Reevaluation of the Crooked Ridge River—Early Pleistocene (ca. 2 Ma) age and origin of the White Mesa alluvium, northeastern Arizona

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ABSTRACT

Essential features of the previously named and described Miocene Crooked Ridge River in northeastern Arizona (USA) are reexamined using new geologic and geochronologic data. Previously it was proposed that Cenozoic alluvium at Crooked Ridge and southern White Mesa was pre–early Miocene, the product of a large, vigorous late Paleogene river draining the 35–23 Ma San Juan Mountains volcanic field of southwestern Colorado. The paleoriver probably breached the Kaibab uplift and was considered important in the early evolution of the Colorado River and Grand Canyon. In this paper, we reexamine the character and age of these Cenozoic deposits. The alluvial record originally used to propose the hypothetical paleoriver is best exposed on White Mesa, providing the informal name White Mesa alluvium. The alluvium is 20–50 m thick and is in the bedrock-bound White Mesa paleovalley system, which comprises 5 tributary paleochannels. Gravel composition, detrital zircon data, and paleochannel orientation indicate that sediment originated mainly from local Cretaceous bedrock north, northeast, and south of White Mesa. Sedimentologic and fossil evidence imply alluviation in a low-energy suspended sediment fluvial system with abundant fine-grained overbank deposits, indicating a local channel system rather than a vigorous braided river with distant headwaters. The alluvium contains exotic gravel clasts of Proterozoic basement and rare Oligocene volcanic clasts as well as Oligocene–Miocene detrital sandine related to multiple caldera eruptions of the San Juan Mountains and elsewhere. These exotic clasts and sandine likely came from ancient rivers draining the San Juan Mountains. However, in this paper we show that the White Mesa alluvium is early Pleistocene (ca. 2 Ma) rather than pre–early Miocene. Combined 40Ar/39Ar dating of an interbedded tuff and detrital sanidine ages show that the basal White Mesa alluvium was deposited at 1.993 ± 0.002 Ma, consistent with a detrital sanidine maximum depositional age of 2.02 ± 0.02 Ma. Geomorphic relations show that the White Mesa alluvium is older than inset gravels that are interbedded with 1.2–0.8 Ma Bishop–Glass Mountain tuff. The new ca. 2 Ma age for the White Mesa alluvium refutes the hypothesis of a large regional Miocene(?) Crooked Ridge paleoriver that predated carving of the Grand Canyon. Instead, White Mesa paleodrainage was the northernmost extension of the ancestral Little Colorado River drainage basin. This finding is important for understanding Colorado River evolution because it provides a datum for quantifying rapid post–2 Ma regional denudation of the Grand Canyon region.

INTRODUCTION

Cenozoic alluvium in a bedrock-bound paleovalley is perched on the Colorado Plateau in northeastern Arizona (USA) only 60 km east of the Grand Canyon (Fig. 1; Hereford et al., 2013). The paleovalley’s possible significance to carving of the Grand Canyon is emphasized by a southwest-descending slope toward the Grand Canyon and lag gravels derived from a distant source. This alignment points 300–400 km northeast, directly toward a possible source in the San Juan Mountains of southwestern Colorado, and lag gravels in the study area apparently support such an origin. Minor amounts of pebble to small cobble gravel in the alluvium are composed of Proterozoic basement and Oligocene volcanic rocks (Lucchitta et al., 2011, 2013, fig. 10, Tables 1 and 2) resembling those in the San Juan Mountains volcanic field (Lipman, 1989). The paleovalley is the topographically highest and therefore oldest geomorphic feature in this erosional landscape, suggesting substantial antiquity. These characteristics, i.e., proximity and slope toward the Grand Canyon, exotic gravels, and assumed antiquity, led workers to conclude that the paleovalley was formed by an ancient river, probably the combined ancestral San Juan and Animas Rivers, that drained the late Paleogene San Juan Mountains volcanic field (Cooley, 1960; Hunt, 1969; Stokes, 1973; Lucchitta et al., 2011, 2013). This
conceptual paleoriver, called the Crooked Ridge River by Lucchitta et al. (2011, 2013), was thought to be involved in the early carving of the Grand Canyon; overall the evolution of the canyon is a topic of debate (Karlstrom et al., 2012).

This paper is a reassessment of the hypothetical foundations of the Crooked Ridge paleoriver, i.e., its geomorphology, geology, depositional environment, sediment source, and age. These key elements of the paleoriver are examined using new (2013 and later) and unpublished data sets. The data include topical field mapping (Fig. 2), stratigraphy, sedimentology, pedogenesis, carbonate geochemistry, detrital zircon provenance, sanidine geochronology, and tephrochronology. Among our principal findings is that the alluvium and associated paleovalley system are younger than ca. 2 Ma and older than 1.2–0.8 Ma, based on 40Ar/39Ar dating of tuff and detrital sanidine and inset relations between dated geomorphic surfaces.

This young age at the base of the alluvium in the White Mesa–Crooked Ridge area poses insurmountable problems for earlier interpretations. The age also disallows any relation between the alluvium and the Crooked Ridge paleoriver, which Lucchitta et al. (2013, p. 1427, 1430) suggested was active during eruption of the 35–23 Ma San Juan Mountains volcanic field. Moreover, proposed correlation (Cooley et al., 1969; Hereford et al., 2013) of the alluvium with the mid-Miocene to late Pliocene Bidahochi Formation (Dallegge et al., 2003; Dickinson, 2013) seems impossible. Despite the exotic lag gravels, the presence of the ancestral San Juan River in the White Mesa–Crooked Ridge area after 2 Ma is unlikely based on the substantial elevation difference between the low-elevation mid-Pleistocene (Wolkowinsky and Granger, 2004) San Juan River and the relatively high elevation study area. This and other information reported herein motivate us to recommend abandonment of the term “Crooked Ridge River” as applied to early Pleistocene deposits in the study area. The age, geology, and geomorphology of these deposits are substantially different from those attributed to the Crooked Ridge paleoriver by Lucchitta et al. (2011, 2013).
The immediate study area extends 57 km northeast from The Gap, a wind gap in the Jurassic rocks of the Echo Cliffs monocline, to the north end of White Mesa encompassing all or parts of 12 7.5′ topographic quadrangle maps (Fig. 2). Additional localities were studied on northeast Black Mesa and Blue Point on the Moenkopi Plateau (Fig. 1). Deposits of the ca. 2 Ma alluvial system are preserved on Crooked Ridge and White Mesa. A narrow, sinuous ridge capped by lag gravel connects the Crooked Ridge and White Mesa outcrops. This is the Crooked Ridge of modern topographic maps and the geomorphic expression of the hypothetical Crooked Ridge paleoriver of Lucchitta et al. (2011, 2013). Examination by Lucchitta et al. (2011, 2013) of the Crooked Ridge outcrop, lag gravels northeast of the ridge, and gravel quarries on southern White Mesa provided the interpretive basis of the Crooked Ridge paleoriver.

Billingsley et al. (2012) mapped the alluvium at Crooked Ridge and southern White Mesa as “Pliocene? and Miocene? sedimentary deposits.” These deposits are informally referred to herein as the early Pleistocene White Mesa alluvium, which is represented by the characteristic and abundant outcrops on White Mesa. The ancient valley in which the alluvium was deposited is referred to as the early Pleistocene White Mesa paleovalley system within the larger White Mesa paleodrainage basin. Alluvium of similar age on the Moenkopi Plateau (Fig. 1) is within the paleodrainage basin and correlates with the White Mesa alluvium.

Workers were previously concerned mainly with the paleogeomorphic implications of lag gravels in the White Mesa-Crooked Ridge area, and did not describe the characteristics, composition, or extent of the White Mesa alluvium (Cooley, 1960; Hunt, 1969; Stokes, 1973; Lucchitta et al., 2013). Cooley et al. (1969) mapped (without the benefit of modern topographic maps) alluvium on White Mesa and correlated it with the Bidahochi Formation based on similar topographic positions in the landscape. Hunt (1969) referred to lag gravels on White Mesa as the Kaibito gravels and related them to a Miocene San Juan River. However, Cooley et al. (1969), Hunt (1969), and Stokes (1973)
evidently did not recognize the geologic and geomorphic connections among White Mesa, Crooked Ridge, and The Gap, that were first reported by Lucchitta et al. (2011). Cooley et al. (1969) considered Crooked Ridge geologically younger than White Mesa and did not discuss The Gap.

**LANDSCAPE-SCALE GEOMORPHOLOGY OF THE WHITE MESA PALEOVALLEY**

The study area is a structurally intact, discontinuous remnant of an early Pleistocene paleovalley system replete with alluvial fill and paleochannels that postdate initial carving of the nearby Grand Canyon. Northeastern Arizona in general and the study area in particular is a landscape of progressively lower and younger low-relief erosional geomorphic surfaces of broad extent. Earlier workers (cited in Cooley et al., 1969) recognized this pattern and related it to multiple cycles of regional downcutting alternating with non-deposition or alluvial aggradation. These are accordant surfaces of similar elevation forming mesas, plateaus, and pediments that are typically overlap lain by lag gravels or locally derived alluvium. Cooley et al. (1969, plate 3) correlated these surfaces using their relative elevation; numerical geochronology was unavailable at that time (1955). Whether the accordant surfaces are coeval everywhere is unknown, although our dating of tuff associated with the surfaces indicates that they are essentially contemporaneous in the study area.

The White Mesa paleovalley system occupies the highest and oldest terrain in a region extending over 150 km from north of the Moenkopi Plateau and northwest of Black Mesa to Navajo Mountain (Fig. 3A). A line of section drawn southwest of White Mesa (Fig. 3B) shows accordant surfaces at ~1800 m elevation on the Moenkopi Plateau, Middle Mesa, White Point, Crooked Ridge, and Paria Plateau east of Kaibab uplift. Cooley et al. (1969, plate 3) considered these higher surfaces in the study area to be the L2A erosional surface; the White Mesa alluvium underlies this surface. In the Cooley et al. (1969) model, the accordant surfaces and related deposits were parts of a regional landscape that existed mostly before the present canyons of the Colorado River system. However, the ca. 2 Ma White Mesa alluvium and the 1.99 Ma Blue Point tuff (Table 1; Fig. 1) on the Moenkopi Plateau demonstrate that the L2A surface is younger than initial carving of the Grand Canyon.

The main geomorphic features composing the base of the paleovalley from northeast to southwest are White Mesa, Crooked Ridge, composed of the Crooked Ridge lag gravels and the Crooked Ridge outcrop of White Mesa alluvium, and The Gap in the Echo Cliffs monocline (Fig. 2). White Mesa is a...
The topography of White Mesa and the Moenkopi Plateau is inverted in the sense that deposits once in the lowest parts of the landscape, an abandoned ancient stream channel and valley, are now preserved on the highest terrain as drainage divides and on top of mesas and plateaus (Fig. 3). White Mesa straddles the drainage divide between the Colorado and Little Colorado Rivers. The mesa drains to the Colorado River in Glen Canyon and is as much as 1 km above the base level at Lees Ferry, Arizona (Figs. 1 and 3B). On the Little Colorado River side of the drainage divide, Begashibito Wash (a tributary of Moenkopi Wash; Figs. 1 and 2) drains the mesa, and Begashibito headwaters adjoin the San Juan River drainage basin 39 km east of the northeast end of White Mesa. The mesa is 0.9 km above the junction of Moenkopi Wash near the head of the Little Colorado River Gorge knickzone (Cook et al., 2009) that formed in resistant Paleozoic bedrock downstream of Cameron, Arizona.

Relative to the Colorado River in the Grand Canyon, White Mesa is 1.4 km above the junction of the Little Colorado and Colorado Rivers (Fig. 1) and is 1 km above the junction of the Colorado and San Juan Rivers. This inversion was accomplished by regional denudation after deposition of the White Mesa alluvium ca. 2 Ma. Denudation is related to capture of the northern Little Colorado River drainage basin by the San Juan and Colorado Rivers, whose drainage divides have shifted south and east.

### TABLE 1. KEY LOCALITIES MENTIONED IN THE TEXT

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†Detrital sanidine sample locality.

†Datum World Geodetic System 1984.

19-km-long remnant of the paleovalley system, consisting of a northern and southern portion, incised through the Dakota Sandstone (upper Cretaceous) into the underlying Entrada Sandstone (Jurassic).

The topography of White Mesa and the Moenkopi Plateau is inverted in the sense that deposits once in the lowest parts of the landscape, an abandoned ancient stream channel and valley, are now preserved on the highest terrain as drainage divides and on top of mesas and plateaus (Fig. 3). White Mesa straddles the drainage divide between the Colorado and Little Colorado Rivers. The mesa drains to the Colorado River in Glen Canyon and is as much as 1 km above the base level at Lees Ferry, Arizona (Figs. 1 and 3B). On the Little Colorado River side of the drainage divide, Begashibito Wash (a tributary of Moenkopi Wash; Figs. 1 and 2) drains the mesa, and Begashibito headwaters adjoin the San Juan River drainage basin 39 km east of the northeast end of White Mesa. The mesa is 0.9 km above the junction of Moenkopi Wash near the head of the Little Colorado River Gorge knickzone (Cook et al., 2009) that formed in resistant Paleozoic bedrock downstream of Cameron, Arizona.

Relative to the Colorado River in the Grand Canyon, White Mesa is 1.4 km above the junction of the Little Colorado and Colorado Rivers (Fig. 1) and is 1 km above the junction of the Colorado and San Juan Rivers. This inversion was accomplished by regional denudation after deposition of the White Mesa alluvium ca. 2 Ma. Denudation is related to capture of the northern Little Colorado River drainage basin by the San Juan and Colorado Rivers, whose drainage divides have shifted south and east.
The 26-km-long sinuous Crooked Ridge connects the White Mesa paleo-valley with the Crooked Ridge outcrop (Fig. 2). The outcrop is 11 km long and both ridge and outcrop are above the surrounding topography with ~100 m of inverted relief. The Gap is the southwestern terminus of the paleo-valley. Lag gravels at The Gap overlying Navajo Sandstone (Jurassic) are ~1 m thick with pebbles and small cobbles of Cretaceous sandstone and exotic clasts of quartzite, other Proterozoic metamorphics, and rare Proterozoic granite. Assuming that the alluvium was 50 m thick (the maximum observed in the study area) at The Gap, the elevation at the top of the alluvium was 1740 m and the width at The Gap was ~2.6 km (Fig. 4A), although the present width of The Gap is likely increased by subsequent wind deflation and fluvial erosion. Just southwest of the study area, the Red Dot Hills compose a topographic and structural barrier composed of the east-dipping resistant sandstone of the Shinarump Member of the Triassic Chinle Formation (Fig. 2). The barrier precluded a direct south-westward path to the Grand Canyon, as indicated by the absence of beveled bedrock surfaces; it is more likely that the paleo-valley followed the north-south strike of the Echo Cliffs monocline.

The margins of the paleo-valley in the Crooked Ridge area are not well defined. Nonetheless, Lucchitta et al. (2013) suggested that a paleo-valley here was 15 km wide and >1 km deep. The Mormon Ridges and Preston Mesa bound Crooked Ridge on the north and south (Fig. 2). A topographic cross section drawn from White Point over Preston Mesa and northwest across Crooked Ridge to the Mormon Ridges broadly resembles the profile of a valley (Fig. 4B). However, the resemblance is superficial because the valley-like profile between the slope of Preston Mesa and the Mormon Ridges is below the 1790 m elevation of Crooked Ridge, showing that before topographic inversion the ancient valley bottom was higher and the valley narrower. Subsequent erosion modified the cross-valley profile, making it difficult to estimate the width of the paleo-valley. It is likely that the paleo-valley north of Preston Mesa was no wider than the southern White Mesa paleo-valley (Fig. 5). The maximum depth of the paleo-valley from the summit of Preston Mesa to the top of Crooked Ridge is 250 m. Although an older paleoriver could have carved a deep canyon from Preston Mesa to and through The Gap, no evidence of it was found in the present topography, and the White Mesa alluvium is substantially younger than the hypothetical paleocanyon of Lucchitta et al. (2013).

In the headwaters of Kaibito Creek (Fig. 5), the mostly uneroded margins of the paleo-valley are well preserved. The northwest-facing side of the paleo-valley is particularly evident at the heads of the west to west-northwest–flowing tributaries of Kaibito Creek. Here, the Dakota and Entrada Sandstones form the steep bedrock margin of the paleo-valley that rises 70–100 m above the top of the alluvium. On northernmost White Mesa, erosion related to topographic inversion has removed the formerly elevated southeast-facing margin of the paleo-valley. Square Butte (Fig. 2), however, remains as

Figure 4. (A) Topographic profile (A–A′, Fig. 2) on crest of Echo Cliffs, an east-dipping monocline, showing reconstructed width of paleochannel at The Gap. V.E.—vertical exaggeration. (B) Profile (B–B′, Fig. 2) showing gravel-capped Crooked Ridge and paleo-valley between Preston Mesa and the Mormon Ridges. White Point is a pediment and L2A surface of Cooley et al. (1969). U—upthrown; D—downthrown.
an isolated and elevated erosional remnant of the southeast-facing valley margin. On southern White Mesa, the northwest- and southeast-facing valley margins are also missing due to erosion related to topographic inversion. The alluvium onlaps Entrada Sandstone at the northwest side of southern White Mesa paleovalley, which is near the inferred margin of the paleovalley (Fig. 5). Three inselbergs with steep slopes of Entrada Sandstone capped by ledge-forming Dakota Sandstone are evidence of a former valley that was roughly parallel with the southeast face of northern White Mesa (Table 1, site 6).

The paleovalley gradient is useful for estimating the elevation of the headwaters of the paleodrainage north and northeast of White Mesa that were removed by post–2 Ma denudation. The gradient was determined from 4 control points placed from The Gap to northeast White Mesa (Fig. 2), a distance of 57 km. The control points are at or within 2–3 m of the base of the alluvium. The gradient of the paleovalley was estimated from the slopes of the six possible combinations of the 4 control points; the median slope is 0.0067, or ~0.007. The gradient profile connecting the four points shows no substantial knickzones or deviations from the median gradient. The study area was likely affected by isostatic rebound related to late Miocene to Pliocene regional denudation that continues to the present (Hoffman, 2009; Pederson et al., 2013; Lazear et al., 2013). In the Monument upwarp area (Fig. 1), denudation is 1–2 km. The study area is on the southern flanks of the uplifted area.

The San Juan River almost certainly did not cross the high-elevation terrain of the White Mesa–Crooked Ridge area after ca. 2 Ma. The San Juan at Bluff, Utah (Fig. 1), was in its present course 140 m above the active channel (elevation 1320 m) at 1.36 (+0.2/-0.15) Ma (Wolkowinsky and Granger, 2004). This elevation is substantially below the northeast terminus of the paleovalley at

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**Figure 5.** Topical geologic map of White Mesa area showing tributary paleochannels entering southern White Mesa paleovalley. Northeast (NE) paleochannel 3 and south paleochannel contain exotic gravel clasts, whereas others have clasts composed primarily of upper Cretaceous sandstone. Basal contact of Entrada Sandstone is not mapped. Contact of alluvium with bedrock is dashed where covered.
northeast White Mesa. Here the top of the alluvium is 2124 m (Table 1, site 3), 800 m above the San Juan River locality and well above all intervening topography, including most of Skeleton Mesa and all of Monument Valley (Fig. 1). The minimum height above the San Juan River increases to ~1.8 km by projecting the linear slope of the paleovalley along a northeast trend. Whether the incision was 800 m or 1.8 km, the estimated mid-Pleistocene incision rate at Bluff (110 m/m.y.; Wolkowinsky and Granger, 2004) is too low to accommodate this much downcutting in ~2 m.y.

**GEOLGY OF THE WHITE MESA ALLUVIUM**

Here we describe and interpret the stratigraphy and depositional environment of the alluvium, the source of gravel in the alluvium, tributary paleo-channels of the White Mesa paleovalley that point toward sediment sources, and the paleohydrology of the alluvium based on carbonate geochemistry. New topical geologic mapping identifies the early Pleistocene White Mesa alluvium and documents its presence on White Mesa and Crooked Ridge (Fig. 2). The most informative and abundant outcrops are on White Mesa (Fig. 5), which is considered the area most characteristic of the alluvium. On White Mesa and most of Crooked Ridge, the alluvium is generally not well exposed and is difficult to measure and describe without motorized mechanical excavation, which is precluded by logistics and cultural considerations. Outcrops at most localities are blanketed by younger eolian sand; slope weathering obscures stratification, and even where well exposed, sedimentary structures in the sands are rare to absent possibly due to bioturbation or diagenetic alteration. These conditions preclude meaningful paleocurrent analysis. The stratigraphic sections described and illustrated here are among the few in which the alluvium is adequately exposed (Fig. 6).

**Stratigraphy and Depositional Environment**

The White Mesa alluvium ranges in thickness from 20 to >50 m, and is typically 30–35 m thick. On White Mesa, the alluvium overlies the Navajo and Entrada Sandstones. Downstream of the Red Lake monocline to The Gap (Fig. 2), the alluvium overlies Navajo Sandstone. The bulk of the White Mesa alluvium is very poorly sorted clayey sand and interbedded clay; gravel beds are subordinate. Four stratigraphic units are present: discontinuous basal gravel, a lateral accretion clay-sand unit present only at Crooked Ridge, an interbedded clay and very fine grained sand unit, and a prominent ledge-forming petrocalcic soil at the top of the alluvium found only at Crooked Ridge (Fig. 6; Supplemental File 1). The interbedded clay and very fine grained sand unit is present throughout the area and is typical of the alluvium.

The basal gravel is 0–9 m thick. At Crooked Ridge (Fig. 7A) and where present on White Mesa, the gravel has an immature appearance consisting mainly of subangular to subrounded clasts of sandstone supported in a coarse sand matrix. The clasts are pebbles to small cobbles of poorly sorted coarse-grained to pebbly pale yellowish sandstone derived from the Dakota Sandstone and pale red clasts of Navajo Sandstone. Rare metamorphic, igneous, and volcanic clasts of presumed San Juan Mountains origin are also present in the basal gravel at Crooked Ridge and on southern White Mesa (Table 1; Lucchitta et al., 2011, 2013).

The lateral accretion clay-sand unit at Crooked Ridge consists of poorly sorted sand displaying lateral accretion surfaces, channel forms, and overbank fines (Fig. 6). Lateral accretion surfaces are prominent sigmoidal-shaped features in the cross-stratified sands. The lateral accretion unit overlies and appears to crosscut the interbedded clay unit (Fig. 7B), although several beds in the lateral accretion unit resemble those of the interbedded clay and very fine grained sand unit, suggesting that they could interfere. No evidence of weathering, strong soil development, or other indicators of a hiatus are present at the contact, although a thin (10 cm thick), soft carbonate horizon underlies the contact. The lateral accretion unit has not been found on White Mesa.

Throughout the area, the interbedded clay and very fine grained sand unit shows multiple beds of poorly sorted sand overlain by silty clays with subhorizontal (or horizontal) stratification extending continuously across the outcrop (Fig. 7C). The sands are clayey and have distinctive pale grayish shades of green, red, and yellow with subtle motting and a sharp contact with underlying beds. Motting and low chroma values likely result from reduced iron minerals (gleization) related to accumulations of organic matter and locally shallow water tables in near-floodplain sediment (Kraus, 1997). Clay beds overlie the sand beds along a contact that is typically gradational, suggesting that they are forming-upward couplets or cycles. The couplets probably represent individual episodes of channel and floodplain aggradation. Clays are light olive-gray (5Y 5/2) with a pale greenish cast resembling the color of the Mancos Shale (upper Cretaceous), which was the likely source of the clays. These fine-grained sand and clay deposits are the defining characteristic of the White Mesa alluvium. The continuity of stratification, multiple fining-upward cycles, and poorly sorted sands suggest deposition in a multistory, relatively low energy suspended sediment aggradational channel system within a bedrock-bound paleovalley (Miall, 2010).

Fossil evidence also supports the interpretation of a low-energy fluvial environment. Thin, essentially contemporaneous marker beds of light colored platy limestone containing small, 1–5-mm-diameter thin-walled gastropods are present 2–3 m above the base of the alluvium at widely spaced localities on Crooked Ridge and southern White Mesa (Table 1, sites 10 and 12). The limestones are 5–15 cm thick, of limited area (<10 ha), and are intercalated with clay beds of the interbedded clay and very fine grained sand unit. At the southern White Mesa outcrop, two limestone beds are present separated by 2 m of clay. The specimens are too poorly preserved for identification beyond family level (C. Powell II, 2014, personal commun.), which is Gastropoda Family Lymnaeidae. This taxon has a fossil record going back to the Mesozoic, so it cannot date the alluvium. However, the ecology is well known; the taxon lives in ponds, lakes, or slow-moving streams. A lake or marsh-like environment is favored based on the fine-grained platy character of the limestone.

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*Supplemental File 1. Petrocalcic layer. Please visit http://dx.doi.org/10.1130/GEOS124.51 or the full-text article on www.gsapubs.org to view Supplemental File 1.
This fossil evidence and the sedimentologic characteristics of the alluvium do not support and are inconsistent with the vigorous braided stream model of the Crooked Ridge paleoriver (Lucchitta et al., 2011, 2013).

**Gravel Beds**

Gravel beds are subordinate to the beds of fine-grained sediment in the White Mesa alluvium. A gravel bed 1–2 m thick is typically present at the top of the alluvium. Hillslopes below this gravel are typically covered with clasts derived from the upper gravel; this exaggerates the amount of gravel in the alluvium. Gravel beds as thick as several meters are present within the interbedded clay and very fine-grained sand unit, but are discontinuous and typically not traceable beyond several hundred meters. Gravel in the alluvium generally has a matrix-supported fabric. Regardless of stratigraphic position, the gravels appear texturally immature with abundant coarse sand matrix and numerous subangular to subrounded clasts (Fig. 7A). Their lateral discontinuity and immature texture suggest that the gravel beds were not deposited by a large and energetic fluvial system.

**EXPLANATION**

- **DZ**: Detrital zircon and sanidine, DS
- **..** Lateral accretion surface
- **w** Calcareous horizon, 10-20 cm thick
- **k** Petrocalcic layer
- **≥** Carbonate nodules
- **Clay, dense**
- **Clay, interbedded silt and sand**
- **Sand, very fine to medium, poorly sorted, clay drapes, lateral accretion surfaces**
- **Sand, very fine to fine, poorly sorted, massive**
- **Sand, medium to coarse, cross stratified**
- **Gravel, granule to cobble, sandy**

Figure 6. Stratigraphic correlation of White Mesa alluvium, Crooked Ridge to northern White Mesa (Fig. 2). Green is petrocalcic layer. NE—northeast paleochannel.
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**Figure 7. Units of White Mesa alluvium at Crooked Ridge and southern White Mesa paleovalley (Fig. 2).**

(A) Basal gravel units at Crooked Ridge (Table 1, site 1). Gravel is 9 m thick and consists of two subunits distinguished by sand content and clast size. Pale reddish cobbles and small boulders are local bedrock of Navajo Sandstone; pale yellowish clasts are Cretaceous sandstone. Rare, exotic subrounded pebbles and small cobbles composed of quartzite; other metamorphics, igneous, and volcanic rock (Lucchitta et al., 2011, 2013) are present.

(B) Crooked Ridge outcrop showing main stratigraphic units of White Mesa alluvium above basal gravel and contacts between units (Table 1, site 1). Stratigraphic units: 1—interbedded clay and very fine grained sand unit (dashed line); 2—lateral accretion clay sand unit; 3—petrocalcic layer (solid line). Bedforms: LA—lateral accretion; CH—channel; FF—overbank fines. Note lack of channeling in the interbedded clay and sandy very fine grained unit. LA corresponds to area in figures 4 and 7 of Lucchitta et al. (2011, 2013).

(C) Exposure of interbedded clay and very fine grained sand unit, southern White Mesa paleovalley (lat 36.50634, long –111.05634; World Geodetic System 1984). Numbers refer to four coarse to fine couplets, each bound by sharp contacts (solid line) consisting of very poorly sorted fine-grained sand overlain gradationally (dashed line) by dense to fissile clay. Basal coarse sand and gravel unit is present; note continuity of stratification.
Where gravel is present, whether at the base, middle, or upper portions of the alluvium, pebbles, cobbles, and large boulders derived from Cretaceous sandstone predominate. For the most part, these clasts resemble the Dakota Sandstone as described by Repenning and Page (1956). They are very pale orange (10YR 7/2) to pale yellowish-orange (10 YR 8/6) sandstone with fine-to-medium-grained clear and stained quartz grains, and common black accessory minerals. Iron-rich concretions are abundant in Dakota Sandstone outcrops; they occur in the gravels as irregularly shaped pebbles with rounded corners. The Mesaverde Group (upper Cretaceous), 210 m above the top of the Dakota Sandstone (Nations et al., 1995), has two ledge-forming sandstones (Toreva Formation and Yale Point Sandstone) that are possible sources of gravel in the White Mesa alluvium. Clasts of Mesaverde Group sandstones have not been found in gravels of the White Mesa alluvium, although Lucchitta et al. (2013) suggested that they may be present. Bedrock older than the Navajo Sandstone was likely not exposed along the upstream course of the paleovalley, as inferred from the projected gradient of the alluvium and 1:250,000-scale structure contour maps (O’Sullivan and Beikman, 1963; Haynes et al., 1972; Hackman and Wyant, 1973; Haynes and Hackman, 1978; Ulrich et al., 1984; Dillinger, 1990).

In the White Mesa area, boulder trains several hundred meters long are aligned with bedrock margins of the paleovalley. Well-exposed boulder alignments occur in the west- to west-northwest–flowing headwater drainages of Kaibito Creek below the Dakota Sandstone rim rock (Fig. 5). Boulders of Dakota Sandstone and less commonly Entrada Sandstone to 1–2 m on an edge form the boulder trains. Some of the Dakota Sandstone boulders contain *Gyrphaea newberryi* derived from an oyster-rich bed present regionally at the top of the Dakota Sandstone and in the basal 15 m of the overlying 210-m-thick Mancos Shale (Repenning and Page, 1956; Nations et al., 1995). Preserved outcrops of the Mancos Shale on White Mesa are too thin and discontinuous to map; how much of the shale was present on top of this portion of White Mesa is speculative. Hillslopes of shale above the paleovalley were present, and they probably had the characteristic dendritic drainage pattern of the Mancos Shale. The height of these hills was probably less than the thickness of the Mancos Shale, because sandstone boulders of Toreva and Yale Point formations are absent in the boulder trains, which suggests that these sandstone formations were not present on White Mesa.

Exotic clasts of quartzite, other metamorphic rocks, and volcanics in gravel beds of the White Mesa alluvium typically have distinctive shapes and surface features (Fig. 8). The clasts generally have multiple facets, unsmoothed reentrants, jagged cracks, rough uneven surfaces, and a variety of odd and asymmetric shapes. As much as 90% of pebbles and small cobbles in the White Mesa alluvium display these features along with distinctly nonellipsoidal shapes. In contrast, approximately one-third of such clasts from late Pleistocene deposits of the San Juan River near and upstream of Bluff, Utah, have rounded facets and somewhat irregular shapes. Most San Juan River clasts appear approximately ellipsoidal, which is the usual shape of clastic sedimentary particles (Cui and Komar, 1984). Peterson (1979) described fac-

![Figure 8. Randomly chosen gravel clasts of White Mesa alluvium and late Pleistocene gravels of San Juan River. (A) Pebbles and small cobbles from northeast paleochannel 3. (B) Cobbles from Pleistocene gravel of San Juan River in Four Corners area (Fig. 1). Labels: r—rough and pitted surface; s—asymmetric nonellipsoidal shape; f—rounded facet; fm—two or more rounded facets. Surfaces features and shape of gravel clasts in White Mesa alluvium differ substantially from those of San Juan River.](image)
Tributary Paleochannels

We describe here the composition of gravel clasts in tributary paleochannels present on White Mesa from which the source of the gravel and the direction of the source from White Mesa are inferred. Five paleochannels are exposed around and just below the rim of the mesa; these converge to form the 5–6-km-wide southern White Mesa paleovalley (Fig. 5; Table 1, sites 4–8). Three of the paleochannels combine on southern White Mesa from the northeast (clockwise from 1 to 3), another from the north, and another from the south. The defining characteristic of the paleochannels is the shape of the contact between bedrock and alluvium. In cross section, the contact forms the perimeter of a spatially restricted flat-floored channel-like feature with subvertical walls incised into bedrock of the Navajo, Entrada, or Dakota Sandstones. Paleochannels range from 10 to 40 m deep and 150 to >500 m wide (Fig. 9). Above the upper margin of the paleochannels, the contact is on a spatially extensive, low relief slightly undulating erosional surface; this configuration accounts for essentially all of the mapped contact between alluvium and bedrock. Deposition of the alluvium began in these paleochannels; sediment eventually filled and then overtopped the paleochannels, resulting in widespread deposition over the adjoining low-relief bedrock surface. At Crooked Ridge, the alluvium occupies and overtops a steep-walled paleochannel 15–20 m deep and several hundred meters wide incised into Navajo Sandstone.

Clast composition of gravel differs among the White Mesa paleochannels, reflecting subbasins of the paleodrainage. Clasts in the basal gravel of the north paleochannel (Table 1; Fig. 5), which is 220 m wide, are almost entirely angular to subangular Cretaceous sandstone and rare quartzite (a single quartzite clast was found); no volcanics are present. Gravel beds in northeast paleochannel 1 (Fig. 6), which has a preserved width of >500 m within the estimated 5-km-wide northern White Mesa paleovalley, contain abundant Cretaceous sandstone clasts and quartzite cobbles; one small cobble of irregularly shaped porphyry of unknown origin was found. Composition of clasts in these two paleochannels suggests a source terrain of mainly Cretaceous strata. Northeast paleochannel 2 lacks alluvium along the southeast-facing rim of White Mesa, but three inselbergs in the area define the margins of a former channel (Fig. 5).

Gravel at the top of the alluvium of northeast paleochannel 3 (Fig. 6) contains abundant clasts derived from Cretaceous sandstones, minor amounts of quartzite, other metamorphic clasts, and a variety of volcanic clasts, along with dark colored coarsely crystalline petrified wood. The exotic volcanic clasts in northeast paleochannel 3 include several varieties identical to those illustrated by Lucchitta et al. (2013). In addition, this paleochannel and south paleochannel contain distinctive rounded pebbles of carbonate cemented feldspathic sandstone that is also present at both quarries. A thin sandstone bed petrographically similar to the feldspathic sandstone clasts is present on Black Mesa (Fig. 1; Table 1, sites 13 and 14). Northeast paleochannel 3 evidently drained a terrain composed largely of Cretaceous strata that in turn was apparently overlain by late Paleogene to Neogene sedimentary deposits containing detritus composed of feldspathic sandstone, quartzite, other metamorphics, and volcanics originally derived from the San Juan Mountains and elsewhere.

The south paleochannel on the southern rim of White Mesa (Fig. 9) has two gravel beds containing rare volcanic clasts similar to those described at Crooked Ridge and the White Mesa quarries by Lucchitta et al. (2013), along with the usual Cretaceous sandstone and quartzite clasts. At 150 m, this paleochannel is the narrowest of the 5, suggesting it had a relatively short reach. The south paleochannel was probably not a minor reentrant in White Mesa paleovalley. Although relatively narrow, preserved deposits in the paleochannel extend 550 m south-southeast of the exposed subvertical walls of the paleochannel, where they are truncated by the southeast-facing escarpment of White Mesa. Moreover, flow in the south paleochannel was most probably not to the south, as this would require that White Mesa paleovalley had two outlets, one to the south and another much larger outlet draining to the southwest toward Crooked Ridge and The Gap. Two outlets require a drainage divide to split the southern White Mesa paleovalley, but no evidence of a divide is present in the flat low-relief paleovalley.
Paleohydrology

The paleohydrology of the White Mesa alluvium is inferred from the previously described fossiliferous limestones using carbon and oxygen isotopic data. These data are compared in Figure 10 with groundwater carbonates of the Bidahochi Formation, Cape Solitude on the east rim of the Grand Canyon (Fig. 1), and the modern Colorado River. The ponded conditions indicated by the ecology of the gastropods reflect times of groundwater saturation on the floodplain of the White Mesa alluvial system. The Bidahochi carbonates differ from the carbonates in the White Mesa alluvium; this seems reasonable based on detrital zircon data (described herein). The Cape Solitude carbonate developed within the uppermost Permian Kaibab Limestone on top of the rim of the canyon. Scarborough (2001) interpreted the origin of the carbonate as groundwater rather than pedogenic. The isotopic chemistry of the limestone at Crooked Ridge and White Mesa is essentially identical with that of the carbonates at Cape Solitude. Perhaps most important, the White Mesa carbonates differ substantially from the carbonate geochemistry of the Colorado River. Recharge of the Colorado River is from high-elevation snowmelt in the southern Rocky Mountains. This implies that groundwater from runoff during deposition of the White Mesa alluvium had a distinct, relatively low elevation source that differed from snowmelt runoff of the Rocky Mountains.

DETRITAL ZIRCON PROVENANCE

Here we use detrital zircon data to explore the provenance of early Pleistocene and Neogene sedimentary deposits in the study region (Supplemental File 2*). Zircon data from the White Mesa alluvium, the fluvial member of the Bidahochi Formation, and the largely eolian Chuska Sandstone (Oligocene) were analyzed and compared with zircons of the modern San Juan and Little Colorado Rivers (Fig. 1). The samples were analyzed using standard techniques (described online at AZ Laserchron Publication Tools, www.laserchron.org).

Five detrital zircon samples of the White Mesa alluvium were collected at four localities (Fig. 2); four were from the base and one was from the upper one-third of the alluvium (Fig. 6). Different samples of White Mesa alluvium yield variable detrital zircon populations that do not correlate closely with each other (Table 2; Fig. 11). Nevertheless, 14 of 20 sample pairs (70%) yield P (probability) values from Kolmogorov-Smirnov (K-S) analysis of >0.05, implying with >95% confidence that zircon in each sample pair could have been selected at random from the same parent population.

The provenances of young sedimentary assemblages of the southern Colorado Plateau (Table 3; Fig. 12) are not closely related (P = 0.000–0.007). Notably, the provenance of the White Mesa alluvium is not closely related (P = 0.007) to the Bidahochi Formation and modern Little Colorado River. An exception is the close pairing of detrital zircon populations in the modern Little Colorado River with late Miocene (ca. 6 Ma or younger) fluvial strata of the Bidahochi Formation (P = 0.89). This relationship is expected because both Bidahochi samples were collected near Chambers, Arizona (Fig. 1) in the Rio Puerco paleovalley (Dickinson, 2013), and the modern Rio Puerco enters the Little Colorado River upstream of the Little Colorado sampling sites near Winslow and Cameron (Kimbrough et al., 2015). Five Bidahochi Formation grains (4% of the total) are younger than 84 Ma, whereas the modern Little Colorado contains no grains that young. This difference evidently did not markedly influence K-S statistics, thereby showing the imprecision of K-S analysis for subtle details of grain populations.

The detrital zircon age population of the Oligocene Chuska Sandstone (Dickinson et al., 2010) differs significantly by K-S analysis (P = 0) from those of both Miocene or Pliocene and modern assemblages of the southern Colorado Plateau (Table 3), which suggest to us that Chuska sources made only a subordinate contribution to White Mesa alluvium. The only grains younger than 75 Ma in any Chuska Sandstone samples are 6 grains dating to 28–26 Ma (weighted mean 27 ± 1 Ma at 2o) from uppermost Chuska at Roof Butte in the northern Chuska Mountains (Fig. 1). The grains represent 6% of the detrital zircons at Roof Butte, but only 1.5% of the total Chuska detrital zircon population. A cluster of 4 detrital zircons in the White Mesa alluvium date to 29–27 Ma (weighted mean 28 ± 2 Ma at 2o); however, they occur jointly with 9 younger detrital zircons and an older cluster of 5 detrital zircons at 36–31 Ma (weighted mean 33 ± 3 Ma at 2o).
### TABLE 2. PROBABILITY VALUES FROM STATISTICAL KOLMOGOROV-SMIRNOFF ANALYSIS OF U-Pb AGES FOR DETRITAL ZIRCON POPULATIONS IN FIVE SANDSTONE SAMPLES FROM THE WHITE MESA ALLUVIUM

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<td>P values from K-S analysis without errors in the cumulative distribution function</td>
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**Note:** K-S—Kolmogorov-Smirnoff; P—probability. See text Figure 11. Samples are listed from upstream to downstream except that RP-AZ-1 and RP-AZ-2 are in the same stratigraphic section. Where P > 0.05 (bold numbers) there is <95% confidence that 2 zircon age populations were not derived by random grain selection from the same parent population. Dash indicates 1.0.

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**Figure 11.** Normative probability plots of U-Pb ages for detrital zircon populations in five samples of White Mesa alluvium (Fig. 2) arranged from upstream (top) to downstream (bottom). Prominent age peaks are labeled to the nearest 5 m.y. and minor grains older than 2000 Ma (5% of total) in U-Pb age are omitted from plots. N—number of samples; n—total number of detrital zircon grains. (For data, see Supplemental File 2.)
TABLE 3. PROBABILITY VALUES FROM STATISTICAL KOLMOGOROV-SMIRNOFF ANALYSIS OF U-Pb AGES FOR DETRITAL ZIRCON POPULATIONS IN SAND AND SANDSTONE SAMPLES

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<th>Chuska</th>
<th>Bidahochi</th>
<th>Little Colorado</th>
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<td>–</td>
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<tr>
<td>Little Colorado</td>
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<td>0.036</td>
<td>0</td>
<td>0.686</td>
<td>–</td>
</tr>
<tr>
<td>P values from K-S analysis without errors in the cumulative distribution function</td>
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<td>Little Colorado</td>
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<td>0.027</td>
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Note: K-S—Kolmogorov-Smirnoff; P—probability. See text Figure 12. Samples are from 5 Cenozoic depositional suites of northern Arizona and southern Utah, including the White Mesa alluvium (WMA); where P > 0.05 (bold numbers) there is <95% confidence that 2 zircon age populations were not derived by random grain selection from the same parent population. WM-CR—White Mesa–Crooked Ridge. Dash indicates 1.0.

Figure 12. Normative probability plots of U-Pb ages for detrital zircon populations in two samples of modern rivers and three samples of Oligocene–Miocene sedimentary strata of southern Colorado Plateau (Fig. 1). Data for San Juan and Little Colorado Rivers and Bidahochi Formation are in Kimbrough et al. (2015); Chuska Sandstone data are in Dickinson et al. (2014). Explanation as in Figure 11 (4% of grains older than 2000 Ma omitted from plots). N—number of samples; n—total number of detrital zircon grains. Note the lack of 35–23 Ma grains from San Juan Mountains volcanic field in San Juan River plot.
K-S congruence for the White Mesa alluvium and the modern San Juan River (Table 3) indicates that the two populations are statistically different (P = 0.005). Notable in the modern San Juan is the lack of any grains younger than 35 Ma derived from the San Juan Mountains volcanic field. Several other differences are also interesting: a prominent San Juan River age peak ca. 65 Ma that is nearly absent from the White Mesa alluvium curve; a prominent age peak ca. 95 Ma that is much reduced for the San Juan River curve; a composite 175–145 Ma age peak on the San Juan River curve (crest at 160 Ma) that is represented by only a narrow 170 Ma peak on the alluvium curve; and a Grenville peak (ca. 1060 Ma) in the alluvium more prominent than and displaced in age from San Juan River Grenville peaks (Fig. 11).

Age peaks reflecting southwest Laurentian basement are present in all southern plateau Cenozoic assemblages (Fig. 12). Yavapai (1.8–1.7 Ga) and Mazatzal (1.7–1.6 Ga) province rocks are represented by the 1720–1675 Ma zircon, and 1445–1425 Ma grains are from younger anorogenic plutons intrusive into both provinces. These grains are not diagnostic of provenance, as Colorado Plateau basement was exposed during the Cenozoic in the Mogollon highlands to the south and parts of the Colorado Rockies to the north, and reworking of those detrital zircons from Phanerozoic strata of the Colorado Plateau is likely. Oligocene (30–25 Ma) age peaks in the Neogene and Quaternary sedimentary formations may derive initially from the volcanic fields of the San Juan Mountains to the northeast or secondarily from the Mogollon-Datil field to the southeast; however, low precision of the detrital zircon data do not allow quantitative distinction between these volcanic fields and perhaps those of the Basin and Range.

Detrital zircon U-Pb ages loosely constrain the maximum age of the White Mesa alluvium to no older than early to mid-Miocene, i.e., after ca. 20–15 Ma. The youngest single detrital zircon grain from the White Mesa alluvium has an age of 15 ± 4 Ma (see Supplemental File 2). The youngest 4 grains that overlap in age at 1σ have a weighted mean age of 19 ± 2 at 2σ (95% confidence); the youngest 12 grains that overlap in age at 2σ (where 2σ ≤ 5 Ma) have a weighted mean age of 23 ± 1 at 2σ. Because no strata can contain detrital zircon younger than its depositional age, these relations indicate robustly that the White Mesa alluvium is no older than ca. 25 Ma, probably no older than ca. 20 Ma, and possibly younger than ca. 15 Ma. From this and considering the age of the two youngest grains (15 and 19 Ma), detrital zircon data restricts the age of the alluvium to younger than 20–15 Ma. This is in contrast to the pre–early Miocene assignment of Lucchitta et al. (2011, 2013).

## TUFF AND DETRITAL SANIDINE 40Ar/39Ar GEOCHRONOLOGY

Dating detrital sanidine grains using the 40Ar/39Ar method offers an important complement to detrital zircon geochronologies, primarily because 40Ar/39Ar sanidine ages are very precise, typically having analytical errors of tens of thousands of years for Cenozoic grains. We define the early Pleistocene age of the White Mesa alluvium using dated tuff and detrital sanidine. The mid-Pleistocene minimum age of the alluvium is inferred from an inset geomorphic relation between the White Mesa paleovalley and a younger, lower surface associated with a tuff of known age. The geochronology of Oligocene–Miocene reworked ash-fall in the ca. 2 Ma White Mesa alluvium was investigated and linked to several calderas of similar age.

### Maximum Early Pleistocene Age of the White Mesa Alluvium

Three independent dates establish the maximum early Pleistocene age of the alluvium. One date is from tuff interbedded with basal White Mesa alluvium on the Moenkopi Plateau and the others are detrital sanidine in the basal alluvium at Crooked Ridge and southern White Mesa. The tuff, herein referred to as the Blue Point tuff, is 10–15 cm thick, friable, and 2 m above the base of an ~3-m-thick gravel that underlies 17 m of well-stratified alluvium (Figs. 1 and 3B; Table 1, site 19). Although Blue Point is 50 km south of southeasternmost White Mesa, the grain size, color, and bedding characteristics of the alluvium on Blue Point resemble the White Mesa alluvium. Geomorphically, the deposits on the Moenkopi Plateau are inverted, and the landscape position of the deposits is similar to the White Mesa paleovalley (both were mapped as the same geomorphic surface by Cooley et al., 1969). Based on these sedimentologic and geomorphic characteristics, the alluvium on Blue Point is interpreted to correlate with the White Mesa alluvium. Individual sanidine dates in the tuff range from 2.7 to 1.9 Ma. Of 49 fused grains, 41 have normally distributed dates with a mean of 1.993 ± 0.002 Ma (Fig. 13A; Supplemental File 3). This date is considered the eruption age of the Blue Point tuff and a direct age of the basal White Mesa alluvium on the Moenkopi Plateau.

Detrital sanidine was extracted from bulk samples previously collected for detrital zircon analysis at Crooked Ridge and the Highway 21 quarry in southwestern White Mesa paleovalley, which are 37 km apart (Figs. 2 and 6; Table 1, sites 2 and 16). Approximately 100 grains from each sample were dated; the individual dates range from ca. 1,179 to 1700 Ma. During the mineral separation process, recovery of volcanic sanidine from plutonic or metamorphic K-feldspar is maximized by choosing optically clear K-feldspars, which enhances identification of age populations that may closely approximate depositional ages (i.e., Heizler et al., 2013). Optically clear crystals older than ca. 500 Ma are most likely basement grains (microcline and orthoclase) rather than sanidine; however, the majority of grains younger than 250 Ma are probably sanidine. These Mesozoic grains are likely recycled from bedrock units such as the Chinle Formation and Entrada and Dakota Sandstones.

The basal coarse sand and gravel unit was sampled at both localities. Sample contamination by loose sediment was eliminated by horizontal and vertical excavation with a hand shovel, forming fresh exposures of 0.5–1 m². Crooked Ridge exposes an essentially complete section of the alluvium (Figs. 6, 7A, and 7B), and the sample was collected <1 m above the underlying Navajo Sandstone. Only the basal gravel unit, however, is present at the Highway 21

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*Supplemental File 3. 40Ar/39Ar data. Please visit [http://dx.doi.org/10.1130/GES01124.S4](http://dx.doi.org/10.1130/GES01124.S4) or the full-text article on www.gsapubs.org to view Supplemental File 3.*
quarry, although complete stratigraphic sections are present within 1–1.5 km. The lithology and elevation of the basal gravel at the quarry are similar to those of nearby complete stratigraphic sections. The quarry sample was collected 3.1 m above the underlying Entrada Sandstone. Dated detrital grains in the two samples varied from euhedral to highly rounded and frosted, probably indicating minimal transport to substantial abrasion during transport in the White Mesa fluvial system. Frosting of relatively soft sanidine may indicate eolian transport.

Both samples yielded at least 3 detrital grains that are younger than 2.7 Ma. Two from each set yield dates of 1.84 ± 0.05 and 2.02 ± 0.02 Ma (Fig. 13A).
at the Highway 21 quarry and Crooked Ridge, respectively. These maximum depositional ages are statistically different; the younger age is from slightly higher in the stratigraphic section, which possibly relates to sedimentation rate. The eruptive source of the tuff and detrital sanidine is unknown; however, they are younger than the regionally extensive Huckleberry Ridge eruption, with a tightly clustered age of 2.1 Ma (Ellis et al., 2012; Singer et al., 2014). Our conclusion from the combined direct dating of an interbedded tuff and dated detrital sanidine is that the basal White Mesa alluvium was deposited at 1.993 ± 0.002 Ma (i.e., ca. 2 Ma), consistent with a detrital grain maximum depositional age of 2.02 ± 0.02. Slightly higher parts of the alluvium are younger than 1.84 ± 0.05.

**Minimum Age of the White Mesa Alluvium**

A mid-Pleistocene minimum age of the alluvium and paleovalley was established using inset geomorphic relations between the Bishop Tuff–Glass Mountain tuff at Blue Canyon (Figs. 1 and 3B; Table 1, site 17; Geib and Spurr, 2002) and the Lava Creek B ash on northeast White Mesa (Table 1, site 18). Northeast of Blue Point and inset 130 m below the base of the 1.99 Ma tuff, the 0.8–1.2 Ma Bishop Tuff–Glass Mountain tuff at Blue Canyon is interbedded with 5–7 m of gravel that is 120 m above Moenkopi Wash. This gravel and related surface forms the L2B erosional surface mapped by Cooley et al. (1969). They mapped the surface downstream along Moenkopi Wash and upstream along Begashibito Wash to the drainage divide between the Little Colorado and Colorado Rivers, where the L2B surface is inset ~100 m below the southeast-facing side of White Mesa (Fig. 2). This inset demonstrates that the Bishop Tuff–Glass Mountain tuff postdate the erosion and inversion of the east side of the mesa. Thus, the White Mesa alluvium is older than the Bishop Tuff–Glass Mountain tuff. On the northeast end of White Mesa near sample locality WMZ-NUP, the ca. 640 ka Lava Creek B ash disconformably overlies the White Mesa alluvium in a shallow swale-like feature on an erosional slope crosscutting the alluvium. This disconformable relationship and young age of the Lava Creek B ash are consistent with the inset geomorphic association between the Bishop Tuff–Glass Mountain tuff and the alluvium.

**Detrital Sanidine Provenance**

Sanidine is a common product of Cenozoic caldera eruptions related to the Oligocene ignimbrite flare-up of the western United States (Lipman, 2007) and to younger Neogene and Quaternary eruptions. The caldera eruption timing is well known for the San Juan Mountains (Lipman, 2007; Lipman and McIntosh, 2008), Mogollon-Datil (McIntosh et al., 1992), and Marysvale volcanic fields (Best et al., 2013). Because of the precise age of single sanidine crystals and the equally precise measure of caldera volcanism, it is possible to link individual detrital grains to contemporaneous caldera eruptions. Based on the 2 previously described tuff samples, the detrital sanidine geochronology of the White Mesa alluvium indicates that reworked 40–20 Ma Oligocene–Miocene volcanic sanidines are present as detritus in the ca. 2 Ma alluvium and its paleodrainage. Details of the detrital sanidine and zircon distributions are plotted at various time spans in Figures 13B–13D to demonstrate temporal distinctions. Figure 13B is the sanidine age distribution between 20 and 0 Ma, which reveals a rich record of Miocene–Pleistocene volcanic sources represented by one detrital zircon grain in that age range. For example, possible sources for the 18.7 Ma population are the Apache Leap Tuff or the Peach Spring Tuff located near Phoenix and Kingman, Arizona, respectively (cf. Ferguson et al., 2013). The 40–20 Ma spectra (Fig. 13C) show that ~100 sanidine grains are in this age range. A dense clustering of ~38 grains is between 31 and 27 Ma. The ages are not precise enough to unequivocally distinguish between individual San Juan or Mogollon-Datil caldera eruptions that are both possible source regions, but mean values strongly indicate a San Juan Mountains source. The most prominent peak in both samples is 28.20 ± 0.03 Ma, which is clearly sanidine from the Fish Canyon Tuff. This age is nearly identical to the Bloodgood Canyon Tuff of the Mogollon-Datil field (McIntosh et al., 1992). However, the K/Ca ratio of ~70 is diagnostic of the Fish Canyon Tuff, whereas the ratio for Bloodgood Canyon Tuff sanidine is ~20. The K/Ca ratio demonstrates a powerful fingerprinting aspect of detrital sanidine geochronology that can link detrital grains directly to caldera sources.

The terrain of the ca. 2 Ma White Mesa paleodrainage, as previously documented, was Cretaceous strata overlain by younger deposits and lag surfaces containing gravel clasts composed of rare Oligocene volcanics of San Juan Mountains origin. However, detrital sanidine geochronology indicates that multiple age Oligocene–Miocene ash-fall deposits were also present in the ca. 2 Ma White Mesa paleodrainage (Figs. 13B, 13C). Our interpretation is that over time sanidine, as ash fall and alluvial detritus, was deposited in one or more fluvial systems that substantially predated the White Mesa paleodrainage. These earlier fluvial systems apparently contained Oligocene volcanic clasts comileding with essentially contemporaneous ash fall and detrital sanidine from the San Juan volcanic field. It is unclear how these fluvial systems carried San Juan Mountains detritus across the present Chinle Valley and much of northeastern Arizona (Fig. 1). A lag gravel older than the White Mesa alluvium on Black Mesa (Table 1, sites 13 and 14) was related to the Crooked Ridge paleoriver by Lucchitta et al. (2011, 2013), whereas Cooley et al. (1969) considered the lag gravel to be an even older erosion surface. The record is fragmentary, and additional data are needed, but these lag gravels and associated carbonate-cemented fluvial deposits described herein could be remnants of Oligocene–Miocene detritus that was later reworked into the ca. 2 Ma White Mesa alluvium.

**DISCUSSION**

The detrital sanidine ca. 2 Ma age of the White Mesa alluvium provides evidence for a much younger erosional history than was previously envisioned for this region (Hunt, 1969; Lucchitta et al., 2011, 2013). Moreover, the area of
regional denudation was possibly quite large, as suggested by paleodrainage reconstruction (Fig. 14). Reconstruction is possible by upslope extension of the several paleochannels and downslope extension of the White Mesa paleovalley toward the Little Colorado River valley. Upslope extension of the paleovalley system into its ancient drainage basin is based on the elevation of the Dakota Sandstone as shown on the 6 previously cited 1:250,000-scale structure contour maps.

Downstream of The Gap, blocked to the southwest by the Red Dot Hills (Fig. 2), the paleodrainage turned south to south-southeast, following the strike of the Echo Cliffs monocline 32 km to the end of the structure. Here it probably joined the ancestral Moenkopi Wash near the base of the ca. 2 Ma White Mesa alluvium present at the northwest end of the Moenkopi Plateau at an elevation of −1520 m, −200 m above the wash (Fig. 1). The paleovalley likely continued 18 km south before joining the Little Colorado River at a structural low near Cameron. Upstream of Cameron, the ancestral Little Colorado possibly joined with ancient high-level versions of Dinnebito and Oraibi washes. These washes, including Moenkopi, could have extended northeast beyond the present northeast-facing rim of Black Mesa. Beheaded valleys prominently exposed on the rim of Black Mesa are evidence that the washes extended farther northeast (Schmidt, 1989).

Five paleochannels converged on White Mesa paleovalley from the north, northeast, and south (Figs. 5 and 14). The north paleochannel, dominated by clasts composed of Cretaceous sandstone, may have extended roughly north into the Navajo Mountain area, where a divide, perhaps near Navajo Mountain, likely separated the paleochannel from the Colorado River. Northeast paleochannel 1, apparently the largest of the five, and also dominated by clasts of Cretaceous sandstone and lacking exotic volcanic clasts, may have extended far to the northeast along the 0.007 gradient of the paleovalley, probably ending at a drainage divide south of the San Juan River. A portion of the paleovalley system represented by northeast paleochannel 3 (perhaps in combination with northeast paleochannel 2) probably extended east-northeast of White Mesa where it intersected the Organ Rock monocline. Following a

Figure 14. Possible course and extent of White Mesa paleodrainage (dashed blue lines). Shaded pattern is inferred former extent of eroded Cretaceous terrain based on published previously cited structure contour maps. Paleochannels: np and sp—north and south paleochannel; nep 1—northeast paleochannel 1; nep 2 and 3—northeast paleochannel 2 and 3. Headwaters region in Navajo Mountain area, Monument Valley, and parts of Chinle Valley removed during regional denudation beginning after 2 Ma. San Juan Mountains piedmont inferred from Cather et al. (2008). Distribution of Bidahochi Formation is mostly from Dickinson (2013).
strike valley along the monocline, possibly at the Dakota Sandstone–Mancos Shale contact, the paleovalley could have extended farther northeast over the present Monument Valley to a drainage divide with the San Juan River. Older lag gravels and deposits containing exotic volcanic clasts were present near the paleochannel course on Black Mesa. These ancient gravelliferous deposits may have been remnants of the Oligocene San Juan Mountains pediment, a belt of detrital and volcaniclastic deposits around the San Juan Mountains (Cather et al., 2008). We cannot exclude, however, that the exotics were originally deposited by a pre–2 Ma San Juan–like paleoriver. South paleochannel, the narrowest and probably shortest paleochannel (Fig. 9), drained the Black Mesa area, which was a Cretaceous terrain overlain by Cenozoic lag gravel and deposits containing late Paleogene to early Neogene volcanic clasts.

The volume of Cretaceous strata removed south of the San Juan River and southeast of the Colorado River is large. Although the former boundary of the missing terrain is subject to substantial uncertainties, the boundary is constrained by the Colorado River on the northwest and the San Juan River to the north (Fig. 14). The elevations of structure contours on the eroded basal Cretaceous section within the former boundary are mostly well above present topography, except in the Black Mesa structural basin. Thus, the area of Cretaceous strata eroded after deposition of the White Mesa alluvium probably exceeds 10,000 km². Assuming a thickness of ~300 m (Dakota Sandstone plus Mancos Shale), the volume of eroded Cretaceous rock was more than 3000 km³; the volume increases substantially if the ~465-m-thick upper Cretaceous Mesaverde Group was eroded. The total volume of sediment removed to reach the present elevation of the master river is even larger, as a thick section of bedrock underlying the Dakota Sandstone was also eroded.

The divide separating the White Mesa paleodrainage from the San Juan and Colorado Rivers was probably the edge of an abandoned, possibly deep canyon with steep sides (Fig. 14). Most of the paleocanyon is missing, as suggested by low elevations along both rivers. However, the Straight Cliffs, only 6 km north of the Colorado River in Glen Canyon, is likely a remnant of the right side (facing downstream) of the paleocanyon (Figs. 1 and 3A). The left side was probably between the Colorado River and the flanks of Navajo Mountain. The top of the Straight Cliffs (Navajo Point) is 1 km above the 500 ka Ca pediment (Garvin et al., 2005) and 1.25 km above the Colorado River. However, evidence of the Colorado and San Juan Rivers on top of or adjacent to the Straight Cliffs such as alluvium and beveled surfaces (Hackman and Wyant, 1973) is apparently lacking, precluding calculation of incision rates because the depth of incision is poorly constrained. Rates to 830 m/my. were estimated for incision of Glen Canyon (Cook et al., 2009), although this rate may be inflated by minimum ages derived from cosmogenic exposure dating (Darling et al., 2012). Nevertheless, the ca. 2 Ma age of the high-elevation White Mesa paleodrainage suggests incision was rapid especially in areas of soft Mesozoic bedrock (Cook et al., 2009; Darling et al., 2013; Karlstrom et al., 2014). This rapid incision coincided with voluminous bedrock erosion totaling several thousand cubic kilometers of Cretaceous strata only in the White Mesa paleodrainage.

CONCLUSIONS

The ca. 2 Ma White Mesa paleovalley, previously termed the Crooked Ridge River of late Eocene to early Miocene age (Lucchitta et al., 2011, 2013), extends 57 km northeast from The Gap to White Mesa in northeastern Arizona (Figs. 1 and 2). Fine-grained alluvium, ~20–50 m thick, is exposed at two localities, Crooked Ridge and White Mesa (Figs. 5 and 7). The alluvium is best exposed on White Mesa, which provides its name. The alluvium is informally referred to as the White Mesa alluvium, the geomorphic setting of which is the White Mesa paleovalley within the White Mesa paleodrainage.

The age of the alluvium and paleovalley has heretofore been poorly constrained. Detrital zircon suggests a maximum age of 20–15 Ma. This estimated age was substantially reduced by detection and dating of detrital sanidine and tuff at the base of the alluvium. Applying the 40Ar/39Ar method to sanidine from the base of the alluvium at three widely spaced locations yields an age of ca. 2 Ma, the age of the basal alluvium (Fig. 13A). Its minimum age is mid-Pleistocene, based on onset geomorphic relations between the Bishop Tuff and Glass Mountain tuff (0.8–1.2 Ma) at Blue Canyon (Figs. 1 and 3B) and the White Mesa alluvium. These ages confirm that the White Mesa alluvium and paleovalley are not related to the conceptual Crooked Ridge River of Lucchitta et al. (2011, 2013). In addition, the young age and high landscape position of the paleodrainage document rapid denudation starting after 2 Ma that probably continues to the present. More than 10,000 km³ of the ancestral northern Little Colorado River drainage basin was removed (Fig. 14).

Fossil and sedimentologic evidence indicate that deposition of the White Mesa alluvium was in a relatively low energy suspended sediment aggradational channel system. This is consistent with the immature texture and lateral discontinuity of gravel and the predominance of very fine gravel sand and clay that are characteristic of the alluvium (Fig. 7). A small, thin-walled gastropod (Gastropoda Family Lymnaeidae) present in limestone beds at Crooked Ridge and southern White Mesa inhabits slow-moving streams and marsh-like environments. Therefore, the alluvium was likely not deposited in a large, vigorous braided river; rather, the deposits resemble those of washes currently draining Black Mesa (Fig. 1) in grain size and stratification.

The White Mesa alluvium was derived largely from upper Cretaceous Dakota Sandstone and Mancos Shale. GRAavel clasts in the alluvium are primarily Dakota Sandstone. Detrital zircon data suggest that sand-size sediment was also derived from Cretaceous rocks (Figs. 11 and 12). Clay beds in the alluvium have the distinctive color and platy character of the Mancos Shale. Exotic gravel in the alluvium is composed of granite, quartzite, other metamorphics, and rare to absent volcanics originally derived from the San Juan Mountains of southwestern Colorado. Surface texture and shape of these clasts indicate that most were reworked (Fig. 8), probably from older surficial deposits and lag surfaces that overtied Cretaceous bedrock in the White Mesa paleodrainage. This source of far-traveled detritus was present during deposition of the alluvium in the ca. 2 Ma White Mesa paleodrainage, which was bound by the San Juan and Colorado Rivers to the north and northwest, respectively.
The alluvium detrital sanidine geochronology confirms that multiple age Oligocene–Miocene ash-fall deposits from the San Juan Mountains and elsewhere were preserved in what became the early Pleistocene White Mesa paleodrainage (Figs. 13C, 13D). These specifically include the voluminous 28.2 Ma Fish Canyon Tuff and other tuffs of the San Juan Mountains. This conglomering of fluvial and ash-fall volcanic detritus suggests that a fluvial system much older than 2 Ma flowed across northeastern Arizona from the San Juan Mountains volcanic field. These older deposits are cryptic, but at least one fluvial system was abandoned after integration of the Colorado River system at 8–5 Ma (Spencer et al., 2001; House et al., 2008). Regional denudation after 2 Ma removed the White Mesa paleodrainage north, northwest, and northeast of White Mesa along with substantial evidence of prior fluvial systems. The only direct evidence of an older system is possibly lag gravel and thin feldspathic sandstone of poorly known provenance on high-level beveled surfaces on top of Black Mesa (Fig. 1; Cooley et al., 1969).

The characteristics of the White Mesa alluvium and paleodrainage described and interpreted herein are unlike those proposed for the Crooked Ridge River of Lucchitta et al. (2011, 2013) or those of the Miocene paleoeriver posited by Cooley et al. (1969), Hunt (1969), and Stokes (1973). Specifically, the alluvium and paleodrainage are not contemporaneous with eruption of the 35–23 Ma San Juan Mountains volcanic field; rather, they are early Pleistocene (ca. 2 Ma). Sedimentological and fossil evidence support a low-energy depositional environment, not a vigorous braided river. Alluvium was mostly derived from a local source of Cretaceous bedrock that supplied sand-size sediment and gravel composed of abundant Cretaceous sandstone. Instead of a primary San Juan Mountains origin, exotic grains of detrital sanidine and pebble to small cobbles were reworked into the alluvium from the remnants of an inadequately identified, substantially older fluvial system. Groundwater-carbonate chemistry of the saturated floodplain indicates low-elevation runoff rather than the snowmelt runoff of an imposing mountain range.

We recommend that the term “Crooked Ridge River” (Lucchitta et al., 2011, 2013) not be applied to the preserved sedimentary and geomorphic record of early Pleistocene deposits on Crooked Ridge, White Mesa, and the Moenkopi Plateau. The White Mesa alluvium system, as we interpret it, records the fluvial activity of a former tributary of the Little Colorado River that was comparable to ancient versions of washes currently draining Black Mesa. Dating of detrital sanidine, not available previously, complements detrital zircon work, thereby transforming our understanding of the White Mesa alluvium and post–2 Ma regional denudation of northeastern Arizona.

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