

## 4. On the ophitic texture and the order of crystallization in basaltic magmas.

By

Torsten Krokström.

---

### 1. Introduction.

Since long ago there has been some controversy among petrologists how to interpret the ophitic texture displayed by most dolerites and a great number of other basaltic rocks. The fairly well developed idiomorphic outlines of the lath-shaped plagioclases compared with the generally absolute absence of idiomorphism of the pyroxenes for a time led most authors to the assumption that all of the plagioclase crystallized out first and was then followed by pyroxene. In 1910, however, FENNER (5: 218—227) referring to an investigation of the Watchung basalts argued that both minerals — plagioclase and pyroxene — must have been crystallizing together already from the very beginning of the crystallization act and that the ophitic texture was simply the result of a simultaneous growth of the two components. He was able to show that even in very quickly chilled rocks which were almost entirely composed of glass the few phenocrysts were made up by pyroxene as well as by plagioclase. Further he tried to demonstrate that in the basalts in question the idiomorphism of the plagioclase was not quite so well-defined as is generally claimed for in ophitic rocks. Later on these views were still more emphasized by BOWEN in his elaborate work on the evolution of the igneous rocks where he made them a fundamental principle of his theory of the development by crystallization only of late salic differentiates from a basaltic magma (2: 67).

In a previous paper on the Breven dolerite dike of middle Sweden the present author has touched incidentally upon this problem (10: 259), but it seems as if some facts gathered from the microscopic investigation of those and some other Swedish dolerites were worthy of a somewhat closer consideration. It must be pointed out, however, that none of the features observed are in any way rare — on the contrary, they may probably be met with in a great many rocks. Anyhow, a discussion of this very important problem might be of some interest.

## 2. Terminology.

Before entering into that discussion, however, it is necessary to take some questions of nomenclature into consideration, as there seems to be a rather great confusion concerning the term »ophitic» and more or less synonymous textural terms. Recently JOHANNSEN (7: 43—49) has given a rather detailed historical account of this question. For further particulars the reader is referred to this very valuable work. Summing up his statements, however, we may gather mainly the following dates. The most conspicuous feature of the textures in question being the diverging lath-shaped feldspars it is quite natural that almost all terms suggested have referred mainly to this divergent radiating arrangement. It was described as ophitic, doleritic, diabasic, *diabaskörnig*, *divergentstrahlig-körnig*, *basio-phitisch*, *granitotrachytisch* etc. Of these terms only the first four are nowadays more extensively used. By and by, however, it became clear that the radiating arrangement of the feldspars might be combined with at least three different modes of development of the interstitial pyroxene. Several attempts were made to distinguish between them. Thus ROSENBUSCH (11: 191) limited the term ophitic by using it only for rocks with lath-shaped feldspars — which should not usually touch each others — embedded in a *mesostasis* of later augite. KEMP (9: 159) accepting this suggestion proposed the term diabasic for rocks in which only small interstices between the lath-shaped feldspars are filled by subordinate amounts of pyroxene. Between ROSENBUSCH's ophitic texture and KEMP's diabasic there ought to have been, consequently, only a gradual difference. Still another development is represented by rocks in which the interstices between the feldspars are occupied by aggregates of discrete augite grains and not entirely filled by augite portions belonging to the same large individual as those of adjacent interstices. For this texture HOLMES on EVANS' suggestion proposed the name intergranular (6: 191).

Turning now from this historical account gathered from JOHANNSEN's work (*loc. cit.*) we may consider how the different terms mentioned above are generally used in modern petrological literature. The writer thinks that many if not even most petrologists still use anyone of the terms ophitic, doleritic, diabasic, or *diabaskörnig* as a collective name in order to connote rocks which show diverging radiating feldspars, no matter how the interstitial pyroxene is developed. It might be admitted that the distinction made by KEMP (*cf.* above) between diabasic and ophitic was hardly necessitated and, anyhow, the term diabasic might as well be substituted by subophitic which seems also to have been the case in later years. On the other hand the proposal made by EVANS and HOLMES seems very convenient. For several purposes a distinction must necessarily be made between the really ophitic texture where the interstitial pyroxene portions

over large areas show a simultaneous extinction and thus belong to the same large individual forming a *mesostasis* around the feldspars, and the texture named intergranular by EVANS and HOLMES, where the interstices are occupied by independent grains of pyroxene. It might, however, be questioned if this term is likely to be accepted by the majority of petrologists. Perhaps it is a little inconvenient to add a new name to the *embarras de richesse* already present. Several of the older names may as well be preferred and the present writer is inclined to find the term doleritic rather good. Of course, even in this case a gradual transition may be traced between rocks where the interstices are occupied by idiomorphic or subidiomorphic pyroxenes and rocks where they are entirely filled by pyroxene material, the outlines of the latter being determined only by the surrounding plagioclase laths. This texture may be named sub-doleritic. In both cases the characteristic feature is the different orientation of the fillings of adjacent interstices. Of course, even in rocks of doleritic or sub-doleritic textures the pyroxenes may to some extent be pierced by plagioclase laths but never to such a degree that the pyroxene may be characterized as a *mesostasis* embedding the feldspars. Most important is, however, that the name ophitic should be clearly restricted to the sense suggested above and in the following pages this restriction is made.

As a consequence of the above discussion the writer endeavours to propose a terminology of the textures in question which for sake of perspicuousness is summarized in table I below.

Table I.

Textural description		Name of texture
The pyroxene shows over large areas a uniform orientation	The plagioclase laths are entirely enclosed within the large pyroxene areas	Ophitic.
	The pyroxene is subordinate in amount and forms a filling in the small interstices between the feldspars	Sub-ophitic
The pyroxenes of adjacent interstices are of different orientation	The pyroxene grains are idiomorphic or subidiomorphic	Doleritic
	The pyroxenes have their outlines determined only by the surrounding plagioclase laths	Sub-doleritic

### 3. Textural statements.

Now we may turn to the principal scope of this paper, *viz.* the order of crystallization in basaltic magmas and the petrological significance of the ophitic texture.

The westernmost part of the large dolerite dike at Breven in Middle Sweden consists of a fairly uniform olivine dolerite occupying an area about 10 km. long and on an average 800 m. wide. A rather detailed account of the petrology of this rock has been previously published by the present writer (10). In this connection only some facts should be recapitulated and treated somewhat more in detail. The rock consists of plagioclase, orthopyroxene, clinopyroxene and olivine (see also the geometrical analysis given on page 208 below). It is most remarkable that the two pyroxenes show quite similar textural relations against the plagioclase. They occur as portions or patches of varying size and of angular outlines determined only by the plagioclase laths. Generally a rather great number of these



Microphoto by the author.

Fig. 1. Olivine dolerite S. of Kortorp near the western end of the Breven dike. Nicols crossed. Magnification 14 diameters.

angular patches show simultaneous extinction although they are entirely separated from each other by the feldspars. It has also been stated by universal stage measurements that this simultaneous extinction really implies an exactly identical optical orientation of the different portions, and thus it ought to be beyond doubt that they belong to the same individual. The pyroxene individuals — as defined by the areas occupied by patches of the same orientation — may often attain a diameter of 12 mm. and even more. Thus it happens that in some slides only one or two individuals may be observed although the volume-

percentage of pyroxene is rather high. Within these pyroxene areas large and abundant plagioclase laths are scattered, exhibiting generally quite sharp and rectilinear outlines. In fig. 1 and 2 two microphotographs are given which illustrate the mutual relations of the two minerals. Fig. 1 represents plagioclase and orthopyroxene, fig. 2 plagioclase and clinopyroxene. In both cases all pyroxene patches belong to the same individual. Although the technical difficulties render it almost impossible to give, in a reproduction, the same impression as is gained in the microscope it is thought that the relations may be fairly well understood from these pictures.

Often it may be observed how cracks within the feldspars widen as approaching the margins and at last pass into wedge-formed openings. In several cases these openings are entirely filled by pyroxene material forming wedges which emanate from an adjacent large individual. In other cases

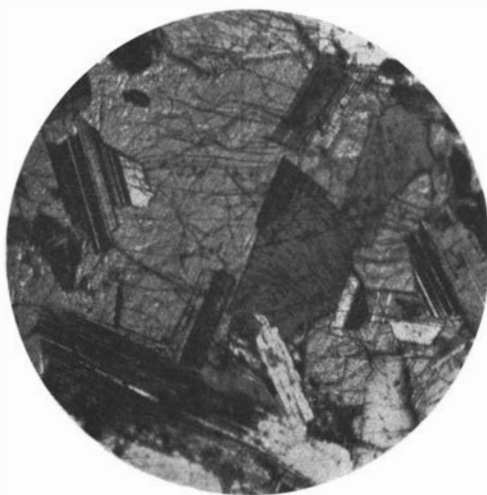
two plagioclase laths developing a length of several mm. may lie side by side, roughly parallel, and then from the neighbouring pyroxene a string protrudes which fills all the space between the laths though this space may sometimes have a width of only a fraction of a mm. Furthermore there are observed elsewhere within a pyroxene patch fairly small pieces of plagioclase that may to all probability be interpreted as fragments broken off from adjacent larger plagioclase laths occurring in the same pyroxene individual.

#### 4. Significance of textures.

From the details described above we must infer that the crystallization of the plagioclase was distinctly earlier than that of the pyroxenes. Further, as the plagioclase laths exhibiting these relations may belong even to the largest feldspar crystals present in the rock it may be rather safely concluded that the very greatest part of the feldspar was already consolidated before the pyroxene began to crystallize. The arrangement of the latter gives a strong impression that in the latest stages of crystallization a residual liquid of pyroxenic composition has flowed into all cavities accessible and has congealed there.

As an evidence of the simultaneous growth of pyroxene and plagioclase in »ophitic» rocks (*cf.* however, below on pp. 202—203) FENNER (5: 226) states that in the Watchung basalts the plagioclase laths wedge out toward the central portion of the diopside grains. In the rocks discussed in the present paper no such relation has been observed. On the contrary, rather broad laths may enter into an adjacent pyroxene without displaying any change of dimensions or idiomorphism. That would scarcely be possible had the pyroxene begun to crystallize before the laths in question had attained their present size.

It may also be mentioned that in an olivine dolerite from the Hällfors dike (situated about 35 km. in a north-easterly direction from the Breven dike) the writer in several cases observed plagioclase as inclusion in olivine. It is quite out of question that in this case the feldspar may



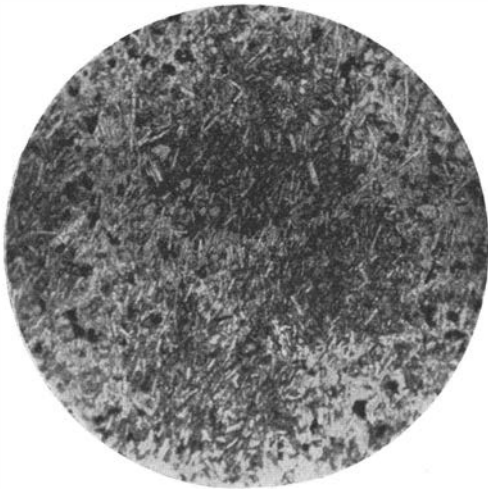
Microphoto by the author.

Fig. 2. Olivine dolerite from Gubbhult, near the western end of the Breven dike. Nicols crossed. Magnification 14 diameters.

represent fillings in corrosion cavities of the olivine only, for the inclusions are in some cases of a fairly good idiomorphic development and always of an angular, rectilinear shape. In this case it ought thus to be proved that the feldspar began to crystallize even before the olivine.

By the courtesy of Prof. H. G. BACKLUND and Dr. D. MALMQVIST the present author has further been allowed to make for this paper some microphotographs of a tertiary olivine basalt from Greenland. The rock sample was collected by BACKLUND in 1929 at Loch Fyne near the southern summit of Mt. Nordhoek. Together with some other Greenlandic rocks it is at present the object of an investigation by MALMQVIST the results of which will be published shortly. In that connection the chemical

analysis of the rock will also be given but it may be stated already now that this analysis does not differ essentially from analysis A of table II (page 208). The rock consists mainly of plagioclase, pyroxene and olivine and its texture is illustrated by fig. 3. Most interesting are, however, the relations between plagioclase and pyroxene which may be studied on fig. 4 and 5. It is observed how the large pyroxene grains are crowded by minute laths of feldspar which display a fluidal arrangement quite similar to that of the feldspars which are not surrounded by pyroxene. It is quite obvious that the plagioclase



Microphoto by the author.

Fig. 3. Olivine basalt from Loch Fyne, Greenland. Ordinary light. Magnification 14 diameters.

inclusions were consolidated at a time when the pyroxene material was still fluid. It is true that these feldspar inclusions are slightly smaller than the laths outside the pyroxene areas but the difference is rather insignificant. Thus even in this case it can hardly be doubted that by far the greater part of the feldspar crystallized distinctly in advance of the pyroxene.

Thus, from the description given above we are forced to conclude that the ophitic texture — in the restricted sense previously defined — must be due to a late crystallization of the pyroxenes and, indeed, there is no indication at all that even a slight crystallization of that mineral might have set in at an early stage. This result is entirely at variance with those reached by FENNER and BOWEN (*cf.* above p. 197). A somewhat closer study of FENNER's paper (5), however, seems to bring about

that the evidence which is brought forward by him refers to rocks whose texture should not be named ophitic. The microphotographs and drawings are rather indecisive. They are not easily interpreted but in the text there is stated that »the pyroxene is in stouter forms of an irregularly angular outline. The grains show a tendency to coalesce in groups of individuals of different extinction» (5: 224—225). Thus it seems rather probable that the texture in question is doleritic or subdoleritic but not ophitic. Consequently, the results of FENNER's investigation are not bearing especially



Microphoto by the author.

Fig. 4. Olivine basalt from Loch Fyne, Greenland. Ordinary light. Magnification 54 diameters.

upon the problem under discussion in this paper. As to BOWEN's statements (2) they do not — as far as the present writer has been able to find — include any unequivocal textural description. Because of that it is rather difficult to settle whether the facts brought forward by him may be of a more general application than those given by FENNER, or not. BOWEN — it is true — refers to some observations mentioned by the authors of the admirable Mull Memoir (1) which, indeed, seem to be fairly consistent with his conception. Thus, they state (1: 16): »It is noteworthy, however, that the ophitic augites of the Mull Plateau Type often completed their growth well within the crystallization-period of the associated feldspars». This is, of course, a very important statement, although it would have been desirable to find any further particulars concerning the facts upon which it is based. As to the textures the authors in question seem to make rather detailed distinctions but nevertheless one statement may rise some

doubt whether the texture which is here named ophitic is not really a sub-doleritic one. On page 137 of the paper cited above we may read: »In its structural relation to the feldspar (labradorite) the augite varies from thoroughly ophitic to hypidiomorphic. Where hypidiomorphic the augite may occur either in long crystals or equidimensional grains. In the latter case it determines a hypidiomorphic granular structure... The word granular is here substituted for JUDD's term granulitic as applied to the structure of basalt-lavas that have not suffered contact-alteration.» As char-



Microphoto by the author.

Fig. 5. Olivine basalt from Loch Fyne Greenland. Ordinary light. Magnification 54 diameters.

acteristic of the granulitic texture JUDD mentions (8: 68) that the pyroxene grains »assume more or less rounded outlines, and are imbedded in a plexus of lath-shaped crystals of feldspar; in polarized light these grains are seen not to be parts of one large crystal, but to have very different orientations». Comparing these two quotations it is rather difficult to realize how a variation from the ophitic to the granular texture may be possible.

### 5. Power of crystallization.

If, however, the texture in question is really sub-doleritic the difficulty disappears and in that case another strong evidence in favour of BOWEN's conception is withdrawn. And, indeed, even when admitting the possibility that the relations of the Mull rocks have been misinterpreted by the present writer and that their texture is decidedly ophitic it seems as if already the



facts described above from the Swedish and Greenlandic dolerites would exclude entirely the possibility of the generalisation which is made by BOWEN when assuming that in all basaltic magmas pyroxene and plagioclase crystallize together at a very early period. In support of this view BOWEN further refers to the fact that »it has never been shown in any basalt that *all or practically all* the plagioclase has crystallized and left pyroxene substance alone or practically alone as a glass base . . . In largely glassy types . . . the earliest microlites as well as any phenocrysts there may be are of both augite and labradorite.» (2: 69. Italics by BOWEN.) In this connection, however, two facts must be borne in mind. Firstly the proof is only a negative one and secondly the permanent presence of phenocrysts or microlites of pyroxene may be explained on purely physical grounds. DOELTER (4) has made laboratory investigations of the power of crystallization of several minerals. Of augite he states: »Er ist unter den gesteinsbildenden erprobten Mineralien dasjenige, welches die grösste Krystallisationsgeschwindigkeit und das grösste Krystallisationsvermögen besitzt, daher auch sehr schwer in glasigem Zustande zu erhalten ist; ferner wechseln beide mit der Temperatur stark, so dass man je nach den Temperaturgebieten bald grosse Krystalle, bald kleine Körner erhält, aber fast niemals Glas, sofern Unterkühlung überhaupt stattfindet». In order to give an idea of the quantitative relations a diagram from DOELTER's paper is reproduced below (*loc. cit.* page 613, fig. 6 of the present paper). It seems, indeed, very likely that those relations may be solely responsible for the permanent presence of pyroxene phenocrysts in largely glassy basalts.

Considering the influence of the power of crystallization we may, however, get a step further. BOWEN himself admits that objections may be raised against the evidence of these quenched glass phases as the basalts crystallized from strongly undercooled magmas the order of crystallization of which may not be directly compared with that of more slowly cooled masses. Against these objections he states (*loc. cit.* page 69): »This objection is not likely to favour the conception that the plagioclase separates out completely at an early stage in the more slowly cooled masses, for the more slowly a basaltic liquid is cooled the more its texture approaches the gabbroid which indicates essentially contemporaneous crystallization of pyroxene and plagioclase».

It must, however, be strongly doubted whether this argumentation is entirely valid. It postulates a relation that is hardly proved, *viz.* that there is a continuous change in the order of crystallization from undercooled magmas to more slowly cooled masses. Of course, the principal factors governing the order of crystallization is the chemical composition of the liquid and the thermal relations, but as DOELTER has pointed out (4 a) there are also some other factors which are generally of quite subordinate importance but may at circumstances attain an influence not to be neglected.

Such a factor is the power of crystallization. It has already been suggested that the early pyroxene phenocrysts in glassy basalts may be due to the very high power of crystallization of this mineral. Indeed, it is very likely that in such undercooled liquids the physical factors are of a greater influence than the chemical ones as controlling the order of crystal separation. If that be true we cannot compare directly the relations within these liquids with those of more slowly cooled magmas. It is most remarkable that BOWEN himself in another connection seems to be quite aware of the

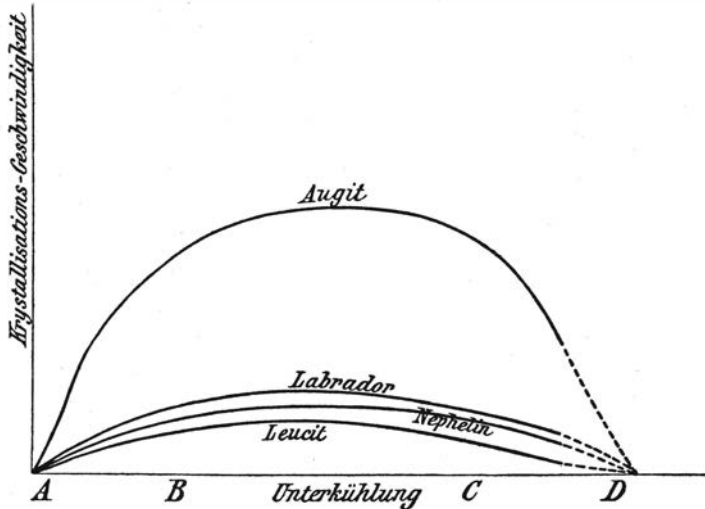


Fig. 6. Rate of crystallization of some rock-forming minerals. (After Doelter.)

necessity of this distinction: »In any case such rapidly cooled rocks are not reliable indications of the course of crystallization in slowly cooled magmas which are the only magmas of importance in connection with the problem of crystallization differentiation» (*loc. cit.* page 79).

Now, if accepting the impossibility of such a comparison we must admit that the tendency of basaltic magmas to assume a gabbroid texture in the course of slower cooling does not prove that at medium-rate cooling (dikes and minor intrusions) the plagioclase could not have crystallized essentially in advance of the pyroxenes.

## 6. Theoretical considerations.

However, BOWEN tries to support his conception not only by referring to the evidences of rocks but also by a deduction on purely theoretical grounds (*loc. cit.* pp. 64—66). That would thus seem to prove the quite general validity of his views. Consequently, the conclusion arrived at above as to the late crystallization of the pyroxenes in really ophitic rocks is

quite incompatible with this theoretical deduction. BOWEN starts from the system albite-anorthite-diopside experimentally investigated and on its triangular projection he erects a tetrahedron the apex of which is represented by  $\text{FeSiO}_3$ . This tetrahedron is reproduced after BOWEN as fig. 7 below.

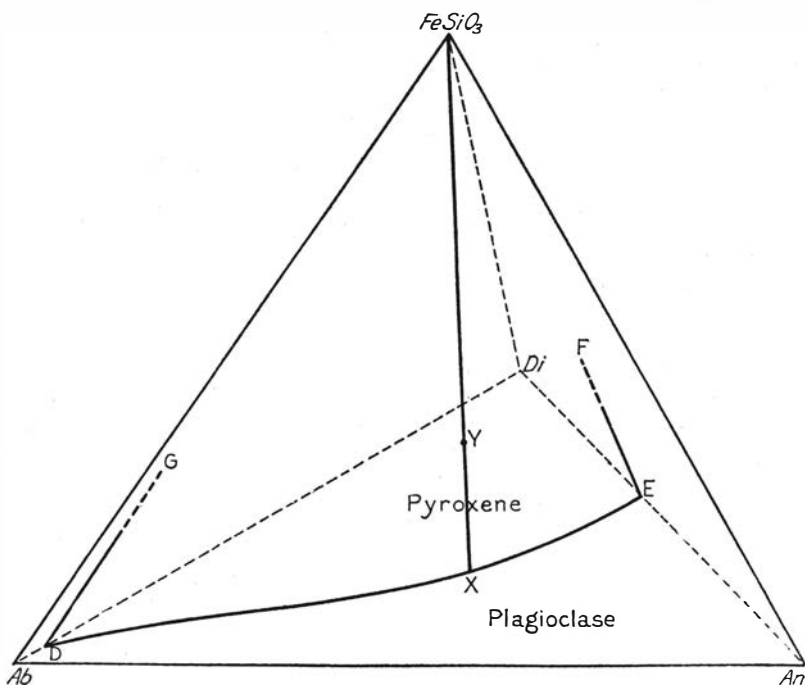


Fig. 7. Tetrahedron illustrating the composition of a quaternary liquid (Y) which approaches basaltic composition. After BOWEN.

Assuming the individualisation curve of the ternary system to rise into the tetrahedron BOWEN now states that a liquid of the composition Y (*cf.* fig. 7) must fall rather near the boundary surface thus formed. Consequently, no matter what mineral begins to crystallize first — plagioclase or pyroxene depending on the location of the point Y relatively to the boundary surface — the boundary must be reached rather soon and after that the crystallization will proceed as a simultaneous separation of both minerals. The mixture Y is recalculated by oxides and compared with WASHINGTON's average values of Deccan traps (**12**: 797). From the fairly good agreement of the two »analyses» BOWEN concludes that his theoretical liquid Y would illustrate the course of crystallization of basaltic magmas in general. In table II on page 208 the two »analyses» given by BOWEN and WASHINGTON are quoted. Further there are inserted two analyses of the Swedish olivine dolerites whose texture has been described above. It is immediately observed that the analysis A deviates but slightly more

from no. II than does no. I. As to the analysis B the agreement with the Washington average numbers except for the value of alumina is even more pronounced than that of no. I. Yet the rocks represented by A and B have been shown above to give unequivocal evidence of quite another course of crystallization than that deduced by BOWEN. From this fact it may be inferred that a generalisation of this theoretical deduction is not justifiable.

Table II.

	I.	II.	A.	B.
SiO <sub>2</sub> . . . . .	53.7	50.6	46.5	48.2
Al <sub>2</sub> O <sub>3</sub> . . . . .	13.2	13.6	16.9	18.1
FeO . . . . .	10.9	12.8	10.3	10.8
MgO . . . . .	6.1	5.5	9.8	5.9
CaO . . . . .	13.1	9.5	9.5	9.9
Na <sub>2</sub> O . . . . .	3.0	2.6	3.1	2.3
K <sub>2</sub> O . . . . .	—	0.7	0.6	1.5

I. Chemical composition of the quaternary mixture Y (*cf.* fig. 2) quoted from BOWEN.

II. Average chemical composition of Deccan traps (after WASHINGTON).

A. Chemical analysis of olivine dolerite from Krustorp, Sweden. Quoted from WINGE (13: 195).

B. Chemical analysis of the olivinebearing marginal facies of the central dolerite of the Breven dike, Johannisberg, Sweden. Quoted from KROKSTRÖM. (10: 303.)

In the analyses II, A and B all iron is stated as FeO and TiO<sub>2</sub>, H<sub>2</sub>O and minor constituents are omitted.

In a previous paper (10: 253) the present author has given several geometrical analyses of the rock represented by the analysis A. of table II. As the rock in question over a large area of extension shows a remarkable mineralogical constancy an average of these analyses would probably give a fairly good idea of its main mineralogical composition. In table III such an average is given.

Table III.

Average of eight geometrical analyses of the western olivine dolerite of the Breven dike, Sweden.

	Weight-%.
Plagioclase (Ab <sub>32</sub> An <sub>68</sub> —An <sub>22</sub> An <sub>78</sub> ) . . . . .	61 %
Pyroxene (For composition see below) . . . . .	15 %
Olivine (24—32 % fayalite silicate) . . . . .	21 %
Accessories (Mainly ore) . . . . .	4 %

About a third of the total pyroxene amount is made up by orthopyroxene with 42 % FeSiO<sub>3</sub> and the rest by a clinopyroxene of the approximate composition 45 % MgSiO<sub>3</sub>+30 % CaSiO<sub>3</sub>+25 % FeSiO<sub>3</sub>.

If the rock of table III could be represented within BOWEN's tetrahedron its projective point would fall at a good distance from the boundary surface and the deviation would be in the plagioclase direction. Further the point would occupy a rather high position with respect to the  $\text{FeSiO}_3$ -corner. In consequence of the constituents chosen for the tetrahedral projection, however, this rock may not be projected into it although its chemical composition, as has already been shown, agrees fairly well with the average basalt. This is a most remarkable fact that holds for many rocks of »basaltic» composition. Thus already this inconsistency seems to advise against attributing too great an importance to the deductions from the quaternary system in question. Moreover, it may be doubted, whether this mode of projection is correct theoretically. The system albite-anorthite-diopside consists of four components, *viz.*  $\text{CaO}$ ,  $\text{MgO}$ ,  $\text{Na}_2\text{O}$ , and  $\text{SiO}_2$ , but it may be represented as a ternary (or rather pseudoternary) one because from a mixture of the components no compound is formed which cannot be represented within the triangle. When adding  $\text{FeSiO}_3$ , however, this condition is not likely to hold good as olivine may most probably form from liquids within the tetrahedron thus obtained but cannot be represented in it. We must thus bear in mind that the system is a five-component one and the condition is not *à priori* given that would allow us to represent it by a tetrahedron as a pseudo-quaternary system. In view of these considerations it must be questioned if any inference gained from the study of this tetrahedron (of which, furthermore, only the basis is sufficiently known) is bearing upon the problem just under discussion.

Now, it may be objected against the above considerations that they all refer to olivine-bearing rocks which were formed from undersaturated magmas. This quality — undersaturation — is apparently not characteristic of the parental magma suggested by BOWEN. Although it may be true that a great number of olivine-rich rocks were formed by crystal accumulation — as is convincingly argued by BOWEN — it must, of course, be supposed that even really undersaturated magmas exist. It is rather difficult, otherwise, to realize how such magmas might generate on a large scale from a saturated parental liquid by crystallization only. As will be evident later on the writer is not inclined to accept the view that all rocks have derived from a single parental magma but it may be agreed that a rather large group of rocks may have originated from a single liquid of about basaltic composition. This liquid, however, ought to have been undersaturated in silica. This assumption is further supported by the following considerations. Of course, it shall not be denied that a basaltic magma *may* display the order of crystallization claimed by BOWEN but the mere occurrence of rocks showing another order implies a great difficulty if the parental liquid is assumed to have been saturated in silica. If we start from such a liquid and accept the postulate that its composition would necessitate a simulta-

neous crystallization of pyroxene and plagioclase, then it is very difficult to explain how by any mode of crystal separation a magma might generate that, on further cooling, would precipitate plagioclase but no pyroxene in the early stage of crystallization. That would imply a sudden hiatus in the formation of pyroxene, a phenomenon that would be entirely at variance with all experience. However, magmas of the last-mentioned type undoubtedly exist as was shown above. The difficulty is avoided if we assume the original magma to have been undersaturated. Then plagioclase and olivine crystallized almost simultaneously and not before the saturation point was reached pyroxene began to separate. At this time the very greatest part of the plagioclase had already consolidated and the residual liquid of a *pyroxenic composition* when congealing could embed the plagioclase laths ophitically or subophitically.

It may thus be safely concluded that the information gained from olivine-bearing rocks is of as great an importance as the evidence of olivinefree ones.

The author has examined summarily a rather great number of dolerites, diabases and basalts from different Swedish localities. In view of the above considerations it was most interesting to find that the extremely well-developed ophitic texture was encountered only in the olivine-bearing types. That ought to prove the correctness of the deductions given above.

## 7. Fractional crystallization and rock genesis.

Of course, the above considerations must have certain consequences as regards the conception of rock genesis in general. Already in 1926 FENNER (5 a) objected against BOWEN's views that all rocks, even those of a granitic composition, should have derived from a parental magma of basaltic type and later on he has still more emphasized this opinion (5 b, 5 c). It is hardly needed to recapitulate his rather convincing arguments as they ought to be familiar to most petrologists. It is most remarkable, however, that in the present paper considering the problem from an almost entirely different point of view much the same result is arrived at as was previously reached by FENNER.

The problem may be put in two distinct questions, *viz.*:

1:0 May a residual liquid of granitic composition generate from a basaltic magma by means of crystallization?

2:0 In such a case, may the world granites be accounted for by such residual liquids?

As to the first question it has been suggested in the previous pages that the evidence of rocks does not tend to confirm an evolution in a granitic direction of a basaltic magma. As the same view has been con-

vincingly defended by FENNER it would perhaps be unnecessary to take the second question under consideration. Yet we shall call attention to some facts of interest.

Accepting the opinion suggested above, *viz.* that the parental magma of most basaltic rocks was undersaturated in silica and admitting that from this parental liquid a saturated magma of basaltic composition may generate by crystal separation we shall try to follow the evolution of this »secondary» liquid a little further. Because of the fundamental principle that — eutectic crystallization provided — the precipitation of any mineral species must be continuous and considering the previous evolution of the liquid we are compelled to assume that even the very earliest phase of a further crystallization must be characterized by a separation of plagioclase. Thus it seems to be quite out of question that in such a magma pyroxene should be able to crystallize in advance of the feldspars. On the contrary, it is most probable that these two minerals began to separate simultaneously because the largest excess of plagioclase had crystallized already during the period of olivine formation. Indeed, it has been given above several examples of pyroxene embedding those early plagioclase laths.

Now, several authors have objected against BOWEN's views that it seems rather inconsistent to think of granites and related rocks as formed from residual solutions as it is a well-known fact that just these rocks are quantitatively dominating in the earth's crust (*cf.* for instance 3). FENNER also tried to give a comprehension of the quantitative relations of the different liquids successively appearing within the triangle albite-anorthite-diopside (5 a: 764). He found that before a granitic composition was reached more than 88 % of the original basaltic magma must have been used up. It must be admitted that this calculation is somewhat misleading as FENNER assumes the original magma to occupy a position rather near the diopside corner whereas BOWEN (*loc. cit.*, p. 65) emphasizes that his basaltic parental liquid is not likely to deviate essentially from the boundary curve of the triangle (*cf.* fig. 7 on page 207). If due consideration is given to that statement the percentage reached by FENNER becomes somewhat too high. If, however, the original liquid was undersaturated in silica every liquid within the triangle must be considered as a residual one generated by the separation of olivine which was accompanied by a simultaneous crystallization of plagioclase. It seems probable that during these processes a rather important part of the original liquid was used up before the saturation point was reached. Thus the correction of FENNER's value of 88 % necessitated by the location of the starting point on or very near the boundary line is probably more than counterbalanced by the process lastly considered. Consequently, if we accept the undersaturated character of the parental magma we may safely emphasize still more the objection raised by FENNER against considering the large rhyolitic extrusions and the

large granitic batholiths to be such a very small percentage of a basaltic magma.

A rough estimate of the rock distribution of the Breven dike shows that about 40 % of the total area is occupied by purely granitic rocks. Admitting the difficulty of drawing general conclusions from such a measurement in a single section it must nevertheless be considered very probable that the bulk composition of the dike comprises an amount of granite that may hardly be explained as a residual portion. Now, it has been urged by the present author (10) that this Breven granite is due to a distinctly later intrusion than the doleritic parts of the dike but emanating from the same magma basin. The dominating rôle of the granite may then be explained by the assumption that at the time when the liquid had become granitic the energy of intrusion was greater than during the earlier stages. But even in this case great difficulties arise against an application of the theory of differentiation by crystallization. The olivine-free dolerite — which is the most acid rock belonging to the early intrusions — when intruding could not have left behind a liquid of such a composition that it might congeal as a granophyre. Because, the least calcic plagioclase of the dolerite still contains about 25 % An while in the granophyre An is practically wanting and similar discontinuities may be traced with respect to the other minerals too. As there are no traces of a primary rock intermediate between the dolerite and the granophyre we are compelled to assume that the granitic magma was generated in consequence of gravitative settling of basic minerals. The lower parts of the magma reservoir would then have been filled by a sort of crystal »porridge» of a basic composition. In view of these considerations it is rather difficult to account for the very latest magmatic manifestation within the dike, *viz.* a finegrained and sometimes glassy rock the composition of which does not differ essentially from the main olivine dolerite (10: 280—288). Had this rock been the result of a pouring out even of the last residua at the bottom of the magma chamber we should expect to find a coarsely porphyritic rock with a very sparse *mesostasis* of a rather acid composition. And, if we don't admit the possibility that the bottom portions might have been brought up, then the last basic extrusion remains wholly inexplicable. The same difficulty is met with in all cases when a magmatic cycle of increasing acidity ends by an intrusion (extrusion) of basic material. Yet this seems to be a very common evolution as is easily inferred from almost all petrological descriptions of volcanic cycles. Several instances are quoted in the Breven paper (10: 322).

#### 8. Some aspects of liquid immiscibility.

The present author does not wish to defend the theory of liquid immiscibility in silicate systems but it should be pointed out that the pheno-



mena last considered are far more readily explained by that theory. The increasing acidity of the successive intrusions is due to a proceeding unmixing accompanied by a gravitative separation of the heavy basic portions. At the last stages of the magmatic activity the waning intrusive energy does not suffice to carry upwards the acid liquid of increasing viscosity, while the more mobile basic portion may still continue, to some extent, the intrusion (extrusion) act. As already stated these suggestions are not made in order to claim that in the formation of the Breven dike liquid immiscibility has been necessarily operating. Such a statement would by no means be sufficiently supported. Yet the above considerations show that the liquation theory may sometimes offer a fairly good explanation where the fractional crystallization seems to go short.

Against the theory of rock differentiation by liquation BOWEN (2: 9—10) argues, *inter alia*, that any rock formed in that way must necessarily show a blotchy appearance as unmixing must proceed until crystallisation sets in. This inference is gained from the diagram (fig. 8) which is quoted from BOWEN. He states: »If, for example, cooling were interrupted at some temperature between FK and ED and time allowed for the accumulation of all the globules as a separate layer, as soon as cooling was resumed new globules would form in *each layer*, and their accumulation by the slow process of gravitative adjustment would begin again. It is plain then, that, whatever complications are assumed, the magma must arrive at the temperature ED in a blotchy condition . . .» (Italics by BOWEN).

Now, let us take up some quantitative considerations. A calculation from the diagram fig. 8 brings forward that the liquid K has a composition 34% A + 66% B while the liquid D shows 31,8% A + 68,2% B. In order to convert K into D, globules of A must separate to an amount slightly less than 3,2% of the total of K. Moreover, this figure is a maximum value as the liquation curve is likely to be considerably steeper than in the diagram given. Indeed, in the later stages of the liquation process even the formation of 1 à 2% globules ought to require a considerable

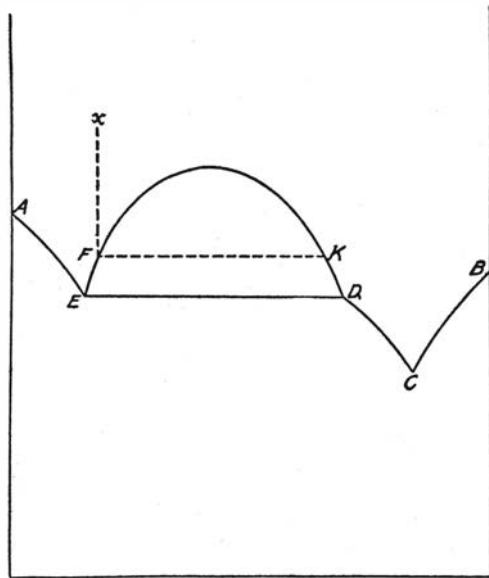


Fig. 8. Diagram illustrating behaviour of a binary mixture with partial miscibility. After BOWEN.

cooling and as cooling proceeds, the formation of new globules is probably entirely counterbalanced by the gravitative settling of the older ones. Thus, provided that after the system has passed the uppermost parts of the liquation curve, time is allowed for a separation of two distinct layers, then it may hardly be assumed that these layers contain at any time more than 1 à 2 % of globules. Whether the condition of an interruption of cooling is likely to be satisfied or not depends, of course, on the absolute temperature at which unmixing begins. If this condition is kept, however, the blotchy appearance of a rock intruded at any later stage must be rather insignificant. It is well-known to every petrologist who has made some geometrical analyses, how far inconspicuous a constituent is that amounts to 2 % only of the total. Indeed, the interstitial granophyre fillings of many basalts and dolerites generally exceed this percentage several times.

In this connection a few words should be added concerning a statement of BOWEN's. He writes (*loc. cit.* p. 11): »Referring to the actual results obtained by GREIG we find that, of important rockforming oxides, CaO, MgO, FeO and Fe<sub>2</sub>O<sub>3</sub> show immiscibility with SiO<sub>2</sub> but only at high silica concentrations, whereas Na<sub>2</sub>O, K<sub>2</sub>O and Al<sub>2</sub>O<sub>3</sub> show complete miscibility with SiO<sub>2</sub> in all concentrations. No rocks are known which have the compositions required for the appearance of immiscibility on the basis of these data. Rocks of high silica content never have CaO, MgO and FeO as the principal additional constituents; on the contrary they are always rich in Al<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O and K<sub>2</sub>O.»

Unless the present author has entirely failed to understand BOWEN's views, the statement of the last two sentences may hardly be used as an argument against the appearance of liquid immiscibility in nature. If there were really rocks with high silica together with an elevated content of CaO, MgO and FeO, then the operation of liquid immiscibility would be disproved. The fact that such rocks have not been found, however, though proving nothing, seems to support the assumption that the immiscibility relations experimentally found by GREIG (5 d) do play some part in the genesis of rocks.

## 9. Conclusion.

On the preceding pages a lot of facts have been presented that seem to be rather inconsistent with a universal application of the theory of fractional crystallization. It is frankly admitted that some of these facts are rather special and no general conclusions may be drawn from them. But they appear to demonstrate that the generalisations made by BOWEN on theoretical grounds may not be universally valid. Of course, this statement by no means implies that fractional crystallization may not be a very important factor governing the formation of rocks. It must only be realized

that its general applicability is not sufficiently proved and that several possibilities of explanation must be taken into consideration in every special case.

It may appear that some parts of this paper have taken the form of a criticism of Dr. BOWEN's works. It is, however, quite impossible to touch upon these problems without discussing several of his suggestions and it is thought that the very important question of rock formation and rock differentiation may be solved only by such a discussion. The present writer wishes to express his profound admiration of the fundamental and elaborate investigations made by Dr. BOWEN and he hopes it will be realized that no air of controversy is aimed at. The above discussion is only a modest attempt to give some contributions to the solution of a central problem of modern petrology.

*Mineralogical and Geological Institution of the University of Upsala.  
March 1932.*

### List of References.

1. BAILEY, E. B. and others. Tertiary and post-tertiary geology of Mull, Loch Aline, and Oban. Edinburgh 1924.
2. BOWEN, N. L. The evolution of the igneous rocks. Princeton 1928.
3. DALY, R. A. Igneous rocks and their origin. New York 1914.
4. DOELTER, C. Krystallisationsgeschwindigkeit und Krystallisationsvermögen geschmolzener Mineralien. Centralblatt für Mineralogie etc. 1903, 608—619.
- 4 a. — Ueber einige petrographische Fragen. Centralblatt für Mineralogie etc. 1902, 545—551.
5. FENNER, CL. N. The crystallization of a basaltic magma from the standpoint of physical chemistry. American Journal of Science, 29 (1910), 217—234.
- 5 a. — The Katmai magmatic province. Journal of Geology XXXIV (1926), 673—772.
- 5 b. — The crystallization of basalts. American Journal of Science XVII (1929), 225—253.
- 5 c. — The residual liquids of crystallizing magmas. The Mineralogical Magazine XXII (1931), 539—560.
- 5 d. GREIG, J. W. Immiscibility in silicate melts. American Journal of Science 13 (1927), 1—44, 133—154.
6. HOLMES, A. The basaltic rocks of the arctic region. The Mineralogical Magazine, 18 (1918), 180—223.
7. JOHANNSEN, A. A descriptive petrography of the igneous rocks I. Chicago 1931.
8. JUDD, J. W. On the gabbros, dolerites and basalts of Tertiary age in Scotland and Ireland. Quarterly Journal of the Geological Society of London, 42 (1886), 49—97.

9. KEMP, J. F. A handbook of rocks for use without the microscope. 2d. ed. New York 1900. (As this paper was not accessible to the author it is quoted after JOHANSEN, no. 7 of the above list).
10. KROKSTRÖM, T. The Breven dolerite dike. A petrogenetic study. Bulletin of the Geological Institution of Upsala, 23 (1932), 243—330.
11. ROSENBUSCH, H. Mikroskopische Physiographie der massigen Gesteine. Second Edition, Stuttgart 1887.
12. WASHINGTON, H. S. Deccan traps and other plateau basalts. Bulletin of the Geological Society of America, 33 (1922), 765—804.
13. WINGE, K. Om diabas-granitgängen vid Breven. (On the dolerite-granite-dike at Breven). Geologiska Föreningens i Stockholm Förhandlingar (Transactions of the Geological Society of Stockholm) 18 (1896), 187—200.

*Printed 7/4 1932.*

