Geomorphic Features and Processes of the Shivwits Plateau, Arizona, and Their Constraints on the Age of Western Grand Canyon

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Abstract: Late Miocene through Pleistocene basaltic lava flows on the Shivwits and Uinkaret Plateaus allow the reconstructing of landscape and geomorphic processes at various times within this interval. Conclusions are: (1) The landscape of the region has been controlled by the northeast retreat of scarps in Mesozoic rocks. (2) By 9 Ma, the southernmost Shivwits Plateau was already stripped down to the Permian Kaibab Limestone, and the Grand Wash Cliffs had their present location and shape. (3) The Triassic Moenkopi Formation and Shinarump Conglomerate were still present just north of Grand Canyon 7.5 to 6 Ma. (4) Sublava topography adjacent to the present Grand Canyon shows no evidence of canyon incision 7.5 to 6 Ma. (5) The Shinarump-over-Moenkopi scarp has retreated northeastward at ~4 km/Ma, but the upper Grand Wash Cliffs, developed in Paleozoic limestones, have retreated at only 0.6 km/Ma. (6) The Vermilion Cliffs were only a few km north of the present western Grand Canyon 8 to 6 Ma, so present topography and topographic elevations cannot be used to construct drainage-development hypotheses. (7) Gravel of possible southern derivation and preserved beneath a 6 Ma lava cap north of Grand Canyon may be an additional indicator for a post-6 Ma age of western Grand Canyon.

The Shivwits Plateau forms the northern boundary of western Grand Canyon (Figure 1), and contains critical geologic information concerning the canyon's history. For this reason, we mapped the southern half of the plateau in 1972 and 1973 at a scale of 1:24,000. This mapping was published at very reduced scale. Additional information regarding the plateau is contained in a Ph.D. dissertation (Lucchitta, 1966) and in Lucchitta (1984). These publications are not usually readily available, yet the data continue to be useful. A brief synopsis of features that have a bearing on Grand Canyon is presented in this paper, whose focus is geomorphic features, the evolution of the landscape, and the processes that can be inferred from them. Unless otherwise stated, the information presented here in telegraphic form is derived from these publications.

General Features

The Shivwits is the westernmost plateau north of Grand Canyon. Its western edge is at the great fault-line scarp of the Grand Wash Cliffs, which also mark the abrupt boundary between the Colorado Plateau and the Basin and Range Province to the west. The precipitous southern and southeastern boundary is the western part of Grand Canyon, and the eastern one is at the Hurricane Cliffs, produced by the Hurricane Fault. The country in between these boundaries is a subdued and mature tableland developed mostly on the Permian Kaibab Limestone, punctuated by erosional remnants of Triassic Moenkopi Formation protected by Tertiary lava caps, and by clifflines along faults. The southern part is a basaltic lava plateau dotted with small subdued and eroded shield volcanoes. This is especially true of the great south-pointing finger that ends at Kelly Point and is surrounded on three sides by the precipices of Grand Canyon. Most of the plateau is at an elevation of 1800 to 1900 m. The highest point is Mount Dellenbaugh, a volcano, at 2156 m. A few other volcanic centers exceed 2000 m elevation. In comparison, the Hualapai Limestone, the uppermost Miocene top of the basin fill in the Grand Wash trough west of the Shivwits, is at elevation ~900 m, and the bottom of western Grand Canyon is <400 m.

The Paleozoic and lower Mesozoic strata of the Shivwits Plateau have a slight dip to the northeast. At the southwestern edge of the plateau,

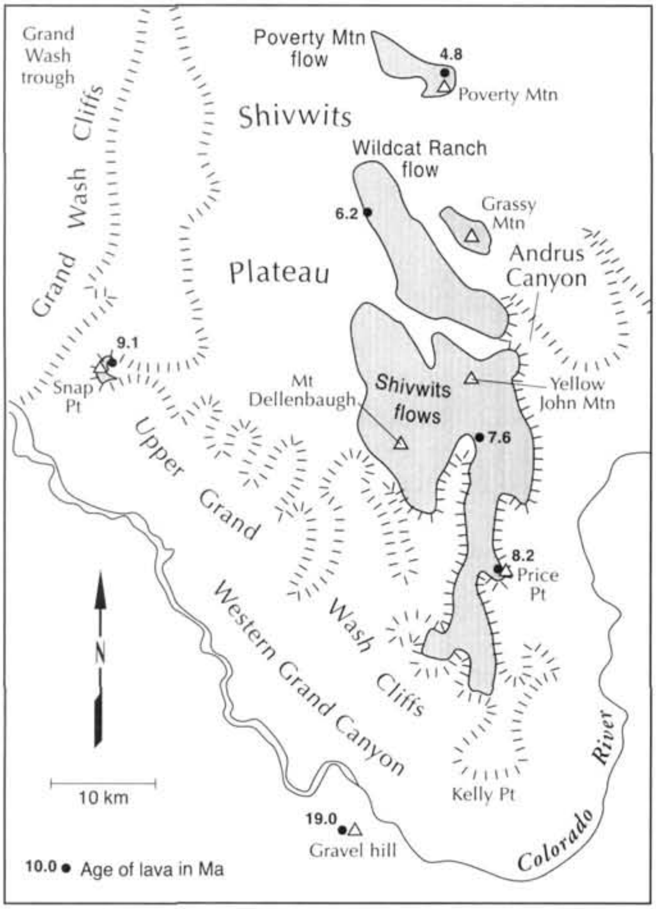


Figure 1. Location map showing basalt flows and their ages

however, this dips steepens to several degrees, a consequence of the pre–Basin and Range, Laramide-age Mogollon highlands, a belt of uplift that formed the mountainous southern rim of what is now the Colorado Plateau. Lucchitta called the downfaulted northwest extension of this belt the "Kingman uplift." The dip of the strata, even though gentle, has had a major effect on the geomorphic development of the area. We can work this development out because Miocene basaltic flows of various ages have preserved features of the landscape that existed when the lavas were emplaced.

Prelava Landscape and Geomorphic Processes

1. At the southern end of the Shivwits, lavas rest directly on the Permian Kaibab Limestone. These lavas are 7.6 Ma (Lucchitta and McKee, 1975) to 8.2 Ma (Wenrich and others, 1995). An even older basalt (9.1 Ma, Haman, personal communication, 1975) also rests on the Kaibab at Snap Point. This shows that Mesozoic rocks had been stripped away from the southernmost Shivwits Plateau by 9.1 to 7.6 Ma.

2. The surface beneath lavas as young as 6 Ma is smooth, extensive, and of very low relief, even at the edge of the plateau, where now the topography drops precipitously into Grand Canyon. This is good evidence that Grand Canyon topography did not exist when the lavas were emplaced.

3. There is no evidence of Shivwits lavas cascading into Grand Canyon, even at effusive centers such as Price Point. On the other hand, lavas only a million or so years older at Snap Point did cascade down the Grand Wash Cliffs, at whose bottom they pooled in Nevershine Mesa. This shows that the Grand Wash Cliffs already existed essentially in their present form by 9.1 Ma, which agrees with evidence of many kinds from the Grand Wash trough. It also reinforces the contention that no Grand Canyon existed when the Shivwits lavas were emplaced, because, otherwise, they would have cascaded into the canyon and should be visible as erosional remnants.

4. The smooth sublava surface is interrupted in places by channels as much as tens of meters deep. One notable channel is at Snap Point, another at Price Point. The gravels contained in these channels are of local derivation and composed predominantly of Kaibab limestone and chert. Significantly, material derived from the Mesozoic section, for example durable pebbles from the Shinarump Member of the Chinle Formation, is largely absent from the southernmost part of the Shivwits Plateau. These gravels define a consequent drainage flowing northeast, down the structural slope.

5. Farther north on the plateau, very well rounded cobbles of pink quartzite are present in places between the basalt and underlying Moenkopi Formation. These are very much like the indestructible cobbles of the Cannonball Member of the Claron Formation (we did not pursue this question to any degree). Whatever their precise origin, the cobbles are likely to be reworked from lower Tertiary units. There are two ways of accounting for the presence of the quartzite cobbles on the Shivwits. Either they are a lag, in which case units like the Claron would at one time have been present on the Shivwits Plateau; or they were brought here by streams tapping likely source areas for the cobbles to the north. The latter would represent a former drainage to the south for much of the Shivwits. As we shall see below, the two processes may have succeeded each other with time.

6. A very different gravel is exposed between 6 Ma basalt and Moenkopi on the west flank of Grassy Mountain, at ~36°16′ 44″ N. 113°26′ 20″ W. (Note: It is important not confuse this with gravel on the north flank of the mountain, which is part of the basal Timpoweap Member of the Moenkopi Formation.) The gravel in

question contains cobbles of granitoids of various kinds, pebbles of black chert, and cobbles of weakly metamorphosed silicic volcanic rocks, all embedded in unweathered arkosic sand. This sand suggests that the deposit is not reworked and that no great time elapsed between emplacement of the gravel and its burial by the ~6 Ma lava, which is part of the Wildcat Ranch flows. The silicic volcanic rocks resemble the Proterozoic rocks of the Alder Series and equivalents of Mingus Mountain and other areas of central Arizona, leading us to propose that the deposit reflects northwest drainage from central Arizona as recently as ~6 Ma. Inasmuch as Grand Canyon lies across this drainage path, we also believe this indicates that Grand Canyon is younger than the 6 Ma lavas, in keeping with other observations from the Shivwits and elsewhere.

Young (personal communication 1991) is of the opinion that the black chert may be derived from the Eleana Formation, present in the Basin and Range country to the west, thus indicating a westerly derivation for the gravel. However, this is unlikely because the Grand Wash Cliffs have been a barrier to drainage from the west since long before 6 Ma. Furthermore, had the gravel come from the west, it should be associated with the Gold Butte rapakivi granite, a distinctive coarsely porphyritic rock widely exposed in the southern Virgin Mountains, and ubiquitous as detritus in the Grand Wash trough, both directly west of the Shivwits Plateau. We saw no clasts of this granite in the gravel. Finally, a westerly derivation does not account for the silicic volcanic rocks, which are not present (to our knowledge) in that direction. A westerly source could be accommodated if the gravel were older than movement of the Grand Wash Fault, that is, pre-middle Miocene. But this cannot be the case because the Grassy Mountain area was covered by the Shinarump and, probably, other Mesozoic formations until just before 6 Ma (see below), whereas the gravel rests on the Moenkopi. In our opinion, the black chert is more likely derived from local outcrops of the Shinarump.

Young (personal communication, 2001) also suggests that the metavolcanic rocks may be derived from Cretaceous volcanic centers in central Arizona, or from the Claron Formation to the north or northwest. However, the nearest exposure of Cretaceous volcanic rocks is near Wickenburg, which, according to Lucchitta's mapping in west-central Arizona, is likely to be in an area of southerly topographic slope in early Tertiary time. Concerning reworking from the Claron, if this were the case, one would expect the Grassy Mountain gravel to also include reworked clasts of the quartzite that is to be found in the general region. We saw no such quartzite in the gravel. Furthermore, reworking from the early Tertiary Claron is not consistent with the unweathered granitic material in the gravel.

At the present state of knowledge, we believe the Grassy Mountain gravel represents a combination of locally derived material such as the black chert (reworked from the Shinarump), and far-traveled material such as the granitic and metavolcanic clasts, probably derived from the south. In essence, we still think that the gravel predates formation of western Grand Canyon, but readily admit that the subject of paleodrainage in the entire western Grand Canyon region is poorly understood and needs much more study. In any case, the Shivwits gravel is unrelated to the gravel beds on the Hualapai Plateau, which are much lower topographically and probably much older as well. Working out the regional relations between the gravels would make a fine thesis.

7. Except for the southern part of the Shivwits Plateau, middle Miocene through Pliocene lavas rest on the Triassic Moenkopi Formation in much of northern Arizona near Grand Canyon, including the Flagstaff area. This shows that Mesozoic strata formed the landscape in this wide region. The present Kaibab-dominated landscape is a new development. It is a safe bet to postulate that Mesozoic units above the Moenkopi were also present on the Shivwits and Unikaret Plateaus shortly before middle Miocene time. The combination of a characteristic of the lavas with the northeast dip of the strata is very useful for sorting out the Moenkopi landscape and determining the rate at which it changed. The characteristic of the lavas is that they become younger northeastward (see Wenrich and others, 1995, Figure 2b.; we found the same thing earlier in our much more restricted sampling of the Shivwits lavas). The gentle dip of the strata results in a northeast retreat of scarps and clifflines. Such scarps are common in the Mesozoic section, wherever a resistant layer caps less resistant ones. A good example is the Shinarump Conglomerate above the Moenkopi sandstone and mudstone. The combination of these characteristics means that we can construct a movie showing the development of the landscape through time.

8. Satellite images and regional geologic maps show that many flows in the Shivwits and Uinkaret Plateaus are elongated in a north-northwest direction, which is approximately the strike of the strata. When vent areas are also taken into consideration, it is clear that the lavas systematically flowed north-northwest. This was the drainage direction for the region by about 9 Ma, a direction quite different from the modern one. This strike-controlled direction contrasts with the northeast downdip consequent direction at the southern end of the Shivwits Plateau, and the obsequent southwest direction of the quartzite-bearing streams flowing down the south- or southwest-facing scarp developed on Mesozoic rocks and analogous to today's Vermilion Cliffs and Grand Staircase (see below). Taken together, these drainage directions form a dendritic pattern.

9. In many places, Shinarump pebbles are present not only under the basalt flows, but on top as well, this in areas where there now is no nearby high ground that could serve as a source for the pebbles. A good example is in the country northeast of Yellow John Mountain. The only reasonable way to get the pebbles where they are is if a scarp capped by the Shinarump existed northeast of the valley down which the basalt flowed. This way, Shinarump pebbles would have littered the floor of the valley before the basalt, and would have continued to be shed onto the basalt once it was in place (see Lucchitta, 1975, p. 101, fig. V-A-3). In the case of the Yellow John area, the northeast source direction is now the site of Andrus Canyon, a deep tributary of Grand Canyon (diagrams in Lucchitta, 1975, p. 101, fig. V-A-3). This is evidence that, when the 7.5 to 8 Ma basalt was emplaced, Andrus Canyon, and by extension, Grand Canyon, did not yet exist. Instead, the typical landscape at the time was cuesta troughs aligned with strike and bounded on the northeast by scarps facing southwest.

10. In many places, the elongate basalt flows, of whatever age, bury the featheredge of the Moenkopi Formation against the underlying Kaibab Limestone. The flows enable us to work out several things. First, the featheredge is the bottom of the valley down which the lava flowed. The valley was bounded on one side by the northeast-dipping Kaibab Limestone, and on the other by the Moenkopi-Shinarump scarp, which faced southwest. This arrangement can be seen today in a general way in the valley of the Little Colorado River northeast of Flagstaff.

    Second, we can map several lava-filled valleys of this kind, all at the featheredge of the Moenkopi on the Kaibab. Since the valley-filling lavas are progressively younger to the northeast, the featheredges give us a datum by which to measure the rate of retreat of the Moenkopi-Shinarump scarp, using the age of the lava flows as the time element. The distance between featheredges must of course be measured in a northeast direction, perpendicular to strike. We first did this using the 7.5 to 8 Ma Shivwits basalt of the Mount Dellenbaugh area, and the 6.2 Ma basalt of the Wildcat Ranch flow to the north, just west of Grassy Mountain. The difference in age is 1.3 to 1.8 Ma, and the strike separation of the featheredges is about 9 km, which gives a rate of scarp retreat of 7 to 5 km/Ma. Another determination can be made using the Wildcat Ranch flow and the 4.8 Ma Poverty Mountain flow to the north. Here, the age difference is 1.4 Ma, and the (poorly constrained) strike separation some 5 km, for a retreat rate of retreat of ~3.6 km/Ma. Going directly from Mount Dellenbaugh to Poverty Mountain, the rate is ~4.7 km/Ma. Throwing caution to the wind, we can calculate overall rates over longer distances, where factors such as movement on faults can complicate the issue. A 1.4 Ma flow blankets the featheredge near Dutchman Draw, at the north end of the Shivwits. The strike separation from the Mount Dellenbaugh featheredge is ~30 km, and the age difference is 6.6 Ma, for a rate of ~4.5 km/Ma. Finally, a 0.83 Ma flow buries the present featheredge near Clayhole Wash, at the north end of the Uinkaret Plateau. The strike separation from the Mount Dellenbaugh featheredge is 27.5 km (projecting strike here is difficult), the age difference is ~7.2 Ma, and the rate ~3.8 km/Ma. These are all imprecise, back-of-the-envelope calculations, but the decent agreement between the various rates emboldens us to propose that the rate of retreat of the Moenkopi-Shinarump scarp probably was around 4 km/Ma. This is a high rate, which shows that the landscape of northern Arizona was very different even a short time ago from what it is today. In thinking about past landscapes, it is necessary to factor in the rapid migration of Mesozoic rocks and the scarps contained in them.

11. In the present topography near Kanab, Utah, the southern lip of the Shinarump scarp is approximately 8 km south of the face of the Vermilion Cliffs, the lower part of the Grand Staircase. The intervening belt of subdued terrain is developed in the Triassic Chinle Formation. If present relations are any key to the past, the Vermilion Cliffs and perhaps even much of the Grand Staircase would have been in the southern Shivwits Plateau 9 to 6 Ma, probably near the present Andrus or Parashant Canyons. This trend can be extrapolated to near Flagstaff, Arizona, using preserved remnants of Moenkopi Formation for control.

12. The final element of the ancient landscape to be considered is the upper Grand Wash Cliffs, a 450 m escarpment cut into upper Paleozoic rocks and forming the southern edge of the Shivwits Plateau. In contrast to the Grand Wash Cliffs proper, formed by Miocene movement of the Grand Wash Fault at the west edge of the plateau, the upper cliffs are an erosional feature formed by the resistant Kaibab and Toroweap limestones overlying the Hermit Shale. Stratigraphically and geomorphically, they are the northwesternmost continuation of the Mogollon Rim of central Arizona (Lucchitta, 1966, 1975). Before movement of the Grand Wash Fault, the cliffs extended westward into what is now the Grand Wash trough, and perhaps even farther west. As is the case with scarps in the Mesozoic section of the plateau, the upper Grand Wash Cliffs are an erosional escarpment retreating northeastward, down the structural slope and away from the Laramide belt of uplift to the south and southwest. But here the similarity ends.

Whereas the Mesozoic scarps have retreated at a high rate, the tough limestone cap rock of the upper Grand Wash Cliffs has allowed only a much slower rate of retreat. This is evidenced by the fretted and embayed character of the cliffs and by a hill with important geologic relations described by R.A. Young (1982) on the south rim of western Grand Canyon, near Separation Canyon. Here a 19.0 Ma (Wenrich and others, 1995) basalt flow caps a gravel sequence, some of which contains angular clasts of upper Paleozoic rocks. The clasts can only have come from the upper Grand Wash Cliffs to the north, because upper Paleozoic rocks had long been stripped elsewhere by the time the lavas were emplaced. The angular clasts indicate that they were part of a colluvial apron extending southward from the cliffs. Assuming that the cliffs at that time were where the gravel is now, they would have retreated about 11 km to their present stand (determined by connecting the southernmost prominences of the cliffline), and would have done so in 19 Ma, for a rate of 0.6 km/Ma. This is a maximum value for the retreat rate because the ancient cliffs in fact must have been some distance northeast of the gravel hill. Even this maximum rate is six to seven times lower than that for the Mesozoic cliffs on top of the Shivwits Plateau.

13. The gravel at Separation Canyon provides a constraint of 19 Ma for the age of western Grand Canyon, as pointed out by Young (1989), because a colluvial apron bringing upper Paleozoic rocks to the hill could not have extended across Grand Canyon. Furthermore, the lava that caps the gravel would have flowed into Grand Canyon and other canyons that surround the hill, had they existed at the time.

In a Nutshell

The late Miocene landscape of most of Grand Canyon country, and northwestern Arizona in particular, was a landscape of Mesozoic rocks, with relatively small exposures of Paleozoic rocks on the Hualapai Plateau south of the canyon. The Mesozoic rocks formed erosional scarps facing southwest and retreating northeast down the structural slope. From 6 to 8 Ma, the Shinarump scarp, the Vermilion Cliffs, and perhaps most of the Grand Staircase may have been located in the southern Shivwits Plateau, possibly extending from there southeast across the Cataract Creek basin to the Flagstaff area. Scarps and valleys retreated northeast, downdip, at rates averaging about 4 km/Ma.

Drainage at the southern end of the plateau was on the Kaibab Limestone and to the northeast, down the structural slope. Drainage on the face of the scarps was to the southwest. Both were tributary to northwest-trending strike valleys occupying the featheredge of the Moenkopi Formation on the Kaibab Limestone. Together, they formed a dendritic drainage pattern. Lavas of various ages flowed northwest down the then-current position of these valleys.

There was no evidence for western Grand Canyon as recently as 6 Ma, and considerable evidence against its presence at that time. The upper Grand Wash Cliffs also are an erosional scarp retreating northeast down the structural slope formed by the Laramide-age Mogollon highlands uplift. This scarp has retreated at a rate of about 0.6 km/Ma. Gravel derived from the scarp and capped by a 19 Ma lava flow further constrains the age of western Grand Canyon to a maximum of 19 Ma.

Searching for the Pre–Grand Canyon Colorado River: The Muddy Creek Formation North of Lake Mead

Joel L. Pederson

Abstract: Resolving the path of the pre–Grand Canyon Colorado River drainage on the southern Colorado Plateau is a major conundrum, and the Muddy Creek Formation basin fill north of Lake Mead has been cited as the potential terminal deposits of this paleoriver. Sedimentologic and petrologic investigations reveal that there is a component of exotic river sediment in this basin fill, but it seems unlikely that this was the site of long-term deposition by a sizeable paleo–Colorado River.

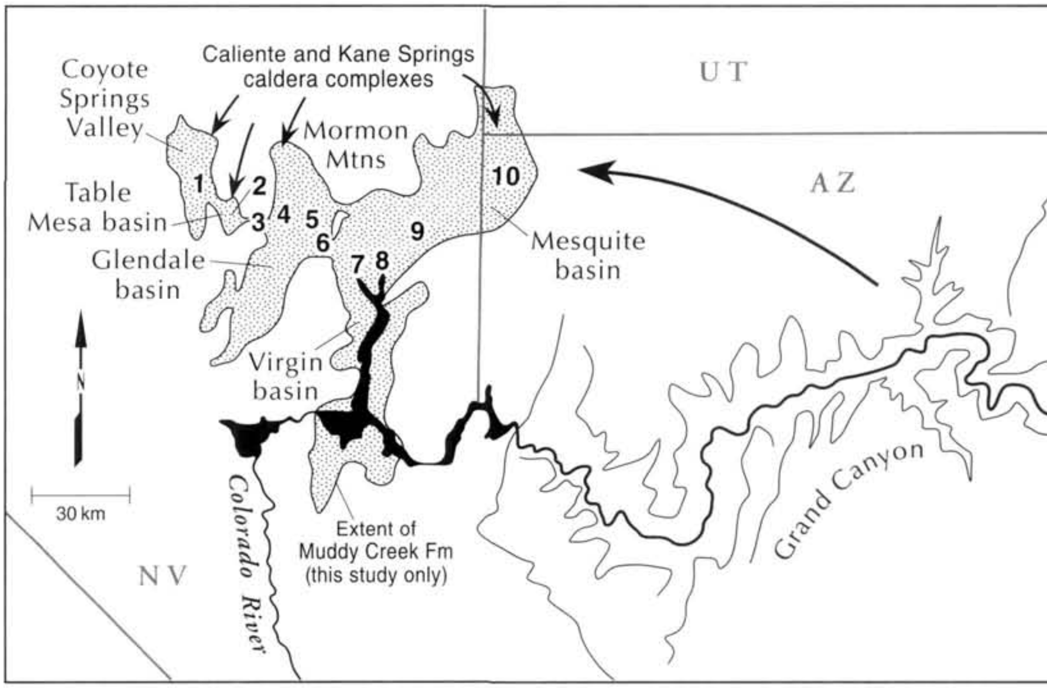
The path of the pre–Grand Canyon Colorado River and whether it existed at all remain major unanswered questions about late Cenozoic landscape evolution of the Colorado Plateau. An important assumption framing this debate has been Hunt's (1969) conclusion that an upper Colorado River drainage existed on the northern Colorado Plateau as early as Oligocene time. The main working hypotheses for the southern Colorado Plateau have been that, prior to Grand Canyon incision and the present-day path of the river, this upper Colorado River: (1) issued to the southeast along the Little Colorado River trough (McKee and others, 1967), (2) crossed the Kaibab upwarp terminating in the southwestern Colorado Plateau (Hunt, 1956), or, perhaps the most accepted hypothesis, (3) crossed the upwarp and followed the strike valleys of the Arizona Strip country into the Basin and Range Province (Figure 1; Lucchitta, 1990). Regarding the first hypothesis, we now know because of greatly improved age control that the Bidahochi Formation was deposited in the Little Colorado River trough during part of the time in question (Ort and others, 1998). But it is apparent that the Bidahochi basin is not a viable location for the terminus of the Miocene Colorado River because of its very low sediment accumulation rates and its lack of sedimentologic evidence for a large river (Dallegge and others, this volume). This leaves the idea that the river exited the Colorado Plateau to the west, and the best candidate for a Miocene sedimentary record of this potential drainage in the Basin and Range (hypothesis 3, preceding) is the Muddy Creek Formation north of Lake Mead (Figure 1).

Sedimentologic observations and petrologic data that address the origin of Muddy Creek Formation sediment are described here. Longwell's (1928) original assessment of the Muddy Creek in the southern Virgin Basin was that its fine-grained sediment is incompatible with a Colorado River origin. But recent research on the sedimentology, stratigraphy, and petrology of the Muddy Creek basin fill in its northern basins led to the idea that it may represent the terminal delta deposits of the paleo–Colorado River before integration and incision of Grand Canyon (Pederson, 1998; Pederson and others, 2000b). If this turns out to be true, the Muddy Creek Formation would be an analog for the younger Bouse Formation along the lower Colorado River corridor and the Imperial and Palm Springs Formations in the Salton Trough (Lucchitta, 1972; Buising, 1990). Yet results of ongoing sedimentologic and petrologic study of the Muddy Creek Formation indicate that a paleo–Colorado River is not necessary to account for the basin fill.

Muddy Creek Formation North of Lake Mead

The Muddy Creek Formation is regionally important as the substrate for the growing Las Vegas metropolitan area, for its groundwater resources, and for its clues to regional spring history (Schmidt and Dixon, 1995). It has been loosely defined as the late-stage basin fill of this series of somewhat interconnected basins in the Lake Mead area (Stock, 1921; Bohannon, 1984; Bohannon and others, 1993) (Figure 1 and location figure). It is important to note that this discussion

Figure 1. Regional geography. Large arrow indicates hypothetical path of late Miocene Colorado River; smaller arrows indicate paths of volcanic detritus into the northern Muddy Creek basin; and numbers 1 to 10 mark sample and description localities.



excludes basin fill of the Grand Wash trough, which is labelled Muddy Creek Formation by some workers (e.g., Longwell, 1946; Lucchitta, 1972; Spencer and Patchett, 1997) and has a very different and important role in the Grand Canyon incision story.

Basin and Range extension, characterized by dip slip on normal faults, detachment faulting, and large-scale transfer zones with oblique slip (Anderson, 1971; Stewart, 1980), formed the depositional basins of the study area. Significant tectonism ceased after early and middle Miocene time (Anderson, 1971; Bohannon, 1984; Bartley and others, 1988), and upper Miocene and Pliocene basin fill of the Muddy Creek Formation was accommodated in basins that were underfilled. The study of late-stage (post-tectonic) continental-basin sediment is in its infancy (Langford and others, 1999; Smith, 2000), but much of the Muddy Creek Formation may be a characteristic example of such sediment, with mostly fine grained facies deposited in poorly understood, mostly subaerial, sedimentary environments. Although basins had internal surface drainage for much of their history, evidence reviewed below indicates that depositional systems eventually overtopped low divides between basins and the region became hydrologically and sedimentologically interconnected, though not externally drained. Basins were subsequently integrated into the present-day Colorado River drainage, which led to downcutting and incision of the fill (Bohannon, 1984; DiGuisseppi and Bartley, 1991; Schmidt, 1994).

The age of the Muddy Creek Formation has been previously estimated at 10 to 5.88 Ma, with the younger age being a maximum upper constraint from a K-Ar date on basalt capping Fortification Hill at the southern end of Lake Mead (Damon and others, 1978). Two gray ash beds previously K-Ar dated by Metcalf (1982) at 7.2 ± 0.3 and 5.9 ± 0.2 Ma are exposed in Muddy Creek basin fill of Table Mesa basin (Figure 1). The lower ash can be traced widely in the basin and has been redated by geochemical correlation to the 5.59 ± 0.05 Ma Wolverine Creek Tuff (Pederson, 1999; Morgan and McIntosh, in press). Though younger than the previous upper age estimate at Fortification Hill, this date is from the lower member of the formation in Table Mesa basin. Thus the upper Muddy Creek Formation is younger than previously established, up to late Pliocene in age (see below), and the upper age varies from basin to basin according to the local timing of incision associated with drainage integration.

There has been little direct study of the sedimentology of the Muddy Creek Formation (Kowallis and Everett, 1986; Dicke, 1990). In general, this basin fill consists of several laterally gradational facies, yet is mostly composed of interbedded calcareous mud and sand that can be gypsiferous and which contains locally extensive fossil-spring travertine (Longwell, 1946; Bohannon, 1984; Kowallis and Everett, 1986; Schmidt, 1994). Pebbly to cobbly fluvial gravel is found in the Virgin Basin and northern Glendale basin, but in most areas coarse facies are restricted to piedmont stream gravel found at the immediate mouth of large mountain drainages and rare exposures of buried hillslopes and colluvium (Pederson and others, 2000a).

Where intensively studied in Table Mesa basin (Figure 1, location map), the Muddy Creek Formation has been split into lower, middle, and upper lithostratigraphic members (Pederson, 1999), and it is useful to apply this stratigraphic framework to neighboring basins. The lower member is specific to Table Mesa basin, includes the 5.6 Ma tuff, and is characterized by a large volume of spring-discharge travertine and laterally correlative saline lake or playa deposits (Schmidt and Dixon, 1995; Pederson, 1999). The sharp contact between the lower and middle members represents an abrupt change to much more siliciclastic-rich deposition, suggesting basin interconnection and the introduction of extrabasinal sediment at this time, which is supported by sedimentary petrology (Pederson, 2000b). The middle member in Table Mesa basin is only ~80 m thick but is typical of Muddy Creek sediment in neighboring basins to the east where its greater thickness is partly due to its longer and earlier history of deposition. This "typical" Muddy Creek sediment is dominated by pink-to-light-brown, laminated, ripple cross-stratified or massive calcareous sandy mud interbedded with minor thin beds of very-fine-to-fine sand. It is slightly gypsiferous, lacks fossils, and may have been largely deposited in an alluvial slope environment (Smith, 2000), though it is coarser and more "fluvial" in the Mesquite and Virgin basins to the east (Kowallis and Everett, 1986).

The top several meters of the middle member in Table Mesa basin and the Glendale basin coarsen upward to matrix and then clast-supported pebbly gravel. The conformable contact between the middle and upper members marks a significant change to deposition of piedmont gravel, recording the strong progradation of detritus from the local mountainsides into the basin (Pederson and others, 2000b). This contact is gradational at basin edges but sharper toward basin centers, and has been previously identified as the top of the Muddy Creek Formation in the Glendale basin (Schmidt, 1994). Schmidt (1994) recognized that this upper gravel is Pliocene in age based upon its physical correlation to fine-grained spring-lacustrine deposits that contain Blancan-age mammalian fossils. An ash bed in these fine-grained deposits (at Hogan Springs) has been geochemically correlated to the ~3.04 Ma Upper Horse Hill ash, confirming this (Williams, 1994; Pederson, 1999).

The initial change to overall incision of the basin fill and deposition of inset piedmont gravels in Pliocene time is marked by what Schmidt (1994) calls the regrade gravel, which lies in very low angular unconformity on upper Muddy Creek gravel. These two gravels are commonly identical in character and difficult to distinguish, except in more distal areas where the unconformity lies on finer-grained facies of the middle member.

Sediment Sources for the Muddy Creek Formation

The Virgin Mountains on the southern flank of the Mesquite basin include Proterozoic metamorphic rock, but the mountains surrounding Coyote Springs Valley, and Table Mesa, Glendale, and Virgin basins are dominated by a 3000 m thick Paleozoic sedimentary succession (Langenheim and others, 1962; Page and Pampeyan, 1996), ~97 percent of which is marine carbonates. One may intuit that, like most of the Basin and Range, sediment of the Muddy Creek Formation was derived from surrounding mountainsides. Yet carbonate rock is very difficult to weather in the desert climate of the area because chemical dissolution is at a minimum, and this bedrock has high rock-mass strength making physical weathering difficult as well (Pederson and others, 2001). Sedimentary petrologic studies in the western study basins confirm that the minor insoluble residue of carbonates in the local mountains could not have provided the significant fine-grained siliciclastic detritus of the Muddy Creek Formation (Pederson and others, 2001). What are the extrabasinal sources of this sediment?

A series of outcrops along a west-to-east transect from Table Mesa basin through the Glendale basin and into the Virgin Basin were studied with the intent of seeing how the exposed Muddy Creek Formation changes laterally. Locations are all ~30 m below the top of the middle member and correspond to localities 1 through 10 from west to east on Figure 1. The Glendale, Mesquite, and Virgin basins were sedimentologically interconnected at this stratigraphic level. At first glance, the exposed Muddy Creek Formation along this west-to-east transect generally grades from gypsiferous sandy mud that coarsens upward and to the east to pebbly alluvium. For example: (1) locality 2 in Table Mesa basin has muddy sand and sandy mud as described above, (2) fill at locality 4 in western Glendale basin is composed of thin, wavy bedded mud and sandstone with infilled channel forms visible in places, (3) locality 6 on the east side of the Glendale basin has massive sand that contains root casts and is heavily bioturbated, (4) locality 7 on the west side of Mormon Mesa in Virgin Basin has sand with large-scale crossbedding (interpreted as eolian because foresets coarsen upward) interbedded with pebbly-to-muddy facies interpreted as representing fluvial channel and overbank settings, and (5) at localities 8 and 9 fluvial deposits become coarser and pebbly facies of fluvial channels become more common. These general observations led to the hypothesis that a large fluvial system (paleo–Colorado River) emptying into the Mesquite basin may have been the major source of siliciclastic detritus (Pederson, 1998). Yet localities 1, 5, and 10 have notably south-directed paleocurrent indicators (instead of westward) and do not follow the trend of coarsening to the east, with 1 and 5 being coarser and "more fluvial" than neighboring localities, and the easternmost of all localities (10) having relatively fine grained deposits.

Comparing order-of-magnitude estimates of the volume of the Muddy Creek Formation and very broad estimates of the sediment load of a paleo-upper-Colorado River may illuminate whether such a river could supply this volume of sediment in a reasonable time frame. Estimating the volume of the basin fill is difficult because the spatial limits of what can be considered continuous Muddy Creek Formation are subjective and poorly understood. The formation covers an area of ~5200 km^2 if the shaded area of Figure 1 is taken as its limits. The few well-borehole and geophysical data available indicate the thickness of the Muddy

Creek Formation varies greatly among basins (Bohannon and others, 1993; Page, in press). An average thickness of 250 to 1000 m is a reasonable range for Muddy Creek basin fill across the area if one approximates a basin as having a triangular cross section, and thus averaging about half its maximum depth. This results in a basin-fill volume of 1300 to 5200 km^3.

It is an even more uncertain task to estimate the sediment load of the hypothetical paleoriver. Historic data from 1914 to 1957 at Lees Ferry upstream of Grand Canyon may be used as a starting point for calculating the sediment load of a paleo–Colorado River, considering the drainage upstream of this point may approximate the geology and relief the river would have encountered before incision of Grand Canyon, and assuming that regional precipitation was broadly similar to present-day amounts. Prior to Glen Canyon Dam (completed 1963), the river's avrage suspended sediment load was 1.02×10^{11} kg/yr (Iorns and others, 1965). Suspended load accounted for ~90 percent of the river's total load, with a ~4:1 ratio of mud to sand, which seems to be consistent with the texture of Muddy Creek basin fill. If one adds between 10 and 15 percent for bed load, subtracts 25 to 50 percent to account for additions to the historic sediment load from human disturbance, and then converts to volume by using a density range of 1500 to 2200 kg/m^3 for uncompacted sediment, one arrives at a sediment yield of between 0.026 and 0.059 km^3/yr. With the estimated range of volumes for the Muddy Creek basin fill, it would take about 20 to 200 ky for a hypothetical paleo–Colorado River to supply this sediment. This time range is at least an order of magnitude less than is reasonable for deposition of the Muddy Creek Formation, suggesting the Colorado River hypothesis may be faulty, or that the paleoriver was much smaller than estimated here.

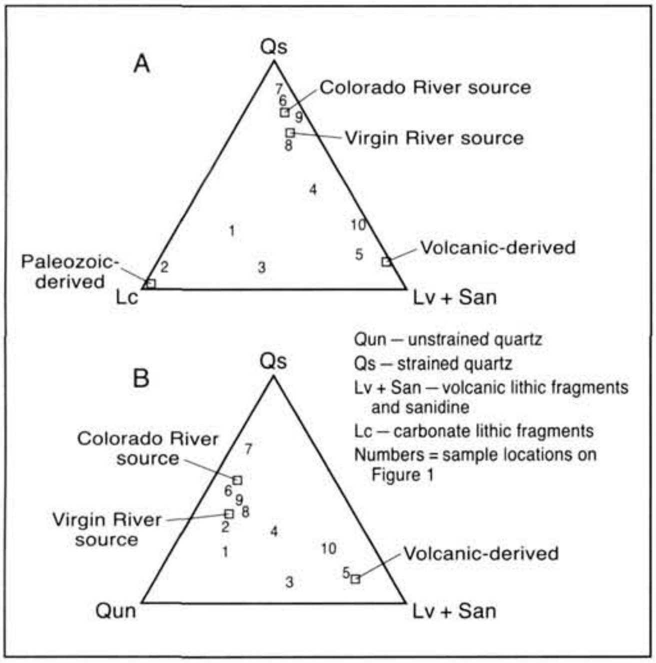


Figure 2. Ternary plots of Muddy Creek Formation samples and samples representing possible sediment sources. Numbers correspond to samples from locations on Figure 1.

A) Plot with axes that include all major sediment sources;

B) Plot with axes that concentrate on exotic sediment sources.

To test this hypothesis in a more concrete manner, provenance analysis from sedimentary petrology was performed on samples from the same west-to-east transect of localities mentioned above. Fine-sand fractions of samples were permanently mounted as thin sections, stained for K-feldspar, and grain types were counted to a total of 400 using an automated point-counting stage. Analyses were also made on samples representative of four distinct sediment sources: (1) a lower-member sample from Table Mesa basin derived from local Paleozoic bedrock, (2) a sample from Pleistocene alluvium of Beaver Dam Wash in the Mesquite basin derived from volcanic terrain of the Caliente caldera complex (Figure 1), (3) Pleistocene Virgin River deposits sampled where the river enters the eastern Mesquite basin, and (4) Pleistocene Colorado River deposits at Lees Ferry. Plotting all transect and source-area samples with axes designed to distinguish sediment sources reveals that only the three westernmost samples have significant local Paleozoic carbonate bedrock contributions (Figure 2A), whereas most samples appear to include combination of exotic river and volcanic sources.

If a paleo–Colorado River source existed at the east end of the Mesquite basin, we may anticipate that sample compositions would become increasingly similar to Colorado River sediment from location 1 to location 10. But when plotted with axes that concentrate on exotic sediment sources (Figure 2B), samples appear to follow a random path rather than becoming increasingly "Colorado-River-like" from west to east. Results indicate a significant contribution to the Muddy Creek Formation by volcanic sources in some areas (locations 1, 3, 4, 5 ,10, which includes the easternmost sample locality). The presence of volcanic detritus at these particular localities is consistent with the sedimentologic and paleocurrent observations mentioned above. It also matches the present-day pattern and location of large drainages that have source areas in the volcanic terrain of the Caliente and Kane Springs caldera complexes entering the study basins from the north (Figure 1). Colorado River and Virgin River sediment are similar compositionally, and most sample compositions can be explained as a mixture of local, volcanic, and paleo–Virgin River sources. These initial petrologic data suggest that the Muddy Creek Formation need not have a paleo–Colorado River source, and that Miocene sediment pathways likely imitated present-day drainage patterns in the basins.

Conclusions

Paleogeographically, the Muddy Creek Formation is a logical candidate for terminal deposits of a pre–Grand Canyon Colorado River, though it is only late Miocene in age and can not account for the river's path earlier in geologic time. Sedimentary and petrologic data indicate there very likely was an exotic stream sediment source entering the Mesquite basin in late Miocene time. On the other hand, Pederson and others (2001) conclude that bedrock type in this tectonically quiescent, dry setting is the first-order control on sediment yield, with volcanic hillslopes in the region providing disproportionately large amounts of detritus relative to carbonate bedrock. Field observations and initial sedimentary petrologic data are consistent with this, indicating a significant amount of the siliciclastic detritus in the Muddy Creek Formation is derived from volcanic terrain to the north and delivered by streams through the gaps to the west and east of the Mormon Mountains, just as in the present landscape (Figure 1). The potential of a paleo–Colorado River sediment source is further undermined by recognition that the exotic stream source could be the paleo–Virgin River and that the Muddy Creek Formation comprises a disproportionately small volume of sediment. Further work is essential to resolve the path of this ancient and elusive river.

Acknowledgments

I thank Jamie Farrell for providing some of the petrographic data and Keith Howard and Ivo Lucchitta for helpful reviews of the manuscript.