The Muddy Creek Formation at Colorado River in Grand Wash: The Dilemma of the Immovable Object

by

Earl M. P. Lovejoy[1]

Abstract

It has previously been noted that the Colorado River could not have flowed west through Grand Wash contemporaneously with deposition of the Muddy Creek fanglomerates. This paper suggests that the Colorado River turned sharply south in Grand Wash and flowed into Red Lake Valley in "Muddy Creek time." Sandstones in Grand Wash at the mouth of Grand Canyon are considered here to be gravel-deficient river sands, gradational with the contemporaneous fanglomerate laterally and with the younger and higher Hualapai limestone vertically. If this is correct, then the earlier course of the Colorado River could have been through Grand Canyon to Grand Wash throughout Cenozoic time, following its Paleogene origin as an obsequent stream; thus, the Muddy Creek Formation in Grand Wash need not be considered the "immovable object" that Hunt considered it to represent, and the evidence upstream of an early origin for the river system, Hunt's "irresistible force," becomes compatible with the evidence at Grand Wash.

Introduction

Hunt (1956) summarized evidence from the Colorado Plateau that indicates a great span for the period of post-uplift erosion, Hunt's "irresistible force." The Muddy Creek Formation, a Pliocene fanglomerate, lies athwart the course of the Colorado River at Grand Wash (Fig. 1) in a position believed by Blackwelder (1934), Longwell (1946), and Lucchitta (1966) to imply that the river could not have flowed through Grand Wash prior to or during deposition of the Muddy Creek fanglomerates, the "immovable object" of Hunt (1956). The dilemma of the "irresistible force" and the "immovable object" has led many to seek either alternative courses for the Colorado River, either to the south through the Peach Springs and Truxton Valleys, or to the north near St. George, Utah, or alternatives to the fluvial process, prior to deposition of the Muddy Creek sediments (Hunt, 1969; Goetz and others, 1975).

Longwell (1946) wrote:

> One of the major unresolved problems of the region is the date of the origin of the Colorado River itself as a through-flowing stream in its present course . . . Solution of this problem would throw a flood of light on regional Tertiary events and relationships that are now obscure [p. 817]. [And] it is not possible to outline a full history of the Colorado River without resort to speculation [p. 834].

Neither Blackwelder (1934) nor Longwell (1946) believed that the Colorado River could have flowed through Grand Wash before or during deposition of the Muddy Creek Formation. Lucchitta (1966, 1967, 1972) and Goetz and others (1975) have accepted their interpretations and have presented a hypothesis for an alternative course for the Colorado River north of its present position. Shoemaker (1975) has extended this concept and hypothesized a course all the way to the Pacific Ocean across Nevada prior to development of basin-and-range structure. Thus, the hypothesis conceived by Blackwelder (1934) and fortified by Longwell (1946) remains with us.

Nevertheless, on the basis of regional studies in the Basin and Range and Colorado Plateau provinces, I believe that an alternative hypothesis based on the available evidence might provide a reasonable and alternative answer to some of the "major unsolved problems" of the region. If the alternative interpretation of the evidence at Grand Wash offered here is reasonable, the Grand Wash dilemma may not exist because the "immovable object," the Muddy Creek Formation at Grand Wash, would then

[1]Department of Geological Sciences, The University of Texas at El Paso, El Paso, Texas 79968.

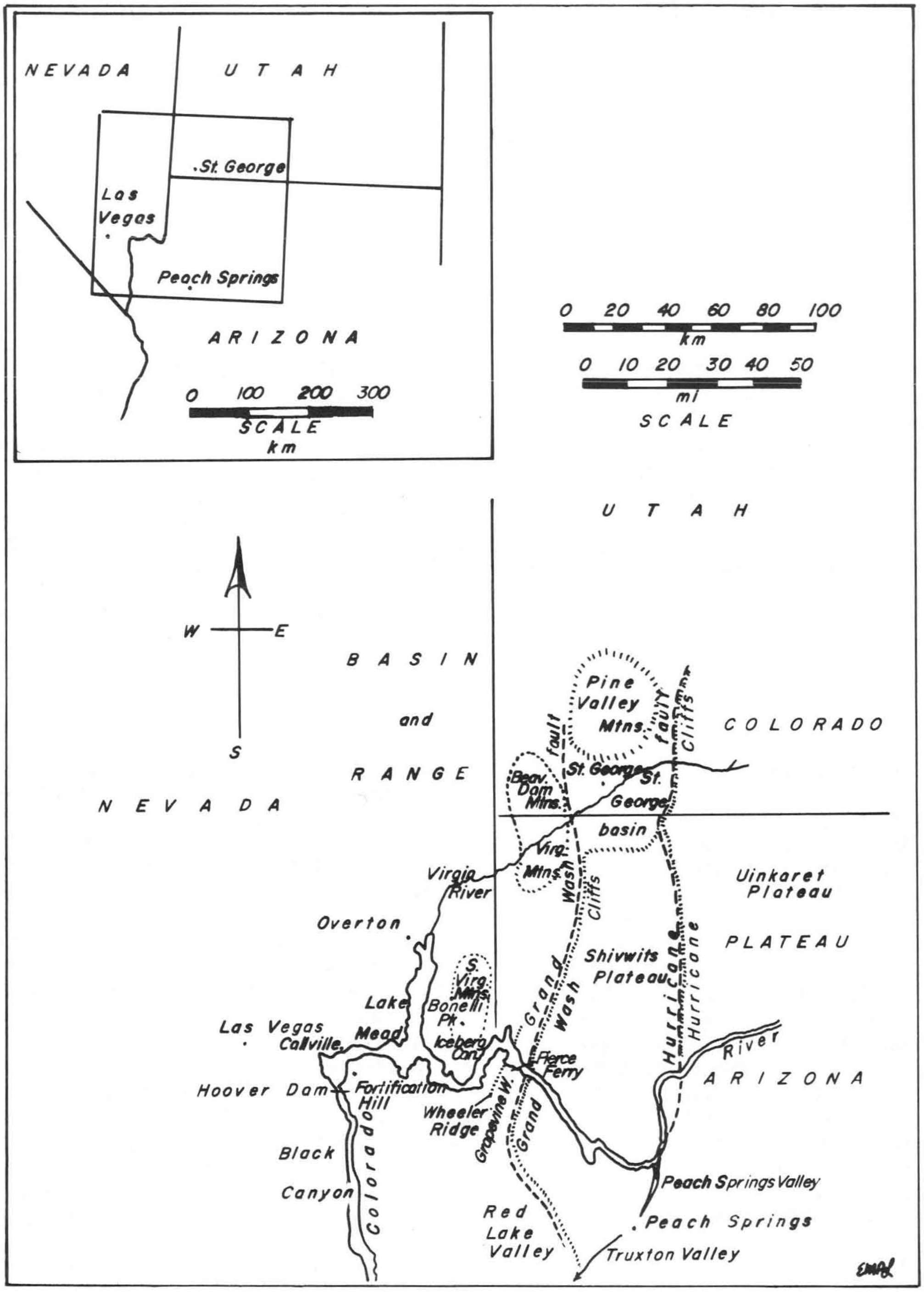

Fig. 1. Index map of study area.

be shown not to have been "immovable" after all.

As Blackwelder (1934, p. 564) noted: "Science advances not only by the discovery of facts but also by the proposal and consideration of hypothesis . . ."

Time of Uplift of the Colorado Plateau

Solution of the problem at Grand Wash depends greatly on the determination of the period of relative uplift of the Colorado Plateau with respect to the Basin and Range province along its great boundary faults, the Grand Wash and Hurricane faults. Longwell (1945) believed that the Grand Wash fault was of Laramide age. Shoemaker (1975) is the latest in a long list of workers beginning with Gardner (1941) who have presented substantial and cogent evidence that the Colorado Plateau uplift began as late as Miocene time. Certainly, a Pliocene uplift (McKee and others, 1967) after deposition of the Muddy Creek deposits at Grand Wash is not possible because the Muddy Creek Formation has not been displaced in Grand Wash along the Grand Wash fault (cf. McKee and McKee, 1972, and Lovejoy, 1973b). Indeed, Anderson and Mehnert (1979) have concluded that most if not all of the Colorado Plateau uplift on the Hurricane fault occurred in the Quaternary. However, there is excellent evidence along the only place in the Hurricane fault zone where the date of faulting can be clearly demonstrated that 85 percent of the stratigraphic separation on the Hurricane fault occurred in pre-Miocene time and that faulting had begun in Paleocene time (Lovejoy, 1964, 1973a, 1978b). Further, evidence along the northern extension of the Grand Wash fault (Moore, 1972), which Dobbin (1939) termed the "Cedar Pocket Canyon fault," indicates a pre-Miocene period for most of the stratigraphic separation on that fault (Lovejoy, 1976a). Evidence supplied by Young and Brennan (1974) is interpreted to indicate major fault movement prior to 17 m.y. ago.

I suggest that a Laramide age for the Colorado Plateau uplift ought to be considered as a basis for further geomorphic analysis. Therefore, alternative explanations for the genesis of the Colorado River, tied to the tectonics of the region, as noted by Longwell (1946), perhaps might be considered in addition to those of McKee and others (1968); but compare Hunt (1968), Lucchitta (1972), and Hamblin (1970) and other contributors to the literature on the subject.

Late Neogene Stratigraphy at Grand Wash

Blackwelder (1934) and Longwell (1946) considered the Muddy Creek Formation to represent a great amount of boulder gravel transported east from the vicinity of Bonelli Peak (Figs. 2 and 3) to the foot of the Grand Wash Cliffs. Boulders up to 6 m long of Rapakivi granite (Volborth, 1962) traceable to Bonelli Peak moved east down a piedmont slope. They lie on both sides of the west-flowing Colorado River east of Wheeler Ridge; the surface lag boulders represent a disproportionately large part of the clasts on the present surface (Figs. 4 and 5).

The Muddy Creek Formation fills a depositional trough west of the Grand Wash Cliffs. The plateau block was uplifted with respect to the Basin and Range province to the west along the Grand Wash fault prior to "Muddy Creek time," because as Longwell (1945) showed, the fault lies buried beneath the unfaulted Muddy Creek Formation in Grand Wash. Along the west side of Grand Wash is Wheeler Ridge, composed of Paleozoic strata, which dip up to 70° E. in an excellent example of reverse drag (cf. Longwell, 1945). On the west side of Wheeler Ridge is Wheeler fault, which has displaced Muddy Creek strata down on the west side only 500 to 1,200 feet (150 to 360 m) (Lucchitta, 1966, p. 140-142), several kilometers west of the buried Grand Wash fault. Stratigraphic separation on Grand Wash fault is unknown, although Longwell (1945, p. 114) suggested that it might be as much as "20,000 ft" (6,100 m). Thus, at Grand Wash, post-Muddy Creek throw represents less than 6 percent of the Cenozoic fault throw.

The pertinent late Neogene stratigraphy in Grand Wash includes, among others, three units important in this analysis: (1) the fanglomerate facies of the Muddy Creek Formation noted by Blackwelder (1934), (2) "the sandstone-siltstone facies" of the Muddy Creek Formation noted by Lucchitta (1966, p. 99-105), and (3) the Hualapai lacustrine limestone noted by Longwell (1946).

The Fanglomerate Facies of the Muddy Creek Formation

The fanglomerate facies or piedmont deposits described by Blackwelder (1934) and Longwell (1946) consist of a sequence of fanglomerates up to 90 m thick, which contains clasts of Rapakivi granite and schists derived from the west. The bulk of the deposit consists of cobbles and small boulders of schist and granite derived from the Precambrian terrane 8-10 km west of Grand Wash. Lake Mead now locally covers its base in Grand Wash. Where it lies on the Kaibab Formation east of Wheeler Ridge local accumulations of Paleozoic carbonate cobbles and boulders occur, but nowhere are they stratigraphically higher than 10 m above their contact with the limestone; these cobbles were locally derived from the Kaibab formation of Wheeler Ridge as it was being buried by Muddy Creek boulders from the west. The Rapakivi granite boulders were probably carried in mud flows down the old (now deeply dissected) pediment surface between Bonelli Peak and Grand-Grapevine Wash. This facies can be followed south 40 km from the Colorado River along the west flank of Grapevine Wash. Thus, conditions leading to deposition of the fanglomerate facies must have been the same along the west

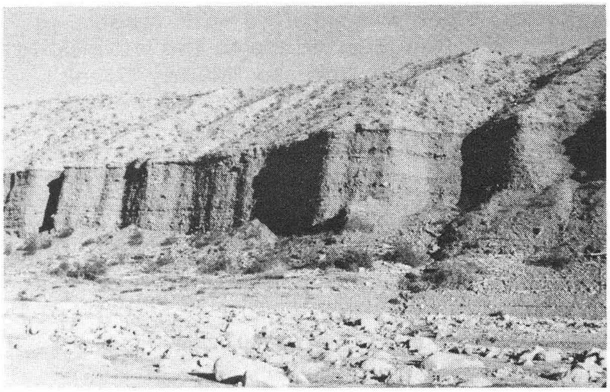

Fig. 2. Exposures of the Muddy Creek Formation bolson fanglomerate on the north side of Colorado River about 1 km east of Wheeler Ridge.

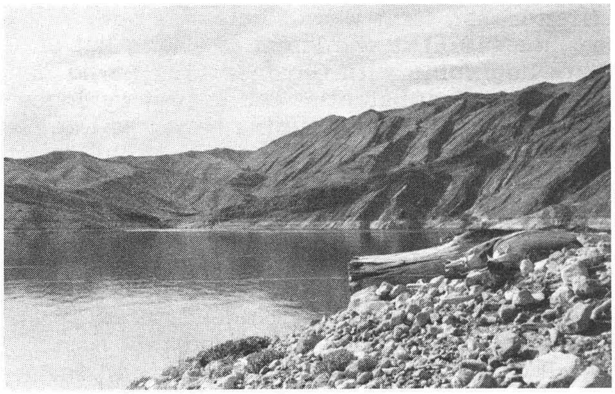

Fig. 3. Muddy Creek fanglomerate resting unconformably on steeply dipping upper Paleozoic carbonate rocks on the east side of Wheeler Ridge. View is toward southwest.

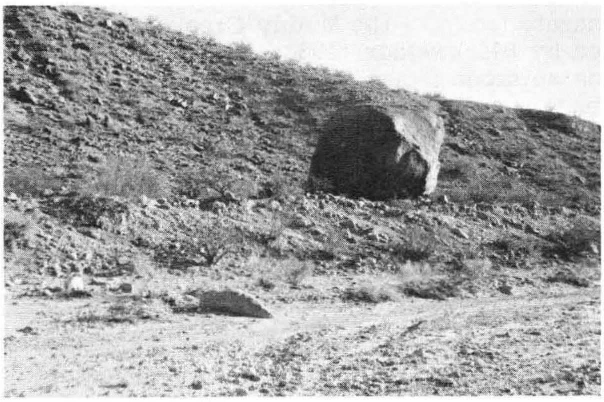

Fig. 4. "Lag" boulder of Rapakivi granite on north shore of upper Lake Mead about 1 km east of Wheeler Ridge.

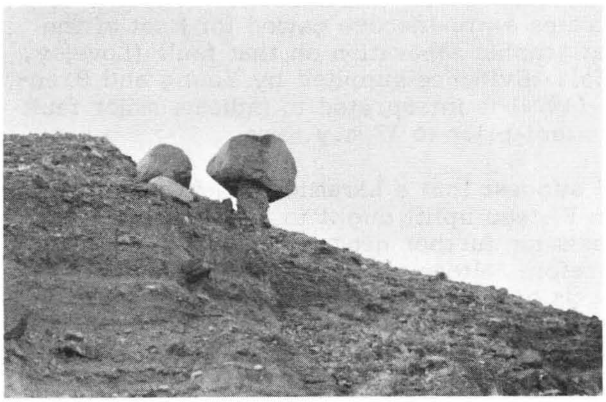

Fig. 5. Pedestal formed by boulder of Rapakivi granite on north shore of Lake Mead east of Wheeler Ridge.

side of present Grapevine Wash south for a distance of 40 km almost to Red Lake Valley.

As Blackwelder and Longwell realized, the river could not have flowed west through Grand Wash at the time of deposition of these materials. Lucchitta (1966, p. 115-116) showed that large indigenous "Muddy Creek" fan deposits derived from the Grand Wash Cliffs north of the present Colorado River extended out into Grand Wash, hence the Colorado River could not have flowed north in Grand Wash in "Muddy Creek time." However, similar deposits do not occur south of the river along the edge of Grapevine Wash (Lucchitta, 1966). The fanglomerate dips from up to 15° E. where it lies on the Kaibab Formation on the east side of Wheeler Ridge to horizontal in the center of Grand Wash, probably initial dip.

The Sandstone-Siltstone Facies of the Muddy Creek Formation

The sandstone-siltstone facies consists of well-bedded quartzose, fine-grained sands, and silts at least 100 m thick along the Colorado River, where the base is covered by Lake Mead. This facies lies unconformably on the Paleozoic beds at the base of Grand Wash Cliffs in some places, with only minor gravel from the overhead Paleozoic strata, a point of major significance in Longwell's (1946) analysis.

Bedding dips up to 8° W. at the base of the lower Grand Wash Cliffs, probably initial dip. South of the river the sandstone lies on slightly dropped landslide blocks, indicating that the lower Grand Wash Cliffs existed during "Muddy Creek time" essentially as they do today. Only a high and rugged cliff could have produced such blocks. The lower Grand Wash Cliffs that have been protected from erosion by burial beneath Muddy Creek sediments are now exhumed. Their present aspect is essentially that which they had in "Muddy Creek time" except for the minor erosion that has affected them since exhumation. The upper Grand Wash Cliffs have receded variable distances and have undergone erosion not only since the time when the lower cliffs were buried but for a much longer period in the Cenozoic (Longwell, 1946; Lucchitta, 1966).

The presence of indigenous carbonate fanglomerate gravel in the sandstone along the base of the cliffs but absence of exotic rounded river gravels in the sandstone led Blackwelder (1934) and Longwell (1946) to believe that no river could have existed here during deposition of Muddy Creek sediments. Indigenous carbonate gravels are interbedded with the sands at the mouths of local steep canyons.

North of the river, as noted by Lucchitta (1966), the exposed Muddy Creek Formation contains, among other rock types, alluvial limestone fanglomerates along Grand Wash Cliffs. South of the river younger colluvium and alluvium cover the base of the Muddy Creek Formation in Grapevine Wash where it lies on pre-Cenozoic rocks.

In my opinion, the two Muddy Creek facies sediments noted here were deposited, respectively, on (1) a long east-sloping pediment of the southern Virgin Mountains and (2) a short fluvial to deltaic, sublacustrine, gently west sloping surface originating at the foot of Grand Wash Cliffs at Grand Canyon. Similar modern deposits are forming in upper Lake Mead east of Grand Wash in the lower Grand Canyon. These two original slopes formed the sides of a broad depositional basin in the vicinity of present Pierce Ferry. The sands may have been deposited at an initial dip west, perhaps modified by later compaction or tilting; the western fanglomerate was deposited at a steeper initial dip east. This basin, partly filled with a south-flowing river and then a lake on its east side in the early stages, maintained its form through the period of clastic infilling of the Grand-Grapevine Wash because materials came simultaneously from both east (river) and west (fanglomerate). Dips of the two facies differ because sublacustrine transport of the eastern fine-grained facies required gentle slopes, whereas subaerial pediment surface mudflow transport of the fanglomerate required steeper slopes.

Lucchitta (1966, p. 99-105) thoroughly described this sandstone, calling it the "sandstone-siltstone" facies, the name used here, and noted not only its absence north of Lake Mead where it does not occur at the level of the river but its probable extension south beneath the Hualapai Limestone of Grapevine Mesa. He observed cross-bedded micaceous sandstones interbedded with coarse-grained fanglomerate to the west. He noted specifically that in "the Grapevine Wash subbasin, the fine-grained deposits underlie an area centered on Pierce Ferry and are well exposed along Grapevine Wash [p. 102]." Lucchitta (1966, p. 115-116) showed that Muddy Creek alluvial fans derived from the Grand Wash Cliffs extended far out into the basin north of the present Colorado River and that the sandstone-siltstone facies did not extend north of the present river. No river gravels occur in this sandstone.

Although Lucchitta (1966) fully described this "sandstone-siltstone" facies at the mouth of Grand Canyon in Grand Wash, in his description of the Lake Mead Area," Lucchitta (1972, p. 1939-1940) did not consider this unit to constitute important evidence of the presence of the Colorado River in Grand Wash in Muddy Creek time, because he wrote: "No evidence for an ancestral Colorado River debouching from the Colorado Plateau in Muddy Creek time, as suggested by Lovejoy (1969), is present in Muddy Creek deposits of the Grand Wash trough." Blair (1978, p. 1159) notes that "a basalt . . . in the lower part of the Muddy Creek Formation, has been dated at 10.9 ± 1.1 m.y."

The Hualapai (Hualpai) Limestone

Near Grand Canyon, remnants of Hualapai limestone (Longwell, 1946) form a large mesa south of the Colorado River and east of Iceberg Canyon. Several patches of similar limestones lie west of the Wheeler fault south of Lake Mead about 150 m lower than those at Grand Wash (Wilson and Moore, 1959). The Hualapai limestone seems to have formed along the southeast shallow shores of a lake. An air-fall tuff within the Hualapai Limestone Member has been dated at 8.44 ± 2.2 m.y. B.P. (Blair, 1978, p. 1159). Its present maximum elevation near the Colorado River is 2,950-3,000 feet (900-915 m).

Blair (1978), utilizing evidence and analysis based on chert, carbon isotope ratios, and fossils, interpreted the Hualapai limestone as marine, thereby implying an uplift of 900-915 m above sea level in 8 m.y. Cornell (1979) concluded that the analysis based on chert is specious, that the carbon isotope data fall in the range of lacustrine limestones, and that six species of environmentally tolerant fossils do not prove a marine environment.

Pre-Hualapai lake sediments and evaporites appear to have partly filled closed basins so that water depth around the southeastern shore was probably shallow from Grand Wash to Black Canyon south of Fortification Hill. LaRocque (1960, p. 78) has noted that ". . . in deep lakes marl accumulates only in the epilimnion, in shallow parts of the lake, especially in shallow bays." Although the "Hualapai Lake" (late "Muddy Creek Lake") may have been deep elsewhere, for example, near Callville or Overton, Nevada, it was probably shallow where the Hualapai limestone now exists between Grapevine Wash and Fortification Hill.

This may explain the puzzling angular discordance in Grand Wash between the algal Hualapai limestone and the underlying continental clastic facies discussed by Hunt (1969, p. 113) and considered by him to represent a significant hiatus. This angular discordance, if considered to be a "normal" angular unconformity, would imply deposition, deformation (perhaps by compaction, if not tectonism), emergence, erosion, inundation, and renewed deposition. However, I suggest that it was the result of a different sequence of events: with increasing "Muddy Creek Lake" inundation following Colorado River capture of the "ancestral Rio Grande" in the "Four Corners region" (Lovejoy, 1959), the point of clastic sedimentation in "Muddy Creek Lake" receded up Grand Canyon until the lake water near the river mouth at Grand Wash was clear (Lovejoy, 1969, 1976c, 1977). Sand filled the lower Grand Canyon and gravel and sand filled its upper reaches. The algal Hualapai limestone accumulated here directly on the clastic Muddy Creek sediments late in the development of "Muddy Creek Lake" because nutrient-rich warm water of the Colorado River entered the there-clear "Muddy Creek Lake" water. Algal mats grew close to and parallel with the lake surface. With fluctuations in the slowly rising "Muddy Creek Lake" surface, this limestone grew lakeward along the shoreline near and south of the river mouth with horizontal bedding. These horizontal limestone beds overlay originally gently basinward-inclined clastic beds, thereby producing what can be seen from a distance as an angular discordance that resembles a "normal" angular unconformity. Thus, there need be no hiatus between the uppermost Muddy Creek sands and the basal Hualapai algal limestone deposits, as would be implied by a "normal" angular unconformity. Certainly, Lucchitta (1966, p. 108) shows no evidence of an unconformity.

The Red Lake Salt Mass

Peirce (1972) described a ("100 cubic miles") deposit of halite in Red Lake Valley playa south of Grapevine Wash at least 4,000 feet (1,200 m) thick and noted (1972, p. 5):

> Evaporites including halite, gypsum, and carbonate (Hualapai Limestone) are associated with the largely Pliocene Muddy Creek Formation in the Lake Mead region to the north. It appears reasonable to consider that the salt in Hualapai Valley may be Pliocene in age but not necessarily the precise time equivalent of halite previously recognized in the Muddy Creek Formation.

Peirce (1972, p. 5) also considered the "nonmarine halite" to have formed in a "rapidly subsiding closed basin in later Tertiary time."

Such an immense volume of evaporite salt implies a prodigious volume of salty water which, if not marine, must have been fluvial in origin but probably not saltier than the modern Colorado River. I suggest that the Red Lake salt mass represents the late terminus of the Colorado River as it flowed south in Grapevine Wash during the last part of the time it was filling the Basin and Range province prior to its overflow to form the present drainage system south of Fortification Hill (cf. Lucchitta, 1972).

Interpretation of River History at Grand-Grapevine Wash

Figure 6 shows an interpretation of the history of the Colorado River at Grand-Grapevine wash. Figure 6A show the river in Grapevine Wash flowing to Red Lake-Hualapai Valley; sand and silt are in the river; gravel is on the pediment. Figure 6B shows lakeshores a-d; d lies in the canyon. Figure 6C shows higher shores e-g; water backs far up the canyon raising the upriver base level. Fig. 6D shows highest lake level (915 m); river aggrades upstream throughout the plateau meandering on deep alluvial-filled valleys. Figure 6E shows result of lake breaching (overflow?) near Fortification Hill (?); all plateau meanders entrench. Figures 6F-6H show river incision and limestone erosion to present.

Analysis by Analogy

Daly (cited in Lull, 1945, p. xi) noted:

> What geology, like every other science, needs today is a frank recognition that imaginative thought is not dangerous to science, but is the life blood of science. . . . At bottom, each "exact" science is, and must be speculative, and its chief tool of research, too rarely used with both courage and judgement, is the regulated imagination. . . . Science is drowning in facts.

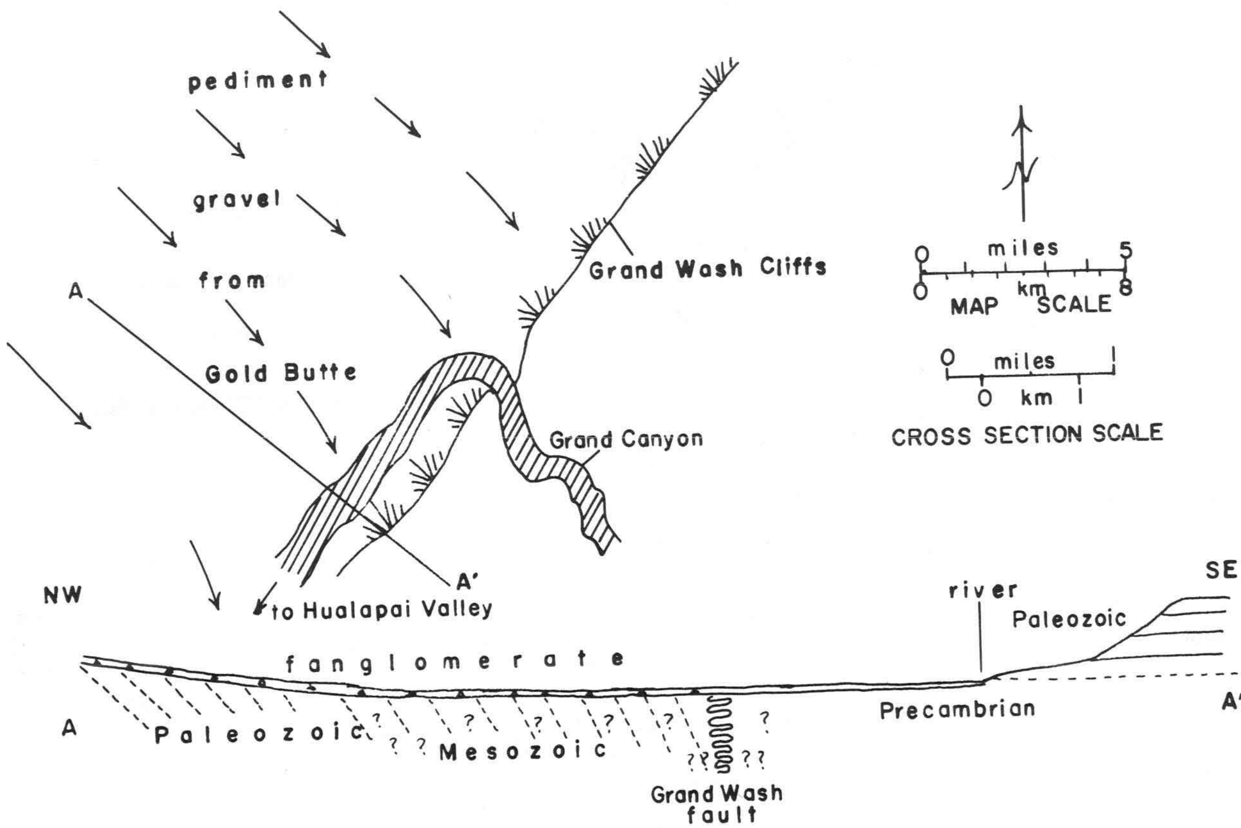

Fig. 6A. The river in Grapevine Wash flowing to Red Lake-Hualapai Valley; sand and silt are in the river; gravel is on the pediment.

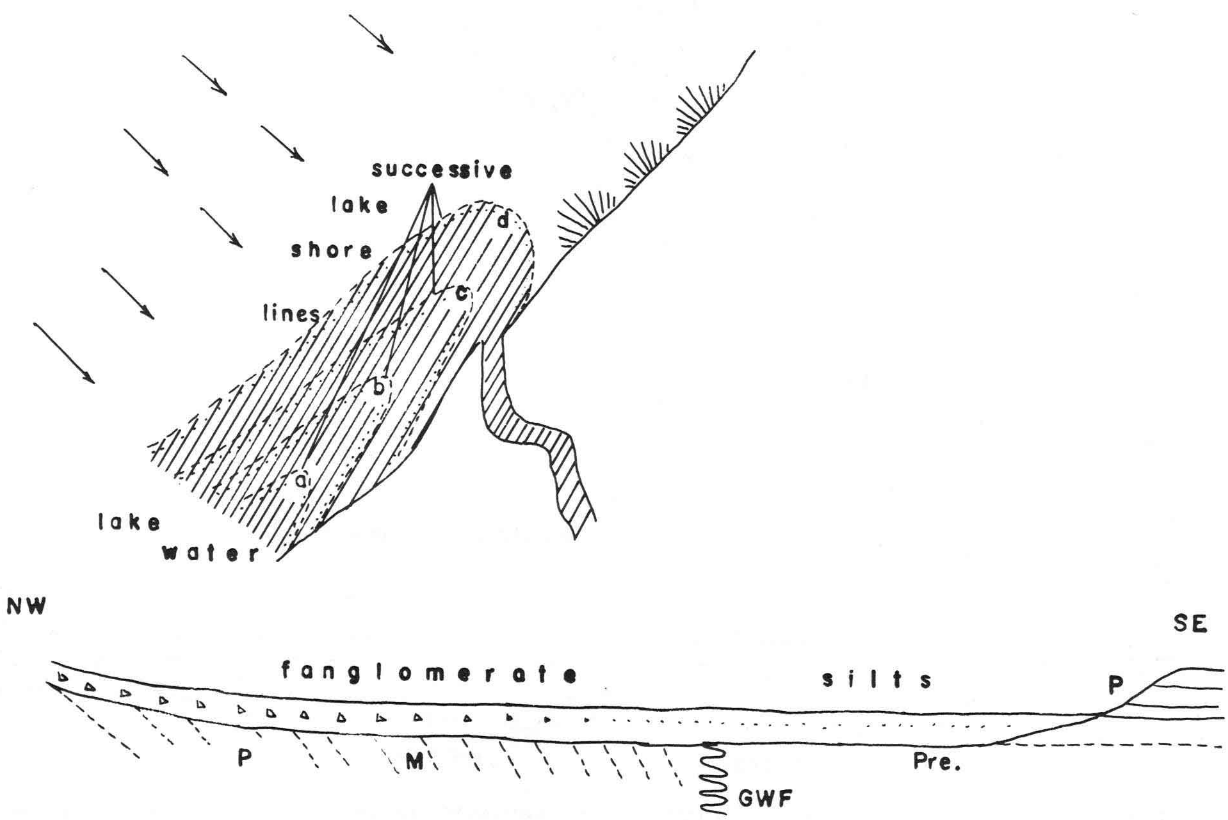

Fig. 6B. Lakeshores a-d; d lies in the canyon.

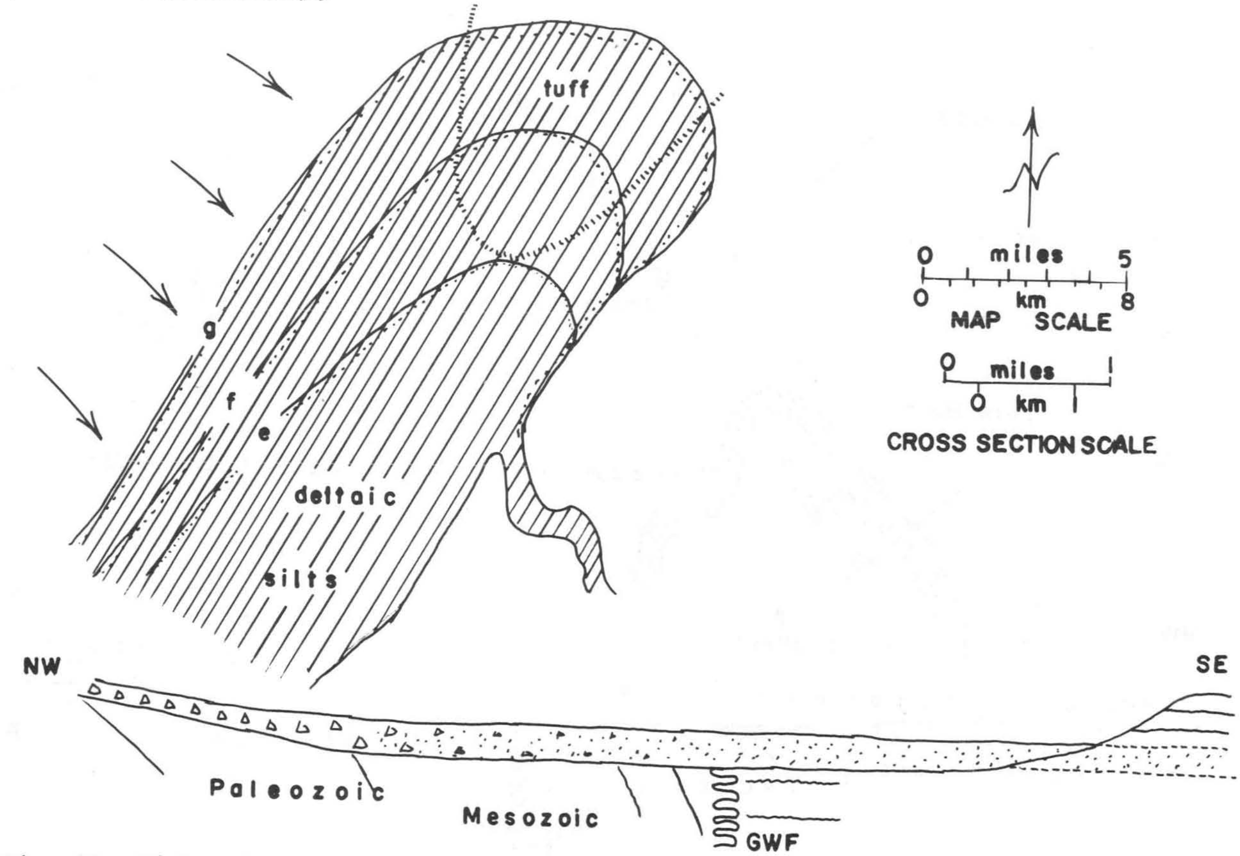

Fig. 6C. Higher shores e-g; water backs far up the canyon raising the upriver base level.

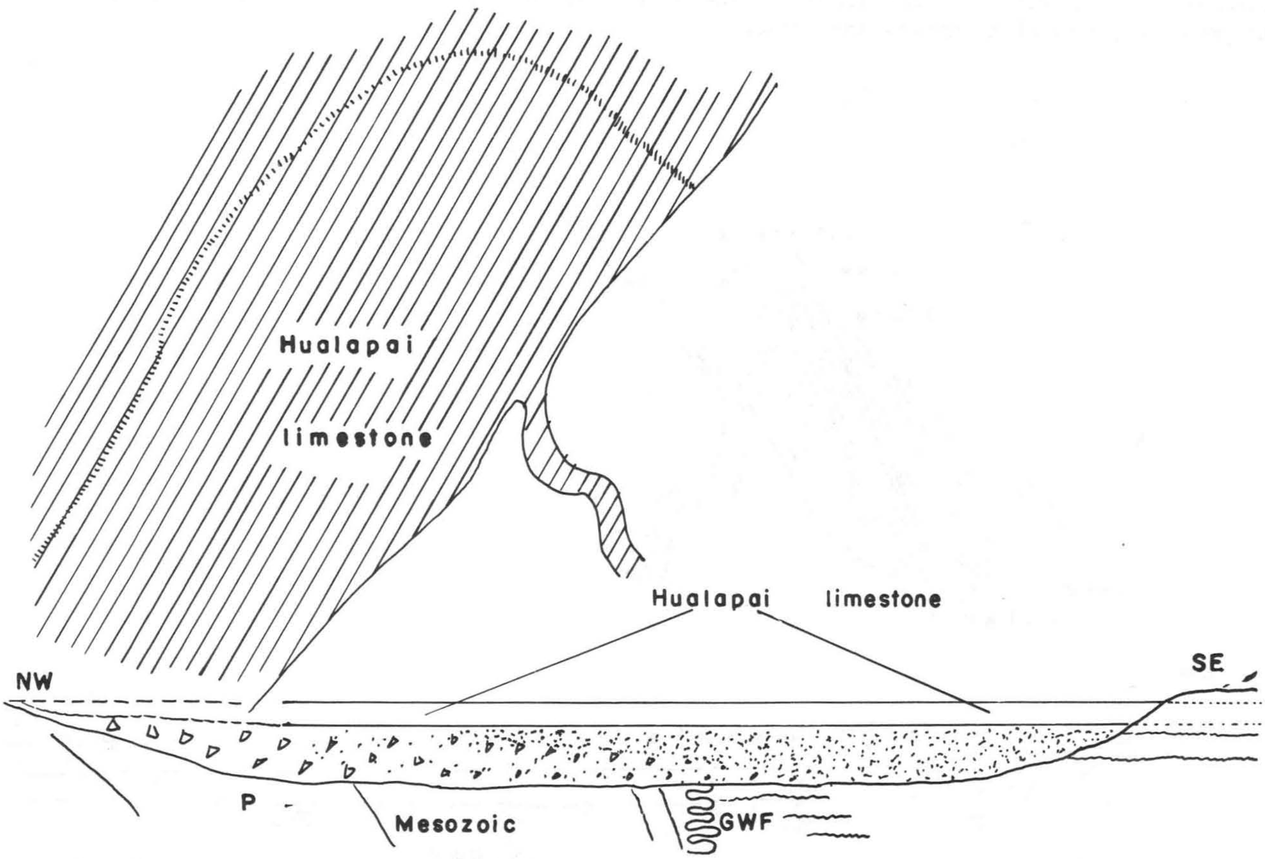

Fig. 6D. Highest lake level (915 m); river aggrades upstream throughout the plateau meandering on deep alluvial-filled valleys.

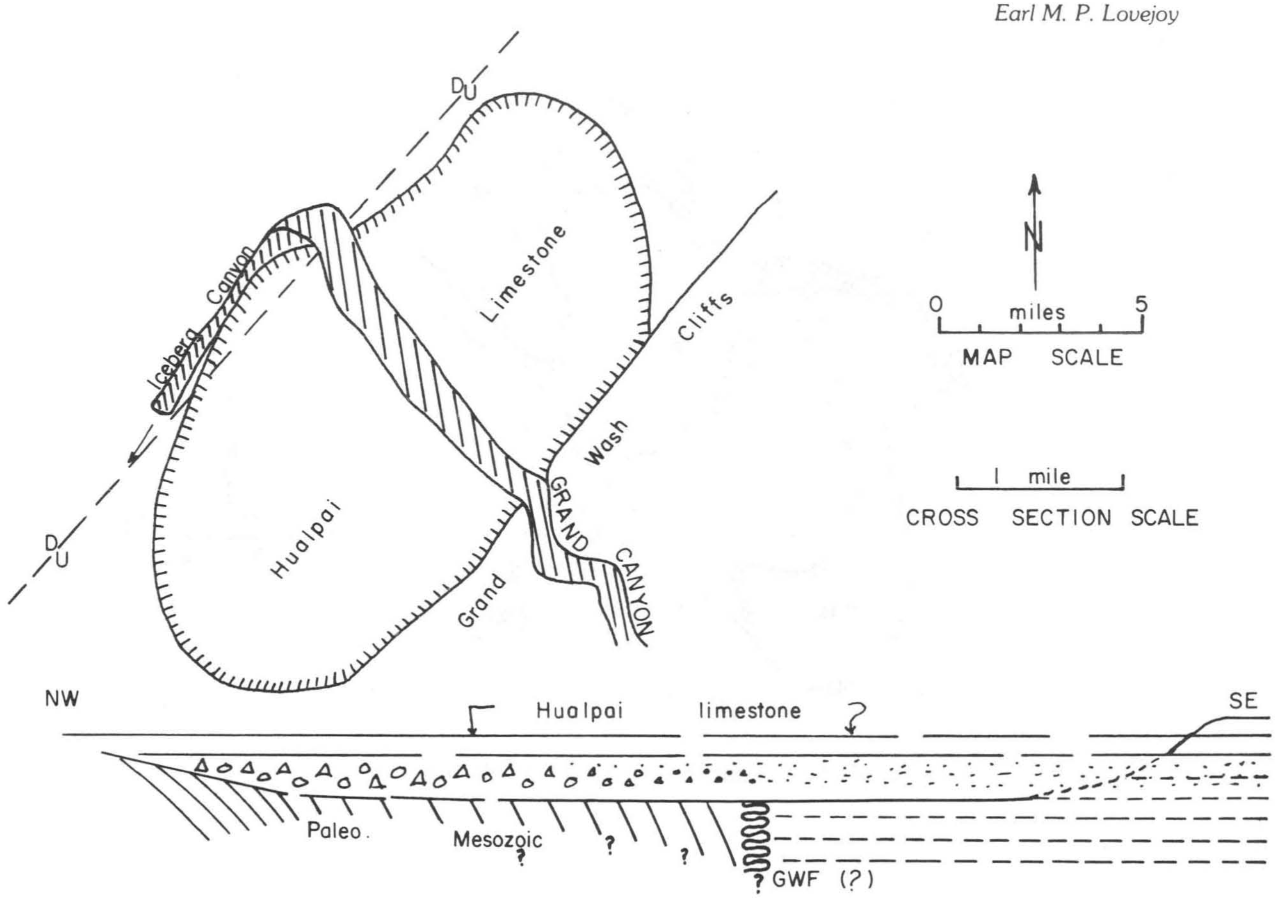

Fig. 6E. Result of lake breaching (overflow?) near Fortification Hill (?); all plateau meanders entrench.

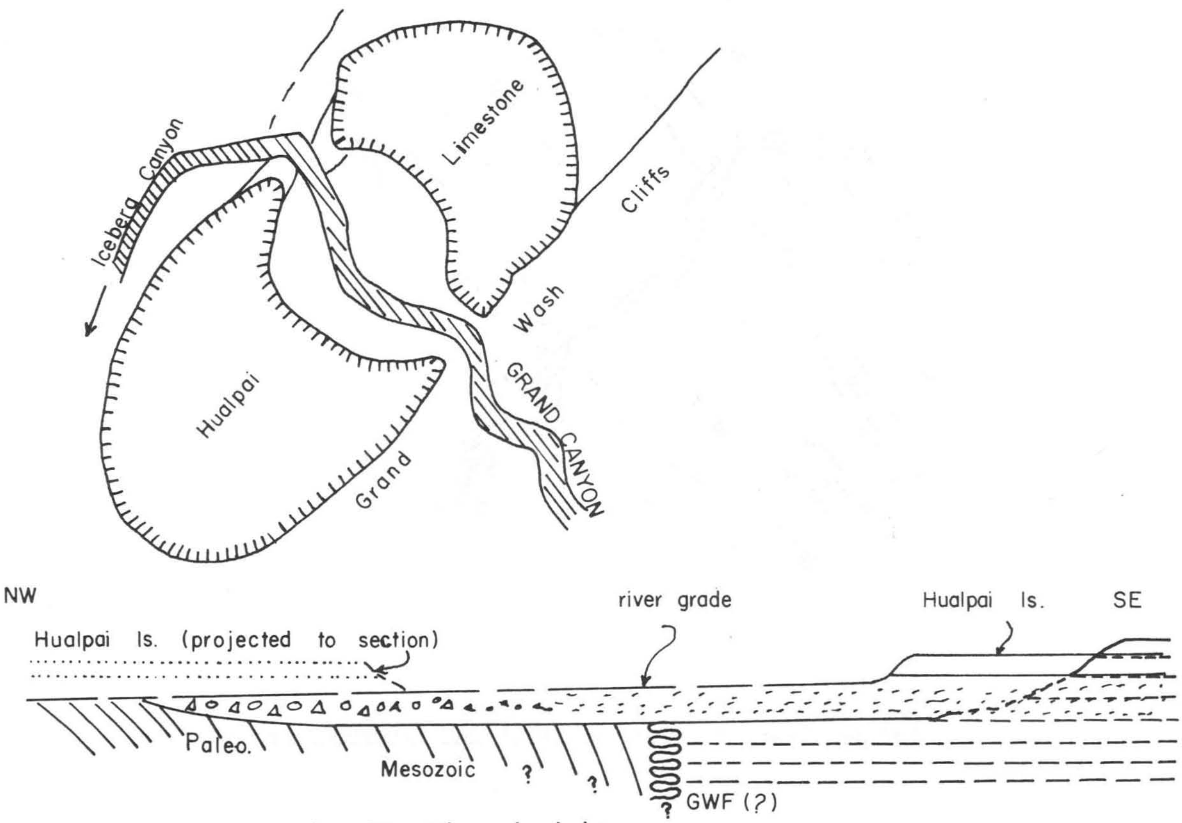

Fig. 6F. River incision.

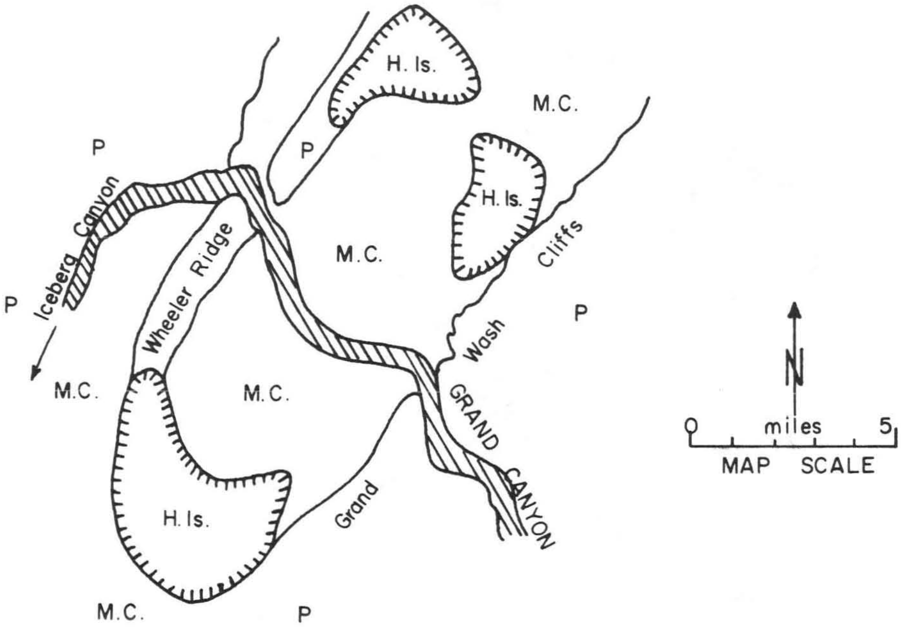

Fig. 6G. Continuing river incision.

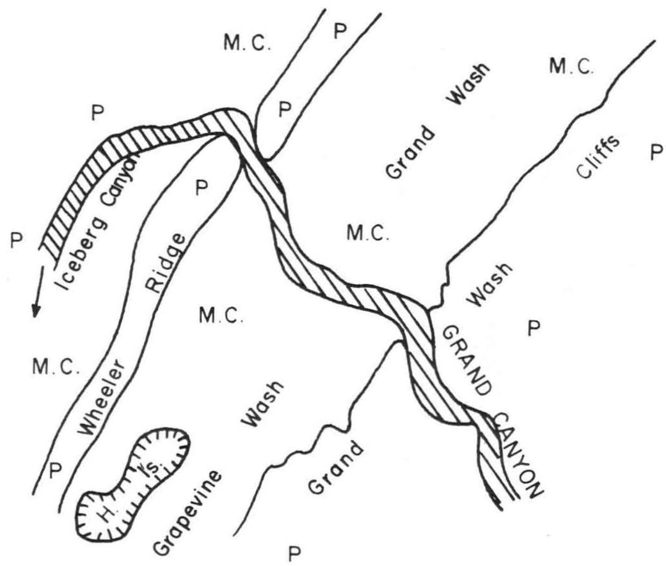

Fig. 6H. Present level of river incision and limestone erosion.

Analogy as a powerful imaginative tool is also implied by the aphorism that "the best geologist is he who has seen the most geology." Several analogs are shown here that bear on the problem.

The suggestion has been made that the Colorado River turned 90 degrees left and flowed south along the foot of Grapevine Wash Cliffs at the mouth of the Grand Canyon (Lovejoy, 1969). An analogous course is followed by the Rio Grande at the mouth of Santa Helena Canyon, Big Bend, Texas, where the river emerges from the upthrown Mesa de Anguila fault block west of the Terlingua fault (Fig. 7). Although the Rio Grande at this point may have been either antecedent (Maxwell, 1968, p. 91-92) or, in my opinion, superimposed from an Oligocene volcanic cover into the Cretaceous strata and fault-block structure, its present course is maintained by: (1) steep-gradient, soutwest-flowing streams, bringing in sediment coarser grained than that carried by the river, which force the river southwestward against the Mesa de Anguila fault block (Maxwell, 1968, Figs. 91 and 92 and Plate II) and (2) southwest-dipping strata of the northeastern downthrown fault block, which by a process of homoclinal shifting also force the river southwestward against the upthrown block. In my opinion, these two processes are analogous to those that operated in Grand Wash in "Muddy Creek time": the reverse drag eastward dip of the pre-Cenozoic strata originally forced the Colorado River eastward against the Grapevine Wash Cliffs, first as the result of faulting and second as the result of homoclinal shifting, and later the influx of very coarse fanglomeratic material from the west maintained the river's southward course against the fault at the base of the cliff. I suggest that younger alluvium and colluvium now mask the old river deposits between Grand Canyon and Red Lake Valley.

The absence of river gravels in the sandstone-siltstone facies in Grand Wash is not proof of its nonfluvial origin, in my opinion. Analogous conditions exist in two locations, one in Nevada and one in Texas.

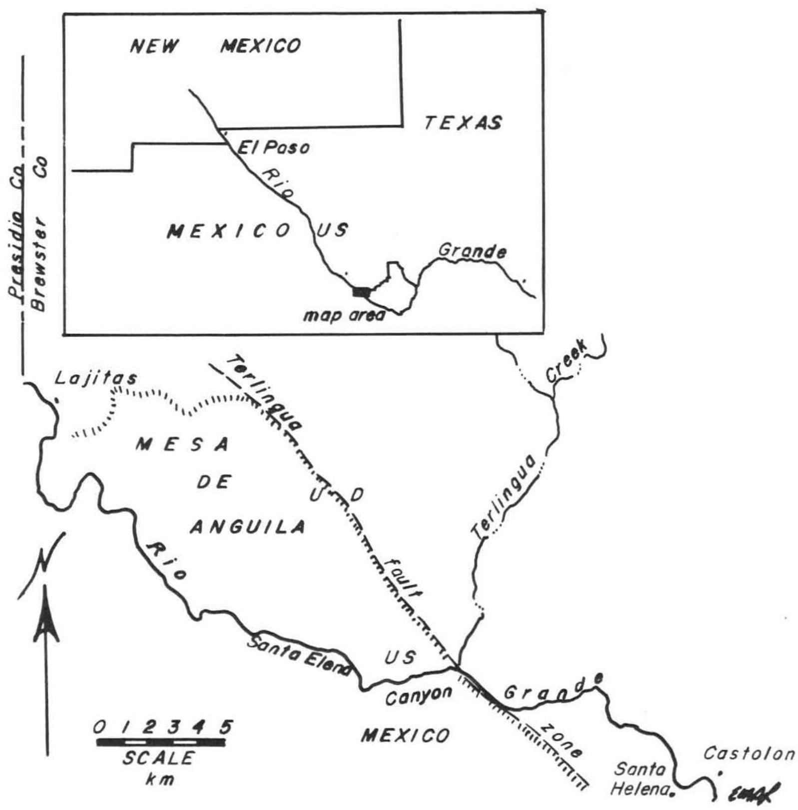

Fig. 7. Index map of the Mesa de Anguila, Texas-Mexico region showing the course of the Rio Grande between Lajitas and Castolon, Texas where the Rio Grande emerges from Mesa de Anguila at Terlingua fault and turns 60° southeast at the mouth of Santa Elena Canyon. The river is forced against the cliffs of Mesa de Anguila by southwestward-flowing pediment drainage.

In Nevada, in the steep-walled canyon of the east-flowing Truckee River 19 km east of Reno, which lies in Truckee Meadows (Fig. 8), the Pleistocene fluvial and lacustrine sediments that partly fill the canyon do not contain river gravels. They lap onto wall bedrock with little to no indigenous coarse colluvium derived from these steep (in places >45°) walls. In my opinion, the rate of sedimentation of fine-grained material in this canyon was extremely (for a short time, infinitely) high compared to the rate of sedimentation of coarse-grained material from the adjacent canyon walls. Upstream in Truckee Meadows, abundant coarse (cobble) Pleistocene river gravels have been mined out from a large gravel pit on the north side of the entrance to Truckee Canyon; these river gravel accumulated in Truckee Meadows and were not carried downstream in the river in Truckee Canyon; thus, gravel sedimentation occurred upstream from Truckee Canyon at the same time that fine-grained sediments accumulated 16 km downstream. I suggest that this is analogous to the situation in Grand Wash where Colorado River gravels did not accumulate in the sandstone-siltstone facies because the low river gradient allowed only sand and silt to be carried by the river at that point at that time; gravels were deposited at steeper gradients upstream because the river gradient in the Grand Canyon decreased when the base level (due to Muddy Creek Lake) rose at Grand Wash.

In Texas, near El Paso (Fig. 9) the Blancan Fort Hancock Formation consists of river sands, silts, and clays with very little gravel; the overlying Blancan and Irvingtonian Camp Rice Formation consists of coarse fluvial sands and cobble and pebble gravels (Strain, 1966; Lovejoy, 1976b; Willingham, 1979). The change from non-gravel to gravel deposition could have occurred as the result of (1) climatic changes in the Pleistocene (Lovejoy, 1976b), (2) change in base level downstream (Strain, 1965-1980), or (3) basin integration upstream and progradation of basin fill downstream (Willingham, 1979). Some combination of all may also have applied. In any case, the sudden influx of river gravels in the Camp Rice Formation after a long period of non-gravel sedimentation in an otherwise similar river environment proves that gravels need not be present in all fluvial deposits.

I suggest that in the pre-Pleistocene Colorado River gravels might not have been a major consituent of river sediment but that gravels became important only with the onset of Pleistocene freeze-thaw cycles in the Colorado River drainage system. The absence of river gravels

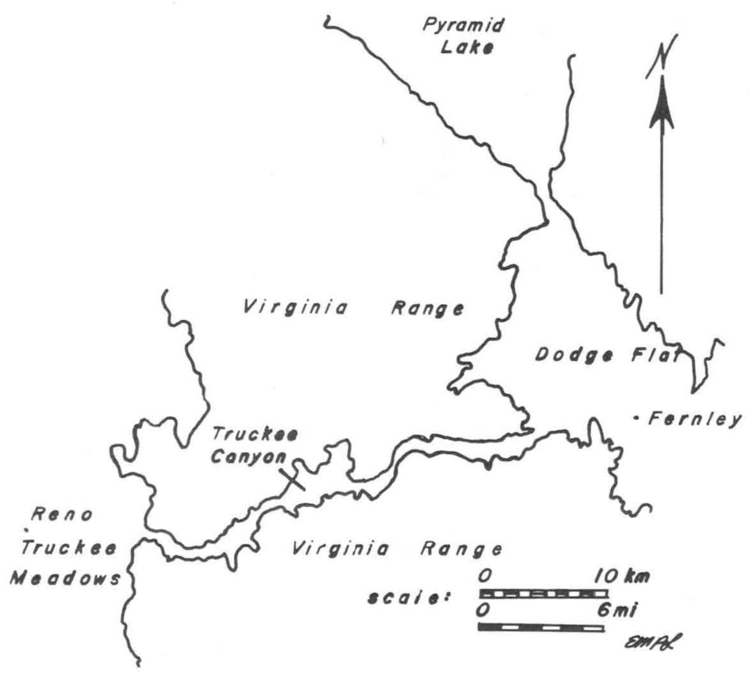

Fig. 8. Index map of Reno, Nevada region showing the course of the Truckee River from Truckee Meadows at Reno through the Virginia Range to Dodge Flat, thence north to Pyramid Lake on the east side of the Virginia Range. Lake Lahontan sediments crop out widely in the narrow lower valley of the Truckee River, Truckee Canyon, in the Virginia Range.

in Miocene sediments in Grand Wash might indicate deeper chemical weathering and less mechanical weathering in the drainage basin.

If these analogs are correct, the gravel-free quartzose sandstone and siltstone in Grand Wash can be explained as a river deposit, obviating the need for any alternate courses for the Colorado River in Muddy Creek time.

Sedimentation in the Basin and Range Province

If the evidence can be reasonably interpreted in the described way, then the Colorado River may have flowed into the Basin and Range province at Grand Wash since the river formed in the Colorado Plateau in the early Cenozoic (Lovejoy, 1976c, 1977). Hunt (1968) pointed out that the fundamental flaw in the hypothesis proposed by McKee and others (1964) lay in its inability to account for the disposition of the great amount of sediment that had been eroded from the Colorado Plateau for a major period of time in the history of the river. A similar argument against the present interpretation might be raised; the following discussion addresses this problem.

I have tried to show elsewhere (see Lovejoy, 1978b; also Rowley and others, 1978, for a discussion; Lovejoy, 1978a, for a review of the evidence and reasoning) that basin-and-range faulting had been underway extensively in Paleocene and Eocene time and was over three-fourths finished by the end of the Oligocene and that the Colorado Plateau had been primarily uplifted in the same time (Paleogene). I also suggested that the early development of the Colorado River involved beheading of a southeast-flowing ancestral Rio Grande somewhere in the Four Corners region by a headward-eroding Colorado River. Prior to the time of that beheading most of the sediment of the *"upper" Colorado River* (above the Four Corners country point of beheading) had been carried into the Gulf of Mexico. Therefore, in this interpretation, only a relatively small amount of the material eroded from the "middle" Colorado River drainage basin (i.e., between the point of beheading and Grand Wash) had to be carried through Grand Canyon into the Basin and Range province before the time of integration of the river into Pacific waters.

The material eroded from the Colorado Plateau by the pre-beheading "middle" Colorado River that flowed into the Basin and Range province prior to its overflow into Pacific waters was primarily Mesozoic and Carboniferous sand, silt, and clay. These fine-grained materials were carried on low-gradient streams westward from Grand Wash into tectonically deepened basins where basinal infilling and integration

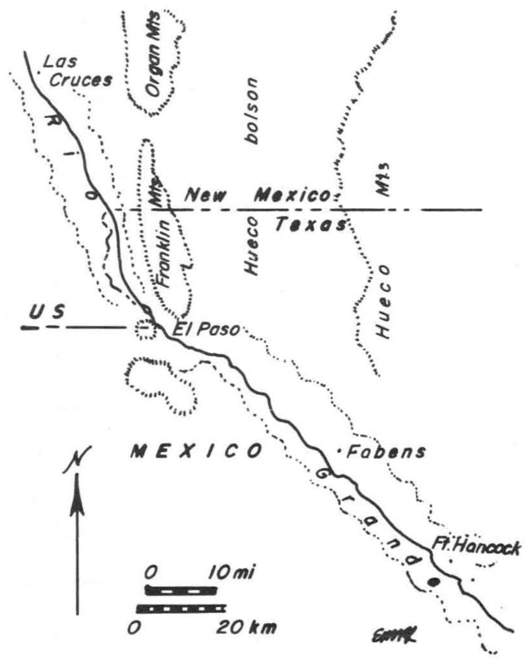

Fig. 9. Index map of El Paso, Texas region showing the course of the Rio Grande from Las Cruces, New Mexico to Fort Hancock, Texas. The Fort Hancock Formation crops out widely along the edges of the river valley, shown by the dotted lines parallel with the course of the river.

accompanied by river progradation outward from the Grand Wash point of emergence was accompanied by secularly decreasing rates of basin sinking. Early in the Paleogene, sediment infilling rates were low but basinal depression rates were rapid; in the early Neogene, sediment infilling rates increased and basinal tectonic depression rates decreased. At some time, sedimentation rates equalled and then surpassed tectonic depression rates and the basins began to fill and overflow. The sediment and dissolved material was spread through the Basin and Range province of northwestern Arizona, southern Nevada, and eastern California. Manifestations of this process may include the Oligocene Horse Spring Formation, which occurs in thick deposits as far east as the Muddy Mountains and as far west as the Amargosa Desert (and perhaps Death Valley).

Basins of the Basin and Range province are 1.5 to 3 km deep on an average, and basins cover about half of the Basin and Range province of southern Nevada and eastern California, an area of about 100,000 km^2; thus a volume of 1.5 to 3.0 x 10^5 km^3 of basin fill could be accommodated. The region eroded by the Colorado

River downstream from the "Four Corners country" covers an area of about 50,000 km^2 from which a thickness of sediment of about 2 km has been eroded; the volume of eroded material is about 1.0×10^5 km^3. Thus, a Paleogene-developed Basin and Range province could have accommodated the Paleogene sediment load of the western part of the Colorado Plateau. Drainage of the Colorado River could have been into the Basin and Range province until the Muddy Creek lake overflowed south of Fortification Hill sometime between 11 and 5 m.y. ago (Lucchitta, 1972).

The provenance of the fanglomerate lies in the southern Virgin Mountains in Precambrian rocks that were originally overlain by a thick sequence of Paleozoic carbonate strata. The fanglomerate contains no carbonate clasts from that southern Virgin Mountains source area; therefore, a period of time long enough since block faulting to have resulted in the erosion of a great thickness of Paleozoic strata must have preceded the time of deposition of the fanglomerate. The erosional resistance of the same Paleozoic rocks in the greatly uplifted Colorado Plateau block is manifested by the short distance of cliff retreat from the Grand Wash fault certainly in the past 11 m.y. (since deposition of the fanglomerate) and possibly since Laramide time when the fault may have begun to develop (Longwell, 1945, p. 114). In addition to the loss of the Paleozoic strata from the southern Virgin Mountains, there has been a loss of several thousand feet of Precambrian crystalline rock (Longwell, 1945, p. 115, Fig. 12, and p. 114).

Thus, prior to deposition of the fanglomerate in Grand Wash 11 m.y. ago, erosion stripped a great section of resistant strata from the southern Virgin Mountains. Where did that erosional debris go? It probably lies deeply interred in adjacent basins of the Basin and Range province. If that is so, then the ancient river sands, silts, and clays from the pre-Muddy Creek Colorado River could also lie interred in similar basins mixed with that locally derived debris.

Conclusions

The Muddy Creek Formation in Grand Wash contains a fluviatile sandstone derived from the east and contemporaneously deposited with the fanglomerates derived from the west that were considered by Blackwelder (1934), Longwell (1946), and Lucchitta (1966) to preclude a west-flowing Colorado River in Grand Wash in late Miocene time. The sandstone may be gravel-free fluvial sediment deposited from the Miocene Colorado River as it turned a right angle to flow south toward Red Lake during a basin-and-range infilling stage. Subsequent to infilling, lake formation, and overflow in the Basin and Range province in late Miocene and Pliocene time, the Colorado River established its present course to the Gulf of California. The evidence upstream of a great antiquity for the Colorado River drainage system, Hunt's "irresistible force," is therefore shown to be in full agreement with the history of the river in Grand Wash. The concept of immovability of the object, which is the Muddy Creek Formation, however, is apparently the product of thought engendered in times and places precursory to our own; perhaps these interpretations are but precursors to other less errant concepts. I can but echo Blackwelder (1934, p. 564):

> The foregoing sketch of the origin and history of the Colorado River is frankly theoretical. Science advances not only by the discovery of facts but also by the proposal and consideration of hypotheses, provided always that they are not disguised as facts. This view will not meet with general acceptance. There are doubtless many facts unknown to me that will be brought forward in opposition. Perhaps their impact will prove fatal to the hypothesis. In any event, the situation will be more wholesome, now that we have two notably different explanations, than it was . . .

Acknowledgments

The major field work for this project was undertaken in 1953 through 1955 while flying and examining uranium deposits for the U.S. Atomic Energy Commission in southwestern Utah, northwestern Arizona, and southeastern Nevada. Ten months and 800 hours of low-level flying as well as extended field ground work in that period in the region provided the basis for these ideas. Permission to publish was given by the U.S. Atomic Energy Commission; opinions stated here do not necessarily reflect those of the Commission or its personnel. Additional visits to Grand Wash were made in 1960, 1962, and 1970. Angela Sanchez typed the manuscript. Earlier versions of the paper have been reviewed and improved by C. B. Hunt, Frank Kottlowski, W. R. Seager, and Jerry Mueller.

References

Anderson, R. E., and Mehnert, H., 1979, The Hurricane fault in Utah as a predominantly Quaternary structure [abs.]: Geol. Soc. America Abstracts with Programs, v. 11, p. 66.

Blackwelder, Eliot, 1934, Origin of the Colorado River: Geol. Soc. America Bull.,

v. 45, p. 551-566.

Blair, W. N., 1978, Gulf of California in Lake Mead area of Arizona and Nevada during late Miocene time: Am. Assoc. Petroleum Geologists Bull., v. 62, p. 1159-1170.

Cornell, W. C., 1979, Gulf of California in Lake Mead area of Arizona and Nevada during late Miocene time: Discussion: Am. Assoc. Petroleum Geologists Bull., v. 63, no. 7, p. 1139-1140.

Dobbin, C. E., 1939, Geologic structure of St. George district, Washington County, Utah: Am. Assoc. Petroleum Geologists Bull., v. 23, no. 2, p. 121-144.

Gardner, L. S., 1941, The Huricane fault in southwestern Utah and northwestern Arizona: Am. Jour. Sci., v. 239, p. 241-260.

Goetz, A. F. H., Billingsley, F. C., Gillespie, A. R., Abrams, M. J., Squires, R. L., Shoemaker, E. M., Lucchitta, I., and Elston, D. D., 1975, Application of ERTS images and image processing to regional geologic problems and geologic mapping in northern Arizona: NASA Tech. Report 32-1597, JPL, Cal. Tech., 96 p.

Hamblin, W. K., 1970, Structure of the western Grand Canyon region, *in* The western Grand Canyon district, Guidebook to the geology of Utah, No. 23: Utah Geological Society, p. 3-20.

Hunt, C. B., 1956, Cenozoic geology of the Colorado Plateau: U.S. Geol. Survey Prof. Paper 279, 99 p.

____1968, Colorado River [Book Review]: Geotimes, v. 13, no. 2, p. 39.

____1969, Geologic history of the Colorado River: U.S. Geol. Survey Prof. Paper 669-C, p. 59-130.

LaRocque, Aurèle, 1960, Molluscan faunas of the Flagstaff formation of central Utah: Geol. Soc. America Memoir, 100 p.

Longwell, C. R., 1945, Low-angle normal faults in the Basin and Range province: Am. Geophys. Union Trans., v. 26, part 1, p. 107-118.

____1946, How old is the Colorado River?: Am. Jour. Sci., v. 244, p. 817-835.

Lovejoy, E. M. P., 1959, Hurricane fault problem, Utah and Arizona [Abs.]: Geol. Soc. America Bull., v. 70, p. 1732.

____1964, The Hurricane fault zone, and the Cedar Pocket Canyon–Shebit–Gunlock fault complex, southwestern Utah and northwestern Arizona: Ph.D. dissertation, University of Arizona, Tucson, 195 p.

____1969, Grand Wash problem at Grand Canyon [abs.]: Geol. Soc. America Abstracts with Programs, v. 1, part 5, p. 46.

____1973a, Major early Cenozoic deformation along Hurricane fault zone, Utah and Arizona: Am. Assoc. Petroleum Geologists Bull., v. 57, p. 510-519.

____1973b, Age of the Colorado Plateau: Discussion: Geol. Soc. America Bull., v. 84, p. 3135-3136.

____1976a, Cedar Pocket Canyon (Grand Wash)–Shebit–Gunlock fault complex, northwestern Arizona and southwestern Utah: Reinterpretation of the time of faulting: Arizona Geol. Soc. Digest, v. 10, p. 133-150.

____1976b, A little problem concerning Fort Hancock–Camp Rice "mixed round gravels" correlation in the El Paso–Las Cruces region as viewed by a skeptic, *in* Symposium on the stratigraphy and structure of the Franklin Mountains: El Paso Geological Society, p. 99-103.

____1976c, Pre-Pliocene river system development, Colorado Plateau and southern Rocky Mountains: A theory [abs.]: Geol. Soc. America Abstracts with Programs, v. 8, p. 603.

____1977, Neogene Colorado River Development in Colorado Plateau: A theory [abs.]: Geol. Soc. America Abstracts with Programs, v. 8, p. 457.

____1978a, Report on the evidence and a theory for the prediction of tectonic activity in the Basin and Range province of Nevada and Utah for the next one million years: Pacific Northwest Laboratories, Battelle Memorial Institute Report, 331 p.

____1978b, Age of structural differentiation between the Colorado Plateau and Basin and Range provinces in southwestern Utah: Discussion: Geology, v. 6, no. 9, p. 572.

Lucchitta, I., 1966, Cenozoic geology of the upper Lake Mead area adjacent to the Grand Wash Cliffs, Arizona: Ph.D. dissertation, Pennsylvania State University, University Park, 218 p.

____1967, Pierce Ferry area, *in* McKee, E. D., Wilson, R. F., Breed, W. J., and Breed, C. S., eds., Evolution of the Colorado

River in Arizona: Museum of Northern Arizona Bull. 44, p. 4-5.

____1972, Early history of the Colorado River in the Basin and Range province: Geol. Soc. America Bull, v. 83, p. 1933-1948.

Lull, R. S., ed., 1945, Problems in geology and geophysics (Daly Volume): Am. Jour. Sci., v. 243a, 5th series.

Maxwell, R. A., 1968, The Big Bend of the Rio Grande: Bureau of Economic Geology, University of Texas, Austin, Guidebook no. 7.

McKee, E. D., and McKee, E. H., 1972, Pliocene uplift of the Grand Canyon region: Time of drainage adjustment: Geol. Soc. America Bull., v. 83, p. 1923-1932.

McKee, E. D., Wilson, R. F., Breed, W. J., and Breed, C. S., eds., 1967, Evolution of the Colorado River in Arizona: Museum of Northern Arizona Bull., v. 44, 67 p.

Moore, R. T., 1972, Geology of the Virgin and Beaver Dam Mountains, Arizona: Arizona Bureau of Mines Bull. 186, 65 p.

Peirce, H. W., 1972, Red Lake salt mass: Arizona Bureau of Mines Fieldnotes, v. 2, no. 1, p. 4-5.

Rowley, P. D., Anderson, J. J., Williams, P. L., and Fleck, R. J., 1978, Age of structural differentiation between the Colorado Plateau and Basin and Range provinces in southwestern Utah: Geology, v. 6, p. 51-55.

Shoemaker, E. M., 1975, Late Cenozoic faulting and uplift of the Colorado Plateau [abs.]: Geol. Soc. America Abstracts with Programs, v. 7, no. 7, p. 1270.

Strain, W. S., 1965-80, Personal communications: Professor emeritus, University of Texas, El Paso.

Strain, W. C., 1966, Blanca mammalian fauna and Pleistocene formations, Hudspeth County, Texas: Texas Memorial Museum Bull., no. 10, p. 55.

Volborth, A., 1962, Rapakivi-type granites in the Precambrian complex of Gold Butte, Clark County, Nevada: Geol. Soc. America Bull., v. 73, p. 813-832.

Willingham, D. L., 1979, Stratigraphy of the Pliocene-Pleistocene upper Santa Fe Group in the El Paso region, west Texas and south-central New Mexico [abs.]: Geol. Soc. America Abstracts with Programs, v. 11, p. 305.

Young, R. A., and Brennan, W. J., 1974, Peach Springs tuff. Its bearing on structural evolution of the Colorado Plateau and development of Cenozoic drainage in Mohave County, Arizona: Geol. Soc. America Bull., v. 85, p. 83-90.