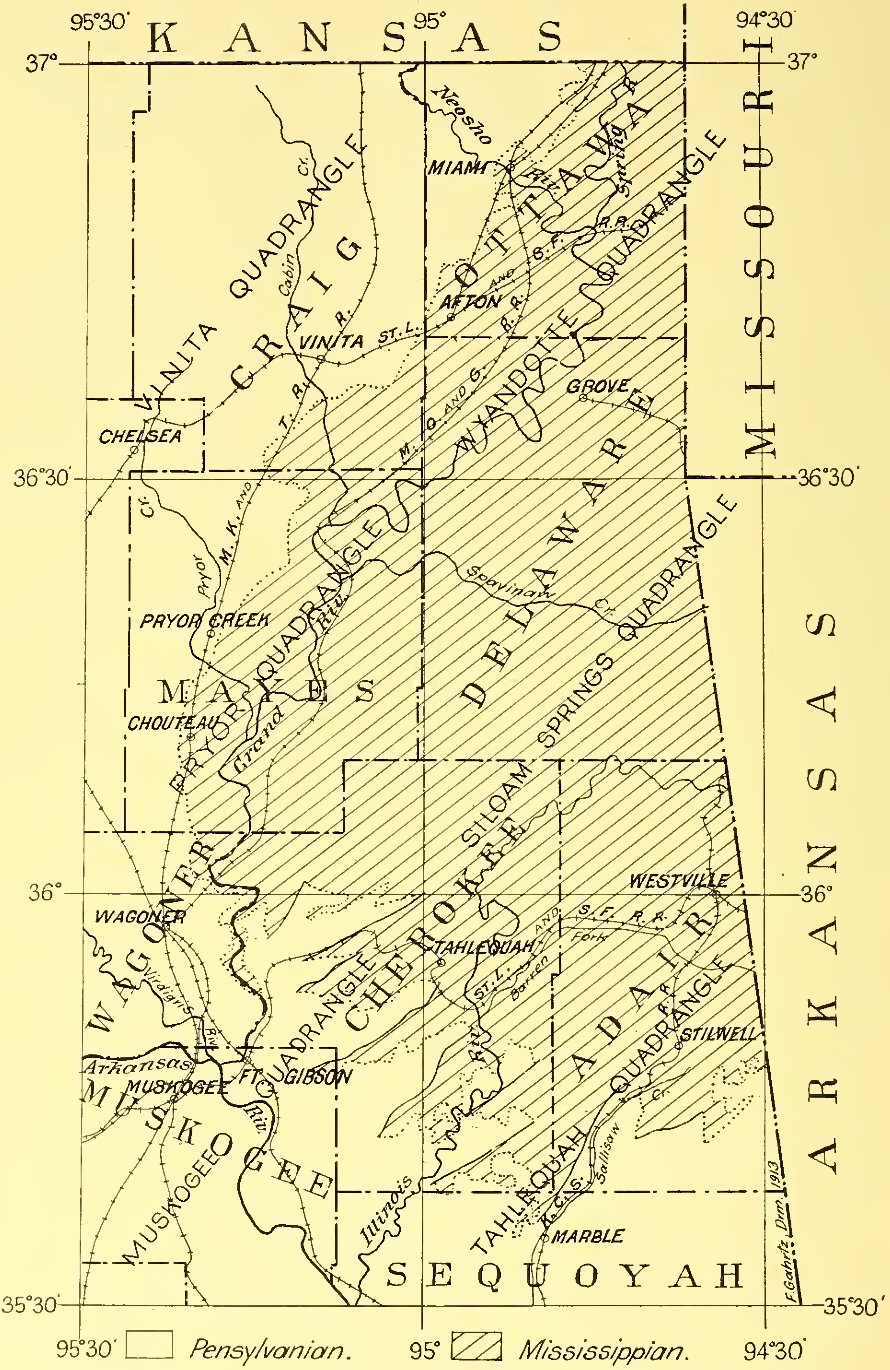

FIG. 1.—Sketch map of a portion of Northeastern Oklahoma showing the Mississippian area.

published several years ago. The Wyandotte quadrangle was surveyed by C. E. Siebenthal in 1907, and the Vinita quadrangle by D. W. Ohern in 1909, but the folios have not been published. The references to the geology of the Tahlequah and Muskogee quadrangles are to be attributed to the folios (Nos. 122 and 132 respectively) of the *Geologic Atlas of the United States*, prepared by Joseph A. Taff. It is not thought necessary to give footnotes for the individual references.

STRATIGRAPHY AND PALEONTOLOGY

The Mississippian rocks of Northeastern Oklahoma comprise the following formations named from the base up: Boone formation, unnamed limestone, Fayetteville shale, and Pitkin limestone. The stratigraphy of all these formations varies considerably as the outcrops are followed west from the Arkansas line along the south side of the area and then north along the west side.

Boone formation.—The Boone formation covers by far the greater part of the area under consideration. In the Tahlequah and Siloam Springs quadrangles some of the deeper valleys are cut through the Boone into the underlying Devonian, Silurian, and Ordovician rocks, but the outcrops of these rocks are narrow and the Boone covers all the area indicated, except a comparatively narrow belt around the margin, which is occupied by the younger formations, and the outliers of these formations.

The Boone consists principally of limestone and chert, with a total thickness of from 100 to 350 feet. At or near the base of the formation there is locally a limestone member of up to 30 feet or even more in thickness. The upper part of this limestone is free from chert, thick-bedded, light-colored, and crinoidal. Near the Arkansas line, in the Tahlequah quadrangle, the limestone is locally absent so that the cherts rest directly on the Chattanooga shale. In no place in this quadrangle is the limestone reported as being over 15 feet in thickness. This thickness is exceeded in the Siloam Springs quadrangle, and the limestone is continuous to the northwest so far as observed. In the northern part of the area there are several feet of shaly limestone and flaggy limestone below the thick, crinoidal ledge which in this region is 10 to 15 feet thick.

This lower limestone member is correlated with the St. Joe limestone (marble) member of the Boone formation in Arkansas. It is well exposed in the Siloam Springs quadrangle along the Illinois River and some of its tributaries, along Spavinaw Creek in the Siloam Springs and Pryor quadrangles, and along the larger tributaries of Grand (Neosho) River in the Vinita and Wyandotte quadrangles. From collections made along the Illinois River in the Siloam Springs quadrangle, the following brachiopods have been identified: *Rhipidomella michelinia* L'Eveille, *Chonetes logani* N. and P., *Productus fernglenensis* Weller, *P. sampsoni* Weller, *P. sp.*, *Spirifer grimesi* Hall, *S. vernonensis* Swallow, *S. fernglenensis* Weller, *S. choteauensis* Weller, *Spiriferina subtexta* White, *Cyrtina burlingtonensis* Rowley, *Reticularia pseudolineata* Hall (?), *Cleiothyris royssi* L'Eveille (?), *Athyris lamellosa* L'Eveille, and *Ptychospira sexplicata* W. and W. The remainder of the fauna has not been studied, but the corals and some of the bryozoa appear to be identical with those described by Weller[1] from the Fern Glen formation, and which occur in the lower beds described in the next paragraph.

Locally there are darker-colored limestones with greenish shales below the St. Joe member. Taff describes these as occurring in one outcrop near the northern border of the Tahlequah quadrangle, where they have a thickness of 6 feet. A few miles to the north in the Siloam Springs quadrangle these same dark-colored limestones and green shales reach a thickness of about 40 feet, but they vary greatly in thickness in very short distances. The fauna of these rocks shows them to be equivalent to the Fern Glen formation of Missouri. To the northwest these rocks thin rapidly and in the northeastern part of the Pryor quadrangle along Spavinaw Creek, and in the southeastern part of the Vinita quadrangle along Big Cabin Creek there is only a layer of soft green clay shale, less than a foot thick, between the Chattanooga shale, and the St. Joe member of the Boone. Although no fossils have been found in this shale layer, it is believed to represent the Fern Glen on account of its character and position.

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[1] Stuart Weller "Kinderhook Faunal Studies," V, The Fauna of the Fern Glen Formation, *Bull. G. S. A.* xx, 265–332.

The following species have been identified from the Fern Glen horizon in the Siloam Springs quadrangle: *Cyathaxonia arcuata* Weller, *C. minor* Weller, *Cladochonus americanus* Weller, *Amplexus brevis* Weller, *Fistulipora fernglenensis* Weller, *Cystodictya cf. lineata* Ulrich, *Actinocrinus rubra* Weller, *Rhipidomella michelinia* L'Eveille, *Schizophoria swallovi* Hall, *Productus fernglenensis* Weller, *P. sampsoni* Weller, *P. sp.*, *Camarotoechia persinuata* Winchell, *Spirifer vernonensis* Swallow, *S. fernglenensis* Weller, *S. grimesi* Hall, *S. choteauensis* Weller, *Spiriferina subtexta* White, *Athyris lamellosa* L'Eveille, *Cleiothyris prouti* Swallow, *C. royssi* L'Eveille, and *Platyceras paralius* W. and W. There are also several unidentified species of bryozoa, principally fenestellids. The *Productus* listed as *P. sp.* is a large species known to occur also in the Chouteau limestone of Missouri.

The greater portion of the Boone consists of limestone and chert. In most of the good exposures observed by the writer, the limestone and chert occur in alternate layers averaging about one to two feet in thickness. In many cases, however, the chert is distributed irregularly through the limestone as lenses and nodules. The cherts are often fossiliferous but practically no work has been done on the paleontology of the Boone in Oklahoma. In the Muskogee and Tahlequah folios Taff lists the following species from the cherts in the upper part of the formation: *Amplexus fragilis* White and St. John, *Glyptopora keyserlingi* Prout, *Fenestella multispinosa* Ulrich, *Polypora maccoyana* Ulrich, *Hemitrypa proutana* Ulrich, *Pinnatopora striata* Ulrich, *Spirifer logani* Hall, *Reticularia pseudolineata* Hall, *Productus setigerus* Hall, *Derbya keokuk* Hall, and *Capulus equilaterus* Hall. In a small collection from a few miles east of the town of Pryor Creek in the Pryor quadrangle the writer has noted *Productus setigerus*, *Spirifer logani*, and *Derbya keokuk*. This fauna is decidedly indicative of Keokuk age.

In general it may be said that there are no strata in the Boone in Oklahoma which permit the formation to be divided into members. In the Joplin district in Missouri, Siebenthal[1] distinguishes the Grand Falls chert and Short Creek oolite members. In the

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[1] C. E. Siebenthal, Joplin District folio (No. 148), *Geologic Atlas of the United States, U.S. Geol. Survey*, 1907.

paper on the Mineral Resources of Northeastern Oklahoma[1] the same author describes the Short Creek oolite as being present in the eastern half of the Wyandotte quadrangle but does not mention the Grand Falls chert member. The extension of these members to the southwest is problematic.

As has been said the fauna of the Boone indicates the great mass of it to be of Burlington-Keokuk age. It has been reported[2] to the writer that fossils suggestive of Warsaw age have been found above the Short Creek oolite in Missouri. No collections from this horizon in Oklahoma have been studied and the exact age of the upper beds of the Boone formation in the State must be considered an open question as yet.

Unnamed limestone.—The upper limit of the Boone formation is one of unconformity. If the upper part of the cherts of the Boone are of Keokuk age, the time interval represented by the unconformity includes all of Warsaw, Salem, St. Louis, and Ste. Genevieve time. It is possible that more detailed work in the Boone area may prove some of the lower of these formations to be present, but so far as is known now they are absent.

Immediately above the cherts of the Boone in the Tahlequah quadrangle come a few feet of limestone which in this quadrangle were mapped with the Boone. In the Muskogee quadrangle, this limestone was found to be somewhat thicker and to be separated, at least locally, from the Boone by a thin layer of shale. The fossils proved the shale and limestone to be of Chester age, so they were considered as part of the overlying Fayetteville shale. North from the Muskogee, through the Pryor quadrangle this limestone thickens very rapidly until it attains a thickness of 90 or 100 feet along Grand (Neosho) River east of Choteau and Pryor Creek. In the Pryor quadrangle these rocks can be easily mapped and must be regarded as a formation. In view of the fact that this formation has been studied in the Vinita quadrangle, and that it will probably be named in the reports of the United States Geological Survey, no name is proposed here. This formation includes all the rocks between the Boone chert and the typical

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[1] *Bull. U. S. Geol. Survey No. 340.*

[2] Personal communication from H. A. Buehler.

black clay shale of the Fayetteville shale. The correlation of these rocks to the north of the Pryor quadrangle is yet in doubt. They seem to keep the same general characteristics across the corner of the Vinita quadrangle that they have in the Pryor. In the Wyandotte quadrangle, however, there is considerable sandstone in the lower part of the Fayetteville shale, or below it, which Siebenthal[1] calls the Batesville sandstone. On a sketch map of the Pryor quadrangle sent the writer he uses the field term, sub-Batesville limestone, and it is understood that the same term was used in the Wyandotte quadrangle. Since the Batesville sandstone of Arkansas does not extend into Oklahoma on the south side of the uplift, it does not seem that the name can be used in the Wyandotte quadrangle, although the sandstone there occupies practically the same stratigraphic position as the typical Batesville. Siebenthal's sub-Batesville limestone is almost certainly the northward continuation of the unnamed Chester limestone formation of this paper, and the sandstone called Batesville may also belong to it.

The fauna of these limestones between the Boone and Fayetteville formations, so far as the collections have been studied, is as follows: *Productella hirsutiformis* Walcott, *Productus pileiformis* McChesney, *P. cestriensis* Worthen, *P. inflatus var. coloradoensis* Girty (?), *Liorhynchus carboniferum* Girty, *Camarotoechia purduei* Girty, *Moorefieldella eurekensis* Walcott, *Spirifer increbescens* Hall, *Reticularia setigera* Hall, *Seminula subquadrata* Hall, *Derbya keokuk* Hall, *Eumetria marcyi* Shumard, and *Deltopecten batesvillensis* Weller. There are also several species of bryozoa in the upper part and of pelecypods in the lower part of the formation that have not yet been identified. One layer of arenaceous and calcareous shale near the base is marked by a large trilobite. The fauna has, however, been determined with sufficient completeness to correlate these limestones with some degree of certainty with the Spring Creek limestone and the Moorefield shale and possibly with the Batesville sandstone of Arkansas.

The unconformity between this limestone and the underlying Boone chert has already been noticed. In the Tahlequah and

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[1] C. E. Siebenthal, "Mineral Resources of Northeastern Oklahoma," *Bull. U.S. Geol. Survey No. 340*, p. 190, 1908.

Muskogee quadrangles this unconformity is not very striking as is shown by the mapping of the Chester limestone in the Tahlequah with the underlying Boone and by its separation from the Boone in the Muskogee only on account of the fauna and the thin layer of shale at the base of the limestone. In the Pryor quadrangle, however, this unconformity is very pronounced and the hills of typical Boone chert protrude through the limestone in several places, and in at least one place (hill just east of the town of Pryor Creek) through a considerable portion of the Fayetteville shale. The tops of some of the hills of Boone chert are at approximately the same level as the tops of other hills in the vicinity which are capped by the Pitkin limestone. The conditions are represented diagrammatically in Fig. 2. When these hills were first observed they were thought to be structural domes but more careful work has shown that the limestones and Fayetteville shale lie up against the chert in a horizontal position so that the presence of a pronounced unconformity seems to be the only hypothesis which accounts for the hills of chert above the level of the unnamed limestone and the Fayetteville.

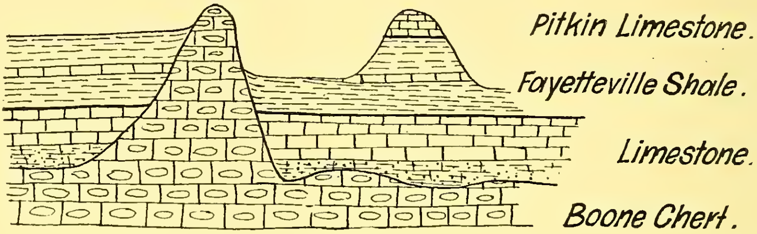

Fig. 2.—Diagram illustrating unconformity at top of Boone formation in the Pryor quadrangle.

Fayetteville shale.—Near the Arkansas line in the Tahlequah quadrangle the Fayetteville shale is reported as reaching a thickness of 120 feet, but in the Muskogee quadrangle it is said by Taff not to exceed 60 feet. In a section measured southeast of Ft. Gibson by Ohern and the writer, however, the Fayetteville shows a thickness of about 100 feet. The formation consists principally of blue to black, fissile clay shales with thin limestones, usually lenticular. In the Tahlequah quadrangle there is a sandstone member, the Wedington, which reaches a thickness of 40 feet. It thins out to the west and disappears about the middle of the quadrangle. In the Pryor quadrangle, the Fayetteville has the same general characteristics as to the south in the Muskogee quadrangle. The limestones thicken somewhat to the north, and are more persistent while the formation as a whole thins considerably. On the bluff of Grand River southeast of Choteau, the thickness is 90 feet. The basal 18 feet are composed of alternating layers of black shale and blue, dense limestone averaging about 6 inches in thickness. The limestone has a conchoidal fracture, is non-fossiliferous and weathers to a very light gray color. About the middle of the formation is a bed of limestone 12 feet thick, of which some layers are composed in large part of the shells of *Productus pileiformis* and *P. cestriensis*. This limestone is persistent for some miles to the north. So great a thickness has not been observed elsewhere, but this may be due to the poorer exposures.

The following species were collected from the limestones of the Fayetteville about 4 miles southeast of Ft. Gibson in the Muskogee quadrangle: *Lingulidiscina sp.*, *Productella cf. hirsutiformis* Walcott, *Productus sp.*, *P. pileiformis* McChesney, *P. cestriensis* Worthen, *P. cf. inflatus var. coloradoensis* Girty(?), *P. cf. subsulcatus* Girty, *Moorefieldella eurekensis* Walcott, *Spirifer arkansanus* Girty, *S. increbescens* Hall, *Martinia glabra* Martin(?), *Spiriferina sp.*, *Camarophoria sp.*, *Reticularia setigera* Hall, *Seminula subquadrata* Hall, and *Eumetria marcyi* Shumard. The following additional species are listed by Taff in the Muskogee folio: *Septopora cestriensis* Prout, *Archimedes compactus* Ulrich, *A. communis* Ulrich, *A. intermedius* Ulrich, *A. swallovanus* Hall, *Polypora corticosa* Ulrich, *Spiriferina spinosa* N. and P.

To the north, in the southeastern corner of the Vinita quadrangle, it is necessary to consider the Fayetteville and Pitkin horizons together. The section of the Mississippian rocks above the Boone chert in this vicinity is made up of four limestones and three shales. The lowest limestone is the unnamed limestone at the top of the Boone which has been considered. The topmost limestone is about 15 feet thick, and is probably the Pitkin limestone, although there is some doubt as to this correlation. The other two limestones are thin, not over 5 feet in thickness. They and the shale between them are very fossiliferous, bryozoa being especially abundant. Exceptionally well-preserved shells of *Productus*, and *Chonetes* as well as screws of *Archimedes* and specimens of other bryozoa weather from the shale in abundance. The *Productus* is the species which is doubtfully identified with *P. inflatus var. coloradoensis* Girty, in previous lists in this paper. The *Chonetes* is a rather large, flat species which is apparently unnamed. Specimens of the same species from Arkansas are in the University of Chicago collection.

In addition to these forms the following species have been identified from the two lower limestones: *Lioclema gracillimum* Ulrich, *Fenestella cestriensis* Ulrich, *F. serratula* Ulrich, *Streblotrypa nicklesi* Ulrich, *S. distincta* Ulrich, *S. major* Ulrich, *Stenopora tuberculata* Prout, *Polypora cestriensis* Ulrich, *Pinnatopora vinei* Ulrich(?), *Pinnatopora sp.*, *Cystodictya nitida* Ulrich, *C. cf. lineata* Ulrich, *Thamniscus furcillatus* Ulrich, *Productus cestriensis* Worthen, *Spirifer increbescens* Hall, and *Spiriferina transversa* McChesney.

Pitkin limestone.—In the Tahlequah quadrangle the Pitkin limestone varies in thickness from about 5 feet to 70 feet. In character it varies from an impure, shaly limestone to a massive blue, crystalline limestone. In the Muskogee quadrangle the thickness of the Pitkin varies little from 50 feet. The formation in this quadrangle consists of light blue to brown, granular, earthy, slightly oolitic strata interbedded with fine textured massive layers. The individual beds vary from thin, platy layers, often separated by thin shale partings, to massive layers 2 feet in thickness. In this quadrangle the Pitkin is apparently perfectly conformable above the Fayetteville and below the Morrow formation of Pennsylvanian age. Indeed, the line between the Pitkin and the Morrow is very difficult to follow, and the separation is usually made on the basis of fossils. From the Muskogee quadrangle north, the Pitkin thins very rapidly and also changes in physical characteristics. The massive, pure limestone phase disappears and the formation becomes argillaceous and ferruginous. Locally the limestone is very sandy. In these localities the beds are thick, and on weathering show intricate cross bedding. Where there is little sand in the formation the limestone is thin bedded and platy. The surfaces of the thin plates are usually covered by fossils in a more or less weathered condition; bryozoa are particularly abundant but are commonly poorly preserved.

The thickness of the Pitkin in the Pryor quadrangle is seldom over 20 feet and is usually less. From the middle of the quadrangle northward the Pitkin is locally absent, and the sandstones of the Pennsylvanian lie upon the shale of the Fayetteville, or in some places, upon the limestone about the middle of that formation. In such cases the basal portion of the Pennsylvanian sandstone is conglomeratic, containing pebbles of limestone up to an inch or more in diameter. The Mississippian-Pennsylvanian unconformity is thus very noticeable in the Pryor quadrangle, although it is not evident in the quadrangle to the southward. As noted in a previous paragraph, the correlation of the Pitkin in the Vinita quadrangle is in doubt. The topmost of the four limestones in this vicinity is probably the Pitkin. In the paper previously mentioned Siebenthal refers to the Pitkin as being present in the Wyandotte quadrangle, but gives no details concerning it. The section, however, is known to be very similar to that of the Vinita quadrangle.

The fauna of the Pitkin is very similar to that of the limestones of the Fayetteville. *Archimedes* is very abundant and the limestone was called the Archimedes limestone in the older reports of the Arkansas survey. The bryozoa which occur so abundantly in the formation in the Pryor quadrangle have not been studied as yet. The fauna is undoubtedly very similar to that already listed from the Chester limestones in the Vinita quadrangle, which may be in part from the Pitkin horizon.

SUMMARY

The Mississippian area in Northeastern Oklahoma is continuous with the Ozark region of Missouri and Arkansas. The section includes the Boone formation, unnamed limestone of Chester age, Fayetteville shale, and Pitkin limestone. The Boone formation and chert is from 100 to 350 feet thick and ranges in age from Kinderhook to Keokuk. The Kinderhook is represented by shale and limestone occurring locally at the base of the formation which are correlated with the Fern Glen formation of Missouri and Illinois. The great portion of the Boone is of Burlington-Keokuk age. The Warsaw, Salem, and Ste. Genevieve are supposed to be absent, the formations above the Boone being of Chester age. At the base of the Chester is a formation consisting principally of limestone which is very thin along the southern part of the area, but thickens to at least 100 feet along the western side, where the unconformity between it and the Boone is very marked. The Fayetteville shale thins from the Arkansas line westward and northward. The sandstone member (Wedington) disappears and limestones become more important. The Pitkin limestone thickens and becomes more regular in thickness westward from the Arkansas line into the Muskogee quadrangle, and then thins rapidly and becomes argillaceous and ferruginous to the northward. In the Pryor and Vinita quadrangles it was locally removed by erosion before the deposition of the overlying Pennsylvanian rocks.

It should be repeated that the work on these rocks is still in progress and that this paper is merely a statement of the facts concerning them so far as they are known at present. The faunal lists given are admittedly very incomplete, their aim being to list only the better known or more abundant species.

PETROLOGICAL ABSTRACTS AND REVIEWS

EDITED BY ALBERT JOHANNSEN

RAMSAY, WILHELM. "Ueber die Verbreitung von Nephelinsyenitgeschieben und die Ausbreitung des nordeuropäischen Inlandseises im nördlichen Russland," *Fennia*, XXXIII (1912), No. 1, pp. 17.

On the Kola Peninsula the high mountains of Umptek and Lujavr-Urt consist of nephelite syenite. Other nephelite rocks occur in the foothills of Turja and probably in the neighborhood of Kuollejavr. The author gives a sketch map of the region over which fragments of these rocks have been distributed by glacial ice.

A. J.

REINISCH, REINHOLD. *Petrographisches Praktikum, II Teil, Gesteine.* Gebrüder Borntraeger, Berlin, 1912. Pp. viii+217, figs. 48. M. 7.60.

In this, the second edition, the same general mode of treatment has been followed as in the first. The book has been increased in size by the addition of 37 pages and 26 figures, even though the chapter on the chemical relationships of the igneous rocks has been omitted. The parts dealing with eruptive and metamorphic rocks have been rewritten entirely and numerous analyses have been added. The origin of the rocks is not touched upon, the work dealing simply with the rocks themselves and their determination under the microscope. They are described both megascopically and microscopically, and their metamorphism and weathering is discussed. Not only are chemical analyses given, but each analysis is also recalculated according to the Osann system. The book is strongly bound in linen, the press work is good, and the illustrations, which are unusually good line drawings, are clean and sharp. The addition of a diagram showing the relationship between the different rock types would have been a help to beginners, since for such the book is intended.

ALBERT JOHANNSEN

Ries, Heinrich. *Building Stones and Clay Products.* John Wiley & Sons, New York, 1912, 8vo, pp. xvii+415, figs. 20, pls. 59. $3.00 net.

A handbook for architects. In Part I the important building stones of the United States are discussed with regard to their desirability as structural material, and with brief petrographic descriptions.

Part II opens with a chapter on the properties of clay, following which the clay products used as structural material are taken up and discussed, chiefly in their technologic aspects.

The principal interest to the geologist is found in the rather complete catalogue of quarries, with brief description of the stone obtained and lists of various structures in which these stones have been used.

The work is not intended as an exhaustive treatise, but aims to give mply the fundamentally important facts, and in this it seems to be fairly successful. Albert D. Brokaw

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Rinne, F. "Baueritisierung, ein kristallographischer Abbau dunkler Glimmer," *Berichten d. math.-phys. Kl. kgl. sächs. Gesell. d. Wiss., Leipzig,* LXIII (1911), 441–45.

The author proposes the name Bauerite for bleached biotite, and Baueritization for the process of bleaching. A. J.

Schaller, Waldemar T. "New Manganese Phosphates from the Gem Tourmaline Field of Southern California," *Jour. Wash. Acad. Sci.,* II (1912), 143–45.

Schaller, Waldemar T. *Beitrag zur Kenntnis der Turmalingruppe.* Inaug. Diss. München. Leipzig, 1912. Pp. 343.

Scrivenor, John Brooke. "The Gopeng Beds of Kinta (Federated Malay States)," *Quar. Jour. Geol. Soc.,* London, No. 270, Vol. LXVIII (1912), 140–63.

In this interesting article the author gives a geologic and petrographic description of the Gopeng beds, and advocates the theory that they were formed as a result of glacial action. These beds, which are described as resembling "drift composed of till and bowlder-clays," are found overlying strata of Carboniferous age and are considered older than an associated Mesozoic granite. The Gopeng beds carry commercially valuable deposits of tin which is found for the most part as disseminated grains of cassiterite. In his conclusion the author presents a brief summary of the geologic history of the region about Gopeng.

HEATH M. ROBINSON

SKEATS, E. W., and SUMMERS, H. S. "The Geology and Petrology of the Macedon District," *Bull. Geol. Surv. Victoria.* Victoria, 1912. Pp. 58, map, and pls. 28.

The granodiorite of this region is shown to be intruded into the dacite, and an altered zone was found in the dacite at its contact with the granite. Two new rock types, macedonite and woodenite, are described. They somewhat resemble orthoclase basalts and have some characters in common with mugearites. A number of rocks previously determined by Professor Gregory are here redescribed. Twenty-nine analyses of igneous rocks are given and computed in the Cross, Iddings, Pirsson, Washington system.

A. J.

SKEATS, ERNEST W. "The Occurrence of Nepheline in Phonolite Dykes at Omeo," *Australasian Asso. Adv. Sci.*, XIII (1912), 126–31.

STEWART, CHARLES A. "The Geology and Ore-Deposits of the Silverbell Mining District, Arizona," *Bull. 65, Amer. Inst. Min. Eng.*, 1912, 455–505.

Among the igneous rocks described are alaskite, alaskite porphyry, biotite granite, quartz porphyry, andesite, rhyolite porphyry, hornblende andesite porphyry, and an almost pure quartz rock.

A. J.

TYRRELL, G. W. "The Late Palaeozoic Alkaline Igneous Rocks of the West of Scotland," *Geol. Mag.*, IX (1912), 69–80, 120–31.

The writer divides the late Palaeozoic intrusive rocks of the west of Scotland into three groups, those with conspicuous analcite, those with conspicuous nephelite, and those without conspicuous analcite or nephelite, but which may contain either or both as accessories. Among the first class he describes analcite-syenite, teschenite, picrite-teschenite, lugarite, and monchiquite. Lugarite resembles the heronite of Coleman, and is related to leucocratic teschenites and to ijolites. It occurs in the form of a sill 4 feet thick in the Lugar teschenite-picrite complex, and as dikes penetrating the picrite. In hand specimens it shows a grey or greenish-grey groundmass crowded with barkevicite prisms up to

3 inches in length, and smaller black augites. In thin section the rock is seen to be composed of analcite, nephelite, plagioclase (probably Ab_1An_1), barkevicite, titanaugite, ilmenite, and apatite. The rock may be regarded as an ijolite in which the greater part of the nephelite has been displaced by original analcite, and in which barkevicite is a prominent constituent as well as augite.

The rocks of the second class are theralite, essexite, and kylite. The latter rock consists of about 31 per cent labradorite, 4 per cent nephelite, 1.3 per cent, analcite, 26 per cent titanaugite, 32 per cent olivine, 3.3 per cent ilmenite, 1.7 per cent biotite, 0.7 per cent apatite. Megascopically it is compact, fresh, phanerocrystalline, rather fine grained, and of a grey or greenish-grey color. In thin section the phenocrysts are seen to be olivine, titanaugite, and plagioclase, the latter in places zonal and ranging from Ab_4An_5 to Ab_5An_3. A little orthoclase occurs. A chemical analysis is given.

Rocks of the third type are alkali dolerites.

ALBERT JOHANNSEN

WATSON, THOMAS L., and HESS, FRANK L. "Zirconiferous Sandstone near Ashland, Virginia, with a Summary of the Properties, Occurrence, and Uses of Zircon in General," *Univ. Virginia Pub., Bull. Phil. Soc. Charlottesville*, I (1912), 267–92.

WATSON, THOMAS L. "Kragerite, a Rutile-bearing Rock from Krageroe, Norway," *Amer. Jour. Sci.*, Fourth Series, Vol. XXXIV, 509–14.

Kragerite was briefly described by Brögger in 1904 as a new member of the aplite series and a differentiation product of a gabbro magma. As described by Watson the rock is megascopically medium-grained granitic, and light in color. The prominent constituents are light-grey and pink feldspar, black rutile, and a little quartz. The rutile is in small grains partly disseminated but mostly segregated along roughly parallel lines which give the rock a streaked or banded appearance. The minerals are albite-oligoclase predominant with a little microcline and orthoclase, rutile, and a little quartz and ilmenite. In the rutile-rich portion rutile is predominant accompanied by biotite partly altered to chlorite, apatite, and an altered mineral probably feldspar. The rock occupies a new position in the quantitative system.

E. R. LLOYD

WEINSCHENK-CLARK. *Petrographic Methods.* McGraw-Hill Book Co., New York, 1912. Pp. xx+396, figs. 371.

This work is the authorized English translation of the third edition of Weinschenk's *Anleitung zum Gebrauch des Polarisationsmikroskops*, and the second edition of *Die Gesteinsbildenden Mineralien.* The English title is rather misleading in that it promises less than is given in the book.

The translation follows the German text closely enough to be correct, yet is free enough to be easy reading. Part I begins with a description of lenses and microscopes, and gives instructions for testing and adjusting them. The following one hundred pages are devoted to methods of observation in ordinary, and in parallel and convergent polarized light. Many methods are presented, and the phenomena observed and conclusions to be drawn from them are given, although but little theoretical explanation is attempted. The first part closes with an appendix giving descriptions of rotating, heating, projecting, photographic, and drawing apparatus.

The second part takes up the cutting of thin sections, the separation of mineral constituents by various chemical and physical means, and methods of micro-chemical investigation, staining, determination of specific gravity, etc. The chapter on the development of rock constituents is extremely valuable for beginners, giving excellent figures of various textures (called structures by the translator), and describing intergrowths, inclusions, and so on. The descriptive portion of the book consists of 139 pages with 153 figures, including line drawings of crystal forms and half-tones of thin sections. The descriptions of the various minerals are short but good, and give the principal characteristics. The fact that unusual rock minerals are omitted is to be commended. The methods for the determination of the feldspars are given rather too briefly, however. The volume concludes with 36 pages of tables for the optical determination of minerals.

The book is well printed on good paper and the cuts have come out fairly well, although, in avoiding the annoying glaze of the paper of the German original, much detail has been lost in the half-tones. The loss here seems greater than the gain. Typographical errors, especially under the illustrations, are numerous. On the whole the book is an excellent one and is extremely well adapted to classes beginning the study of microscopical petrography.

ALBERT JOHANNSEN

REVIEWS

Underground Water Resources of Iowa. By W. H. NORTON and OTHERS. Iowa Geological Survey. Vol. XXI, Annual Reports for 1910 and 1911. Pp. 28–1186.

This report treats of the sources, conditions of occurrence, chemical ingredients, and amount of the underground waters of Iowa. The waters are considered under three heads: (1) artesian waters, which rise within the tube because of hydrostatic pressure; (2) waters of the country rock; and (3) waters of the drift. Important conclusions regarding these, especially the first, are based upon chemical analyses, deep drillings, and the structure and lithology of the rocks. The state is arbitrarily divided into eight districts, and more or less specific information is set forth for each.

The principal aquifers noted are the Saint Peter and the Prairie du Chien formations of the Ordovician system, and the Jordan, Dresbach, and underlying sandstones (unexposed) of the Cambrian. Superiority is generally ascribed to the Saint Peter, chiefly because it is efficient, accessible, and identifiable over about three-fourths of the state; it, however, is not tapped in the southwestern part, where it lies at great depth and its waters are likely to be mingled in the wells with the highly mineralized waters of the Carboniferous strata. In the western part of the northwest district the Dakota sandstone is a boon to good water conditions. The Paleozoics, especially the lower members which outcrop in Wisconsin, Minnesota, and Northwestern Iowa, dip gently to the southwest in the form of a wide, open trough which leaves the state at the southwest corner. The strata, however, have sufficient variations in structure and lithology to make forecasts somewhat uncertain. The water of artesian wells of the northeast quarter of the state is said to be the purest.

Reasonable consideration is also given to the water conditions of the country rock and drift, and a list of typical well-logs in the townships of each county is published. But the main stress is laid on municipal and industrial supplies, as evidenced by the frequent advices and cautions concerning the procuring of the same. Maps and structure sections clarify the geologic horizon of the important aquifers.

The book is of great value to the state for its clear exposition of the elemental factors entering into the artesian conditions of Iowa, for its appeal to the people to pursue intelligent methods in obtaining their water-supply, and for its emphasis on the increasing necessity of securing drinking-water free from organic matter. This creditable volume was planned during the régime of the late state geologist, Samuel Calvin, and completed under his successor, G. F. Kay. The work was carried on by the State Survey in co-operation with the United States Geological Survey.

M. M. Leighton

The Coal Deposits of Missouri. By Henry Hinds. Missouri Geological Survey, Vol. XI, 2d Series, pp. 503; pls. 23; figs. 97; maps 7.

The present volume which is the result of co-operation between the Missouri Geological Survey and the U.S. Geological Survey, concerns itself with an economic discussion of the coals of Missouri. Quite properly, a mere outline of the stratigraphy is given and the deeper scientific problems are to be presented in a later report.

The arrangement of the volume is admirable. A short general discussion of the stratigraphy and structure is followed by a chapter on the mode of occurrence of the coals and a description of the different beds and fields. Statistics are presented showing production for various periods. The detailed report by counties arranged alphabetically, is a very desirable feature. Most of the letters of inquiry received by state surveys refer to counties, and it is thought that the grouping of detailed information into county units best meets the needs of the average reader.

Separate chapters are devoted to the quality and efficiency of the coals. In general, the fixed carbon and heat value decrease gradually across the state from south to north and west, the best coals occurring where the Ozark uplift had its greatest devolatilizing effect. Unfortunately, in the chapter on chemical analysis, it is not always clear whether figures given represent values "as received," "air-dried," or "moisture-free." In the tabulated analyses, emphasis is placed on "air-dried" values, whereas most engineers and consumers now compare coals either "as received" or on the "moisture-free" basis. On the latter basis, the coals of the entire state contain an average of 12,363 B.t.u. Tabulated results of tests on steaming, under boiler, for producer gas, on washed coal, and on coking and briquetting are presented in the final chapter.

In districts where quadrangles have been surveyed topographically, full-size lithographed sheets are used to present the geologic features. Many of the figures are graphic sections showing the physical characteristics of the coal beds. A large geologic map of Missouri is included.

It is estimated that the original coal tonnage of the state, not including beds or parts of beds less than 14 inches thick, was 79,362,016,000. One hundred and ten million tons have been mined and perhaps 50,000,000 tons have been left in the ground as pillars. Probably 60 per cent of the remaining coal can be recovered, giving Missouri a future production of 47,702,108,400 tons.

The value of such a report to the commercial interests of Missouri can scarcely be overestimated. The author is to be congratulated on the useful and attractive form in which so much detailed information is made available.

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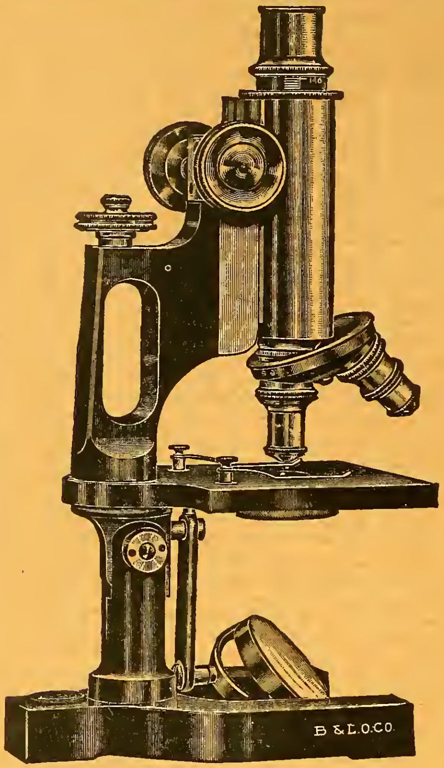
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A SUMMARY OF THE OROGENIC EPOCHS IN THE GEOLOGIC HISTORY OF NORTH AMERICA

ELIOT BLACKWELDER
University of Wisconsin

INTRODUCTION

Ever since the appearance of Dana's *Manual of Geology*, students of American geology have been familiar with the idea that the earth's crust has from time to time suffered crumpling along sinuous belts, many of which have a suggestive parallelism to the margins of the ocean basins. Of these the folding of the rocks now underlying the Appalachian Mountains serves as an example and is undoubtedly one of the most widely known. Frequent notices of such epochs of deformation appear in later works by American geologists, and in recent years the general principle has been clearly stated by Chamberlin.[1] This principle, well supported by evidence from many points of view, is that the lithosphere is not an absolutely incompetent mass, but that it has sufficient powers of resistance to the forces which tend to deform it to be able to accumulate stresses for long periods of time without perceptible deformation. These periods of accumulation are periods of quiescence, during

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[1] T. C. Chamberlin, "Diastrophism the Ultimate Basis of Correlation," *Jour. Geol.*, XVII (1909), 685–93.

which base-leveling of the surface is widely extended.[1] Each period of quiescence and stress-accumulation is terminated by a short epoch of deformation during which the rocks yield to the overpowering stresses to such an extent as to produce temporary equilibrium among the stresses and thus inaugurate a new period of quiescence during which the cycle of planation of the surface may be repeated. Illustrations of the principle may be found in the history of any of the well-known mountain systems such as the Appalachians, the Rocky Mountains, or the Alps and their contemporaries.

For the purposes of the present paper, the sharp foldings and often intense plications of strata are to be discriminated from those gentler but more widespread movements generally termed "warping." With the latter are often associated faulting of the so-called normal type, and volcanic activity. These things, although different in kind, are not unrelated. There is ample evidence that rock folding is often accompanied or followed by volcanic action; and one of the phenomena attending the plication along a narrow strip may be much more widespread warping with more or less normal faulting. Nevertheless, it is not clear that all four are necessarily present as phenomena of any one period of readjustment. In the strict etymological sense, folding, warping, faulting, and volcanic action are all "oro-genic" disturbances (*oros*="mountain," *gennao*="to produce"), since each may, independently of the others, give rise to mountain forms. In this paper, however, the word "orogenic" will be used in a somewhat limited sense and applied only to those epochs characterized by prominent rock folding.[2]

Recent textbooks and other general works on the geology of North America display an interesting lack of agreement as to the number of orogenic epochs recognized, in the emphasis placed upon

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[1] As an additional but quite distinct factor in lowering the lands Chamberlin also introduces the idea of a slow glacier-like creep of the continental masses outward toward the ocean basins during the quiescent periods. Since planation and crumpling may alternate, whether body creep is a real process or otherwise, such a process will not be considered in this paper.

[2] The term "revolution" is often given to these disturbances but appears to be too strong a word, in view of the frequent recurrence of such events, the world over.

them, and in the conscious discrimination between the crumplings and disturbances of other kinds. For example, Lyell[1] in 1855 makes no specific mention of such events; Dana[2] in 1875 enumerates seven more or less distinct epochs; Leconte[3] in 1891 gives four; Dana[4] again in 1895, eight more fully detailed than in 1875; Chamberlin and Salisbury[5] in 1905, six; Scott[6] in 1907, five; and Haug[7] in 1910–11, four (for North America). Dana was apparently among the first to see clearly that there had been a succession of foldings separated by periods of relative inactivity, and he early realized their importance as milestones in the progress of the earth's history. If all writers on the geology of local districts had even in recent years been as careful as Dana to distinguish between folding and mere change of level, or between folding, faulting, and volcanic activity, it would now be much easier for students of geologic history to interpret the local reports which necessarily form the basis of such general studies as this. We should not then be left in doubt as to just what an author means by the phrase, "a disturbance at the close of the Eocene" or "saecular changes in Acadia"; nor would the "Appalachian revolution" be described as extending from the close of the Mississippian to the end of the Trias and affecting most of North America.

The following list (Table I) of orogenic epochs is compiled for the use of students of geologic history without any pretense of adding materially to the existing fund of knowledge upon the subject. Like codifications in general, it may serve quite as much to call attention to the existing lack of knowledge on many points, as to present what is already known. Each of the orogenic epochs deserves to be the subject of a special investigation, for the purpose of ascertaining more exactly the date and duration of the disturbance, its relations to those in other continents, the special

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[1] Sir Charles Lyell, *Elements of Geology*, 5th ed.

[2] J. D. Dana, *Manual of Geology*, 2d ed.

[3] Jos. Leconte, *Elements of Geology*, 3d ed.

[4] *Op. cit.*, 4th ed.

[5] T. C. Chamberlin and R. D. Salisbury, *Geology*, Vols. II, III.

[6] W. B. Scott, *Introduction to Geology*, 2d ed.

[7] Émile Haug, *Traité de Geologie*, Vol. II.

TABLE I

OROGENIC EPOCHS

Period	Division	Orogeny	Region Affected
Quaternary		<Santa Barbaran	California
Pliocene			
Miocene	Upper	<Antillean	Coast Ranges, Antilles, etc.
	Middle		
	Lower		
Oligocene			
Eocene	Upper		
	Middle		
	Lower	<Laramide ? }	Rocky Mountain system
(Paleocene)	Basal	<Laramide }	
Cretaceous		<Oregonian	California, Oregon, etc.
Comanchean			
Jurassic	Upper	Nevadian	Sierra Nevada, Alaska Range, etc.
	Middle		
	Lower		
Triassic		<Appalachian	Appalachians to Newfoundland
Permian			
Pennsylvanian	Upper	<Arkansan	Southern Arkansas and Oklahoma
	Middle		
	Lower		
Mississippian			
Devonian	Upper	Brunswickian	Acadia to Central Virginia
	Middle		
	Lower		
Silurian		Taconic	Gulf of St. Lawrence to the Carolinas (?)
Ordovician	Upper		
	Middle		
	Lower		

TABLE I—*Continued*

Period	Division	Orogeny	Region Affected
Cambrian			
		<Penokean	South of Lake Superior (with extensions)
Algonkian	Keweenawan		
	U. Huronian		
		<Mesabian	North of Lake Superior (with extensions)
	M. "		
	L. "		
Archean		Laurentide ? ?	(Indefinite)

phenomena characteristic of it, and the distribution of the effects in varying degree.

THE INDIVIDUAL EPOCHS OF DEFORMATION

Laurentide orogeny (*late Archean*).—This may be included in our table more for the sake of completeness than because much information can be given concerning it. In the Lake Superior district, and particularly north of Lake Superior, the Archean rocks are generally more deformed and metamorphosed than the Algonkian strata which overlie them unconformably. In nearly all other districts where the Archean has been identified the same condition prevails. Whether these facts are to be interpreted as indicating a single almost universal orogenic disturbance just before the Algonkian deposits were laid down, or several, if not indeed many, such disturbances affecting successive strips of the continent at different times, is not now determinable. Considering the periodicity and local effects of the foldings in later geologic times, the latter view is perhaps the more favored one.

Mesabian orogeny (*late Middle Huronian*).—In northeastern Minnesota and adjacent portions of Canada the Upper Huronian (Animikean) strata lie gently tilted upon the contorted and partly metamorphosed beds of early Huronian and Archean age. The interval during which these folds were made and truncated has been termed the "Eparchean interval" by Lawson,[1] and by him

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[1] A. C. Lawson, *Bull. Dept. of Geol. Univ. of Cal.*, III (1902), 51–62.

pronounced the most important stratigraphic break in the pre-Cambrian sequence. The emphasis thus placed on the mid-Huronian unconformity is due to the consideration of only a limited belt north of Lake Superior. When a much larger region is examined, this glorification of the mid-Huronian orogeny appears unwarranted. The nearly parallel relations of all the Huronian series south of Lake Superior proves that there the rocks were not folded in the mid-Algonkian. Recently Leith[1] has reviewed our knowledge of the mid-Huronian unconformity, showing that a conspicuous angular discordance between sedimentary beds of pre-Cambrian age has been found farther east in the Sudbury and Cobalt districts of Ontario, and on into Quebec. It is not certain that it is the same unconformity and that it is of mid-Huronian age in all of these localities, but it seems within the bounds of probability that such a correlation may be established in the future.

The lack of fossiliferous strata of the ages involved still prevents us from correlating the Algonkian sections of widely separated parts of the continent. Were it not for this fact, we might be able to ascertain in large measure the real extent of the Mesabian folding. Suggestively similar relations are found in the Rocky Mountains from Wyoming to Arizona, for in those states comparatively unaltered late Algonkian rocks rest upon highly contorted and metamorphosed sedimentary beds usually referred to the early Algonkian. The outcrops of these folds are largely covered by later strata and in isolated exposures the structural lines do not seem to follow a single general direction.

Penokean orogeny (*late Algonkian* = (?) *post-Keweenawan*).—Again the Lake Superior region supplies the standard of reference. After the extrusion of the Keweenawan basalts overlying the essentially undeformed Upper Huronian strata, the region immediately south of Lake Superior was compressed into folds trending nearly east and west. This apparently produced the Lake Superior synclinorium. In parts of northern Michigan the folding was intense, leaving the strata quite schistose and in nearly vertical attitude. Large batholitic intrusions accompanied the folding. On the north side of Lake Superior, however, the deformation was

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[1] *Proceedings of the Internat. Geol. Congress*, Toronto, 1913.

so mild that on the Mesabi Range and in Thunder Bay the Upper Huronian beds are still only gently inclined. Westward the Penokean orogenic disturbance can be traced with some confidence to the Cuyuna Range of central Minnesota, and southward perhaps as far as the Baraboo district of southern Wisconsin, where rocks usually referred to Middle or Upper Huronian are highly folded. Eastward it extended an unknown distance into Ontario.

In reference to the late Algonkian orogeny, as to its predecessors, it is not yet possible to trace the extension of the folding much beyond the Lake Superior district because of the present uncertainty as to the ages of the strata. It is worth noting, however, that rocks believed to be of late Algonkian age, more or less strongly folded before the deposition of the Paleozoic beds, exist in the Black Hills of South Dakota, in Colorado, Montana, Utah, Arizona, and perhaps other western states and Canadian provinces. These beds are now so generally covered by younger rocks, that no continuous system of mountain folds has been worked out. The two Algonkian epochs of folding in the Rocky Mountains have been discussed by S. F. Emmons.[1]

Taconic orogeny (*late Ordovician*).—Because its effects are most evident in New England, the "Taconic revolution" was recognized more than fifty years ago by that group of geologists among whom Dana was ever a leader. Even today it would be difficult to improve upon the description, given in the early editions of Dana's *Manual of Geology*, of this signal event in the history of eastern United States. Because of its relation to fossiliferous strata, it is the first of the deformational epochs of which the age can be determined with a high degree of accuracy in the geologic scale and traced with confidence over a large area. Its effects in closely folded and even metamorphosed strata have been traced from the vicinity of Quebec (city) in Canada south through Vermont and western Massachusetts to New York City. Strong suggestions that it extended southwestward as far as Virginia have already been cited by Dana and others, but it is doubtful whether we shall soon know how far in that direction the crumpling was felt. The

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[1] S. F. Emmons, "Orographic Movements in the Rocky Mountains," *Bull. Geol. Soc. Am.*, I (1890), 245–86.

Cambro-Ordovician rocks were folded in the Gaspé Peninsula and as far as northwestern Newfoundland. The belt of deformation was apparently wide enough to include most of New Brunswick, perhaps Nova Scotia, nearly all of Maine, and probably even Rhode Island. The warpings and changes of level which accompanied the folding affected a large part of the eastern interior of the United States and doubtless Canada. These movements have lately been summarized by Schuchert.[1] In western United States, however, there appears to be evidence of nothing more than a change of relative altitude between the sea-level and the land surface.

Brunswickian (*late-middle Devonian*).—Although the folding of the older rocks in eastern Canada, just before the deposition of the Carboniferous measures, was well known to Logan, Dawson, and other pioneer Canadian geologists, and is noted by Dana in all the editions of his *Manual*, the event has received much less attention than it deserves from geologists in general. Several of the more recent textbooks of geology make no mention of the occurrence, and it is sometimes ignored in discussions of Devonian paleogeography where it is a factor of importance. Dawson's description,[2] although reflecting some provincial bias, may serve to call attention once more to the importance of the Devonian disturbance. He says in part:

> The whole surface of Acadia was thrown into a series of abrupt folds—great masses of plastic granitic matter invading every opening in the shattered masses. This period surpasses every other, in the geological history of the eastern slope of the American continent, in its evidence of fracture of the earth's crust. To this period we must refer the greater part of the intrusive granites of Eastern America, and to it also is referable the greater part of the metamorphism of the Silurian rocks, and the origin of the numerous metallic veins by which these are traversed.

As there appears to be in current use no name for this folding, the term "Brunswickian" is suggested to meet the evident need.

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[1] Charles Schuchert, "Paleogeography of North America," *Bull. Geol. Soc. Am.*, XX (1908), 488–89.

[2] Sir William Dawson, *Geology of Nova Scotia, New Brunswick, and Prince Edward Island*, 2d ed. (1891), pp. 665–66.

The tract within which the rocks were crumpled during this epoch stretches from western Newfoundland through Cape Breton Island, Nova Scotia, New Brunswick, Maine, and probably southern New England, and was wide enough to include on the northwest the Gaspé Peninsula in eastern Quebec. Farther southwestward, the evidence becomes scanty, but the marked unconformity beneath the basal Carboniferous beds near Boston and in Rhode Island suggests that it extended at least as far as Long Island Sound. Willis[1] has shown that the great thickness of late Devonian and early Carboniferous clastic rocks in Maryland and Virginia strongly suggests the rise of mountain ranges immediately to the east, in the region now occupied by New Jersey and eastern Virginia. Using the same criterion, the dwindling and eventual disappearance of such formations between Virginia and Alabama suggest that the folding did not extend the entire length of the present Appalachian Mountain belt.

Although there are some discrepancies in the evidence and hence some disagreement among writers on the subject, the testimony of unconformities on the one hand, and of thick clastic formations on the other, indicates that the Brunswickian disturbance culminated after the middle of the Devonian but considerably before the close. In Acadia the folds had been truncated before the Lower Carboniferous (Mississippian) period and beds of that age were deposited upon the eroded stubs.

Arkansan (*mid-Pennsylvanian*).—The folded structures underlying the mountains of Arkansas and Oklahoma were made, as nearly as can be inferred from current correlations, in the latter part of the Pennsylvanian period. Thus in the central Arkansas coal field the deformation followed the laying-down of the lower Pennsylvanian coal measures,[2] but no younger strata exist there. In the Arbuckle Mountains of Oklahoma it occurred after the deposition of the Caney shale (early Pennsylvanian ?) and before that of the Franks conglomerate (late Pennsylvanian). In the Wichita Mountains still farther west in the same state, the folds had been truncated before the deposition of the Oklahomian (early

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[1] Bailey Willis, *Geol. of Maryland*, IV (1902), 23–93.

[2] A. J. Collier, "Coal Fields of Arkansas," *U.S. Geol. Survey, Bull. 326*, p. 24.

Permian) red beds. Thus it is the conclusion of Taff[1] "that the Arbuckle uplift [= crumpling] began near the middle and culminated near the close of Pennsylvanian time, previous to the deposition of the red beds."

The folds are sharply compressed and cut by overthrusts and other faults as in the Appalachians, but there are no contemporaneous igneous intrusions and the rocks were not much metamorphosed. In Oklahoma, the Arkansan system of folds trends east by south, but the strike becomes more nearly east and west in Arkansas. Extensions of the system in the line of strike are unknown, because both to the west and to the east the folded beds are concealed by overlapping horizontal strata of later age. The same is true to the south. Southwestward in the Llano[2] district of central Texas, early Pennsylvanian strata are the youngest involved in the very mild folding and faulting which the stratified rocks now show. Their deformation may perhaps be related to the Arkansan disturbance. North of the Arkansas River the Carboniferous strata still lie almost horizontal, and in Kansas there is not so much as a disconformity between the early and later Pennsylvanian strata. In the Ozark region of Missouri and northern Arkansas the very gentle flexures and normal faults may possibly be referable to this epoch, but as yet the evidence is of little weight. Slight deformation of the Mississippian and older strata along the Mississippi River in Illinois, Iowa, and Missouri, and the making of the LaSalle anticline of Illinois seem to have in large measure preceded the Pennsylvanian, and if so, are not to be correlated with the Arkansan orogeny. The disturbance seems too slight to include, in the present list, as a distinct orogeny.

The folding of the Ouachita beds has been referred by Dana and others to the Appalachian revolution. However, unless published correlations are seriously in error we must conclude that the Ouachita folds had been formed and truncated before the deposition of the latest Pennsylvanian sediments, whereas the Appalachian folds were not begun until after the early Permian strata had been

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[1] J. A. Taff, "Geology of the Arbuckle and Wichita Mountains," *U.S. Geol. Survey, Prof. Paper 31*, p. 80.

[2] Sidney Paige, *U.S. Geol. Survey, Llano Folio, No. 183*, Texas.

laid down. It is now generally agreed that the climax of that disturbance came near the close of the Permian period. If these correlations are correct, we must then recognize two separate orogenic epochs. There is apparently ground for correlating the Arkansan crumpling with that which produced the Armorican and Variscian systems of western Europe, which Haug[1] assigns to the opening of the Stephanian (upper Pennsylvanian) epoch.

Appalachian orogeny (*late Permian*).—This epoch of folding was the first to be well recognized in America and is without doubt the one now best known to students of American geology. Its effects have been traced from Alabama to New York and from southern New England to Newfoundland. The southeast limit of the area affected is everywhere concealed either by the ocean or by much younger undeformed deposits. To the northwest the limit is rather sharply defined where the folds give way to the horizontal strata of the Cumberland and Alleghany plateaus. There are, it is true, some broad gentle swells in these apparently horizontal beds, and those flexures were probably produced at the same time as the Appalachian folds. In western New England and adjacent parts of New York and Canada, the limits are less easily ascertained because little now remains but pre-Devonian or even pre-Silurian strata, and those had been already folded either in the Brunswickian or the Taconic epoch or both. Available evidence, although meager, indicates that the crumpling and overthrusting at the close of the Permian were even more intense in the Piedmont and New England regions than in the Appalachian Mountains themselves.

Reasons have been given above for believing that the Ouachita region was not deformed at this time. If this conclusion is correct it may be said that the western three-quarters of North America was not affected by the Appalachian orogeny except that there were, over large areas, mild epeirogenic movements which made notable changes in the relations of land-masses and seas.

Nevadian (*late Jurassic*).—The folding of the rocks in the Sierra Nevada at the close of the Jurassic was established by Whitney and his associates about half a century ago, but it seems to be less widely understood that the entire west coast of North,

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[1] Émile Haug, *Traité de Geologie*, II, Part I (1910), p. 829.

and probably South, America was affected at about the same time. Smith[1] has called this the "Cordilleran revolution," but since it affected less than half of the great mountain tract of the West, to which we usually apply the name "Cordilleras," the designation seems likely to mislead and will perhaps tend to perpetuate a widespread popular misconception of the western mountains as all belonging to one great system instead of two or three systems. The term "Nevadian" has therefore been substituted in this paper, in allusion to the Sierra Nevada.

The system of folds made at this time trends in a north-northwesterly direction more or less parallel to the Pacific shore of today, but by no means coinciding with it. South of the typical area in the Sierra Nevada, the Jurassic folds may be traced into western Mexico and probably Lower California. Northward along the strike it may be traced through Oregon, the Cascade and Olympic ranges of Washington, the Coast Range of British Columbia, and the St. Elias and Alaskan ranges beyond. There are even suggestions of its extension into the Aleutian chain. Its western limit is concealed everywhere by the Pacific Ocean or by unconformably overlapping younger deposits which have themselves been folded subsequently. To the east and northeast, the Nevadian system of folds is involved with the overlapping Laramide system and it therefore becomes a difficult task to discriminate the two. The eastern limit of the Nevadian folds seems to be reached approximately near Bisbee, Arizona, where Comanchean sediments overlie unconformably the deformed Paleozoic strata, and the ill-defined boundary may be traced northwestward through eastern Nevada,[2] western Idaho, central British Columbia, the upper Yukon valley in Canada, and central Alaska in general. There is good evidence that it did not affect Alaska north of the Yukon nor the eastern ranges of Mexico.

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[1] J. Perrin Smith, *Science*, XXX, 346–51.

[2] It should be noted that much of this region has been so modified by igneous intrusions and faulting of much younger date that the results of the Nevadian orogeny have been in large measure lost to view. It is these later disturbances which have made the present Basin Range province of Nevada distinct from the Sierra Nevada province of California, though both were once parts of the Jurassic belt of folding.

Throughout this great belt, which doubtless has extensions in Asia on the west and also in South America, the folding was accompanied or followed by the intrusion of enormous masses of granitic rocks, the commonest types among which are granodiorite and quartz-diorite. In the intensity of the folding there was much variation, but through California and Washington, at least, it was great.

Although nearly all writers on the subject agree in assigning this epoch of diastrophism to the Jurassic period or its close, there is considerable difference of opinion as to a more precise date. The Alaskan geologists have usually referred it to the middle Jurassic. Stanton and the earlier Californian geologists assigned it to the end of the Jurassic. According to J. P. Smith it took place just before the Portlandian epoch of the late Jurassic. These differences of opinion are probably in large part due to the difficulty of correlating the faunas of such widely separated countries as California, Alaska, and Europe, rather than to any real difference in the date of the disturbances in the several regions.

Oregonian orogeny (*post-Comanchean*).—In the literature of Pacific coast geology there is much evidence to indicate that the deposition of the Shasta and related series (Comanchean) was followed by crumpling of the strata, accompanied by the intrusion of igneous rocks, especially peridotitic varieties, now changed to serpentine. The phenomena have been found interruptedly from southern Mexico through California, Oregon, and Washington to southeastern Alaska. In all cases they lie near the coast, and in no instance are they known to occur east of the area affected by the Nevadian orogeny. As in that preceding orogenic epoch, so here, the folds appear to be roughly although not exactly parallel to the edge of the Pacific basin. In most districts the folding was of moderate intensity but in southwestern Oregon the Comanchean strata stand on edge in isoclinal attitude.

All inferences as to a period of deformation between the lower and the upper Cretaceous necessarily rest upon the correlations of the strata involved. On the whole, the Comanchean and Cretaceous beds of the Pacific province are only sparingly fossiliferous and many of the species, such as *Aucella*, are of large vertical range and hence of doubtful value in correlation. The various writers on Pacific coast geology are, therefore, by no means in harmony as to the ages of some of the strata. The existence of a conspicuous angular unconformity is conceded. Above this conformity lies either the Chico (upper Cretaceous) or certain Eocene formations. Below it lie much more highly folded and locally even metamorphosed rocks which may in general be referred to as the *Aucella* beds. These have yielded both invertebrates and plant remains. The former have been classified usually as lower Cretaceous, but sometimes as late Jurassic; the plants nearly always as Jurassic. At present the balance of qualified opinion seems to be in favor of regarding the system as largely Comanchean but in part late Jurassic. This orogeny, if it was a fact, is among the least-known in the later part of the earth's history.

Laramide orogeny (*post-Cretaceous*).—The deformative movement which gave birth to the Rocky Mountain system is one of the three best-known events of its kind in North America. The folds thus produced trend north by west from southeastern Mexico to western Texas, thence across New Mexico, Colorado, Wyoming, Montana, western Alberta, and the northwest provinces of Canada into northern Alaska, finally reaching the Arctic Ocean at Cape Lisburne. Although there may have been folding in Central America also at this time, the fact that the same region suffered a further crumpling in the midst of the Tertiary has largely if not entirely obliterated evidences of earlier deformation there. The post-Cretaceous folds reappear, however, in full force in the Andean system of South America. On the eastern or inland side of the system the limits are generally distinct, for the folds pass somewhat abruptly into the nearly horizontal strata of the Great Plains. There are, however, some outlying tracts of disturbance characterized by gently tilted strata and laccolithic intrusions, as in the Black Hills of South Dakota and the Uvalde district of Texas. The same general condition seems to prevail throughout the extent of the system. On the westward or Pacific side the limits are much less definite because the post-Cretaceous folds are not easily distinguished from those of the Nevadian epoch, except where late Cretaceous strata are present; and it is an embarrassing fact that outcrops of rocks of this age are comparatively scarce in the plateau region between the Pacific and Rocky Mountain systems. Such facts as are now available suggest that the western limit of the Laramide disturbance passes through central Arizona, eastern Nevada, western Idaho, and central British Columbia to the Yukon valley. This tentative division of the provinces is supported by the fact that the Comanchean rocks in the Bisbee region, Arizona, have been gently tilted and faulted but only slightly folded; the Cretaceous rocks near the headwaters of the Yukon River have been folded, and the same is true of beds of similar age on the northeast side of the Seward Peninsula in Alaska. On the other hand, along the Pacific slope in California, Oregon, Washington, British Columbia, and Alaska, wherever both upper Cretaceous and Eocene strata are present, they are generally either conformable, or separated by a mere disconformity. At the north end of the Sacramento Valley, California, the upper Cretaceous strata still remain almost horizontal.

There is substantial agreement among geologists that the Laramide orogeny marks approximately the close of the Cretaceous period. Nevertheless, until the existing controversy over the correlation of the latest Cretaceous and earliest Eocene formations of western United States is satisfactorily settled, the exact date of the deformation remains uncertain. In some parts of western Wyoming and Colorado there are suggestions of two episodes of crumpling separated by a short but definite epoch of erosion and the deposition of sediments in the earliest Eocene (Paleocene). Similar phenomena are reported from Yellowstone Park and southwestern Montana.

Throughout its range the Laramide orogeny was marked by great volcanic activity, which manifested itself in the production of laccoliths and volcanic cones with their associated dikes, sills, flows, and fragmental deposits. Locally in parts of Idaho and western Montana granitic batholiths were intruded at this time, but they are much less characteristic of the Laramide system than of the Nevadian.

Antillean orogeny (*middle-to-late Miocene*).—It has long been known that the dominant structural features of the California and Oregon coast ranges were produced in the Miocene period. To the north the deformation may be traced through the Oregon Coast Range to the Olympic Mountains of Washington, thence through the coastal islands of British Columbia, to the southern Alaska coast, and on into the Aleutian chain. To the south the same deformation is reflected in the tilted and more or less disturbed Eocene beds of Lower California. Beginning in southwestern Mexico, a belt of complexly folded and faulted rocks with volcanoes extends through Honduras and other Central American states, through the West Indian islands to Venezuela. These folds involve Eocene, Oligocene, and even Miocene strata, but are unconformably overlapped by the undisturbed Pliocene. Eastward and northward the effects of the Antillean disturbance wane into gentle folds and finally into mere warping, accompanied by normal faults and volcanic structures. Decided folding of early Tertiary strata extends as far east as southwestern Nevada, the Blue Mountains of Oregon, the Cascade Range and Okanagan regions of Washington, at least the western part of the Fraser River basin of British Columbia, and the upper Yukon valley. In Alaska it affected the Kuskokwim Mountains and Nunivak Island, but not the Mt. Wrangell district or the region north of the Yukon River. Even as far east as the Rocky Mountain states of Wyoming, Colorado, and Montana, the Eocene and Oligocene strata are locally somewhat tilted and broken by normal faults, suggesting that the Antillean disturbance made itself felt in a mild way as far east as the edge of the Great Plains. Eastern United States suffered no folding but there was some warping, especially in Florida and the Gulf states.

By comparison with the Nevadian and Laramide disturbances, it will be seen that the Antillean orogeny affected an area as large as, or even larger than, the Nevadian, and again the strongest folding is found nearest the Pacific coast. Almost throughout the range of the Miocene disturbance, whether mild or severe, volcanoes broke forth and scattered their lavas and fragmental deposits far and wide. In that respect the epoch may have exceeded even the Laramide orogeny. Batholiths of the Antillean epoch are reported from the Cascade Mountains of Washington and British Columbia; they are probably the youngest known.

Nearly all authorities agree in assigning this event to the middle Tertiary, and by many it is referred to the close of the Miocene period. In the John Day basin of central Oregon, according to Merriam and Sinclair,[1] gentle folding closed the deposition of the early Miocene sediments, and preceded the Columbia lava outflows. In the northern part of the Cascade Mountains of Washington a similar event is recorded by Smith and Calkins.[2] The most accurate estimate of the date of the deformation seems to be that which has been made in the Coast Range of southern California by Arnold[3] and others, who show that it followed the deposition of the lower-middle Miocene sediments (Monterey shale), and preceded that of the upper Miocene (Santa Margarita).

Santa Barbaran orogeny (*early Pleistocene*).—Recent studies in the oil-bearing districts of southern California have brought to light the fact that, although the region was considerably affected by the Antillean orogeny, it was as much or even more closely compressed after the deposition of the marine Pliocene formations. Thus in the region about Santa Barbara, the Pliocene has been not only folded but overturned, and locally lies beneath overthrust masses of earlier Tertiary strata. In the Coalinga oil district[4] on the southwest side of the great valley of California, the effects of the Santa Barbaran disturbance are much more pronounced than those of the middle Miocene folding.

Although it has long been known that warping, gentle changes of level, and normal faulting proceeded on a large scale early in the Pleistocene period, particularly in western United States, there are but few places outside of California where actual folding has been assigned to this age. Possibly we should refer to the Santa Barbaran folding the gentle flexures in the late Miocene lavas of central Washington and the Cascade Mountains, as well as the latest gentle folds in the Olympic Range of the same state. To the

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[1] J. C. Merriam and W. J. Sinclair, *Bull. Dept. of Geol. Univ. of Cal.*, V (1907), 174.

[2] G. O. Smith and F. C. Calkins, *U.S. Geol. Survey, Snoqualmie, Wash., Folio, No. 139.*

[3] Ralph Arnold, "Environment of the Tertiary Faunas of the Pacific Coast of the United States," *Jour. Geol.*, XVII (1909), 509–33.

[4] *Ibid.*, "Geology of the Summerland Oil District, California," *U.S. Geol. Survey, Bull. 321.*

north the comparative scarcity of Pliocene strata renders the tracing of the folding in that direction more difficult. In the region of the Antilles, Pliocene strata are much more abundant, but there they are apparently not folded and only very gently tilted.

GENERAL CONSIDERATIONS

The table of orogenic epochs given above is still far from complete, and tabulations of this kind are necessarily subject to correction. The most evident defects relate to the pre-Cambrian. Until the pre-Cambrian terranes in widely separated districts have been correlated much more securely than at present, we shall not know how many orogenic epochs fell within the Archeozoic or even the Proterozoic era; and we shall know but little of the true extent of those ancient orogenies which are already recognized as facts. Again, the effects of some orogenic movements, especially near the borders of the continent, have been so masked by later crumplings or have been so largely buried beneath younger sediments or by the sea itself, that the record, once clear, is now largely destroyed. Thus we know nothing of the southwestward extension of the Appalachian system of folds beneath the sediments of the Gulf coastal plain; and on the Pacific slope the complex structure and metamorphism render it difficult to get information about any orogenic epochs which that region may have suffered before the Jurassic. Some of these limitations will gradually be removed as the making of critical local studies progresses.

In most of the known epochs of orogeny, a single elongate belt was affected, while much broader surrounding regions experienced nothing more revolutionary than changes of level, gentle warping, a little faulting, and sometimes volcanic activity. Most of the folded belts were thousands of miles in length and a few of the best-known measured many thousands. The Laramide system of the Americas extended over about half of the earth's circumference, and the Miocene folded belts are long enough to reach more than one and a third times around the globe.

The belts vary from 50 to more than 600 miles in width and in Asia locally exceed 1,000 miles. The average width of the crumpled zones is, however, between 100 and 300 miles. Where the folding is closest, the zone is likely to be narrower than where the folds are open and wavelike. If this is generally true, it may mean that the narrowest places are narrow because they have been the most compressed.

The crumpled strips produced at each epoch overlap more or less, but rarely coincide. Thus the Mesabian orogeny affected the north side of Lake Superior while the Penokean affected the south side. Again, the Laramide and Nevadian zones are largely distinct, although they overlap considerably. Successive foldings in the same general region were usually roughly parallel to each other and resulted in an ever-widening belt of crumpled strata. In North America we have at least three such composite zones, the Cordilleras in the west, the Atlantic system in the east, and the ancient systems of the Canadian shield where nearly all structures trend east by north.

Although overlapping of the limits is common, it is rare that the locus of greatest intensity occurred twice in the same place. The Sierra Nevada region, intensely folded in the Jurassic, was but little affected in the Miocene, although the Coast Range to the west and parts of Nevada to the east both suffered folding at that time. Intense crumpling produces a thickening of the deformed strip and therefore increases its competency to resist further thrusts and to transmit them to regions beyond. It seems probable, also, that the intrusion of great batholiths such as accompanied the Nevadian orogeny must notably strengthen the mass within which they congeal, and thus render it less liable to yield to compression in later periods.

Many students of the subject have shown that some of the disturbances were inter-continental. For example, there appears to have been some crumpling in northwestern Europe, corresponding approximately in time to the Taconic orogeny in eastern North America. The Brunswickian likewise has its counterpart in the mid-Devonian deformation in Scotland. The Arkansan seems to correspond in time to the Armorican orogeny of western Europe, the Nevadian to the folding of the eastern interior ranges of Asia, and the Antillean almost unquestionably to the rearing of the great Alpine system of Eurasia. These striking correspondences strongly suggest that the orogenic forces are not local but planetary. Chamberlin[1] regards the crumplings on two sides of an ocean as a result of the subsidence of the earth segment beneath that ocean.

The folding along the relatively narrow belts was nearly always accompanied by more or less warping and volcanic activity over adjacent, much wider areas. The warpings have not infrequently disturbed stream activities and strand-lines over large portions of continents, as at the close of the Permian and in the Miocene. The transitions from the folded to the merely warped areas are in some cases abrupt and in others gradual, through gently folded or faulted tracts. Where the demarcation is sharp, as the east side of the Rocky Mountains, there may have been some original line of weakness such as a decisive initial dip; whereas in the cases of gradual transition the underlying mass may be tolerably uniform in resistance, and may therefore permit the force to be transmitted through it and die away gradually.

In several instances observed relations indicate that the most effective compression was accomplished on the side toward the ocean basins. Thus we have the closely appressed folds and overthrusts of the Laramide system in western Montana and Idaho changing into gentle open folds farther east. Again, in the Appalachian orogeny, the Rhode Island district was more closely crumpled and metamorphosed than Pennsylvania on the northwest side of the deformed zone; and a like comparison may be made between the region of great overthrusts and isoclinal folds in North Carolina on the southeast and the open arches of northern Alabama on the northwest. For at least some of the orogenic systems there seems to be a significant arrangement of the batholithic intrusions on the seaward side of the zone, with superficial volcanoes and laccoliths along the landward side. This is perhaps only another way of saying that the batholiths are characteristic of the more intensely folded parts of the zone, while the superficial volcanic features occur where the rocks have been less deformed. It is admitted, however, that this distribution of intensities and phases of igneous activity cannot be demonstrated for many of the epochs and may be accidental rather than significant.

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[1] T. C. Chamberlin and R. D. Salisbury, *Geology*, I (1904).

There is a conception familiar to present-day geologists, that the great mountain systems coincide with geosynclinal depressions in which sediments have previously accumulated to unusual thicknesses. The Appalachians have served as a classic example. In the opinion of some, the trough was deepened by lateral pressure and the deposition of the sediments thus invited. The extreme isostasists, on the other hand, view the trough as a result of the loading of the strip by the deposition of thick sedimentary beds. Willis urged the importance of the initial dips developed in these geosynclines in predetermining the locus of the folded belt when the compressive force became effective. It is prudent, however, not to assume that there is a causal relationship between belts of thick sediments and subsequent mountain folding, merely because one preceded the other. Much of the thickness of the Appalachian sediments was directly due to the ruggedness of the land-mass of Appalachia, from time to time in the Paleozoic era; and it should be recalled that at the close of the Permian not only the Appalachian geosyncline, but a still broader region to the east, was intensely deformed. The observed relations may be stated in another way, namely, that sediments accumulate rapidly along mountainous coasts, and that coasts in turn are liable to repeated crumplings, for reasons not here discussed. Hence the two phenomena are generally associated.

In each great portion of the continent there have been successive roughly parallel crumplings, separated by long periods of quiescence, and, in some cases at least, eventually terminated by a cessation of activity which has endured down to present times without premonition of change. In the Lake Superior region, three, and probably many more orogenies, were passed before the Cambrian, but in all subsequent time there have been none. In the Atlantic mountain system three or more crumplings before the Triassic have been followed by a stability prolonged until the present, and with no suggestions of an end. In the western Cordilleras the orogenic activities seem to have slumbered until the Jurassic, but since then the region has been subjected to repeated compressions and is the one in which future disturbances are most likely to take place.

When the earlier and later orogenic epochs are compared, there appears a suggestive sameness running through the whole series. Although we are still unable to express geologic chronology in terms of years, an estimate expressed in terms of epochs or thickness of strata suggests that the crumplings were no more frequent in the Paleozoic era than in later periods; nor do the facts seem to imply that the earlier disturbances were more intense or more widespread. In fact, if we should take the available data without making allowance for the greater loss of record pertaining to the earlier periods, we might reach the improbable conclusion that they had been more widespread, more severe, and more numerous since the Triassic than before.

THE CAUSES OF OROGENIC EPOCHS

It is beyond the purpose of this paper to discuss the origin of earth folding.

From the very nature of its effects, the cause of orogenic epochs must be sought in tangential compression affecting the rocks of the earth's outer shell. As to the origin of that force there is, however, no unanimity. It constitutes a problem for which several hypotheses have been offered. These are explained and critically analyzed in the writings of Dana,[1] Reade,[2] Chamberlin,[3] Willis,[4] Taylor,[5] Leith,[6] and others.

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[1] J. D. Dana, *Manual of Geology*, 4th ed. (1895).

[2] T. Mellard Reade, *Origin of Mountain Ranges*, p. 125.

[3] T. C. Chamberlin and R. D. Salisbury, *Geology*, I (1905).

[4] Bailey Willis, "Research in China," *Carnegie Institution*, II (1907).

[5] F. B. Taylor, "Origin of the Earth's Plan," *Bull. Geol. Soc. Am.*, XXI (1910).

[6] C. K. Leith, *Structural Geology* (1913).

THE STRENGTH OF THE EARTH'S CRUST

JOSEPH BARRELL
New Haven, Connecticut

PART VI. RELATIONS OF ISOSTATIC MOVEMENTS TO A SPHERE OF WEAKNESS—THE ASTHENOSPHERE.[1]

INTRODUCTION AND SUMMARY

In studies on the nature of isostasy it is necessary to distinguish between, first, the existence of isostasy; second, the limits of isostatic equilibrium; and third, the mode of maintenance of this equilibrium.

The first has long been known, the knowledge of the existence of some relation of density counterbalancing elevation having been gradually developed since the middle of the nineteenth century through the determination of the local deviations of the vertical as shown by the comparison of the astronomic and geodetic latitudes for the same station. This was a problem which arose in both astronomy and geodesy. It was found, when the attractive effect of the mountain regions was computed, that they did not deflect the vertical at adjacent stations as much as was to be expected from their visible masses. The phenomenon was first pointed out

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[1] An abstract of Parts V, VI, and VII of this series was given at the April, 1914, meeting of the American Philosophical Society at Philadelphia under the title, "Relations of Isostasy to a Zone of Weakness—the Asthenosphere." See *Science*, XXXIX, 842.

by Petit in 1849.[1] Archdeacon Pratt of Calcutta showed a few years later that whereas a discrepancy of 5.2″ existed between the geodetic and astronomic latitudes of Kalianpur and Kaliana, the calculation of the effect of the Himalayas called for a difference of 15.9″.[2]

These facts were definitely formulated into a theory of isostasy by the Astronomer Royal of Great Britain, G. B. Airy, within a year following the appearance of Pratt's paper,[3] though it remained for Dutton to recognize the large geologic significance and to coin for the relations of elevation and density the word isostasy.[4] Following this Putnam and Gilbert showed by gravity measurements that a considerable degree of regional isostasy existed over the United States.[5] Since then has appeared the much more detailed work of Hayford and Bowie, the computations made by the computing office of the United States Coast and Geodetic Survey under their directions making possible this present investigation.

Thus there has developed through more than half a century evidence beyond controversy which shows that the earth's crust in its larger relief and, within certain limits, even its smaller features, such as the great plateaus and basins, rests more or less approximately in flotational equilibrium.

The second division of the larger problem of isostasy, that of the areal limits and degree of perfection of isostatic adjustment, is the subject which has been dealt with in the previous parts of this investigation. It has been found that, although the relations of continents and ocean basins show with respect to each other a high

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[1] "Sur la latitude de l'Observatoire de Toulouse, la densité moyenne de la Chaine des Pyrénées, et la probabilité qu'il existe un vide sons cette chaine," *Comptes rendus de l'Acad. des Sc.*, XXIX (1849), 730.

[2] "On the Attraction of the Himalaya Mountains and of the Elevated Regions beyond Them, upon the Plumbline in India," *Phil. Trans. Roy. Soc.*, Vol. CXLV (1855).

[3] G. B. Airy, "On the Computation of the Effect of the Attraction of Mountain Masses as Disturbing the Apparent Astronomical Latitude of Stations in Geodetic Surveys," *Phil. Trans. Roy. Soc.*, Vol. CXLV (1855).

[4] "On Some of the Greater Problems of Physical Geology," *Bull. Phil. Soc. Wash.*, XI (1889), 53.

[5] *Bull. Phil. Soc. Wash.*, XIII (1895), 31–75.

degree of isostasy, there is but little such adjustment within areas 200 to 300 km. in diameter, or of limited differential relief. Individual mountains and mountain ranges may stand by virtue of the rigidity of the crust. Even under the level plains equally great loads are permanently borne, loads produced by widespread irregularities of density not in accord with the topography above. Isostasy, then, is nearly perfect, or is very imperfect, or even nonexistent, according to the size and relief of the area considered.

The third division, the mode of maintenance of isostasy and its bearings on problems of the crust, remains to be considered. This condition of isostatic equilibrium exists at present in spite of the leveling surface actions and compressive crustal movements of all past geologic time. There must be, consequently, some internal mode of restoring more or less perfectly an isostatic condition, either by frequent small movements, or by more infrequent and larger ones.

Erosion and sedimentation result in a lateral transfer of matter, and to maintain isostasy there must be some lateral countermovement in the earth below, but in regard to how or where or when this is done, and as to what are its effects, there has been no unanimity of opinion, nor convincing demonstration.

In considering the problems of crustal dynamics some authors have regarded earth shrinkage and consequent tangentially compressive forces as controlling the nature of diastrophism, including movements of both orogenic and epeirogenic character; others, the advocates of extreme isostasy, have thought to see even in folding only the secondary effects of movements maintaining isostatic equilibrium. The first point of view emphasizes the strength and elasticity of the crust, with long-deferred periodic discharge of stress. The second point of view calls for an interpretation based on the weakness and plasticity of the crust, with resulting nearly continuous small movements restoring the delicate vertical balance destroyed by gradational actions. To what degree are the two points of view compatible and within what limits is each dominant? The problem of this chapter involves, therefore, not only the mode but the limits and effects of the movements which more or less completely maintain or restore isostasy.

The method of attack is largely one of exclusion. By showing what hypotheses cannot apply, the way is prepared for conclusions in better accord with the fields of fact and theory.

The results show that conditions of isostatic equilibrium cause the light and high segments to press heavily against the adjacent lower and heavier ones, most heavily above. The tendency is consequently for the high areas to spread with a glacier-like flow over the low areas. This tendency, however, is effectively resisted by the strength of the crust. Upon the disturbance of equilibrium by erosion and deposition there are two kinds of stresses produced which tend to restore equilibrium. The first is a tendency of the heavy column to underthrust the lighter, but it could never produce compression and folding at the surface. This force would be most effective under the hypothesis of great crustal weakness, so that the vertical stresses could be transmitted in a horizontal direction within the lithosphere as in a fluid. Even in that case, however, it would not be the dominating force. The actual isostatic movements consist of a rising of the eroded areas, a sinking of those which are loaded. This involves shear or flexure around their boundaries. The columns must be large enough so that the excess or deficiency of mass can become effective in producing deformation. When the accumulating vertical stresses have overcome the strength of the crust, the excess pressure from the heavy area is transmitted to the zone below the level of compensation. This deep zone is in turn the hydraulic agent which converts the gravity of the excess of matter in the heavy column into a force acting upward against the lighter column and thus deforms the crust of the eroded area. By this means even the continental interiors are kept in isostatic equilibrium with the distant ocean basins. This implies a great depth and thickness to the zone of plastic flow. Although it must be plastic under moderate permanent stresses, this does not imply by any means a necessarily fluid condition, and fluidity is disproved by other lines of evidence.

The zone of compensation, being competent to sustain the stresses imposed by the topography and its isostatic compensation, must obey the laws pertaining to the elasticity of the solid state and is to be regarded therefore as of the nature of rock. Consequently there may be extended to all of it the name of the lithosphere, even though it includes from time to time molten bodies, the constituents of the pyrosphere.

The theory of isostasy shows that below the lithosphere there exists in contradistinction a thick earth-shell marked by a capacity to yield readily to long-enduring strains of limited magnitude. But if such a zone exists it must exercise a fundamental control in terrestrial mechanics, in deformations of both vertical and tangential nature. It is a real zone between the lithosphere above and the centrosphere below, both of which possess the strength to bear, without yielding, large and long-enduring strains. Its reality is not lessened because it blends on the limits into these neighboring spheres, nor because its limits will vary to some degree with the nature of the stresses brought upon it and to a large degree by the awakening and ascent of regional igneous activity. To give proper emphasis and avoid the repetition of descriptive clauses it needs a distinctive name. It may be the generating zone of the pyrosphere; it may be a sphere of unstable state, but this to a larger extent is hypothesis and the reason for choosing a name rests upon the definite part it seems to play in crustal dynamics. Its comparative weakness is in that connection its distinctive feature. It may then be called the sphere of weakness—*the asthenosphere*, and its position among the successive shells which make up the body of the earth is as follows:

The atmosphere	Including the biosphere
The hydrosphere	
The lithosphere	Including the pyrosphere
The asthenosphere	
The centrosphere, or barysphere	

Each has played its fundamental part in the development of earth-history.

STRESS-DIFFERENCES BETWEEN CONTIGUOUS COLUMNS OF THE CRUST

Stresses under conditions of isostatic equilibrium.—The continental platforms slope down into the ocean basins at grades which range mostly from one in ten to one in thirty. Some of the great foredeeps show both the greatest depths of water and the steepest descents. The Chilean coast, for instance, at lat. 25° S., slopes from the Andes to a depth of 7,500 meters with a submarine grade of one in eight. Under the hypothesis of nearly perfect isostasy, which will be favored in this discussion, this would be taken to show the contiguity of areas in the crust of markedly unlike density.

Let the slope between such areas be regarded as a thick partition between two columns, each in isostatic equilibrium. These rest then upon the substratum below the zone of compensation with the same pressure and stand vertically in equilibrium.

In so far as the rock within the crust is subjected to mere cubic compression, equal in all directions and increasing with depth, there is no distortional force. In so far, however, as side pressures in one column are not balanced by equal side pressures from the adjacent columns, there is a stress-difference which does produce a distortional strain. If the stress-difference exceeds the elastic limit a permanent deformation results which reduces the stress and eases the strain. It is the plan of this paper to discuss the nature of the stress-differences on the partition separating two contiguous columns of the crust, of markedly unlike density; first, when these are in isostatic equilibrium, and second, when not in such equilibrium. Fig. 13 is drawn to show graphically these relations.

The land-column of the crust is marked *M;* the submarine column is *N;* *O* is the earth-shell below the zone of isostatic compensation; *P* is the column of sea-water. The vertical partition between the unlike columns stops in reality, according to the hypothesis, at the bottom of the columns. It is here extended down through the earth-shell *O–O* in order to discuss the deformation which would take place in the latter shell. *M* and *N* represent what is here called the lithosphere; *O–O* the zone which it is proposed to call the asthenosphere.

In case A, isostatic equilibrium is assumed and the pressures of the two lithospheric columns are equal upon the asthenosphere. But, assuming for the moment that the vertical pressures are freely transmitted as lateral pressures, it is seen that a marked horizontal unbalanced pressure is produced by the land-column against the sea-column, as represented by the horizontal lines of the stress diagram. The top of the land-column is balanced only against the negligible weight of the atmosphere and the lateral stress gradient is there highest. The next portion below is balanced against the

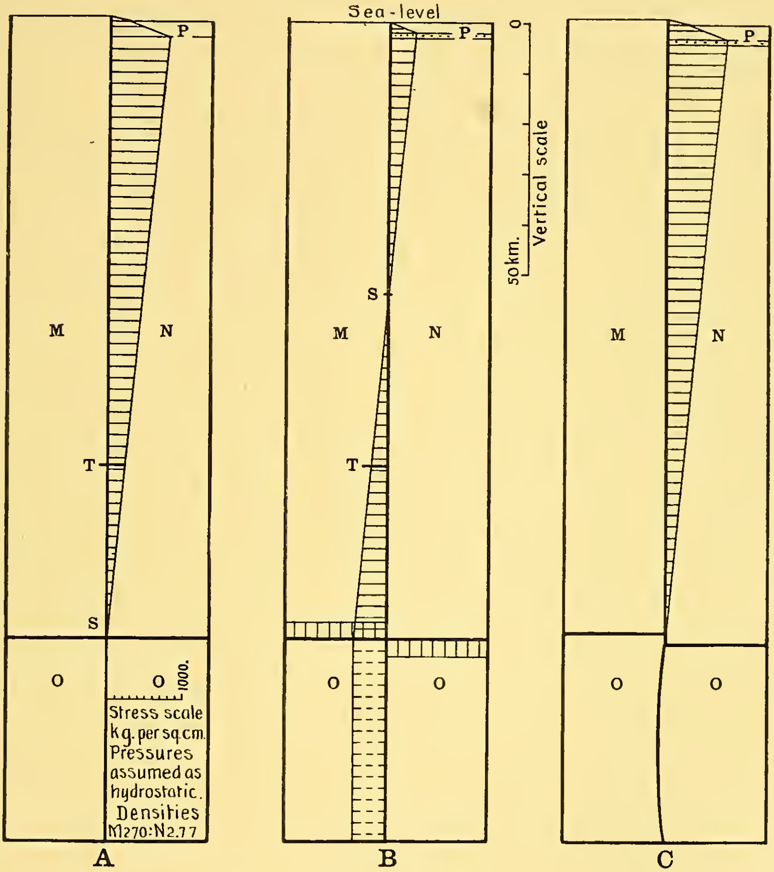

FIG. 13.—Diagram illustrating pressure-relations of the crust for marginal portions of the continental shelf and oceanic basin, interpreted as balanced by uniformly distributed isostatic compensation. Stress-differences are shown by cross-lined diagrams, the pressures being regarded as transmitted hydrostatically. The actual lateral stress-differences, for stresses within the elastic limit, are about one-fourth of the hydrostatic pressures here shown.

A. Columns in isostatic equilibrium.
B. Relations after base-leveling.
C. Relations after re-establishment of isostatic equilibrium.

sea-water and the stress gradient becomes less high. The maximum thrust occurs at the bottom of the ocean and is from the land toward the sea. Below this level the density of the sea-column is greater than that of the land-column. This, with increasing depth, gradually balances the excess pressure, and at the base of the lithosphere both the lateral and vertical pressures of both columns by hypothesis are equal.

In this diagram the pressures of the columns are imagined to act hydrostatically, but, in reality, for stresses *within the elastic limit*, this would not be so. Further, in so far as the partition is much wider than the difference in elevation of the columns, it has a gentle surface slope and will tend to give the upper part of the land-column competence to hold itself in by its own strength and that of the partition. The approximate ratio which the actual lateral pressure-differences on the two sides of the partition hold to the assumed hydrostatic pressures may be perceived from the results of a recent work by Love entitled *Some Problems of Geodynamics*.[1] In chaps. ii and iii he considers the problems of the isostatic support of continents and mountains. As a basis for the analytic treatment he assumes, first, the existence of complete compensation within a depth of one-fiftieth of the earth's radius, 127 km.; second, that at this depth all stress-differences disappear, the pressures below being of the nature of hydrostatic pressures, the only kind which could occur if a fluid layer existed at and below the depth of 127 km.; third, it is known that the heterogeneities of mass in the lithosphere only slightly modify the form of the geoid, and it is accordingly assumed that there is no such effect. Love thus treats of the limiting case of a crust exhibiting perfect isostasy, its surface relief not modifying the form of the geoid given by the ocean surface, and resting with its base upon a fluid zone. As such, his solution is of great value, but he states: "It must, however, be understood that the special form (of the hypothesis of isostasy) is introduced for the sake of analytical simplicity rather than physical appropriateness."[2]

The artificiality of the assumption of the existence of no stress-differences below the zone of compensation is shown by the law of

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[1] Cambridge University Press, 1911.

[2] *Op cit.*, p. 7.

density distribution which results. With only these three limiting assumptions, the number of unknown quantities remains larger than the number of equations, and the results are, strictly speaking, indeterminate; but by making various reasonable further assumptions definite solutions in accordance with these may be obtained. The elimination of stress-differences at the base of the lithosphere, taken as equivalent here to the zone of compensation, requires, however, that there shall be a peculiar relation of densities. To compensate an elevation it must be offset by matter below of less density than the mean for that depth, but in order to quench the stress-differences at the base of the lithosphere there must be between the light matter and this base a layer of more than mean density for that depth. Thus the light layer must perform a two-fold function, compensating not only the elevation above but the heavy layer below. For depressions in the crust there must be a reverse arrangement, matter of more than mean density existing immediately below the surface. But above the base of the lithosphere there must be a layer of less than mean density for that depth. The artificialities of this scheme would be sufficient to form a disproof of the initial assumption which determined it, but it also seems to be directly disproved by the evidence brought forward in the earlier parts of the present article. Nevertheless, the exact mathematical solution of this difficult problem is of great value as giving the results of the assumptions of extreme isostasy.

For the largest inequality of the crust, regarded as a zonal harmonic of the first order, that represented by the land and water hemispheres, Love shows that the lateral stress-differences under this hypothesis of isostasy reach a maximum at a depth equal to one-third of the zone of compensation and are equal to only 0.006 of the weight of a column of rock of height equal to the maximum height of the inequality. For harmonics of the second and third orders, representing the continents, the fractions are 0.0134 and 0.0208. These results, Love states, are extremely favorable to the hypothesis of isostasy, since the inequalities could be supported by any reasonably strong material.

There are two criticisms, however, to be noted while citing this conclusion. First, it is known that the crust is vastly stronger than these requirements, so that such a perfected isostatic arrangement is not demanded on the score of crustal weakness. Second, the harmonic curves giving these figures are of a gently sweeping character; whereas, the actual continents are in many places high on their margins, and from these margins they slope with comparative steepness to the mean depth of the ocean floors. The stresses set up beneath the continental margins are accordingly a closer approximation to those imposed by lofty mountain ranges. Assume that compensations of the continental margins are perfect and the problem becomes that which Love takes up in the following chapter, namely, the isostatic support of mountains, except that we deal with only one great slope, whereas the theory calls for a succession of mountains and valleys.

It is shown that for such a compensated series, postulating the distribution of densities previously discussed, the greatest stress-difference exists at the mean surface, beneath the crests, and reaches a value equal to half the weight of a column of rock equal to half the height of the crests above the valley bottoms. From this maximum the stress-difference decreases to zero at the base of the zone of compensation. The solution by G. H. Darwin for uncompensated mountains and valleys gave a maximum stress-difference equal to 74 per cent of half the height, this maximum occurring at a depth equal to about one-sixth the distance between mountain crests. Even with perfect isostatic compensation, distributed after the fashion assumed by Love, the stress-differences for mountains and valleys are seen consequently to be two-thirds in value of those produced by an uncompensated relief, and are approximately one-fourth of the hydrostatic pressures. This fraction, one-fourth, happens also to be the same as Poisson's ratio, the ratio of the lateral expansion to the vertical shortening of a free rock column under vertical stress.

Now the distribution of density has been found to be more or less irregular, and there is no evidence of such a reversing layer at the base as Love has postulated. Stress-differences will consequently extend below the isostatic compensation. If, however, the latter is not uniformly distributed, but is concentrated somewhat in the outer half of the lithosphere, the stress-differences will become small at and below the base of the lithosphere. On account of the incompleteness of local compensation, the irregularities and uncertainties of the actual facts of nature, the Gordian knot of a solution may be cut by simply assuming for present purposes the form of diagram given by hydrostatic pressures due to a compensation uniformly distributed. The approximate stress-differences will be given by taking one-fourth of the values given by the hydrostatic pressures. This transfers the problem from the difficult field of zonal harmonics to the simple one of hydrostatics, and perhaps does not introduce errors greater than those involved in the differences between nature and the postulates which form the foundation of the solution by zonal harmonics. This hydrostatic diagram is shown accordingly in Fig. 13.

It is held by the advocates of extreme isostasy, however, that for long-continued stresses the crust is very weak; in other words, the elastic limit is low, and slow plastic deformation readily occurs which tends to dissipate the stress-differences and reestablish isostatic equilibrium. To the extent to which this is true, the real diagram of lateral stresses would approach the hydrostatic diagram here given and measure the forces producing plastic flow.

It has remained, however, for the opponents of the hypothesis of local and nearly perfect isostasy to point out, what is here illustrated graphically, that the extreme theory requires a belief in vertical weakness but lateral strength. If it were not for lateral strength the land-column would crowd against the sea-column, more at the top than at the bottom. Flowing out with a glacier-like motion over the upper part of the sea-column, the land-column would settle at the top and become shorter. This in turn would bring about a vertical elevatory pressure against its bottom, the column would rise, lateral creep would continue with equal pace, and the end result would be a density stratification in which the continental crust would come to overlie the oceanic crust. The limit of such an action would be given by the decreasing surface gradient, this finally becoming so gentle as to stop the glacier-like flow. The lack of such an effect implies of course that the lateral stresses of the outer part of the lithosphere lie within the elastic limit. Therefore they may be regarded as having not more than a quarter of the value shown in Fig. 13A.

The suggestion of the existence of opposing modifying factors is to be found in conclusions from the previous parts of this investigation—that compensation may be in many places concentrated somewhat in the outer half of the zone as here shown and in other places fade out through a notable distance below. These two variations in the distribution of compensation would modify the stress diagram in opposite directions.

Modifications of stresses produced by base-leveling.—Consider next the case of complete erosion to sea-level, as shown in Fig. 13B. The rock from the land-column has been deposited as sediment over the sea-column. As the columns are supposed to act as units the sediment is shown as spread uniformly. The lateral stress diagram beneath the bottom of the sediment shows a rate of decrease the same as in case A, but the value of the hydrostatic stress at any depth is diminished by the sum of the depths of erosion and deposition. The lateral stress now changes in sign at a point *S* and at this depth is a line of no lateral stress. Above this depth the continental segment tends still to spread over the ocean, but less effectively than before; below this depth the oceanic segment now thrusts against the continental crust.

If the ocean water be eliminated from the diagram and base-leveling should bring both columns to a uniform surface, then the neutral depth *S* advances to the surface and the lateral stress diagram in B is just the reverse in value to A. In that case there is no lateral thrust at the surface, but at all depths below there is an excess pressure against the continent reaching a maximum at the bottom of the lithosphere. This extreme case cannot apply to the ocean except for that limited width over which is built out a continental shelf. To the degree to which the weight of this shelf is supported by the ocean crust beyond, the column beneath the shelf would not operate with its full pressures against the land. The case would apply better to the complete erosion of level-topped plateaus situated within a continent.

For the lateral pressure within the lithosphere to become effective in a landward undertow would require a lesser rigidity of the crust at the bottom than at the top. Such a lesser rigidity may be granted, but it is seen then that the landward undertow would be greatest at the bottom and could not advance above a depth indicated on the diagrams by T. At this point the stress is of the opposite sign but of the same value as for the state of isostatic balance in case A. If seaward flow did not take place at this level in the first case, landward flow could not take place in the second.

For the extreme case where isostasy is completely destroyed by surface leveling, no water body remaining, T will rise upward to a depth equal to one-half the depth of the zone of compensation. If the surface of complete compensation be 76 miles deep, this gives a minimum depth of 36 miles. For the undertow to reach this height implies, however, not only the limiting case of complete destruction of isostasy, but a crust only one-half as rigid at depth T as at the surface and a previous state of expansive surface stress as great as the outer crust could bear. On the other hand, if tangential pressures due to centrospheric shrinkage should co-operate with the stresses tending to restore isostatic equilibrium, underthrust would become more effective below, but overthrust would also become effective above.

The disappearance of isostatic compensation at a certain level means the disappearance of notable heterogeneity in the earth-shell below, as argued in Part V (pp. 446–48). One of the possible suppositions to explain this is to suppose that this shell is weaker than the crust above and therefore the lateral thrust due to an assumed initial heterogeneity would cause a lateral flow, a density stratification, and a resulting disappearance of the postulated heterogeneity. This supposition of a weaker zone finds support in other lines of evidence. Therefore, although some lateral flow at the base of the lithosphere may occur during the restoration of isostatic equilibrium, it is to be expected that the bulk of such flow will be below, for there the substance is more plastic and the lateral stress is throughout at a maximum.

Let attention be given next to the vertical as contrasted to the lateral unbalancing brought in by the destruction of isostatic equilibrium. The land-column becomes lighter, the sea-column heavier, by amounts which are shown in the *vertically lined* stress diagrams at the base of the lithosphere in case B. Supposing that vertical readjustment of the columns is prevented for a time by the strength of the crust, the vertical stresses will be taken up by a vertical shearing strain along the partition between the two columns. This shear is equal in amount to the difference in total weights of the columns. Let the shear per unit area be called s. It acts over a surface taken as 122 km. high. Let this height be called h. The weight of the columns will vary with their breadth in the plane of the drawing. If the breadth of each be taken as b and the weights per unit area as M and N (N including rock, sediment, and sea-water), then for a cross-section of unit thickness the total difference in weight is $(N-M)b$ and the total shear is this same amount, provided that the columns are not sustained in part by other boundaries. But the total shear is also sh. Therefore

$$sh=(N-M)b$$

$$s=(N-M)\frac{b}{h}$$

For narrow columns b is small, giving to s a small value and consequently one within the elastic limit. Let b become broad and s will then become large and exceed the elastic limit. The *lateral* pressures, on the contrary, are less dependent upon the breadth, and, if the problem were regarded as one of hydrostatic pressures, would be wholly independent of breadth. The formula shows that the broader the columns, the more readily they will readjust by vertical shear between the columns. Now unless failure by vertical shear took place between the upper part of the columns the heavy column would be held up, the light column would be held down, except for the partial effect of sagging in case the columns were very broad. The lateral landward pressure at the base could therefore not become effective. The loaded portion of the crust must fail first by shear or flexure of its upper portion. Whatever be the distribution of strength it would appear then that the primary yielding is the vertical one and the landward force of undertow can become only secondarily effective.

The hypothesis of local and nearly complete isostasy requires that the elastic limit for vertical shear should be very low in order that narrow columns should be able to rise or sink. This may be illustrated by the following example:

Suppose a region 50 km. in radius possesses a mean departure from isostatic equilibrium equal to 76 m. of rock (250 ft.) and that the surrounding regions are out of adjustment by the same amount but in the reverse direction. This is the maximum area for regional isostasy which in Hayford's opinion is to be expected, and 250 ft. is the mean departure from isostasy as given by him in his Minneapolis address. But in this example the adjacent regions are each assumed to be out of adjustment in opposite directions by this amount and, therefore, the differential load is twice this or 500 ft. of rock. The case is one which he would regard consequently as rather extreme. Now a cylinder 100 km. in diameter and 122 km. deep could not fail through its bending moment, as in the flexing of a beam. It would have to fail as in punching a rivet hole through a metal plate, in other words, by circumferential shear. The shearing stress per unit area is obtained by dividing the total load by the total shearing surface. With the data taken as above this gives $s=8.4$ kg. per sq. cm. or 120 lbs. per sq. in. But strong rock at the surface can readily carry a shearing stress of from 700 to 1,000 kg. per sq. cm. (10,000 to 14,000 lbs. per sq. in.). Isostatic perfection to this degree would therefore require the zone of compensation as a whole to be only about one-hundredth as strong under permanent stress as is solid rock at the surface. This calculation alone would tend to show that the loads and areas by which the crust departs from isostatic equilibrium have been much underestimated by the advocates of extreme isostasy.

It should be noted, however, that, following the lines of his rejoinder to Lewis, Hayford would answer that he regarded the landward isostatic flow as taking place within the zone of isostatic compensation and the vertical shear as operating, consequently, through a depth far less than the thickness of the entire zone of compensation. There are, however, a number of inconsistencies in this argument, some of which have already been made evident. Others will appear as a result of the later discussion of this chapter. But it may be noted that even granting this contention—that only the outer third of the zone of compensation was involved—the unit shearing stress would be multiplied only by two or three and would still imply a weakness in this part of the crust to resist long-enduring shear or bending stresses, its capacity being only 3 or 5 per cent at most as great as is found to exist in surface rocks for stresses of human duration.

Relief of stress accompanying restoration of isostasy.—It is seen from the preceding analysis that the movement of the unbalanced columns toward a new state of equilibrium will be partly by vertical shear in the neutral ground between them, but, where the areas are large in comparison with the thickness of the zone of compensation, the easiest mode of yielding may be by flexure, showing at the surface as crustal warping. Both modes of yielding serve to transmit the excess vertical stresses of the heavy and sinking column into the asthenosphere. If the latter be indeed a shell of weakness it will transmit these pressures more or less hydrostatically. The vertical pressure-differences will act within it as lateral pressures making for flow toward the lighter column. It is shown in Fig. 13B that the maximum horizontal stress in so far as it approaches a hydrostatic distribution acts throughout the whole depth of this zone, so that it not only is weaker than the crust above, but is subjected to maximum stress over a greater area. It will yield by flowage therefore either if of small depth and very plastic, or of great depth but more rigid. If the columns are adjacent and narrow as compared to the thickness of the shell of weakness, then the principles of plastic flow would require that the flow be chiefly in the upper part of this shell. If, however, the columns are of considerable breadth compared to the thickness of the asthenosphere, and especially if at a distance from each other, then the principle of least work would determine that the middle strata of this shell should flow the farthest and the whole would to some degree participate. If an imaginary partition were extended downward through this shell as shown in A and B of Fig. 13 this partition would be found warped after the movement as shown in C of the same figure.

It was seen in an earlier part of this discussion that, even supposing deformation became effective by means of the lateral stresses within the lithosphere and without the existence of a zone of weakness below, still only the basal part below the point *T* would be competent to give a landward movement during the restoration of isostatic equilibrium. But now it is seen that in the asthenosphere the lateral pressures are transmitted with greater amount, from a greater distance, and with a greater cross-section. The zone is one without notable isostatic compensation within it and is presumably more plastic than the basal part of the lithosphere. Therefore there is good reason to believe that the subcrustal undertow is restricted to the asthenosphere.

The forces actually needed to produce flowage would be in reality but a fraction of those indicated in Fig. 13B as existing in the asthenosphere. The reason is that the greater part of the vertical forces is consumed in producing flexure and shear in the lithosphere. Only a residuum is needed to produce a slow plastic flow in the shell below. For that reason broken lines are used in that part of the stress diagram. The energy consumed within the lithosphere by its deformation will be nearly independent of the breadth of the columns; it will actually tend to become somewhat less with breadth because flexure on large radii will be favored. The energy consumed in the asthenosphere will, on the other hand, increase with the breadth of the columns, but will be spread over a greater area. The temperature effect due to the absorption of energy would appear to be a minor factor, for it cannot exceed that energy which is supplied by the average vertical stress-difference multiplied by the vertical distance moved. The average vertical stress-difference will be the mean between that at the beginning of movement and that residual stress remaining after the movement is completed.

In determining the scale of the diagrams of Fig. 13 the following data were chosen. The land-column was taken in A as having a surface elevation of 1,000 m. and a density of 2.70; the sea as 3,000 m. deep, and the rock below as possessing a density of 2.77. The sea-water has a density of 1.03. These relations give an isostatic balance at a depth of 122 km. In B, erosion of the land to sea-level is supposed to have taken place and the sediment spread with same unit weight over the sea-column that it had as rock upon the land. These relations give a depth of 54 km. to *S* and 88 km. to *T*.

It should be repeated, however, in closing this topic, that the solutions here given are approximate only and assume that isostatic compensation results in lateral stress-differences which show the same distribution of forces as a diagram of hydrostatic pressures, differing only in magnitude. The writer is inclined to think that the actual facts of nature call in most cases for some depression in depth of the critical points beyond those here shown. Especially is there likely to be under the margins of a continent in isostatic equilibrium some permanent lateral stress-difference within the asthenosphere, due to the compensation above and tending toward a landward undertow. Upon the unbalancing due to erosion and sedimentation this would cause the lateral stress-differences within the asthenosphere to rise more quickly to the low elastic limit and permit more readily than would otherwise be the case a regional readjustment toward isostasy.

RELATIONS OF UNDERTOW TO THE ZONE OF COMPENSATION

Present status of the problem.—The causes of vertical movements Dutton[1] made twofold. He clearly distinguished on the one hand between those internal forces leading to expansion or contraction, which tend, by producing changes in density, to create isostatically a new surface relief, and, on the other hand, those isostatic readjustments following erosion and sedimentation, readjustments which tend not to make a new, but to restore the older, relief. Folding he regarded as unrelated to the former, as a result of the latter. He had shown earlier (in fact, he had the honor of being the first to show) that the time-sanctioned hypothesis of cooling as a cause of crustal shrinkage and consequent mountain-making was inadequate to account for either the distribution or amount of folding.[2] From this he was led to regard folding as due, not to any kind of contraction, but as a compressive movement of one section

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[1] "On Some of the Greater Problems of Physical Geology," *Bull. Phil. Soc. Wash.*, XI (1889), 51–64.

[2] C E. Dutton, "A Criticism upon the Contractional Hypothesis," *Am. Jour. Sci.*, VIII (1874), 113–23.

of the crust against another, presumably offset by tension in some other region. Dutton's argument is that the crust beneath the plateau is unloaded by erosion, that the crust beneath the basin is loaded by sedimentation. An isostatic movement, rejuvenating the relief, must, by causing the overloaded basin to settle, produce a squeezing-out of matter beneath the sinking area, and a crowding-in of matter beneath the rising area. The surficial movement of sediment is from the high area toward the low. The deep-seated movement is from the low toward the high. Thus the cycle becomes completed and the mass of matter above the level of complete compensation remains the same in each column. The seaward movement of the sediment, as a frictional resistance against the river bottoms, produces only an insignificant drag, but the return subterranean movements by viscous or solid flowage must produce a pronounced drag upon the crust in the direction of the rising region. Dutton's reasoning is clear, but the effectiveness of the action rests upon several assumptions. First, it omits the influence of the surface relief and the degree to which that tends to a lateral spreading movement from the high toward the low regions. Secondly, it postulates a low rigidity to the crust, as he in fact notes. Thirdly, it involves the conception of a strong undertow fairly near the surface in order that the crust above may be too weak to resist the viscous drag. As there were little quantitative data available at the time when Dutton formulated this corollary of his theory of isostasy he could not have tested the validity of these assumptions, but raised the problem for those who should come after him.

This theory of folding took a somewhat different form in the mind of Willis, as expressed in the concluding chapter of his *Research in China*.[1] This work in many ways is of the very first importance and gives a comprehensive view of the geological history of the whole continent of Asia. As to the nature of the movements, he finds that the continent of Asia may be resolved into positive and negative elements, the former areas tending to stand high, the latter tending to stand low. These tendencies are latent during comparatively long periods of quiet and resultant peneplanation,

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[1] Vol. II (1907), Carnegie Institution of Washington.

but become operative during epochs of diastrophism. The compressive movements, on the other hand, have pressed and welded the positive elements together, the axial directions of folding representing the compression of the negative zones lying between.

The cause of the diastrophism Willis ascribes to differences in specific gravity, restricted, according to Hayford's determination, to the outer hundred miles of the earth's body; the vertical movements being chiefly due to isostatic readjustment between the several continental elements, the compressive movements being due to the tendency of the heavier oceanic segments of the earth to spread and underthrust the outer portions of the whole continental mass. This theory of the cause of lateral compression was discussed by the present writer in a review of Willis' work,[1] and the objections stated against it there are in part the same as will be elaborated farther on in the present article.

Hayford took up the same subject in his address, delivered at Minneapolis on December 29, 1910, as retiring vice-president of Section D (Mechanical Science and Engineering) of the American Association for the Advancement of Science, the title of his paper being "The Relations of Isostasy to Geodesy, Geophysics, and Geology."[2] This is a paper of broad scope intended to show how vertical movements not in apparent accord with isostasy and also movements of folding may be explained as secondary results of isostatic adjustment and really in harmony with the hypothesis of nearly continuous movement in a crust of low rigidity and of almost complete isostasy. This part of his theory is essentially the same as Dutton's but is elaborated in greater detail.

Harmon Lewis called attention to the defects in this theory of deformation,[3] but Hayford made a rejoinder, positive and sweeping in its style, to this and other lines of criticism by Lewis.[4]

The names of Dutton, Willis, and Hayford deservedly carry much weight and must be accepted at their face value by geologists

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[1] *Science*, N.S., XXIX (1909), 257–60.

[2] Published in *Science*, N.S., XXXIII (1911), 199–208.

[3] "The Theory of Isostasy," *Jour. Geol.*, XIX (1911), 620–23.

[4] John F. Hayford, "Isostasy, a Rejoinder to the Article by Harmon Lewis," *Jour. Geol.*, XX (1912), 562–78.

who have not themselves made a critical study of the problems of isostasy. The arguments which the writer advanced in 1909 against this hypothesis were published under a title which apparently did not call attention to them. The style of Hayford's reply to Lewis is crushing and conveys the impression that Lewis has been completely refuted. It is because of these reasons that the subject calls here for fuller development.

In his Minneapolis address Hayford outlines a theory of the principles of diastrophism which turns upon his conclusion that isostasy is so nearly complete that areas of even limited size average only 250 feet from the level of isostatic equilibrium. He assumes chemical and physical changes to be induced in the crust by the changing load due to erosion and sedimentation. These he thinks are superimposed upon the effects of nearly continuous vertical movements of isostatic readjustment. The vertical movements in turn produce a lateral undertow which is given as a cause of localized heating and folding. Apparently this is regarded as a complete mechanism of deformation since the author raises the query:

> Is it at all certain that under the influence of such actions the geological record at the earth's surface at the end of fifty to one hundred million years would be appreciably less complicated than the geologic record which is actually before us? I think that it would be fully as complicated as the actual record.[1]

This theory of folding as the result of subcrustal undertow is illustrated by means of two diagrams. In Fig. 1, the zone of viscous flow from the sinking toward the rising area is placed in the lower quarter of the zone of isostatic compensation. In Fig. 2 it is shown in the middle of that zone, dying out both above and below. Apparently then, as shown by these two different conceptions, the author cited was guided by no definite theory, based upon the mechanics of materials, as to the factors which would determine the depth of this zone of undertow and its relations to the zone of compensation.

Harmon Lewis in his paper on the "Theory of Isostasy" has discussed various aspects of the isostatic theory as developed by

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[1] *Op. cit.*, p. 206.

Hayford, and among them this question. Regarding the possibility of folding by means of isostatic undertow, Lewis concludes:

> Now, according to the theory of isostasy, compensation would be essentially complete, and if compensation is complete the depth of compensation as determined by Hayford's geodetic work would be as great as 60 miles. Hence, the undertow postulated by isostasy would exist chiefly below 60 miles. It is decidedly questionable that an undertow even much nearer to the surface than 60 miles would cause the observed folding in the upper few miles of the crust.[1]

In regard to this criticism by Lewis concerning the cause of folding, Hayford states in reply:

> On pp. 621–22 Mr. Lewis sets forth the argument that there is much geological evidence of horizontal movements in the outside portions of the earth, especially in the form of folding, that the controlling movements of isostasy are assumed to be vertical and hence cannot account for folding, and that the horizontal movement or undertow concerned in isostatic readjustment must be below the depth of compensation and hence so far below the surface as to be very ineffective in producing folding.
>
> There are two fatal defects in this argument as applied to controverting anything that Hayford believes or has written.
>
> First, Hayford has already indicated clearly his belief that the undertow concerned in isostatic readjustment is above, not below, the depth of compensation. In both the figures published in his Minneapolis address the undertow is clearly indicated as being above the depth of compensation and it is also so indicated in the corresponding text. As Hayford puts the undertow comparatively near the surface, where it is conceded that it would be effective in producing folding, the existence of extensive folding is a confirmation, not a contradiction, of his theory of the manner in which isostatic readjustment takes place. It is certainly not fair to hold Hayford responsible, either directly or by inference, for any theory which someone else may believe which involves an undertow situated entirely below the depth of compensation. Mr. Lewis apparently believes such a theory.
>
> Second, the movements which produce isostatic readjustment are necessarily horizontal, not vertical. If two adjacent columns of the same horizontal cross-section extending from the surface to the depth of compensation have different masses the readjustment to perfect compensation must involve a transfer of mass out of one column, or into the other, or from one to the other. In any case the transfer must be a horizontal movement. Hayford has already shown in print more than once that he understands that vertical movement alone does not produce isostatic readjustment. Moreover, a careful reading

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[1] *Op. cit.*, p. 622.

of his Minneapolis address will certainly show that he believes that the total amount of material moved horizontally during isostatic readjustment, and especially the total number of ton-miles of such movement, is vastly in excess of the corresponding quantities concerned in the vertical components of the movement which takes place. Hence the folding and other abundant evidence of past horizontal movements observed by geologists confirm Hayford's hypothesis as to the manner in which isostatic readjustment takes place, instead of conflicting with it as Mr. Lewis' article would lead one to think.[1]

The present writer, however, believes with Mr. Lewis in the theory that an undertow must be essentially below the zone of compensation and is incapable of producing surficial folding. The reasons have been given in part in the consideration of the stress-relations, as they would exist under the hypothesis of extreme isostasy. But there are other reasons why the subject should be discussed in further detail. One reason is that, if Lewis is right on this point and Hayford wrong, it is desirable that this should be made clear, in justice to Mr. Lewis as well as to the subject. The other reason is that here in reaching a conclusion we can advantageously pursue a method of exclusion. By showing that isostatic undertow cannot take place within the zone of compensation, for various reasons besides those discussed in the stress diagrams, we reach the conclusion that it must take place in a level below that zone. Furthermore, by noting the conditions which would hinder lateral flowage we may arrive at a conclusion as to those which must exist to greater or less degree in order to permit it.

Objections against undertow in the zone of compensation.—The pressures which occur during a state of isostasy and after the destruction of that condition have been discussed. It was seen that the pressures making for the undertow necessary to restore isostasy were greatest at the bottom, but, more especially, below the bottom of the zone of compensation. The possibility remains to be considered, however, that perhaps the distribution of the rigidity of the crust more than offsets the distribution of pressures. Suppose the middle of the zone of compensation should be very weak and the crust at and below the bottom be very strong. Then,

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[1] *Op. cit.*, pp. 573, 574.

if the restoration of isostasy was deferred until assisted by strong tangential pressures due to centrospheric shrinkage, it might be held that isostatic undertow could take place within the zone of compensation and between *S* and *T* of Fig. 13B. If, furthermore, compensation should be not uniformly distributed but taken as largely concentrated in the upper part of the zone of compensation, which however is contrary to the Hayfordian hypothesis, then the forces making for undertow may correspondingly rise in the crust. For these reasons it is seen that the previous argument from the distribution of pressures is not final and that the physical conditions involved in lateral flowage must also be considered.

The only positive reason which has been advanced for seeking to place the undertow within the zone of compensation is in order to utilize its viscous drag as a cause of folding. To become effective the drag must be strong, the crust above by contrast weak and therefore thin. The crumpling pressure on the *surface* of the crust cannot be transmitted directly from the sinking area, as is shown in Fig. 13, since the thrusting force is greatest at the bottom. It must be supposed to arise from the viscous drag of the undertow. But viscosity decreases the hydrostatic head with increasing distance from the source. Therefore, to permit a viscous flow at a distance from the source of pressure implies a mobility within that level of the crust which would make it wholly incapable of carrying the stresses necessary to maintain its own isostatic equilibrium. Therefore this level, by the very terms of the general conception of isostasy, would become the bottom of the zone of compensation.

As another mechanical defect of the theory under review, it is to be noted that the section of undertow taken by Hayford as in the middle of the zone of compensation is not given as involving more than half of that zone. This is as if a viscous fluid were transmitted through a pipe in which the cross-section of pipe and fluid were equal. To assume that the fluid is free to escape into a region of less pressure at the far end and yet gives such a frictional resistance against its walls as to be able to crumple up the pipe is to assume that the two are of the same order of strength. The materials of pipe and fluid might almost be interchanged.

In such viscous flow the tendency would be for a swelling and bursting to appear at the near end rather than a through flowage with a crumpling of the pipe at the far end.

Finally, the greatest theoretical difficulty is encountered when it is sought to transmit matter from beneath the regions of oceanic marginal sedimentation to beneath the regions of a continental interior. Either directly or indirectly there must be a subcrustal transference going forward all the way between these distant regions; for example, from beneath the Mississippi and Colorado deltas to the fields of erosion in the Rocky Mountains, if a condition of even approximate isostasy is to be maintained throughout. This does not mean of course that an individual ton of plastic rock is transferred a thousand miles to balance a ton of sediment. Each subcrustal unit may be transferred only a mile, but it involves a subsurface movement of matter all the way from the regions of sedimentation to the regions of erosion.

Now this implies a *continuous pressure-gradient*, and even under the conception of great crustal weakness, a pressure-gradient which could fold the weak cover-rocks would be far higher than that needed for the movement of a continental glacier. Any large degree of viscous resistance in the zone of undertow would therefore require, in order to initiate movement, an enormous defect of isostasy under the distant continental interior, an enormous excess under the marginal oceans. After a rejuvenative movement had started, it would be slow, the frictional and deformative resistances nearly balancing the deforming force. Therefore inertia of the moving mass could not carry it appreciably beyond the point where the moving force, weakened by loss of head, would just balance the resistances to further movement. It would be expected, in consequence, that a residual pressure-difference would remain, even after a period of restorative isostatic movement. But an inspection of the map of New Method anomalies given in Part II, p. 153, does not show any such anomaly gradients as would comport with this expectation. A vast region of the continental interior extending from Lake Superior to the Rio Grande and westward to beyond the front ranges of the Rocky Mountains shows average positive anomalies, indicating an excess of matter, not a deficiency. To the westward is a broad region of average negative anomaly reaching a maximum at centers near the Pacific coast and no marked excess is shown near the mouths of the great rivers. Such a lack of regional relations would appear to show that the anomalies are due much more to local loads and irregularities upon and within the lithosphere, and to bowings due to great compressive movements unrelated to isostasy, rather than to the existence of an isostatic gradient leading from the ocean borders to the interior fields of great erosion. Therefore either the idea of strong viscous drag by undertow or else the very doctrine of isostasy—one or the other—must be abandoned. But it has been seen that if undertow exists in a comparatively plastic stratum, then that physical condition will cause it to be the bottom of the zone of compensation. Thus the application of every pertinent engineering principle reduces the initial hypothesis of surface folding by isostatic undertow, and, especially by undertow within the zone of compensation, to an absurdity.

Undertow restricted to a sphere of weakness—the asthenosphere.—All of this accumulative argument has not been advanced merely to show that a certain view is wrong. Rather has it been the intention to prepare the ground for what would appear to be a sounder theory of the mode of maintenance of isostatic equilibrium.

As for the basis of that theory, Schweydar, from the mathematical analysis of the measurement of the tides in the crust by means of the horizontal pendulum, has found that they are in accord with the assumption of the existence of a slightly plastic zone about 600 km. thick beneath a more rigid crust 120 km. thick.[1] It would appear that the geodetic evidence of isostasy points also toward the existence of such a thick and somewhat plastic zone beneath the more rigid lithosphere. It gives no knowledge of the exact thickness or depth, but for convenience the figures given by Schweydar will be assumed. It is a matter of importance to note however that, although the quantitative limits are uncertain, the suggestions given both by the tides and by isostatic

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[1] "Untersuchungen über die Gezeiten der festen Erde und die hypothetische Magmaschicht," *Veröffentlichung des k. k. Preusz. geodät. Institutes*, Neue Folge No. 54, Leipzig (1912, B. G. Teubner).

compensation point to a zone of weakness much deeper and thicker than the figures which have customarily been taken as a probable depth of origin of magmas. The latter however rests upon uncertain extrapolation, whereas the figures for the limits of the asthenosphere, although of no exactness and perhaps 20 or 50 per cent from limits which finally may be chosen, have at least been determined by more direct evidence. In such a thick shell of weakness, the readjustment, after an erosion cycle, of a continental interior to isostatic equilibrium would require but very little viscous shear and but little lateral movement.

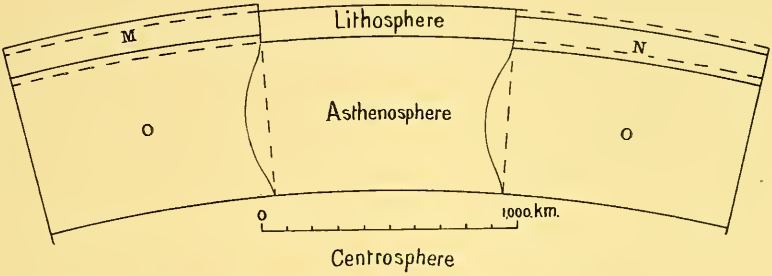

FIG. 14.—Diagrammatic vertical section of the crust, to show nature of undertow in the asthenosphere necessary to restore isostatic equilibrium in a positive interior continental area after a cycle of erosion. Effects of a vertical movement of 0.5 km. exaggerated 60 times. Asthenosphere grades into contiguous spheres and best limitations in depth are not known.

To give quantitative visualization to this conclusion Fig. 14 is drawn. Suppose a plateau area 1,000 km. wide in a continental interior to be separated from the region of sedimentary deposit by an intermediate region 1,000 km. across. Take a section 1 km. wide through these regions. Let an erosion cycle cause the removal on the average of 0.5 km. of rock from this area to be deposited over an equal area of sea-bottom. Then, during an epoch of diastrophism, assume complete recovery of isostatic equilibrium by undertow in a sublithospheric zone of weakness 600 km. thick. The vertical section of rock eroded is 500 sq. km. in area. As we have chosen a width of section of 1 km. we may also speak of this as the volume, 500 cu. km. To restore the mass of this column, 500 cu. km. must be added to it and flow past the vertical line which bounds it on the seaward side. As this zone of flow is 600 km. deep, the actual lateral movement, if all depths move equally, will be but 0.83 km., since 0.83×600=500. If the flowage is supposed to increase regularly from top and bottom to the middle the movement of the middle layer would be 1.66 km. A previously vertical line 600 miles long through this asthenosphere would then be bent at the middle by this amount and its two halves make angles of 0°19′ with the vertical. Each layer a kilometer thick would move horizontally 5.6 m. with respect to each adjacent layer of kilometer thickness. These figures bring out the insignificant degree of the plastic deformation in such a deep zone which is needed to restore isostatic equilibrium, even for a large interior continental area after erosion amounting to two-thirds of the present average elevation of the North American continent.

As a matter of fact the cross-section of the plastic deformation would not be a triangle, but a sinusoidal curve, so that the maximum linear flow for thickness of 600 km. would be between 0.83 and 1.66 km.

This illustration makes it clear that the isostatic rejuvenation of continental interiors as well as of the margins, which meets such grave difficulties under the hypothesis of a thin and shallow zone of isostatic undertow, is eliminated by adopting the hypothesis of a thick and plastic sublithospheric shell, such as has been found to be suggested by independent evidence.

The idea of folding as a result of isostatic undertow definitely may be abandoned, but the absence of a notable isostatic gradient has some further significance. It is seen from Fig. 14 that if the fields of great erosion and deposition are within a few hundred kilometers of each other the rejuvenative undertow, under the laws of stress distribution in plastic bodies, would involve mostly a limited tract in the outer part of the asthenosphere; whereas, if the undertow must extend over distances of 1,000 km. or more, then the whole depth of the asthenosphere will become involved. The amount of stress-difference and of plastic shear per unit of volume may therefore be no greater in the one case than in the other. Especially, if the middle of the asthenosphere is its weakest part, a movement generated by areas large enough to involve the whole of this zone would go forward under less stress-difference per unit of area than for more local adjustments. The absence of a notable continental gradient is suggestive therefore of a deep zone of weakness, least resisting in its central portions, and of very marked plasticity in comparison with the rigidity of the lithosphere above. This does not involve, however, the conception of a truly fluid zone, but merely that of a comparatively plastic solid.

The existence and nature of this zone of weakness is seen to enter vitally into the theory of isostasy and must of course bear with equal importance on other branches of terrestrial dynamics as well. It is proposed therefore to elevate it to equal rank with the other shells of the earth and to name it for that quality which, from the standpoint of diastrophism, is its most significant feature as compared to the zones above and below. This is its inability to resist stress-differences above a certain small limit. Its name, therefore, is the sphere of weakness—the asthenosphere.

[*To be continued*]

A COMPARISON OF THE CŒUR D'ALENE MONZONITE WITH OTHER PLUTONIC ROCKS OF IDAHO

C. A. STEWART
University of Idaho

The rough mountainous area comprising nearly all of the central part of Idaho and adjacent portions of Montana is an enormous batholith of quartz-monzonite of late Mesozoic age. In the northern part or "panhandle" of the state the predominating Algonkian sediments are cut by irregular masses of acidic intrusives which are quite generally believed to be outliers of the great batholith to the south. It is the purpose of this paper to point out that among these intrusives of northern Idaho is a type distinctly different from the other acidic intrusives of the state, and to propound for future field-workers the problem of its relationship to them.

The quartz-monzonites of central Idaho and those found in the southern part of the state are light-gray, granular rocks with biotite the chief dark silicate, and often containing muscovite. Porphyritic development of the feldspar and variations in the relative amounts of the minerals are common, but taken as a whole they are remarkably uniform rocks. I have seen this quartz-monzonite in place in the vicinity of Moscow, of Elk City, and in the Dixie mining district, and have examined specimens of it from other localities, and in every case it showed the same general characters. Professor D. C. Livingston has traversed great areas of it along the Salmon River; and the various United States Geological Survey reports by Lindgren, Eldridge, and Umpleby all describe the same light-gray, *micaceous* quartz-monzonite of which some of us have come to speak familiarly as the "Idaho granite." In the extreme north of the state around Priest Lake I have crossed many miles of the same rock.

Indeed it would be difficult in a pile of mixed specimens from these localities to distinguish the rocks from the various districts. Should there be in this pile, however, a sample of the average intrusive from the Cœur d'Alene district, the most casual observer would note a difference. This rock, according to Calkins,[1] is

> a medium-grained granular rock of which the constituents megascopically recognizable are feldspar, hornblende, and a little quartz. Of the feldspars, striated plagioclase, opaque and white, in rather small idiomorphic crystals can be distinguished from somewhat larger, grayish, and more transparent imperfectly formed crystals of alkali feldspar. The two are present in nearly equal amounts. The microscope shows, in addition to the constituents named, a little biotite, some small prisms of light-green monoclinic pyroxene with titanite and magnetite as abundant accessories.

Variations from this type are noted, especially in respect to the relative amounts of the minerals, but none of them resembles the rock from central Idaho, from which all of the Cœur d'Alene monzonite differs in the smaller amount of quartz, in the presence of hornblende, and in the lack of megascopic mica. The chemical differences are indicated by Table I.

TABLE I

ANALYSES OF INTRUSIVE ROCKS FROM IDAHO

	A	B	C	D	E
SiO_2	61.41	72.07	68.42	69.56	65.23
Al_2O_3	17.99	15.51	15.01	15.29	16.94
Fe_2O_3	2.93	0.31	0.97	0.86	1.60
FeO	1.39	1.01	1.93	2.06	1.91
MgO	1.30	0.35	1.21	0.69	1.31
CaO	4.75	1.93	2.60	2.81	3.85
Na_2O	4.01	4.02	3.23	3.97	3.57
K_2O	4.59	4.09	4.25	3.36	3.02
H_2O-	0.11	0.03	0.54	....	0.18
H_2O+	0.68	0.30	0.73	0.86	0.88
TiO_2	0.53	0.16	0.50	0.55	0.66
P_2O_5	0.19	0.11	0.13	0.16	0.19
All other	0.46	....	0.38	....	0.44
Total	100.24	99.89	99.95	100.17	99.78

A. Quartz-monzonite, near Gem, Idaho (Cœur d'Alene).—*Prof. Paper 62, U.S. Geol. Survey*, p. 47.
B. Quartz-monzonite, Mill Creek, Mont.—Lindgren, *Prof. Paper 27, U.S. Geol. Survey*, p. 18.
C. Quartz-monzonite, Hailey, Idaho.—Lindgren, *20th Ann. Rept., U.S. Geol. Survey*, p. 81.
D. Granite, Shafer Butte, Boise Co., Idaho.—Lindgren, *loc. cit.*
E. Biotite granite, Willow Creek Dist., Boise Co., Idaho.—Lindgren, *18th Ann. Rept., U.S. Geol. Survey*, p. 40.

The magmatic symbols for these rocks are as follows (calculation of A by Calkins, *loc. cit.*, and of C, D, and E by Washington, *Prof. Paper 14, U.S. Geol. Survey*):

A = I · 5 · 2 · 3, pulaskose.
B = I · 4 · 2 · 3, toscanose.
C = I · 4 · 2 · 3, toscanose.
D = I · 4 · 2 · 4, lassenose.
E = I · 4 · 3 · 4, yellowstonose.

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[1] *Prof. Paper 62, U.S. Geol. Survey*, pp. 46–47.

The Cœur d'Alene rock, therefore, falls in a separate order, emphasizing its smaller quartz content. The striking difference in the habit of the ferromagnesian constituents is, of course, not shown by the quantitative classification. Rock of the Cœur d'Alene type is known also from the following localities:

1. On Vermillion Creek in Montana, where Calkins[1] found a rock "distinctly different from the intrusive masses to the west, and showing marked affinity with the masses of monzonite and syenite exposed to the southwest in the Cœur d'Alene district." The ferromagnesian mineral is either aegirine-augite or masses of hornblende and biotite pseudomorphic after pyroxene.

2. At the junction of Black Prince Creek with the St. Joe River where Pardee[2] found "a porphyritic monzonite" of "marked resemblance to the dominant rock in the intrusions of the Cœur d'Alene." Biotite, in addition to the distinctive hornblende, is reported to occur in this rock, but the quartz is in rather small amount.

3. On Gold Hill in the northern part of Latah County I have found a porphyritic, hornblendic monzonite that can in no way be distinguished from specimens from the Cœur d'Alene. Only twenty miles south of this locality are the Thatuna Hills, composed of the micaceous, quartzitic monzonite described as characteristic of the great batholith of central Idaho. In fact, it was the striking difference between the rocks from these two places that first called my attention to this problem. Unfortunately the intervening country is covered by Tertiary basalt, so the relationship between the rocks cannot be determined.

The other intrusives in northern Idaho, although showing considerable variation from the central Idaho type, nowhere, as far as I can learn, resemble this characteristic hornblende monzonite, and in most places they show marked affinities with the central Idaho type.

Reference to the map (Fig. 1) shows that the occurrences of the Cœur d'Alene type all fall in the northeast-southwest line that has already been noted by Calkins for the Cœur d'Alene and Vermillion

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[1] *Bull. 384, U.S. Geol. Survey*, p. 47.

[2] *Bull. 470, U.S. Geol. Survey*, Pt. I, p. 46.

Creek outcrops. When, in addition to this striking linear arrangement, we consider the fact that nowhere throughout the other extensive areas of Idaho acidic intrusives as described by Lindgren,

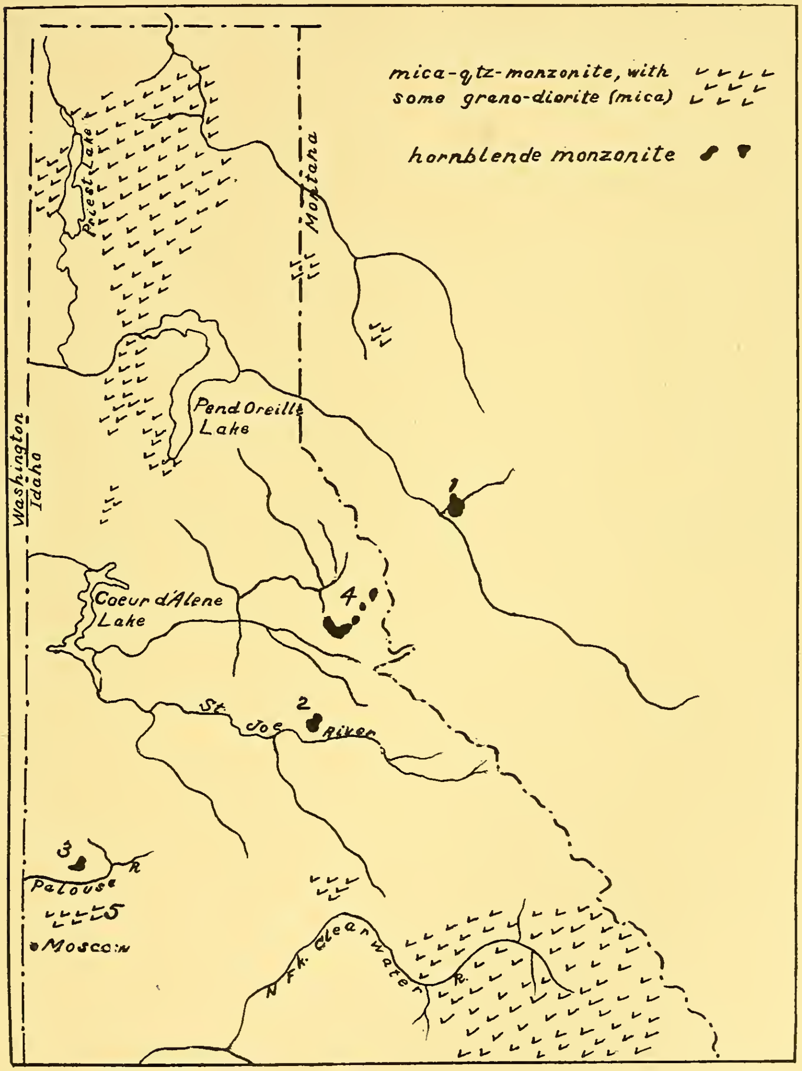

FIG. 1.—Acidic intrusives in Northern Idaho: 1, Vermillion Creek, Montana; 2, Black Prince Creek; 3, Gold Hill; 4, Cœur d'Alene District; 5, Thatuna Hills.

Calkins, Eldridge, and Umpleby, or where seen by Professor Livingston or the writer, is there any rock like this Cœur d'Alene type, it seems evident that we are dealing with something more significant than a single vast batholith underlying all of the state.

It is of course possible that the main Idaho batholith does underlie the Cœur d'Alene and neighboring districts at great depths, and that the exposures of the Cœur d'Alene type are offshoots reaching up into the overlying sediments and slightly differentiated. In view, however, of the proximity and nearly equal elevation of the Gold Hill and Thatuna Hills occurrences, I am inclined to regard the Cœur d'Alene type as the result of a separate intrusion, connected indeed in ultimate origin with the main batholith, but nevertheless distinct from it. Very probably it should be classed as a complementary intrusive, somewhat later than the main mass but from the same source. If this be true, we may expect to find monzonite of the Cœur d'Alene type cutting the micaceous quartz-monzonite. Until such a discovery is made, we must hold the problem in abeyance, content with the fact that the Cœur d'Alene intrusives, and those northeast and southwest of them, are distinctly different from the average type of Idaho quartz-monzonite.

A GRAPHIC METHOD OF REPRESENTING THE CHEMICAL RELATIONS OF A PETROGRAPHIC PROVINCE

FRANK D. ADAMS
McGill University, Montreal

During recent years questions concerning the chemical composition of rock magmas, and the relation of these to one another, have been made the subject of extended investigation on the part of petrographers. A great number of rock types, and of many variations presented by these types, have been analyzed with great accuracy, so that now the material available for such studies has enormously increased.

As it is a matter of difficulty in comparing a long series of analyses to grasp clearly their various points of resemblance or difference, and to recognize the relationships, often more or less obscure, presented by the different types, investigators have from time to time sought to express the results of these analyses graphically so that by a comparative study of forms rather than figures the relationships in question might be brought out more clearly and presented in a more striking manner.

It is unnecessary here to consider in detail the various methods of graphic representation suggested by different workers. A review of the various methods proposed will be found in a paper by Iddings which appeared some years since.[1] Some of these methods, as for instance that of Reyer, show the relative proportions of the several chemical constituents present in the rock by means of a figure in which areas representing the various constituents are variously shaded or distinguished by different conventions. Others, such as that employed by Harker, indicate the relative proportions of the constituents by means of a curve on a plain surface. In a third class, such as those used by Brögger, the composition of the rock is represented by a geometrical outline whose shape would vary as the composition of the rock changed.

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[1] J. P. Iddings, *Prof. Paper 18, U.S. Geol. Survey*, 1903.

Each of these methods of graphic representation has its peculiar merits, and each has also its disadvantages, which become manifest when it is desired by means of them to compare a long series of analyses, as for instance those representing a whole petrographic province.

In connection with some studies on the character and relations of the very striking series of alkaline rocks composing the petrographical province of the Monteregian Hills, which are now being carried on at McGill University, the attempt has been made to secure a more satisfactory expression of the chemical relations of the rocks of this province by employing a graphic representation in three dimensions. It is desired in the present brief paper to give an outline of the method employed and the result obtained.

Each of the analyses, 36 in number, was first plotted in the form of a curve which showed the actual and relative proportions of each of the chief constituents present in the rock. These are: silica, titanic acid, alumina, ferric oxide, ferrous oxide, lime, magnesia, potash, soda, water, carbonic dioxide.

The manganous oxide present was placed with the ferrous oxide and any small percentages of baryta or strontia with the lime. For purposes of simplicity other constituents, such as chlorine and sulphuric acid, which are occasionally present in small amount, were neglected, although of course it would be possible to represent them in the curve were it considered desirable to do so.

This curve was constructed by drawing a horizontal line, and marking off on it a series of points at equal distances from one another. At each of these points an ordinate was erected. On the first of the ordinates was plotted the molecular proportion of silica present in the rock. On the next ordinate the amount of titanic acid was similarly plotted, and on each of the others in succession the molecular proportions of the other constituents of the rock in the order enumerated above was shown. The points so obtained were then connected, and a curve thus constructed which shows in graphic form the chemical composition of the rock. In Fig. 1 there is seen the curve thus obtained for a camptonite occurring in the form of a dyke cutting the Trenton limestone at the reservoir extension on the slope of Mt. Royal. A curve was obtained in a similar manner for each of the 36 analyses of the series.

These curves were then combined so as to give a value to the third dimension. For this purpose each curve was traced on a

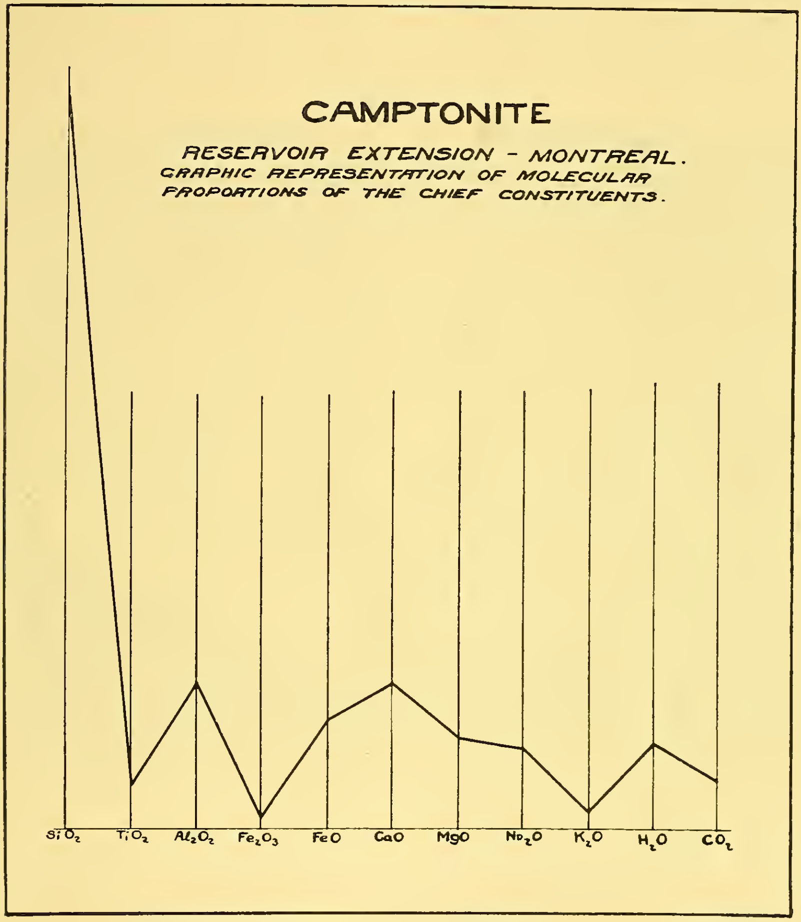

Fig. 1

thin rectangular sheet of metal, which was then cut so that its upper edge presented the outline of the curve, while the other three edges retained their rectilinear character. The form of the sheet representing the analysis of the camptonite has thus exactly the form of the diagram shown in Fig. 1.

These sheets of metal were then arranged in an upright position in a stout wooden frame, one in front of the other, at a distance of one inch apart. That of the rock having the highest content of silica was placed at one end of the series, while the others were arranged in the order of decreasing silica content, the most basic rock occupying the other end of the series. The spaces between the plates were then filled in with plaster of paris, the plaster between the successive sheets being smoothed down, so that the model thus completed presented a warped surface, passing transversely across which can be distinctly seen the traces of the curves representing the composition of the constituent rocks of the series.

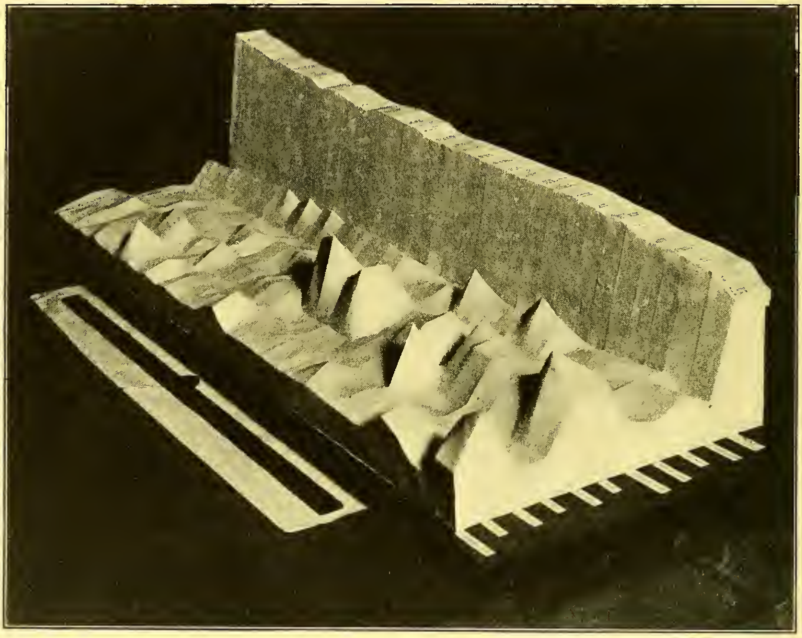

Fig. 2.—Model showing the chemical composition of the various rock types of the petrographical province of the Monteregian Hills.

The model thus obtained is shown in Fig. 2. A margin about one inch in width was left on the silica side of the model, to give space opposite the curve of each analysis to attach a small label having printed on it the name of the rock and the locality from which it was obtained. In a similar manner the base on which the model rests is made to project a short distance at one end, so that another set of labels showing the chemical constituents represented in the analyses may be placed upon it. In this way, looking down the length of the model the character of the variation in the content of any chemical constituent in the series of rocks composing this petrographical province can be seen at a glance.

The predominance of any constituent, or group of constituents, in a certain part of the series is shown by a hill rising from the surface of the model, the shape of the hill varying according to minor variations in chemical composition of the rocks of this portion of the series. Depressions, on the other hand, indicate low percentages of a constituent, or group of constituents, in certain portions of the series.

The model shown in Fig. 2, representing the chemical relations of the rocks constituting the Monteregian Hills, combines the results of 36 analyses, the rocks ranging in composition from the acid nordmarkite of Mt. Shefford, containing 65.43 per cent of silica, at one end of the series, to the basic alnoite of Point St. Charles, near Montreal, holding 29.24 per cent of silica, at the other end. The intervening portion of the model shows the chemical composition and the mutual relations of the magmas of intervening acidity represented by the pulaskites, nepheline syenites, essexites, rouvellites, tinguaites, camptonites, montrealites, tawites, rougemontites, yamaskites, monchiquites, etc., of this petrographical province.

The model is 36 inches long, 12 inches wide, and 8½ inches high at the highest part. It appears to present in a clear and rather striking manner the chemical relations of the alkaline magmas of this peculiar petrographical province, and similar models might be readily constructed which would set forth the characteristic relations of other provinces.

THE MODE OF FORMATION OF CERTAIN GNEISSES IN THE HIGHLANDS OF NEW JERSEY—*Concluded*

CLARENCE N. FENNER
Geophysical Laboratory, Carnegie Institution of Washington

PART II. DISCUSSION OF CERTAIN THEORETICAL PRINCIPLES INVOLVED IN THE INJECTION OF THE MAGMA

It has been pointed out that the granitic magma which was intruded into the original series seems to have been of a rather thin consistency. Nevertheless the degree of fluidity could hardly have approached, even approximately, that of water or an ordinary aqueous solution. The manner in which strata have been crumpled and twisted by movements of the magma argues a very effective degree of viscosity, as does also the support seen to have been offered to thinly tabular sheets of strata standing in a nearly upright position and evidently free for considerable distances from other support than that given by the adjacent magma. On the other hand, certain phenomena indicate that magmatic fluid was absorbed by the strata with little difficulty. At first sight these properties appear quite inconsistent with each other; nevertheless it seems possible to harmonize them. In order to derive a probable explanation of this and certain other phenomena it is necessary to consider certain of the properties of magmatic solutions.

At the present time it is well recognized that the temperature of fusion of the individual minerals of a rock, or even the temperatures required to fuse the aggregate, afford no indication of the temperatures at which the magma from which the rock crystallized was liquid in the interior of the earth. Since the time of Elie de Beaumont[1] the importance of the rôle played by water and other so-called mineralizers in lowering the temperature of fusion and increasing the liquidity of magmas has been perceived; and acidic magmas are regarded, for a number of reasons, as having

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[1] Elie de Beaumont, "Note sur les émanations volcaniques et métallifères," *Bull. soc. géol. fran.* (2), IV (1847), 1249–1333.

contained large amounts of water. Nevertheless the property of critical temperatures of liquids appears at times to be somewhat of an obstacle to a clear comprehension of the miscibility of rock magma with water and other volatile substances at a high temperature. The critical phenomena seem sometimes to be understood to imply that at temperatures above 374° C. water, under all circumstances, ceases to be a liquid and becomes a gas. A better statement would be that at the critical temperature and at the corresponding pressure the properties of liquid and vapor cease to differ. The discontinuity of properties which characterizes the transformation from liquid to vapor at lower temperatures and pressures disappears. Moreover, the critical temperature of a liquid is not a fixed point but varies with the amount of material in solution. With pure water the critical phenomena appear at 374° C., but when water holds material in solution the vapor pressure is lowered and the critical point is raised. The greater the amount of dissolved material the greater is the displacement.

These facts have been emphasized in an investigation recently carried out by G. W. Morey[1] in the Geophysical Laboratory, of which the results have just been published. In one experiment 2 gm. of a glass of the composition $K_2O:1.7\ SiO_2$ was heated with 4.842 gm. water to a temperature of about 360° in a gold crucible within a gas-tight steel bomb. The result was a pasty glass containing 32 per cent water. In another experiment 2 gm. of glass of the same composition as before and 5 gm. water were exposed to a temperature of 490° under the same conditions. The product obtained was a hard glass containing 20 per cent water.[2] In the latter experiment the temperature was far below that at which the dry materials would begin to melt and at the same time more than 100° above the critical temperature of water alone, and the formation of a strongly hydrated glass is a striking phenomenon.

There is, therefore, no theoretical difficulty in supposing that fused silicates may form a homogeneous solution with water and other volatile substances at high temperatures, and the properties

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[1] G. W. Morey, *Jour. Amer. Chem. Soc.*, XXXVI, 2 (1914), 215–30.

[2] Evidence was obtained which showed that even those glasses which became highly rigid when cooled formed mobile liquids at the temperature of the experiments.

imparted by the presence of such volatile matter—increase of mobility and greater chemical activity—will be retained.

The ease of flow manifested by the New Jersey granite which has been described is therefore quite understandable; nevertheless it seems to have retained a quite effectual degree of viscosity, as has been pointed out in describing the field phenomena. The facility, then, with which magmatic material seems to have been transfused into the adjacent strata is not at once intelligible. The difficulties in harmonizing the phenomena which are exhibited will be better appreciated by a calculation of the rate at which a fluid under pressure enters minute pores. For instance, an approximate calculation by Poiseuille's formula shows that if we assume a liquid having a coefficient of viscosity of 1.0 (about one-tenth that of glycerine at 19° C. or 100 times greater than that of water at the same temperature) and conceive it to be pressed with a force of 810,000 gm. per square cm. (corresponding to an overhead load of about 3 km. of rock strata) against a surface of 1 sq. cm. pierced with 1,000 holes, each having a radius of 0.0001 cm., and suppose the thickness of the partition to be 1 dm., then in one year only 0.1 c.c. would ooze out on the far side.

The assumptions made are far from exact. The form and disposition of the pores in rocks do not correspond to the straight cylindrical tubes to which Poiseuille's formula closely applies, and the exact degree of viscosity is unknown, but the most important factor is the diameter of the pores, for the flow is about as the fourth power of this dimension. Thus if we had assumed pores of a radius of 0.0004 cm. (probably an excessive estimate of size for the pores of ordinary rocks under heavy load) we should have derived a value of 25 c.c. per year.

It seems, on the whole, that we can expect little movement of the magma as a unit into minute pores, and we shall have to seek an explanation of its transfusion into the adjacent rock from other considerations.

Among the phenomena shown in the field several facts merit emphasis. As I have already mentioned, the introduction of the magma seems to have been effected with remarkably little disturbance of the previously existent relations of the original layers.

It is true that the larger bodies of granite show a tendency toward a lenticular outline, indicating that in such instances the adjacent rock has been forced apart; and it is found also that flexures of a minor order have been produced in the layers, but the striking fact remains that frequently evidences of the original structure survive in the midst of large masses of granite and show little disturbance of position. The most noticeable evidence in this respect is the parallelism shown by the bands of inclusions with the regional strike of the gneisses. This is observable even in those cases where assimilation by the magma has proceeded so far that the included material no longer appears as distinct bands but merely as dark-colored *schlieren* of indefinite outline. Moreover, the presence of faint parallel lines of dark minerals within the granite alongside of inclusions, as well as a certain parallelism visible in the arrangement of the component minerals of granitic masses in which no distinct xenoliths are perceptible, implies that some sort of structural framework of solid material was retained. It cannot be supposed, therefore, that the injection of the magma was of a sudden and violent nature or that it entered by simply wedging the original rock apart along the dividing laminae and occupying the spaces made. On the contrary, it must have gained access in such a slow and quiet manner that in many places delicate structural relations were left undisturbed. In fact the process appears to have possessed many of the features of a gradual substitution rather than the violent characteristics of intrusion as we often picture them.

The advocates of *lit-par-lit* injection to whom reference has been made have supported the theory that the advance of the main body of magma was preceded by that of a more attenuated portion. They believe that these solutions in advance, which were probably similar in composition to that of the main body but characterized by the presence of a larger percentage of the volatile ingredients, exercised functions of a preparatory character, metamorphosing the material into which they penetrated and rendering it gradually more susceptible to the action of the magma which followed. Lacroix's conception[1] may be illustrated by the following quotation,

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[1] A. Lacroix, "Le granite des Pyrénées et ses phénomènes de contact," *Carte géol. de France, No. 71* (1900), p. 26.

in which he describes certain contact rocks formed by the action of a granite batholith upon schists:

> The characteristic of the contact phenomena of this type consists essentially in the addition of volatile or transportable materials, emanating from the magma and modifying generally in a manner more or less profound the chemical and mineralogical constitution of the sediments traversed. . . . .
>
> In the regions which form the object of this study, and in many others, the disposition of the sedimentary beds in relation to the granite, the existence in the midst of the latter of sedimentary fragments which, in spite of their transformation, have preserved the same orientation as the peripheral schists and limestones to which they belong, finally the absence of important dislocations at the immediate contacts, tend to show that the granitic magma has been brought to its position in a slow and progressive fashion by imbibition and dissolution of the sediments for which it has been substituted.
>
> In proportion as the granitic magma appeared in the sedimentary beds it was preceded and accompanied there by its cortège of transforming emanations, and what it had to dissolve to make place for itself was no longer normal sediments, but transfused rocks, transformed or in process of transformation by fixation of the emanations which had gone out from its own mass.
>
> The most intense modifications undergone by the schists metamorphosed into leptynolites consist essentially in the development of a large quantity of feldspars, quartz, biotite, etc. The limit toward which these leptynolites, which are often comparable from a mineralogical standpoint with gneisses, tend is the mineralogical composition of granite itself.

In a recent article Sederholm[1] describes contact-effects of a rapakivi granite upon older hornblende-schists, with introduction of typical minerals from the rapakivi. He is able to trace out the transitional changes in the minerals of the schist by absorption of material from the granite. "Microscopically as well as macroscopically it is shown, therefore, that the whole schist-mass has been permeable for gases and juices (*Säfte*) which have gone out of the granite magma, as well as for the magma itself in further progress of change. This contact would have convinced even the most zealous anti-injectionists."

The ideas which are formulated in these quotations have met with opposition from some geologists, but the objections seem to be based partly upon a misconception. The advocates of the

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[1] J. J. Sederholm, "Ueber ptygmatische Faltungen," *Neu. Jb.*, XXXVI (September, 1913), Beilage-Band, p. 491.

doctrines have evidently had in mind their application to a certain type of phenomenon and do not imply that all granitic intrusions have occurred under like conditions or been accompanied by similar effects. It seems to be considered at times that the observations of Lacroix in the Pyrenees are opposed by those of Brögger in the Christiania region, but these two geologists themselves evidently perceived that they had to do with processes of a different nature and that the same phenomena should not be sought or the same explanation applied. Lacroix[1] has discussed Brögger's views and says: "None of the arguments which this scientist deduces from the study of his region bears against the theory of assimilation, applied to the Haute-Ariège; the facts which he has described are in effect the antithesis of those which I have set forth in this memoir." He suggests that the dissimilarities may be attributed to differences in the depth at which the intrusions took place in the two regions.

Brögger[2] also states that it would not be justifiable without further evidence to apply his observations on the Christiania district to the granite regions of the older primitive rocks and regionally metamorphosed fold-mountains. Evidently both Lacroix and Brögger recognize the fact that the type of granitic intrusion to which each has devoted his attention is not the only form which is found.

The relations which Michel-Lévy, Lacroix, Sederholm, and others have described offer an array of evidence in confirmation of their views, and there seems to be no inherent obstacle to accepting them.

In trying to account for the formation of a dilute magmatic solution in advance of the main invasion several possibilities suggest themselves.

It appears probable that the escape of volatile constituents through pores of the wall-rock too minute in size to permit unchanged magma to follow would have a tendency in this direction. Field evidence appears to warrant the view that considerable quantities of vapors have often escaped in this manner and that

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[1] A. Lacroix, "Le granite des Pyrénées et ses phénomènes de contact," *Carte géol. de France, No. 64* (1898), p. 63.

[2] W. C. Brögger, *Die Eruptivgesteine des Christiania-Gebietes,* II (1895), 152.

important results have been accomplished through their agency. We must suppose that these gases will exert a fluxing or solvent action upon the minerals of the walls, so that some fraction of them shall form a solution with these minerals, giving rise to a sort of secondary magma within the walls.

Moreover, during the advance of streams of magma between layers of rock, such as is characteristic of *lit-par-lit* injection, it seems almost inevitable that by contact with the cooler walls a portion of their load of dissolved material should be deposited. Thus the solutions ahead would become progressively more dilute, but with the rise of temperature ultimately produced in the walls by the stores of heat imparted to them by a number of closely adjacent streams of magmatic solution unchanged magma would finally enter among the layers and carry farther toward a conclusion the processes of transformation initiated by the solutions in advance.

By whatever means a differentiation of the magma-streams is effected, the advance of the magma into the wall-rock would be attended by phenomena of various sorts, such as impregnation of the walls, solution and removal of some of the components of the wall-rock, and reactions with the minerals with which the solution came into contact.

When the chemical nature of the wall-rock differs greatly from that of the magma the reactions between the two might be expected to effect striking results. Limestones seem especially fitted to react with the magma, but other rocks may participate in a like manner. For this reason it may not be possible to decide what the nature of the original rock has been, as was pointed out in considering the character of the strata invaded by the magma in the New Jersey example. Instances of the extreme effect produced by such reactions were found by Adams and Barlow[1] in the Haliburton-Bancroft area. A passage in their publication refers to a certain contact of a granite batholith with the limestone wall-rock, and reads as follows:

> . . . . The limestone bands fade away imperceptibly into the amphibolite, the latter being undoubtedly produced by the alteration of the limestone. These rocks are invaded by the granite, traversing them in apophyses which swarm

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[1] Adams and Barlow, "Geology of the Haliburton and Bancroft Areas," *Memoir No. 6, Canadian Geological Survey* (1910), p. 101.

> through them in all directions, often running parallel to the banding, and elsewhere cutting across it. . . . . The alteration is due not only to the proximity of the main mass of the batholith, but to the immense amount of granitic material which occurs intruded through the series, sometimes in large masses, but very frequently in thin bands which have found their way in between the beds of the invaded limestone, changing it into amphibolite, and presenting a typical instance of *lit-par-lit* injection. The granite, furthermore, not only penetrates this amphibolite series, but floats off masses of it, which, in the form of bands, streaks, and isolated shreds, are seen thickly scattered through the granite in the vicinity of the contact. . . . . The separate fragments of amphibolite, where completely surrounded by the granite, while clearly nothing more than masses of altered limestone, are rather harder, and have a more granitized appearance than the rock which is still interstratified with the limestone.

From the various descriptions which have been cited it appears that the type of intrusion to which the term *lit-par-lit* injection has been applied presents evidences that the invasion of the magma is preceded by the advance of a wave of metamorphism into the wall-rock, by which the character and composition of the original material are radically altered. By the deposition of magmatic minerals and by the removal in solution of certain of the previous constituents, the composition tends to approach that of the magma itself, and when blocks of wall-rock are finally engulfed in the magma their composition may be so changed that their assimilation effects but little change in the composition of the latter.

If this conception is well-grounded the zone of metamorphism which surrounds areas of *lit-par-lit* injection is not to be considered as wholly an after-effect of intrusion, due to expulsion of volatile substances during the consolidation of the magmatic mass, but also as due to a preliminary process, ultimately leading up to an invasion of the magma and assimilation of the altered material.

SUMMARY

A description has been given of the structural relations observed in a certain area of banded gneisses of pre-Cambrian age in Northern New Jersey, where unusually favorable conditions for observation have been found. The structures shown here are believed to be typical of those prevailing over considerable areas in this portion of the state. Evidence is given leading to the belief that the structures at this locality cannot well be attributed to the squeezing-out of a partly differentiated magma or to the shearing and recrystallization of a solidified rock, but that their origin must be looked for in a process involving the injection of a thinly fluid granitic magma between the layers of an original rock of laminated structure. Structures which still survive in the larger bodies of granite indicate that the process of injection was carried out in a most quiet and gradual manner, and possessed many of the characteristics of a substitution of the original material by the magmatic solution rather than the features of a violent intrusion. The observed relations are very similar to those which French geologists have described under the name of *lit-par-lit* injection, and the mode of operation is believed to have been essentially the same.

Certain features observed in the gneisses imply properties of the magma which at first sight do not appear mutually consistent. Thus the degree of viscosity indicated by the presence of thinly tabular sheets of inclusions within the granite, standing nearly upright and unsupported except by the magma on either side, does not harmonize with the facility with which magmatic material has been transfused into the original rock. In trying to reconcile these features inquiry has been directed toward a consideration of certain of the properties of magmatic solutions. The question of the critical temperatures of volatile substances is discussed in its bearing upon their condition within the magma. Further, the problem of a possible differentiation of a magma when injected into a wall-rock in a multitude of adjacent streams is taken up, as related to the views expressed by the advocates of *lit-par-lit* injection. Several methods by which this might be accomplished appear possible, and it is suggested that the escape of gases from the magma into the wall-rock would have a tendency in this direction and that at the same time the deposition of magmatic minerals by contact of tongues of magma with the cooler walls would effect results of a similar nature. Thus the advance of the main body of magma would be preceded by that of a more dilute portion, which would be able to impregnate the wall-rock with facility and initiate processes of transformation and solution which the more concentrated body following would carry farther toward completion.

December, 1913

A COMPARISON OF THE CAMBRIAN AND ORDOVICIAN RIPPLE-MARKS FOUND AT OTTAWA, CANADA[1]

E. M. KINDLE
Geological Survey of Canada, Ottawa

Introduction.—We are told by an eminent geographer that "the most important part of the geological labors of the ocean is hidden from our eyes."[2] The evident truth of this observation affords a sufficient reason for making a careful record of every fact which may help to throw light on the processes of sedimentation. Ripple-marks on sandstones and sandy shales are among the most familiar of the characters with which marine sediments have been impressed, but we have yet much to learn concerning them. These features when fully understood will tell us much more of the local physical conditions under which they were formed than we are at present able to infer from them. It still remains for future research to determine whether a law can be deduced which will connect the length and height of waves with the width of the ripple-marks resulting from the simultaneous water oscillation. Among the present needs in connection with the effort to acquire a more fundamental knowledge of ripple-mark phenomena appear to be recorded data on (1) the different types of ripple-marks to be met with in a given set of beds where the factors of depth and texture of sediment are uniform, (2) characteristics which distinguish ripple-marks associated with particular kinds of sediment from those found in other sediments.

The observations in this paper are recorded with this twofold object in mind. The Cambrian and Ordovician sediments both show well-developed ripple-marks in horizons which are exposed in the Ottawa district. The Cambrian ripple-marks which will be described occur in sandstone, while those in the Ordovician are impressed upon limestone.

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[1] Published with the permission of the Director of the Geological Survey of Canada.

[2] Elisée Reclus, *A New Physical Geography*, Vol. II (1890), "The Ocean," p. 103.

Cambrian ripple-marks.—Cambrian sandstone is extensively exposed in a flat-topped hill 12 miles west of Ottawa, just south of the intersection of the Canadian Northern and Grand Trunk railways. The rock is a hard, white to buffish-gray, moderately coarse sandstone. It is thin-bedded, lying in strata 2–10 inches thick. Some of the strata are beautifully ripple-marked.[1] All of the ripple-marked beds and those associated with them appear to be quite barren of fossils, although a *Lingulepis acuminata* Con. occurs abundantly a little lower in the section along the railroad. Two distinct types of ripple-marks occur in the highest beds exposed on the hilltop. Both of these are shown in Fig. 1. The type seen in the smaller slab on the right of the picture is better shown in Fig. 2. The ripple-marks shown on the large slab are symmetrical, the two sides of the ripple ridge having the same slope or curvature. Those seen on the smaller slab and in Fig. 2 are asymmetrical, the slope of the ridges on one side being much steeper than that of the ridges on the other side. The symmetrical ripple-marks show some features in which they differ from those usually met with in sandstones.

Fig. 1.—Ripple-marks in Cambrian sandstone. The large slab shows the symmetrical type with low ridges and broad flat troughs; the asymmetrical type is represented by the small slab at the right of the picture.

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[1] I am indebted to Mr. L. D. Burling for directing my attention to these ripple-marks.

Instead of the usual rounded or angular trough between the crests, the ripple ridges rise from interspaces which are almost or quite flat. The gently rounded parallel ridges are separated by flat interspaces generally one and one-half to two times their width. Traces of a diminutive ridge in the middle of the flat-bottomed trough may sometimes be noted. This type of ripple-mark is comparable in its essential features with, though not precisely like, a form of ripple-mark which I have seen developed in Lake Deschênes near Ottawa. A photograph of these sand ripple-marks made from a cast of a mold taken under water at Lake Deschênes is here reproduced in Fig. 3. Comparison of the two figures shows broad, nearly flat troughs in each separating the comparatively narrow rounded ridges. In the Lake Deschênes specimens the miniature secondary ripple-marks are more clearly developed than in the sandstone ripple-marks. The lake ripple-marks were formed under natural conditions in water 6 inches deep and were under observation during and after their development for a period of three days. They are the product of water oscillation resulting from a very gentle on-shore breeze. This breeze and the accompanying wavelets were not strong enough to produce the asymmetrical type of ripple-mark with steep leeward and gentle windward slopes which results from more vigorous movement of the water and leaves a record of the direction of the movement of

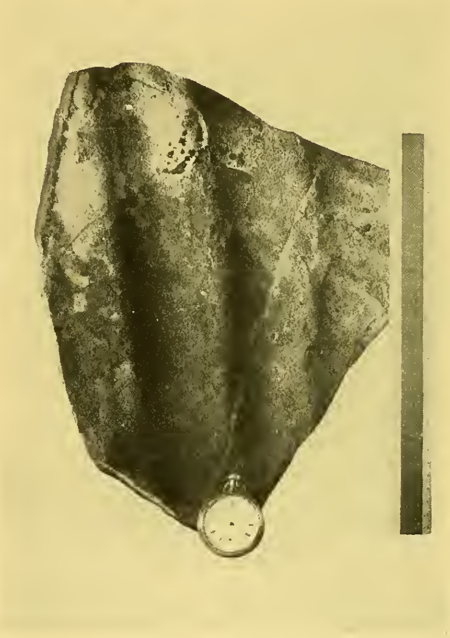

FIG. 2.—Cambrian sandstone slab showing asymmetrical type of ripple-mark.

the waves or currents concerned in its production. The similarity in type of the Cambrian and Lake Deschênes ripple-marks shown in Figs. 1 and 2 suggests the inference that the Cambrian impressions probably represent the work of winds and waves of a very gentle character.

In beds which lie within a very few inches of the symmetrical ripple-marks which have been described occur the asymmetrical ripple-mark type shown in Fig. 2. The ripple-marks in the specimen shown in Fig. 2 have a width from crest to crest of 3 inches and a trough depth of one-fourth inch. Their lee and stoss slopes are, respectively, 9°–15° and 20°. These ripple-marks trend about S. 35 E. and present their steep sides toward the northeast. Ripple-marks of this type represent either a wind or water current moving in a northeasterly direction. An interesting feature of these ripple-marks is the presence of a second set of much finer and less distinct ripple-marks which show sometimes clearly but generally faintly on the stoss slopes of the prominent ripple-marks. These secondary ripple-marks cross the others at an angle of about 45°. If they are the product of wind rather than current action, they indicate a shift of wind of nearly a quadrant from the position which it must have maintained during the development of the larger ripple-marks. At the time these Cambrian sands were deposited the nearest shore of the Cambrian sea lay five or six miles to the northeast if we may judge from the close proximity and relative elevation of the archean rocks in the Laurentian mountains on the opposite side of the Ottawa valley. The wind or current direction indicated by both of these sets of ripple-marks therefore appears to indicate a general on-shore direction.

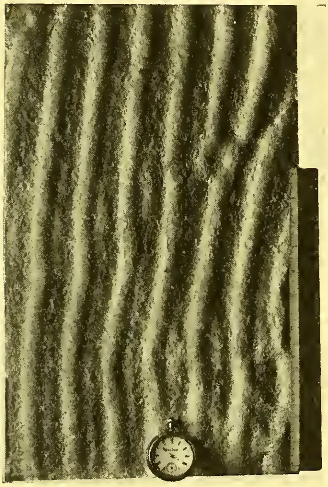

Fig. 3.—Cast from mold of sand ripple-marks taken under water at Aylmer, Quebec. Compare with Fig. 1.

Trenton limestone ripple-marks.—The extensive quarry in the Trenton limestone at the cement mill one-half mile northwest of Hull, Quebec, exposes a section with a vertical thickness of nearly 100 feet. Three or four horizons in this section show, in the vertical walls of the quarry face, contacts between adjacent beds which are very suggestive of ripple-marks of large dimensions. The imperfect exposures of the lower of these horizons leaves room for some question as to their true nature but it appears clear that the uppermost is an example of ripple-marks. Only the uppermost of these horizons, which is admirably exposed for study through the stripping of the stone to this level over an area of considerable extent, will be considered here.[1] This bed lies 10–15 feet below the top of the quarry in the part of the section called by Dr. Percy Raymond[2] the crinoid beds.

The limestone here is a dark-gray rock lying in strata usually 6 inches to a foot in thickness. The regular horizontal contact of these strata gives way at the horizon under discussion to a billowy trough and crest contact. This is much less regular in profile than the profile of the ordinary ripple-mark as seen in most sandstones. The somewhat irregularly rounded summit of the ridges and their variable width might suggest on brief examination an unconformity; their parallelism and the identity of the fauna on both sides of this horizon, however, render this explanation untenable. The ridges trend approximately east and west and their axes are from 2 to 3 feet apart. No sharp crests are to be seen. All of them, as shown in the photographs (Figs. 4 and 5), are rounded or somewhat depressed on top. The troughs have an average depth of about 6 inches below the crest and frequently coalesce, thereby producing many short ridges. An interesting feature connected with these ripple-marks is the occurrence on them at some points of numerous crinoid stems some of which have the heads attached as shown in Fig. 6. These are often two feet or more in length and indicate by their presence that the crinoids lived on this part of the sea bottom shortly after the formation of the ripple-ridges in water

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[1] These were brought to my notice by Mr. W. A. Johnson.

[2] "Excursions in Neighborhood of Montreal and Ottawa," *Guide Book No. 3* (1913), p. 143.

which was sufficiently quiet not to break up the stems into the small sections usually found in limestone. Above the ripple-marks 6 or 8 inches, however, there is equally clear evidence of current action

Fig. 4.—General view of ripple-marks in Trenton limestone at cement quarry, Hull, Quebec.

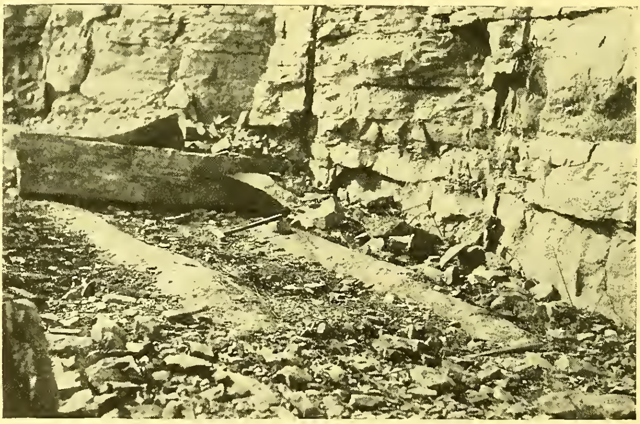

Fig. 5.—Close view of ripple-marks in quarry at Hull, Quebec

at a later period having been involved in the distribution of the materials comprising some of the beds. At this level a band of cross-bedded limestone a few inches in thickness occurs with layers inclined at about 27°. The material comprising these current-built beds consists largely of small fragments of crinoid stems and other fossils.

Comparison of limestone and sandstone ripple-marks.—These Trenton limestone ripple-marks show a striking contrast with those of the Cambrian sandstone which have been described, in the matter of size. Instead of an amplitude of 2 or 3 inches which characterizes the Cambrian ripple-marks, these have a width of 2 or 3 feet from crest to crest. This discrepancy in size is of interest because it exists between the great majority of the examples of limestone ripple-marks and sandstone ripple-marks which have come under my notice. I have observed very few cases where the amplitude of ripple-marks in sandstone exceeded a few inches.[1] On the other hand, six of the eight photographs in my collection illustrating limestone ripple-marks, which represent as many different geological horizons and widely separated localities, show an amplitude of more than one foot. The data given in geological literature relative to limestone ripple-marks are often too incomplete to furnish data on the amplitude, but where given the amplitude is likely to be represented by a figure much larger than those which usually represent the amplitude of sandstone ripple-marks.

The earliest description of limestone ripple-marks with which I am acquainted relates to ripple-marks of large amplitude. This occurs in Dr. John Lock's description[2] of the "Blue Limestone" (Ordovician) of southwestern Ohio. Under the head of "Waved Strata," he described a stratum in which "the upper side is fluted out in long troughs 2–3 feet wide and about 2 or 3 inches deep, the edge or ridge between them being generally sharp. . . . . These waves are not local, but may be traced in the same stratum over tracts of many miles."[3]

Dr. August Foerste states[4] that "wave-marks (ripple-marks) occur in Ohio, Indiana, and Kentucky, in abundance in the Lower Eden, Upper Richmond, and upper Brassfield limestones. They

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[1] Mr. G. K. Gilbert has recorded one exceptional case in the Medina sandstone in which the amplitude is reported to be several feet (*Bull. Geol. Soc. Am.*, X, 135).

[2] *Geol. Surv. of Ohio* (1838), p. 246, Pl. 6.

[3] Lock expressed the belief that these were not ripple-marks because "all geologists will agree that the blue limestone has been formed far below the reach of ripples."

[4] Letter to the writer.

occur in great numbers, but not so abundant, also in the Middle Eden. In Kentucky they are common also locally in the Mount Hope bed, at the base of the Maysville. They occur often near the middle of the Arnheim and at various intervals in the Lower and Middle Richmond in the three states mentioned." Dr. Foerste has recorded[1] a considerable number of observations on the limestone ripple-marks in the Ordovician and Silurian formations of these three states. Most of those which he observed appear to be of large size, those seen at one locality having crests 49 inches apart which rise 3½ inches above the troughs.[2] Foerste remarks that "their unusual size will, however, attract attention even from one familiar with the work of the sea." Moore and Allen[3] have published photographs and descriptions of Upper Ordovician (Richmond) limestone ripple-marks with an average amplitude of 2.63 feet which occur in eastern Indiana.

In New York state, Miller[4] has described ripple-marks in the Trenton limestone of Lewis county which measure 24–56 inches from crest to crest with troughs 4–7 inches deep. At another locality in the same state, Professor Cushing[5] has described ripple-marks in the Trenton limestone with an amplitude of 9–15 inches and a depth of 1–3 inches. Cushing remarks concerning these that "they are considerably broader than the usual ripple-marks in sandstones." This observation, it may be noted, tends to confirm the opinion already expressed by me that sandstone ripple-marks have generally a comparatively small amplitude.

But few references to ripple-marks on Silurian limestones have come under my notice. Two of these which relate to New York and Ohio localities may be cited. East of Lockport, New York, Kindle and Taylor[6] report ripple-marks in the uppermost member

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[1] "On Clinton Conglomerates and Wave-Marks in Ohio and Kentucky," *Jour. Geol.* III (1895); 1–10 (reprint). "The Richmond Group along the Western Side of the Cincinnati Anticline in Indiana and Kentucky," *Am. Geol.*, XXXI (1903), 333–61.

[2] *Jour. Geol.*, III, 37.

[3] *Proc. Ind. Acad. Sci. 1901* (1902), pp. 216–18, Pls. 1–3.

[4] *Bull. N.Y. State Mus. No. 135* (1910), p. 36.

[5] *Bull. N.Y. State Mus. Nat. Hist. No. 77* (1905), p. 34.

[6] *Folio U.S.G.S. No. 190* (1913), p. 7.

of the Clinton limestone which have crests 18–30 inches apart with troughs 2–4 inches deep. Foerste[1] mentions ripple-marks in the Springfield dolomite, west of Peebles, Ohio, one-fourth mile. Professor Prosser[2] states that the ripple-marks at this locality occur in two beds. "In the lower layer the crests of the ripples are 22 inches apart and the trough 4 inches deep. In the upper layer the crests are 45 inches apart and the troughs $4\frac{1}{2}$ inches deep."

In the Devonian, I am acquainted with but three examples[3] of ripple-marked limestones. Each of these shows an amplitude of 2 feet or more.

The only notice of Mesozoic limestone ripple-marks[4] which has come to my attention records the occurrence of ripple-marks in limestone of Jurassic age in Utah with an amplitude of 6–12 inches.

The examples cited above from the literature of limestone ripple-marks plainly indicate the large size usually attained by ripple-marks in pure limestone. It must be noted, however, that ripple-marks of small size also sometimes occur in limestone. A photograph of ripple-marks on a dolomitic limestone with a smaller amplitude than the sandstone ripple-marks reproduced in this paper has recently been published;[5] and Miller[6] mentions Ordovician examples with an amplitude of 1–2 inches. Foerste[7] has observed that large and small limestone ripple-marks in the Ordovician of the Ohio valley are seldom associated but confined to distinct horizons. One must therefore conclude that the generally larger size of limestone as compared with sandstone ripple-marks results from some factor other than the different physical characteristics of the two kinds of rock. It seems probable that the explanation is to be sought in the fact that limestones are generally formed somewhat farther from the shore and in deeper water than sandstones. The different average amplitude of sandstone and limestone

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[1] *Jour. Cin. Soc. Nat. Hist.*, XVIII (1896), 167.

[2] Letter to the writer, February 6, 1914.

[3] One of these has been described (*Ottawa Nat.*, XXVI [1912], 1–3, Pl. 7).

[4] G. K. Gilbert, *Science*, III (1884), 375–76.

[5] Kindle and Taylor, *Folio U.S.G.S. No. 190* (1913), Pl. 25.

[6] *Bull. N.Y. State Mus. No. 135* (1910), p. 36.

[7] Letter to the writer.

ripple-marks may be related to the relative average depths at which limestone and sandstone sediments accumulate. In other words, the usual large amplitude of limestone ripple-marks may be a function related to the depth of the water in which they are formed. If we apply this as a working hypothesis to the case under consideration, we must conclude that the ripple-marks in the Trenton limestone near Ottawa were formed under water of considerably greater depth than those in the Cambrian sandstone. The presence of long crinoid stems upon the limestone ripple-marks is significant in connection with the question of the depth of the water under which they were formed. They were developed during an interval when a luxuriant crinoid fauna flourished in this part of the Trenton sea. All of the members of this order which live in the present seas are found, with a very few exceptions, in comparatively deep water. The living stalked crinoids are found chiefly at depths of more than 200 fathoms; a few extend into 140 fathoms and a very limited number into 58 fathoms, while one or two species are known in still shallower water. Geologists are accustomed to infer the

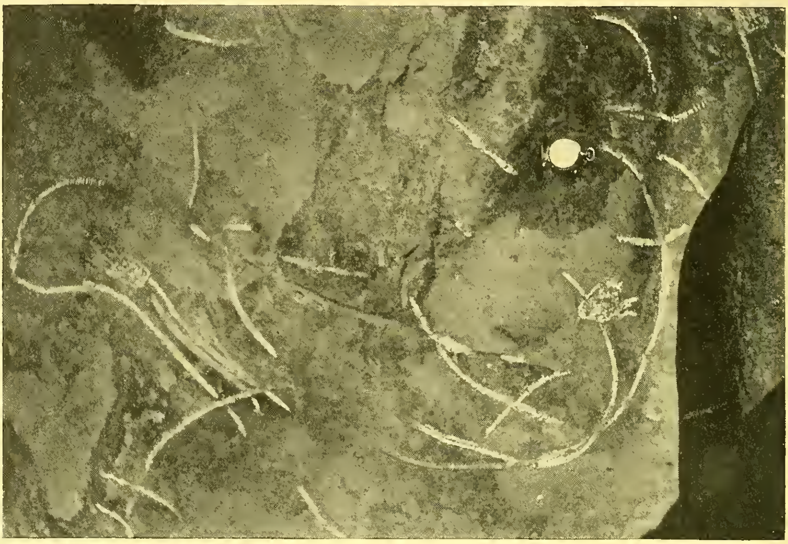

Fig. 6.—View showing profusion of crinoidal remains found on the surface of some of the ripple-marks in cement quarry at Hull. Photograph by L. D. Burling.

former existence of shallow seas where corals are the dominant fossils, and it seems an equally safe deduction to infer a sea of considerable depth where stalked crinoids comprise the dominant element in the fossil fauna as they do in the ripple-mark horizon under consideration. The occurrence on the ripple-marks of numerous crinoids in which the head remains joined to nearly complete stems (Fig. 6) affords direct evidence that they lived in water of sufficient depth to be seldom disturbed by wave action. The well-known fragile character of the union of the individual segments of a crinoid column and of the head and column could not be expected to survive the bottom disturbance of ordinary wave action. It is probable that the ripple-marks on which the crinoids rest are the result of storm waves of unusual size whose oscillations penetrated to a depth not affected by ordinary waves. It appears from these considerations that both the physical and the faunal evidence suggest for the ripple-marks in the Trenton limestone an origin in water of greater depth than the ripple-marks in the Cambrian limestone.

NEW AND LITTLE-KNOWN INSECTS FROM THE MIOCENE OF FLORISSANT, COLORADO

T. D. A. COCKERELL
University of Colorado

TRICHOPTERA

Phryganea wickhami n.sp.

♂ Upper wing as preserved uniform light reddish brown, with the venation distinct but not dark; length 22 mm., width 8½; apex of wing to base of discoidal cell 13¾ mm.; length of discoidal cell 6 mm., of cellula thyridii not quite 7½; venation normal for a male, the media with only three branches; R_1 apically with a very strong double curve. The shape of the wing is practically as in *P. latissima* Ulmer, from amber; the venation differs from that of the amber species as follows: R_2 leaving discoidal cell more basad, about 2⅓ mm. before R_3 leaves it; separation of M_1 from M_2 at same level as separation of R_3 from discoidal cell; upper apical corner of cellula thyridii (separation of M_2 from M_3) only a short distance basad of separation of R_2 from discoidal cell; oblique basal side of cell between Cu_1 and Cu_2 longer; cell below Cu_2 smaller. In the characters of venation wherein *P. wickhami* differs from *P. latissima*, it agrees closely with *P. singularis* Ulmer, another amber species.

From the other Florissant species of *Phryganea*, *P. wickhami* is distinguished especially by the shape of the wings, which are not elongated as in *P. miocenica* Ckll., or with the apical margin truncate as in *P. labefacta* Scudder.

Miocene shales of Florissant, Wilson Ranch (H. F. Wickham). At the same place Professor Wickham found one of each sex of *P. labefacta*.

NEUROPTERA

Raphidia pulveris n.sp.

Anterior wing 11 mm. long, not quite 3⅓ broad; costal area broad, with ten cross-veins; stigma about 2 mm. long, the lower side a little over 1 mm., oblique cross-vein very distinct; two cells on costa beyond stigma; subcosta ending nearly 1 mm. below base of stigma; three discoidal and three cubital cells; no closed cells beyond the discoidals; upper discoidal beginning at about level of end of subcosta, and ending a short distance beyond middle of lower side of stigma; second discoidal more produced basally than in *R. rhodopica*, its base not invaded by fork R_2–R_3, which falls some distance beyond its end; cell in fork R–R_5 scarcely hexagonal, its lower median face very short; R_2 branched at level of end of lower side of stigma, its upper branch branching again with each of the branches forked near margin, its lower branch simple; R_3 forked close to wing-margin; R_4 simple at end, but R_5 forked; six forks on lower margin of wing, not counting R_3 or R_5; cells below Cu_1 (not the cubital cells of descriptions) nearly as in *R. rhodopica*, except that the anal cells are different in detail, two large ones joined by a very narrow isthmus.

Posterior wing about 10 mm. long; apical field practically as in anterior wing, base and costa differing as usual. The end of R_2 is different, the second division of the upper branch being simpler while the lower branch has a very long narrow fork; R_3 is simple at end; there are six marginal forks basad of R_5, as in the upper wing, but the first is so long that its corner joins the end of the third discoidal cell; an almost rectangular cross is formed near the middle of the wing where the cross-veins leave the media above and below.

Miocene shales of Florissant, Wilson Ranch (H. F. Wickham). The upper wing is the type; the lower wing is on a different slab, but, from its close resemblance to the upper, evidently belongs to the same species. In Rohwer's table in *Am. Jour. Sci.*, XXVIII, 534, this runs to *R. mortua* Rohwer, but differs by the much larger number of cross-veins in the costal area, subcosta joining costa nearer stigma, and marginal V-shaped cells much more numerous. It is no doubt allied to *R. mortua* and *R. exhumata* Ckll., but there are so many small differences that I can only consider it distinct. There is also much resemblance to *Archiraphidia tumulata* (Scudd.), but there are too many differences to regard it as a variety of that species.

Modern species of *Raphidia* show so much variation in the venation, even on the two sides of the same animal, that fossil species distinguished by the structure of the wings must be regarded as more or less provisional. Possibly the material will never be sufficient to decide definitely whether we have too many or too few specific names.

Osmylidia requieta (Scudder)

Professor Wickham found a hind wing, 14 mm. long, at the Wilson Ranch.

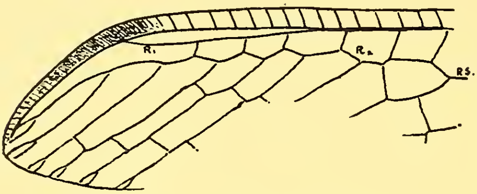

FIG. 1.—*Osmylidia requieta* (Scudd.), hind wing

PALAEOCHRYSA Scudder

The living genus *Allochrysa* Banks cannot be distinguished from this, unless we are prepared to recognize as generic characters which would split the known species into still other genera. *Allochrysa* contains three species: *Palaeochrysa virginica* (Fitch) of the Eastern United States; *P. parvula* (Banks), from Florida; and *P. arizonica* (Banks), from Arizona.

Palaeochrysa fracta n.sp.

Anterior wing about 15 mm. long, 5½ broad; hyaline with dusky stigmatic region; venation pale ferruginous, probably green in life; radial sector originating far basad of "third cubital" cell; costal area broad, terminating about 6 mm. before tip of wing; at least 17 costal cross-veins; about 16 cross-veins between radius and sector, the cells very broad (high), the middle ones twice as high as long; "third cubital" divided by a straight vein in the middle, but the upper division strongly and acutely produced basally, so that the basal angle between the sections is practically a right angle; radial sector giving off 13 oblique branches below; media beginning to zigzag just after leaving "third cubital," its general course gently curved until it meets the radial sector two cells before the apical

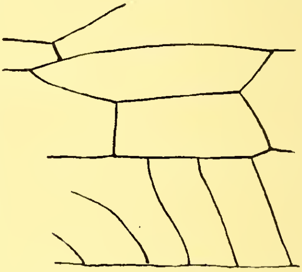

FIG. 2.—*Palaeochrysa fracta*. "Third cubital" cell and adjacent parts.

margin; three veins running from "third cubital" to hind margin; eleven forked veins on hind margin, the first at the tip of the radial sector, at apex of wing; eight simple veins from Cu_1 to hind margin before the first forked one, and one simple vein between the second and third forks.

Miocene shales of Florissant, Wilson Ranch (H. F. Wickham). Nearest to *P. vetuscula* (Scudder), which agrees in having the radial sector originating far basad; but the "third cubital" cell is different.

Palaeochrysa wickhami n.sp.

Anterior wing about 9 mm. long; hyaline, with dark venation; radial sector originating scarcely basad of lower basal corner of "third cubital" cell; costal area with eight cross-veins visible, but at least 10 were present; 9 or 10 cells between radius and sector, the middle ones about square (their shape entirely different from those of *P. fracta*), the basal one long; between R_s and M are seven oblique cells and a basal one of irregular shape (above the "third cubital"); between media and cubitus are nine cells; six simple nervures from cubitus to hind margin before the forked ones begin; "third cubital" divided straight across the middle, neither part much produced basally or apically; one nervure from near middle of "third cubital" to margin, and one meeting the nervure which bounds its outer side. The basal part of cubitus is straight, and the media is not dislocated.

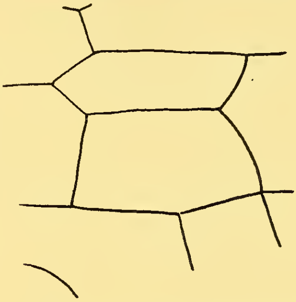

FIG. 3.—*Palaeochrysa wickhami.* "Third cubital" cell.

Miocene shales of Florissant, Wilson Ranch (H. F. Wickham). Remarkable for the small size and dark nervures; it might be a *Nothochrysa*, except for the forked veins going to hind margin. It differs from *P. vetuscula* not only in the much smaller size, but also in not having R_s originating far basad of the double cell, and also in having only one nervure from double cell to margin. In this last character, and also in the shape of lower part of double cell, it differs from *P. ferruginea* and *P. concinnula*.

HYMENOPTERA

Cryptocheilus hypogaeus n.sp.

♀. Robust, about 17 mm. long; anterior wings about $10\frac{1}{4}$ mm.; antennae thick, about $6\frac{1}{2}$ mm. long, not curled up at end; legs apparently normal for the genus; metathorax with strong transverse grooves. Head and thorax black, abdomen dark, possibly brown in life; antennae with scape dark, flagellum ferruginous; femora dark, tibiae and tarsi probably ferruginous in life; wings with two transverse dark clouds, one at and just beyond the basal nervure, with a lobe extending apicad, the other, large and diffused, below the base of the marginal cell; the large pale area between the bands may have been orange or yellowish, a suggestion of this color remaining; apical region and margin of wing pallid. Venation ordinary; upper angle of second submarginal cell less than a right angle; outer border of third submarginal cell very faint, seen with difficulty. Claws rather short, with a single large sub-basal tooth, the outer side of which presents a gentle slope, instead of being vertical as Bingham figures for *Cryptocheilus nicevillii* (*Salius nicevillii* Bingh.).

The following wing-measurements are in microns. I give also some measurements which I made from the type of *Cryptocheilus laminarum* (*Salius laminarum* Roh.).

Length of marginal cell	2800	(*laminarum* 2640)
Lower side of marginal cell beyond third submarginal	800	(*laminarum* 800)
Greatest width of marginal cell	640	
First submarginal on marginal	224	(*laminarum* 224)
Second submarginal on marginal	800	(*laminarum* 880)
Third submarginal on marginal	1200	(*laminarum* 896)
Third submarginal on third discoidal	640	(*laminarum* 720)
Second submarginal on third discoidal	640	(*laminarum* 690)
Second submarginal on first discoidal	352	(*laminarum* 432)
Lower end of basal nervure basad of transversomedial	720	(*laminarum* 560)
Length of transversomedial	400	
Basal nervure on first submarginal cell	320	
Basal nervure on first discoidal	720	
Greatest (diagonal) length of first submarginal	2896	
Greatest (diagonal) length of first discoidal	2960	

In the hind wing, the approximating ends of the cubital and transversomedial are about 64 microns apart, the cubital more apicad, not more basad as it is in *Cryptocheilus sericosoma* (*Pompilus sericosoma* Sm.).

Miocene shales of Florissant, Wilson Ranch, a very beautiful specimen (H. F. Wickham). In Rohwer's table (*Psyche*, April, 1909) this runs nearest to *Cryptocheilus florissantensis* (*Hemipogonius florissantensis* Ckll.), but differs by the great inequality in the widths of the second and third submarginal cells above, and also by the lack of a dusky cloud on the outer margin of the wing. It is actually nearest to *C. laminarum*, which has a dusky band in the region of the basal nervure, although it is light and inconspicuous in the type. I hesitated at first whether to refer the insect to *C. laminarum*, but there are so many differences in the details of the measurements that I can only regard it as distinct.

It appears that in Miocene times *Cryptocheilus* was producing a number of closely allied species, exactly as in the modern fauna, and in all this time there is no evidence of any generic modification.

Janus disperditus Cockerell

Wilson Ranch (Wickham). Professor Wickham was so fortunate as to pick up the reverse of my original type!

Hemichroa eophila Cockerell

Wilson Ranch (Wickham). About 9 mm. long, anterior wing $7\frac{1}{2}$; thus smaller than the type, but otherwise similar.

HEMIPTERA

Tingis florissantensis n.sp.

Length of body about 3 mm.; robust, black, of ordinary form; elytra extending perhaps half a mm. beyond abdomen; antennae not especially long, length about 1280 μ, the last joint about 240 μ long; pronotal lateral margins not much expanded,

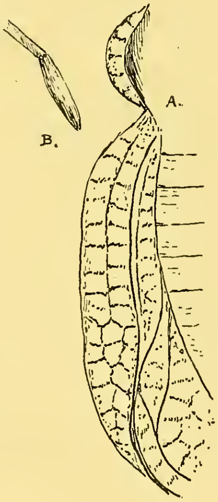

FIG. 4.—*Tingis florissantensis*. A. Side of thorax and elytron; B. end of antenna.

with a single row of areolae; costal area of elytra with two rows of areolae, except at widest part, beyond middle, where are two sets of three areolae in a transverse series; general form and structure of elytra as in *Gargaphia*.

Miocene shales of Florissant (University of Colorado Expedition). An ordinary looking species, quite distinct from those described by Scudder. Scudder's genus *Eotingis* is singularly like the living *Celantia* Distant, from Ceylon, agreeing in practically everything except the structure of the thorax, which in the fossil genus lacks the vesicular enlargements.

DIPTERA

PROTOPHTHIRIA n.g. (Bombyliidae)

Similar to *Phthiria*, but proboscis stouter, less than twice length of antennae; abdomen much longer than thorax; face longer.

Protophthiria palpalis n.sp.

Length 8 mm., wing 6 mm., robust; head, thorax, and legs dark, probably black in life; shape of head (lateral view) much as in *Phthiria sulphurea*, but face longer (as long as antenna) and occiput more obtuse; antennae much as in *P. sulphurea*, the third joint broad basally and tapering at end, the end narrower than in *P. sulphurea* (antennae therefore quite different from those of *P. pulicaria*); no long hairs at end of antennae; face not hairy; palpi very well developed (990 μ long), formed as in *P. sulphurea*, but proboscis only extending about 480 μ beyond palpi; thorax (in lateral view) not greatly humped, much as in *P. sulphurea*, except that the scutellum is less promi-

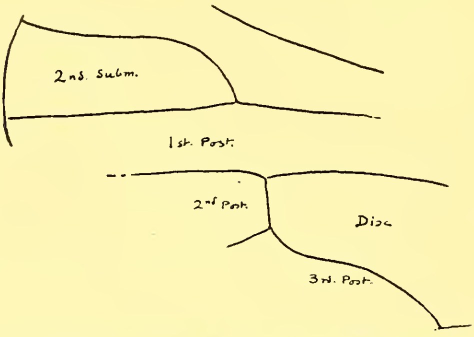

FIG. 5.—*Protophthiria palpalis*, part of apical field of wing.

nent, and there is little or no hair; abdomen thick, about 5 mm. long, with thin but conspicuous pubescence, the hairs quite long, and (as in *P. sulphurea*) especially abundant at end of sixth segment; legs long and slender, hind legs about 8 mm. long.

Wings hyaline, the costa darkened; two submarginal and four posterior cells; anal cell closed at or almost at margin; second submarginal cell little expanded apically, and not angled above near base; second vein not turned backward at end; first posterior cell widely open.

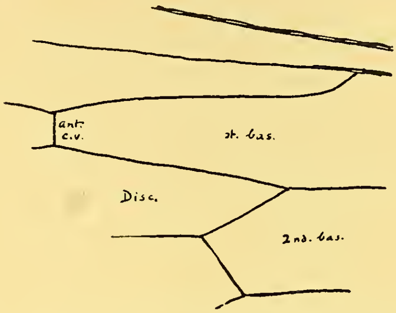

FIG 6.—*Protophthiria palpalis*, ends of basal cells.

The following measurements are in microns:

Second basal cell on discal, about	360
Second basal cell on fourth posterior	224
Separation of second and third veins to anterior cross-vein	1,200
Basal corner of discal cell to anterior cross-vein	880
Anterior cross-vein to base of second submarginal cell	1,840
Lower side of second submarginal cell, about	1,680
Transverse (vertical) diameter of second submarginal a little beyond middle	560

Miocene shales of Florissant, Wilson Ranch (Wickham). Among the Florissant fossils this comes nearest to *Lithocosmus*, but the form of the second submarginal and first posterior cells is quite different. The venation is essentially that of *Phthiria* and *Acreotrichus*, while the characters of the head are rather those of *Phthiria* than *Acreotrichus*, though differing from both.

ALOMATIA n.g. (Bombyliidae)

A genus of Lomatiinae with rather long and narrow abdomen; antennae close together, stout, the basal joint very bristly, the apical one elongate-fusiform, bare; wings with two submarginal and four posterior cells; anal cell closed at margin of wing; anterior cross-vein oblique, at about the end of first fourth of discal cell; end of praefurca considerably (at least 480 μ) basad of anterior cross-vein; second vein bent upward, but its inner angle at end less than a right angle; second submarginal large, including apex of wing; first posterior widely open.

Alomatia fusca n.sp.

Length about 6 mm.; wing $4\frac{3}{5}$ mm.; head apparently pale, no long proboscis visible; thorax and abdomen dark, probably black in life, abdomen rather elongate, about 4 mm. long, less than 2 mm. broad near base; wings dark fuliginous.

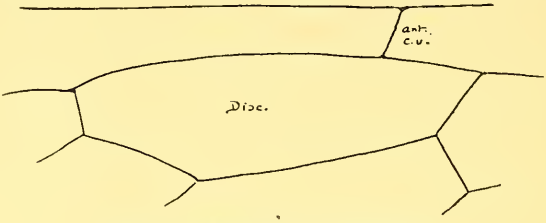

Fig. 7.—*Alomatia fusca*, discal cell

The following measurements are in microns:

Lower side of second submarginal cell	624
Upper end of anterior cross-vein to basal corner of second submarginal cell	1,600
Lower end of anterior cross-vein to apex of discal cell	800
Lower end of anterior cross-vein to base of discal cell	272
Second basal cell on discal	192
Second basal cell on fourth posterior	160

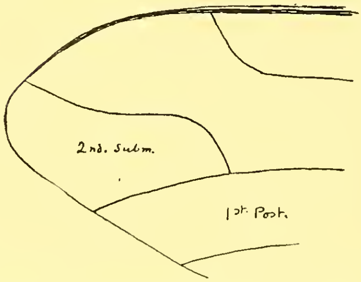

Fig. 8.—*Alomatia fusca*, end of wing

The vein separating the discal cell from the third posterior shows a single uniform gentle curve.

Miocene shales of Florissant, Wilson Ranch (Wickham). In my manuscript table of Bombyliid genera (based on venation) this runs to the vicinity of *Oncodocera*, *Lithocosmus*, and *Protophthiria*. It is, however, remarkable for the position of the anterior cross-vein. From *Protophthiria* it is also easily known by the different termination of the second vein, and many other details. From *Lithocosmus* it is known especially by the first posterior cell being without apical contraction. In Verrall's table of Lomatiinae it runs closest to *Prorachthes*. The praefurca of *Alomatia* ends at least 240 μ basad of basal corner of discal cell, which is contrary to Verrall's diagnosis of Lomatiinae, but his own figure of *Lomatia lateralis* shows a similar condition. The antennae of *Alomatia* are curiously like those of *Thereva*.

FIG. 9.—*Alomatia fusca*, antenna.

PROTOLOMATIA n.g. (Bombyliidae)

A genus of Lomatiinae, related to *Lomatia*, to which it runs in Verrall's table of Lomatiinae. It differs in the long, parallel-sided abdomen, and the much less oblique anterior cross-vein. Among the fossil genera it is nearest to *Megacosmus*, the species of which are much larger, with broader abdomen, and have the end of the second vein curved strongly backward (not far from vertical in the new genus), and the side of the second basal cell on discal very long.

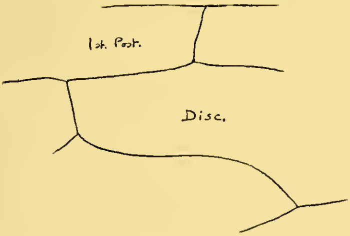

FIG. 10.—*Protolomatia antiqua*, apex of discal cell.

Protolomatia antiqua n.sp.

Length about 9 mm.; wing 6¾ mm.; body dark, slender; abdomen parallel-sided, its width 1¾ mm.; antennae slender, about 1200 μ long; thorax and abdomen without evident hair. Wings hyaline, faintly dusky; venation nearly as in *Lomatia lateralis*, but praefurca longer, anterior cross-vein much less oblique (about as in *Megacosmus secundus*), upper apical side of second basal cell shorter.

The following measurements are in microns:

Length of praefurca	512
First posterior cell on first submarginal	1,250
First posterior cell on second submarginal	1,150

Width of first posterior cell on outer margin of wing	288
Discal cell on first basal	1,360
Discal cell on first posterior	592
Second basal on discal	240
Second basal on fourth posterior	160
Anal cell on wing margin	400

Miocene shales of Florissant, Wilson Ranch (Wickham). The remarkably numerous and diversified Florissant Bombyliidae still fail to include any Anthracinae. Probably, as parasites, these Bombyliids took the place of the Tachinidae, which were rare if not wholly absent.

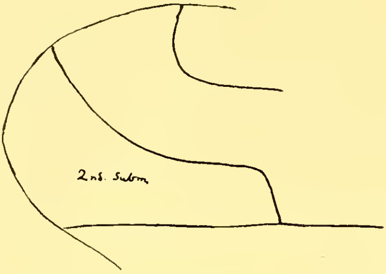

FIG. 11.—*Protolomatia antiqua*, apex of wing.

Asilus peritulus Cockerell

Wilson Ranch (Wickham). A wing, about 11½ mm. long.

Hirmoneura melanderi Cockerell

Wilson Ranch (Wickham). Total length 19 mm.; the abdomen long and tapering.

Syrphus willistoni Cockerell

Wilson Ranch (Wickham). Length about 10½ mm.; wing a little over 8½. Other specimens which I have referred to this species are considerably smaller; I believe that there are two species of this type, but at present I cannot satisfactorily separate them.

PETROLOGICAL ABSTRACTS AND REVIEWS

EDITED BY ALBERT JOHANNSEN

WINCHELL, ALEXANDER N. *Directions for Laboratory Work in Optical Mineralogy.* Published by the Author, Madison, Wis., 1911. Pp. 36. Wrappers.

This very useful little pamphlet for laboratory use was first published for students at the University of Wisconsin. It is now reprinted with the omission of the original slide numbers but with blank spaces into which may be written those of any collection of thin sections. Problems are given in the use of the microscope for determinations by ordinary light, parallel polarized light, crossed nicols with parallel light, and crossed nicols with convergent light. Throughout the book references to the proper pages in the author's *Optical Mineralogy* are given for the explanation of the phenomena observed.

A. J.

WINCHELL, ALEXANDER N. *Geology of the National Mining District, Nevada.* Min. and Sci. Press, 1912. Pp. 16.

Describes various rocks occurring in Nevada. Suggests the name auganite for "a volcanic rock consisting essentially of basic plagioclase and pyroxene. The plagioclase is usually labradorite, but may be more basic. . . . . Having provided the new name for rocks ordinarily called augite andesite, it is possible to use the latter name for rocks which are actually varieties of andesite, and consist essentially of acid plagioclase and pyroxene." The reviewer believes that augite andesite, in the past, has been so used by most petrographers. Auganite, therefore, appears to be suggested for olivine-free basalt, the dividing line between andesite and basalt being plagioclase of the composition Ab_1An_1.

A. J.

WOYNO, TADEUSZ JERZY. "Petrographische Untersuchung der Casannaschieter des mittleren Bagnetales (Wallis)," *Neues Jahrb.*, XXXIII (1911), 136–207.

The Casanna schists in the central Bagnetals consist of a complex of metamorphosed rocks whose chief constituents are glaucophane, epidote, chlorite, albite, sericite, quartz, and calcite. In most of the rocks the amount of soda is greater than potash. Of these rocks, two, prasinite and epidote glaucophane schist, are derived from igneous rocks.

A. J.

WRIGHT, FRED. EUGENE. "Mikroskopische Petrographie vom quantitativen Gesichtspunkte aus," *Neues Jahrb.*, XXV (1913), 753–75.

A translation of an article by the same writer in the *Journal of Geology*, XX (1912), 481–501.

WRIGHT, FRED. EUGENE. "A New Thermal Microscope for the Measurement of the Optical Constants of Minerals at High Temperatures," *Jour. Wash. Acad. Sci.*, III (1913), 232–36.

Describes and illustrates a new thermal microscope for the determination of the birefringences, extinction angles, and optic axial angles of minerals at temperatures between 10° C. and 1200° C.

A. J.

WRIGHT, FRED. E., and VAN ORSTRAND, C. E. "The Determination of the Order of Agreement between Observation and Theory in Mineral Analyses," *Jour. Wash. Acad. Sci.*, III (1913), 223–31.

The authors discuss the principles underlying the calculation of mineral formulas.

A. J.

WRIGHT, FRED. EUGENE. *The Methods of Petrographic-Microscopic Research.* Carnegie Institution, Publication No. 158. Washington, 1911. Pp. 204, pls. 11.

The author found, in his work on silicate preparations in the Geophysical Laboratory, that the ordinary methods of determining minerals microscopically were not always sufficient in working with artificial fine-grained products, and it was necessary to devise new methods or modify old ones. While many of the results of the author's comparative studies on the relative merits and accuracy of a number of these methods have been published at different times in the *American Journal of Science*, they are here brought together in proper relations to other available methods. As stated by the author, the different methods best adapted for the microscopic examination of fine-grained and artificial preparations are here considered with special reference to their degree of accuracy and range of general application.

In the introduction, the petrographic microscope and its several mechanical and optical parts are described. This is followed by chapters dealing with the methods for determining refractive indices, birefringence, and extinction and optic angles. There are also reproduced some extremely useful charts, such as Wulff's stereographic net, Hilton's gnomonic projection net, Fedorow's refractive index diagram, and various others.

The book is an extremely valuable contribution to the literature of petrography, and is especially important for the author's comparative study of the value of different methods. It may be studied with profit by all advanced students.

A. J.

WRIGHT, FRED. EUGENE. "The Index Ellipsoid (Optical Indicatrix) in Petrographic Microscopic Work," *Amer. Jour. Sci.*, XXXV (1913), 133-38.

The writer suggests abandoning the "elasticity ellipsoid" and the symbols for the "axes of elasticity" in the explanation of the phenomena of light in crystals. He would use instead only the indicatrix and the symbols for the refractive indices, regarding the use of other symbols as bewildering to the student. The reviewer's experience has been that students can grasp much more readily the idea of an ease (or difficulty) of vibration in a certain direction in a crystal, and a corresponding rate of movement at right angles to it, than they can the inverse relation of the refractive indices. The reviewer long ago abandoned the terms "axes of elasticity" and substituted for them "ease of vibration axes."

A. J.

WRIGHT, FRED. EUGENE. "Oblique Illumination in Petrographic Microscope Work," *Amer. Jour. Sci.*, XXXV (1913), 63-82.

A study of the cause and effect of oblique illumination in the study of mineral plates. A sliding diaphragm in the focal plane of the condenser is considered by the author to be the best method for producing this illumination. He points out that in the measurement of extinction angles, central illumination with parallel plane-polarized light is essential.

A. J.

WÜLFING, E. A. "Fortschritte auf dem Gebiete der Instrumentenkunde," *Fortschritte der Min., Krist., u. Petrog.*, III (1913), pp. 63–92.

A summary of the progress made, during the past decade, in mineralogical and petrographical instruments, including goniometers, microscopes, microscope accessories, conoscopes, total reflectometers, photometers, chromoscopes, lighting-, projection-, grinding-, and separating-apparatus, sclerometers, electromagnets, electric ovens, drawing instruments, etc. A bibliography of 214 articles, and brief descriptions of the various instruments are given.

A. J.

WÜLFING, E. A. "Eine einfache Vorrichtung für konstante Wasserbäder," *Zeitschr. f. angew. Chemie*, XXVI (1913), pp. 87–90.

Describes a new water bath for constant temperatures.

A. J.

WÜLFING, E. A. "Ueber die objektive Darstellung der Grenzkurven bei Kristallen," *Sitzb. Akad. Wiss. Heidelberg*, 1912, Ab. 19, pp. 14.

WÜLFING, E. A. "Ueber Projektion mikroskopischer Objekte ins besondere im polarisierten Licht," *Sitzb. Akad. Wiss. Heidelberg*, 1911, Ab. 36, pp. 40.

Describes a lantern for projecting microscopic objects. With this instrument it is possible to project interference colors of minerals, interference figures, to show the optical character of minerals, and in fact to show upon the screen all of the phenomena seen with the polarizing microscope.

A. J.

WÜLFING, E. A. "Ueber kristallographische Kaleidoskope," *Neues Jahrb.*, I (1912), 37–50.

Describes an apparatus by means of which crystal form, crystal symmetry, etc., may be clearly shown to students.

A. J.


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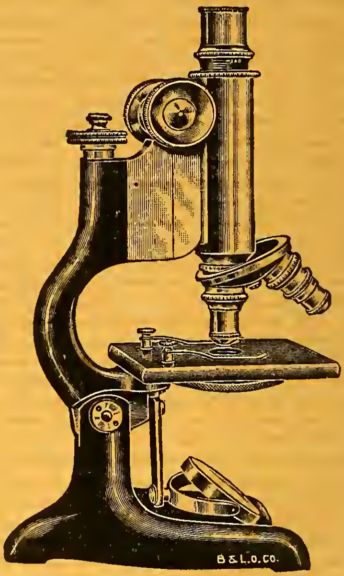

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VOLUME XXII NUMBER 8

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A SEMI-QUARTERLY

NOVEMBER-DECEMBER 1914

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NOVEMBER-DECEMBER 1914

THE STRENGTH OF THE EARTH'S CRUST

JOSEPH BARRELL
New Haven, Connecticut

PART VII. VARIATION OF STRENGTH WITH DEPTH AS SHOWN BY THE NATURE OF DEPARTURES FROM ISOSTASY

SECTION A, PRESENTATION OF THEORY[1]

INTRODUCTION AND SUMMARY

The first five parts of this article have concurred in showing that the crust is very strong when measured by its capacity to support great deltas, individual mountain ranges, or great internal loads due to irregularities in density not in accord with the topography. On the other hand, the altitudes of the continents as a whole, or of large sections of the continents, agree with the demands of nearly perfect isostasy. In Part VI it was shown, however, that, although even perfect isostasy threw very considerable stresses

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[1] Section B, on Applications of the Theory, will be published in the following number of this *Journal*. The Introduction and Summary apply however to both sections.

upon the outer part of the crust, the maintenance or restoration of the isostatic condition through geologic time in spite of the opposing geologic activities implied the existence of an undertow below the zone of compensation. The existence of this regional isostasy for continental interiors as well as for ocean basins suggests, furthermore, that this zone of undertow is both thick and relatively very weak to resist shearing stresses. But if such a zone exists it must have important bearings on other branches of terrestrial dynamics besides that of isostasy. Its importance gives it a right to a distinct name, and it has been called here the zone of weakness—the asthenosphere. It is desirable to test its reality and its character by other lines of evidence, and such another line forms the basis of this part.

George H. Darwin has investigated the problem of the stress-differences imposed on the earth by the weights of continents and mountains. In his work the earth was assumed to possess competent elasticity throughout and the topography to be without isostatic compensation. Love has more recently treated the contrary problem of the isostatic support of continents and mountains, assuming as governing conditions that isostatic compensation was perfect within a depth of one-fiftieth of the earth's radius, 127 km., and that all shearing stresses due to topography and compensation disappeared at that depth. Below there is assumed to exist only hydrostatic pressures. In other words, Darwin postulates no isostasy and no asthenosphere; Love postulates perfect isostasy and a perfect asthenosphere. As there is known to be no truly fluid universal shell within the earth, and as isostasy for limited regions is far from perfect, the truth must lie between these two extremes. The asthenosphere must have some degree of strength and a measure of its strength is derived in this part by a study of the nature of the departures from isostasy.

For this purpose is discussed the nature of the stresses as worked out by Darwin. Then the departures from isostasy are analyzed into harmonic series. Those of long wave-length are seen to be of low amplitude, those of short wave-length of high amplitude. Now the departures from isostasy are according to their very nature without compensation and their stress effects will therefore follow Darwin's law except in so far as the great rigidity of the outer crust will permit it to sustain loads after the manner of a continuous beam. It is shown, however, that the outer crust is inefficient as a beam, so that the results of applying Darwin's analysis will probably not be greatly modified.

It is found that the departures from isostasy are such as throw great stress-differences upon the zone of compensation, here called the lithosphere. The maximum stresses imposed by the loads found to exist within the United States lie furthermore within the outer two-thirds of that zone. The stress-differences due to this cause reach maxima probably between 3,000 and 5,000 pounds per square inch.

Within the asthenosphere, on the contrary, the stresses caused by the departures from isostasy are very small, under the United States the stress-differences at depths of from 400 to 600 km. reaching maxima probably between 500 and 600 pounds per square inch, between a sixth and tenth of those existing at higher levels.

Now the nature of those geologic actions which oppose isostasy, both the great compressive movements and the great cycles of erosion and sedimentation, are such that they tend to destroy the isostatic adjustments of whole continents and large parts of continents. By these broad actions they tend to bring larger and larger stress-differences upon the zone lying more than 200 km. deep. The limitation of their action as shown by the dominance of regional isostasy is therefore to be regarded as an effect of weakness in that zone. This then is another proof of the reality of an asthenosphere. The proof in Part VI depended upon the dynamics necessary for isostatic undertow; the proof in this part depends upon the limitations of stress with depth as measured by the existing departures from isostasy.

This is as far as the present fragmentary data and imperfect theory can safely go, but in order to visualize the arguments a curve of strength is given which shows how great a falling-off of strength there is from the upper part of the lithosphere to the middle of the asthenosphere. Below, the strength undoubtedly again increases, but the evidence for that is supplied by other lines of research than that opened by the geodetic data.

The results of this part suggest that in future investigations by mathematicians upon the elastic competence of the earth, a probable case would be to consider the isostatic compensation as uniformly tapering out through a depth twice as great as the depth given for uniformly distributed compensation, that is, tapering out through about 244–254 km. Further, it is not in accordance with nature to assume that at this depth all shearing stresses disappear. Such an assumption brings in artificialities nearly as great as those involved in Darwin's assumption of no isostatic compensation. Rather should the stress relations be solved as limited by some such curve as is here shown, and determined by the nature of the departures from isostasy. It is possible that this may add still further difficulties to the mathematical treatment of the subject, yet only by closer recognition of the realities of nature can mathematical analysis become of increasing value.

SECTION A, PRESENTATION OF THEORY

RELATIONS OF LOADS AND STRESSES

Stresses imposed by harmonic surface loads.—A harmonic series gives a succession of sweeping curves such as are shown in Fig. 15. The vertical scale may be made of any size and the curves may be regarded as sections across a series of hills and valleys, or, on progressively larger scales, anticlinoria and synclinoria, geanticlines and geosynclines, continents and ocean basins. The parts of the curves convex upward will then represent loads above the mean surface and give rise to stresses acting downward. The broad hollows give negative loads and the surface beneath is strained upward by the pressures from surrounding regions. The inequalities of the earth's surface may be taken as approximating to harmonic undulations of simple or complex nature. By so taking them, the stresses which they produce on the earth's interior may be evaluated.

G. H. Darwin treated this problem in his paper "On the Stresses Caused in the Interior of the Earth by the Weight of Continents and Mountains."[1] In this are investigated the stresses given by positive and negative loads whose distribution follows a law

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[1] *Phil. Trans. Royal Soc.*, CLXXIII (1882), 187–230.

of zonal harmonics arranged on the surface of a sphere. The harmonic series of the second order corresponds to oblateness of a spheroid and also serves as a basis for computing the tidal strains. The zonal harmonics of the fourth order correspond to an equatorial continent and two polar continents, the eighth order adds to these two annular continents in about latitude 45°, and so on. The higher orders, above thirty, correspond to a succession of anticlinoria and synclinoria, or mountains and valleys. For all above the second harmonic the depth of maximum stress lies within the outer half of the earth's radius.

Darwin's solutions were made on the assumption that there are no differences of density beneath continents and oceans and that all the relief of the earth is upheld by its rigidity. He reached the conclusion that continents such as Africa and America gave a maximum stress-difference of about four tons per square inch at a depth of about 1,100 miles. The later demonstration of the existence of regional isostasy nullifies this conclusion except for the amount by which the topography of large areas is not completely compensated. Even this part can to some extent be regarded as sustained by a rigid crust floating upon a deeper zone which acts dynamically nearly as a fluid. There are reasons for believing, however, that this latter conception is extreme in the other direction and not justified by the evidence. It is thought that by the collective support of the arguments brought out in this part the assumption will be finally justified—that for the outstanding loads not in isostatic equilibrium the work of Darwin continues to apply.

In the mathematical analysis, the loads which represent the areas and heights of the regional departures from isostasy are regarded as members of an infinite harmonic series of ridges and furrows disposed on a plane. One wave-length is the distance from crest to crest, or mid-furrow to mid-furrow. Darwin showed, as illustrated in Figs. 15 and 16, that the magnitude of the stress-difference at any point within the crust due to a surficial harmonic load depended upon the depth below the mean horizontal surface measured in terms of the wave-length and not at all on the position of the point considered with reference to the ridges and furrows. Further in regard to the direction of the stress-difference, it is shown, as illustrated in Fig. 15, that in passing uniformly and horizontally through the crust on a line at right angles to the direction of the ridges, the stress axes revolve with a uniform angular velocity. In relation to depth, the maximum stress-difference, as shown in Figs. 15 and 16, occurs at a depth equal to $\frac{1}{2\pi}$ of the wave-length and is then equal to $2\,gwh\epsilon^{-1}$ or in gravitation units of force to $0.736wh$, in which h is the height from the mean plane to the top or bottom of the undulations and w is the weight of a unit volume.

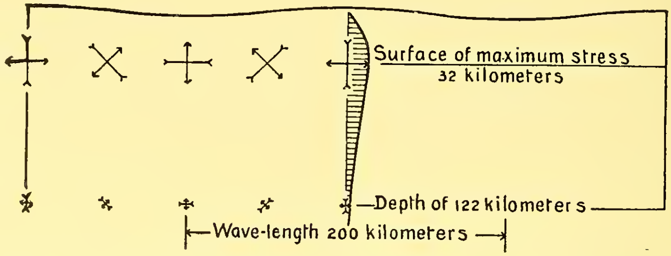

FIG. 15.—Diagram showing in vertical section uncompensated harmonic mountains and valleys with relative magnitude and direction of stress-differences, which they impose on the crust below. Mountain crests drawn as 5 km. above valley bottoms. Wave-length 200 km. Stresses shown to a depth of 122 km. Maximum stress for this wave-length is at 32 km.

It is important to note that the value of this maximum depends only on the height and density of the mountains and is independent of the distance from crest to crest. The depth at which this maximum is reached depends, on the other hand, upon the wave-length and not upon the height or density of the mountains. The effect of a doubling of the wave-length upon the vertical distribution of the stress-differences is shown in Fig. 16.

It is seen that the lateral pressure due to the elevations, instead of being at the surface as it would be under hydrostatic conditions or as in completely compensated mountains and valleys with the special distribution of density assumed by Love,[1] is at a depth of about one-sixth of the wave-length. The maximum stress is, furthermore, but 37 per cent of the full amount of the hydrostatic

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[1] *Some Problems of Geodynamics* (1911), chaps. ii and iii.

lateral pressure. Fig. 16 shows that uncompensated features with a wave-length up to 200 km. impose the stresses almost wholly within the lithosphere, taking this as limited by a depth of 122 km.

The crust increases in strength to a certain maximum, perhaps from 10 to 30 km. deep, as shown by the experiments of Adams.

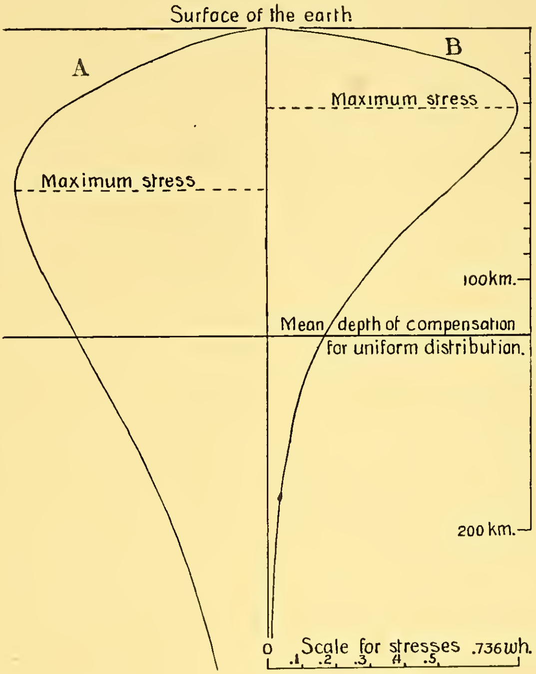

FIG. 16.—Diagram showing the distribution in the crust of stress-differences due to parallel uncompensated harmonic mountains and valleys: A, curve showing relative magnitude and depth of stress-differences corresponding to a distance of 400 km. between crests of parallel mountain ranges. B, curve showing the same for a distance of 200 km. between crests of parallel mountain ranges.

At greater depth the strength, according to the theory developed in Part VI, and as recognized by Love and others in treating of isostasy, is to be regarded as decreasing and passing by transition into the asthenosphere. Consequently it is seen that the distribution of stress imposed by a wave-length of 200 km. conforms well to the distribution of strength, the greatest strain coming on the strongest part.

Darwin obtained his results by making the initial assumption that the earth substance was incompressible but possessed elasticity of form. The introduction of the factor of compressibility Darwin showed to affect the result largely in the case of the second harmonic, but for harmonics of infinitely high orders the resulting stresses are independent of the modulus of compression. Consequently he states, "it may be concluded that except for the lower harmonic inequalities compressibility introduces but little change in our results."[1]

Modifications imposed by long and large wave-lengths.—In Fig. 16, curve A shows that for a wave-length of 400 km. the depth of maximum stress is 64 km. and at 122 km. the stress is 75 per cent of the maximum. If this should be regarded as the beginning of the asthenosphere it would mean that a large part of the stress would be thrown on to the zone incapable of sustaining large stress-differences. If the wave-length became 2,000 km. the lithosphere would be subjected to but small stress-differences and the maximum strain would occur at a depth of 320 km., the middle of the sphere of weakness. In order that Darwin's solution should hold for these cases the height of the arches would have to be so small that the resulting stress-differences would not exceed the elastic limit of the asthenosphere. For greater loads disposed on the surface in these large wave-lengths the stress relations would approach those of a rigid crust overlying a fluid substratum. Of this problem Darwin states, "The evaluation of stresses in a crust, with fluid beneath, would be tedious, but not more difficult than the present investigation" (on the stresses caused by the weight of continents and mountains).[2] It is a different problem from that solved by Love; the latter considering the stresses in such a crust caused by a condition of isostasy, not by a lack of isostasy. The limited mathematical training of the present writer does not permit here the definite solution of this problem, but some general observations can be made.

For wave-lengths very large in comparison with the depth of the lithosphere the stress-differences, if confined within the crust, approach those existing in a continuous beam, each span being

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[1] *Scientific Papers*, II, 500.

[2] *Ibid.*, II, 502, footnote.

stressed by a continuous load, greatest at the center in accordance with the harmonic curve and acting in the reverse direction from the adjacent spans. This is a very simple limiting case. The maximum bending moment would be on the cross-section at the crest of each downward and upward arch. For a given height of load the bending moment would increase with the square of the span or wave-length. The maximum bending stresses would be horizontal, acting as tensile and compressive stresses at the top and bottom of the lithosphere. In the middle of the lithosphere there would exist a neutral surface suffering neither tension nor compression, but subjected to horizontal shear. The theory of beams shows that the strength is limited by the marginal tensions and compressions, not by the internal shear. As the lithosphere is, however, weakest on the upper and lower margins, its material is poorly arranged to resist the bending stresses. The greatest resistance to bending in a certain plane is given by the form of an I-beam, but the crust is analogous to a beam in which a single flange should intersect its middle, giving a cross-shaped section. The earth's crust is consequently a peculiarly weak structure to resist harmonic loads of great wave-length, and as the strength varies inversely with the bending moment it varies inversely with the square of the wave-length. It is seen then that wave-lengths of continental breadth are very poorly supported by the strength of the crust, but if they reach notable amplitude must rest chiefly upon the asthenosphere. The consideration of the stress diagram given by a wave-length of 200 km. showed why very pronounced departures from isostasy can occur in one direction over areas up to at least 100 km. across and why marked regional compensation extends commonly to limits of 100–200 km. radius. The stress effects produced by harmonic loads a thousand kilometers or more in a wave-length show, on the other hand, why regional compensation of the same vertical magnitude cannot extend effectively across a whole continent. It explains why the United States as a whole is in nearly perfect isostatic equilibrium with respect to the ocean basins.

Nature of stresses imposed by internal loads.—Take the case of harmonic loads distributed on a plane *S–S*, Fig. 17, within an indefinitely extended elastic solid. The amount and direction of the vertical stress upon this plane are shown by the vertical lines, the scale of stresses being one-twentieth of the value for the stress-diagram shown by the horizontal lines. On this plane, *S–S*, a small unit mass is subjected to stress equal in all directions and not to stress-difference, since the stress is essentially the same on the small contiguous unit masses. The reasoning is the same as

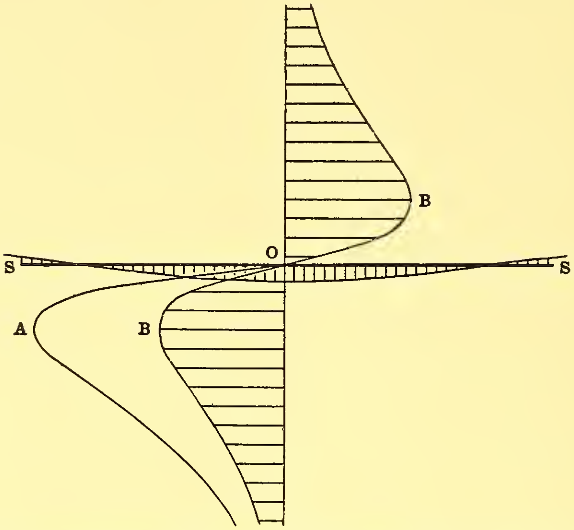

FIG. 17.—Stress-diagrams for harmonic loads distributed on a plane: A, diagram for loads upon a limiting surface of a solid extending indefinitely from this surface. B, diagram for loads upon a plane within an indefinitely extended solid. The scale for loads is one-twentieth of the scale for the resulting stresses. A little more than one-half wave-length is shown.

that for harmonic loads distributed on the limiting surface of a solid except that here there is an indefinitely extended solid on each side of the plane. The stress at any point of the plane acts positively on one side, negatively on the other. Half of the load will be carried on each side. Consequently if *OA* is the curve showing the stress-differences at various depths for a harmonic load on the surface of the earth, then *BOB* will be the stress-curve for the same load carried on a plane deep within the lithosphere. For this to be approximately true, however, the wave-length would have to be small in comparison with the depth of the loaded surface. Then the upper half of the stress-diagram will lie within the lithosphere. The lower half of the curve would also have to lie within the elastic competence of the crust for corresponding depths. Suppose the plane to lie near to either boundary of the lithosphere. The case now approaches that of a surface load, one side of the stress-diagram becomes largely cut off and the other increases. The exact analysis is of course difficult and will not be attempted.

Assume the loaded plane to be at a depth of 61 km., half the depth of the lithosphere. The strength of the middle would not then be utilized for support of the load. For a wave-length up to 100 km. Fig. 17 shows fairly well the distribution of stress and it would be contained mostly within the middle of the lithosphere. For wave-lengths of 200 km., however, the margins of the lithosphere would be subjected to greater strain than the interior, the stress-diagram would be modified toward that existing in a loaded beam, and, if the margins are weak, the structure is poorly adapted to support the load. If the loaded plane is at greater depth, the same wave-length will throw a greater proportion of the strain upon the asthenosphere and the deeper parts of the lithosphere. If these are incapable of supporting the resulting stresses, again a modification of the diagram would occur, involving bending moments in the stronger part of the crust.

If, now, it be assumed that the upper half of the lithosphere is decidedly stronger than the lower half and that the maximum strength is at some depth below the surface, it is seen that the maximum outstanding masses which the crust could carry would be disposed in the outer quarter or third of the lithosphere. But this is just what was found to be the case as the result of the studies made in Part V. Therefore the accordance between the geodetic evidence and the consequences of the assumption raise it to the dignity of a presumption. It may be taken as a working hypothesis that the greater outstanding masses are limited in their positions by the limitations of crustal strength. Mental reservation must be made, however, as to the possibility of other more important determining factors, such for example as the nature of igneous activity, in limiting the zone of large outstanding masses. An accordance of fact with theory is not a proof, but it raises a presumption that the theory is correct.

Nature of stresses imposed by perfect isostasy.—This topic, although not directly in line with the subject of this chapter, must receive brief mention here since the stresses in the crust are compounded of those due to the departures from isostasy with those resulting from a state of perfect isostasy. The stress resulting from the isostatic support of continents and mountains has been ably worked out by Love.[1] But his treatment started with the limiting though improbable assumption that at a depth of one-fiftieth of the earth's radius all stress-differences disappeared, as though the layer below were truly fluid. This required a complicated and equally improbable curve of density, opposite in sign above and below, in order that the topography should be compensated, the ocean surface remain a level surface, and yet the stress-differences become zero at the required depth. Nevertheless the solution is valuable as a limiting case in showing the general character of the internal stresses which must exist. He showed that isostatically compensated harmonic mountains and valleys gave maximum stress-differences on the axial lines of mountains and valleys and that it amounted to about one-fourth of the theoretical hydrostatic pressure. The stresses decrease rapidly with depth.

In contrast to Love's hypothesis of the distribution of density, that of Hayford may be considered. This is that the excess or defect in density needed for compensation is uniformly distributed to a depth of 122 km. Again, a rigorous mathematical treatment must be left to those competent to undertake it, but it would appear that such distributions of density would throw very considerable stress-differences within the asthenosphere; or, if this was incompetent to carry such, would bring large stress-differences upon the bottom of the zone of compensation, opposite in sign to that in the upper half, whereas at an intermediate level depending upon the wave-length would be a region of no stress-difference. This distribution of stress resulting from the hypothesis may be taken as a strong argument against the existence of a uniform distribution

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[1] *Some Problems of Geodynamics* (1911).

to the isostatic compensation. In order to have the larger relief and its compensation fitted to a crust strongest in its upper part and shading into a zone of weakness, the zone of compensation should die out with depth and lie mostly in the upper half of the zone of strength, since the stress-differences would die out at a depth greater than the disappearance of the compensation. This conclusion is seen to be in closer accord with several other lines of evidence which have been noted than is the contrary assumption of uniform compensation.

[*To be continued*]

THE ANALCITE BASALTS OF SARDINIA

H. S. WASHINGTON
Geophysical Laboratory, Carnegie Institution of Washington

Introduction.—In his well-known paper[1] entitled "Die Producte des Vulcans Monte Ferru," Doelter first noted the presence of "leucite basalts" at this volcano, as well as near Pozzo Maggiore, giving a brief description and an analysis. Later, Dannenberg[2] and Deprat[3] confirmed the occurrence of leucite rocks at Ferru, and showed that these flows belong to the closing period of volcanic activity. In the autumn of 1905 I visited Sardinia for the Carnegie Institution of Washington, making a special study of the different volcanoes of this island. Although my observations were necessarily brief, I was able to confirm the opinion of these geologists. The first analysis, which I made some years ago, of a specimen from Scano gave such unexpected results as regards the alkalies that I made two others of these so-called leucite rocks from other localities. All three were in harmony. Since these rocks have always been considered to be and have been cited as being leucitic, although in reality the so-called leucite is analcite, it seemed to me that a special note would be of interest. The lavas of Monte Ferru and of the other Sardinian volcanoes will be described in other papers.

I have to thank my friends, Professor J. V. Lewis for the photographs of the thin sections, and Doctors F. E. Wright and H. E. Merwin of the Geophysical Laboratory for the optical study of the analcite and biotite.

Occurrence.—Although these basalts vary somewhat in their modal characters, yet they are so closely allied that they may well be described together. One prominent locality, already noted by Doelter,[4] is a massive flow, from 6 to 10 m. thick, on the other

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[1] C. Doelter, *Denks. Akad. Wiss. Wien*, XXXIX (1878), 41.

[2] A. Dannenberg, *Neu. Jahrb.*, Beil. Bd., XXI (1905), 48.

[3] G. Deprat, *C.R.*, CLV (1907), 823.

[4] C. Doelter, *op. cit.*, p. 78.

side of a small stream just north of Scano, a village on the northeastern flank of Monte Ferru. The basalt here overlies a flow of the ordinary gray trachyte of the Sennariolo type, the trachyte resting on white tuffs. Below these are tertiary marls. To the south of Scano is another flow, possibly connected with that to the north. This forms a ridge known as Binzale Prunu, which extends in a southeast direction for about 2 km. and shows three summits, called Monti Columbargiu, Martu, and Lepere. I collected lavas from the Scano flow, and from that of Binzale Prunu along the road between Scano and Cuglieri below Monte Columbargiu, and at a quarry below Monte Martu called Cava Tuvamurtas. Similar basalts were also collected at a small cone west of Bonorva, a small town east of Pozzo Maggiore, which apparently belongs to the closing phase of the last period of small cones in Sardinia. At a locality called Ghizo, to the west of Monte Urtigu, the culminating point of Monte Ferru, there is a small exposure of a similar rock containing many copper-colored biotite tables. The color of these biotite crystals makes the peasants believe that the rock is an ore of copper, and a peasant whom I met near by told me about a King Mastino, a sort of *Bergkönig*, to whom all the copper belongs. It is supposed that this king lives beneath the earth and has cast a spell upon the copper ore so that men cannot extract the copper from it.

Megascopic characters.—These lavas are all very dense, compact, and aphanitic. Apart from nodules of olivine and augite, to be described presently, the Scano flow shows few phenocrysts, a few small crystals of augite and olivine and very sparing biotites being the only ones visible. This lava is a rather darkish gray. The lava of Bonorva, which also carries olivine nodules, much resembles this except that there is no biotite. The lava flow of Binzale Prunu is almost black, quite aphanitic, though with alteration it assumes a brownish or even reddish color. In this are many tables of a bronzy biotite which are smaller but more numerous in the lava from the quarry, but larger and less numerous in that from Monte Columbargiu. The tables of this biotite are all a light chestnut brown, but when altered have a red color and a luster resembling that of copper. Dr. Merwin found that the angle

$2E=40°–45°$ and the refractive index $\gamma_{na}=1.65–1.655$. These figures are high and much resemble those of some biotites of Vesuvius. There was not sufficient material to make an analysis of them. In this rock also there occurred rather abundant crystals (1–3 mm.) of a pale, greenish olivine. The rock of Ghizo is a dark brick red with many bronzy biotite tables. I was not able to obtain any fresh specimens of this, so that for the present it may be left out of consideration.

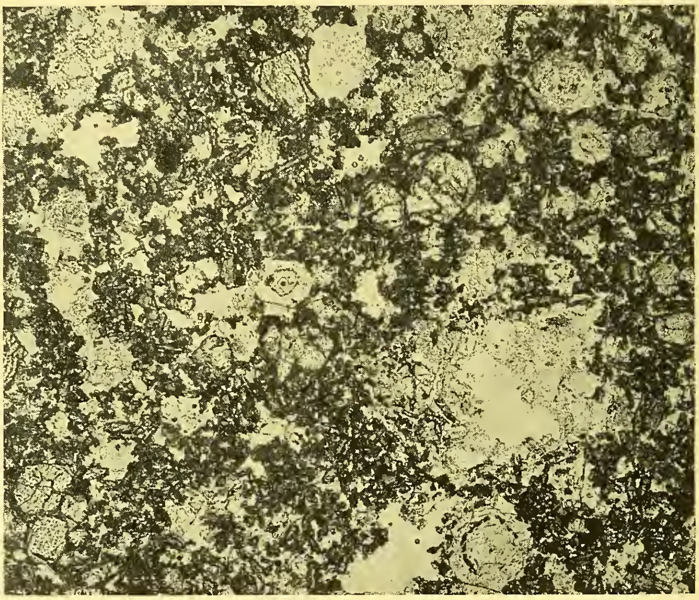

FIG. 1.—Analcite basalt, Scano

Microscopic characters (*Figs. 1 and 2*).—In all these basalts, the phenocrysts of augite and olivine are not very prominent in the thin section. The olivines vary from 0.1 to 0.5 mm. in diameter, and are generally anhedral, euhedral crystals being comparatively rare. They are colorless and quite fresh, except for a thin border of transparent bright-yellow alteration product, apparently allied to iddingsite, the amount of which is never very great. There is never any serpentinization. The augites are colorless, anhedral, smaller than the olivines, and comparatively rare. One sees scattered through the groundmass circular areas which are clear and colorless. The diameter of these varies somewhat, in those of Scano being from 1 to 2 mm., while in that from Binzale Prunu it is never over 0.1 mm. These are almost exactly the same as the small leucites of the leucitic lavas of the Italian Peninsula. The boundaries are more or less well defined, often by a circular line of small grains. They contain the ordinary inclusions common to leucite, of augite and magnetite microlites, which form either a central core or a circular wreath. They are never radially arranged. All these leucite-like crystals are absolutely isotropic, even when the sensitive tint is used, and no optical anomalies or twinning phenomena are seen between crossed nicols. The observations of Dr. Wright showed that these crystals have a refractive index of 1.502, which is lower than that of leucite and above that of analcite.

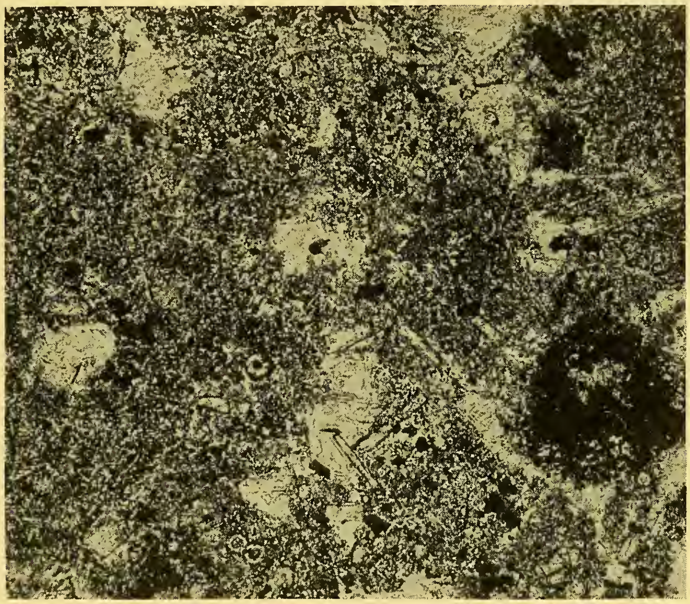

FIG. 2.—Analcite basalt, Monte Columbargiu

The microscopic groundmass is composed of abundant very small prisms of augite and fewer anhedral grains of olivine and magnetite, scattered without any definite arrangement in an abundant colorless glass. Nothing was found which could be considered to be feldspar. There are some small needles of apatite.

Nodules.—The lava flow north of Scano is remarkable for the abundance of nodules of olivine and augite, which have been already partially described by Doelter.[1] Those of olivine seem to be most numerous. They are rounded, varying in size from that of a hazelnut to that of one's fist. They are composed of grains, from 1 to 2 mm. in diameter, of a transparent olivine, of a light greenish-yellow color, with a few small grains of magnetite. These grains are not very coherent, the nodules crushing down readily beneath the finger. An analysis of this olivine, extremely fresh, carefully purified and dried at 110°, gave me the results in A (Table I),

TABLE I

	A			B
SiO_2	41.24	0.687	0.689 (1.00)	43.77
TiO_2	0.10	0.001		....
Al_2O_3	0.21	0.002		....
Fe_2O_3	0.48	0.003		0.61
Cr_2O_3	Nil			....
FeO	8.36	0.116	1.367 (1.99)	24.90
MnO	Trace			....
NiO	0.21	0.003		....
MgO	49.90	1.248		29.21
CaO	Nil			Trace
	100.62			98.49

those in B being an analysis by Doelter (*op. cit.*, p. 78). The specific gravity was 3.307 at 20°. The amount of nickel is noteworthy, as is also the entire absence of chromium, an element often occurring in olivine. There was only an unweighable trace of manganese and absolutely no lime. Leaving out of consideration the very small amounts of alumina and ferric oxide, as impurities, the ratio $RO:(Si, Ti)O_2 = 1.99; 1.00$, which is that of an orthosilicate. That of $FeO:MgO = 1:10.5$, so that the olivine is distinctly magnesian. The optical properties of this olivine will be studied later.

Doelter's analysis is clearly defective. The sum is very low and the relation $RO:SiO_2$ does not approach that of an orthosilicate.

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[1] C. Doelter, *op. cit.*, p. 78.

Elsewhere[1] Doelter speaks of an olivine of Scano, of which Ippen made an analysis (not given). It is stated that the results of this correspond to the composition $7(Mg_2SiO_4) \cdot 3(Ca_2SiO_4)$. This would be a most extraordinary olivine, unique in mineralogy, and almost corresponding to a monticellite, although occurring in an igneous rock. But unfortunately the analysis has never been published, and one does not even find it in the elaborate *Handbuch der Mineralchemie* of Doelter, either under monticellite or under olivine. Regarding this olivine, Professor Doelter has been kind enough to write me (December 31, 1907) that it is white, forming isolated grains, and not in granular nodules like the olivine described above. He says that its locality is near Scano, that it is very rare, and that it has nothing in common with the olivine of the nodules.

The nodules of augite are subangular and smaller than the others, from 1 to 5 cm. in diameter. They are very compact, not granular, each one made up of a single crystal of the pyroxene, often twinned, and more or less split up through cleavage. The pyroxine is greenish-black, and it seems to be free from inclusions. An analysis gave me the following results:

SiO_2	50.13	NiO	0.02
TiO_2	1.91	MgO	13.73
Al_2O_3	7.08	CaO	20.06
Fe_2O_3	1.10	Na_2O	1.88
FeO	4.41	K_2O	0.25
MnO	0.05	H_2O	0.11
			100.73

Its chemical composition will be discussed later, when its optical properties shall have been studied.

Chemical composition.—Analyses made by me of three of these basalts are here given (Table II), along with several others of related rocks.

The three analyses of Sardinian basalts resemble each other quite closely in their general features. As regards most of the constituents, they are not specially noteworthy. Silica is rather low for basalts, and titanium is high, the latter a feature common

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[1] C. Doelter, *Phy. Chem. Miner.* (1905), 64.

to the rocks of Sardinia, as has been already pointed out.[1] The presence of a noteworthy amount of nickel is also of interest. The most striking feature—when the presence of "leucite" is considered—is the small amount of alkalies and the dominance of soda over potash. The presence in all three of from 2½ to 4 per cent of water, in spite of the evident freshness of the rocks, is also noteworthy.

TABLE II

	A	B	C	D	E	F	G
SiO_2	44.85	44.37	46.54	45.59	44.16	40.81	42.30
Al_2O_3	12.55	11.36	12.68	12.98	12.96	13.08	18.22
Fe_2O_3	3.33	7.23	3.41	4.97	8.07	6.40	17.30
FeO	5.30	3.49	5.29	4.70	3.10	7.20	....
MgO	10.27	9.28	10.09	8.36	10.83	10.03	6.66
CaO	8.32	8.50	8.00	11.09	12.26	10.12	11.01
Na_2O	4.77	3.67	5.11	4.53	1.32	2.43	1.31
K_2O	0.72	0.74	1.64	1.04	0.72	0.31	2.93
H_2O+	2.01	3.28	2.35	3.40	2.41	3.97	0.55
H_2O-	0.95	1.95	0.25	0.51	0.46	0.82	....
TiO_2	5.07	5.21	3.98	1.32	2.06	3.86	....
ZrO_2	....	....	....	0.03	....	....	....
P_2O_5	1.17	0.99	0.91	0.91	1.03	0.88	Trace
Cl	....	....	....	0.05	....	....	....
MnO	0.07	....	....	0.14	....	0.07	Trace
NiO	0.23	....	....	....	....	....	....
BaO	....	....	....	0.13	....	....	....
SrO	....	....	....	0.12	....	....	....
	99.60	100.07	100.25	99.87	99.98	99.98	100.28

A. Analcite basalt [III. (5) 6. 2. 5]. Scano, Monte Ferru, Sardinia. H. S. Washington, analyst.

B. Analcite basalt [III. 5. (2) 3. (4) 5]. Monte Columbargiu, Monte Ferru. H. S. Washington, analyst.

C. Analcite basalt [III. 6. 1 (2). 4]. Bonorva, Sardinia. H. S. Washington, analyst.

D. Analcite basalt [III. 6. 2.″ 4 (5)]. The Basin, Cripple Creek, Colorado. Hillebrand, analyst. Cross, *Jour. Geol.*, V (1897), 689.

E. Leucite basalt [III. 5. 4. 4]. Dobernberg, near Tetschen, Bohemia. R. Pfohl, analyst. J. E. Hibsch, *T.M.P.M.*, XV (1896), 255.

F. Analcite basalt [III. 5.″ 4.″ 5]. Rathjordan, County Limerick, Ireland. G. T. Prior, analyst. G. T. Prior, *Min. Mag.*, XV (1910), 317.

G. Leucite basalt. Scano, Monte Ferru, Sardinia. C. Doelter, analyst. C. Doelter, *Denks. Akad., Wiss. Wien*, XXXIX (1878), 80.

Doelter's analysis (G) of the Scano rock is obviously at fault in several particulars. The alumina is much too high because of the non-separation of TiO_2 and P_2O_5, and probably also in part through the incomplete separation of MgO from Al_2O_3, as his MgO is much

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[1] H. S. Washington, *Q.J.G.S.*, LXIII (1907), 69.

lower than that of any of the three rocks analyzed by me. His Fe_2O_3 is also undoubtedly too high (apart from the non-determination of FeO), presumably because zinc was used for the reduction preparatory to titration with permanganate, part of the TiO_2 being thus reduced and estimated as Fe_2O_3. His alkalies are also low, and it seems possible that they have been interchanged. This analysis may therefore be left entirely out of consideration. Dannenberg (*op. cit.*, p. 50) gives the silica percentage of the Scano rock as 44.16, which agrees very well with my results, especially as a little silica would be recovered from the alumina precipitate.

Occurrence of analcite.—The results of these analyses render it highly improbable that the leucitic mineral is really leucite, and indicate clearly that it is analcite. To test this, the alkalies were determined in the portion of the Scano rock soluble in warm dilute hydrochloric acid. This gave $Na_2O = 2.66$ and $K_2O = 0.12$ in percentages of the rock; that is, more than half the soda and about one-sixth of the potash. Some of this soda is probably derived from the glass base, but its amount is so great, and that of potash so small, that it leaves no doubt that the rounded isotropic crystals are analcite. The entire absence of twinning lamellae and optical anomalies is also in harmony with this supposition, as it is well known that analcite, especially when not freely crystallized in cavities, is much less prone to show such phenomena than is leucite.[1]

The very fresh condition of the rocks analyzed precludes the idea that the analcite is secondary and replaces an original leucite—a supposition which is often invoked apparently only because of a disbelief that a hydrated, zeolitic mineral like analcite can be primary. The occurrence of primary analcite has been shown by several petrographers,[2] and there is also considerable experimental evidence, which cannot be gone into here, that confirms the view that such a primary character is not only quite possible, but very

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[1] The absence of cleavage does not militate against the idea here advanced, as it is not a strongly marked characteristic of small analcites in thin section.

[2] W. Lindgren, *Proc. Cal. Acad. Sci.*, III (1890), 51; L. V. Pirsson, *Jour. Geol.*, IV (1896), 686, and *U.S.G.S., Bull. 237* (1905), 154; W. Cross, *Jour. Geol.*, V (1897), 684; J. W. Evans, *Q.J.G.S.*, LVII (1901), 38; G. W. Card, *Rec. G.S.N.S.W.*, VII (1902), 100; A. Lacroix, *Mater. Min. Mad.*, I (1902), 197.

probable in many cases. Indeed, in view of the experimental formation of analcite at temperatures of 500° and higher, the known presence of water in rock magmas, and the great lowering of the melting-point through its presence, the primary character of the analcite is the only rational view in such cases as these and many others, where the rock is unquestionably fresh and unaltered. Such an explanation is far simpler and more intelligible than the invocation of the entire, or almost entire, replacement of potash by soda in a single mineral of the rock through assumed soda-bearing solutions of quite hypothetical origin, with no alteration of the other minerals. At the same time, of course, there is no question that in some cases, where the rock has undergone alteration, the analcite present is secondary, as it is in that from Rathjordan.

It may be mentioned that the occurrence of primary analcite in monchiquites and analcite basalts and other such rocks has a bearing decidedly adverse to Brun's hypothesis that lavas are water-free, as does also the fact, well known to all petrographers, that many unquestionably fresh and recent pitchstones and other glassy rocks carry up to 10 per cent of H_2O.

With my three analyses are given others of closely similar rocks, which likewise contain small, rounded crystals of a mineral which looks like leucite and which in all cases is entirely isotropic and without twinning. Indeed, those from Colorado and Ireland were considered to be leucite basalts until chemical analysis showed the true character of the isotropic minerals. These two carry no biotite. In the case of the Bohemian rock, which, like those of Binzale Prunu, contains large plates of biotite, Hibsch apparently overlooked the significance of the dominance of soda over potash. This has been pointed out by Prior in the paper cited. Chemically, they are much like the Sardinian lavas, but are higher in CaO and also in TiO_2. The last two are also much lower in soda.

Classification.—The norms of the three Sardinian basalts analyzed by me are given in Table III. From this it appears that the Scano rock (A) falls in the subrang represented by the symbol III. (5) 6. 2. 5, there being just sufficient normative nephelite present to be taken into consideration. This subrang is as yet only represented by the Scano rock and a basalt glass from the Val di Noto, Sicily,[1] and the name of *scanose* has been given to it by me.[2] The Columbargiu rock falls in the subrang ornose, with the symbol III. 5. (2) 3. (4) 5. The Bonorva rock has the symbol III. 6. 1 (2). 4. This subrang, III. 6. 1. 4, has been called pienarose by Brouwer,[3] but a recalculation of his analysis shows that the pienarite (aegirite phonolite) described by him is really in III. 5. 1. 4. The name pienarose should therefore be applied to this subrang (III. 5. 1. 4), and the name pilandose may be given to III. 6. 1. 4, in which falls a Pilandsberg lujavrite described by him.[4]

TABLE III

NORMS OF ANALCITE BASALTS OF SARDINIA

	A	B	C
Or	4.45	4.45	15.59
Ab	28.30	31.44	15.98
An	10.56	11.95	3.61
Ne	6.53	....	14.62
Di	17.93	15.12	23.79
Hy	....	5.00	....
Ol	12.18	7.84	10.21
Mt	2.32	....	4.87
Il	9.73	9.45	7.60
Hm	1.76	7.23	....
Pf	....	2.18	....
Ap	2.69	2.35	2.02

Mode.—Owing to the very fine grain, the confused fabric, and the presence of abundant glass, it is impracticable to determine the mode by Rosiwal's method, and calculation of the mode by readjustment of the norms is also subject to some uncertainty through the presence of analcite. An attempt has, however, been made to determine the modes by comparison of the several norms with the respective thin sections, and checked by a Rosiwal measurement of the analcite areas. The results are given in Table IV, but they are to be regarded as only rough approximations.

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[1] G. Pontes, *Atti Ac. Gioen.* (5), III, No. X (1910), 7.

[2] H. S. Washington, *C.R. XII Cong. G. Int.*, 1913.

[3] H. A. Brouwer, *Transv. Nefel. syen.* (1910), 50.

[4] *Ibid.*, p. 132. This course has been decided on in conference with Drs. Cross and Iddings.

These three are all similar in their general features. In C, it is evident that some of the normative olivine has gone into the biotite. It may be added that the small amount of excess TiO_2 (represented normatively as perofskite) has been assigned to biotite, the somewhat abnormal composition of which is indicated by its optical characters. The large amount of glass is very striking, as well as the general composition which must have been assigned to it in each case had it crystallized. For A and B, it would have about the composition Ab_1An_1, including a little orthoclase with a small amount of analcite. In C, the 40 per cent would be distributed approximately as follows: orthoclase, 15; andesine (Ab_2An_1), 20; analcite, 5. While the figures given here and in the table are admittedly only rough approximations, yet there can be no doubt that they give an idea of the general order of the various minerals present.

TABLE IV

	A	B	C
Analcite	8	5	10
Augite	20	20	25
Olivine	12	6	10
Biotite	....	5	....
Ores	15	18	13
Apatite	3	2	2
Glass	42	44	40

A. Mode of analcite basalt. Scano.
B. Mode of biotite-analcite basalt. Monte Columbargiu.
C. Mode of analcite basalt. Bonorva.

Rock name.—The name of analcite basalt, first proposed by Lindgren,[1] is entirely applicable to these rocks, and is preferable to that of monchiquite, which was originally applied to rocks in which the analcite is present in the base or as a glass of the same composition. It is worthy of remark that, had the rock solidified under such conditions as to be holocrystalline, the modes given above show that a very considerable amount of andesine or labradorite would have been present (as has been the case in the Bohemian rock cited above). In this case, the name analcite basanite would have been appropriate.

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[1] W. Lindgren, *Proc. Cal. Acad. Sci.*, III (1890), 51.

The presence of considerable biotite in the rocks of Binzale Prunu and Ghizo is so striking that they may be considered to form a special type of analcite basalt, which may be called ghizite, if a special name be deemed advisable.

The occurrence of analcite in these rocks, as well as in those of Colorado, Ireland, and elsewhere, which, without chemical analysis, can only with great difficulty be distinguished from leucite, so that the rocks are on superficial examination considered to be leucite-bearing, indicates the necessity of chemical analysis, and the advisability of a revision of some of the occurrences of so-called leucitic rocks. This is especially true of certain regions, such as Bohemia, Kula,[1] and Trebizond, where basalts containing a mineral supposed to be leucite occur, but where the rocks and the regional magmas are eminently sodic rather than potassic. As a general rule, as is well known, analcite is apt to occur in the rock base as the last, or one of the last, products of crystallization, but its undoubted occurrence in the instance described in this paper and those occurrences cited in the table of analyses show that its presence in leucite-like phenocrysts may be much more general than has been hitherto supposed, and may clear up some of the obscurities surrounding the occurrence of leucite.[2]

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[1] It now seems highly probable, in view of the present study, that the supposed leucites of the "leucite" kulaites of Kula are in reality analcites. Though the potash is higher than in the rocks cited above, yet they are dominantly sodic, and the supposed leucites rarely show optical anomalies.

[2] Cf. H. S. Washington, *Jour. Geol.*, XV (1907), 277.

ON THE CONDITIONS UNDER WHICH THE VEGETABLE MATTER OF THE ILLINOIS COAL BEDS ACCUMULATED

T. E. SAVAGE
University of Illinois, Urbana

All students of the subject agree that coal was derived from vegetable material which has undergone imperfect decomposition without free access of air. The complete explanation of the coal beds involves, among other things, an explanation of (1) the method and conditions under which the plant material accumulated; (2) the kinds and proportions of the different plants that contributed the vegetable material; and (3) the chemical changes by which the plant tissues were transformed into coal. The first part of the problem, with regard to the method and the conditions under which the vegetable matter of the coal beds accumulated, can be studied somewhat independently of the other two, and the solution should be found in the structural features of the coal beds and associated strata.

Two important theories have been proposed to explain the mode of accumulation of the vegetable matter of coal beds. The older of these, known as the "transport or driftage theory," assumes that the vegetable materials grew on land areas, whence they were carried by streams and deposited in the bodies of water where they accumulated. The other, known as the "swamp or growth-in-place theory," was suggested in 1778, and assumes that the vegetable matter of coal beds accumulated in swamps practically in the places where the plants grew.

The following facts presented in the principal coal beds of Illinois make impossible the application of any form of the transport theory of accumulation of the vegetable material: (1) the great extent of the coals—the Herrin (No. 6) and Springfield (No. 5) beds extend in practical continuity over at least 7,000 square miles, and probably over a considerably greater area in the state; (2) the regularity of thickness of the coals—the Herrin (No. 6) bed ranges from 7 to 9 feet over a known area of at least 5,000 square miles. A thin band of shale or shaly coal ("blue band"), one-half to two inches thick, is present 18–24 inches above the floor of this coal over practically the entire area of its distribution, and the thickness of the benches above and below the "blue band" is remarkably uniform. The Springfield (No. 5) bed, also, scarcely varies one foot in thickness over more than 5,000 square miles; (3) the small percentage of mineral matter or ash in the coal shows that very little mud and sand sediments were mixed with the plant remains as they accumulated.

In times of flood the amount of mud and sand carried by streams is so great compared with the amount of vegetable matter, and the latter is deposited so irregularly, that it can scarcely be imagined how the plant material of these coal beds could have been carried by streams into the Illinois basin, and have accumulated in practical continuity over such extensive areas, in anything like such uniform thickness, and with so little mingling of mineral sediments. Extensive areas of relatively pure vegetable matter are known to be accumulating in swamps at the present time, but there is no known place where plant remains transported by streams during floods are accumulating as a continuous bed over any considerable area in anything approaching regularity of thickness and without a very large mixture of sand and mud; nor does it seem probable that pure transported vegetable deposits have ever accumulated over any considerable area in the past.

From a study of the small coal basins of France in recent years Fayol, supported by De Lapparent and other French geologists, has revived the transport theory of accumulation of the vegetable matter of coal beds. However, practically every geologist who has studied extensive coal beds, especially those of the Appalachian region of the United States, with which the coal beds of Illinois are comparable, has rejected the transport theory of accumulation as applied to those beds. Rogers Brothers, Lesquereux, Dawson, Andrews, Dana, Orton, Stevenson, White, and Ashley have all accepted the growth-in-place theory of accumulation of the vegetable matter of extensive coal beds as the only one that is consistent with the facts. It seems safe to assume, then, that the vegetable matter of the coal beds of Illinois accumulated practically in the places where the plants grew.

The acceptance of the growth-in-place theory of accumulation does not settle the question whether the basins bordered the sea, as lagoons, or occupied broad depressions over coastal plains, as the Dismal Swamp, or covered large areas over river flood plains; nor is it purposed to discuss this phase of the question at this time. The fact that the vegetable matter of coal beds accumulated under water in the places where the plants grew does not prove that the water was ever more than a few inches, or at most a very few feet, in depth, even where coal beds 5–10 feet thick have been formed. On the contrary, the structural features of the coal beds indicate conclusively that the water in which the vegetable matter accumulated was very shallow as well as that it was very quiet.

STRUCTURAL FEATURES OF THE COAL BEDS

One of the more conspicuous structural features of the coal beds of Illinois, which are representative of the larger beds everywhere, is their stratification, the more prominent bedding planes being 3–5 or more inches apart. These bedding planes form partings along which the coal separates rather easily, and they usually show well-developed bands of "mother coal" or mineral charcoal. These stratification planes often become more conspicuous when the bed is weathered, but some of them are prominent on unweathered faces. Such a conspicuous clean parting of mineral charcoal occurs 20–24 inches below the roof of the Herrin coal over several hundred square miles in western and southern Illinois, and appears to be almost coextensive with that bed. Along this charcoal zone the coal separates so perfectly that where the overlying shale does not stand well in the mines the bench above this parting is left for a roof. Five or six inches higher is another mineral charcoal parting almost equally well developed and persistent.

Between the more prominent partings and bedding planes the coal from roof to floor is made up of alternating bright and dull laminae, which are usually $\frac{1}{2}$ to $\frac{1}{32}$ of an inch thick, though in places they are considerably thicker. The aggregate dull bands generally make up nearly or quite one-half of the coal beds, and they appear to be of the same general nature as the bedding planes mentioned above. They are often rather uniform in thickness over considerable areas, but in places they thicken for some distance and in others they thin down to knife-edge partings. The bright laminae appear to be rather homogeneous in structure; but where the coal is split along well-developed dull laminae the cleavage planes almost always show distinct mineral charcoal surfaces. A typical dull lamina appears to be composed of a film of dull, structureless coal at the top, which passes downward into coarse-textured, fibrous, mineral charcoal in the middle part, and this, in turn, grades downward into a film of dull, structureless coal below.

The features above described are not peculiar to Illinois coals. H. S. Rogers and others have noted the alternations of laminae of bright and dull coal, and the predominance of mineral charcoal in the dull laminae, in the coals of the Appalachian region, and the writer has observed the same characteristics in the coals of Iowa. They have been described from coal beds generally in different parts of the world. The mineral charcoal is so constantly present, and so intimately mingled in, and constitutes such an important part of, the dull laminae of the coals of Illinois that they must have been developed together, and a satisfactory explanation of the one must also explain the other.

THE "MOTHER COAL" OR MINERAL CHARCOAL

Two main explanations have been proposed to account for the origin of mineral charcoal. One of these, held by many paleobotanists and chemists in recent times, explains the mineral charcoal as formed from charred plant tissues resulting from forest fires sweeping over land areas, the charred fragments being subsequently swept by flooded streams into the basins, where they were deposited with the mass of vegetable matter there in process of accumulation.

This explanation assumes that a considerable part of the vegetable matter of the coal was transported material, which assumption is open to all of the objections to the transport theory mentioned above. It assumes that a very important proportion of the coal was derived from plant tissues that had been charred by fires previous to their accumulation, and that these charred fragments had been carried into the coal basin by streams in such enormous quantities as to cover the surface of practically the entire area of the present coal beds, 5,000–8,000 square miles or more in extent; that this process took place not only once but was repeated as many times as there are persistent dull, charcoal-bearing laminae, requiring scores of recurrences of such charcoal deposition during the accumulation of the vegetable matter of each of the large coal beds. It assumes such a depth of water above the accumulating vegetable matter that the charred fragments brought in by the streams could be freely floated out above the mass of vegetable matter already present to every part of the basin, and, most impossible of all, that the streams that carried such vast quantities of charred vegetable matter carried little or no mud or mineral sediments. If it is assumed that the water of the basin was so shallow that the clay and sand brought down by the streams were strained out in the meshes of the tangled plant débris at the margin, then the same vegetable sieve would catch the charred plant fragments and not permit them to be distributed to every part of the accumulating coal beds. This explanation is not in harmony with the facts of the vertical and horizontal distribution of the mineral charcoal bands in the coal beds.

The modification of this view assumes that the mineral charcoal represents partially burned vegetable matter resulting from fires sweeping over the surface of the marshes in which the vegetable matter of the coal beds was accumulating. It is not probable that fires started by lightning would travel over water-covered swamps with only the living undergrowth and green leaves and branches of the trees to support the flames, and if they did, they would not leave such uniform and thick layers of charcoal as occur in well-developed dull laminae. If it is assumed that the surface of the vegetable matter that had accumulated in the swamp had been exposed and dried before the fires swept over it, then the conditions involved would be similar to those under which the charcoal is interpreted as having been formed by the partial atmospheric decay of the upper surface of the vegetable material of the bog exposed during periods of unusual low water.

It seems to the writer that the explanation of mineral charcoal as resulting from the temporary exposure and partial atmospheric decay of the surface portion of the vegetable matter in the bog, instead of the assumption that it must have been charred by fire, is much more consistent with the following facts: (1) the frequent repetitions of the dull laminae containing such large amounts of mineral charcoal; (2) the larger number of plant spores in the dull laminae than in the bright coal; (3) the numerous pinnae and pinnules of ferns[1] in the midst of the mineral charcoal fragments; (4) the absence of layers of ash that would result from the burning of the vegetable matter at the surface of the bog; and (5) the changes that take place in the vegetable matter at the surface of shallow marshes during periods of drought and exposure at the present time.

EXPLANATION OF THE BRIGHT AND DULL LAMINAE

In explaining the origin of the bright and dull laminae, Dawson[2] maintained that it is the outer bark of flattened tree trunks that alone formed the shining coal. In a recent paper on the origin of bright laminae of coal, Pringle,[3] of the Geological Survey of Great Britain, reaffirms Dawson's view.

The serious objection to this view is the fact that the bright and dull laminae of the coal beds are so nearly parallel and are often continuous for long distances. Trees that are overturned in swamps fall in various directions, and their trunks lie across one another at different angles. If the cortical portion of tree trunks formed the bright laminae of coal, these bright laminae would not be continuous for long distances, and the dull laminae would be broken at short intervals by small areas of bright coal representing the cross-sections and oblique sections of the cortical

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[1] David White, *Econ. Geol.*, III (1908), 302.

[2] J. W. Dawson, "On the Conditions of the Deposition of Coal," *Quar. Jour. Geol. Soc.*, XXII (1866), 141.

[3] John Pringle, "On the Origin of Bright Laminae of Coal," *Trans. Edin. Geol. Soc.*, X, Pt. 1 (1912), 33.

portions of tree trunks that lay at different angles and at different levels from those that formed the bright bands in any exposure. The distribution of the bright and dull laminae is not consistent with this explanation.

Microscopic examination of bituminous coal has shown that spores are more numerous in the dull laminae than in the bright, and hence some geologists have concluded that the dull laminae resulted from the greater number of spores in these bands, while the bright laminae were formed from the more woody portions of the plants. However, a study of the dull laminae shows that, while they may contain spores in greater abundance than the bright laminae, yet they are very largely composed of mineral charcoal, which certainly has been derived from plant tissues other than spores.

The alternation and great extent of the bright and dull laminae are such constant features of the coal beds, and the mineral charcoal is so generally present in the dull laminae, that any adequate explanation of the origin of these features must involve agencies that were repeatedly operative over practically the entire area of accumulation of the coal beds. The only recurrent agency of such widespread action is change in the water level of the basin during the time the vegetable material was accumulating.

If it is assumed that the dull laminae resulted from the flooding of the basin, we should have associated with the dull laminae bands of mud deposited during such times of flood. We are not left to speculate with regard to the effects of flooding of the basin during the progress of accumulation of the vegetable matter of the coal, for we have such an example in the clay band or "blue band" of the Herrin (No. 6) coal, which extends over practically the entire area of its distribution, and is clearly a mud parting due to flooding. Black shale partings, common in portions of some coal beds, as in coal No. 1, are also records of flooding of the coal-forming marshes. The typical dull laminae and mineral-charcoal zones in the large coal beds of Illinois, as elsewhere, are not such mud partings. They usually contain only a slightly, if any, greater percentage of ash than the bright bands and are practically free from clay silt. They contain a relatively smaller percentage of volatile matter and a larger proportion of fixed carbon than the bright bands. A number of proximate analyses of mineral charcoal compared with those of average coals from the same beds are given in Table I. It will be seen from this table of analyses that the mineral charcoal generally contains but little, if any, more ash than the average coal of the bed in which it occurs.

TABLE I

PROXIMATE ANALYSES OF MINERAL CHARCOAL AND AVERAGE COALS FROM THE SAME SEAMS

(*a*) Charcoal Samples; (*b*) Average Samples

	Water	Volatile Matter	Fixed Carbon	Ash	Ash in Charcoal above or below That in Average Sample
1*a*..................	1.17	19.77	72.13	6.93	+4.69
1*b*..................	1.94	39.26	55.83	2.24	
2*a*..................	.75	20.36	71.07	7.82	+3.04
2*b*..................	1.37	37.80	54.46	4.78	
3*a*..................	2.39	12.40	75.34	9.87	+4.20
3*b*..................	1.68	34.97	57.00	5.67	
4*a*..................	.52	14.32	64.03	21.13	+3.92
4*b*..................	1.04	28.01	49.24	17.21	
5*a*..................	.55	9.92	81.37	8.16	−1.97
5*b*..................	.85	16.85	69.58	10.13	
6*a*..................	.85	88.36	87.64	3.15	−2.18
6*b*..................	1.19	20.76	71.70	5.33	
7*a*..................	.57	20.98	70.37	8.08	−2.52
7*b*..................	.77	17.11	70.74	10.60	
8*a*..................	.85	10.49	84.01	4.65	−3.74
8*b*..................	.94	17.85	72.15	8.39	
9*a*..................	1.58	23.96	64.28	10.18	− .54
9*b*..................	2.33	34.91	52.03	10.72	

Nos. 1–8, analyses by McCreath, *Second Geological Survey of Pennsylvania*, Vol. MM, pp. 1–107; moisture at 225 degrees F.

No. 9, analyses Illinois Geological Survey, Herrin (No. 6) coal, Williamson County, Illinois; moisture air-dried.

After discussing the original amount and the composition of the ash contained in living species of such types of coal plants as lycopods, ferns, and equiseta, Stevenson[1] concludes that "one should expect to find in ordinary [pure] coal not much less than 6 per cent of ash, or even more, in which silica and alumina should predominate greatly." He thinks it probable that coals containing less inorganic matter than the plant substance should have yielded have

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[1] J. J. Stevenson, "The Formation of Coal Beds," *Proc. Am. Phil. Soc.*, LII (1913), 107.

had some of the original inorganic content removed in solution. It is also probable that some coals which locally contain more than the original amount of inorganic content, as pyrites lenses, etc., have been situated in places favorable for deposition of minerals rather than solution, and in this way have become enriched in their mineral content. It is also probable that in many places a small percentage of the inorganic constituents of the coal, above that originally present in the plants, may have come from wind-blown dust that settled over the coal basin during the long period of accumulation of the vegetable matter. The amount of ash in a coal bed varies very considerably at different levels and in different places even in the same mine. Among the possible causes of such variation are differences in the proportions of the kinds of plants that formed the coal, removal and deposition of mineral matter by solutions, and wind-blown dust. Hence, in the absence of definite evidence of sediment contributed by water, such as black shale or mud partings, it is thought that, as far as the bearing on the conditions of accumulation of the vegetable matter is concerned, not much significance can be attached to the variation in the amount of ash in a coal bed of a small percentage above or below the original amount that may have come from the plants that formed the coal.

The analyses given on p. 761 show that the mineral charcoal contains a smaller percentage of volatile matter and a larger percentage of fixed carbon than the average coal of the same bed. The proximate analyses (Table II) of the bright and dull laminae of the bituminous coal bed, cited by Pringle,[1] indicates that the dull laminae are similar in composition to mineral charcoal, as regards the smaller percentage of volatile matter, and the larger percentage of fixed carbon compared with the bright or the average coal.

TABLE II

	Water	Volatile Matter	Fixed Carbon	Ash
Dull laminae.............	1.68	14.71	77.17	6.44
Bright laminae...........	1.75	31.63	63.96	2.66

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[1] John Pringle, *Trans. Edin. Geol. Soc.*, X, Pt. 1 (1912), 33.

Lesquereux[1] described the changes that occur in the vegetable matter at the surface of swamps during dry periods as follows:

> Wherever the growth of peat in submerged bogs is checked by dryness or other causes the upper surface of the peat becomes crusted, hardened, and transformed into a thin coating quite impervious to the entrance of any kind of foreign matter, and it is upon this hard upper crust that the boggy humus forms, or, whenever the land becomes resubmerged, a new peat vegetation begins. In such cases such a crust remains as a parting between two layers of peat.

Von Gumbel in 1883 suggested: "It is very probable that in occasional drying of the swamp, followed by renewal of flooding, lies the explanation of the alternating bright and dull coal bands."

In discussing the process of putrefaction of vegetable matter of coal as described by Renault, David White[2] says that if uninterrupted the process of putrefaction goes on until all the softer tissues are disintegrated and decomposed, leaving only the most indestructible parts, immersed in a dark subgelatinous, plastic, or liquid mass, the fundamental matter. This fundamental matter not only envelops the undestroyed woody matter, but it infiltrates the surviving tissues to a greater or less extent. Where the impregnation is complete, we find dense, glossy, and shining coal. In many instances the impregnation has been imperfect, and sometimes intergrades to a charcoal or "mother of coal."

It is thought by the writer that the oft-repeated lowering, probably of only a very few inches, of the water level in the shallow swamps, and the consequent exposure of successive levels of the vegetable matter to the air, is the only adequate explanation that accounts for the extensive bedding planes practically free from clay sediments, the general distribution and alternation of the bright and dull laminae, and the large amount of mineral charcoal in the latter, as they occur in the coal beds of Illinois, the bright laminae resulting from putrefaction entirely under water, and the dull laminae and mineral charcoal resulting from partial atmospheric decay previous to the more complete subaqueous putrefaction.

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[1] L. Lesquereux, *Second Geological Survey of Pennsylvania, Ann. Rept. for 1885*, p. 118.

[2] David White, "Some Problems in the Formation of Coal," *Econ. Geol.*, III (1908), 303.

According to this view, the dull laminae and mineral charcoal partings of the coal beds are the records of repeated interruptions of accumulation, during which the surface of the vegetable material in the swamp was above water and exposed to atmospheric decay, resulting in the destruction of the softer parts of the plant tissues, leaving them in an indurated and more or less skeletonized and fibrous condition. On resubmergence these residual portions of the vegetable materials were not so readily impregnated with the fundamental matter of the bog as were those parts of the mass that had not suffered partial atmospheric decay, and hence are of dull appearance. Such periods of arrested accumulation of the plant material, due to the exposure of the surface of the vegetable matter of the bog, would be favorable for the accumulation on such a surface of a relatively larger proportion of spores than would be mingled with the vegetable mass during periods of submergence and of normal vegetable growth in the bog, and the resistant nature of the spore cases would permit their better preservation than the ordinary plant tissues during such times of exposure. These conditions would explain the greater abundance of spores in the dull than in the bright laminae of the coal beds. The variation in thickness of the dull laminae would be due to the unevenness of the surface of the exposed vegetable matter in the bog. The relatively smaller percentage of volatile matter and larger percentage of fixed carbon in the dull laminae and mineral charcoal would be explained in part by the fact that, during the times when the surface of the vegetable mass was above water and exposed to atmospheric decay, the volatile products of decomposition escaped into the air, and in part because the dull laminae were not subsequently infiltrated with the hydrocarbons of the fundamental matter to the same extent as the bright laminae.

The foregoing interpretation of the structural features of the coal beds leads to the following very definite conclusions:

1. That the beginning of vegetable accumulation of the coal beds was in a very shallow swamp.

2. That the swamp deepened so slowly, either by subsidence of the area or from the gradual building-up of the border or outlet by sedimentation, or both, that the plants were able to adjust them-

selves to the changes, and the accumulation of vegetable matter in a general way kept pace with the increasing depth.

3. That throughout the entire period of accumulation of the coal beds the water of the swamp was so shallow that during the oft-recurring cycles of drought successive levels of the vegetable mass were temporarily exposed and so modified by partial atmospheric decay as to result in the formation of the dull laminae with their mineral charcoal.

4. That the time involved in the accumulation of the vegetable material of a coal bed was the time necessary for the growth of the plants plus the time recorded in the interruptions of accumulation indicated by the dull laminae and charcoal partings of the coal, which would very greatly increase the usual estimate of time required.

BEREA SANDSTONE IN ERODED CLEVELAND SHALE[1]

WILBUR GREELEY BURROUGHS
Oberlin, Ohio

In Lorain County of northern Ohio occurs the greatest development of the Bedford-Berea unconformity.[2] This unconformity extends throughout other portions of the state.[3] It is found as channels over 100 ft. deep filled with Berea sandstone, as in the Amherst district, and from these pronounced forms declines in prominence to Berea sandstone filled channels 2–3 ft. deep, as that on Indian Creek at Stoneville, Ashtabula County, Ohio; or to a thin sandstone layer of the Bedford eroded away in the center where it crosses Phelps Creek, southeast of Painesville, Ohio.[4]

All of the channels eroded in the Bedford formation have either been confined to that formation, or have started in the Bedford and penetrated into the Cleveland formation which lies below the Bedford. These channels eventually were filled with Berea sand which, on consolidating, formed the Berea sandstone.

The most northerly Berea sandstone in Ohio.—The most northerly occurrence of Berea sandstone is that outcropping on the shore of Lake Erie, two miles east of Vermilion, Lorain County. Here the Berea sandstone extends from the top of a 25-ft. lake-cliff to the water's edge, under which it dips.

As far as the writer is aware, the first and only mention ever made of this body of Berea sandstone was made by E. M. Kindle

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[1] Published by permission of the Director of the Ohio State Geological Survey. Read before the Twenty-third Annual Meeting of the Ohio Academy of Science, at Oberlin, Ohio, November 29, 1913.

[2] W. G. Burroughs, "The Unconformity between the Bedford and Berea Formations of Northern Ohio," *Jour. Geol.*, XIX, No. 7 (1911), 655–59.

[3] Charles S. Prosser, "The Disconformity between the Bedford and Berea Formations in Central Ohio," *Jour. Geol.*, XX, No. 7 (1912); Charles S. Prosser, *Geol. Surv. Ohio*, *Bull. 15*, Fourth Series; H. P. Cushing, manuscript.

[4] Charles S. Prosser, *Geol. Surv. Ohio*, *Bull. 15*, Fourth Series, p. 277, and B, of Plate XVII, p. 274.

who ascribed its position to faulting.[1] Kindle stated that "in the vicinity of Lorain and for several miles to the westward, the shales [Cleveland] are concealed along the lake by glacial deposits. The shale cliffs reappear again, however, near the mouth of the Vermilion River. Here along the shore east of the river, broad, low anticlinal rolls prevail. These are interrupted by a fault which brings the Berea sandstone down to lake level and beneath which it dips at 45 degrees."

The writer wishes to advance another theory than that of faulting, for the occurrence of the Berea sandstone in the place which it occupies in the Cleveland shale; but first, a detailed description of the geology of this locality is necessary.

The Berea sandstone is composed of massive beds 10–15 ft. thick, with a total height of 20–30 ft. from the water's edge to the highest point of sandstone; the average would be about 25 ft. On the horizontal, the sandstone extends about 100 ft. It dips beneath the lake at an angle of 45 degrees. The stone, itself, is gray, with a moderately coarse grain.

West of the Berea sandstone there is no outcropping of rock for about 200 yds., when the Cleveland shale, that elsewhere forms the lake-cliffs of this region, again comes to the surface and continues westward as the lake-cliff. The covered area is composed of glacial drift.

On the east side of the sandstone, soft, blue-gray shale extends from the lake beach up the lake-cliff, until near the top of the bank the gray shale turns reddish in color. This reddish shale, however, is due to oxidation, for on digging into it, the gray shale is found at a depth of 5 in. from the surface. The red shale is simply oxidized gray shale. The shale is capped by drift, 5 ft. thick.

A concretionary sandstone layer, 1 ft. thick, occurs interbedded in the gray shale at about 20 ft. vertically up the bank when first seen beside the Berea sandstone. The gray shale and the concretionary sandstone layer extend eastward 75 ft. on the horizontal, when they are covered for 125 ft. by drift. At the end of the

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[1] E. M. Kindle, "Stratigraphic Relations of the Devonian Shales of Northern Ohio," *American Journal of Science*, August, 1912, pp. 187–213. For reference to quotation see p. 208.

covered area, the Cleveland appears, forming the customary Cleveland shale lake-cliff. Here, where the cliff is formed of the Cleveland formation, the Cleveland shale is thin-bedded with very fine, knifelike edges, black and brittle. Interbedded in this type of Cleveland shale is a 5-ft. bed of soft, thin-bedded, greenish-gray shale, which resembles closely the gray shale beside the Berea sandstone. This greenish-gray shale of the Cleveland is not the same as the shale beside the Berea sandstone, however, for where last exposed the concretionary layer, above mentioned, at this point 12 ft. vertically above the beach, was dipping eastward toward the greenish-gray Cleveland shale 125 ft. horizontally away. But no sandstone layer occurs in the greenish-gray Cleveland, nor in the black Cleveland, whatsoever. The concretionary sandstone layer ceased to exist when the Cleveland was reached. Hence the two gray shales are not the same.

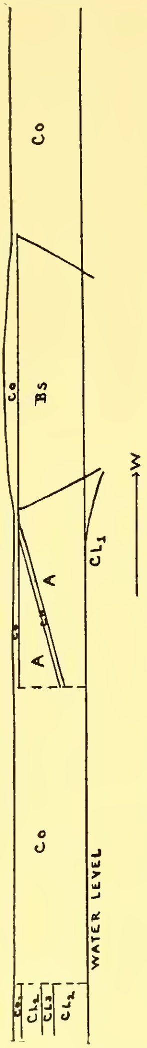

FIG. 1.—Section of channel in Cleveland shale filled with Berea sandstone, on the shore of Lake Erie.

Co=covered area; *A*="alluvial" gray shale; *Cn*=concretionary sandstone; *Bs*=Berea sandstone; Cl_1=black, massive, hard Cleveland shale; Cl_2=black, thin-bedded, brittle Cleveland shale; Cl_3=greenish-gray, soft Cleveland shale.

Horizontal and vertical scales=$\frac{1}{8}$ inch=10 feet.

Going once more back to the Berea sandstone, we find at the water's edge, under the gray shale, a jet black, rather massive Cleveland shale, harder and heavier than the Cleveland shale forming the lake-cliffs to the east. This massive Cleveland shale starting 25 ft. to the east of the Berea sandstone dips westward toward the sandstone at an angle which will cause the base of the Berea to be less than 10 ft. below the surface of the lake at the point where it dips under the water. The Cleveland and Berea are within a few feet of each other when the Cleveland dips beneath the lake under the Berea. No other rock appears to be between the Berea sandstone and the massive Cleveland shale.

The Berea sandstone narrows somewhat in its horizontal dimensions as it descends toward the Cleveland shale beneath. Its sides, though somewhat covered, present the appearance of the sloping sides of a channel, such as is seen where the Berea sandstone fills a channel in the eroded horizon of the Bedford shale. West of the sandstone the lake sands cover the massive Cleveland shale.

One-half mile, slightly to the west of south from this Berea sandstone on the lake shore, gray, moderately coarse-grained Berea sandstone beds one inch to one foot thick outcrop from the bank on the south side of the electric car line. The total height of the exposure is 5–10 ft., and the horizontal distance about 100 ft. The formation is dipping 6 degrees toward S., 18 degrees E., and striking N. 72 degrees E. A few yards to the north, black, thin-bedded Cleveland shale comes to the surface in the ditch beside the New York, Chicago & St. Louis Railroad track. The vertical distance between the Berea and Cleveland outcrops is less than 10 ft. The exact contact is covered.

South of this Berea sandstone outcrop, 100 yds., is an abandoned Berea sandstone quarry, its bottom filled with water and débris. The depth of the sandstone to the water is 20 ft. The pit is about 125 ft. square. The sandstone is gray, moderately coarse grained, beds 8 ft. thick. The top 5–10 ft. of the formation are of thin-bedded sandstone layers, capped by 1–3 ft. of clay. The amount of area underlain by this Berea sandstone appears, from surface indications (for save in the places mentioned the clay drift covers the sandstone), to be 8–10 acres.

Two miles south of this sandstone, along the Lake Shore & Michigan Southern Railroad tracks, the rock is entirely Cleveland shale, and continues to be Cleveland shale until farther south we get the overlying main body of Bedford shale and Berea sandstone. The nearest portion of Berea sandstone to the Berea sandstone in which the quarry is situated, and to that along the lake, is the main body of the Berea formation 2 miles southeast of the quarry, and $2\frac{1}{2}$ miles southeast of the Berea sandstone on Lake Erie.

THE HYPOTHESIS OF FAULTING

Now, if these isolated bodies of Berea sandstone owe their present position to faulting, the downward movement, as measured by present horizons, must have been an approximate vertical displacement of 120 ft., for that is the vertical distance between the base of the nearest portion of the main body of the Berea formation, and the base of the Berea sandstone dipping under Lake Erie. This is a very great throw for this region where all other vertical displacements, as far as the writer is aware, are less than 75 ft. at the most. Also, the presence of several acres of sandstone one-half mile to the south of the sandstone on the lake shore, would hardly have occurred in such quantity through the gentle faulting to which these regions of northern Ohio have been subjected.

BEREA SANDSTONE IN ERODED CLEVELAND SHALE

The writer advances the following theory for the formation of these isolated and most northerly bodies of Berea sandstone: At the same period when the deep channels in the Bedford shale of the Amherst district, 5½ miles to the southeast, were being cut, a stream, as shown by the exposed gray shale and Berea sandstone, cut a channel 175 ft. wide (and without doubt a far greater width could be proven if the outcrops were not covered) into the Cleveland shales.

The Cleveland shale of this district was thus a land area at probably the same time that the Bedford to the south was above the level of the sea. When deposition took the place of erosion, alluvial sediments were deposited in this channel in the Cleveland shale. These sediments later formed the soft gray shale, previously described. The concretionary sandstone bed was laid down at the time these alluvial gray sediments were deposited. As occurs in certain of the Bedford channels, the deposited material slumped toward the sides of the channel, which accounts for the dip of the concretionary sandstone bed toward the Cleveland shale which formed the side of its channel.

Later, the soft alluvial material was worn away to some extent and the Berea sands deposited in the channel thus formed. The slanting side of the Berea sandstone at its contact with the gray shale of the present day marks the side of this old channel.

THE BEDFORD-BEREA UNCONFORMITY AND THE DEVONIAN-CARBONIFEROUS LINE

Some geologists have questioned the erosion of the Bedford formation prior to the deposition of the Berea, as being of much value in determining the position of the Devonian-Carboniferous line. They argue that the time would be very short indeed, geologically, in order that the soft Bedford shale might be worn away to the extent which we find it, and that the cycle of erosion would therefore be of very slight importance.

Hence, an eroded channel in the Cleveland shale of the magnitude of the one described should help to show that the period of erosion of the Bedford was of much longer duration than was to be inferred by the channels in the soft Bedford shale, for the rather hard Cleveland shale is not especially easy to erode. The time required in the removal of the Cleveland would be far greater than that required in any of the Bedford channels.

Therefore, the interval of erosion of the Bedford prior to the Berea deposition was of greater length than has been shown by any other evidence set forth up to the present time.

Consequently, the Berea sandstone filled channel in the eroded horizon of the Cleveland shale acts as evidence in favor of placing the Devonian-Carboniferous line between the Bedford and Berea formations.

THE AVERAGE IGNEOUS ROCK

W. J. MEAD
University of Wisconsin

The chemical composition of the average igneous or crystalline rock of the earth's crust is of sufficient interest to geologists and petrographers to have elicited several attempts at compiling average analyses. Clarke[1] summarizes the three most important averages of igneous rock analyses—those by Clarke, by Harker, and by Washington. These averages agree fairly well, showing very small differences in the amounts of the various oxides, and there is little to be said of the relative merits of the three determinations.

One question, however, has been repeatedly raised, i.e.: Does the average of all igneous rock analyses represent with any degree of certainty the actual average of the igneous rocks of the earth's shell? Obviously, if the average analyses of Clarke, Harker, and Washington are to represent correctly the composition of the igneous rocks of the earth's crust, it is necessary that the samples of the various types of igneous rock be proportional to the amounts of these several types in the earth's crust. If not, these average analyses are misleading.

In the course of certain investigations in the Metamorphic Laboratory at the University of Wisconsin, the writer has attempted to check Clarke's average igneous rock by comparing it with the composition of the sediments, and the results obtained are thought to be of sufficient interest to warrant their presentation here.

If we are correct in the assumption that the oxides of the bases and the silica of the sediments have as their ultimate source the igneous rocks, then a properly weighted average of the sediments (excluding water and carbon dioxide) would represent very closely the average composition of the igneous rocks from which these sediments were derived. Certain discrepancies are to be expected

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[1] F. W. Clarke, "Data of Geochemistry," *U.S. Geol. Survey, Bull. 491*, 1911.

owing to the segregation of certain constituents, such as the mineral matter in the sea and certain mineral deposits not included in the sedimentary rocks. The solution of this problem was attempted by the writer and the results published in this journal.[1]

The former problem may be briefly stated as follows: given, the average composition of the igneous rocks and of the shales, sandstones, and limestones; to find the relative abundance of these three important types of sediments. The present problem, while somewhat similar, differs materially, and may be stated as follows: assuming that the average igneous rock may be closely approximated in composition by some combination of average granite and average basalt, what ratio of granite to basalt best explains the composition of the sediments as expressed by average analyses of the shales, sandstones, and limestones, respectively; and simultaneously with this solution, what ratio of shale, sandstone, and limestone would result from the redistribution of this combination of granite and basalt? The above might be stated in the form of an equation as follows:

> x granite$+y$ basalt$=a$ shale$+b$ sandstone$+c$ limestone, given average analyses of granite, basalt, shale, sandstone, and limestone to solve for x, y, a, b, c.

Note that no assumption is made as to the relative abundance of shale, sandstone, and limestone, and that the solution of the problem is based in no way on the results previously obtained[2] *or on any assumption as to the average composition of the igneous rocks.* The data used in this problem are given in Table I. The average granite and average basalt, columns 1 and 2, are those compiled by Dr. Daly.[3] The average analyses of the shales, sandstones, and limestones, respectively, are those compiled by Clarke.[4] Since the water and carbon dioxide of the sediments are for the most part derived from the hydrosphere and atmosphere, it is necessary in this problem

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[1] W. J. Mead, "Redistribution of Elements in the Formation of Sedimentary Rocks," *Jour. Geol.*, XV (1907), 238–56.

[2] W. J. Mead, *op. cit.*

[3] R. A. Daly, "Average Chemical Compositions of Igneous-Rock Types," *Proc. Amer. Acad. Arts and Sciences*, XLV (1910), 211–40.

[4] F. W. Clarke, *op. cit.*, p. 28.

to recalculate the analyses of the sediments, excluding these constituents. The analyses of the igneous rocks are recalculated on a water-free basis. Since the problem does not permit of a rigorous solution, graphic methods have been used which permit of viewing in perspective, as it were, the various relations and conceptions involved.

TABLE I

	1	2	3	4	5	6	7	8
SiO_2	70.47	49.65	58.38	64.00	78.66	83.95	5.19	9.02
Al_2O_3	14.90	16.13	15.47	16.94	4.78	5.10	.81	1.41
Fe_2O_3	1.63	5.47	4.03	4.42	1.08	1.15	.54	.94
FeO	1.68	6.45	2.46	2.69	.30	.32		
MgO	.98	6.14	2.45	2.68	1.17	1.25	7.90	13.74
CaO	2.17	9.07	3.12	3.42	5.52	5.90	42.61	74.10
Na_2O	3.31	3.24	1.31	1.43	.45	.48	.05	.09
K_2O	4.10	1.66	3.25	3.56	1.32	1.41	.33	.57
TiO^1	.39	1.41	.65	.71	.25	.27	.06	.10
P_2O_5	.24	.48	.17	.19	.08	.085	.04	.07
Totals	99.87	99.70	91.29	100.04	93.61	99.915	57.53	100.04
Fe	2.45	8.86	....	5.19	....	1.055	....	.66

1. Average granite.
2. Average basalt.
3. Average shale.
4. Average shale recalculated to 100 per cent, omitting H_2O and CO_2.
5. Average sandstone.
6. Average sandstone recalculated to 100 per cent, omitting H_2O and CO_2.
7. Average limestone.
8. Average limestone recalculated to 100 per cent, omitting H_2O and CO_2.

Trilinear co-ordinates are used in Fig. 1; the triangle labeled in the corners "Shale," "Limestone," and "Sandstone," respectively, serves as a base on which ratios of these three components may be indicated by points, and a series of ratios represented by lines. The algebraic sum of the perpendicular distances from any point inside or outside of the triangle to the three sides of the triangle or their extensions equals the altitude of the triangle, considering distances toward the opposite apex as positive, and distances away from the opposite apex as negative. *Any point on the dotted line labeled "SiO_2, Gr." represents in parts per hundred the ratio in which shale, sandstone, and limestone may be combined to yield the same amount of silica as the average granite.* This line is obtained by finding the proportion in which sandstone and limestone combine to yield the same percentage of silica as the average granite, and also the proportion in which shale and limestone combine to the same end. These points platted on the sides of the triangle determine the line. In a similar manner lines are drawn for the various oxides[1] for both the average granite and the

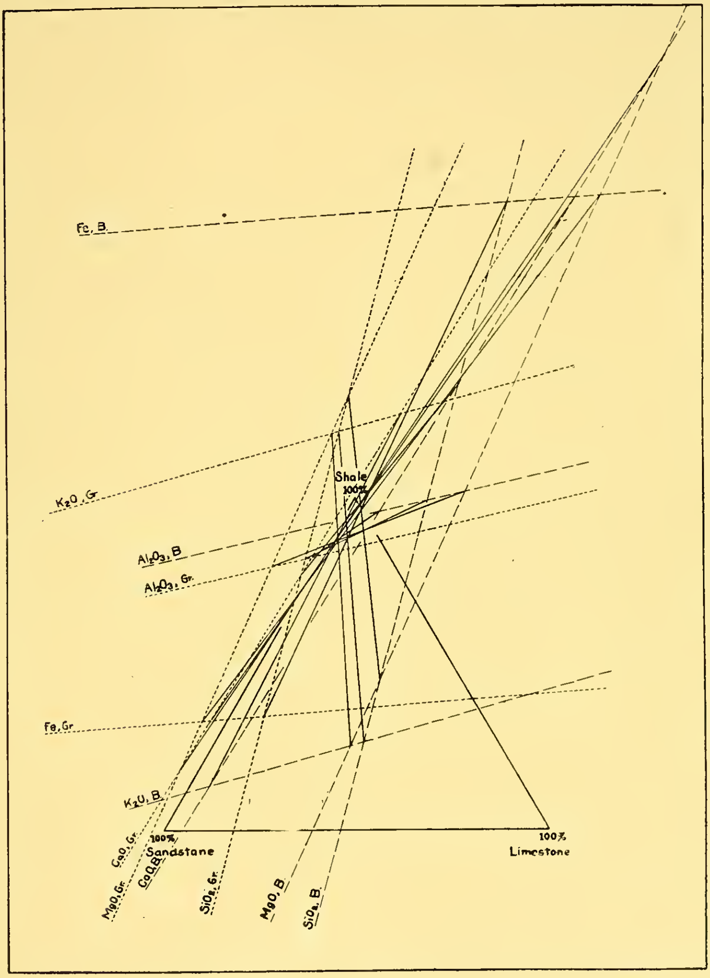

FIG. 1.—Graphical expression of the relations of any combination of granite and basalt and the ratios of sediments derived from them.

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[1] Iron is calculated as total Fe, the oxides not being considered separately.

average basalt. The very low soda content of the sediments due to the segregation of that constituent in the sea causes the soda line to fall too far outside the triangle to be shown. If the sediments were derived from the average granite, the lines of the several oxides would come very close to intersecting at a point, but since this is not true, the lines for granite are widely distributed and their intersections fall over a wide area. This is likewise true of the basalt lines.

The point of intersection of the dotted silica and alumina lines indicates the ratio of shale, sandstone, and limestone containing the same amount of silica and alumina as the average granite. Similarly the intersection of the broken silica and alumina lines indicates the ratio of shale, sandstone, and limestone containing the same amount of silica and alumina as the average basalt. *The line connecting these two points of intersection is the locus of the intersections of the silica and alumina lines for any combination of granite and basalt.* In this manner lines connecting similar intersections of granite und basalt lines have been drawn. *If the sediments were derived from some combination of granite and basalt, these lines connecting intersections should intersect at a common point.* However, because of the nature of the data, we may expect at best that these lines will intersect within a small area. An examination of the diagram, Fig. 1, shows that this is exactly what happens; i.e., there is a distinct tendency for these lines to converge and intersect within a limited area. If the lines connecting intersections crossed each other at a common point, the ratio of granite to basalt would be measured by the ratio of the distances from the point of intersection to the "granite" and "basalt" ends of the lines respectively.

In order to determine whether there is any tendency toward the expression of a definite ratio of granite to basalt by the grouping of the points of intersection on each of the several connecting lines, these lines have been transferred from Fig. 1 to Fig. 2, where by means of a proportional triangle each line is automatically divided into ten equal parts. The points of intersection of any line with the other lines are marked by short lines crossing the line considered. Inspection of the proportional triangle on which these lines have been placed shows that there is marked uniformity in the ratio of granite to basalt, as expressed by the positions of intersection on these several lines. The average of the ratios expressed by the points of intersection on each line has been indicated by a large dot near the line, and the positions of these dots on the scale of the proportional triangle show a distinct concordance. By averaging the ratios expressed by the dots on the several lines, the average ratio of granite to basalt is found to be 65 parts granite to 35 parts basalt, i.e., this is the proportion of granite to basalt which may be most closely approximated by some combination of derived sediments represented by their average analyses here employed.

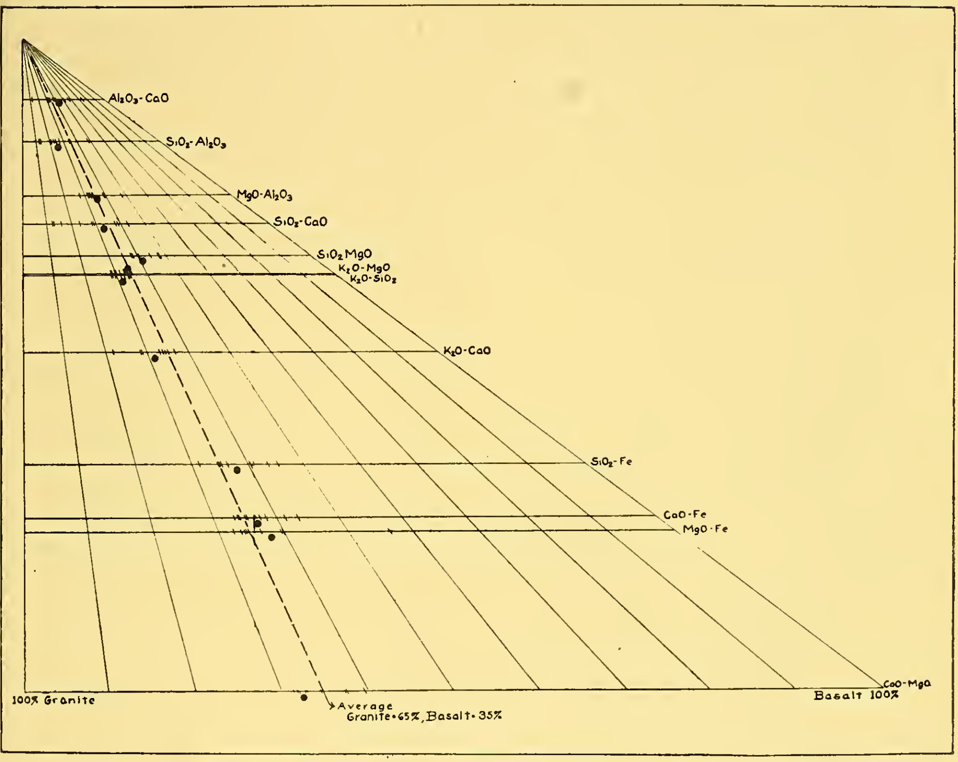

FIG. 2.—Proportional triangle used as a scale on which to measure the granite-basalt ratios expressed by the position of intersections on the full black lines in Fig. 1.

This solution assumes that the average analyses of granite, basalts, shales, limestones, and sandstones used are approximately correct, and that the average igneous rock may be represented by some combination of granite and basalt. So far as these assumptions are not true, solution fails, but the fact that the graphical method admits of selecting a definite ratio of granite and basalt and that this ratio yields an average so similar to the average for the igneous rock obtained by Clarke and others seems to indicate that the data and assumptions are not in serious error.

In Table II, column 1 is the average analysis obtained by combining the average granite and the average basalt in this ratio. For purposes of comparison the average analyses of igneous rocks obtained by Clarke, Harker, and Washington are placed in parallel columns.

TABLE II

	1	2*	3	4	5*	6*
SiO_2	62.18	61.82	+1.36	+2.2	60.76	58.96
Al_2O_3	15.35	15.51	− .16	−1.03	15.87	15.99
Fe_2O_3	2.97	2.67	+ .20	+ 7.5	4.92	3.37
FeO	3.35	3.45	− .10	− 2.9	2.78	3.93
MgO	2.79	4.02	−1.23	−30.5	3.82	3.89
CaO	4.58	4.96	− .38	− 8.45	4.97	5.28
Na_2O	3.28	3.51	− .23	− 6.5	3.28	3.96
K_2O	3.24	3.04	+ .20	+ 6.6	2.85	3.20

* F. W. Clarke, *op. cit.*, p. 25.

1. Average granite and average basalt, combined in ratio of 65 to 35.
2. Clarke's average igneous rock.
3. Differences between 1 and 2, on basis of total rock.
4. Differences between 1 and 2, in percentage for each constituent.
5. Harker's average igneous rock.
6. Washington's average igneous rock.

The differences between column 1 and the three average analyses of igneous rocks are small. The differences between column 1 and Clarke's average igneous rock are expressed in terms of the entire rock and in percentage of each constituent in columns 3 and 4 respectively. The most striking result of the comparison is the marked similarity between the combined granite and basalt and the average analyses. The greatest differences are for silica and magnesia, the combination of granite and basalt being slightly more acidic than the other averages.

The most important conclusion is that the average analyses of Clarke, Harker, and Washington are closely checked by this method, and that of the three analyses Clarke's average is most closely approximated. The nature of the data obviously does not permit of drawing any definite conclusions as to the cause of the slight differences between Clarke's averages and the averages here obtained.

The greatest difference occurs for MgO, the combined granite basalt showing 30.5 per cent less MgO than Clarke's average. This difference is so much greater than for any of the other oxides that it may be of significance. It is possible that igneous rocks collected largely for petrographic purposes would include the unusual and interesting alkaline and ultra-basic types, the syenites, peridotites, etc., in an amount out of proportion to their abundance as compared with the more common granite and basalt types. The alkalies, lime, silica, and alumina would not be materially affected by this, as the alkaline rocks would offset the basic varieties, but the range of MgO content being much greater (varying from 1 per cent or less in the alkaline rocks to 30–40 per cent in the peridotites), this oxide would tend to be increased by the inclusion of an excess of the less common rocks.

Ratio of shale, sandstone, and limestone.—The foregoing solution, while yielding rather definitely the ratio of granite and basalt best explaining the composition of the sediments, simultaneously yields the ratio of shale, sandstone, and limestone resulting from the redistribution of this hypothetical average igneous rock. In Fig. 3 the lines for the several oxides were obtained by drawing lines parallel and between the granite and basalt lines on Fig. 1, at distances representing the 65–35 ratio. These lines in Fig. 3 intersect within a small area and a point at the center of this area expresses a ratio of 88 parts shale, 9 parts sandstone, and 3 parts limestone. Since water and carbon dioxide were excluded from the analyses of the sediments in obtaining these ratios, it is necessary to recalculate to include these constituents, which gives 87 parts shale, 8 parts sandstone, and 5 parts limestone. This ratio differs from the ratio of 80:11:9 previously obtained by the writer,[1]

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[1] W. J. Mead, *op. cit.*

by showing more shale, less sandstone, and less limestone, but in a general way is similar in showing the great predominance of shale over the other two sediments.

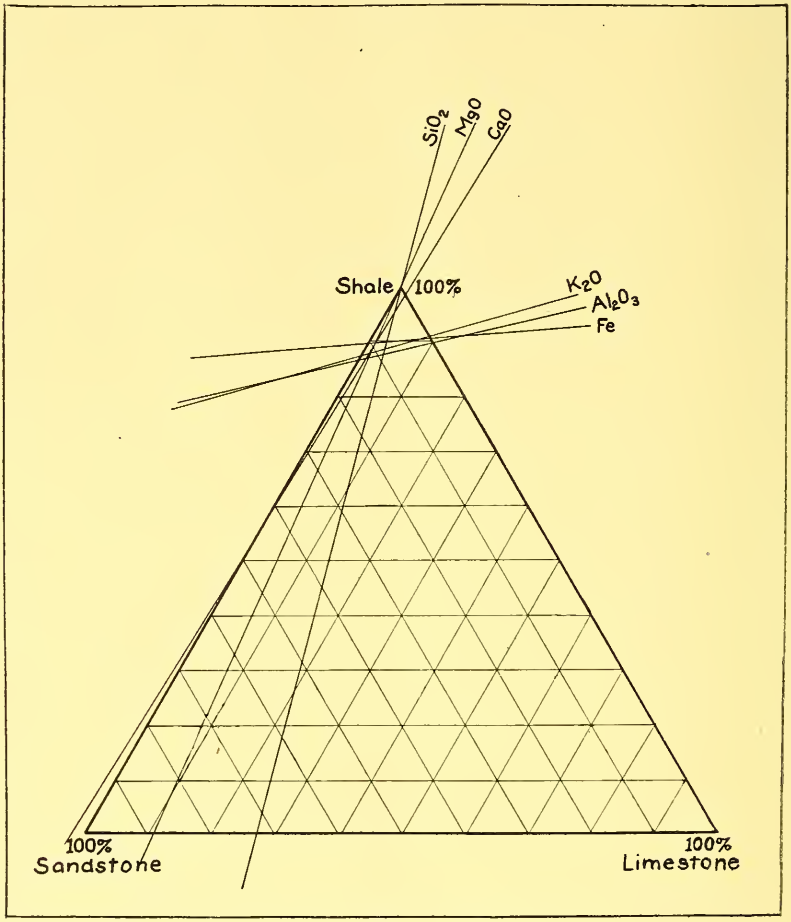

FIG. 3.—The lines on the triangle show for each constituent the proportions in which the three sediments combine to yield the same amount of that constituent as the combination of 65 parts granite and 35 parts basalt. Compare with Fig. 4.

A further comparison of the combined granite and basalt with Clarke's average igneous rock is afforded by comparing Fig. 4 (which represents for Clarke's average exactly what Fig. 3 represents for the combined granite and basalt) with Fig. 3. The lines in Fig. 3 intersect within a much smaller area than in Fig. 4, which is simply another way of expressing the closer accordance of the granite basalt average with the sediments as compared with Clarke's.

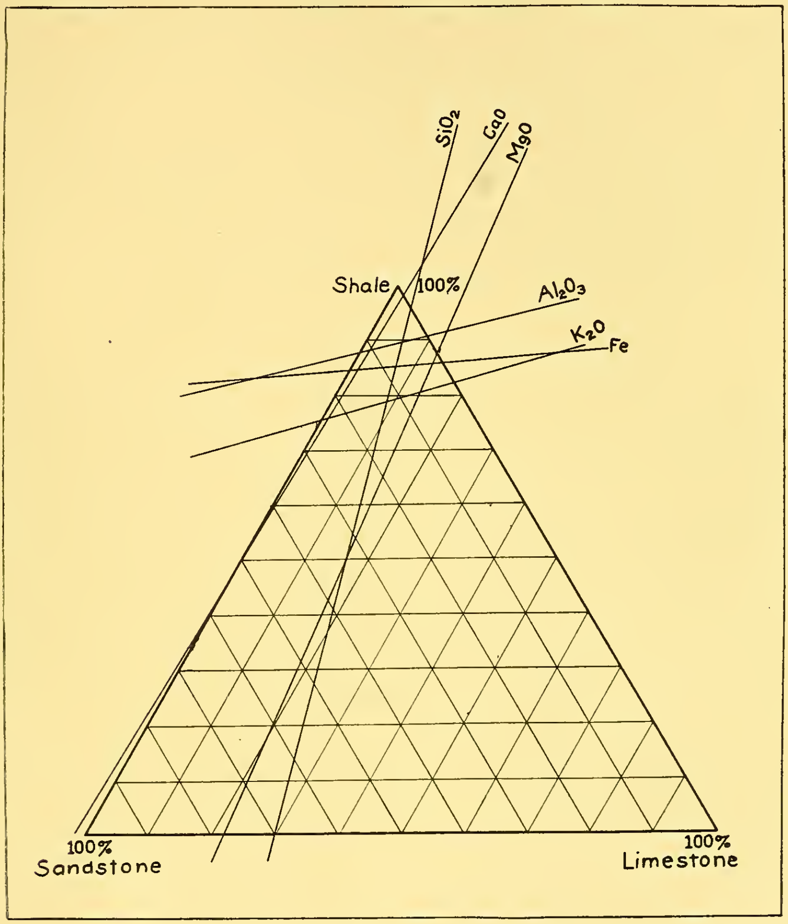

FIG. 4.—The lines on the triangle show for each constituent the proportions in which the three sediments combine to yield the same amount of that constituent as Clarke's average igneous rock. Compare with Fig. 3.

EOCENE HORIZONS OF CALIFORNIA

CLARENCE A. WARING
California State Mining Bureau, San Francisco

During the past few years geologists of California have been devoting considerable attention to the Eocene, with the result that three horizons are now recognizable. In order of their deposition these are the Martinez, Tejon, and Ione formations.

MARTINEZ FORMATION

The Martinez formation has so far been found in the Mt. Diablo region, Contra Costa County; in the Santa Monica Mountains, northwest of Los Angeles; and on the west side of the Santa Ana Mountains. It is characterized by sandstones and shales, not unlike those of the Chico (Upper Cretaceous) formation, and by a fauna strikingly similar to those of the eastern Midway formation, with which it is to be correlated. In the Santa Monica Mountains it is characterized by *Venericardia planicosta* var. *venturensis* var. nova, which is similar to *V. planicosta* Harris.[1] Several other new species have also been found, the most characteristic of which here described are from the Santa Monica Mountains.

Crassatellites branneri n.sp.—Shell about 55 mm. high, trigonal, slightly longer than high; beaks subcentral, prominent, deeply excavated front and back, incurved, with sides sloping equally and rapidly, most abrupt in advance, slightly convex behind; lunule cordate; anterior end broadly rounded; posterior truncated and flattened from the umbonal ridge to the cardinal and posterior margins. Surface marked by lines of growth and fine radiating lines which are especially apparent in worn specimens. Leland Stanford Junior University Paleontological Collection. Named in honor of Dr. J. C. Branner.

Lima perrini n.sp.—This giant circular lima has a thick shell with nacreous, and outer prismatic layer. The diameter is about

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[1] *Bull. Am. Pal.*, No. 4, p. 58, Fig. 13.

160 mm. The umbones are small and the cardinal margin slopes gradually to the posterior where it becomes rounded and grades into the circular margin below. The beaks are slightly excavated in front, and the margin slopes at a 35-degree angle into the rounded anterior margin. The hinge is very thick and has a deep wedge-shaped ligament pit sloping from the interior edge of the shell to the exterior edge at the anterior end of the hinge line. A single large sub-posterior muscle impression marks the interior of the shell. The surface is ornamented by many fine radiating lines, and the prismatic shell layer gives the surface a silken appearance. It belongs to the subgenus Acesta. Leland Stanford Junior University Paleontological Collection. Named in honor of Dr. J. Perrin Smith of Stanford University.

Pseudoliva reticulata n.sp.—Shell subconical, whorls four, spire low, suture linear. Altitude 20 mm., width 12 mm. Inner whorls almost covered by body whorl, which is concave. Aperture wide, posterior angular, anterior produced slightly into a canal. Outer lip simple, inner lip incrusted and marked by a fold revolving from the end of the canal around to the inner lip, representing the former positions of the end of the canal. Surface ornamented by longitudinal folds and spiral ribs; where these intersect, small tubercles develop. The middle of the body whorl is impressed by a single revolving line which forms a tooth where it is truncated on the outer lip. Leland Stanford Junior University Paleontological Collection.

Turritella maccreadyi n.sp.—Shell robust, apical angle broad; whorls eleven, rounded, with six or seven strong, nearly equally spaced, spiral ribs. The first five or six whorls are angulated like *T. martinezensis* Gb.[1] Surface below body whorl also ornamented by spiral lines, and whole surface marked by lines of growth. Aperture broad, outer lip slightly sinuous; inner lip sinuous, flattened, and twisted. Leland Stanford Junior University Paleontological Collection. Named in honor of Mr. George McCready of Guanoco, Venezuela.

Nautilus hallidayi n.sp.—Shell immense, being about 36 mm. in greatest diameter. The inner whorls are completely enveloped,

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[1] *Geol. Surv. of California*, Paleontology, Vol. II, p. 169, Pl. 28, Fig. 51.

while the last whorl is more evolute. Dorsum rounded. Aperture elliptical, concave below where it envelops the early coils. The outer volution has a width slightly less than the remaining diameter of the shell. Sutures slightly inflected. Shell pearly. It is probably the oldest species of true nautilus known. Leland Stanford Junior University Paleontological Collection. Named in honor of Mr. T. W. Halliday of Spokane, Washington.

TEJON FORMATION

The Tejon formation occurs principally in Kern, Santa Barbara, Ventura, and Los Angeles counties, with a fringe along the eastern flank of the southern end of the Mt. Diablo Range. Smaller patches outcrop near the coast north of San Diego and in the Santa Ana Mountains. The formation consists of conglomerates, sandstones, and shales, and faunally is characterized by *Turritella uvasana* Conrad, *Morio tuberculatus* Gb., and *Venericardia planicosta* var. *horni.* Gb., which is very similar to *V. planicosta* var. *regia* Conrad of the Aquia formation of Maryland. Several new species have been found, the most striking among which are the following:

Cucullaea morani n.sp.—Shell thick, oblique, very convex; beaks large, broad, prominent, and about one-third the distance from the anterior, incurved and somewhat remote; area oval in shape and about two-thirds the length of the shell. Altitude 36 mm.; longitude 60 mm. Anterior margin broadly rounded and more prominent above; base nearly straight; posterior produced and sharply rounded; umbonal ridge prominent and runs to posterior margin; cardinal margin sloping at an angle of about 45 degrees. Surface marked by alternating single and double radiating ribs which are crossed by fine to coarse lines of growth. Locality one and one-half miles east of McCray Wells, Ventura County. Specimens in Leland Stanford Junior University Paleontological Collection. Named in honor of Mr. R. B. Moran of San Francisco.

Isocardia tejonensis n.sp.—Shell of medium size, thin; valves equal, inflated, rotund, completely closed, margins plain; beaks prosogyrous. Surface marked by concentric bandlike ribs, which become fine and nearly obsolete on the beaks. From one and one-half miles east of the McCray Wells, Ventura County. Specimens in Leland Stanford Junior University Paleontological Collection. This is the first species of *Isocardia* described from the Eocene of California.

Pinna lewisi n.sp.—Shell thin, pearly, mytiliform, equivalve, truncate, and wholly open behind, hinge line long; valves triangular, the apical angle being about 45 degrees; convex along the center line and flaring at the margins. Base of shell notched in the middle and convex on either side. Surface marked by five indistinct radiating ribs and concentric lines of growth. From one and one-half miles east of McCray Wells, Ventura County. Specimen in Leland Stanford Junior University Paleontological Collection. Named in honor of Mr. J. O. Lewis of San Francisco.

IONE FORMATION

The Ione formation is typically represented on the east side of the San Joaquin Valley, extending from a point twenty miles east of Merced to a point forty miles south of Auburn. It is to be correlated with the marine Eocene sediments of Corral Hollow, those in the northern part of the Mt. Diablo Range, and with those on the eastern flank of the St. Helena Range. The formation is characterized by clayey shales and sandstones and by such fauna as *Turritella merriami* Dickerson[1] and *Venericardia planicosta* var. *ionense* var. nova, which is similar to *V. marylandica* Harris[2] and *V. potopacoensis* Harris.[3] The formation is probably to be correlated with the Nanjemoy, which, it is thought by Harris, ranges higher than Chickasawan and Upper Lignitic.

The three horizons each have typical faunas among which the *Venericardia* and *Turritella* are represented by very characteristic species. The evolution of *Venericardia planicosta* Lamarck seems to have been from a square-ribbed variety to one with broad, rounded ribs, and then finally to a smooth form. Conditions were favorable for its more rapid evolution during the Tejon period and a wide range of variation is noted.

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[1] *Bull. Dept. Geol., Univ. of Calif.*, Vol. VII, No. 12 (April, 1913), p. 284, Pl. 13, Fig. 6.

[2] *Maryland Geol. Surv.*, "Eocene," pp. 178–79, Pl. XI, Figs. 4–7.

[3] *Ibid.*

CONTEMPORANEOUS DEFORMATION: A CRITERION FOR AQUEO-GLACIAL SEDIMENTATION

FREDERIC H. LAHEE
Massachusetts Institute of Technology

Previous records of deformation in unconsolidated strata.—Deformation in unconsolidated strata has been observed and recorded by many writers on geological subjects. Faults having a displacement ranging from a fraction of an inch to a few feet are often seen in sections of glacial sandplains, eskers and kames, and in river terrace deposits.[1] Being due probably to removal of some lateral or subjacent supporting material, these faults are nearly always of the normal type. Folds in unconsolidated sediments are of much less common occurrence. J. B. Woodworth has figured and described such deformation in the kame gravels west of Fresh Pond, in Cambridge, Massachusetts.[2] These folds, having a height of as much as 10 feet, were overturned southward in a way to indicate that they had been formed by the thrust of a readvancing ice lobe. The same features were described a few years earlier by Woodworth and Marbut.[3] Similarly, contortion in the Columbia formation on Martha's Vineyard and Block Island has been ascribed to the pressure exerted by overriding Pleistocene ice.[4]

In all the instances noted above the deformation was in no way associated with the deposition of the beds. It was distinctly subsequent in point of origin. In the pages that follow is described a

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[1] The present writer described one good example of this phenomenon several years ago (*Science* [IV], XXVIII [1908], 654).

[2] *Essex Institute Bull.*, XXIX (1898), 71.

[3] *U.S. Geol. Survey, Ann. Rept. 17* (1896), Pt. 1, p. 990.

[4] J. B. Woodworth, "Unconformities of Martha's Vineyard and of Block Island," *Bull. Geol. Soc. Am.*, VIII (1897), 197–212; "Glacial Origin of Older Pleistocene in Gay Head Cliffs . . . . ," *ibid.*, XI (1900), pp. 455–60. Shaler, at an earlier date, believed these folds were of orogenic origin. See, e.g., his "Report on the Geology of Martha's Vineyard," *U.S. Geol. Survey, Ann. Rept. 7* (1888), p. 345; and his "Tertiary and Cretaceous Deposits of Eastern Massachusetts," *Bull. Geol. Soc. Am.*, I (1890), 446–47.

kind of distortion, which is believed to have been contemporaneous with the accumulation of the strata.[1]

The Squantum slates described.—On the eastern coast of Squantum Head, in Boston Harbor, Massachusetts, is a series of slates overlying the Squantum tillite.[2] The formation is of late Carboniferous or of Permian age. The slates are very fine-grained

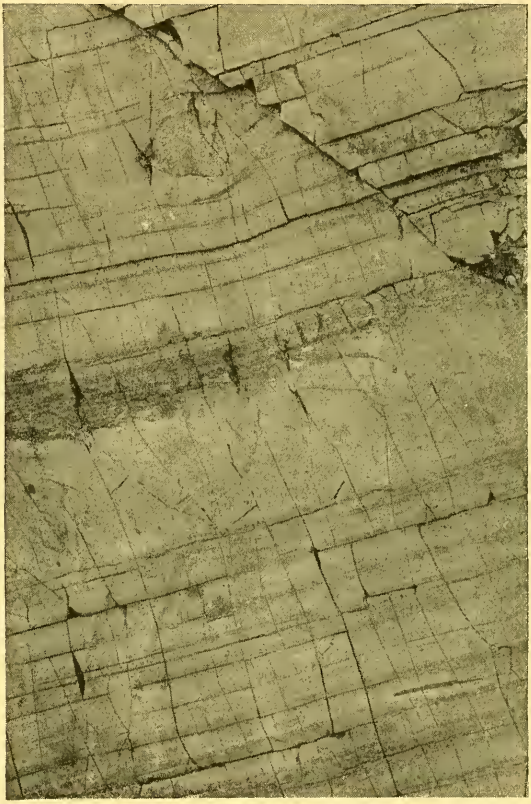

FIG. 1.—The Squantum banded slates. Near the middle of the picture is a zone in which the strata have been closely folded. Above this zone may be seen an isolated pebble, about three inches in diameter, which is thought to have been dropped by floating ice.

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[1] The same type of distortion was described by James Geikie in clay beds overlying till at Portobello, Scotland; see his *Great Ice Age* (3d ed., New York, 1895), pp. 271–74.

[2] R. W. Sayles, "The Squantum Tillite," *Bull. Mus. Comp. Zoöl.*, LVI, No. 2 (1914), 141–75.

sandstones and coarse and fine mudstones. These variations in texture are frequent, thus giving rise to a very uniform, closely spaced bedding lamination or banding (see Fig. 1). The strata have a pretty regular southeastward dip of 20°–25°. Minor undulations are seen here and there, but these are easily recognized as of orogenic origin and were no doubt formed at the same time with the larger deformation of which the inclination of the beds is evidence.

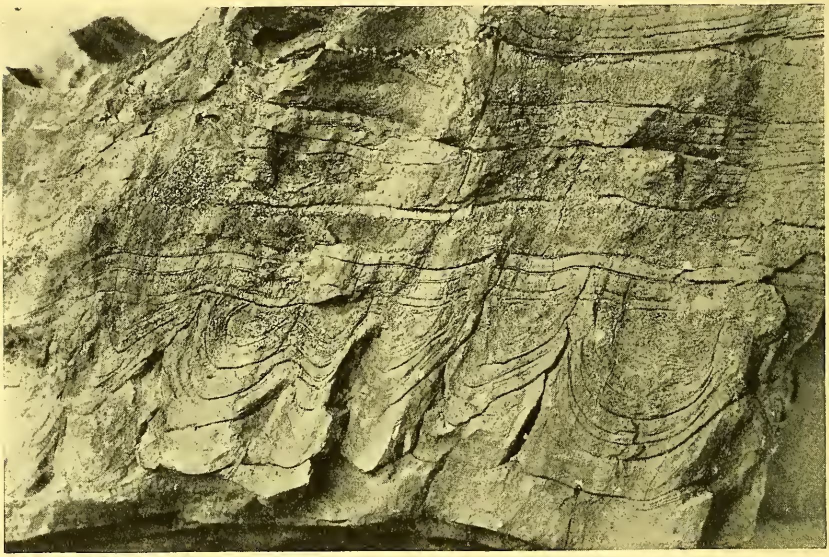

FIG. 2.—Hand specimen of the truncated folds seen at Squantum. Here the folds are not very strongly overturned. The length of the specimen illustrated in the figure is about eight inches.

At several stratigraphic levels in the series, at intervals of a few feet, are belts or zones in which the primary banding has been compressed into small folds (Fig. 1). Downward in the strata these folds diminish in size until they disappear, i.e., they grade into unfolded beds (Fig. 2). Above, they are sharply truncated by beds of similar nature, which have not been distorted. The little folds are all overturned in the same direction. Sometimes the overturning is slight, as in the figure. At other times the overturning may actually pass into overthrust faults having a displacement of an inch or two. Zones showing this sort of distortion are not at all uncommon in the finer clastics of Squantum Peninsula.

Inferences as to the origin of the Squantum slates.—The characters of the Squantum slate series suggest the following conditions of origin: (1) Muds and silts were quietly accumulated in a body of water practically unaffected by currents, or, at least, by changing currents. (2) Occasionally a rigid body, submerged deep enough to touch bottom in places, floated by and here and there rubbed over the soft deposits, crumpling them and scraping off the crests of the folds. (3) After the disturbing agent had passed, quiet deposition continued as before.

FIG. 3.—Contemporaneous deformation seen in unconsolidated sand at Woodland. The folds are truncated and overlain by horizontal strata as at Squantum. The photograph does not show the truncated portion of the folds because the beds are of very nearly the same texture at and near the surface of contemporaneous erosion. In the field, however, the relations are clear. The figure illustrates a section about twenty inches long.

In his visits with field classes to Squantum the writer was impressed by this peculiar phenomenon several years ago and he explained it as possibly due to floating blocks of ice. Corroborating this hypothesis is the presence of occasional isolated pebbles and bowlders inclosed in the evenly banded slates (Fig. 1). These were thought to have been carried by the floating ice-blocks, and to have dropped as the ice melted. Mr. R. W. Sayles's study of the tillite of Squantum, cited above, is also confirmatory evidence.

The Auburndale deposits described.—Last November, at Auburndale, Massachusetts, the writer came upon a beautiful exposure of a structure exactly resembling the Squantum zones of deformation, but this time in unconsolidated deposits of a Pleistocene sand plain, (Fig. 3). The structure was seen in a sand pit. The deposit consists of fine and coarse sand and some clay, all regularly stratified with frequent variations in texture. As at Squantum, the zones are repeated at several stratigraphic levels and with no definite spacing or order. Here, then, is an example of aqueous deposition undeniably associated with glacial action. The likeness between the two cases is highly significant, particularly as regards the origin suggested.

Definition.—The relations described above are those of local unconformity associated with deformation of the upper layers of the subjacent strata. The structure is really *local angular unconformity*. Since erosion producing local unconformity is often called *contemporaneous erosion*, we may term the folding and faulting resulting from such erosion *contemporaneous deformation*.

PROBLEMS OF PETROGRAPHIC CLASSIFICATION SUGGESTED BY THE "KODURITE SERIES" OF INDIA[1]

WHITMAN CROSS
U.S. Geological Survey

INTRODUCTION

Petrographic classification has often been retarded or sent on the wrong course, for a time, by the repeated failure of petrographers, often those of deserved reputation as investigators, to observe some broad principles of systematic classification. A petrographic system which is to endure must surely be constructed with the aid of generalizations or other factors which are widely applicable to the rocks of the earth. Premature generalizations have always proved harmful when introduced into system, however helpful they may have been in their proper places, as aids in the study of particular problems. Broad system expresses general relationships of certain kinds, but many systematic propositions or criticisms are made with a desire to emphasize the peculiarities of the rocks of a locality, a district, or, at most, a province. I desire to offer a few observations on this last point apropos of a recent discussion by L. L. Fermor, and this leads to some comments on the classification of igneous rocks contained in Hatch's well-known *Textbook of Petrology.*

A recent publication by Fermor,[2] referring to both local and general problems of petrographic classification, raises a number of questions of more than passing interest. Certain manganiferous rocks of India called the "Kodurite Series" are believed by Fermor to be "a series of differentiated igneous rocks ranging in acidity from quartz-orthoclase rock, through intermediate quartz-kodurites

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[1] Published by permission of the Director of the U.S. Geological Survey.

[2] L. Leigh Fermor, "The Systematic Position of the Kodurite Series, Especially with Reference to the Quantitative Classification," *Records, Geol. Survey of India,* XLII, Pt. 3 (1912), 208–30, Calcutta.

and basic kodurites, to manganese-pyroxenites containing rhodonite and other manganese pyroxenes."[1] The kodurite proper is a rock now much decomposed, but assumed to have consisted of orthoclase, a manganiferous garnet, and apatite. Opal now takes the place of the supposed orthoclase.

What are considered to be difficulties in the way of classifying the kodurite and other highly manganiferous rocks in the Quantitative System lead Fermor to conclude that it fails in several respects when applied to such rocks or to possible ones rich in nickel, barium, strontium, or lime. On the other hand, it is said that classification of the kodurite and other rare rocks by Hatch's system is eminently satisfactory.

The evident fairness with which Fermor has essayed the classification of the kodurite rocks in the Quantitative System relieves his discussion, in most respects, from the charge of controversial tone, notwithstanding his very evident prejudice against some features of that system. The problems presented by such rocks are real ones and must be solved if manganese-rich igneous rocks occur, but there is a point of view from which the result reached by Fermor is very much more satisfactory than it seems to him, as will appear in the following discussion.

THE CHARACTER OF THE KODURITE SERIES

The rocks of the Kodurite Series were specially described by Fermor[2] some years ago. They occur in the Archean Complex of the coastal plain belt of the Madras Presidency about midway between Madras and Calcutta. In view of the importance of this series, if of igneous character, it is necessary to point out at once that this character is by no means self-evident, and that much further proof than that offered by Fermor is necessary before geologists unfamiliar with the occurrence can be expected to accept the view of their igneous origin.

The kodurite rocks occur in a lowland zone of poor exposures, the best being in the manganese mines where the secondary oxi-

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[1] L. Leigh Fermor, *op. cit.*, p. 208.

[2] L. Leigh Fermor, "On the Manganese Deposits of India," *Memoirs, Geol. Survey of India*, XXXVII, Pt. 2 (1909), "Geology," 243–79, Calcutta.

dized decomposition products are exploited. They appear in association with metamorphosed sedimentary rocks of the Khondalite Series, other metamorphosed sediments, rich in garnet, called "calc gneisses," a gneissose granite, and the Charnockite Series, the last two being considered of igneous origin. Fermor points out the banded arrangement of all the rocks, the absence of contacts showing intrusive relations, and the closer association of the Kodurite Series with the metamorphics than with the igneous Charnockite Series. The only cited occurrences thought by Fermor to indicate intrusive character are in two sections, five miles apart, in which the manganese rocks occupy different relations in metamorphic zones which appear to be made up of the same elements.

The principal feature of the rocks interpreted as favoring the hypothesis of their magmatic origin is the mineral and chemical composition, which Fermor believes cannot be explained in any other way.

Before proceeding to review the characters of the rocks I wish to point out that the term "series" is commonly used in India for both metamorphic and igneous rocks as a convenient term by which to group or correlate them as an aid in the analysis of the complex and obscure Archean System. When applied to igneous masses the term has still chiefly a stratigraphic sense, is used for convenience, and is subject to free modification. "Kodurite Series" is applied by Fermor to rocks assumed to have common origin through differentiation, but this view is not as yet justified by chemical investigation or adequate knowledge of relations and the name appears to be simply a practical, justifiable term of convenience for local uses.

The Kodurite Series consists of quartz-orthoclase rock, apatite-quartz-orthoclase rock, quartz-kodurite, orthoclase rock, kodurite, pyroxene-kodurite, biotite-kodurite, spandite rock, apatite-spandite rock, pyroxene-spandite rock, manganese-pyroxenites, and graphitic manganese pyroxenites. These varieties and the intermediate phases have not been described as yet in a connected manner showing the chain of peculiar characters necessary to establish a true petrographic series. But few chemical analyses are offered by Fermor.

The series is almost unique as to its manganese minerals, if they are constituents of true igneous rocks. Garnet, manganiferous pyroxenes, and graphite are, however, common constituents of associated metamorphic rocks in India. The first and heavy burden of proof is then to demonstrate that the kodurite rocks are igneous. Known field relations do not do this, as Fermor freely admits. The lack of definite evidence to the contrary scarcely permits the acceptance of the igneous origin in view of the known occurrences of the peculiar minerals.

I am perfectly willing to admit the possibility of manganese-rich magmas as differentiation products, and even assume that they will be found; so that while not regarding the evidence adduced by Fermor as sufficient to establish the Kodurite Series as magmatic differentiates, I am quite ready to discuss the problems of classification which would be presented by such rocks.

FERMOR'S QUANTITATIVE CLASSIFICATION OF KODURITE AND GARNET ROCK

Assuming that rocks like kodurite may be of igneous origin, let us review Fermor's discussion of the problems involved in the Quantitative Classification of the Kodurite Series. That discussion is based on four hypothetical or "calculated analyses." The kodurite proper is the original rock now much altered through replacement of feldspar, believed to have been orthoclase, by opaline silica. Two of the freshest rocks were analyzed, one from Kotakarra in the Vizagapatam district, and one from Boirani in the Ganjam district. Assuming the replacement of orthoclase by opal, Fermor made an estimate of the original mineral composition of these rocks. The former is thought to have consisted of: apatite 3.36, garnet (spandite) 55.04, orthoclase 41.29, TiO_2 0.29, CuO 0.02; the latter of apatite 2.62, orthoclase 57.80, albite 2.79, garnet (grandite) 36.55, and TiO_2 0.24. From these figures equivalent chemical "analyses" have been calculated, which serve as the basis of classification of kodurite.

The two nearly pure garnet rocks, one from each of the localities above mentioned, are assumed to have the composition of the garnets in the two kodurites, as calculated from the rock analyses.[1]

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[1] *Memoirs*, etc., pp. 256–61.

Table I gives the actual analyses of the Kotakarra (I) and Boirani (II) rocks; the calculated chemical composition corresponding to the estimated original mineral constitution (I*a* and II*a*); and the calculated composition of the garnets in rocks I and II, supposed to fairly represent certain garnet rocks of Kotakarra and Boirani (III and IV). In Table II the norms calculated by Fermor from I*a*, II*a*, III, and IV are also quoted.

TABLE I

Actual and Calculated Analyses

	Kotakarra Kodurite		Boirani Kodurite		Kotakarra Garnet-Rock	Boirani Garnet-Rock
	I	I*a*	II	II*a*	III	IV
SiO_2	54.15*	47.45	60.60†	53.36	37.57	38.18
TiO_2	0.32	0.29	0.27	0.24	....	....
Al_2O_3	11.50	18.00	10.59	16.31	18.98	14.22
Fe_2O_3	6.07	1.91	4.79	4.17	3.47	11.41
FeO	0.90	4.10	0.64	0.79	7.45	2.16
MnO	10.00	9.08	1.07	0.98	16.50	2.68
MgO	0.14	0.13	0.26	0.22	0.23	0.65
CaO	11.67	10.37	13.87	12.54	15.80	30.70
K_2O	0.01	6.97	4.00	9.75	....	....
Na_2O	0.18	....	0.36	0.33	....	....
P_2O_5	1.60	1.42	1.24	1.11	....	....
CaF_2	....	0.26††	....	0.20††	....	....
CuO	0.02	0.02	trace	....	....	....
H_2O 100°+	1.33	....	1.20	....	....	....
H_2O 100°	2.30	....	1.30	....	....	....
Total	100.19	100.00	100.19	100.00	100.00	100.00

* Combined $SiO_2 = 35.50$: free $SiO_2 = 18.65$.

† Combined $SiO_2 = 32.25$: free $SiO_2 = 28.35$.

†† Calculated from fluorine assumed in apatite.

A rock having the composition of I*a* would be, as Fermor has shown, a perpotassic andase in the Quantitative System (II. 5. 3. 1); one like II*a* would be a perpotassic monzonase (II. 5. 2. 1). No perpotassic rock of either of these rangs has been described previously and Fermor proposes the names kodurose and boiranose, which cannot be accepted, as shown below.

The further quantitative classification of I*a* on the basis of the amount and chemical character of the femic constituents is carried out by Fermor in accord with the principles of the system.

Manganese is recognized by calculating its ratio to ferrous iron and establishing subsections of subgrad, one step farther than has been necessary hitherto.[1] Fermor also calculates the position of II*a* to the subsection of subgrad, but the small amounts of magnesia, ferrous iron, and manganese (together but 1.99 per cent) make it quite unnecessary to go beyond the precalcic subgrad. The hypothetical garnet rocks, III and IV, fall in the Salfemanes, and their classification is also calculated by Fermor to subsections of subgrad.

TABLE II

NORMS FROM CALCULATED ANALYSES

	KOTAKARRA KODURITE	BOIRANI KODURITE	KOTAKARRA GARNET-ROCK	BOIRANI GARNET-ROCK
	I*a*	II*a*	III	IV
Orthoclase	35.47	55.60	....	....
Leucite	4.53	1.61	....	....
Nephelite	....	1.50	....	....
Anorthite	28.44	14.15	51.74	38.75
Diopside	....	1.19	....	3.50
Hedenbergite	11.02	....	7.25	....
Wollastonite	0.93	16.71	....	5.49
Akermanite	....	....	6.71	34.87
Fayalite	....	....	5.80	....
Tephroite	12.93	1.39	23.47	3.80
Magnetite	2.76	1.86	5.03	6.96
Hematite	....	2.89	....	6.61
Ilmenite	0.55	0.46	....	....
Apatite	3.33	2.62	....	....
	99.96	99.98	100.00	99.98

The procedure by which Fermor provides a place for manganese-rich rocks in the Quantitative Classification is, as just noted, quite in harmony with the principles of the system, and on that score its authors have no criticism to make. But in regard to the various names proposed by Fermor, we must point out, in response to his request, that all of them are quite unwarranted and cannot be accepted since they are based on "calculated analyses" derived

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[1] See Cross, Iddings, Pirsson, and Washington, "Modifications of the Quantitative System," etc., *Jour. Geol.*, XXII (1912), 552–53.

from analyses of much-altered rocks.[1] With increasing experience it becomes more and more clear that quantitative system names should be based only on good analyses of fresh or but slightly altered rocks. Fermor's "calculated analyses" are clearly liable to errors unfitting them for any systematic use, however valuable and justifiable they may be in discussing the nature of the alteration that has taken place. Kodurite of both types and the garnet rocks are, like many of their associates, very interesting and unusual types and, if their igneous character can be established and good analyses furnished, some of them will undoubtedly fall in divisions of the Quantitative System in which there are at present no other known representatives, and new quantitative names may well be based on them.

Fermor is not satisfied with the result of applying the Quantitative System to the four hypothetical rocks, and points out what he regards as the defects of the system indicated by this case. He considers it a serious flaw in the system that the subrang is reached without reference to the important constituent normative tephroite (12.93 per cent in I*a*) and further that rocks poor in manganese may fall in the same subrang. This criticism touches the fundamental distinction between salic and femic components which it seems unnecessary to discuss at this time. Other criticisms may best be expressed in the following quotations:

> There certainly seems to be something lacking in a system which takes no effective account, until the ninth subdivision of the system is reached, of a constituent that is fourth in order of importance in the chemical analysis and third in order of importance in the norm.
>
> The same criticisms apply to boiranose, but to a much smaller degree on account of the much smaller amount of MnO present; but they apply in an even more striking manner to the Kotakarra garnet-rock (spandite-rock), in which MnO is third in order of importance in the chemical analysis, and tephroite, Mn_2SiO_4, is second in order of importance in the norm, of which it forms nearly 25 per cent.[2]

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[1] Cross, Iddings, Pirsson, and Washington, *Quantitative Classification of Igneous Rocks*, p. 166. This and all other references to the Quantitative System contained in this paper are made with full approval of my colleagues. A review of all names proposed since the Quantitative System was first published will be given by Dr. Washington in a forthcoming new edition of his *Chemical Analyses of Igneous Rocks*.

[2] *Records*, p. 217.

The natural reply to all such criticisms is mainly a reference to certain principles which must be recognized in any systematic classification of igneous rocks. Fermor clearly desires a method of classification specially adapted to the peculiar "Kodurite Series," the rocks he happens to be working with. But a local or provincial "series" is not and cannot be made a broad systematic concept. Such a series has certain features or characters common to other series, but that which specially characterizes a local series is surely not a factor to be prominently introduced into systematic classification of rocks in general. Any comprehensive system must recognize first the factors which are important because common to, though variable in, many rocks, and later take up those which are notable in addition as distinguishing a few.

General petrographic system must bring out through classification the relations of kodurite to other rocks, as well as its peculiarities. The hypothetical kodurite has other notable chemical characters besides its manganese contents. It is assumed to be remarkably rich in potash and poor in soda; rich in lime and poor in magnesia. It is these characters that show the relation of such a type to other rocks, not the unique richness in manganese. To express these broader relations is the object of systematic classification, and it is these factors of general chemical relationship which are logically applied in the Quantitative System.

An igneous rock having the composition assumed for kodurite would be a new and interesting magmatic variety irrespective of its manganese, through its quite abnormal association of high lime and potash with low magnesia and soda. The Boirani kodurite possibly falls in another perpotassic subrang, of higher lime contents even in its salic molecules, and still more markedly calcic in its femic constituents, than kodurite proper. These facts are just what a logical system should bring out before the unusual richness in manganese finds expression. No system can be constructed permitting the application of each of the many chemical elements of igneous rocks in accordance with its order of prominence in each case, now first, now fifth, now tenth.

From this point of view the fact that the unusual richness of the Kotakarra kodurite in manganese finds expression in the eighth place in the Quantitative System seems quite appropriate. It is certainly plain that a scheme recognizing manganese in the third place would, for example, not serve to bring out the actual close relationship which exists between the Boirani and Kotakarra kodurites, for the former has only 0.98 per cent MnO. Fermor himself points out that, considering manganese as the characteristic thing about kodurite, the Boirani rock is classed with it simply for convenience. It is modal garnet and orthoclase or normative anorthite and orthoclase which bring the rocks together.

Fermor expresses the opinion that the Quantitative System does not possess either the elasticity or the comprehensiveness which the writer has said should be found in a satisfactory classification. If by elasticity is meant the possibility of transposing certain fundamental parts of the structure at will, according to the varying prominence of certain constituents in different rocks, the first part of this comment is true, but it may be answered that no real *system* can be so constructed. The section of subgrad necessary to express the manganiferous character of kodurite is, however, not an *appendix*, as Fermor considers it. It is an extreme division of the system connected appropriately with the rest in a manner provided for in the original publication.

"Kodurose," as a subgrad magmatic name, does not itself express all the chemical relations involved, but it is no more necessary to go over all the steps of the classification by which this division has been reached, whenever it is referred to, than it is in using the specific or varietal names of animals or plants. It may be pointed out that where the chemical relations of igneous rocks are in question, the new symbols for expressing quantitative classification do show the whole systematic position far better than does any existing scheme for concise statement in zoölogy or botany.[1] "Kodurose" does express the important relationships of such a manganese rock to other rocks in all important respects—when the system is understood.

Fermor considers the Quantitative System unable to deal with rocks containing large amounts of oxides of manganese, nickel,

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[1] Cross, Iddings, Pirsson, and Washington, "Modifications of the Quantitative Classification," etc., *Jour. Geol.*, XX (1912), 553–57.

barium, strontium, etc., because the system, as published, does not contain all the detail applicable to such cases. He cites, however, the remark by the authors of the system that the above-named oxides are to be grouped with FeO or CaO "unless these unusual components occur in sufficient amounts to make their calculation as special mineral molecules desirable." It was believed by the authors that the principles and methods of the system were so clearly illustrated by the scheme published that petrographers would understand the extension of the framework of the system to rocks in which any rare elements might acquire local prominence. Fermor's treatment of the manganese rocks is in accord with that assumption.

With regard to *sections* it was remarked:

> The application of the above principles [used in the construction of the system] shows, however, that in certain points more numerous subdivisions are needed. This necessity is met by the formation of *sections* of any of the divisions above described. These sections will be based on more special characters according to circumstances.[1]

It is of course possible that igneous rocks may sometime be found containing in notable amounts rare substances which must be introduced into the norm, and where the exact method of procedure in systematic treatment may not be plain. But even in the case of barite, raised by Fermor, its position in the group A of femic molecules is appreciated by him and the recognition of the various molecules of this group in the system, while somewhat complicated, will not prove very difficult. Until the occurrence of barite as an original constituent of igneous rocks is conclusively demonstrated it seems unnecessary to work out the details of its treatment in the Quantitative System. The igneous nature of the quartz-barite rock of Salem, India, mentioned by Fermor, can hardly be considered as proven, at the present time. The new divisions of the Quantitative System which may be made necessary for rocks of unusual chemical composition will not be appendices of the system, in the sense of unrelated appendages.

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[1] *Op. cit.*, p. 127.

CLASSIFICATION OF KODURITE SERIES BY HATCH'S SYSTEM

While Fermor considers the Quantitative Classification of the Kodurite Series unsatisfactory, as illustrated by the four hypothetical rocks specially discussed, he states that he is able to classify the whole series with ease and accuracy in the modified form of the mineralogical system recently proposed by F. H. Hatch,[1] and draws the attention of the American petrographers to the "elasticity of Hatch's classification."[2] Believing the kodurite rocks plutonic, Fermor adds "a mangan-subseries of the potash series" and introduces the Kodurite Series intact, with its new names, in Hatch's system. Whether Hatch considers this claim for the elasticity of his system correct or not I do not know, but I do not understand that *any* existing system permits the introduction of local or provincial series as such in its framework.

The discussion of Fermor's procedure in applying Hatch's system to the Kodurite Series may well be left to the author of that system, but, as one who has studied the subject of systematic classification of rocks from many standpoints, I wish to make the comment that the principles of general system and the considerations that control in the expression of provincial characteristics in a so-called "rock series" are almost antithetical. A scheme containing three or four such series intact would cease to be a system. The term "series" is applied by Hatch and Fermor to very different concepts.

It would seem to me that the case of the Kodurite Series was directly covered by the following statement of Hatch:

> Although names founded on mineralogical variation in constituents other than the feldspars are of little service in classifying rock-types, they are often useful for descriptive purposes. They form no part, however, of the system of classification now undergoing discussion.[3]

HATCH'S PETROGRAPHIC SYSTEM

The classification of igneous rocks presented by Hatch in the fifth edition of his *Textbook of Petrology* (1909), and repeated in

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[1] F. H. Hatch, "The Classification of the Plutonic Rocks," *Science Progress*, October, 1908; *Textbook of Petrology*, 5th ed., 1909; 6th ed., 1910; 7th ed., 1914.

[2] *Records*, p. 225.

[3] *Science Progress*, p. 7.

later editions, is very nearly the same, in effect, as other forms of the mineralogical system which have been in use for many years past. But he introduces certain new factors, intended to give the system greater precision and a quantitative character hitherto wanting. Because of the frankly expressed object of the author to formulate a classification free from the, to him, objectionable features of the Quantitative System, it seems appropriate to review some features of the revised system. I wish to emphasize the fact, however, that the critical comments to be made are, almost without exception, of general application to many earlier propositions and are not personal to Hatch.

The attitude of Hatch toward the Quantitative System and the claims made for his own scheme are in part expressed in the following quotations:

> In the quantitative classification of igneous rocks devised by Messrs. Whitman Cross, Iddings, Pirsson, and H. S. Washington, the hitherto existing nomenclature of rock types is entirely discarded, and a new nomenclature introduced which is based on purely chemical considerations without regard to mode of origin. . . . .
>
> I desire in this paper to show that it is not necessary to throw over the existing rock nomenclature, nor to *disregard mode of origin, in basing a natural system of classification on chemical considerations*.[1]

The element in Hatch's system which underlies the claim that it is a "natural system" is the primary division by "mode of occurrence" into plutonic, hypabyssal, and volcanic rocks. Mode of occurrence is, indeed, a criterion for the classification of igneous rock masses, and Hatch devotes a chapter to this subject. Where this primary division is made, Hatch points out that "volcanic-rocks are, however, connected with their deep-seated or plutonic roots by necks and pipes, or by dikes. A third division of igneous rocks is therefore necessary to embrace these connecting links between plutonic and volcanic rocks. For this division the term *hypabyssal* is used."[2]

But neither Hatch nor any other systematist using plutonic in this sense necessarily means deep-seated or abyssal. He means granular, and yet it is known that certain granular rocks, treated

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[1] *Science Progress*, p. 1. Italics by W. C.

[2] *Textbook of Petrology*, 5th ed., pp. 7 and 8; 7th ed., pp. 5 and 6.

as plutonic, occur side by side with rocks termed hypabyssal, and some have been formed near if not at the surface. In treating the hypabyssal rocks, Hatch shows that he is largely influenced by Brögger's proposition to apply this term to the "Dike rocks" of Rosenbusch. The complex genetic, structural, and textural relations involved in this conception are well known and need not be stated here. And in view of an earlier discussion of this subject[1] I need only repeat that the use of these natural relations of rocks in classification must be appropriate and consistent with the facts, or the result is *unnatural*.

The expression "natural system" as applied to petrographic classifications should, I think, refer to other things as well as to the use of factors of natural occurrence. The rocks themselves have various *natural* characters or properties. The systematist makes use of these characters in classification and should do so as appropriately and consistently as possible. In proportion as the nature of rocks is rationally applied in their classification the result may be termed a natural system. It is with reference to this idea that the further systematic propositions adopted by Hatch will be considered. They are, for the most part, not new.

The next step is the distinction between feldspathic and non-feldspathic rocks. The two groups of substances indicated by this division occur in rocks in all amounts from 0 per cent to 100 per cent for each. If this varying constitution of two exclusive groups of minerals is to be used as a systematic factor in classification, is it not the natural way to recognize the varying proportions of the two groups? To call all rocks distinctively *feldspathic* which contain as much as 10 per cent of feldspar is to ignore the fact that rocks with 10 per cent or more of pyroxene are by the same measure *pyroxenic*. In short, this is a quite unnecessarily arbitrary and unnatural procedure and opposed to the almost universal tendency of modern petrographers to introduce a quantitative element into system wherever it is appropriate and feasible.

It is to be presumed that "chemical considerations" lead Hatch to form three groups of rocks called *acid*, *intermediate*, and *basic*,

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[1] Whitman Cross, "Natural Classification of Igneous Rocks," *Quar. Jour. Geol. Soc.*, LXVI (1910), 470–506.

marked off by the percentages of silica shown on analysis, the lines being drawn at 66 and 52 per cent. These limiting percentages are admitted by Hatch to be "quite arbitrary" but permitting "a convenient separation in accordance with existing records of rock types."[1] The meaning of the latter phrase is not clear to me. Now it must be self-evident that no *chemical* consideration of importance, to say nothing of a principle, requires or suggests a division of igneous rocks by any special silica percentages whatever. Calling the group with more than 66 per cent SiO_2 "acid," and designating all the rocks of this group as the "Granite Family," implies that only rocks of this silica content may contain important amounts of quartz. The application of the name "Syenite Family" to alkalic rocks of the intermediate group implies that they must be quartz-free, or nearly so. And the designation of the group with less than 52 per cent SiO_2 as "basic" implies the generalization that quartz is absent and that silicates of such rocks must be less rich in silica than those of the intermediate group.

The well-known facts are that many rocks having less than 52 per cent SiO_2 contain metasilicates and several per cent of free silica; many intermediate rocks carry 25 to 30 per cent of quartz; and many of 66 per cent carry little or no quartz. It is a fundamental principle, ignored by Hatch, that the petrographic importance of the silica contents of a rock, as influencing the development of its minerals on crystallization, can be determined only by a study of the relative amounts of the associated bases and recognition of their influence in the magmatic solution. This principle is illustrated by the normative calculations on which the Quantitative System is based.

The fact that the silicity[2] represented by 66 per cent SiO_2 has no relation to the presence of free quartz is illustrated by three analyses quoted by Hatch in tables representing the Calc-Alkali Series.[3] In Washington's tables it is shown that the granodiorite of SiO_2 68.65 has 24.2 per cent normative quartz; the tonalite of

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[1] *Science Progress*, p. 2.

[2] A useful term of self-evident meaning recently proposed by Washington (this *Journal*, XXII [1914], 16).

[3] *Science Progress*, p. 9.

SiO_2 63.09 has 22.9 per cent normative quartz; the quartz diorite of SiO_2 57.41 has 11.5 per cent normative quartz. Many rocks are nearly normative in their quartz contents and some carry more than the normative amount.

The ultrabasic rocks furnish further evidence, if such is necessary, that a division of rocks by silica percentage is without reason and without object so far as any relation between chemical and mineral composition is concerned. The line of 52 per cent silica, established by Hatch between intermediate and basic rocks, is passed by the silica of some rocks placed by him in the *ultrabasic* group, e.g., websterite, one analysis of which, cited by him, has 53.25 per cent SiO_2.

The norms of many of Hatch's ultrabasic rocks contain 20 per cent or more of feldspar and lenad. And while such amounts are not common in the *mode* of the plutonic rocks in question, those of the surface or hypabyssal forms of equivalent chemical composition are often notably feldspathic. This well-known variation in mineral composition, due to physical conditions, must be considered in any adequate systematic treatment of the more basic or "ultrabasic" rocks.

After the arbitrary division on silica percentage, Hatch introduces the character of the feldspars and feldspathoids as the factor for the next subdivision. It is his evident intent to emphasize the quantitative element in many places, but this is often by use of the vague terms "predominant," "largely developed," and "subordinate." The meaning attached to such terms is often highly subjective, as appears most striking in the case of the "Feldspathoid Series," which is defined as one "in which nepheline, sodalite, or allied feldspathoid is largely developed, and feldspar subordinate."[1] But Hatch cites, as illustrating the "Feldspathoid Series," the average of nine typical nepheline syenites, given by Brögger, and the norm calculated from this, which must approximate closely to the mode, gives feldspars 69.11 per cent, and nephelite 20.3 per cent. That is, the feldspars, which must be more than three times as abundant as nephelite in a rock of the cited composition, are declared "subordinate," and the nephelite

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[1] *Science Progress*, p. 3.

relatively "largely developed." Many phonolites, foyaites, and nephelite syenites carry but 10 per cent or even less of feldspathoid. There is no indication of the minimum amount of nephelite or leucite which Hatch would consider as placing a rock in the "Feldspathoid Series."

In subdividing the feldspathic rocks still farther, Hatch introduces as a direct quantitative factor the relative percentages of alkali feldspars as against plagioclase, and of soda as contrasted with potash feldspar. This is certainly a step in the right direction, but as it comes after the irrational silica distinction, it loses much of the value it might have in bringing allied rocks together.

It is to be hoped that Fermor will succeed in establishing the origin and chemical character of the interesting rocks called the Kodurite Series. If they possess the characters assumed for them, it appears to me that the Quantitative System will show—so far as it professes to go, that is, in expressing chemical characters—both their general chemical relations to other rocks and their unique special features.

The use of factors of natural occurrence in the classification of igneous rocks does not necessarily make the system natural. The system of Hatch, like many others of allied construction, does not seem to me to use natural factors in a rational way And as actual characters of the rocks are used with unnecessary arbitrariness the right of his and allied systems to be termed natural is open to question.

The systematic treatment of igneous rocks, with all their widely varying important characters, is a matter of great difficulty, and a long time may elapse before petrographers come to a common point of view. It is in the hope of contributing, however slightly, to this understanding, that this discussion has been written.

A PHENOMENON OF THE KANSAN DRIFT IN NEBRASKA

ERWIN H. BARBOUR
University of Nebraska

Among the minor phenomena of the glacial drift in Nebraska there is one which, though rarely observed by the public, is of interest and should be commended to the attention of naturalists. The reference here is to certain large, well-defined masses or blocks of such materials as sand, gravel, and coarse pebbles, which occur imbedded in the drift clays along with glacial bowlders, and which presumably have been similarly transported and deposited. These masses or blocks vary widely in color, texture, and kind. They also vary from the glacial matrix in which they are found and are the more striking by virtue of contrast. They are not of frequent occurrence, but may occasionally be seen in fresh exposures especially in deep railroad cuts. Unfortunately they are quickly effaced by weathering and by growing vegetation. The most notable examples are found in the Milford cut-off of the Burlington Railroad, particularly at Pleasantdale. For a mile or so west of the station at Pleasantdale, especially on the right bank, fine examples occur in almost continuous succession (see the accompanying sketch and photograph).

The drift at this place is a jointed sandy clay of a rusty gray color, of a fairly compact texture, and about twenty-five feet in thickness. It is somewhat startling to find in it great stray blocks of various materials. These blocks are generally large and angular or rounded masses of incoherent soil, sand, and gravel, more or less stratified, cross-bedded, and tipped at all angles. It is still more surprising to find sections of small stream beds and channel deposits tilted and overturned. The dense quartzitic and occasional granitic bowlders characteristic of the Nebraska drift, and these incoherent sand and gravel blocks occur together. Perhaps the arenaceous and argillaceous blocks were likewise dense and coherent at the time of transportation and deposition, the assumption being that they were rigid because frigid. Accordingly we have coined for them, and for a long time

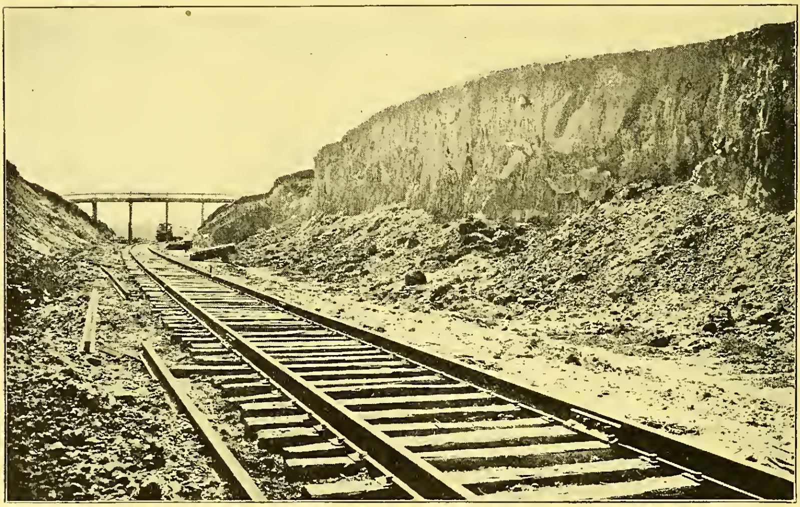

FIG. 1, *A*.—A bank of Kansan drift at Pleasantdale, Nebraska, showing "frigites" of clay, sand, gravel, and pebbles (see *B*). Distance to bridge about 1,000 feet.

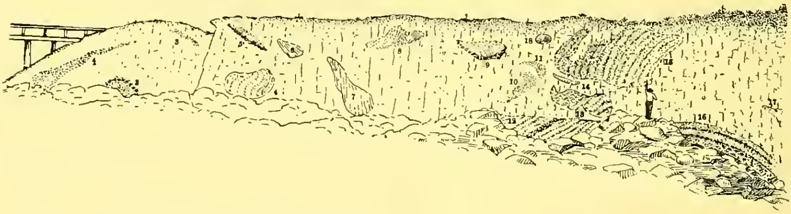

FIG. 1, *B*.—Key to *A*. Nos. 1, 3, 4, 8, 10, 11, 13, 14, 17 represent sand blocks ("sandfrigites"). No. 12 is a large cross-bedded sandfrigite about 30 feet long partly buried by talus. No. 15 is a large very distinct sandfrigite about 30 feet long. Nos. 2, 5, 9, 16 are supposed stream beds ("couleefrigites"). Nos. 6 and 7 are clay blocks ("clayfrigites"). No. 18 is a large Sioux quartzite bowlder. Total length of section about 1,000 feet.

have used as a convenient generic field name, the word "frigites," and have used as specific terms the additional names "soilfrigites," "clayfrigites," "sandfrigites," "gravelfrigites," "couleefrigites," etc., according to the component materials. Perhaps, as has been suggested, these are Aftonian.

Incident to the protracted frigidity of a glacial period is the freezing of soils, sands, and gravel to the rigidity of rock (frigite). Any natural force which could rend and transport rock could rend and transport the rocklike soils and sands. Continental glaciers are powerful graders and levelers. They act resistlessly upon rock and frozen soils and sands, breaking them into blocks and transporting them long distances southward. The load of rocks and frozen blocks is finally dropped by the melting ice, and buried in glacial mud. The blocks are thus preserved in their integrity. A stream bed, or coulee, could in a like manner be frozen, subsequently broken into sections, transported, and deposited.

The term "glacial drift" as used in an unfortunately restricted and local sense in Nebraska refers to that particular portion of the Kansan drift, which is rendered conspicuous by coarse pebbles and bowlders of reddish Sioux quartzite. This layer is pretty generally recognized, and though it may be but a foot or two in thickness it is often expedient to speak of it popularly as "the drift." In a broader sense, however, our drift also includes, though less obviously, extensive beds of glacial clay, generally spoken of as joint clay, which may reach fifty feet in thickness. It has long been said facetiously by eastern geologists that the glacial deposits of Nebraska are "buttered on so thin that one cannot tell the buttered side." It is probable, however, that this bit of good humor would never have become classic had our drift not been confounded with our loess. There may be recognized an older, bottom layer of a dark, or even black color (sub-Aftonian, Jerseyan, or Nebraskan), and a younger, top layer of a lighter color, generally of a yellowish or reddish cast (Kansan), neglecting any Aftonian sands and gravels. The frigites herein described are confined to the Kansan drift.

It so happens that the drift often resembles the loess so closely that they run together, and seem to be terms in the same series. At times it puzzles even those who are experienced to distinguish between them. The southeastern half of Nebraska has for convenience been generally figured as one continuous loess sheet.

It must be noted here that there are extensive "loessless" regions in the southeastern as well as in the northeastern corners and elsewhere in the state. Frozen sand blocks have been observed in the drift of Iowa as well as in Nebraska, but as far as can be learned no examples yet found equal those in the Milford cut-off in point of size, variety, or numbers.

EDUARD SUESS

WILLIAM HERBERT HOBBS

Of men, as of mountains, it is often true that one towers in isolated grandeur well above his fellows. Of the lower eminences there arise questions of relative prominence, but of the one, never. Eduard Suess, who passed from life on April 26, ranked as one of the intellectual giants of his age, and his masterpiece, *Das Antlitz der Erde*, as the greatest work upon geology since the modern science was founded three-quarters of a century ago in *The Principles of Geology* of Sir Charles Lyell. Already past eighty, Suess had for years been fighting the encroachments of advancing age in a hardening of the arteries, and his death following upon a bronchial affection came peacefully at his home in the Afrikanergasse, Vienna. His friends in every land, and they were many and devoted, will in mourning his loss not fail to account it a special mercy that he was spared a knowledge of the world cataclysm, in the storm center of which his country is now struggling under severe reverses, and which its harsh demands upon Servia precipitated. Deeply interested as he was in the political life of his country, and high as he ranked in its councils, the predicament in which Austria-Hungary now finds herself, with the consciousness of responsibility for it, must have rested with especial weight upon him. Passing away when he did, his last years were happy ones, as unsought honors and evidences of devotion and esteem multiplied, with his life work gloriously completed and his son succeeding to his own chair at the University of Vienna.

Professor Suess was born in London, August 20, 1831, where his Saxon father was an importer of Bohemian wool, but while Eduard was still young the family removed to Prague in Bohemia and later to Vienna. England he often referred to as his "native land," and he retained a lively interest in English affairs. Though intended for a commerical career, Suess attended the universities of Prague and Vienna, where his field of specialization was paleontology. In the Austrian capital, his home since 1845, he was in 1852 made an assistant in the geological department of the Hofmuseum and carried out important studies on graptolites and brachiopods. Five years later he was made *ausserordentlicher Professor* in the university while still retaining his position in the Hofmuseum. Later this museum work had to be given up because of increasing duties in the university, and in 1867 he was made *ordentlicher Professor*, or full professor, of geology. After occupying this chair for thirty-four years, he delivered his farewell address July 13, 1901, as much revered as a teacher as he was distinguished as scholar and seer. Among his students he numbered such eminent geologists as Neumayr, Mojsisovics, Fuchs, Waagen, Penck, and the venerable Judd, who has so delightfully described the relations which existed between the master and his disciples. He tells us: "Amid all the fun and frolic, the signs of affectionate respect and devotion to the great teacher were never for a moment wanting." The generations of students which assembled for the farewell lecture in Vienna ranged "from the renowned and gray-haired members of the Royal Academy to the young fellows with sharp eyes." Looking out over this remarkable assembly, Suess thus concluded his address:

> Bulwer Lytton says in his novel: "When a man of great age is surrounded by children, he then sees at the end of his days, not a period, but a comma." This applies in equal measure to the inquirer and his students. This is my good fortune which today becomes my portion. . . . .
>
> And now I have reached the comma. When I became teacher, I did not cease to be a student; and now that I cease to be a teacher, I shall not cease to be a student so long as my eyes see, my ears hear, and my hands can grasp. With this wish, I therefore do not step out, but take up my former position.
>
> And now I thank you all from the depths of my heart for your presence, and beg of you to retain for me a friendly remembrance.

From this discourse, which fortunately has been published in English translation,[1] one is tempted to quote at length, since it reveals the springs of Suess's powerful influence over all who came

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[1] Charles Schuchert, "Farewell Lecture by Professor Eduard Suess on Resigning His Professorship," *Jour. Geol.*, XII (1904), 264–75.

EDUARD SUESS

in touch with him. To know him was to love him for his many noble traits of mind and heart.

The great success of the *Antlitz der Erde,* the four massive volumes of which have been translated into both French and English,[1] is to be ascribed to a wonderful command of the entire field, due to a knowledge of many languages, to the accessibility and assiduous use of vast storehouses of geological literature, and to a quite remarkable grasp upon this full material with a power to generalize. Walking through the library of the Hofmuseum and passing the *Diener,* or servant assistant, whose duty it had been for twenty years to carry books from the library to his study, Professor Suess remarked to the writer: "When the *Antlitz* had appeared the *Diener* showed amazement that it was not larger, and said to me, 'Is that all you got out of the books I brought you?'"

The honest critic must frankly admit that, great as is this masterpiece of geological generalization, it suffers from two rather serious defects. Its author was almost too clever as advocate and parliamentarian and was, moreover, not without bias. With a manner altogether masterful, he could dismiss as it were with a wave of the hand important evidence which was unfavorable to maintenance of his thesis and, with equal ability, could magnify the weight of much less valuable or unimportant observations. Again, his great work suffers from a bewildering detail and an enumeration of localities too small to appear upon maps outside the original articles but upon which the conclusions are absolutely dependent, so that the reader is prevented from following the author's argument. This latter defect Professor Suess fully realized and he would have welcomed the preparation of a special atlas which should supplement his work. To offset this serious defect in overabundance of detail, which tended to make his volumes dry and difficult to read, they were written in a style so full of imagery and of poetic feeling as to hold the reader and compel his admiration. By Sir Archibald Geikie the *Antlitz* has been termed "a noble philosophic poem in which the story of the continents and the oceans is told by a seer gifted with rare power of insight into the past."

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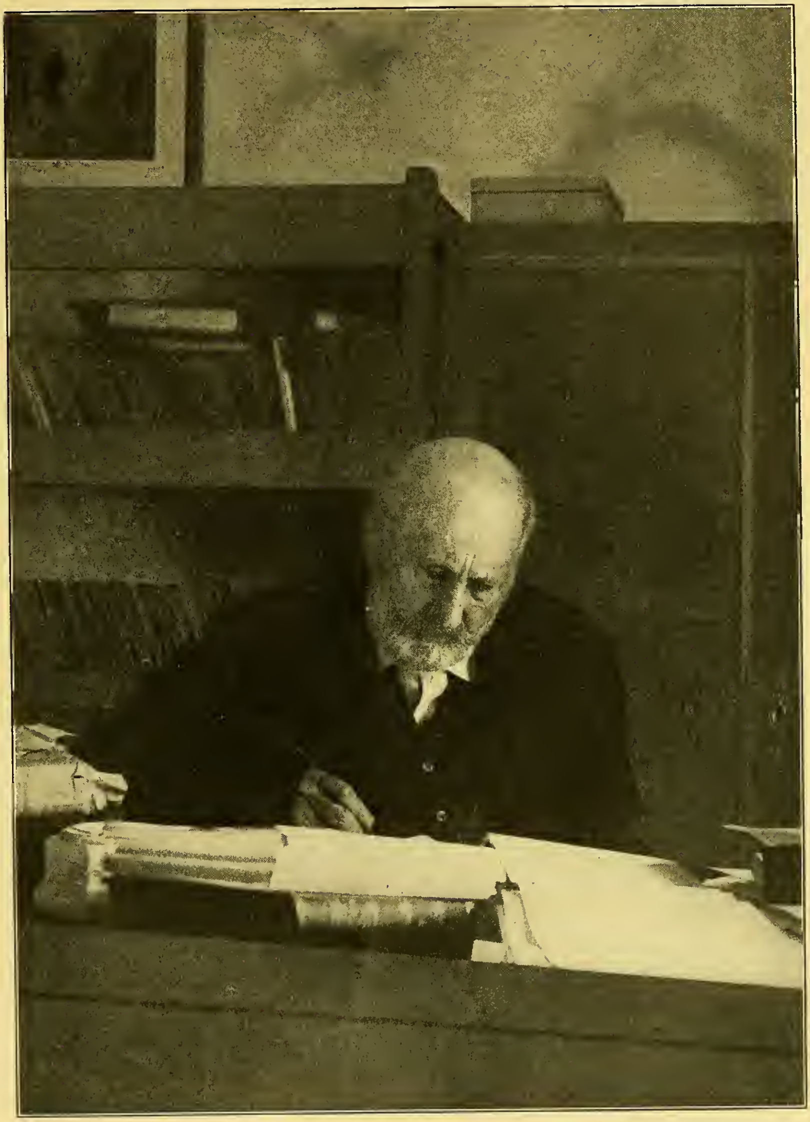
[1] Vol. I is translated into Italian.



PROFESSOR SUESS IN HIS STUDY

(From an unpublished photograph taken by his granddaughter, Fräulein Hedwig Neumayr.)

After first treating of the continents, Professor Suess at the opening of his second volume thus turns his attention to the oceans:

> We have descended from the high mountain country and taken our station at the borders of the sea. The eye roams untrammeled over the vast expanse of water. A great wave approaches; it seems about to reach us; then its crest curls forward, it plunges downward, and with a dull roar the watery flood sweeps far up toward us though without wetting our feet. Now the water streams back and a long green line of sea-weed marks the limit of its advance. Then follows a second and soon a third wave, and from time to time one somewhat higher than the others which whirls the sea-weed still farther up the beach and drives us back to the foot of the cliff.
>
> The roll of the water is repeated like the refrain of a mighty anthem. For hours we could be held captive by the sublimity of the spectacle. But now the crest of the wave is breaking at a greater distance from us, and soon the lowest position of the ebb will be reached. Then the ocean rises and all the abandoned streaks of white mussel shells and the green coils of sea-weed are gathered up again as the foot of the wave advances farther and farther. When six hours have elapsed the point is again reached where we first took up our position, and once more the water laps at the foot of the cliff.
>
> Thus to a stately measure the heavenly bodies move the swaying ocean and bring about its advance and retreat upon the strand.[1]

One other selection may be chosen to afford some idea of the force and beauty of Professor Suess's literary style:

> It is the twentieth of June of the year 1320. The bells are ringing in the bright Sabbath morning and the crowd is saluting with respect a tall and serious figure—the great Dante—who with slightly bowed head is entering the chapel of Santa Helena.
>
> All that can stir the human soul he has felt, and in the realm of the imagination he has traveled greater distances than any mortal before him. The loss of his Beatrice he has survived, and that of his emperor from whom he had awaited a better future for his Fatherland. Now fleeing from the hatred of his own city he has found refuge at the court of the leaders of the North Italian Ghibellines. . . . . With a gift for picture-writing never before equaled he has led his astounded contemporaries up to the abode of the saints and down into the depths of the lower world. Now today he is returning to the starting-point of his most powerful creation, to the critical examination of that which is greater than all the conceptions of poetry—the actual ordering of the universe.

Professor Suess's activity in the political life of Vienna has been somewhat overshadowed by his distinction as a scholar, but

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[1] Author's translation.

he gave freely of his time and his wise counsel both to municipal and national affairs. For ten years he was a member of the Municipal Council of Vienna, and for more than thirty of the Austrian Parliament as the strong exponent of progressive principles and the determined foe of special privilege. His part in the *Kulturkampf* as an anti-clerical made for him many powerful enemies, and this oppositon was reflected in the bitter attacks upon his scientific conclusions in the period before he had achieved world renown. An attribute of greatness was his simple and modest demeanor. Empty honors he scorned, and, unlike so many of his Teutonic colleagues, he declined the high-sounding state titles and remained plain "Professor Suess" to the day of his death. He seemed to take pleasure, however, in the position of President of the Royal Imperial Academy of Sciences, to which with proper pride his scientific colleagues again and again re-elected him; and he did not decline the many memberships in foreign scientific societies which indicated the high approbation of the scientific world. In recognition of his suggestion and carrying to completion of a plan to bring the pure waters of the Alps to Vienna, his fellow citizens conferred upon him their highest honor by making him an Honorary Burgess of the city.

The practical nature of some of his other studies is indicated by his monographs on "The Future of Gold" and "The Future of Silver," widely known and read throughout the world.

REVIEWS

The Ostoleogy of the Chalicotheroidea. By W. J. HOLLAND and O. A. PETERSON. Memoirs of the Carnegie Museum, Vol. III, No. 2, 1914.

No contribution to paleontologic science made by the Carnegie Museum of Pittsburgh presents more material of interest than the recent work on the chalicotheres by Dr. Holland and Mr. Peterson. Though representatives of this peculiar group have been certainly known in America for many years, beginning with the first recognition of remains from the Tertiary of the West by Marsh in 1877, these animals have been among the most imperfectly understood of the American Tertiary mammals.

The marvelous discoveries of Miocene mammals at the Agate Spring quarries in the past few years have fortunately included most excellent material of the chalicotherian genus *Moropus.* With the material obtained by the Carnegie Museum as a basis for comparative study, Dr. Holland and Mr. Peterson have in a most commendable manner taken up the description of the osteology and the affinities of the Chalicotheroidea of America. The present monograph is a very satisfactory description, illustrated with excellent figures representing the osteology of these forms, and bringing into view through comparative study all of the American material.

The paper combines a statement of detailed description and analysis of the skeleton with the generalizations required in reconstruction of the animal, and in the statement of affinities of the genera.

Workers in the field of paleontology and geology are certainly grateful to the authors for bringing together all of the available information on this group, and for giving us this excellent discussion of the osteology and relationships. This paper also furnishes material which makes it possible to determine, compare, and correlate fragmentary chalicotherian material from many widely scattered Tertiary deposits through the West, and to obtain from the study of these fragments more satisfactory conclusions as to the faunal relationships of the beds concerned than have heretofore been secured.

JOHN C. MERRIAM

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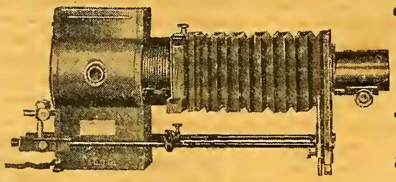

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