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Paleogene rim gravel of Arizona: Age and significance of the Music Mountain Formation

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ABSTRACT

The early Tertiary exotic rim gravel scattered across the Colorado Plateau in Arizona (USA) provides the only widespread evidence concerning the nature of the regional Paleogene drainage system that preceded the emergence of the modern Colorado River. The term "rim gravel" includes a wide range of Laramide (herein ca. 85–40 Ma) and younger reworked quartzite-dominated, arkosic sediments with diverse origins and ages that have been clarified only recently. The parent arkoses, with subordinate gravel lenses, contain volcanic clasts with ages ranging from Late Jurassic to early Eocene. The Laramide-age arkoses were shed off uplifted Precambrian terranes to the south and west; they are separated from their reworked derivatives and younger sediments by a disconformity that is best preserved in the structurally isolated paleocanyons of the Hualapai Plateau. Younger generations of reworked gravels continued to evolve during and following the widespread eruption of basalts of late Oligocene to Pleistocene age. Basaltic clasts in the reworked gravels attest to their much younger ages. Combined paleontologic, stratigraphic, paleomagnetic, K-Ar, U-Th/He, and zircon studies of the parent arkoses indicate that the tectonic framework corresponds to the Laramide orogeny, the concurrent regional erosion of the Colorado Plateau margin, and ensuing widespread deposition. The overall time frame coincides with the similar tectonic history recorded in the early Tertiary strata of southern Utah. Comparable but unrelated quartzite-dominated gravels, reworked southward from the Utah source rocks, are widespread on strath terraces north of the Colorado River. The Utah-derived gravels are products of the much younger Neogene incision of the modern Grand Canyon drainage system. The name Music Mountain Formation redefines the Laramide-age suite of the Arizona rim gravel parent sediments, best preserved on the Hualapai and Coconino Plateaus of northern Arizona, and distinguishes them from younger reworked gravels occurring both north and south of the Colorado River. A lacustrine mollusk assemblage collected from thin limestones intertonguing with Music Mountain arkose constrains the age of one Coconino Plateau exposure to early Eocene, whereas the association with the Laramide orogeny indicates that a Late Cretaceous to middle Eocene time frame comprises the broader geologic setting.

INTRODUCTION

Exotic Rim Gravels of the Southwestern Colorado Plateau, Arizona

The Colorado Plateau of northern Arizona (USA), between the Mogollon Rim and the Colorado River, contains scattered remnants of Tertiary arkosic gravels with exotic clasts derived from rocks that crop out in the Precambrian terranes of the former Mogollon Highlands of central Arizona and the Kingman uplift in the lower Colorado River region of western Arizona (Fig. 1). The Laramide tectonic framework is the backdrop for the fragmentary evidence of the geologic events that shaped the early Tertiary evolution of the drainage that preceded the modern Colorado River system. The term Laramide in this discussion includes the events from ca. 85 to 40 Ma (Campanian–middle Eocene) in Arizona as described by Keith and Wilt (1985), and by the corresponding radiometric age distribution compiled by Damon (1964).

The exotic gravels and successive generations of derivative deposits came to be indiscriminately referred to as Arizona "rim gravel," based on their perceived Mogollon Rim distribution, during the latter half of the twentieth century. The thrust of this paper is to review the origin and evolution of the poorly defined term rim gravel, to describe the true nature and probable age range of the oldest exotic Tertiary gravels that have given rise to several generations of derivatives, and to explain how existing names in the geologic literature, such as the Music Mountain Formation, should either be retained or abandoned in order to correct existing misconceptions. New age data from mollusks (gastropods) collected from lacustrine limestone lenses that occur within undisturbed exposures is included in the Supplemental File[1].

In retrospect, it is clear that the widely scattered, quartzite-dominated gravels described by various researchers include a range of very old (Late Cretaceous? to Paleogene) arkosic sediments and much younger (Neogene–Quaternary) reworked gravels and related lag deposits. In structurally isolated paleocanyon reaches the first generation rim gravel is separated from reworked and younger fluvial deposits by a conspicuous post-Laramide disconformity that represents a potentially lengthy depositional hiatus without significant erosion (Fig. 2; Young, 1999). Outside of the structurally isolated paleocanyon basins, the same post-Laramide interval includes undetermined amounts of erosion that may have removed hundreds of meters of arkosic sediments in some locations. Some references refer to relatively thin surface exposures of lag gravels as rim gravel; however, these deposits are dominated by resistant lithologies with markedly different average compositions compared to their parent sediments. The original arkosic sediments have thicknesses exceeding 200 m in

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[1] Supplemental File. Paleontological analysis. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00971.S1 or the full-text article on www.gsapubs.org to view the Supplemental File.

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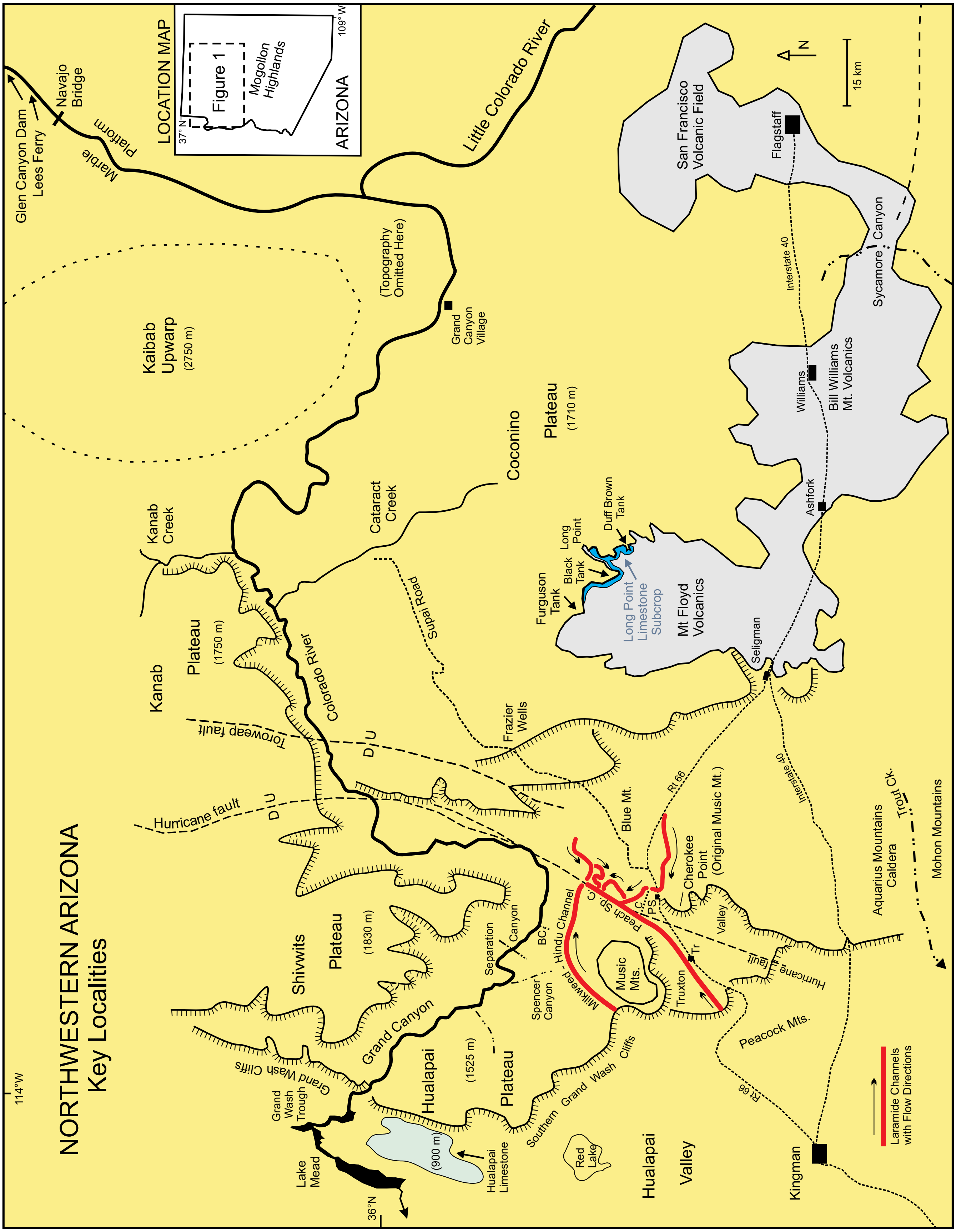

Figure 1. Location map for significant localities mentioned in the text. Tr—Truxton; PS—Peach Springs; BC—Bridge Canyon; D—down; U—up. Dotted line labeled C north of Peach Springs is location of cross section of Figure 4.

Figure 2. Milkweed Canyon Tertiary section, Hualapai Indian Reservation, SE 1/4, Section 17, T. 26 N., R. 13 W (U.S. Geological Survey, 1967b). Buck and Doe Conglomerate (Congl.) is 34 m thick. See also Figure 3. Mt.—mountain; mbr.—member; Fm.—formation; Sp—spring.

some well-preserved localities, but the subordinate gravel lenses constitute as little as 10% of the undisturbed in situ exposures (Young, 1999).

The in situ parent rim gravel outcrops are deeply and thoroughly weathered below the conspicuous disconformity, which apparently marks a period of middle to late Eocene(?) structural quiescence. Precise age control is lacking, but late Oligocene volcanic rocks overlie the rim gravels in some locations. The original arkosic sediments probably span an interval from Late Cretaceous(?) through middle Eocene; the lower age limit can only be estimated at present, based on the Laramide time frame and the age distribution of included volcanic clasts.

Younger generations of gravels and surficial lag deposits, reworked from the original Laramide-age sediments, contain Miocene or younger basalt clasts, which clearly relegate them to Neogene events (Spencer et al., 1995). Early researchers did not recognize or appreciate the distinction between the Laramide-age parent gravels and their reworked Neogene derivatives. Some researchers have inappropriately associated the rim gravel depositional episode that occurred south of the Colorado River with exotic, quartzite-rich gravels of northern derivation but of much younger ages. Understanding the geologic setting that produced the early Tertiary deposits and underlying paleotopography is the initial step in reconstructing the sequence of events that eventually produced the modern, west-flowing Colorado River and impressive Grand Canyon.

Early References to Exotic Plateau Gravels

Observations from 1875 to 1950

Tracing the origin, evolution, and validity of the informal term rim gravel involves a literature search of obscure publications, as well as visits to the actual field localities described in the older literature, in order to view them from a modern perspective. Such efforts are a challenge because rock unit ages, formation names, epoch boundaries, lithologic terms, naming conventions, and local geographic map names have evolved or changed in loosely documented ways over the past century.

A careful interpretation of an early geologic traverse along the southern Grand Wash Cliffs (Fig. 1) by A.R. Marvine of the Wheeler Survey (Wheeler, 1875) includes a description and simplified sketch of exotic plateau gravels at the structurally truncated head of Milkweed Canyon, a location said to be immediately north of Music Mountain (a mislocated name), as a conglomerate with “sandstone, granite, and lava bowlders” (A.R. Marvine, *in* Wheeler, 1875, p. 201, fig. 89 therein).

Note: The original “Music Mountain,” first appearing on the 1858 Ives’ expedition map, but now designated “Cherokee Point” on modern topographic maps, is actually located south of Peach Springs (Fig. 1) on the map drawn by Egloffsteinn and titled, “Rio Colorado of the West” (Ives, 1861). In the interim the plural term, “Music Mountains,” has come to refer less precisely to an ill-defined portion of the southern Grand Wash Cliffs that extend north from the Truxton Valley, and does not include the original location marked on the Ives’ map. The *name, Music Mountain, derives from the closely spaced parallel beds of Cambrian-Devonian limestones on the north face of the cliff that resemble the uniformly spaced staffs or staves on a page of music when viewed at favorable sun angles.*

A.R. Marvine (*in* Wheeler, 1875, p. 201) referred to the modern Milkweed Canyon location north of his mislocated Music Mountain as the "Cañon of New River," in obvious recognition of an older paleocanyon filled with younger sediments (Fig. 1, Milkweed-Hindu channel). The northeastern extension of this Milkweed paleocanyon now includes the type locality for the Music Mountain Formation (Young, 1999). Inexplicably, Marvine mislocated the Miocene basalts below the older gravels at the base of the Tertiary section in his accompanying sketch, presumably because he observed a thick section of basalt flows overlying Precambrian basement rocks on the northwest side of the partially exhumed paleochannel (Black Mesa on Milkweed Canyon NW, Arizona, topographic map [U.S. Geological Survey, 1967b]). During the continuation of his traverse southward along the Peacock and Aquarius Mountains, Marvine (*in* Wheeler, 1875, p. 202–203) mentioned 60–80 ft (~18.3–24.4 m) of "rhyolite" that occupies a "broad but shallow basin in the lower lavas," the earliest known mention of the important stratigraphic marker, the Peach Spring Tuff (see Young and Brennan, 1974; Young, 1999).

However, the most commonly cited early references to exotic Tertiary gravels on the Colorado Plateau are those by Robinson (1907, 1913), whose description of the San Francisco volcanic field alludes to subangular gravel clasts along the Mogollon Rim near Sycamore Canyon, 35 km southwest of Flagstaff, Arizona (Fig. 1), as being composed of "gneiss, jasper, and other metamorphic rocks as well as basic igneous rocks of granitic texture," with less abundant "fairly rounded cobbles of sandstone and chert up to 8 inches in diameter" (Robinson, 1913, p. 30).

Price (1950) subsequently divided the Sycamore Canyon gravels described by Robinson (1913) into Type A and Type B suites. Price's Type A gravel is up to 130 ft (~39.6 m) thick and located stratigraphically between either the Moenkopi or the Kaibab Formations and the overlying basalts. However, Price's (1950) pebble count of Type A gravel contains 8% basalt cobbles, which, given subsequent mapping, requires a Miocene or younger age for that reworked exposure. Failure to distinguish between truly old and subsequently reworked generations of such gravels is a common problem in the older literature, before radiometric age compilations proved the dominantly Miocene–Pleistocene ages of basalts on the plateau margin in Arizona.

Price's (1950) designated Type B gravel is described as having a greater roundness and sphericity with no basalt cobbles, but it also contains petrified logs described as being as large as 2.5 ft (0.76 m) in diameter and with no evidence of wear from fluvial transport. Price (1950) found no Type B gravel in place or undisturbed, and did not precisely define contact relationships, other than to note the gravel was spread over the eroded Moenkopi Formation; his single 100 pebble count of Type B gravel includes quartzite (74), chert (24), and chalcedony (2), which he assumed indicated they were derived from the Shinarump Conglomerate. Despite the lack of basalt cobbles in the Type B gravel, Price (1950) thought they were younger than the Type A deposits, because the Type A gravel contained no Type B clasts. Price changed Robinson's estimated Triassic age for the older Type A gravel to Miocene or Pliocene, and assigned his Type B gravel a Pleistocene age, incorrectly concluding that it only could have developed following late Cenozoic faulting, erosion of the basalt cover rocks, and subsequent conversion of isolated Shinarump Conglomerate outcrops to his residual Type B gravel. Price's (1950) Type B gravel is most likely a reworked derivative of older fluvial deposits.

There were few age determinations available for volcanic rocks in Arizona at the time of Price's (1950) study, and the Miocene-Pliocene boundary was subsequently revised from ca. 12 Ma to 5 Ma in the early 1970s. Such interpretational, temporal, and semantic problems complicated geologists' early understanding of the important differences among the potential sources and various generations of exotic gravel exposures on the plateau.

Gravels Incorrectly Attributed to Reworked Shinarump Conglomerate

It has been assumed by some that many quartz-rich lag deposits were mainly derived from the Shinarump Member (conglomerate) of the Chinle Formation. However, most of the comparatively uniform clasts in existing outcrops of the Shinarump Conglomerate in Arizona consist of relatively small, well-rounded quartz, quartzite, chert, and thoroughly abraded petrified wood fragments. With the benefit of hindsight, Price's (1950) Type B gravels probably should be assigned to a category of reworked Laramide lag gravels, originally deposited prior to the initiation of widespread Miocene volcanism. Some contribution of Shinarump Conglomerate pebbles to exotic rim gravels is possible on the southern Colorado Plateau; however, Shinarump Conglomerate quartzite clasts throughout northern Arizona are considerably smaller than typical rim gravel quartzite clasts, as documented by Stewart et al. (1972). In addition, the presence of very large diameter petrified logs with no evidence of fluvial abrasion in Prices' (1950) Type B gravel indicates that such fossil materials probably represent the indigenous flora, similar to the large petrified logs with delicate bark structures preserved (as described in Young, 1999) and photographed on the Hualapai Plateau (Young, 2011, fig. 8 therein).

Albee's (1956) detailed study of pebble types in the Shinarump Conglomerate reinforces the findings of Stewart et al. (1972) in that Albee's mean pebble size is slightly <2.5 cm. The largest quartzite pebble noted in the combined Shinarump studies was 12.7 cm. In contrast, the abundant quartzite clasts in lag gravels derived from undisturbed Laramide-age arkosic sediments (rim gravels) are commonly as large as 10–25 cm in diameter (some are much larger). Chert pebbles in the Shinarump Conglomerate average between 35% and 50% total clasts, whereas chert is an uncommon constituent in the arkosic gravels in the region west of Flagstaff. A visual comparison of Shinarump Conglomerate clasts and so-called rim gravel clearly demonstrates that they are distinctly different in both average clast size and in bulk composition.

The widely exposed Kaibab surface of the Colorado Plateau north of the Mogollon Rim (Fig. 1) in central and eastern Arizona is littered with isolated patches of resistant lag gravels, sometimes only widely scattered lag pebbles, consisting mainly of quartzites and other very resistant crystalline lithologies reworked from parent rim gravel. The varied lithologies that characterize the original clasts of the in situ, deeply weathered, parent arkose are apparent only in rare gully exposures and fresh roadcuts throughout the region. Holm (2001a, 2001b) described in greater detail the generations of exotic, southern-derived gravels and associated erosion surfaces of the Mogollon Rim in central Arizona; Holm's descriptions and conclusions support the updated view presented in this paper concerning the nature and Laramide age of the oldest gravels.

Gravels of the Coconino and Hualapai Plateaus

Koons (1948a, 1948b, 1964) described 150–250 ft (~45.7–76.2 m) of deeply weathered exotic Blue Mountain gravel on the eastern Hualapai Indian Reservation that extends eastward onto the Coconino Plateau and beneath the Mount Floyd volcanic field to Long Point and beyond (Fig. 1) (Billingsley et al., 2006a, 2006b). Koons (1948b) correctly inferred that the gravels were the result of either Basin and

Range or pre–Basin and Range drainage flowing northward from the Prescott, Arizona, region. However, conflicting descriptions of the relative stratigraphic positions of these exotic gravels and an underlying, locally derived Paleozoic-clast-rich conglomerate (Robbers Roost gravel of Koons, 1948a) in Koons's (1948a, 1948b) publications are contradictory concerning which gravel is actually older, as clarified in Young (1999).

McKee (1951, p. 498) described the exotic gravels of the southwestern Colorado Plateau border as "scattered remnants of once extensive gravel deposits" developed in Pliocene time following "late Miocene or early Pliocene uplift to the south"; he specifically included the gravels described by Price (1950) and Robinson (1913), as well as the Coconino Plateau and eastern Hualapai Reservation gravels described by Koons (1948a, 1948b). McKee (1951, p. 498) asserted that such "Pliocene gravels" could only "have been derived largely from rocks of early Paleozoic and Precambrian age" and carried from the south to reach their current position on eroded Permian strata of the Colorado Plateau. At the time of McKee's 1951 publication, late Miocene and early Pliocene time were assumed to include a significant interval of active Cenozoic plateau uplift and deformation, and Sevier–Laramide-age deformation was not universally recognized as a significant event related to these sediments in Arizona or southern Utah. This view of Arizona geology gradually changed in concert with the extensive radiometric chronology that was largely developed by P.E. Damon and colleagues at the University of Arizona (e.g., Damon and Mauger, 1966), and by E.H. McKee at the U.S. Geological Survey during the 1960s and 1970s (compiled in Reynolds et al., 1986). A better understanding of the geologic history evolved with the gradual acceptance of plate tectonic theory and an appreciation of the orogenic events attributable to the subduction of the Farallon plate.

Gray (1959, 1964) named and described the Hindu Canyon formation (Keroher, 1970), which included an exotic basal arkosic member (Music Mountain Formation), on the central Hualapai Plateau (Fig. 1, Milkweed-Hindu Channel). Gray (1959, 1964) failed to appreciate the antiquity of his three designated formation members and the regional disconformity at the top of his proposed formation. One of us (Young, 1999) adopted Gray's prior terminology and nomenclature insofar as possible, while correcting certain misconceptions in Gray (1959). Mapping between 1962 and 1966 (by Young) on the Hualapai Plateau subsequently identified eight distinct Tertiary formations or members. Initial dating of the early Miocene Peach Spring Tuff in 1964 (formerly Peach Springs Tuff; Young, 1999) demonstrated the early Tertiary potential age range of the underlying exotic gravels. Type localities for all the Tertiary units on the Hualapai Plateau were described in Young (1999) and color images of each rock unit were included in Young (2011).

APPEARANCE OF RIM GRAVEL IN THE GEOLOGIC LITERATURE

Association with the Mogollon Rim

McKee (1951) correctly recognized that the exotic so-called Pliocene gravels of the Colorado Plateau margin in Arizona were clearly older than all the overlying basalt flows, rocks now known to range from Oligocene to Pleistocene in age along the southwestern Colorado Plateau and adjacent Transition Zone. McKee (1951, p. 499) attributed the exotic gravels to erosion resulting from "major uplift of the Colorado Plateau blocks" in late Miocene or Pliocene time, a time frame he attributed to Longwell (1946, 1936). McKee's (1951) references to the gravels present along the Mogollon Rim region (Fig. 1) appear to have initiated the informal designation of the term "rim gravel," which subsequently appeared in the geologic literature.

The term rim gravel first appeared (with quotation marks) in Cooley and Davidson (1963), who included interpretative maps that divided the Arizona Tertiary tectonic history into early, middle, and late stages. Their diagrams clearly depict the strong influence of the Mogollon Highlands and adjacent Mogollon Rim (Fig. 1) as the dominant structural and topographic features in central Arizona that influenced northeast-directed sedimentation onto and along the southwestern margin of the Colorado Plateau (Cooley and Davidson, 1963, p. 20, 23). Although their maps depict drainage flowing northward from the Mogollon Highlands onto the southwestern Colorado Plateau in early and middle Tertiary time, they concluded that the exotic gravels described by both Price (1950) and McKee (1951) were lateral equivalents of the Bidahochi Formation of the Little Colorado River Valley, at that time considered to be no older than 6 Ma (McKee et al., 1967). Volcanic horizons near the base of the Bidahochi Formation are currently dated as 16 Ma (Dallegge et al., 2001).

IN SITU RIM GRAVEL: THE MUSIC MOUNTAIN FORMATION

The arkosic sediments that most accurately reflect the age, external sources, and true character of the earliest Laramide-age rim gravel distributed around the southwestern Colorado Plateau margin can be best appreciated by examining the thickest undisturbed sections, which crop out from the Hualapai Plateau eastward to the vicinity of Long Point, the eastern end of the basalt-capped escarpment located 70 km southwest of Grand Canyon Village (Fig. 1). The arkosic sediments are widely distributed across the uplifted and erosionally beveled edge of the Colorado Plateau, as remnants of extensive braidplain deposits and in incised paleovalleys (Young, 1966, 2011; Billingsley et al., 2006a, 2006b).

In a few localities, such as along the base of the basalt escarpment, 15 km west of Long Point (lat 35.70°N, long 112.77°W), remnants of an even older generation of fluvial conglomerates have survived. These older, well-cemented conglomerates are dominated by clasts derived from the Paleozoic rocks that were being eroded immediately prior to the arrival of the arkosic sediments shed from newly uplifted Precambrian basement rocks during the Laramide orogeny. These older Laramide-age sediments have been neither adequately mapped nor accurately dated, but may have formed during the same general time interval as the Robbers Roost gravel of Koons (1948b). Their antiquity is only apparent where they can be inferred to be stratigraphically below adjacent Laramide-age arkosic sediments. Otherwise they easily can be confused with a wide range of younger gravels, also derived from existing Paleozoic strata. Outcrops of these uncommon Late Cretaceous(?) or early Tertiary gravels were described in Young et al. (1987; field-trip stops 5, 13, and 15). Some conglomerate exposures contain an approximately equal mix of Paleozoic and Precambrian clasts, and thus record the transitional stages when the adjacent Precambrian terranes had only partially emerged from beneath the Paleozoic cover rocks.

Hualapai Plateau, Milkweed Canyon

The type section for the Music Mountain Formation (Fig. 1, Milkweed-Hindu channel) and associated Cenozoic deposits of the western Hualapai Plateau was described in Milkweed Canyon (Young, 1999, 2011). The Tertiary rocks in the Milkweed Canyon section have a total thickness exceeding 305 m (Figs. 2 and 3). The basal Music Mountain Formation overlies Tapeats Sandstone at the designated type section and occupies 49% of the measured Tertiary section (Fig. 2). The numerous implications of this important Milkweed Canyon section for the Tertiary history were further clarified elsewhere (Young, 1966, 1982, 1987, 1989, 2001a, 2001b).

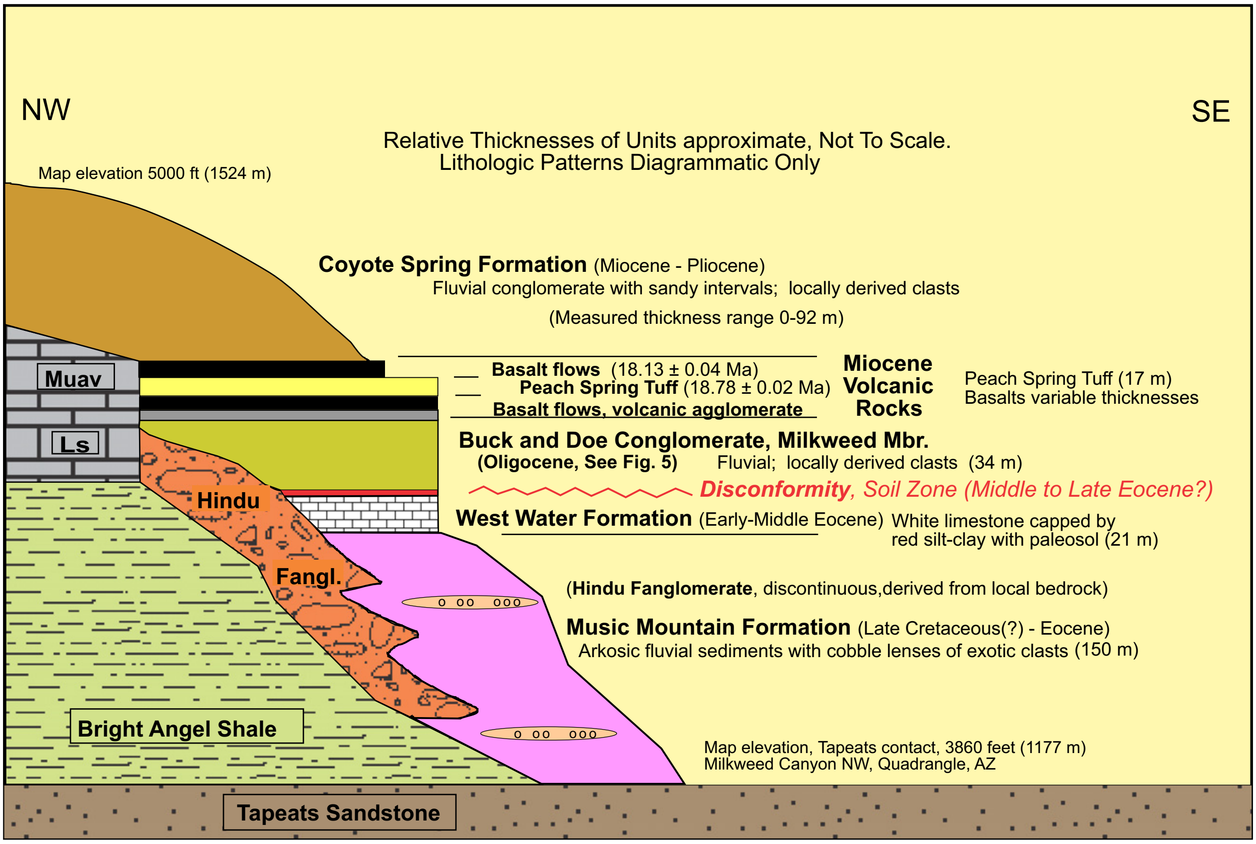

Figure 3. Milkweed Canyon diagrammatic section. View of northwest side of the Tertiary paleocanyon fill exposed in Milkweed Canyon 3 km northeast of Reservation access road (SE 1/4, Section 17, T. 26 N., R. 13 W., Milkweed Canyon, Arizona, topographic map [U.S. Geological Survey, 1967b]). See comparable photograph and location of Figure 2. New basalt age (18.13 ± 0.04, ^{40}Ar/^{39}Ar whole rock) is from Dominguez et al. (2012). Approximate scale is indicated by elevations.

Hualapai Plateau, Peach Springs Canyon and Peach Springs Wash

Music Mountain Formation

The exotic lowermost arkosic gravels throughout the Milkweed, Hindu, and Peach Springs paleocanyons are the stratigraphic equivalent of Koons' (1948a, 1948b) Blue Mountain gravel, but are located on the opposite side of the Hurricane fault (Young, 1966, 1999). The upper Peach Springs Canyon (Peach Springs Wash) Tertiary section is similar to the Milkweed Canyon type section and reaches a total thickness of 370 m; the Music Mountain Formation accounts for the lower 230 m (Fig. 4; Young, 2011). The Peach Springs Wash section is exposed over a considerable horizontal distance (5.4 km) along the upper Diamond Creek Road, which parallels the Hurricane fault through Peach Springs Canyon.

Pebble counts from base to top of the Music Mountain Formation section in Peach Springs Wash and a similarly thick exposure near Frazier Wells along the Supai Road (Fig. 1) both demonstrate that the Music Mountain Formation records the gradual unroofing of the adjacent south and southwest source terranes. The percentage of Paleozoic-derived clasts decreases upsection, while the percentage of Precambrian-derived clasts increases (Young, 2001a, 2001b). The inverted age distribution of dated Laramide-age volcanic clasts collected from the Peach Springs Wash section also supports an unroofing scenario (Young, 2011, see geologic map).

Hunt (1956, p. 30) described the oldest sediments in Peach Springs Canyon as including "water-laid stratified volcanic rocks" and stated that the "volcanic sediments and lavas, at least 150 feet thick, have been folded and probably have been faulted." Extensive post Miocene faulting is obvious along the Hurricane fault zone (Huntoon et al., 1981), but some faults in the Music Mountain Formation terminate at the overlying contact with the basal Buck and Doe Conglomerate and predate the post-Laramide disconformity surface (Young, 2011, figs. 2 and 3 therein). Hunt's descriptions (1956, 1969) do not reflect accurately the sedimentological character, complexity, or structural setting of the oldest exotic sediments in Peach Springs Wash. Although there is evidence of undulatory subsidence, possibly related to slumping above the weathered disconformity (Billingsley et al., 1999), there is no evidence of true compressional folding. The oldest beds also do not contain obvious "water-laid [lacustrine?] stratified volcanic rocks" in the "bottom of the depression" as mentioned in Hunt's (1956, p. 30) reconnaissance descriptions (Young, 1966, 1999, 2011). A small low-angle reverse fault with limited compressional drag folding is present in the Milkweed Member of the locally derived Buck and Doe Conglomerate (Young, 2011, fig. 17 therein; Young et al., 2011). Hunt considered the Peach Springs sediments to be late Tertiary in age, equivalent to the Muddy Creek Formation, and capped by "Quaternary basalts" (Hunt, 1956, p. 53). However, the basalt immediately below the Peach Spring Tuff at Peach Springs (Fig. 4) has been dated as 19.9 ± 0.4 Ma (Wenrich et al., 1995; Billingsley, 2001). Detailed geologic map and explanatory text of the Peach Springs 7.5′ quadrangle (Young, 2011) includes color photographs of each Tertiary formation near Peach Springs.

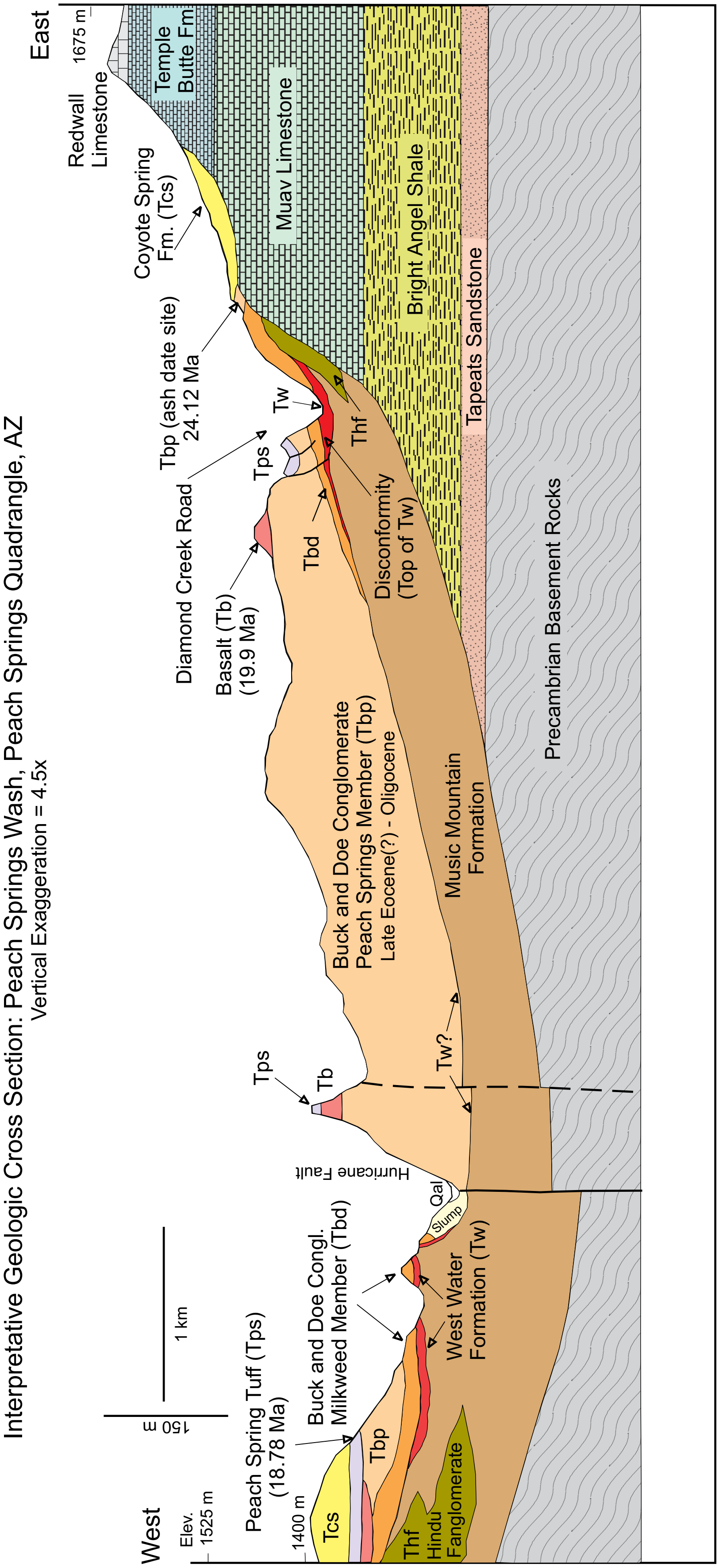

Figure 4. Interpretive geologic cross section of Peach Springs Wash 3 km north of Peach Springs, Arizona (location C in Fig. 1). For additional details and images of all Tertiary stratigraphic units, see Young (1999, 2011). Accompanying Peach Springs geologic quadrangle map with exact cross section location is available online (Young, 2011).

Age and Diversity of Overlying Buck and Doe Conglomerate

The Buck and Doe Conglomerate, which overlies the Music Mountain Formation, is divisible into two distinct members in Peach Springs Wash (Figs. 4 and 5). The older, Milkweed member, the sole representative of that geologic interval at Milkweed Canyon, is widespread across the central Hualapai Plateau and is a strongly cemented conglomerate consisting almost entirely of locally derived Paleozoic limestone clasts. The younger and more restricted arkosic Peach Springs Member contains abundant, relatively unweathered Precambrian cobbles and arkosic sands derived from bedrock exposures that border the adjacent Truxton Valley (Young, 1966, 1999, 2011). The Peach Springs Member is less well cemented and contains a late Oligocene volcanic ash near the top dated as 24.12 ± 0.04 Ma (^{40}Ar/^{39}Ar sanidine) (Figs. 4 and 5; Young et al., 2011; Young and Crow, 2014). The clast composition makes the unit superficially resemble the Music Mountain Formation, although the two are separated by the locally derived Milkweed member gravels, as well as the underlying regional disconformity. However, the Peach Springs Member stratigraphic position and the relatively unweathered condition of its clasts emphasize the greater age and different climatic implications implied by the advanced state of decomposition of Music Mountain Formation clasts.

The areally restricted Peach Springs Member conforms to the approximate drainage basin limits of Peach Springs Wash and pinches out westward near the divide between Peach Springs and Hindu Canyons. The vertical facies change, dominated by exotic Precambrian clasts, records the gradual southwestward headward reexpansion of the Peach Springs Wash drainage in the time of formation of the Buck and Doe Conglomerate to tap nearby Precambrian exposures following the post-Laramide drainage stagnation. This diverse stratigraphic section further demonstrates the importance of distinguishing younger arkosic gravels from deeply weathered parent rim gravel elsewhere.

Tectonic Significance of Local Lacustrine Facies

White lacustrine limestones of very restricted extent are in the two major Music Mountain Formation paleocanyons on the Hualapai Plateau. The dense fine-grained limestone facies are both located adjacent to prominent monoclines (Billingsley et al., 1999). Ponding in the paleocanyons caused by tectonic disruption best explains the field relationships.

Although the Milkweed Canyon section has a 13 m section of white lacustrine limestone near

Figure 5. Location of late Oligocene volcanic ash bed near top of Peach Springs Member of Buck and Doe Conglomerate located at 35.553°N., 133.412°W, ~700 m east of Diamond Creek Road, Peach Springs Wash, Arizona (location in Fig. 4). Arrow indicates 10-centimeter-thick ash near center of low cliff. Ash age is recalculated as 24.12 ± 0.04 Ma (Young and Crow, 2014), revised from slightly younger initial age (23.97 ± 0.03 Ma) reported in Young et al. (2011). BD is arkosic Peach Springs Member of Buck and Doe Conglomerate; CS is Coyote Spring Formation. Height of vertical exposure is 5 m.

the top of the Music Mountain Formation and immediately below the prominent disconformity (Figs. 2 and 3), the exposed Peach Springs Wash section (Fig. 4) contained only a very thin discontinuous marl deposit at the same approximate stratigraphic horizon (Young, 1966, p. 33). The restricted marl exposure was destroyed by improvements to the Diamond Creek Road, and a comparable exposure has not been located. However, four old Santa Fe Railroad logs from water wells drilled within the adjacent town of Peach Springs record a maximum of 118 m of white lacustrine limestone in the uppermost arkosic sediments of the Music Mountain Formation (Young, 1979). The wells are located within the buried paleocanyon tributary that entered Peach Springs Canyon from the southeast (Fig. 1). The Peach Springs wells straddle the axis of the Peach Springs monocline (Billingsley et al., 1999; Young, 2011). The conspicuous structural offsets and thickness variations within the Tertiary limestone intervals recorded in the well logs implies that monoclinal deformation may have been ongoing during deposition of the Music Mountain Formation and might be responsible for the formation of a narrow lake, restricted to the buried canyon, and the predictable deposition of the fine-grained carbonate (Young, 1979, fig. 3 therein). The occurrence of a 1-m-diameter granite boulder within a 7.3 m section of limestone in one of the Peach Springs wells provides additional evidence of a quiet-water environment punctuated by occasional high-energy (tectonic?) disturbances.

The buried limestone is on the upstream side of the paleovalley at the intersection with the Peach Springs monocline, as is the case for the limestone in the Milkweed Canyon paleovalley, which also is intersected by a monocline (Huntoon, 1981). The limestones and marls in Milkweed Canyon and at Peach Springs have produced no age-diagnostic fossils, although a single specimen of the gastropod Genus Physa was collected at Milkweed Canyon, similar to Physa specimens found at Duff Brown Tank (Young and Hartman, 2011; Supplemental File [see footnote 1]). However, the apparent genetic association of lacustrine facies in the upper Music Mountain sediments with both Hualapai Plateau monoclines provides additional circumstantial evidence for the proposed Laramide age of the depositional interval.

Vertical Clast Variations, Hualapai Indian Reservation and Coconino Plateau

Two measured sections of the Music Mountain Formation preserved along the Supai Road (Fig. 1) and at Long Point contain strikingly increased percentages of silicic Laramide-age volcanic clasts near the tops of the preserved, but erosionally truncated, stratigraphic intervals (Young, 2001a, 2001b). This marked increase to ~50% of all in situ clasts contrasts markedly with the usual content of exotic volcanic clasts (1%–7%) at lower stratigraphic levels and in all other measured sections (Young, 2001a, 2001b). This increase can be attributed either to a late Laramide flareup of volcanism in the source region, or as headward extension of drainages southward into the source terranes; the wide age range of the dated volcanic clasts indicates that the latter is more likely. Ages of dated volcanic clasts from all the sampled Music Mountain Formation exposures on the Hualapai and Coconino Plateaus range from Late Jurassic (163 Ma) to early Eocene (51 Ma) (Flowers et al., 2008; Tillquist et al., 2012; Young and Spamer, 2001, Appendix A therein). Specimens collected for the Flowers et al. (2008) study include samples from Long Point (arkose, granite clasts, volcanic clasts) and the eastern Hualapai Plateau (arkose).

PHYSICAL AGE CONSTRAINTS FOR MUSIC MOUNTAIN FORMATION

Uplift Chronology and Laramide Structural Signature

Flowers et al. (2008) presented apatite U-Th/He thermochronologic evidence that the Laramide orogeny resulted in the uplift of the plateau margin and the resulting stripping of the sedimentary strata down to the Kaibab surface by 60–50 Ma. The uppermost preserved sections of the Music Mountain Formation near the highest elevations, such as at Long Point (1570 m), contain dated volcanic clasts as young as 51 Ma (Flowers et al., 2008); this implies that primary deposition continued at least through early Eocene time. The thermochronology also indicates a southwest to northeast progression of the erosional stripping on the plateau, as well as a west to east progression of erosion along the Mogollon Rim. Potochnik (2001) described Laramide-age fluvial red beds in eastern Arizona that overlie beveled Cenomanian rocks and provide additional evidence that early fluvial deposition onto the plateau margin could have begun as early as Late Cretaceous time.

The Laramide orogeny is accepted as the interval when the principal monoclines and associated uplifts of the Colorado Plateau were formed by compressional tectonics (reviewed by Bump and Davis, 2003). The obvious link between the disruption of the Music Mountain Formation paleochannels near their junctions with monoclines and the coincident development of lacustrine facies on the up-gradient side of the abandoned channels is direct evidence for the effective functioning of the Music Mountain depositional system during the Laramide orogeny, and its coincident demise at select localities. However, the lowermost beds of the Laramide-age arkosic gravels deposited across the regional erosion surface throughout the southwestern plateau margin are clearly younger than the related Laramide uplift and initial bedrock erosion interval. Therefore it is unclear what precise time interval is actually represented by the base of the Music Mountain Formation and similar Laramide-age deposits. The evidence that follows in this compilation indicates that the base of the Music Mountain Formation must extend back into Paleocene time, but whether it extends as far back as Late Cretaceous time has not been clearly established. The occasional preservation of undated Paleozoic-clast-dominated gravels below the Music Mountain Formation might record some unspecified portion of the Late Cretaceous history.

Radiometric Ages

In collaboration with Damon (1964) it was first demonstrated that the Music Mountain Formation on the Hualapai Plateau (Young, 1966, 1999) and the equivalent Blue Mountain gravel of Koons (1948a) were significantly older than the early Miocene Peach Spring Tuff (Young and Brennan, 1974). The Peach Spring Tuff source caldera was located, and its age revised slightly to 18.78 ± 0.02 Ma (Damon, 1964; Pearthree et al., 2009; Ferguson et al., 2013). Despite this demonstrated age constraint and the publication of the original 18.3 ± 0.6 Ma Peach Spring Tuff age in McKee et al. (1967), McKee and McKee (1972) proposed that the Type A gravels of Price (1950) and several other exotic gravel outcrops were all younger than 10–8 Ma. Their conclusion was based the ages of the youngest dated basaltic clasts that they collected from selected and widely dispersed gravel outcrops, some obviously reworked, along a broad geographic swath parallel to the Mogollon Rim from east central Arizona to Long Point, Arizona (Fig. 1). Obviously, no Neogene basalt clasts would be present in the parent Music Mountain Formation, as currently defined.

The 24.12 ± 0.04 Ma ash age by Young and Crow (2014) from the Peach Springs Member of the Buck and Doe Conglomerate, located 91 m above the disconformity at the top of the Music Mountain Formation in Peach Springs Wash (Fig. 5), is the oldest dated volcanic horizon located on the Hualapai Plateau. The Oligocene ash may have been derived from the Aquarius Mountains caldera sequence, specifically the thick Fort Rock Creek rhyodacite (Fuis, 1974), which is located 45 km to the south and erupted at approximately the same time (Young and McKee, 1978).

Potochnik (2001) dated two 37 Ma Eocene tuffs in his Mogollon Rim Formation, which overlies unnamed red beds, in the upper Salt River basin of east-central Arizona. These Mogollon Rim Formation sediments are lighter in color, comparatively much less weathered, and are presumed to be somewhat younger than the reddish, more deeply weathered Music Mountain Formation sediments on the Hualapai and Coconino Plateaus. The Mogollon Rim formation may represent the easternmost and youngest prolongation of the original Laramide-age drainage onto the plateau that apparently continued somewhat longer in eastern Arizona, as the denudation chronology of Flowers et al. (2008) implies. The unnamed red beds below the Mogollon Rim Formation may be closer in age to the more western Music Mountain Formation.

Evidence for Extended Gravel Reworking

Young collected a Pleistocene ash in fluvial gravels reworked from the underlying Music Mountain Formation on the eastern Hualapai Indian Reservation that produced two slightly different K-Ar ages of 1.36 ± 0.07 Ma on glass, and 2.31 ± 0.20 Ma on a biotite separate (E.H. McKee, 1987, written commun.). The ash occurs in a shallow abandoned channel on the eastern Hualapai Plateau near the Frazier Wells locality of Koons (1948b) in a roadcut along the Supai Road (Figs. 1 and 6) 2.7 km southwest of Frazier Wells (Frazier Wells, Arizona, topographic map, Section 1, T. 27 N., R. 8 W. [U.S. Geological Survey, 1967a]; Billingsley et al., 2000).

The roadcut exposes a series of overlapping nested fluvial channels (Fig. 6), and it illustrates the difficulty of adequately discriminating among various reworked generations of gravels derived from the in situ Music Mountain Formation. The Pleistocene ash is contained in the uppermost of as many as four nested channels at this locality, all of which underlie a thin quartzite-rich lag gravel that is typical of other surface exposures referred to as rim gravel by past workers. The weathered material at the base of the roadcut (Fig. 6) is the highly weathered Paleogene parent gravel, from which a trachyte clast was collected by H.W. Peirce nearby and dated as 73.4 Ma (Young and Spamer, 2001, p. 245).

An individual viewing the original undisturbed surface near this roadcut would see only a relatively uniform, quartzite-rich lag gravel, typical of many areas where rim gravel lag deposits occur. The obvious lesson to be gleaned from this exposure is that multiple generations of exotic clast gravels could be present at different locations, and at relatively shallow depths, with no practical way to determine their initial depositional age or the significance of the multiple components in such complex sequences.

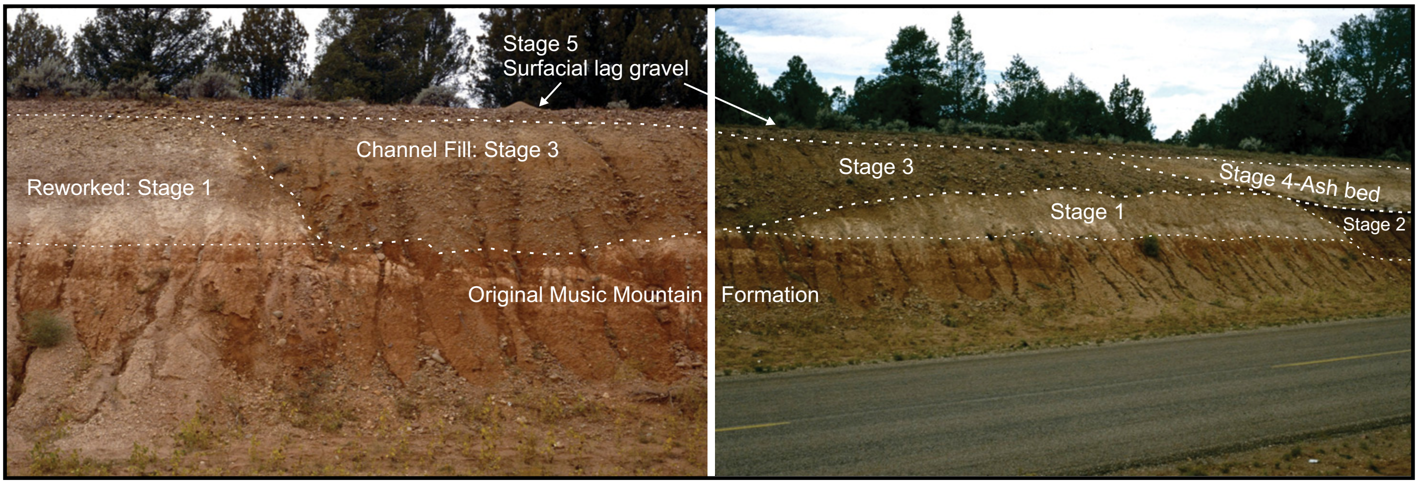

Figure 6. Roadcut exposure (4.6 m high near center) documenting consecutive generations (stages) of weathered and reworked Music Mountain Formation arkose (base of section) near Frazier Wells on eastern Hualapai Indian Reservation (Supai Road, Fig. 1). Stage 4 channel contains ash bed dated as 2.31 ± 0.2 Ma (biotite) and 1.36 ± 0.07 Ma (glass) (E.H. McKee, U.S. Geological Survey, Menlo Park, California, 1987, written commun.). Stage 5 surficial lag gravels that blanket exposure are quartzite dominated and obscure the underlying complexity. Several meters of view are omitted at center due to extended length of roadcut. Location: Frazier Wells, Arizona, topographic map, NW ¼, Section 1, T. 27 N., R. 8 W (U.S. Geological Survey, 1967a).

However, one definitive observation is clear: as soon as the original rim gravel is reworked, the thoroughly weathered matrix components and feldspar-rich clasts are largely disaggregated and destroyed, leaving behind quartzite-rich residues (Fig. 7). Even a single generation of reworking produces a strikingly quartzite-rich derivative that no longer resembles the original parent material in texture or clast composition (Fig. 8). For this reason it is relatively easy to distinguish outcrops where the original Music Mountain Formation has been weathered in place, but essentially preserved, from second or third generation reworked deposits. Conversely, the mere presence of quartzite-rich lag gravels at the surface does little to convey the potentially complex history of a site where such deposits may have a multigenerational history of reworking.

Included Clast Ages

Several published studies have resulted in a dated suite of at least 20 largely silicic volcanic clasts with ages ranging from 163 to 51 Ma that were collected from widespread Music Mountain Formation exposures on the Hualapai and Coconino Plateaus (Young and Spamer, 2001, Appendix A therein; Priest, 2001; Flowers et al., 2008; Tillquist et al., 2012). These clast ages, combined with the aforementioned radiometric dates, indicate that in situ rim gravel (Music Mountain Formation and the potentially related, but younger, Mogollon Rim Formation of eastern Arizona) probably incorporate no volcanic clasts younger than middle Eocene. There is no precise age limit on the basal part of the preserved gravel sections in eastern or western Arizona, except for U-Th/He cooling-age data, which indicate that erosional unroofing of the surface beneath the rim gravel was likely completed by 50 Ma (Flowers et al., 2008; Kelley et al., 2001; Lee et al., 2011).

The apparent age discrepancies, clast compositional differences, and confusing rim gravel descriptions and correlations reported by earlier researchers now can be appreciated in view of the early lack of adequate radiometric age control and the subsequent demonstration that several generations of reworked gravels exist throughout the region, many containing similar multigenerational Precambrian clasts dominated by Precambrian quartzites. However, the younger reworked Neogene gravels that include Oligocene, Miocene, or Pliocene basalt clasts now can be readily distinguished from their parent sources. The possible wide age range of the reworked rim gravel deposits across the region is confirmed by the few ash beds located within different Cenozoic gravel exposures on the plateau that range in age from late Eocene to Pleistocene, an interval that extends from at least 37 Ma to 1.36 Ma.

FOSSIL-BEARING LACUSTRINE FACIES

The lacustrine limestones attributed to the damming of drainage by Laramide-age structural deformation on the Hualapai and Coconino Plateaus may include fossils that could provide improved age constraints for the Music Mountain Formation. However, the only productive fossil horizons discovered to date are restricted to a few relatively thin limestone lenses, rather than the exposures where thicker limestones might be assumed to represent favorable aquatic environments that persisted for longer periods (see fossil plates described in Supplemental File [see footnote 1]).

Limestones near Long Point and Duff Brown Tank

The southeastern margin of Long Point includes the Duff Brown Tank locality first noted by Squires and Abrams (1975; Figs. 1 and 9); the source of the paleontological specimens collected from the 20 km discontinuous outcrop belt of lacustrine limestone extending northwestward from Long Point (as traced in Young, 1982) is herein called the Long Point limestone (Billingsley et al., 2006b). Figure 10 illustrates the local Tertiary stratigraphic units, not all of which are present at any one exposure. The Long Point limestone outcrops are bordered to the northeast by the Supai monocline and the Kaibab upwarp, which locally reverse the northeast regional dip and topographic slope, and may be the obstructions whose deformation was responsible for damming the local fluvial environment to form a shallow lacustrine and marsh environment.

At Duff Brown Tank (Figs. 9 and 10), the truncated Music Mountain Formation is capped

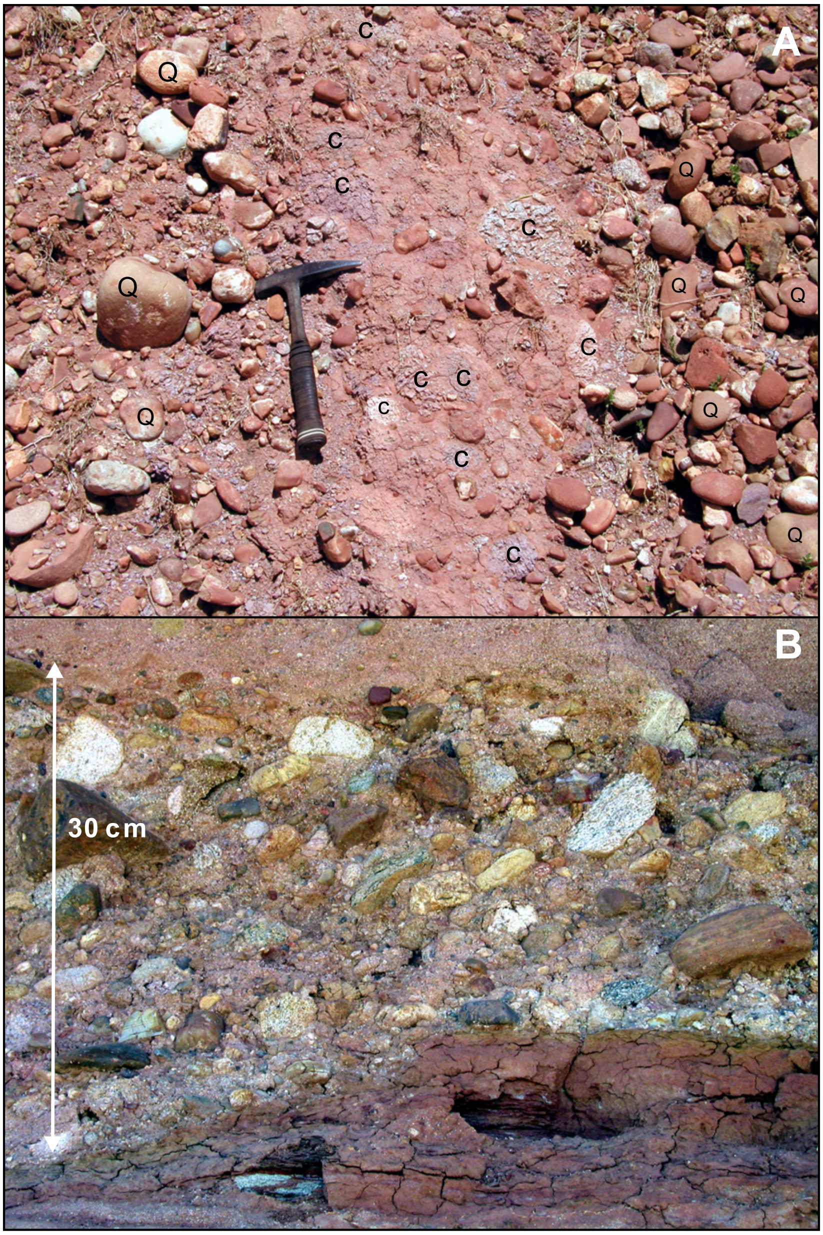

Figure 7. Close-up views of clasts in Music Mountain Formation. (A) Decomposed igneous ghost clasts (C) near center with more resistant, abundant, quartzite cobbles (Q) weathering out at outcrop 25 km southeast of Long Point, AZ (see Fig. 1). Location as in Figure 8A. (B) Slightly more discernible, imbricated, weathered gravel lens illustrating diversity of lithologies prior to physical decomposition of severely weathered feldspar-rich clasts in Peach Springs Wash. Weathered feldspathic clasts are eroded back to plane of section, whereas resistant clasts protrude from face. Note lack of conspicuous dark gray to black chert component in both views in contrast to Figures 16 and 17.

by a 6.76 ± 0.13 Ma Miocene basalt (Billingsley et al., 2006b), which was erroneously reported as 14 Ma by McKee and McKee (1972; similarly referenced in Young, 2001b, p. 10). A minimum of 60 m of the Music Mountain Formation, partially obscured by quartzite-rich lag gravel and colluvium, is discontinuously exposed along an unimproved ranch road at the northeast margin of Duff Brown Tank. For 32 m below the late Miocene basalt the arkosic sediments are interbedded with several poorly exposed thin limestone beds (Figs. 9 and 11), the lowermost of which have produced a diverse assemblage of fossil gastropods (Young and Hartman, 1984; see Supplemental Figs. 1–3 in the Supplemental File [see footnote 1]). The gastropods and some associated microfossils are located within the three lowest limestone beds, 10–20 cm thick (Fig. 9; Howard Spring quadrangle). The fossiliferous beds begin ~30 m below the base of the overlying basalt, which caps an erosionally truncated stratigraphic section, the upper portions of which have been subject to rotational slumping. An additional minimum of 27 m of undisturbed arkosic sediments are exposed in gullies below the lowest fossiliferous limestone bed. Although the lower contact of the Music Mountain Formation at Duff Brown Tank is covered by colluvium, a log for a water well (McGavock, 1968) located 2.3 km northwest of the fossil locality records a similar 67 m thickness of arkosic sediment between the overlying basalt and a single white limestone bed encountered at the bottom of the well (Fig. 11).

At the location marked as Black Tank Camp on the Black Tank 7.5′ topographic quadrangle map (U.S. Geological Survey, 1980b), 9 km northwest of the Duff Brown Tank fossil locality, is a pure white limestone outcrop that is a minimum of 30 m thick (Fig. 11). The lower contact of this cleanly exposed section of dense limestone is also obscured by colluvium (Fig. 10). The thick limestone exposure produced no obvious invertebrate macrofossils despite several days of rigorous searching. However, blocks of similar white limestone, displaced by road grading, immediately south of the Black Tank Camp section contain unidentified algal stromatolites several centimeters in diameter.

Numerous charophytes (green algae) were collected from thin limestone beds throughout the Long Point area (Figs. 9 and 12). The charophytes are locally abundant and relatively well preserved. Monique Feist identified two taxa, the first as Peckichara coronate (Peck and Reker) L. Gambast, which she stated is “restricted to the Lower Eocene, and is also common in the Lower Wasatch and Flagstaff Formations”; the second charophyte identified by Feist is “Nodosochara sp., resembling N. clivulata (Peck and Refer) L. Gambast” (M. Feist, 2006, written commun.; Young et al., 2007). This genus has been reported from the upper Cretaceous to the upper Eocene.

A single poorly preserved ostracod (arthropod) specimen was tentatively identified by Rick Forester (U.S. Geological Survey, Denver, 2001, written commun.) as belonging to the “genus Bisulcocyridea, and likely of the species aravadensis”; the local range for this species in Utah and Colorado rocks is late Paleocene to middle Eocene, according to Forester.

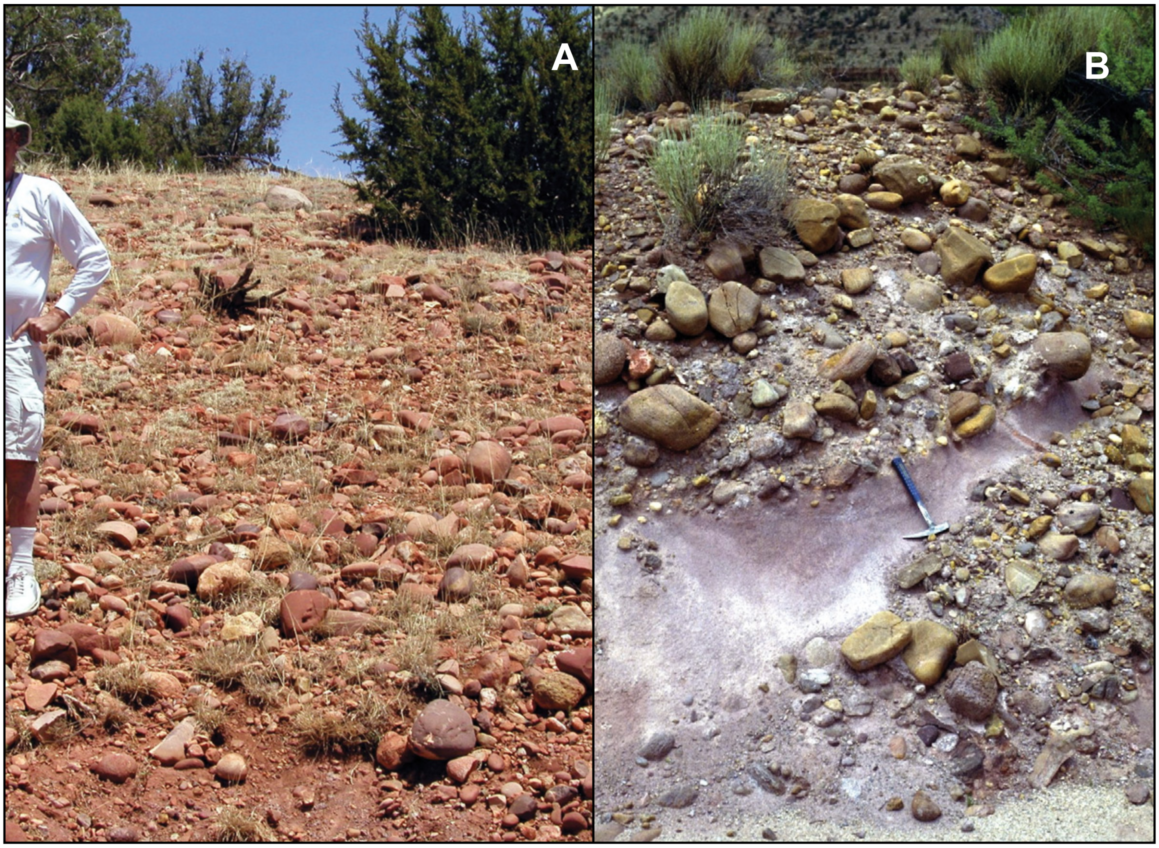

Figure 8. Lag gravels developing on Music Mountain Formation. (A) Lag gravel surface predominantly of quartzite cobbles and boulders developed at Cuerro Tank, Mixon Tank 7.5′ quadrangle (U.S. Geological Survey, 1981c), 36 km northwest of Williams, Arizona (AZ). Parent deposit of A is also shown in Figure 7A (same location). (B) Gravel lenses with conspicuous resistant boulders weathering out of arkose in lower Peach Springs Wash, 7 km north-northwest of Peach Springs, AZ. Resistant boulders protruding from outcrop are predominantly quartzite. Dark gray and black chert is absent or very rare at these locations, and chert litharenite clasts of Figure 15 are absent.

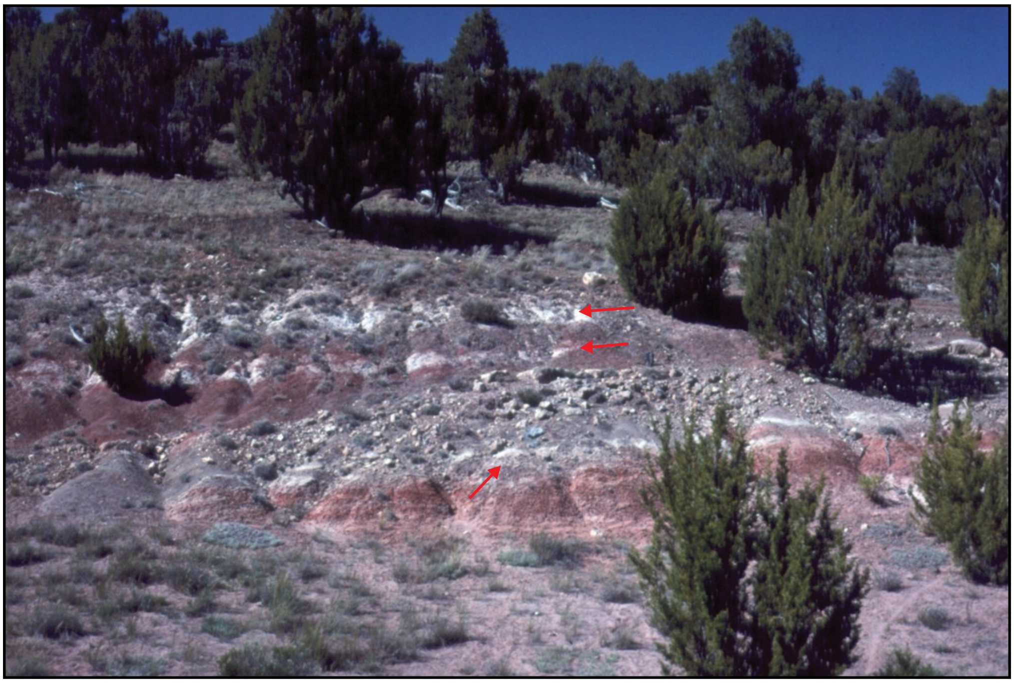

Figure 9. Three lowest Duff Brown Tank fossiliferous limestone beds (red arrows) within Music Mountain Formation where gastropod specimens (illustrated in the Supplemental File [see footnote 1]) were collected. View is to north from edge of Duff Brown Tank. Beds average 20 cm thick. See section and location in Figures 1, 10, and 11. Elevation difference from base to skyline is 57 m.

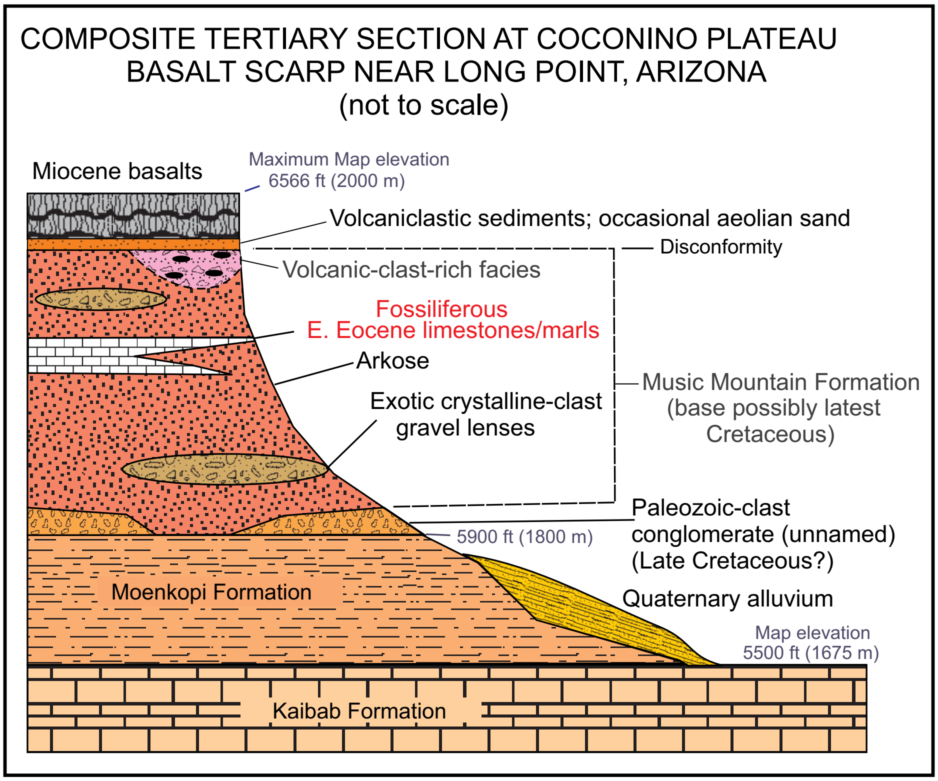

Figure 10. Diagrammatic and composite stratigraphic section of sediments exposed below basalt-capped scarp between Duff Brown Tank and Furguson Tank (Fig. 1). The complete Tertiary section cannot be seen in any one location, but partial exposures are sufficient to verify the stratigraphic order. The basal conglomerate of Paleozoic clasts (Fig. 13) was only observed in the Rose Well Camp East, Arizona, topographic map, Sections 24 and 25, T. 27 N., R. 5 W (U.S. Geological Survey, 1981d). Volcanic-rich clast facies is well exposed near northeast end of Long Point (Tin House, Arizona, topographic map, NE1/4, Section 33, T. 27 N., R. 3 W. [U.S. Geological Survey, 1980a]). E.—early. (See volcanic clast ages in Priest, 2001; Flowers et al., 2008.) Approximate scale is shown by elevations at top and base.

Gastropod specimens were originally sent to one of us (Hartman) in 1982 in an effort to provide a more definitive age assessment of the Duff Brown Tank locality (as described in Young and Hartman, 2011, and as detailed in the Supplemental File [see footnote 1]). In a lengthy treatise, the systematics, biostratigraphy, and distribution of Late Cretaceous and early Tertiary gastropods in parts of the western U.S. and Canada were redefined (Hartman, 1984), and additional studies of related forms in contiguous regions, including Utah and New Mexico, were completed (Hartman, 1981, 1993; Hartman and Roth, 1998).

Early Eocene Age of the Duff Brown Tank Molluscan Fauna

An accurate age assessment of the molluscan fossil assemblage collected from the Duff Brown Tank site requires a detailed review of the lengthy record of Tertiary gastropod studies that have bearing upon the isolated northern Arizona locality. The specimens illustrated and discussed in the accompanying Supplemental File (see footnote 1) can be summarized as follows.

The Duff Brown Tank gastropod fauna consists of 10 taxa: 2 species of viviparids, 2 pleurocerids, 4 hydrobiioids, a depressed planorbid, a physid, and an ellobiid species that together suggest an early Eocene age, although a late Paleocene age cannot be ruled out. Diagnosing the age of the Duff Brown Tank locality, considering the number of issues that complicate species identification and age determination, means that some uncertainty exists until additional supportive fossil data become available. Despite these uncertainties, the Duff Brown Tank locality limestone beds of the Music Mountain Formation should not be considered younger than early Eocene, based on the molluscan evidence. An extensive illustrated discussion of the gastropod fauna is included in the accompanying Supplemental File (see footnote 1).

Thermal Complications

Huntington et al. (2011) completed clumped-isotope thermometry studies on the gastropod shells and calcite cements from the Duff Brown Tank locality to explore their environment and diagenesis. Unfortunately, the crystallization history seems to have been affected by an abnormally elevated heating pulse, presumably created by emplacement of the overlying 91.5-m-thick basalt flows, rather than simply recording the more typical thermal or recrystallization history of such a limestone. The abnormal thermal history also might be problematic for U-Pb dating or alternative methods used to more accurately determine the age of the limestone beds.

ZIRCON DATA FOR SOURCE REGION CORRELATIONS

Dickinson (2013) and Dickinson et al. (2012) described zircon analytical results from the Music Mountain Formation (collected by Young from Peach Springs Wash and by Dickinson near Duff Brown Tank). Dickinson et al. (2012, p. 874) noted that the samples contain “no Paleozoic-Neoproterozoic or Grenville grains.” They stated, “99.5% of the pre-arc detrital zircons were derived from Yavapai-Mazatzal and anorogenic granites” and that subordinate Jurassic and Cretaceous grains could have been derived from “Mesozoic plutons intruding Yavapai-Maztazal basement rocks of Arizona.” The potential correlation of the Oligocene Chuska erg deposits with the Music Mountain Formation as suggested by Cather et al. (2008) is unsupported in the sense that, “Recycling of Music Mountain sand into Chuska sand is not favored, however, by K-S analysis yielding P = 0.01 for comparison of Music Mountain and Chuska detrital zircon populations” (Dickinson et al., 2012, p. 874).

SUMMARY OF EVIDENCE FOR STRATIGRAPHIC RANGE OF THE MUSIC MOUNTAIN FORMATION

The Paleogene Music Mountain Formation of northwestern Arizona is defined as a deeply weathered fluvial arkose with subordinate gravel lenses that occurs throughout the Hualapai Plateau and adjacent Coconino Plateau as well as in contiguous regions (Young, 1999). Its preserved uppermost beds locally may include one or more lacustrine limestones, travertine, or marl beds of variable thickness such as are preserved at Milkweed Canyon, buried beneath the town of Peach Springs, and near Long Point. The red soil and white limestone

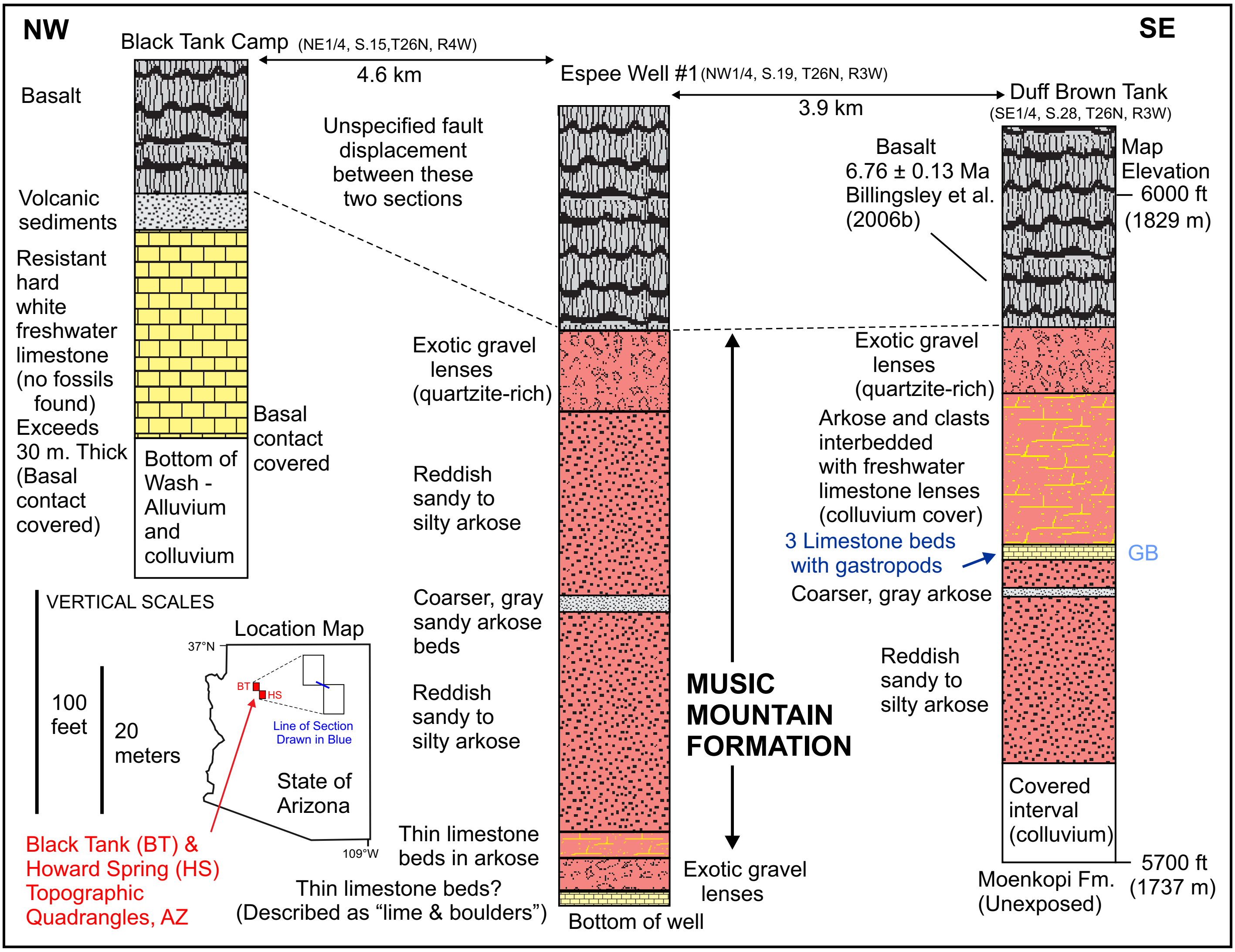

Figure 11. Extrapolated stratigraphic correlations across the Long Point area from Duff Brown Tank to Black Tank from two measured sections and water well log (Fig. 1). Long Point area limestone beds and thin lenses crop out discontinuously below the basalt-capped escarpment for ~20 km from Section 26, T. 26 N., R. 3 W. (Howard Spring, Arizona, topographic map [U.S. Geological Survey, 1981d]) to Section 14, T. 27 N, R. 5 W. (Rose Well Camp East, Arizona, topographic map [U.S. Geological Survey, 1981d]). GB marks horizon of three gastropod-bearing beds of Figure 9. The local thicknesses of limestone beds and thin lenses along the basalt-capped escarpment are highly variable and generally exposed in rotational slumps. The Espee Well log interpreted from McGavock (1968) is located in the northeast corner of the Bishop Lake, Arizona, topographic map (U.S. Geological Survey, 1981a), immediately west of the Howard Spring map. Additional thin limestone lenses, if present within the arkose and gravels, might have been overlooked or assumed to be limestone boulders during logging of the Espee Well.

in Milkweed Canyon was designated as a separate West Water Formation, based on the apparent contrast with the underlying arkosic fluvial sediments. However, the limestone and red soil most likely represent the waning phase of the Music Mountain interval, caused by blockage of the through-flowing drainage, followed by an interval of fine-grained sediment accumulation and weathering under semitropical conditions. The upper boundary of the formation varies from a deeply weathered disconformity to an erosionally truncated surface, depending on physiographic location. The lower Music Mountain beds overlie a regional erosion surface that bevels Precambrian through Permian strata and that may be as old as Late Cretaceous, although that remains unproven.

The establishment of a Laramide age range and southern to southwestern provenance for the Music Mountain Formation is demonstrated based upon the following diverse criteria. These independent lines of evidence, combined with basic field observations of distribution, sedimentology, paleontology, clast provenance, and distinctive weathering characteristics, allow a logical resolution of the range of apparent age estimates and discrepancies appearing in the literature. We propose the formal replacement of the informal term "rim gravel" by Music Mountain Formation (Young, 1999) in northwestern Arizona and formal recognition of a probable longer Late Cretaceous(?) to middle Eocene age.

Figure 12. Limestone bed 40 cm thick eroding from Music Mountain Formation arkose, and exhibiting unidentified vertical hollow tube structures (inset view) at base of Long Point scarp. View is toward west at location 4 km northwest of Duff Brown Tank fossil locality. Charophytes are common in this exposure. Marker pen in enlarged inset view taken from center of main image at A is 14 cm long. Location: N 1/2, Section 17, T. 26 N., R. 3 W., Tin House, Arizona, topographic map, U.S. Geological Survey (1980a).

Distinguishing Criteria

1. The exotic Music Mountain Formation arkose and intercalated gravel beds are thickest, most completely preserved, and best exposed in paleocanyons near the Music Mountains on the Hualapai Plateau, but they also occur as remnants of widespread braidplain deposits extending eastward across the Coconino Plateau and extensive Kaibab surface north of the Mogollon Rim. The separations between adjacent outcrops across this broad region are much shorter than might be assumed as can be seen on the improved maps by Billingsley et al. (2006a, 2006b).

2. The data of Flowers et al. (2008) provide a time frame for the Late Cretaceous to early Eocene stripping of the southwestern plateau margin and deposition of the arkosic gravels by ca. 50 Ma.

3. In situ exposures of the undisturbed parent gravels directly overlie bedrock ranging from Precambrian basement rocks through the Triassic Moenkopi Formation. At localities on the eastern Hualapai Reservation (Robber's Roost gravel of Koons, 1948a, 1948b), south of Seligman, and near Long Point, an even older, Paleozoic-clast-rich conglomerate is preserved that documents pre–Music Mountain Formation preliminary erosion of the Paleozoic cover rocks (Fig. 13; Young, 1966, 2001b). Holm (2001a) made similar observations regarding Paleozoic-clast-rich facies beneath the exotic gravels along the Mogollon Rim.

4. Key Music Mountain Formation exposures are overlain by Miocene basalts or the early Miocene Peach Spring Tuff, but are devoid of Neogene basalt clasts. The Peach Springs Wash section includes an Oligocene ash in the Buck and Doe Conglomerate (Peach Springs Member) located 90 m above the top of the Music Mountain Formation (Young et al., 2011). To the south, near the Aquarius Mountains, exotic gravels are capped by late Oligocene lavas, which overlie eroded Cambrian through Mississippian rocks (Young and McKee, 1978; Goff et al., 1983).

5. Normal and reversed paleomagnetic measurements have been obtained from Music Mountain sediments within a <1 m thickness of fine-grained sediments located close to the

Figure 13. Two views of unnamed, early Tertiary or Late Cretaceous(?), well-cemented conglomerate 15 km west-northwest of Long Point located above eroded Moenkopi Formation beds and stratigraphically below Music Mountain Formation. Conglomerate consists predominately of calcite-cemented sands and clasts of Paleozoic limestones presumably derived from pre–Music Mountain erosion during Late Cretaceous(?) or Paleocene Laramide stripping of the southwest Colorado Plateau margin. Redwall Limestone clasts (B) and imbrication indicate a southern source. Contact with underlying Moenkopi Formation exposed nearby is obscured. Location: SW 1/4, Section 24, T. 27 N., R. 5 W. (Rose Well East, Arizona, topographic map, U.S. Geological Survey [1981d]).

underlying Moenkopi contact near Furguson Tank (Figs. 1 and 14). This magnetic record, located along the basalt-capped escarpment ~20 km west of Long Point, closely matches the pole position of Chron 24 (ca. 56–53 Ma), as measured in the Black Peaks Formation of Texas (Rapp et al., 1983; Elston et al., 1989). Chron 24 is known to include 5 or more normal and reversed intervals, with lengths as short as 40–70 k.y. (Westerhold and Rohl, 2009). Such short magnetically reversed intervals are theoretically consistent with the sedimentary architecture of the closely spaced normal and reversed beds found at the Furguson Tank site (Fig. 14). This assumption is based on the fact that fluvial environments can rework sedimentary bedforms for an extended period without measurably raising or lowering the local channel elevation, thereby allowing for the apparent close vertical spacing of such reversed polarity intervals.

6. Structural field relationships demonstrate that during fluvial deposition the major Hualapai Plateau paleochannels, and possibly the Long Point area, were disrupted by compressional monocline deformation, a tectonic signature that characterizes the Laramide orogeny, and therefore, the resulting lacustrine limestones are not likely to be younger than middle Eocene (Young, 1979).

7. The thick arkose exposures preserved in the tectonically dammed and isolated paleocanyon basins represent complete and relatively undisturbed Paleogene depositional sequences (Peach Springs and Milkweed Canyons). The isolated basin sections are both capped by a thick red paleosol that represents an extended depositional hiatus, with presumably little or no erosion, the development of which is consistent with the type of warm humid conditions postulated for the Early Eocene Climatic Optimum, ca. 54–52 Ma (Young, 1979, 1999).

8. The lacustrine Long Point limestone at Duff Brown Tank (Figs. 1 and 9) contains a suite of mollusks of early Eocene (or late Paleocene) age. Even allowing for some uncertainty in the paleontological assignments, the limestone beds can be no younger than early Eocene.

9. The thick red paleosol development, lacustrine facies, and well-preserved indigenous fossil logs (Peach Springs Wash; Young, 2011, fig. 8 therein) indicate a more humid climatic regime that is incompatible with the onset of post-Eocene drier conditions documented throughout the western United States, and that is clearly reflected in the abrupt sedimentological and color changes seen in the post–Music Mountain stratigraphic section (Fig. 2). Similar climatic changes during the same approximate time interval are described in the sedimentary record for portions of nearby southern California (Peterson and Abbott, 1979).

10. Many thin, quartzite-dominated lag deposits and incomplete or poorly exposed sections where the term rim gravel was earlier applied or assumed in the geologic literature are clearly reworked sediments, because they lack a weathered arkosic matrix, contain ash beds as young as Pleistocene, or include Neogene basalt clasts.

UNRELATED EXOTIC GRAVELS OF NORTHERN DERIVATION

Cooley (1960) described quartzite-rich exotic gravels on strath terraces of the Colorado River and its major northern tributaries in the Glen Canyon region (Fig. 1). These gravels are derived from the erosion of early Tertiary rocks on the High Plateaus in southern Utah. Cooley (1960, p. 22) noted that one exotic

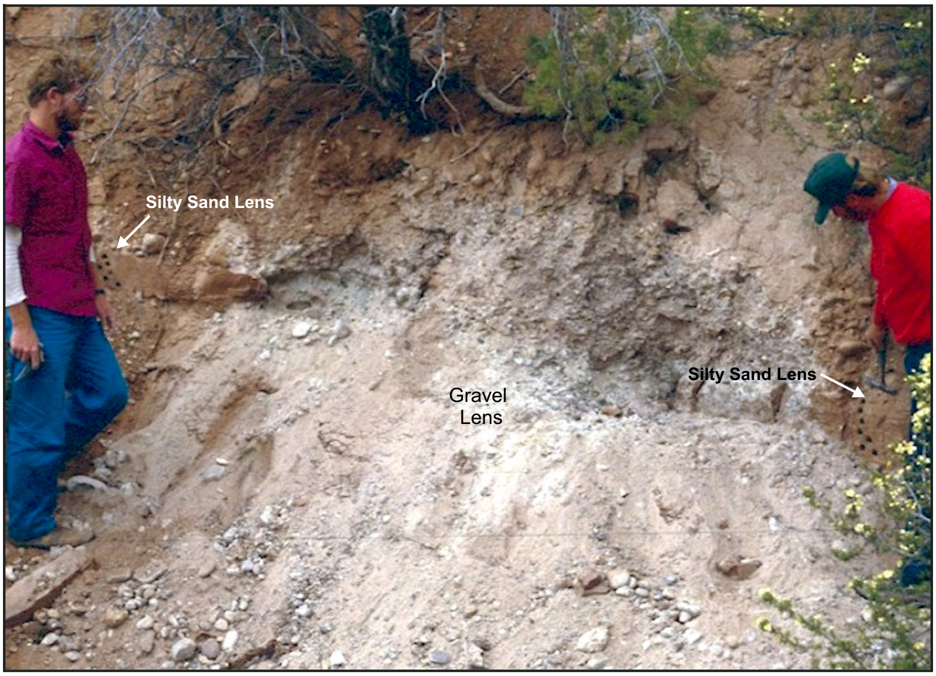

Figure 14. Paleomagnetic sample site in basal Music Mountain Formation near Furguson Tank (Arizona; see Fig. 1); 13 core holes (near white arrows) are shown in two separate, vertically juxtaposed, silty sandstone lenses (reddish brown) that interfinger with a coarse gravel (white area, center). Beds sampled pinch out near center of view and do not connect or overlap horizontally. Bed sampled on left is stratigraphically above bed on right. Section is interpreted as channel gravel interfingering with two finer grained slack-water lenses. Music Mountain Formation has contact with Moenkopi Formation ~2 m below sample interval. The two sampled beds show opposite polarities, but same early Eocene pole position (Elston et al., 1989; Rapp et al., 1983). Locality is on steep, southeast-facing gully 2.7 km east of Furguson Tank, Rose Well Tank East, Arizona, topographic map, S. ½, Section 10, T. 27 N., R. 5 W. (U.S. Geological Survey, 1981d).

clast, a "chert-jasper conglomeratic quartzite, possibly a diagnostic type, is in small amounts present in the Tertiary deposits" (see Fig. 15). Cooley's (1960) underappreciated recognition of southern Utah source terranes for such gravels unknowingly preempted Goldstrand's (1990, 1992, 1994) independent identification of these distinctive chert litharenite clasts as having been reworked from Paleogene rocks such as the Canaan Peak Formation (Fig. 16). The source of the chert litharenite clasts was traced to the Mississippian Eleana Formation of southern Nevada by Goldstrand (1990, 1992, 1994). The chert litharenite clasts, subsequently reworked southward from gravel beds in the Paleogene strata of the High Plateaus of Utah, have since been collected from the majority of widespread unnamed gravel deposits (Fig. 17) in southern Utah and in Arizona, north of the Colorado River, between the Grand Wash Cliffs and eastern Lake Powell (R.A. Young personal data obtained during 2007–2009 reconnaissance surveys with K. Karlstrom, T. Hanks, L. Crossey, and G. Billingsley; Fig. 16).

The reworked Pliocene and Pleistocene exotic gravels on the relatively young strath terraces north of the Colorado River described by Cooley (1960) have no spatial or temporal relationship to the much older Laramide-age rim gravel south of Grand Canyon. Their wide age divergence is obvious in that the Canaan Peak–Claron Formation interval in Utah, source rocks for the younger reworked strath terrace gravels, has essentially the same Late Cretaceous–Eocene

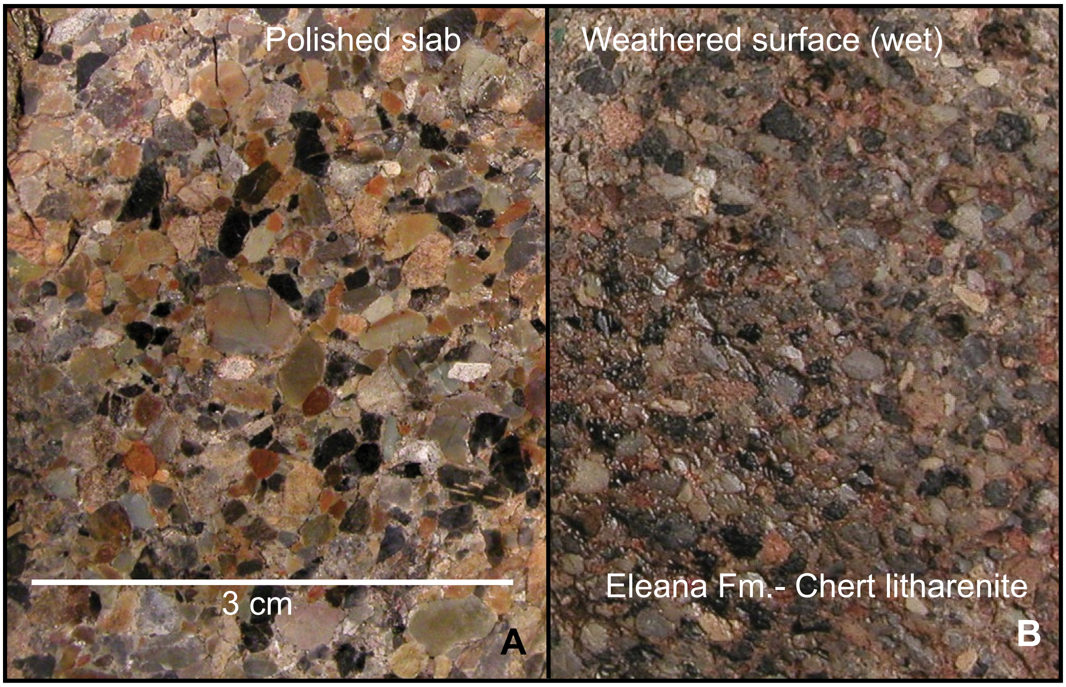

Figure 15. Composition and texture of typical chert litharenite clasts (different views, same specimen) originally derived from beds in Mississippian Eleana Formation (Fm.) (Goldstrand, 1992, 1994), now occurring as reworked pebbles from Canaan Peak–Claron Formation sequence shed into high-level (1220 m) strath terrace deposits north of Colorado River. (A) Polished slab. (B) Wet weathered surface. Specimen collected near Bullfrog, Lake Powell, Garfield County, Utah.

Figure 16. Gravel being reworked from Canaan Peak through Claron Formations. Location is adjacent to Route 12, Pine Lake quadrangle, Garfield County, Utah, ~8 km south-southeast of Powell Point. Note abundance of small black chert pebbles that have approximate diameter of hammer handle; many originally derived from Eleana Formation (Goldstrand, 1992, 1994).

age spread as the Music Mountain Formation of Arizona. Therefore, the various Neogene strath terrace gravels north of the Colorado River represent a series of younger episodes of reworking of the Utah Paleogene strata and may be as much as 40 m.y. younger than the Music Mountain Formation south of the Colorado River.

Miscorrelations and Misinterpretations

It is critical to separate the Laramide age and geologic setting of the Music Mountain Formation, sourced in the Mogollon Highlands and similar Laramide uplifts of Arizona, from much younger generations of gravels subsequently derived by reworking of these widespread Laramide-age deposits.

Additional complications are introduced by those who propose ages as young as Oligocene for the Music Mountain Formation and postulate a temporal equivalence with the deposition of the previously described, much younger, exotic, reworked strath terrace gravels derived from north of the Colorado River in southern Utah (Hill and Ranney, 2008; Hill et al., 2003, 2004, 2006; Scarborough, 2005; Scarborough et al., 2007). These reworked Utah-derived gravels are the result of late Miocene(?) through Pleistocene reworking of Cretaceous–Paleogene Utah conglomerates southward from the Canaan Peak Formation and closely related Late Cretaceous–Paleogene rocks in Utah by Colorado River tributaries, as originally inferred by Cooley (1960). These reworked, quartzite-dominated gravels north of the Colorado River are readily distinguished by their low but persistent percentages of distinctive Eleana chert litharenite clasts (Fig. 15) and abundant Eleana black chert pebbles (Figs. 16 and 17) identified by Goldstrand (1990, 1992, 1994).

Hill and Ranney (2008, p. 485) incorrectly concluded that the paleontologic evidence for an Eocene (or older) age for the Arizona rim gravel or Music Mountain Formation is unsupported because it is mainly based on “charophytes collected near Long Point, Arizona” an incorrect and oversimplified assumption clarified herein; they arrived at their conclusions in part by adopting the speculation in Cather et al. (2008) that the Coconino Plateau rim gravel or Music Mountain Formation could be correla-

Figure 17. (A) In situ Shinarump Conglomerate outcrop located 4.5 km west of Fredonia, Arizona (AZ), compared to three typical late Tertiary (Pliocene?) or Quaternary reworked strath terrace gravel types (B, C, and D) collected north of the Colorado River from southern Utah and northern Arizona. Average Shinarump clast diameters in A are ~1–2 cm (glove fingers for scale); largest is ~3 cm. In B–D, many larger clasts have diameters near hammer head length. All four gravels have clearly visible component of dark gray and black chert (unlike Music Mountain Formation). All but Shinarump also have identifiable chert litharenite clasts as depicted in Figure 15, reworked from Canaan Peak and associated early Tertiary rocks in southern Utah. (B) Cemented gravel from Little Cedar Knoll gravel pit, White Sage Flat quadrangle, 20 km southwest of Fredonia, AZ (Fig. 1, between Kanab Creek and Kaibab upwarp). (C) Lag gravel on south side of Pine Hollow Canyon, Jumping Point quadrangle, AZ, 32 km southwest of Jacob Lake, AZ (Billingsley et al., 2008). (D) Reworked gravel along Route 12, Red Canyon, Utah, 16 km west of Bryce Canyon turnoff.

tive with the Oligocene Chuska erg deposits that occur much further to the east, centered in New Mexico. This speculative age correlation is outweighed by the wealth of independent evidence that supports a Late Cretaceous–early Paleogene time frame for regional Laramide uplift, erosion, and subsequent rim gravel deposition. The zircon data of Dickinson et al. (2012) also negate the Chuska erg connection.

Hill and Ranney (2008) cited no evidence in their reconnaissance surveys that they conclusively identified the requisite chert litharenite clasts or other diagnostic fossiliferous Eleana cherts during their brief visits to known, but largely unmapped, exotic gravel localities north of the Colorado River. However, Hill and Ranney (2008, p. 487, 493) presumed in their conclusions that they adequately distinguished southern-derived Arizona rim gravel from reworked "Canaan Peak-type gravels." Their speculation, that a "proto Eocene Grand Canyon" must have prevented the contemporaneous mixing of Arizona rim gravel with Canaan Peak–type gravels (north and south of the Colorado River) in Oligocene time, is unsupported by the field reconnaissance of Hill and colleagues in a series of reports provided to the U.S. Bureau of Land Management (Hill and Ranney, 2002; Hill et al., 2003, 2004, 2006; Scarborough et al., 2007; Scarborough, 2005).

Furthermore, the claim that Canaan Peak–derived gravels are not present anywhere on the south side of the Colorado River (Hill and Ranney, 2008) is actually refuted by the presence of identifiable Canaan Peak–derived litharenite clasts (Fig. 15) in river gravels on the Marble

Platform near Glen Canyon Dam, east of the old Navajo Bridge (Fig. 1; Young, personal observation; Billingsley and Priest, 2010, 2013). These Utah-derived clasts are clearly related to the much younger interval of modern Colorado River incision. The unique chert litharenite clasts also have been collected (by Young) from the modern Colorado River bedload gravel at Lees Ferry. The related high-level former Colorado River gravels on the Marble Platform downstream from Glen Canyon Dam have been mapped along both sides of the Colorado River gorge north and south of the Navajo Bridge (Fig. 1) near 1100 m in elevation and 200 m above the existing river (Billingsley and Priest, 2010, 2013). The gravel remnants represent former, high-level Colorado River bedload sediments delivered to the Colorado main stem by south-flowing tributaries such as the Escalante, Wahweap, and Paria Rivers.

CONCLUSIONS

The Laramide ages of the youngest volcanic clasts in the Music Mountain Formation indicate that the upper portions of preserved (erosionally truncated?) Paleogene sediments are younger than the included 51 Ma volcanic clasts in some locations (Flowers et al., 2008). The paleontologic data indicate that the fossiliferous lacustrine middle(?) of the erosionally truncated section near Long Point, Arizona, is demonstrably of early Eocene age (estimated 50–55 Ma range) or slightly older. The paleomagnetic results indicate that the interval near the base of the arkosic sediments preserved near Furguson Tank may correlate with Chron 24 (56–53 Ma), although other basal sections could be older. These independent data sets all support Paleocene or early Eocene time as being part of an extended episode of exotic sediment deposition in northwestern Arizona. From the perspective of the tectonic framework of the Laramide orogeny, the uplift, erosional stripping of the Colorado Plateau, drainage incision, and associated deposition probably began in Late Cretaceous time and continued for an interval exceeding 15–20 m.y.

It is reasonable to assume that a thick arkosic gravel blanket in northern Arizona may have extended up to, and an undetermined distance north of, the modern Grand Canyon, perhaps at one time merging with the early Tertiary basin sediments in southern Utah described by Goldstrand (1990, 1992, 1994). The age of the Music Mountain Formation is similar to the ages of the Paleogene Utah conglomerates, such as occur in the Canaan Peak (Late Cretaceous–early Paleocene), Claron (Paleocene–Eocene), and related formations, which were being deposited in similar tectonic settings.

The lithologic differences between the widespread quartzite-rich gravels currently found on opposite sides of the Colorado River are distinct, and no deeply weathered arkosic gravels similar to those in the in situ Music Mountain Formation have yet been located or described north of the Colorado River. The northern-derived, reworked, Canaan Peak and Claron gravels are associated with relatively younger strath terraces within the drainage basins of modern, south-flowing Colorado River tributaries formed during the relatively rapid incision of the modern Colorado River canyons, an event conventionally accepted to have occurred from latest Miocene through Pleistocene time.

The name Music Mountain Formation should be restricted to the thoroughly weathered Laramide-age arkosic in situ sediments of the Coconino and Hualapai Plateaus and immediately adjacent regions that are overlain in places by basaltic volcanic rocks of Oligocene–Pliocene age on the southwestern Colorado Plateau in Arizona. Younger lag gravels of various ages, derived from the reworking of these Laramide-age sediments, are readily distinguishable and should not be confused with their parent sources. The term rim gravel should be abandoned due to its imprecise definition and unfortunate misapplication to a broad range of deposits, many of which may be genetically related, but differ widely in age.

The Eocene Mogollon Rim Formation of Potochnik (2001) in eastern Arizona probably constitutes the youngest evidence for the persistence of regional north-flowing drainage onto the Colorado Plateau from the former Mogollon Highlands of central Arizona. However, its less weathered aspect, slightly younger apparent age, and different clast composition prevent the establishment of any direct lateral or vertical continuity between the Mogollon Rim Formation and the Music Mountain Formation to the west.

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