10-1-2021

A constraint on post–6 Ma timing of western Grand Canyon (Arizona, USA) incision removed: Local derivation indicated by ca. 5.4 Ma fluvial deposits below Shivwits Plateau basalts north of Grand Canyon

Aaron T. Steelquist

George E. Hilley

Ivo Lucchitta

Richard A. Young
SUNY Geneseo

GEOSPHERE

GEOSPHERE

https://doi.org/10.1130/GES02353.1

6 figures; 1 set of supplemental files

CORRESPONDENCE: steelqat@gmail.com

CITATION: Steelquist, A.T., Hilley, G.E., Lucchitta, I., and Young, R.A., 2021, A constraint on post–6 Ma timing of western Grand Canyon (Arizona, USA) incision removed: Local derivation indicated by ca. 5.4 Ma fluvial deposits below Shivwits Plateau basalts north of Grand Canyon: Geosphere, https://doi.org/10.1130/GES02353.1.

Science Editor: David E. Fastovsky
Associate Editor: Nancy R. Riggs

Received 17 September 2020
Revision received 20 April 2021
Accepted 4 June 2021

Published online 1 October 2021

A constraint on post–6 Ma timing of western Grand Canyon (Arizona, USA) incision removed: Local derivation indicated by ca. 5.4 Ma fluvial deposits below Shivwits Plateau basalts north of Grand Canyon

A.T. Steelquist[1], G.E. Hilley[1], I. Lucchitta[2], and R.A. Young[3]

[1]Department of Geological Sciences, Stanford University, 450 Jane Stanford Way, Building 320, Stanford, California 94305, USA
[2]U.S. Geological Survey, Emeritus, 6969 Snowbowl View Circle, Flagstaff, Arizona 86001, USA
[3]Department of Geological Sciences, The State University of New York (SUNY) Geneseo, 1 College Circle, Geneseo, New York 14454, USA

ABSTRACT

The timing of integration of the Colorado River system is central to understanding the landscape evolution of much of the southwestern United States. However, the time at which the Colorado River started incising the westernmost Grand Canyon (Arizona) is still an unsettled question, with conflicting interpretations of both geologic and thermochronologic data from western Grand Canyon. Fluvial gravels on the Shivwits Plateau, north of the canyon, have been reported to contain clasts derived from south of the modern canyon, suggesting the absence of western Grand Canyon at the time of their deposition. In this study, we reassess these deposits using modern geochronologic measurements to determine the age of the deposits and the presence or absence of clasts from south of the Grand Canyon. We could not identify southerly derived clasts, so cannot rule out the existence of a major topographic barrier such as Grand Canyon prior to the age of deposition of the gravels. ^{40}Ar/^{39}Ar analysis of a basalt clast entrained in the upper deposit (in combination with prior data) supports a maximum age of deposition of ca. 5.4 Ma, limiting deposition to post-Miocene, a period from which very few diagnostic and dated fluvial deposits remain in the western Colorado Plateau. Analysis of detrital zircon composition of the sand matrix supports interpretation of the deposit as being locally derived and not part of a major throughgoing river. We suggest that the published constraint of <6 Ma timing of Grand Canyon incision may be removed, given that no clasts that must be sourced from south of Grand Canyon were found in the only known outcrop of gravels under the Shivwits Plateau basalts at Grassy Mountain north of Grand Canyon.

INTRODUCTION

River incision and landscapes of the Colorado Plateau (western United States) have fascinated geologists since John Wesley Powell's expedition in 1869. Scientific investigation of this arid, eroding landscape has yielded information about cyclic incision, drainage integration, and landscape response to erosion on the plateau (Garvin et al., 2005; Karlstrom et al., 2008; Pederson et al., 2013). The central driver of landscape development across the plateau since late Miocene time is the incision of the Colorado River and its predecessors because incision sets the local base level for tributaries, which further dissect upland surfaces. Despite the central role played by incision of the Colorado River in creating these unique landscapes, there is no full consensus of when key portions of this incision occurred. Vast amounts of geologic, thermochronologic, and geomorphic research in the Grand Canyon region (Arizona) have brought significant clarity to the question (described in detail below); however, enough uncertainty exists in the literature to allow for competing hypotheses to persist.

In this study, we characterize the only known outcrop of fluvial gravels underlying volcanic rocks in the Shivwits volcanic field north of Grand Canyon. We test the published hypothesis that the gravels contain clasts of exclusively southern origin, specifically from the central Arizona transition zone, precluding the existence of Grand Canyon at the time of deposition (Lucchitta and Jeanne, 2001). We use modern geochronologic analyses to determine the range of possible sources for exotic clasts and test the assertion that the gravels were deposited at the time of emplacement of the overlying Grassy Mountain basalt. U-Pb zircon analyses of exotic clasts most similar to those identified as being of southern derivation (Lucchitta, 1975) yielded zircon ages inconsistent with terranes of exclusively southern exposure, refuting part of the hypothesis. ^{40}Ar/^{39}Ar analysis of a basalt clast entrained in the upper few inches of the deposit yielded an age of 5.253 ± 0.15 Ma, establishing the maximum depositional age as equal to (within 2σ error) that of the overlying basalt, which previous studies dated at 5.47 ± 0.1 Ma. Additional U-Pb zircon analyses of the sand matrix suggest a recycling of zircon from nearby Mesozoic strata, supporting interpretation of the gravels as being locally derived from erosional escarpments to the north of Grassy Mountain. Thus, while this deposit has not provided an unequivocal constraint on the timing of western Grand Canyon incision, it helps characterize local fluvial systems on the Shivwits Plateau and surrounding plateaus from a key period during integration of the Colorado River system from which very few fluvial deposits are known.

Aaron Steelquist https://orcid.org/0000-0003-3668-7521

THE GRAND CANYON DEBATE

The lithologic character of late Miocene deposits downstream of the mouth of Grand Canyon suggests that the Colorado River did not flow through this area prior to 6 Ma, with only locally derived sediments observed and a distinct absence of Colorado River–derived sediments (Blackwelder, 1934; Longwell, 1946; Lucchitta, 1966, 1972; Lucchitta et al., 1989). This hypothesis, commonly referred to as the "Muddy Creek constraint," is supported by detrital zircon analyses in deposits downstream of the Grand Wash Cliffs, where the Colorado River exits Grand Canyon, which constrain the arrival of Colorado Plateau zircon signatures between 6 Ma and 4.4 Ma (Spencer et al., 2001; Kimbrough et al., 2015; Crossey et al., 2015). The combination of stratigraphic and isotopic $^{87}Sr/^{86}Sr$, $\delta^{13}C$, and $\delta^{18}O$ data from limestones immediately downstream of the modern Grand Canyon demonstrate the dominance of groundwater input to the Grand Wash trough prior to ca. 6 Ma. A marked change in isotopic composition in the upper 50 m of the Hualapai Limestone and subsequent Bouse Formation signals a change in water source at this time, likely the proto–Colorado River (Spencer et al., 2013; Crossey et al., 2015). Geomorphic observations of western Grand Canyon suggest that a low-relief surface dominated the Hualapai Plateau and relict channels that drained this surface are separated from the modern Grand Canyon by steep knickpoints, in turn suggesting a disequilibrium between base-level fall rates that is relatively recent (Darling and Whipple, 2015). In the western Grand Canyon region, documented "rim gravels" that are preserved in paleocanyons suggest aggradation from Paleocene to late Miocene time on the Hualapai Plateau (Young and Crow, 2014), where erosion now acts over the majority of the landscape. These deposits along with others preserved in paleocanyons within the Hualapai Plateau (well summarized in Young and Crow, 2014) represent some of the only remnants of the Cenozoic drainage architecture in the western Colorado Plateau region, making characterization of all remaining fluvial deposits important in determining the late Cenozoic fluvial evolution of the area. These pieces of evidence have led to the dominant interpretation that the westward-flowing Colorado River had not incised into the western margin of the Colorado Plateau prior to 6 Ma.

Low-temperature thermochronologic data from western Grand Canyon have yielded more ambiguous results. Controversial cooling histories measured using the (U-Th)/He and $^{4}He/^{3}He$ thermochronometers in apatite grains suggest that western Grand Canyon was near modern depths by 70 Ma (Flowers et al., 2008; Flowers and Farley, 2012). Wernicke (2011) suggested that western Grand Canyon may have been carved by rivers with headwaters in the Cordilleran arc to the west and Mogollon Highlands to the south. However, this has been questioned by further additional thermochronologic studies showing that the canyon may have become integrated through paleocanyon remnants in some regions while creating new relief in others, resulting in the previously established 6 Ma age constraint (Karlstrom et al., 2014). Recent (U-Th)/He and $^{4}He/^{3}He$ data, along with better understanding of the uncertainties in these methods (see Fox and Shuster, 2014; Fox et al., 2017), have shown that the modern river-level western Grand Canyon had cooled to 40–60 °C by the Laramide (70–50 Ma) (Winn et al., 2017). This corresponds to ~1 km depth, with subsequent cooling to near-surface temperatures occurring after 10 Ma (Winn et al., 2017).

Paleomagnetic measurements on quartzite clasts in a conglomerate have been used to suggest a link between eastern Grand Canyon and the coastal California mid-Tertiary Sespe Formation (Sabbeth et al., 2019). This hypothesis has been substantially refuted due to the ambiguity of paleomagnetic measurements of clasts lacking original geographic context, complex cross-bedding relationships in the proposed source yielding nonunique signatures, and detrital zircon analyses of the orthoquartzite clasts of the Sespe Formation statistically supporting Mojave Desert source regions over an eastern Grand Canyon source region (Karlstrom et al., 2020). Considering all published hypotheses, the broadest possible timing of western Grand Canyon incision has been inferred to be anywhere between 6 and 70 Ma (Elston and Young, 1991; Flowers and Farley, 2012; Kimbrough et al., 2015).

Geologic relations that could directly bracket the timing of incision of Grand Canyon have been reported. Gravel deposits located on the slopes of Grassy Mountain on the Shivwits Plateau (north of Grand Canyon; see Fig. 1) were noted by Lucchitta (1975) as likely being sourced from the Prescott, Arizona, region. These deposits were reported to contain clasts of exotic origin (Lucchitta, 1975, 1984; Lucchitta et al., 1989; Lucchitta and Jeanne, 2001) and to overlie the Triassic Moenkopi Formation and be overlain by Grassy Mountain basalt (Lucchitta, 1975; Billingsley and Wellmeyer, 2003) recently redated by Karlstrom et al. (2017) at 5.47 ± 0.05 Ma. Two characteristics of this deposit could provide additional constraints on the timing of river incision. First, according to Lucchitta and Jeanne (2001, p. 67), these gravels contain "weakly metamorphosed silicic volcanic rocks…[that] resemble Proterozoic rocks of the Alder Series." The primary exposure of the Alder Series is in the central Arizona transition zone that separates the Colorado Plateau from the Basin and Range, southeast of the Shivwits Plateau. The suggestion of Lucchitta and Jeanne (2001), if correct, would require northwestward-flowing rivers to have delivered far-traveled clasts across the modern location of western Grand Canyon at the time of gravel emplacement, thus precluding the canyon's existence at the time. While this portion of the hypothesis conflicts with the presence of the Hindu Fanglomerate (Young and Crow, 2014), which records a southerly drainage from the Shivwits Plateau escarpment across the Hualapai Plateau into the early Eocene, it is appropriate to explore all possible outcrops with bearing on the Grand Canyon controversy. Second, Lucchitta and Jeanne (2001) suggested that the overlying Grassy Mountain basalt was emplaced shortly after deposition of the gravels on the basis of the unweathered appearance of the gravel deposit's fine-grained matrix. If validated, these two hypotheses in conjunction would preclude the existence of a major topographic barrier in the region prior to 5.47 Ma. Verification of the gravels and their provenance has been complicated by the fact that numerous researchers have failed to relocate the outcrop described by Lucchitta (1975). Evidence of ongoing cliff collapse at Grassy Mountain suggests it may no longer be exposed. However,

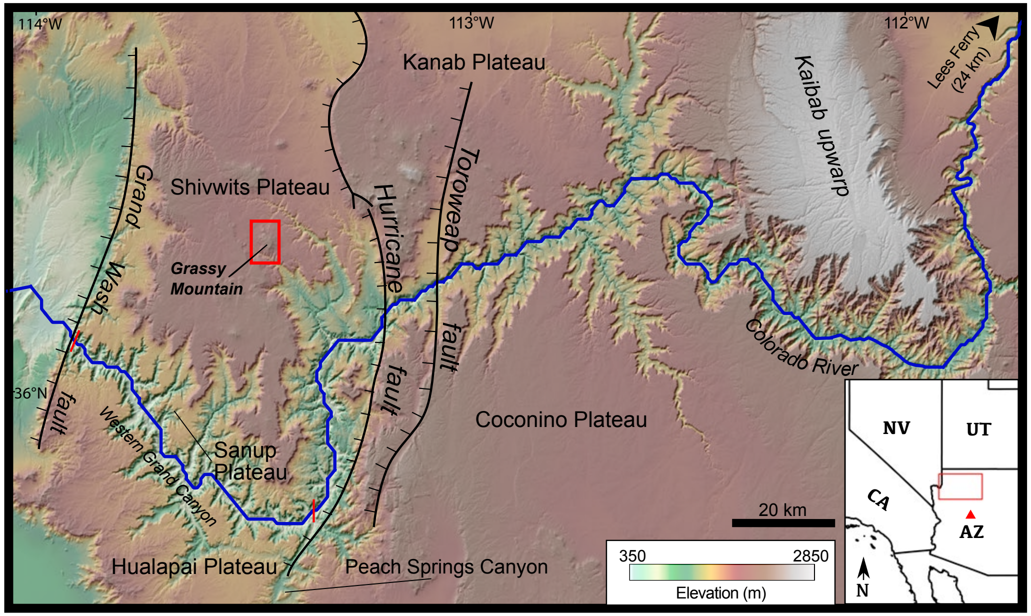


Figure 1. Shaded-relief map of the Grand Canyon region (Arizona, southwestern United States). Major physiographic and tectonic features are labeled. Red box in the detail map indicates the extent of Figure 2A. Short red lines indicate the extent of western Grand Canyon as defined in the text. Digital elevation model and derived hillshade created using 1 arc-second US Geological Survey National Map 3D Elevation Project (3DEP, https://www.usgs.gov/core-science-systems/ngp/3dep). NV—Nevada; UT—Utah; CA—California; AZ—Arizona.

recent investigations of the area identified an outcrop of potentially analogous material. The hypotheses described in Lucchitta and Jeanne (2001) present a testable set of geologic constraints on the fluvial architecture of the western Grand Canyon region that can be readily assessed using U-Pb zircon analysis and $^{40}Ar/^{39}Ar$ analysis of basalt groundmass.

GEOLOGIC BACKGROUND

Grand Canyon is 300 km long, a maximum of 15–20 km wide, and as much as 1.5 km deep. The Colorado River enters the canyon downstream of Lees Ferry, incising into predominantly flat-lying Paleozoic strata and Proterozoic basement rocks of the southwestern Colorado Plateau. The Colorado River exits Grand Canyon at the Grand Wash Cliffs, the boundary that defines the western edge of the Colorado Plateau. The region surrounding Grand Canyon is divided into multiple low-relief plateaus by generally north-south–striking normal faults, including the Grand Wash, Hurricane, and Toroweap faults (Fig. 1), some of which have reactivated and inverted Laramide offset. Of particular interest to this study is western Grand Canyon, commonly defined as the segment between Peach Springs Canyon and the Grand Wash Cliffs. Western Grand Canyon is steeper, narrower, and shallower than eastern Grand Canyon and separates the low-relief Hualapai and Sanup Plateaus (Darling and Whipple, 2015). Remnants of Paleocene through Miocene fluvial deposits can be found throughout the Hualapai Plateau (reviewed in Young and Crow, 2014) and record a Laramide drainage system coming off the formerly prominent Mogollon Highlands to the south and west (Cooley and Davidson, 1963). Post-Miocene erosion subsequently dissected the plateau and partially re-excavated these canyons as tributaries to the modern Colorado River (Elston and Young, 1991; Young, 1987, 2001).

Displacement along the Grand Wash fault began ca. 18 Ma, with roughly 5.5 km of offset accruing in the subsequent 6 m.y., as evidenced by correlation of dated volcanic deposits across the fault scarp (Fitzgerald et al., 1991, 2009; Reiners et al., 2000; Faulds et al., 2001). Wedge-shaped deposition of the 300-m-thick Hualapai Limestone in the Grand Wash trough and proximal basins suggests the normal faulting in the region was also active from 12 to 6 Ma (Lopez Pearce, 2010; Seixas et al., 2015; Crossey et al., 2015; Faulds et al., 2016), though some portions of the Grand Wash fault appear to have ceased motion within this period (Faulds et al., 2016). The Shivwits Plateau is a broad erosional surface cut across the Permian Kaibab Limestone north of the modern canyon that is bounded on the west by the Grand Wash fault. Preservation of geomorphic surfaces by Cenozoic volcanism displays a general southwest-to-northeast trend of escarpment retreat (Lucchitta, 1975, 1984, 1989; Lucchitta and Jeanne, 2001), with remnants of Triassic Moenkopi Formation and later Mesozoic units preserved below capping resistant basalt flows, which follow the same southwest-to-northeast trend (Crow et al., 2011; Walk et al., 2019).

South of the Hualapai and Coconino Plateaus is the transition zone of central Arizona, which separates the southwestern edge of the Colorado Plateau from the Basin and Range province. The transition zone includes the Paleozoic and Mesozoic sedimentary rocks of the Colorado Plateau that were exhumed during a relief-generating episode during the Cretaceous–Paleocene Laramide uplift (Young and McKee, 1978; Young, 2001). Paleocanyons that were incised to Proterozoic basement contain the 65–55 Ma Music Mountain Formation (Young, 2001; Young and Hartman, 2014; Hill et al., 2016), thus requiring exhumation of the Precambrian basement locally prior to deposition of the Tertiary gravels.

The Precambrian Yavapai Supergroup is exposed in the Jerome-Prescott area of Arizona (including Mingus Mountain, roughly 220 km to the southwest) as well as elsewhere throughout the transition zone (Anderson, 1989a). U-Pb zircon analyses have identified unique Paleoproterozoic ages (ca. 1.75 Ga to ca. 1.68 Ga) for multiple silicic volcanic rocks throughout the Arizona transition zone (Anderson, 1989b). Syn- and post-depositional deformation also varies throughout the unique volcaniclastic deposits, such as those found along the margins of the Shylock fault (Karlstrom and Bowring, 1988). Correlation of any silicic volcanic clasts in the Grassy Mountain gravels with source regions in the Arizona transition zone would be possible by comparing U-Pb ages and textural analyses of clasts with corresponding basement affinities.

METHODS

Nadir aerial images were collected along the north slope of Grassy Mountain, encompassing both the Grassy Mountain basalt flow and the escarpment where the Grassy Mountain gravels are exposed. All aerial photos were collected within a two-hour period using a DJI Inspire 1 quadcopter with a gimble-mounted Zenmuse X3 camera. Additionally, ground-based convergent-view images were obtained for each of the three outcrops of gravel identified on the north slope of Grassy Mountain using a Panasonic Lumix G7 camera. All images were corrected for lens distortion and differenced to form a three-dimensional point cloud using structure-from-motion techniques (e.g., Bemis et al., 2014) in PhotoScan Professional (now Metashape) by Agisoft software (version 1.2.6, 2016). Each set of outcrop images was also processed using PhotoScan Professional to create an orthorectified image of the deposits.

Clasts of possible exotic origin were collected from the Grassy Mountain gravel deposit for both in situ and laboratory analysis. Lucchitta and Jeanne (2001, p. 67) described "cobbles of granitoids of various kinds, pebbles of black chert, and cobbles of weakly metamorphosed silicic volcanic rocks…"—diagnostic traits that could link them to the central Arizona transition zone or other locations. Two samples were identified as being of a character similar to that described above (samples ATS-GM15 and ATS-GM16; full description in the Results section). Provenance of apparently non-local clasts was constrained using detrital U-Pb zircon analysis. Zircon extraction was completed via crushing, grinding, Frantz magnetic separation, and heavy liquid processing. Only one clast (sample ATS-GM15) yielded sufficient zircons for analysis. U-Pb ratios for zircon grains lacking significant defects were measured using the Stanford–U.S. Geological Survey sensitive high-resolution ion microprobe–reverse geometry (SHRIMP-RG) instrument (Stanford, California; data in Supplemental Material[1]).

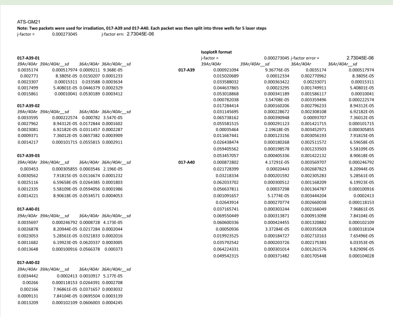
We collected additional zircons from the sand matrix to determine potential source regions. Extracted zircons were mounted in epoxy with FC-1 standard zircon as primary standard (1099.0 ± 0.6 Ma; Paces and Miller, 1993) and R33 as secondary standard (419.26 ± 0.39 Ma; Black et al., 2004). U-Pb analyses were performed at the University of Arizona LaserChron Center (Tucson, Arizona) using laser ablation–inductively coupled plasma–mass spectrometry. Standards, data collection, reduction, and error propagation methodology are described in Gehrels et al. (2008) and Gehrels and Pecha (2014). Best age is determined from $^{206}Pb/^{238}U$ age for analyses with $^{206}Pb/^{238}U$ age <1000 Ma, and from $^{206}Pb/^{207}Pb$ age for analyses with $^{206}Pb/^{238}U$ age >1000 Ma (data in Supplemental Material [footnote 1]).

A clast of angular basalt (sample ATS-GM21) was extracted from the upper beds of the deposit. The angularity and composition of this clast suggested that it was likely sourced from a local eruptive event and was subsequently reworked into the gravel deposits. We crushed the clast to 500–710 mm and separated 100 grains of groundmass for $^{40}Ar/^{39}Ar$ analysis. We analyzed six sample packets of irradiated groundmass grains from the basalt clast using a diode laser in five successive heat steps at the Stanford Noble Gas Lab. The resulting $^{36}Ar/^{40}Ar$ and $^{39}Ar/^{40}Ar$ ratios were used to create an inverse isochron best-fit age (method summarized in Kuiper, 2002) for both samples.

RESULTS

The aerial survey yielded a dense point-cloud recreation of the north slope of Grassy Mountain that clearly depicts the Grassy Mountain basalt flow and the slope-forming Moenkopi Formation (Fig. 2B). The survey area was 2.5 × 10^5 m^2, and 1209 azimuth images were collected. The details of the Grassy Mountain gravel outcrops are not visible in aerial imagery due to vegetative cover. All three outcrops are located at the head of an incised gully that is partially covered by collapsed basalt. No other gullies of similar scale can be observed in the point cloud, nor were any observed while traversing along contour of the exposed Grassy Mountain basalt. This traverse also yielded no additional exposures of the Grassy Mountain gravels; however, clasts were observed on the hillslope tens of meters below the lowest basalt exposure, dominantly quartzite pebbles (<5 cm) as well as a ~15 cm granite clast and ~5 cm microcline crystal.

The Grassy Mountain gravels are red to gray, fine- to medium-grained sandstone with subordinate conglomerate. The deposit is 1.5 m thick (measured at an excavated portion of the central outcrop; Fig. 2C) and is matrix supported, with bed thicknesses ranging from 5 mm to 5 cm (Fig. 2D). The deposit contains an arkosic sand matrix of typically granule size. Clasts are rounded to subangular and range from 1 mm to 5 cm in diameter. An in situ clast count using a standard gridded method proved unfeasible because many clasts selected were too small (<0.5 cm) for proper field identification. Instead,



[1]Supplemental Material. Geochronologic data for both clasts and detrital zircon analyses. Please visit https://doi.org/10.1130/GEOS.S.14736444 to access the supplemental material, and contact editing@geosociety.org with any questions.

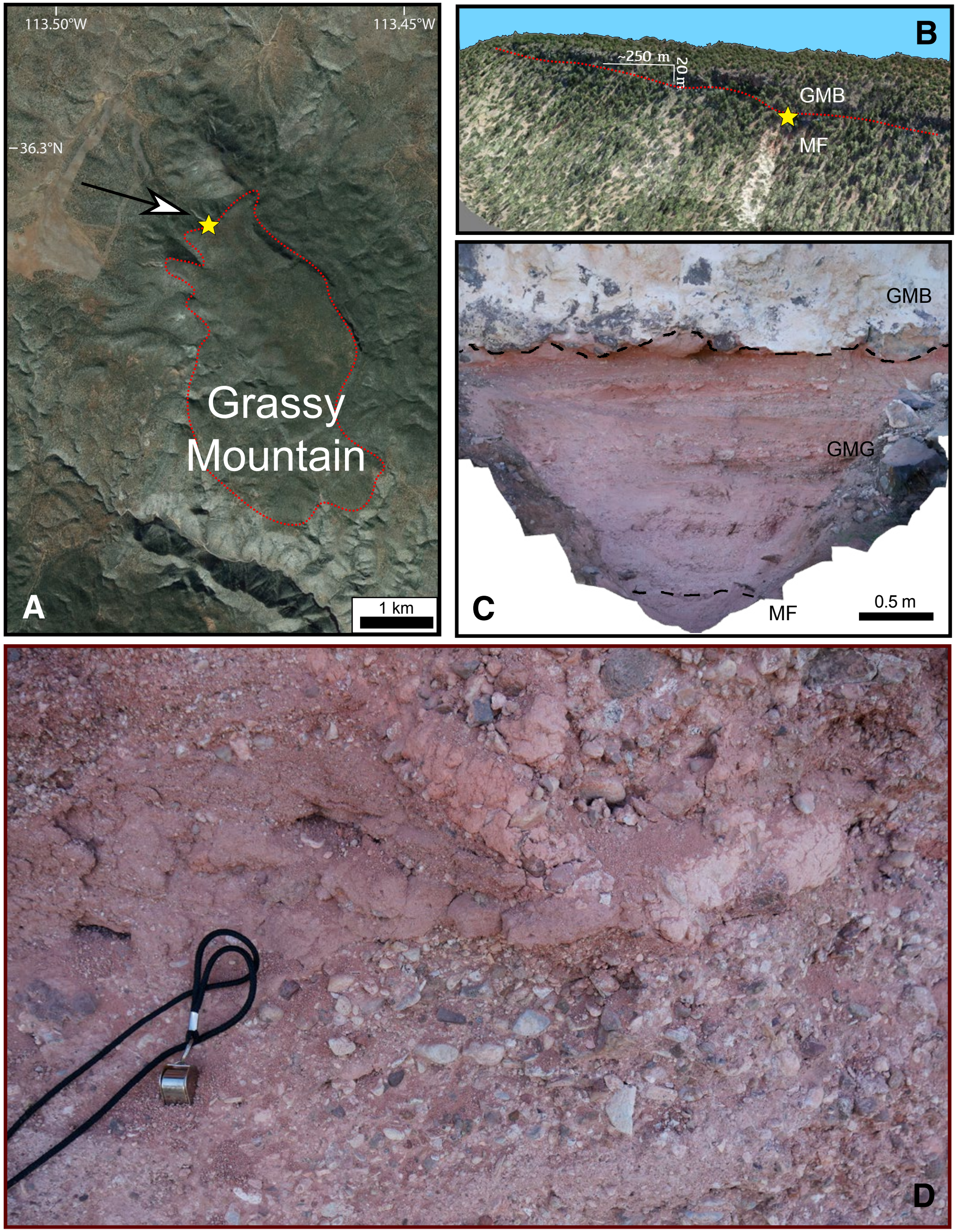


Figure 2. (A) Satellite imagery of Grassy Mountain with approximate extent of Grassy Mountain basalt (dotted red line). Arrow indicates the approximate view of panel B. (B) Point cloud from the uncrewed aerial vehicle (UAV) survey of the northern slope of Grassy Mountain; dotted red line indicates the approximate Grassy Mountain basalt (GMB) and Moenkopi Formation (MF) contact. Outcrop marked with yellow star. (C) Orthographic image of the central outcrop (36.2925°N, 113.4777°W) with GMB, MF, and Grassy Mountain gravels (GMG). (D) Detail image of a gravel bed in the Grassy Mountain gravels (36.2925°N, 113.4778°W); hand lens for scale.

undifferentiated clasts from a horizon containing clasts averaging >3 cm in diameter were brought back and identified post-hoc to increase confidence in proper identification of clast types. The deposit is primarily composed of well-rounded quartzite clasts with a variety of colors, from tan to pink to yellow with dark veins. Most large (>5 cm) clasts are subangular and dominantly sandstone. Basalt clasts can be found in the upper beds of the deposit. Chert pebbles of various colors, limestone clasts (fossiliferous and nonfossiliferous), and limey sandstone clasts are present throughout the deposit; however, the unique black chert pebbles are observed primarily near the base of the deposit. Clast imbrication suggests flow to the west at the time of deposition.

Zircon separation from sample ATS-GM15 yielded 31 grains, of which 24 were used for U-Pb analysis. Ages ranged from 2629 to 280 Ma with significant Phanerozoic contribution (Fig. 3C). A thin section of the clast (Fig. 3B) shows it is primarily quartz with some lithic fragments and iron-oxide cement. The population range of U-Pb ages and thin-section analyses suggest sample ATS-GM15 is of sedimentary or epiclastic origin. While maximum depositional age can be calculated in multiple ways (see Dickinson and Gehrels, 2008), the zircon population analyzed from sample ATS-GM15 strongly suggests a maximum depositional age younger than ca. 1.7 Ga associated with the Arizona transition zone. A youngest single grain (YSG) analysis yields a maximum depositional age of 266 ± 6 Ma, a youngest 1σ grain cluster (YC1σ) yields 574 ± 7 Ma, and a youngest 2σ grain cluster (YC2σ) yields 585 ± 6 Ma (Fig. 3D). Whereas there is significant spread between the end members of these results due to the small number of grains analyzed, they can preclude a Paleoproterozoic age.

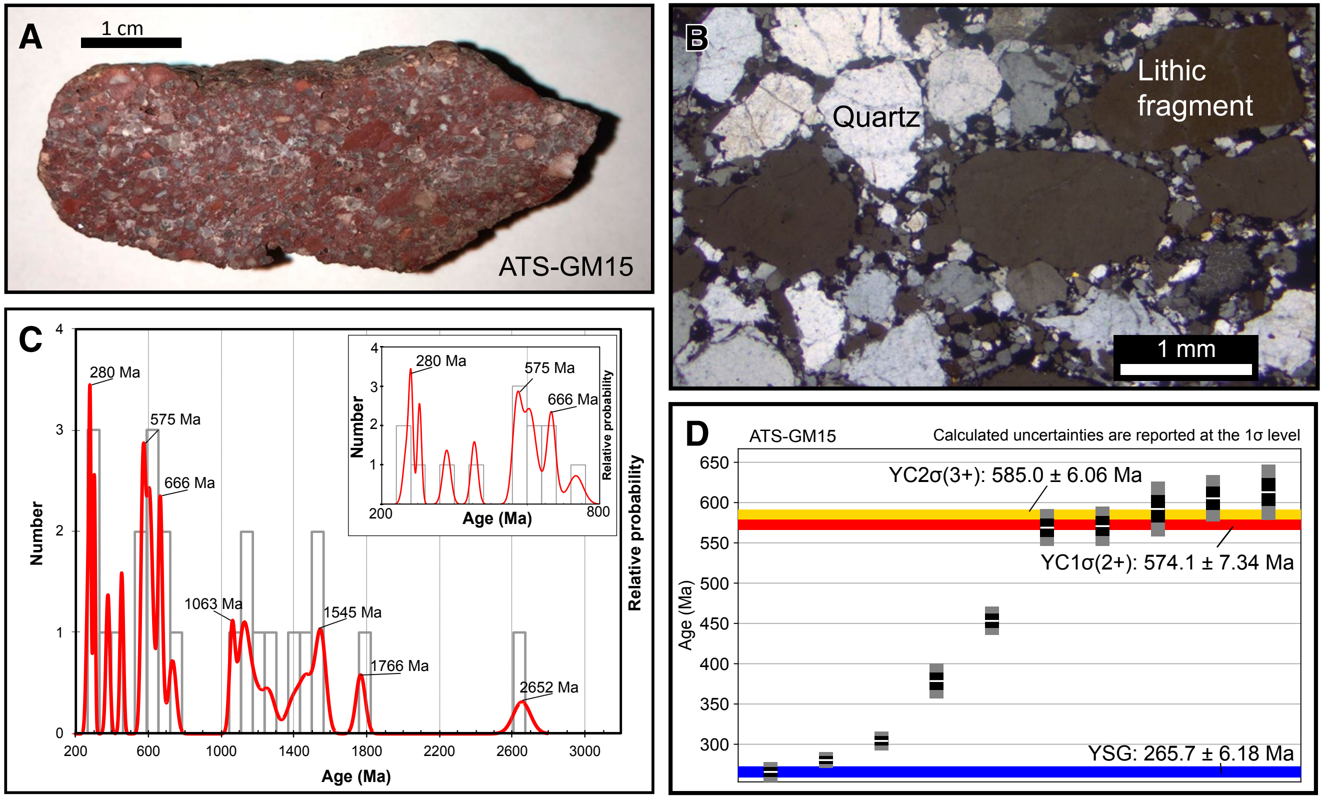


Figure 3. (A) Cut surface of sample ATS-GM15 (36.2925°N, 113.4777°W). (B) Thin section of sample ATS-GM15. (C) Binned zircon ages (gray, 80 m.y. bins) and probability density (red) for zircon ages using U-Pb analysis. Inset shows youngest grain populations with 40 m.y. bin size. (D) Maximum depositional age calculations after Dickinson and Gehrels (2009). YSG—youngest single grain; YC1σ(2+)—youngest cluster of 2 or more grains with overlapping 1σ uncertainty, YC2σ(3+)—youngest cluster of 3 or more grains with overlapping 2σ uncertainty. White bar represents sample age, black bars represent 1σ error, and gray bars represent 2σ error. Plots were generated using detritalPy (Sharman et al., 2018).

The detrital zircon spectrum of the sand matrix ($n = 266$; data in the Supplemental Material [footnote 1]) can be found in Figure 4A. All but five analyses are >209 Ma with 45% within the Triassic and Permian. Given that the Grassy Mountain gravels are inset into the upper Moenkopi Formation (Lower Triassic), we compared these age spectra to previous detrital zircon work from the overlying Chinle Formation by Gehrels et al. 2020) (Fig. 4B).

We collected 30 measurements of $^{40}Ar/^{39}Ar$ (normalized to ^{36}Ar) in groundmass of sample ATS-GM21 and fit these points with an inverse isochron to determine a best-fit age of 5.253 ± 0.15 Ma (Fig. 5) for the entrained clast. This sets a maximum depositional age for the deposit near the Miocene-Pliocene boundary.

DISCUSSION

Analysis of the Grassy Mountain gravel deposits using U-Pb and $^{40}Ar/^{39}Ar$ geochronology failed to support the hypothesis that south-to-north fluvial transport at ca. 6 Ma precludes the existence of western Grand Canyon at the time. While the deposits are somewhat similar in composition and location to that described in Lucchitta and Jeanne (2001), we found no evidence of clasts that can be directly correlated to the Arizona transition zone nor evidence for any far-traveled clasts. Strictly speaking, data from this study do not preclude a ca. 70 Ma western Grand Canyon nor refute a scenario in which canyon incision occurred after the emplacement of the Grassy Mountain basalt. Thus, we are compelled to remove this constraint on the timing of western Grand Canyon incision.

Entrainment of 5.253 ± 0.15 Ma basalt clasts in the deposit sets a Miocene-Pliocene maximum depositional age. Previous $^{40}Ar/^{39}Ar$ analyses by Karlstrom et al. (2017) of a basalt at Grassy Mountain resulted in a 5.47 ± 0.1 Ma plateau age; however, the discrepancy in age is likely due to the difference between use of an inverse isochron (this study) versus plateau age (prior work). However, the ages overlap when considering 2σ errors, thus we conclude that the previously constrained basalt cap age and the basalt clast age are not in conflict and are likely due to analytical differences, giving a depositional age of ca. 5.37–5.40 Ma.

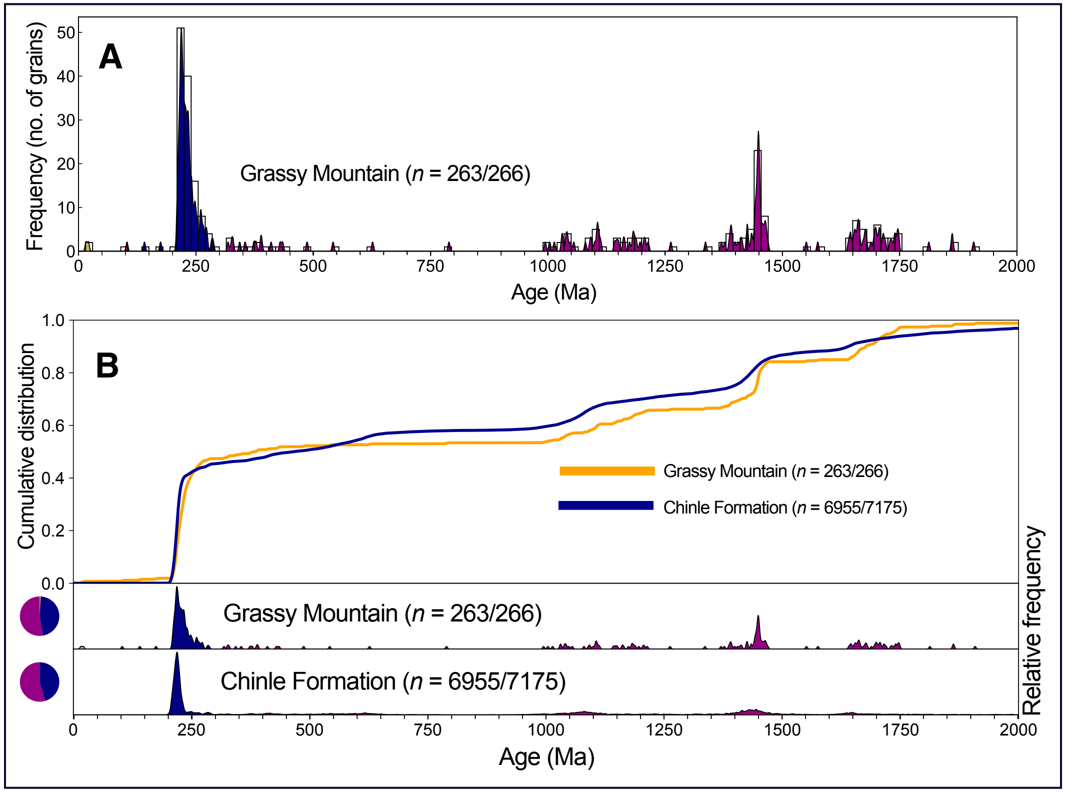


Figure 4. (A) U-Pb detrital zircon kernel density estimation (KDE) age spectra and histogram from the Grassy Mountain gravel sand matrix. Outlined verticals represent grain counts and colored curves represent kernel density estimate for 1 m.y. window. Yellow region represents 65–85 Ma, dark red region represents 100–135 Ma, blue region represents 135–300 Ma, and purple region represents >300 Ma. (B) Cumulative density function and KDE comparing zircon in Grassy Mountain sand matrix to detrital zircon populations for the overlying Chinle Formation (all Chinle Formation members of Gehrels et al., 2020). Pie charts represent relative contribution of grain ages from color bins described in Figure 4A. Data >2000 Ma are excluded.

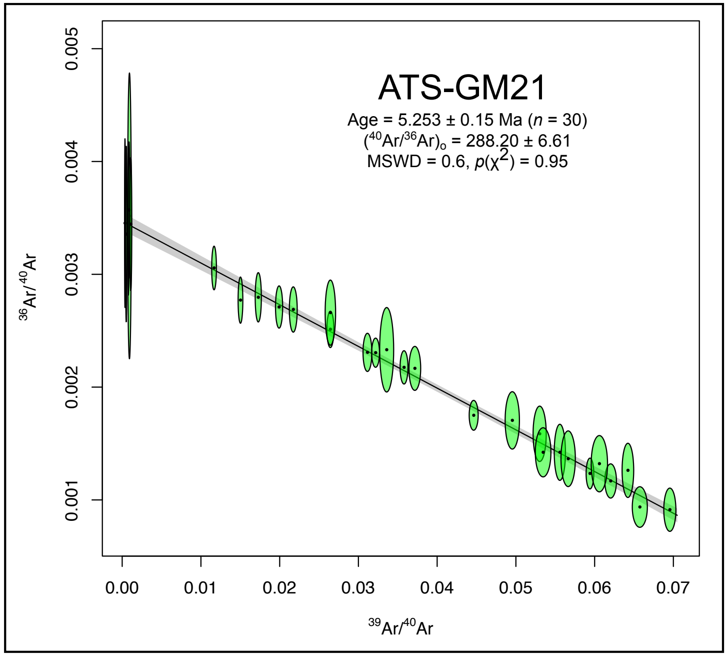


Figure 5. $^{40}Ar/^{39}Ar$ **inverse isochron plot for a basalt clast (sample ATS-GM21, 36.2925°N, 113.4777°W). Green shaded area represents the 1σ error ellipse for measured argon concentration ratios. Gray shaded region represents 1σ error on inverse isochron fit. $(^{40}Ar/^{36}Ar)_o$ is the initial ratio of ^{40}Ar to ^{36}Ar obtained by linear regression. MSWD is the mean square of the weighted deviates for the linear regression, and $p(\chi^2)$ is the chi-squared p-value for the linear fit. Plot created using IsoplotR (Vermeesch, 2018).**

The age of the deposit eliminates source regions to the west because the escarpment created by Grand Wash fault motion prevented eastward-flowing rivers from reaching the Shivwits Plateau by ca. 8 Ma at the latest, though disruption of any transport across the fault likely began closer to the onset of fault motion ca. 16 Ma (Fitzgerald et al., 2009). Deposits from paleo-Lake Hualapai suggest the region immediately west of the Grand Wash fault was internally drained ca. 10–5.6 Ma (Lucchitta, 1966; Spencer et al., 2013; Faulds et al., 2016) and a major south-flowing drainage was established by 4.72 Ma (Walk et al., 2019). However, disruption of any transport across the fault likely began closer to the onset of fault motion ca. 16 Ma (Fitzgerald et al., 2009).

Detrital zircon spectra from the sand matrix support the interpretation of a drainage that did not tap any significant non-local source. Comparison of these spectra with those of detrital zircon of the Chinle Formation (Gehrels et al., 2020), which locally overlies the Moenkopi Formation (into which the Grassy Mountain gravels are inset), shows a close correspondence (Fig. 4B). Modern outcrops of the Chinle Formation can be found to the north of Grassy Mountain in the cliffs of Washington Dome, Utah, roughly ~80 km to the north. Preservation of the late Miocene landscape by lava flows routed down north-northwest–striking valleys shows that drainage in the Pliocene was largely controlled by the recession of erosional scarps (Lucchitta and Jeanne, 2001). While the modern Shivwits Plateau drainages dominantly flow down the structural dip of the resistant Kaibab Limestone to the northeast, those hosted in the Mesozoic strata at the base of the Vermilion Cliffs are dendritic and flow generally southward (Lucchitta and Jeanne, 2001). Conservatively restoring for ~4 km/m.y. of scarp retreat since Grassy Mountain basalt emplacement (Lucchitta and Jeanne, 2001) and considering that the Grassy Mountain gravels are inset into Lower–Middle Triassic Moenkopi Formation, we believe the drainage that deposited the Grassy Mountain gravels had headwaters to the north in erosional escarpments of the retreating Chinle Formation, which are now located near St. George, Utah. Five zircon ages <209 Ma also support the conclusion that the landscape in the area was actively eroding during the deposition of the Grassy Mountain gravels. In this interpretation, the majority of the zircon signature is derived from the erosion of bedrock material (primarily Chinle Formation), while reworking of small remnants or lag deposits contributes the small number of post–209 Ma ages. The dominance of quartzite and chert clasts also supports the interpretation that clasts are primarily sourced from the erosion of proximal Chinle Formation outcrops.

Both the timing and method of integration of the Colorado River through the western Grand Canyon region have been central questions in the landscape evolution of the Colorado Plateau. Thermochronologic data suggest a paleocanyon breached the Kaibab upwarp (Fig. 6) between 25 and 15 Ma (Lee et al., 2013; Karlstrom et al., 2014). Karlstrom et al. (2017) demonstrated that despite a transition from lacustrine to fluvial deposition of the Bidahochi Formation (with a hiatus in depositional record from 14 to 8 Ma), base level in the region surrounding the Little Colorado River (Fig. 6) was relatively stable from 16 to 6 Ma. This suggests that only modest incision or integration upstream of the Grand Wash trough is permitted during this period. This breaching of the Kaibab upwarp would suggest a generally west- to northwest-flowing paleoriver reached the western Grand Canyon region after ca. 15 Ma (conservatively); however, where this river went after crossing the Kaibab upwarp is not known. Arrival of the Colorado River in the Grand Wash trough is broadly bracketed between ca. 5.24 Ma (Crow et al., 2018, 2019) and 4.49 Ma (Faulds et al., 2001, 2016). Integration of the lower Colorado River through Cottonwood Valley (roughly 185 km downstream of where the Colorado River exits Grand Canyon) after 5.24 Ma and into the proto–Gulf of California between 4.80 and 4.63 Ma (Crow et al., 2021) would suggest the Colorado River was integrated through Grand Canyon on the early end of this range. Incision rates calculated from nearby Grand Wash gravels that are capped by a dated basalt flow suggest influence of local Colorado River incision by 4.73 ± 0.074 Ma, though no Colorado River gravels are preserved below the basalt (Crow et al., 2019). Isotopic $^{87}Sr/^{86}Sr$, $\delta^{13}C$, and $\delta^{18}O$ compositions in limestones in basins downstream of the Grand Wash Cliffs show a progressive shift from deep groundwater to shallow groundwater to eventually fluvial input moving downstream, suggesting

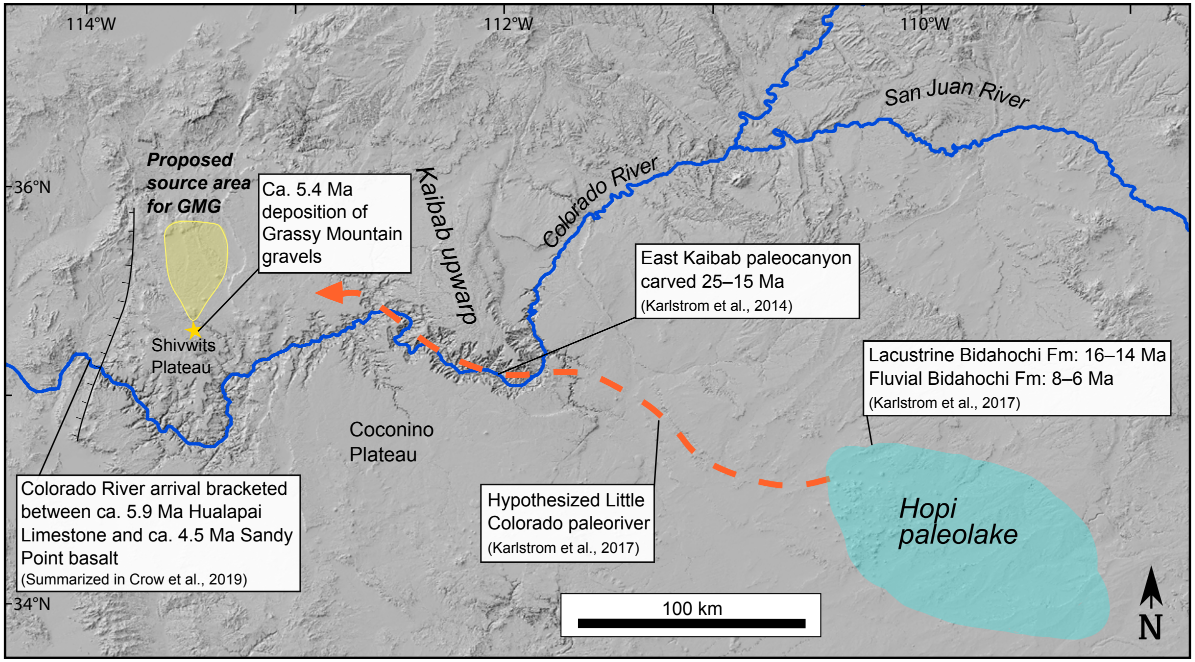


Figure 6. Shaded relief of the southern Colorado Plateau with proposed Grassy Mountain paleodrainage and relevant Grand Canyon integration constraints. Hillshade created using 1 arc-second digital elevation model from U.S. Geological Survey National Map 3D Elevation Project (3DEP, https://www.usgs.gov/core-science-systems/ngp/3dep). GMG—Grassy Mountain gravels; Fm—Formation.

that drainage integration may have been accomplished by a combination of lake spillover and groundwater sapping during this time (Crossey et al., 2015).

The Grassy Mountain gravels are contemporaneous with the latest stages of integration, which brought the proto–Colorado River across the western Grand Canyon region and into the Grand Wash trough ca. 5.24 Ma (Crow et al., 2018, 2019). The Grassy Mountain gravels are most easily explained as representing a small catchment that primarily drained the retreating escarpment to the north, as described above (Fig. 6). This would make the Grassy Mountain gravels drainage a tributary to this soon-to-be-throughgoing Colorado River, which would rapidly incise western Grand Canyon. While the demonstrated provenance of the Grassy Mountain gravels do not have bearing on the mechanism of integration, other deposits of similar age to the Grassy Mountain gravels have the potential to shed light on the way in which the Colorado River integrated during this critical period. Additional preserved deposits, if identified, may also produce a clearer understanding of where the pre–Grand Canyon paleoriver that breached the Kaibab upwarp may have flowed prior to incision of western Grand Canyon. In this sense, the Grassy Mountain gravels are unique in preserving this critical time window. Further study of the outcrop, or others that may be preserved below basalt flows on the Shivwits Plateau, may provide a clearer understanding of how integration progressed in the region and whether the arrival of a throughgoing river may have left the existing drainage network on the Shivwits Plateau largely disconnected from the regional system.

CONCLUSION

We tested the hypothesis that south-to-north fluvial transport at ca. 6 Ma on the Shivwits Plateau precludes the existence of western Grand Canyon at this time (Lucchitta and Jeanne, 2001). No clasts of unequivocally southern non-local origin were found in the existing Grassy Mountain gravel outcrop, and so we conclude that this constraint on Grand Canyon incision should be removed. However, confirmation of the Grassy Mountain gravels as being geologically contemporaneous with the overlying Grassy Mountain basalt make the 5.37–5.40 Ma deposits unique in this area of the Colorado Plateau. Analysis of the detrital zircon spectrum for the deposit supports the interpretation of the

Grassy Mountain gravels as likely deposited by a local drainage rather than a major throughgoing river. The preservation of a Miocene-Pliocene fluvial deposit is unique for the Shivwits Plateau, and further exploration for similarly preserved fluvial deposits could yield additional information about drainage organization at this critical period in the development of the Colorado River.

ACKNOWLEDGMENTS

Thanks to M. Grove, J. Vazquez, M. Malkowski, S. Dobbs, and C. White for analytical assistance, and M. Brandon and C. Baden for assistance in the field. Additionally, thanks to Brian Wernicke, Sue Beard, Kyle House, Karl Karlstrom, Nancy Riggs, and an anonymous reviewer for helpful critiques, which substantially enhanced this manuscript. This work was funded through Stanford McGee/Levorsen grants to Steelquist and U.S. National Science Foundation grant EAR-1649254 for support of the Arizona LaserChron Center.

REFERENCES CITED

Anderson, P., 1989a, Stratigraphic framework, volcanic-plutonic evolution, and vertical deformation of the Proterozoic volcanic belts of central Arizona, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic Evolution of Arizona: Arizona Geological Society Digest 17, p. 57–147.

Anderson, P., 1989b, Proterozoic plate tectonic evolution of Arizona, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic Evolution of Arizona: Arizona Geological Society Digest 17, p. 17–55.

Bemis, S.P., Micklethwaite, S., Turner, D., James, M.R., Akciz, S.T., Thiele, S.T., and Bangash, H.A., 2014, Ground-based and UAV-based photogrammetry: A multi-scale, high-resolution mapping tool for structural geology and paleoseismology: Journal of Structural Geology, v. 69, p. 163–178, https://doi.org/10.1016/j.jsg.2014.10.007.

Billingsley, G.H., and Wellmeyer, J.L., 2003, Geologic map of the Mount Trumbull 30′ × 60′ quadrangle, Mohave and Coconino Counties, northwestern Arizona: U.S. Geological Survey Geologic Investigations Map 2766, scale 1:100,000, https://doi.org/10.3133/i2766.

Black, L.P., Kamo, S.L., Allen, C.M., Davis, D.W., Aleinikoff, J.N., Valley, J.W., Mundil, R., Campbell, I.H., Korsch, R.J., Williams, I.S., and Foudoulis, C., 2004, Improved $^{206}Pb/^{238}U$ microprobe geochronology by the monitoring of a trace-element-related matrix effect: SHRIMP, ID-TIMS, ELA-ICP-MS and oxygen isotope documentation for a series of zircon standards: Chemical Geology, v. 205, p. 115–140, https://doi.org/10.1016/j.chemgeo.2004.01.003.

Blackwelder, E., 1934, Origin of the Colorado river: Geological Society of America Bulletin, v. 45, p. 551–566, https://doi.org/10.1130/GSAB-45-551.

Cooley, M.E., and Davidson, E.S., 1963, The Mogollon Highlands: Their influence on Mesozoic and Cenozoic erosion and sedimentation, *in* Gray, S.I., ed., Arizona Geological Society Digest 6: Arizona Geological Society Digest 6, p. 7–35.

Crossey, L.C., Karlstrom, K.E., Dorsey, R., Pearce, J., Wan, E., Beard, L.S., Asmerom, Y., Polyak, V., Crow, R.S., Cohen, A., Bright, J., and Pecha, M.E., 2015, Importance of groundwater in propagating downward integration of the 6–5 Ma Colorado River system: Geochemistry of springs, travertines, and lacustrine carbonates of the Grand Canyon region over the past 12 Ma: Geosphere, v. 11, p. 660–682, https://doi.org/10.1130/GES01073.1.

Crow, R., Karlstrom, K., Asmerom, Y., Schmandt, B., Polyak, V., and DuFrane, S.A., 2011, Shrinking of the Colorado Plateau via lithospheric mantle erosion: Evidence from Nd and Sr isotopes and geochronology of Neogene basalts: Geology, v. 39, p. 27–30, https://doi.org/10.1130/G31611.1.

Crow, R.S., Block, D., Felger, T.J., House, P.K., Pearthree, P.A., Gootee, B.F., Youberg, A.M., Howard, K.A., and Beard, L.S., 2018, The Colorado River and its deposits downstream from Grand Canyon in Arizona, California, and Nevada: U.S. Geological Survey Open-File Report 2018-1005, 6 p., https://doi.org/10.3133/ofr20181005.

Crow, R.S., Howard, K.A., Beard, L.S., Pearthree, P.A., House, P.K., Karlstrom, K.E., Peters, L., McIntosh, W., Cassidy, C., Felger, T.J., and Block, D., 2019, Insights into post-Miocene uplift of the western margin of the Colorado Plateau from the stratigraphic record of the lower Colorado River: Geosphere, v. 15, p. 1826–1845, https://doi.org/10.1130/GES02020.1.

Crow, R.S., Schwing, J., Karlstrom, K.E., Heizler, M., Pearthree, P.A., House, P.K., Dulin, S., Jänecke, S.U., Stelten, M., and Crossey, L.J., 2021, Redefining the age of the lower Colorado River, southwestern United States: Geology, v. 49, p. 635–640, https://doi.org/10.1130/G48080.1.

Darling, A., and Whipple, K., 2015, Geomorphic constraints on the age of the western Grand Canyon: Geosphere, v. 11, p. 958–976, https://doi.org/10.1130/GES01131.1.

Dickinson, W.R., and Gehrels, G.E., 2008, U-Pb ages of detrital zircons in relation to paleogeography: Triassic paleodrainage networks and sediment dispersal across southwest Laurentia: Journal of Sedimentary Research, v. 78, p. 745–764, https://doi.org/10.2110/jsr.2008.088.

Dickinson, W.R., and Gehrels, G.E., 2009, Use of U-Pb ages of detrital zircons to infer maximum depositional ages of strata: a test against a Colorado Plateau Mesozoic database: Earth and Planetary Science Letters, v. 288, p. 115–125.

Elston, D.P., and Young, R.A., 1991, Cretaceous-Eocene (Laramide) landscape development and Oligocene-Pliocene drainage reorganization of transition zone and Colorado Plateau, Arizona: Journal of Geophysical Research, v. 96, p. 12,389–12,406, https://doi.org/10.1029/90JB01978.

Faulds, J.E., Price, L.M., and Wallace, M.A., 2001, Pre–Colorado River paleogeography and extension along the Colorado Plateau–Basin and Range boundary, northwestern Arizona, *in* Young., R.A., and Spamer, E.E., eds., Colorado River Origin and Evolution: Grand Canyon Association Monograph 12, p. 129–133.

Faulds, J.E., Schreiber, B.C., Langenheim, V.E., Hinz, N.H., Shaw, T.H., Heizler, M.T., Perkins, M.E., El Tabakh, M., and Kunk, M.J., 2016, Paleogeographic implications of late Miocene lacustrine and nonmarine evaporite deposits in the Lake Mead region: Immediate precursors to the Colorado River: Geosphere, v. 12, p. 721–767, https://doi.org/10.1130/GES01143.1.

Fitzgerald, P.G., Fryxell, J.E., and Wernicke, B.P., 1991, Miocene crustal extension and uplift in southeastern Nevada: Constraints from fission track analysis: Geology, v. 19, p. 1013–1016, https://doi.org/10.1130/0091-7613(1991)019<1013:MCEAUI>2.3.CO;2.

Fitzgerald, P.G., Duebendorfer, E.M., Faulds, J.E., and O'Sullivan, P., 2009, South Virgin–White Hills detachment fault system of SE Nevada and NW Arizona: Applying apatite fission track thermochronology to constrain the tectonic evolution of a major continental detachment fault: Tectonics, v. 28, TC2001, https://doi.org/10.1029/2007TC002194.

Flowers, R.M., and Farley, K.A., 2012, Apatite $^{4}He/^{3}He$ and (U-Th)/He evidence for an ancient Grand Canyon: Science, v. 338, p. 1616–1619, https://doi.org/10.1126/science.1229390.

Flowers, R.M., Wernicke, B.P., and Farley, K.A., 2008, Unroofing, incision, and uplift history of the southwestern Colorado Plateau from apatite (U-Th)/He thermochronometry: Geological Society of America Bulletin, v. 120, p. 571–587, https://doi.org/10.1130/B26231.1.

Fox, M., and Shuster, D.L., 2014, The influence of burial heating on the (U-Th)/He system in apatite: Grand Canyon case study: Earth and Planetary Science Letters, v. 397, p. 174–183, https://doi.org/10.1016/j.epsl.2014.04.041.

Fox, M., Tripathy-Lang, A., Shuster, D.L., Winn, C., Karlstrom, K., and Kelley, S., 2017, Westernmost Grand Canyon incision: Testing thermochronometric resolution: Earth and Planetary Science Letters, v. 474, p. 248–256, https://doi.org/10.1016/j.epsl.2017.06.049.

Garvin, C.D., Hanks, T.C., Finkel, R.C., and Heimsath, A.M., 2005, Episodic incision of the Colorado River in Glen Canyon, Utah: Earth Surface Processes and Landforms, v. 30, p. 973–984, https://doi.org/10.1002/esp.1257.

Gehrels, G., and Pecha, M., 2014, Detrital zircon U-Pb geochronology and Hf isotope geochemistry of Paleozoic and Triassic passive margin strata of western North America: Geosphere, v. 10, p. 49–65, https://doi.org/10.1130/GES00889.1.

Gehrels, G.E., Valencia, V.A., and Ruiz, J., 2008, Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation–multicollector–inductively coupled plasma–mass spectrometry: Geochemistry Geophysics Geosystems, v. 9, Q03017, https://doi.org/10.1029/2007GC001805.

Gehrels, G., Giesler, D., Olsen, P., Kent, D., Marsh, A., Parker, W., Rasmussen, C., Mundil, R., Irmis, R., Geissman, J., and Lepre, C., 2020, LA-ICPMS U-Pb geochronology of detrital zircon grains from the Coconino, Moenkopi, and Chinle formations in the Petrified Forest National Park (Arizona): Geochronology, v. 2, p. 257–282, https://doi.org/10.5194/gchron-2-257-2020.

Hill, C.A., Polyak, V.J., Asmerom, Y., and Provencio, P.P., 2016, Constraints on a Late Cretaceous uplift, denudation, and incision of the Grand Canyon region, southwestern Colorado Plateau, USA, from U-Pb dating of lacustrine limestone: Tectonics, v. 35, p. 896–906, https://doi.org/10.1002/2016TC004166.

Karlstrom, K.E., and Bowring, S.A., 1988, Early Proterozoic assembly of tectonostratigraphic terranes in southwestern North America: The Journal of Geology, v. 96, p. 561–576, https://doi.org/10.1086/629252.

Karlstrom, K.E., Crow, R., Crossey, L.J., Coblentz, D., and Van Wijk, J.W., 2008, Model for tectonically driven incision of the younger than 6 Ma Grand Canyon: Geology, v. 36, p. 835–838, https://doi.org/10.1130/G25032A.1.

Karlstrom, K.E., Lee, J.P., Kelley, S.A., Crow, R.S., Crossey, L.J., Young, R.A., Lazear, G., Beard, L.S., Ricketts, J.W., Fox, M., and Shuster, D.L., 2014, Formation of the Grand Canyon 5 to 6 million years ago through integration of older palaeocanyons: Nature Geoscience, v. 7, p. 239–244, https://doi.org/10.1038/ngeo2065.

Karlstrom, K.E., Crossey, L.J., Embid, E., Crow, R., Heizler, M., Hereford, R., Beard, L.S., Ricketts, J.W., Cather, S., and Kelley, S., 2017, Cenozoic incision history of the Little Colorado River: Its role in carving Grand Canyon and onset of rapid incision in the past ca. 2 Ma in the Colorado River System: Geosphere, v. 13, p. 49–81, https://doi.org/10.1130/GES01304.1.

Karlstrom, K.E., Jacobson, C.A., Sundell, K.E., Eyster, A., Blakey, R., Ingersoll, R.V., Mulder, J.A., Young, R.A., Beard, L.S., Holland, M.E., Shuster, D.L., Winn, C., and Crossey, L., 2020, Evaluating the Shinumo-Sespe drainage connection: Arguments against the "old" (70–17 Ma) Grand Canyon models from Colorado Plateau drainage evolution: Geosphere, v. 16, p. 1425–1456, https://doi.org/10.1130/GES02265.1.

Kimbrough, D.L., Grove, M., Gehrels, G.E., Dorsey, R.J., Howard, K.A., Lovera, O., Aslan, A., House, P.K., and Pearthree, P.A., 2015, Detrital zircon U-Pb provenance of the Colorado River: A 5 m.y. record of incision into cover strata overlying the Colorado Plateau and adjacent regions: Geosphere, v. 11, p. 1719–1748, https://doi.org/10.1130/GES00982.1.

Kuiper, Y.D., 2002, The interpretation of inverse isochron diagrams in $^{40}Ar/^{39}Ar$ geochronology: Earth and Planetary Science Letters, v. 203, p. 499–506, https://doi.org/10.1016/S0012-821X(02)00833-6.

Lee, J.P., Stockli, D.F., Kelley, S.A., Pederson, J.L., Karlstrom, K.E., and Ehlers, T.A., 2013, New thermochronometric constraints on the Tertiary landscape evolution of central and eastern Grand Canyon, Arizona: Geosphere, v. 9, p. 216–228, https://doi.org/10.1130/GES00842.1.

Longwell, C.R., 1946, How old is the Colorado River?: American Journal of Science, v. 244, p. 817–835, https://doi.org/10.2475/ajs.244.12.817.

Lopez Pearce, J.C., 2010, Syntectonic deposition and paleohydrology of the spring-fed Hualapai Limestone and implications for 5–6 Ma integration of the Colorado River system through Grand Canyon: Evidence from sedimentology, geochemistry and detrital zircon analysis [M.S. thesis]: Albuquerque, University of New Mexico, 252 p.

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

Lucchitta, I., 1972, Early history of the Colorado River in the Basin and Range province: Geological Society of America Bulletin, v. 83, p. 1933–1948, https://doi.org/10.1130/0016-7606(1972)83[1933:EHOTCR]2.0.CO;2.

Lucchitta, I., 1975, The Shivwits Plateau, *in* Goetz, A.F.H., Billingsley, F.C., Gillespie, A.R., Abrams, M.J., Squires, R.L., Shoemaker, E.M., Lucchitta, I., and Elston, D.P., Application of ERTS Images and Image Processing to Regional Geologic Problems and Geologic Mapping in Northern Arizona: Jet Propulsion Laboratory Technical Report 32-1597, p. 41–72.

Lucchitta, I., 1984, Development of landscape in northwest Arizona: The country of plateaus and canyons, *in* Smiley, T.L., Nations, J.D., Péwé, T.L., and Schafer, J.P., eds., Landscapes of Arizona—The Geological Story: Lanham, Maryland, University Press of America, p. 269–301.

Lucchitta, I., 1989, History of the Grand Canyon and of the Colorado River in Arizona, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic Evolution of Arizona: Arizona Geological Society Digest 17, p. 701–715.

Lucchitta, I., and Jeanne, R.A., 2001, Geomorphic features and processes of the Shivwits Plateau, Arizona and their constraints on the age of western Grand Canyon, *in* Young, R.A., and Spamer, E.E., eds., Colorado River Origin and Evolution: Grand Canyon Association Monograph 12, p. 65–69.

Paces, J.B., and Miller, J.D., Jr., 1993, Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: Geochronological insights to physical, petrogenetic, paleomagnetic, and tectonomagmatic processes associated with the 1.1 Ga Midcontinent Rift System: Journal of Geophysical Research, v. 98, p. 13,997–14,013, https://doi.org/10.1029/93JB01159.

Pederson, J.L., Cragun, W.S., Hidy, A.J., Rittenour, T.M., and Gosse, J.C., 2013, Colorado River chronostratigraphy at Lee's Ferry, Arizona, and the Colorado Plateau bull's-eye of incision: Geology, v. 41, p. 427–430, https://doi.org/10.1130/G34051.1.

Reiners, P.W., Brady, R., Farley, K.A., Fryxell, J.E., Wernicke, B., and Lux, D., 2000, Helium and argon thermochronometry of the Gold Butte block, south Virgin Mountains, Nevada: Earth and Planetary Science Letters, v. 178, p. 315–326, https://doi.org/10.1016/S0012-821X(00)00080-7.

Sabbeth, L., Wernicke, B.P., Raub, T.D., Grover, J.A., Lander, E.B., and Kirschvink, J.L., 2019, Grand Canyon provenance for orthoquartzite clasts in the lower Miocene of coastal southern California: Geosphere, v. 15, p. 1973–1998, https://doi.org/10.1130/GES02111.1.

Seixas, G.B., Resor, P.G., Lopez-Pearce, J., Karlstrom, K.E., and Crossey, L.J., 2015, Constraints on the evolution of vertical deformation and Colorado River incision near eastern Lake Mead, Arizona, provided by quantitative structural mapping of the Hualapai Limestone: Geosphere, v. 11, p. 31–49, https://doi.org/10.1130/GES01096.1.

Sharman, G.R., Sharman, J.P., and Sylvester, Z., 2018, detritalPy: A Python-based toolset for visualizing and analysing detrital geo-thermochronologic data: The Depositional Record, v. 4, p. 202–215, https://doi.org/10.1002/dep2.45.

Spencer, J.E., Peters, L., McIntosh, W.C., and Patchett, P.J., 2001, $^{40}Ar/^{39}Ar$ geochronology of the Hualapai Limestone and Bouse Formation and implications for the age of the lower Colorado River, *in* Young, R.A., and Spamer, E.E., eds., Colorado River: Origin and Evolution: Grand Canyon Association Monograph 12, p. 89–91.

Spencer, J.E., Patchett, P.J., Pearthree, P.A., House, P.K., Sarna-Wojcicki, A.M., Wan, E., Roskowski, J.A., and Faulds, J.E., 2013, Review and analysis of the age and origin of the Pliocene Bouse Formation, lower Colorado River Valley, southwestern USA: Geosphere, v. 9, p. 444–459, https://doi.org/10.1130/GES00896.1.

Vermeesch, P., 2018, IsoplotR: A free and open toolbox for geochronology: Geoscience Frontiers, v. 9, p. 1479–1493.

Walk, C.J., Karlstrom, K.E., Crow, R.S., and Heizler, M.T., 2019, Birth and evolution of the Virgin River fluvial system: ~1 km of post–5 Ma uplift of the western Colorado Plateau: Geosphere, v. 15, p. 759–782, https://doi.org/10.1130/GES02019.1.

Wernicke, B., 2011, The California River and its role in carving Grand Canyon: Geological Society of America Bulletin, v. 123, p. 1288–1316, https://doi.org/10.1130/B30274.1.

Winn, C., Karlstrom, K.E., Shuster, D.L., Kelley, S., and Fox, M., 2017, 6 Ma age of carving Westernmost Grand Canyon: Reconciling geologic data with combined AFT, (U-Th)/He, and $^{4}He/^{3}He$ thermochronologic data: Earth and Planetary Science Letters, v. 474, p. 257–271, https://doi.org/10.1016/j.epsl.2017.06.051.

Young, R.A., 1987, Colorado Plateau landscape development during the Tertiary, *in* Graf, W.L., ed., Geomorphic Systems of North America: Boulder, Colorado, Geological Society of America, Geology of North America, Centennial Special Volume 2, p. 265–276.

Young, R.A., 2001, The Laramide–Paleogene history of the western Grand Canyon region: Setting the stage, *in* Young, R.A., and Spamer, E.E., eds., Colorado River Origin and Evolution: Grand Canyon Association Monograph 12, p. 7–16.

Young, R.A., and Crow, R., 2014, Paleogene Grand Canyon incompatible with Tertiary paleogeography and stratigraphy: Geosphere, v. 10, p. 664–679, https://doi.org/10.1130/GES00973.1.

Young, R.A., and Hartman, J.H., 2014, Paleogene rim gravel of Arizona: Age and significance of the Music Mountain Formation: Geosphere, v. 10, p. 870–891, https://doi.org/10.1130/GES00971.1.

Young, R.A., and McKee, E.H., 1978, Early and middle Cenozoic drainage and erosion in west-central Arizona: Geological Society of America Bulletin, v. 89, p. 1745–1750, https://doi.org/10.1130/0016-7606(1978)89<1745:EAMCDA>2.0.CO;2.