Incision history of the Verde Valley region and implications for uplift of the Colorado Plateau (central Arizona)

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ABSTRACT

The record of Tertiary landscape evolution preserved in Arizona’s transition zone presents an independent opportunity to constrain the timing of Colorado Plateau uplift and incision. We study this record of landscape evolution by mapping Tertiary sediments, volcanic deposits, and the erosional unconformity at their base, 40Ar/39Ar dating of basaltic lava flows in key locations, and constructing geological cross sections along canyons to restore the paleorelief on the Tertiary erosional unconformity to test whether canyon incision requires young (<10 Ma) Colorado Plateau uplift. Our cross sections and new 40Ar/39Ar ages document that in the Verde Valley, relief across the ancestral Mogollon Rim that marks the southern edge of the Colorado Plateau was up to 1000 m averaged ~700 m in the Early-Middle Miocene, which is close to average modern relief of ~800–1000 m. Although Middle-Late Miocene volcanics and sediments in places onlap the ancestral Mogollon Rim, suggesting an erosional origin, northeastward erosional retreat of an earlier tectonic escarpment is both plausible and consistent with displacement histories of the Grand Wash fault to the NW and the Diamond Rim fault to the SE. Interestingly, the coincidence of a rugged, sharply defined Mogollon Rim and a wide bench cut into the Hermit shale below the escarpment today suggests that exposure of the Hermit shale may play an important role in cliff retreat and the morphological expression of the Mogollon Rim in the Verde Valley region. Some modern canyons cut into the retreating escarpment reflect re-excavation, deepening, and headward propagation of Miocene paleochannels largely buried by Middle-Late Miocene basalts. Despite evidence for similar total paleorelief, most canyons show significant (~35%) deepening since 5 Ma with young incision decreasing to the SE. Incision rates during the period of active Miocene volcanism were below 20 m/m.y. but accelerated to 50–80 m/m.y. during the past 5–8 m.y. and were probably 100–160 m/m.y. during the Quaternary. The accelerated incision reflects base-level fall associated with breaching of the Verde Lake basin by ca. 2.5 Ma and integration of the Verde River and thus does not require post-Middle Miocene uplift of the southwestern edge of the Colorado Plateau.

INTRODUCTION

The timing of surface uplift and canyon cutting on the Colorado Plateau has been vigorously debated for more than 100 years (e.g., Powell, 1876; Davis, 1901; Blackwelder, 1934; McKee and McKee, 1972; Spencer, 1996; Karststrom et al., 2008; Moucha et al., 2009; Huntington et al., 2010; Liu and Gurnis, 2010; Flowers and Farley, 2012; Crow et al., 2014; Darling and Whipple, 2015; Karlstrom et al., 2017). As part of this debate, the incision of the Mogollon Rim, the southwestern edge of the Colorado Plateau (Fig. 1), is not well constrained in the literature, and disparate ideas about its formation and incision history have been proposed (Peirce et al., 1979; Lindberg, 1986; Elston and Young, 1991; Holm, 2001). The Cenozoic geomorphic evolution of the transition zone between the southwestern edge of the Colorado Plateau and the Basin and Range Province (Fig. 2) is recorded by discontinuous sedimentary and volcanic deposits from this time interval. The goal of this study is to reveal the incision history of canyons cut into the southwestern margin of the Colorado Plateau, in the upper Verde Valley. The timing and amount of incision of these canyons constrain the uplift of the southwestern Colorado Plateau and thus are relevant to the debate over the timing of Grand Canyon incision and the role of rock uplift as a driver (Karststrom et al., 2008; Flowers and Farley, 2012; Crow et al., 2014; Young and Crow, 2014). Young (<10 Ma) uplift of the Colorado Plateau has been argued to be driving incision in the Grand Canyon, but the uplift history of the Colorado Plateau and the timing of formation of different parts of the Grand Canyon remain debated (Karststrom et al., 2008; Liu and Gurnis, 2010; Levander et al., 2011; Flowers and Farley, 2012; Karststrom et al., 2014; Darling and Whipple, 2015). The Verde Valley region with partially preserved Cenozoic sediments and an extensive and well-preserved volcanic history since Middle Miocene is a good location for constraining the incision history of the SW Colorado Plateau and therefore to test whether young uplift of the Colorado Plateau is required to explain the geology and dramatic local canyon incision. The aims of this study are to: (1) determine if there were multiple periods of canyon cutting into the Mogollon Rim escarpment during the Cenozoic; (2) constrain the timing and amount of incision during each erosional event; (3) determine whether deeply incised modern canyons require significant Late Miocene to recent surface uplift of the SW Colorado Plateau; and (4) resolve how the Mogollon Rim kept its sharp morphology despite the very low retreat rate suggested by previous studies (Mayer, 1979; Ranney, 1988; Elston and Young, 1991) and how along-strike variations in escarpment morphology have been influenced by Quaternary base-level history.

We build on previous studies that have used radiometric ages of lava flows and provenance of Cenozoic sediments to constrain aspects of the history of landscape evolution in the central Arizona transition zone (e.g., Twenter, 1962; McKee and Anderson, 1971; McKee and McKee, 1972; Peirce et al., 1979; Ulrich
and Bielski, 1983; Faulds, 1986; Elston and Young, 1991; House and Pearthree, 1993; House, 1994; Holm, 1998; Holm, 2001; Potochnik, 2001). Key events in this history include the formation of the Mogollon Rim, the timing of drainage reversal from northeastward flow from the Mogollon Highlands to generally southern flow off the Colorado Plateau, and the incision of deep canyons into the Plateau's southwestern margin. Multiple erosional and aggradational events have been described after the drainage reversal, but their timing is poorly constrained overall due to the scarcity of Cenozoic sediments, lack of detailed geologic maps, and shortage of radiometric ages in certain areas. Estimates for the timing of drainage reversal and subsequent canyon cutting vary synchronously with estimates of the formation age of the Mogollon Rim from Paleocene (Elston and Young, 1991) to Late Miocene–Pliocene (McKee and McKee, 1972).

We present 15 Ar/Ar ages from nine lava flows selected to leverage and complement published K-Ar dates, maps, and provenance data. The dated lava flows are emplaced on different erosional surfaces and provide constraints on different episodes of incision and relief production. In addition, multiple cross sections were generated from existing maps supplemented by new field mapping to constrain the geometry and relief of the prevolcanic landscape in the Verde Valley and to address how recent base-level history has influenced the morphology of the study area and determine whether there is a record of post–Late Miocene Colorado Plateau uplift in this landscape. If all Colorado Plateau uplift in the Verde Valley had occurred since the Late Miocene, we would expect little relief on erosion surfaces buried by mid-Miocene lavas (Fig. 3). On the other hand, mid-Miocene lavas burying significant paleotopography at the edge of the Colorado Plateau would constrain the amount of pre–mid-Miocene relief and uplift (Fig. 3). Our cross sections combined with radiometric dating, however, reveal that approximately two-thirds of the modern relief had formed before the emplacement of mid-Miocene basalts. The excavation of paleovalleys and formation of new canyons are readily explained by...
base-level fall associated with the breaching of the internally drained Verde Valley ~2.5 m.y. ago (Bressler and Butler, 1978) but do not necessarily exclude <1 km of Colorado Plateau uplift within the past 10 m.y.

**Regional Geologic Background**

The SW Colorado Plateau in the study area is characterized by low relief with elevations generally above 2000 m and is underlain by lower Paleozoic to Mesozoic sedimentary rocks that dip ~1°–2° to the northeast (Ulrich et al., 1984; Reynolds, 1988; Blakey and Knepp, 1989). Despite the high modern elevation of the Colorado Plateau, its sedimentary strata record little tectonic deformation. However, Laramide monoclines and Miocene to Holocene normal faults are documented (Leighty, 1997), and evidence for reactivation of Laramide reverse faults as normal faults is common (Holm and Cloud, 1990). The Mogollon Rim is the 500-km-long southwestern edge of the Colorado Plateau and generally forms a prominent escarpment with several hundred meters of relief (reaching 700–1000 m in the Verde Valley), separating the Colorado Plateau from the transition zone to the south. The transition zone was a topographic high (Mogollon Highlands) during the Laramide but foundered during extension on high-angle normal faults in Miocene–Pliocene time and comprises mostly Precambrian basement rocks and overlying Cenozoic lava flows and sediments (Reynolds, 1988; Leighty, 1997).

Arizona’s Verde Valley lies at the boundary between the Colorado Plateau and the transition zone (Heindl and Lance, 1960), bounded by the Mogollon Rim to the north and east and the Verde fault with ~1000 m throw in the south-west (Lindberg, 1986) (Fig. 2). It remains unclear how much faulting contributed to the relief on the northeastern valley margin because basin-filling sediments cover possible faults. Therefore, generation of relief at the northeastern valley margin in Early-Middle Miocene may well be associated with slip on faults coeval with the Grand Wash fault to the NW (Bohannon, 1983; Bohannon

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**Figure 2. Geologic map of the Verde Valley region modified from the geologic map of Arizona (Reynolds, 1988). The red rectangle shows the location of Figure 8. Inset: Mogollon Rim location and division of the region into three main physiographic provinces (LV—Las Vegas; PHX—Phoenix; FLG—Flagstaff).**
et al., 1993; Karlstrom et al., 2010; Umhoefer et al., 2010) and the Diamond Rim fault to the SE (Mayer, 1979), although direct evidence is lacking. Normal faulting along the Verde fault on the southwest side of the Valley probably began ~10–15 m.y. ago (McKee and Anderson, 1971) and resulted in a toposynclinal and structural low (House, 1994; Langenheim et al., 2005) (Fig. 2). The combination of the graben structure and volcanic activity at its southern margin inhibited external drainage in Late Miocene and Pliocene (Bressler and Butler, 1978). Hence, from ca. 7.5 to 2.5 Ma, the lacustrine Verde Formation (hundreds of meters thick) accumulated in the Verde Valley (Bressler and Butler, 1978; Peirce et al., 1979). At ca. 2.5 Ma, the Verde Valley was breached, resulting in at least 300 m of exhumation of lake sediments and a significant drop in base level for canyons incised into the Mogollon Rim (House, 1994).

Paleozoic strata dominate the northern part of the Valley, whereas they are mostly covered by Miocene basalt flows at the eastern margin of the Valley (Fig. 2). Lava flows fall into two age categories: (1) the House Mountain and Mingus Mountain volcanic rocks, known as the Hickey basalts, date between 15 and 10 Ma (Reynolds et al., 1988; Damon and Shafiquullah, 1996); and (2) volcanic vents located on the Colorado Plateau with lava flows draping into the Verde Valley are younger than 10 Ma (Damon et al., 1974; Reynolds et al., 1988; Damon and Shafiquullah, 1996).

The first radiometric ages of volcanic rocks led to an interpretation that the Colorado Plateau and the Mogollon Rim formed in Late Miocene time through differential uplift (McKee and McBee, 1972) and that all the canyons in the Verde Valley started to incise the Plateau at ca. 10 Ma. Later studies, however, used sedimentological and radiometric data to argue that the Mogollon Rim formed significantly earlier, in the Oligocene (Peirce et al., 1979) or even Paleocene (Elston and Young, 1991), and that some modern canyons reflect re-incision into broad 200–300-m-deep paleovalleys filled by Middle to Late Miocene lava flows (Holm and Cloud, 1990; Holm, 2001).

In addition to radiometric dating, provenance and paleoflow indicators from Cenozoic pre-Verde Formation sediment deposits were utilized to constrain the evolution and paleogeography of the Verde Valley region (Twenter and Metzger, 1963; McKee and McBee, 1972; Peirce et al., 1979; Lindberg, 1986; Elston and Young, 1991; Holm, 1998; Holm, 2001; Losecke, 2001). Cenozoic sediments are generally found in small isolated patches (Weir et al., 1989) on top the Colorado Plateau, in the canyons, and in the adjacent Verde Valley below the Mogollon Rim. They have received considerable attention, but their correlation proves difficult due to discontinuity of outcrops and deposition on multiple erosional surfaces. In this study, Cenozoic sediments are classified after Holm (2001) and are mainly divided into older Plateau gravels (often called Rim gravels or Mogollon Rim Formation) and younger Valley gravels based on their position relative to the Mogollon Rim and provenance, with Valley gravels containing Cenozoic volcanic clasts.

The Plateau gravels have been described numerous times (Mears, 1950; Cooley and Davidson, 1983) and have been assigned to a northeast-directed stream system, based on southern provenance and paleoflow indicators. Pla-
teau gravels were deposited from Paleocene to Early Oligocene (Peirce et al., 1979; Elston and Young, 1991; Holm, 2001). At that time, streams were flowing from the Mogollon Highlands toward the modern Colorado Plateau (Cooley and Davidson, 1963; Young and McKee, 1978) transporting mostly Precambrian basement rocks exposed only to the southwest. Age constraints on the Plateau gravels are scarce, and discussion about their age is ongoing. Basalt clasts and interbedded tuffs in those deposits yielded constraints from 54 to 28 Ma (Peirce et al., 1979) and 56–37 Ma (Potochnik, 1989) in the eastern Mogollon Rim region. An ash interbedded in the Plateau gravels at Blue Ridge on the Colorado Plateau was dated to 33 Ma (Potochnik, 2001) and is the only age of Plateau gravels near the study area. On the Hualapai Plateau near Peach Springs, Young and Crow (2014) show that the deposition must have begun well before 24 Ma and occurred over a long interval. Moreover, in the Verde Valley region, these depositions lack Cenozoic volcanic detritus indicating deposition before the onset of volcanism in central Arizona in the Oligocene (Reynolds et al., 1986). Therefore, deposition in Paleocene–Eocene times (Elston and Young, 1991) or until Oligocene (Peirce et al., 1979; Holm, 2001) is inferred. However, deposition of Plateau gravels in multiple episodes is well documented in other parts of the Colorado Plateau (Young and Crow, 2014; Karlstrom et al., 2017).

Valley gravels are found below and inset against the Mogollon Rim, and their ages are constrained by overlying basalt flows, entrained volcanic clasts, their provenance, and geomorphic position. A minimum age for the Valley gravels is provided by overlying Middle Miocene basalt flows (15–10 Ma) at various locations (Beavertail Butte, West Clear Creek Canyon, Black Mountain, and west of Camp Verde) (Table 1) (Fig. 4B) (Shafiqullah et al., 1980; Peirce, 1987; Ranney, 1988; Damon and Shafiqullah, 1996). Their provenance is similar to that of the Plateau gravels; however, Holm (2001) documented Cenozoic basaltic clasts found in Valley gravels at three locations, which were confirmed by our field work. This indicates deposition of Valley gravels after the onset of volcanism in central Arizona ~27 m.y. ago (Reynolds et al., 1986). The position of the conglomerates below the Mogollon Rim and southeast-directed paleo-flow measurements (Holm, 2001) indicate deposition in a northwest-southeast–trending valley below the Mogollon Rim between 27 and 15 Ma and after drainage reversal.

## METHODS

In this study, we evaluate the history of Mogollon Rim by mapping, Ar/Ar dating of strategically positioned lava flows, provenance and paleocurrent measurements, and construction of geologic cross sections of all major canyons that incise the Mogollon Rim in the Verde Valley region. Lava flows in

| No. | Age (Ma) | Locality          | Reference                          | Description                                             |
|-----|----------|-------------------|------------------------------------|---------------------------------------------------------|
| 1   | 4.5 ± 0.2| Clarkdale         | McKee and Anderson (1971)          | Flow interbedded in Verde Formation                      |
| 2   | 4.87 ± 0.2| Perkinsville     | McKee and Anderson (1971)          | Flow interbedded in Perkinsville Formation               |
| 3   | 5.31 ± 0.18| Rattlesnake Canyon| Damon and Shafiqullah (1996)     | Highest flow in Rattlesnake Canyon                       |
| 4   | 5.46 ± 0.18| Interstate I-17  | Damon and Shafiqullah (1996)     | Flow interbedded with Verde Formation                    |
| 5   | 6.05 ± 0.91| Oak Creek Canyon | Damon et al. (1974)               | Basal basalt flow at Hwy. 89 switchbacks, northern part of Oak Creek Canyon |
| 6   | 6.26 ± 0.3| Drake             | McKee and Anderson (1971)          | Flow interbedded in Perkinsville Formation               |
| 7   | 6.4 ± 0.25| Woods Canyon      | Peirce et al. (1979)              | Flow capping gravels on Horse Mesa                       |
| 8   | 6.55 ± 0.23| Oak Creek Canyon | Peirce et al. (1979)              | Basal flow of 120-m-thick volcanic sequence             |
| 9   | 8.15 ± 0.3| Oak Creek Canyon | Peirce et al. (1979)              | Basal flow capping large conglomerate channel at Slide Rock |
| 10  | 8.62 ± 0.3| Rattlesnake Canyon| Damon and Shafiqullah (1996)     | Lowest flow in Rattlesnake Canyon                       |
| 11  | 9.30 ± 0.21| Fossil Springs   | Peirce et al. (1979)              | Flat-lying volcanic sequence, 440 m above canyon bottom |
| 12  | 10.16 ± 0.22| Fossil Springs  | Peirce et al. (1979)              | Flat-lying volcanic sequence, 383 m above canyon bottom |
| 13  | 10.57 ± 0.31| West Clear Canyon| Peirce et al. (1979)              | Lowermost exposed flow above buried Supai Formation, near Bull Pen Ranch gate |
| 14  | 12.1 ± 1.3| Casner Mountain   | Peirce et al. (1979)              | Lowest flow from Casner Mountain vent                    |
| 15  | 13.18 ± 0.36| House Mountain  | Ranney (1988)                     | Base of Tertiary basalt exposed in Oak Creek             |
| 16  | 13.9 ± 0.3| Dry Beaver Creek  | Shafiqullah et al. (1980)         | Flow overlies unconsolidated gravels, 0.4 km west of a tributary to Dry Beaver Creek. |
| 17  | 14.54 ± 0.33| House Mountain   | Ranney (1988)                     | Basalt from southeast peak of House Mountain volcanic complex |
| 18  | 14.6 ± 0.4| Wet Beaver Creek  | Peirce et al. (1979)              | Basalt capping gravel above Supai Formation south of campground |
| 19  | 15.08 ± 0.4| Black Mountain    | Damon and Shafiqullah (1996)     | Basal basalt flow capping Black Mountain                 |
| 20  | 15.4 ± 0.4| Dry Beaver Creek  | Peirce et al. (1979)              | Flow on Beavertail Butte                                |
| 21  | 23.7 ± 0.8| Oak Creek Canyon  | McKee and McKee (1972)            | Latte cobble 20 m below 8.15 Ma, basalt flow            |
| 22  | 25.28 ± 0.6| Oak Creek Canyon  | McKee et al. (1998)              | Minette dike in Surveyor Canyon tributary               |
| 23  | 33.32 ± 0.59| Blue Ridge       | Potochnik (2001)                  | Interbedded tuff                                        |

Note: Locations shown in Figure 1.
two different geomorphic positions were dated. The selected lava flows were sampled either as close to the Paleozoic–Cenozoic unconformity as possible in order to provide a minimum age of the erosion surface or from the top of the canyon filling lava sequences to determine incision rates after the lava infilling.

**Ar/Ar Dating**

Samples were crushed using standard crushing procedures, and then for each sample, ~150 mg of the freshest looking shards from the 250–500-µm size fraction were picked and lightly leached (1N HNO₃). After rinsing and drydown, ~100 mg were packed in Al foil, loaded into Al discs, and stacked in a flame-sealed glass vial for neutron irradiation. Standards of HD-B1 with an age of 24.18 ± 0.009 Ma (Schwarz and Trieloff, 2007) were placed within wells adjacent to the samples and throughout the entire stack to permit detailed characterization of the neutron irradiation flux both horizontally and vertically. Samples were irradiated for four hours in the cadmium-lined in-core irradiation tube (CLICIT) facility of the Oregon State University (Corvallis, Oregon [USA]) TRIGA reactor.

Samples were step heated to fusion with a Photon Machines 55W CO₂ laser. Isotope data were collected using a Nu Instruments Noblesse multicollector mass spectrometer, run in single-collector mode. Samples were heated for 10–15 seconds prior to 120 seconds cleanup. Extracted gases were cleaned using 2 GP50 SAES getters (one operated at 450 °C and one at room temperature). The extraction, cleanup, and data collection processes were entirely automated. Average backgrounds ± standard deviations from all five blank runs were used to correct isotope abundances. Air calibrations were collected after every ten analyses to monitor mass discrimination. A ⁴⁰Ar/³⁶Ar value of 295.5 was used to correct the data for mass discrimination (Nier, 1950). A power-law function was used for the mass discrimination correction (Renne et al., 2009).

Berkeley Geochronology Center software “mass spec” was used to regress and reduce age data using the decay constant of 5.543 × 10⁻¹⁰ a⁻¹ from Steiger and Jäger (1977). The isotope data were corrected for blank, radioactive decay, mass discrimination, and interfering reactions. Age uncertainties are reported to 2σ; uncertainties on the isotopic measurements are reported to 1σ.

**Geologic Cross Sections**

Geologic cross sections were generated for Sycamore, Oak Creek, Dry Beaver, Wet Beaver, West Clear Creek, and Fossil Creek canyons (locations on Fig. 1). For all except Oak Creek Canyon, straight profile lines were chosen, roughly following the canyon path. In each section, the elevations of the river profile, mean canyon wall height, and geologic contacts were projected from their map location onto the profile line. Whenever two opposing walls of a canyon differed in height, the average was taken. The data were obtained from published maps referred to in the figure captions. Additional Cenozoic sediments missing in published maps were added from field observations. The cross section for Oak Creek Canyon was generated in the same way, except that the profile follows the river bed and not a straight line. Samples were step heated to fusion with a Photon Machines 55W CO₂ laser (see Supplemental Figures for age spectrum plots of step heating). For the reconstructions of the Paleozoic–Cenozoic unconformity, observed offsets on younger faults were removed. The restoration of the prevolcanic geometry of the Paleozoic–Cenozoic unconformity and viewing it as landscape morphology involve the assumption that the unconformity has the same age along the reconstructed section. Whereas in most cases ages of overlying lava flows suggest that this is a valid assumption (e.g., Fig. 5A), in some cases, this is violated by the occurrence of different sedimentary deposits on the unconformity—the unconformity must be viewed as time-transgressive or as an amalgamation of erosion surfaces (e.g., Fig. 5B).

In this study, the Toroweap Formation and Coconino Sandstone are grouped as Coconino due to the similar appearance in the Verde Valley. Following the
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U.S. Geological Survey (USGS) mapping by Weir et al. (1989), the Supai Group contains everything between the Coconino Sandstone and Redwall Limestone to avoid use of the locally defined Schnebly Hill Formation (Blakey and Knepp, 1989). However, in our evaluation of along-strike variation in the morphology of the Mogollon Rim within Verde Valley, we find it useful to break out the Hermit shale (Fig. 1).

RESULTS

The results for each canyon studied (Fig. 1) are presented sequentially, organized roughly from north to south. The Ar/Ar dates, field observations, and cross sections are presented in the context of the respective canyon. Our data and interpretations are synthesized in the discussion section.

As recognized by previous researchers (Twenter, 1962; Peirce, 1987; Holm, 2001), determining the geometry of the Paleozoic–Cenozoic unconformity allows the reconstruction of former erosional surfaces and thus landscape paleorelief in the Verde Valley. In canyons cut into the cover of volcanic rocks, the erosion surfaces have been preserved by the overlying lava flows and exposed by a combination of recent incision during the re-excavation, deepening, and probably lengthening of paleocanyons and formation of canyons in new locations. However, the unconformity does not represent a single datum but rather a diachronous assemblage of Cenozoic erosion surfaces, where overlying basalt flows and conglomerates sometimes indicate a single surface (e.g., Sycamore Canyon) and sometimes evidence of erosion in multiple episodes (e.g., Dry Beaver Creek Canyon). In all cases, numerous faults and the tilting of sedimentary strata since the formation of the erosion surface must...
be accounted for in estimations of the amount of relief on the unconformity produced by erosion.

It is important to consider that relief that appears to be erosional in the cross sections might have had either a tectonic, erosional, or composite origin. Observations of a buttress unconformity beneath the Valley gravels and Middle Miocene volcanics where they onlap the current or ancestral Mogollon Rim (Fig. 4A) have been interpreted by several researchers as evidence of an erosional origin (Peirce et al., 1979; Ranney, 1988; Ranney, 2010). However, these observations are also consistent with erosional retreat of a tectonic escarpment prior to deposition. Thus Middle Miocene (>15 Ma) tectonic origin of seemingly erosional relief is possible for almost all sites where we document erosional relief. The importance of Middle Miocene erosional relief is that it constrains the fraction of modern relief attributable to faulting since that time.

Sycamore Canyon

Sycamore Canyon is the westernmost canyon in the study area, and its walls expose 490 m of relief on the Paleozoic–Cenozoic unconformity (Fig. 5A). The upper parts of the canyon are mainly eroded Permian strata with thin basalt covers on top of the Colorado Plateau. Toward the mouth of Sycamore Canyon, the Paleozoic–Cenozoic unconformity slopes down gently from 2000 m to below 1500 m. Lava flows at high elevations are preserved on the surface at Casner Mountain and Buck Ridge with dates ranging from 11.4 to 14.7 Ma (McKee and McKee, 1972; Peirce et al., 1979; Damon and Shafiqullah, 1996) (Fig. 5A). A lava flow on Black Mountain sloping down to 1460 m was dated to 15.41 Ma (Damon and Shafiqullah, 1996) and can be used as a minimum age of the underlying conglomerate and the erosion surface (Fig. 4B). Small patches of conglomerates and lava flows less than 50 m above the modern creek and following its course are preserved half way up the canyon and were probably deposited and/or emplaced in the late Quaternary. The reconstruction of the unconformity, by subtracting fault movement, results in a very smooth geometry with a gentle slope and ~460 m of relief related to pre-volcanic (pre–15 Ma) erosion or erosional escarpment retreat. In the middle of the canyon, a lower basalt flow is preserved on another erosion surface—175 m below the mid-Miocene basalt flow and 320 m above the river. We dated this flow to 4.62 ± 0.044 Ma (Table 2). Consequently, we determine average minimum incision rates of 16 m/m.y. between 15.4 and 4.6 Ma and maximum 69 m/m.y. incision rates since 4.6 Ma (Table 3). Exact numbers of how much relief has been generated after volcanism cannot be determined, since the paleorelief of the canyon mouth is not preserved. However, more than 400 m of the incision after the emplacement of Middle Miocene volcanics occurred below the Paleozoic–Cenozoic unconformity at the canyon mouth (Fig. 5) and therefore indicate that about half of the relief was generated since the Late Miocene with incision rates accelerating strongly toward the present.

Oak Creek Canyon

Oak Creek Canyon has a complex geologic history linked to the Oak Creek fault system, which the canyon follows. The Oak Creek fault has a length of ~50 km, strikes chiefly north-south and displays in general 200 m net down-to-the-east movement but preserves a history of reverse motion prior to reactivation as a normal fault (Holm and Cloud, 1990). In the upper canyon, the Paleozoic–Cenozoic unconformity on the east side of the canyon slopes gently to the south until the exposure of two large conglomerate channels at high elevation (Fig. 6). In the next 10 km downstream, the unconformity drops from ~1880 m to 1610 m and subsequently rises again. More than 200 m of relief on the unconformity is due to pre-volcanic erosion (Fig. 6). The geomorphic and stratigraphic positions and compositions of the various mapped Cenozoic conglomerates suggest that at least two different generations of conglomerates are preserved in Oak Creek Canyon—one preserved in deep channels at high elevations cut into the Kaibab Formation and a second ~200 m lower (Peirce et al., 1979), cut into the Upper Supai Formation. At Schnebly Hill Road, a conglomerate at intermediate elevation is cut into the Coconino sandstone near the Oak Creek fault. The channel appears to be located in a splay of the fault, and therefore its relationship to other deposits remains unclear.

The lower conglomerates are buried by Late Miocene basalt flows, while at the head of the modern canyon a sequence of basalt flows of Late Miocene–Early Pliocene age are exposed. Whereas lava flows on either canyon wall are horizontal, these flows at the head of the canyon clearly slope down across topography into an ancestral Oak Creek canyon. The base of the flows was traced and correlated based on mineralogy and with help of a portable X-ray fluorescence detector following the approach of Young (2014). The lowest flow in the sequence was dated to 6.05 Ma (Damon et al., 1974) and slopes only ~15 m down to the south, while the highest flow in the sequence, dated here to 4.75 ± 0.038 Ma, has ~200 m of relief on its base (Fig. 6), suggesting significant incision between 4.7 and 6 Ma at rates of more than 50 m/m.y. The earlier history of faulting and incision along Oak Creek Canyon is more complex, as exemplified by the exposure of the Surveyor Canyon conglomerate at modern river level at the mid-point of the canyon. Whereas the upper and lower perch rocks are composed of conglomerates of the various mapped Cenozoic conglomerates, the Surveyor Canyon conglomerate at first glance suggests that >100% of the incision of the modern canyon had been accomplished prior to its deposition similar to the Paleocene–Eocene paleocanyons on the Hualapai Plateau (Elston and Young, 1991). The local structural setting, however, is complex, requiring a detailed examination.

Surveyor Canyon is a side canyon of Oak Creek Canyon with a minette vent and Cenozoic conglomerates exposed in the bottom of the modern canyon (Fig. 7). The vent comprises several dikes and small lava flows surrounded by volcanic breccias (Mears, 1950). It was emplaced into the upper Paleozoic Coconino, Toroweap, and Kaibab Formations. The dikes consist of vesicular, porphyric minette with up to 4-mm-sized biotite, pyroxene, and plagioclase.
phenocrysts. A dike of the vent was dated to 25.28 ± 0.6 Ma by K-Ar dating (McKee et al., 1998) and re-dated in this study by Ar/Ar dating to 26.73 ± 0.28 Ma (Table 2) to test the accuracy of older K-Ar ages. Age and composition of the dikes are very similar to minette from the Navajo volcanic field (Roden, 1981; Laughlin et al., 1986). Dikes cutting through the Paleozoic rock sequence are found close to the canyon walls, suggesting subsurface emplacement, but features indicating surface conditions can also be found. These features include a lava flow, pillowing, and thin horizontal layers of sand-sized, rounded clastic and volcanic components. The base of the Kaibab Formation in the canyon is 75 m lower than on the eastern and 230 m lower than on the western Oak Creek Canyon wall. The drop on the east side of the canyon is accomplished by a previously unmapped fault close to Oak Creek (Fig. 7). Hence, the modern valley axis coincides with a graben. At the western margin of the vent complex, a small, previously unrecognized conglomerate is exposed (Fig. 7). The contact of the minette and the underlying conglomerate is inclined toward the center of the vent and therefore demonstrates that the conglomerate must be older than the minette. The volcanics either erupted through the sediment or onlapped against a surface eroded into the conglomerate. Close to the vent complex but ~200 m above the canyon bottom, a channel of conglomerate is preserved at Thomas Point at ~1800 m asl (Fig. 7). The Surveyor Canyon conglomerate and the Thomas Point sediments are only 600 m apart horizon tally, have an identical composition, and both lack volcanic clasts. Both consist mainly of rocks that are exposed tens of kilometers to the south—lower and middle Paleozoic rocks with minor upper Paleozoic and rare Precambrian clasts. The mapping of the minette vent suggests a surface eruption in the western part of the vent complex. The inclined contact of the conglomerate in the valley with the minette vent shows that the conglomerate must be older than the vent here dated to 26.73 ± 0.28 Ma. Since the conglomerate and the

| Laboratory ID | Sample ID | Latitude (°N) | Longitude (°E) | Locality (site Fig. 1) | Plateau age (Ma) | 2 SD (Ma) | Isochron age (Ma) | 2 SD (Ma) | Total fusion age (Ma) | 2 SD (Ma) | Site description |
|---------------|-----------|---------------|----------------|------------------------|-----------------|----------|-----------------|----------|----------------------|----------|------------------|
| 818-01        | RO 98_01  | 34.455        | -111.533       | Fossil Springs (9)     | 8.02            | 0.50     | 8.04            | 0.16     | Lava flow at Pocket Point Tank |
| 818-02        | RO 98_02  | 7.95          | 0.16           | 8.12                   | 0.23            | 7.75     | 0.32            |          |                      |
| 818-03        | RO 98_03  | 8.49          | 0.25           | 8.60                   | 0.29            | 8.41     | 0.61            |          |                      |
| 819-01        | RO 57_01  | 34.761        | -111.773       | Lookout Mountain (7)   | 14.604          | 0.066    | 14.53           | 0.24     | Lava flow capping conglomerate |
| 819-02        | RO 57_02  | 15.14         | 0.32           | 14.99                  | 0.23            |          |                |          |                      |
| 819-03        | RO 57_03  | 15.02         | 0.32           | 14.97                  | 0.24            |          |                |          |                      |
| 819-04        | RO 57_04  | 15.12         | 0.32           | 15.11                  | 0.27            |          |                |          |                      |
| 819-05        | RO 57_05  | 15.12         | 0.36           | 15.13                  | 0.26            |          |                |          |                      |
| 821-01        | RO 50_01  | 34.98         | -111.747       | Oak Creek Canyon (8)    | 26.73           | 0.28     | 26.63           | 0.33     | 25.85                | 0.28     | Minette vent     |
| 821-02        | RO 50_02  | 26.37         | 0.24           | 27.70                  | 0.28            |          |                |          |                      |
| 821-03        | RO 50_03  | 26.66         | 0.28           |                       |                |          |                |          |                      |
| 822-01        | RO 46_01  | 34.56         | -111.616       | W. Clear Creek Canyon (1) | 9.39         | 0.77     | 9.26            | 0.16     | Base of volcanic sequence |
| 822-02        | RO 46_02  | 9.59          | 0.13           | 9.96                   | 0.29            |          |                |          |                      |
| 822-03        | RO 46_03  | 9.73          | 0.13           | 9.71                   | 0.34            |          |                |          |                      |
| 824-01        | ROAD 1_01 | 34.91         | -112.064       | Sycamore Canyon (6)    | 4.57           | 0.19     | 4.62            | 0.11     | Lava flow on intermediate erosion surface |
| 824-02        | ROAD 1_02 | 4.58          | 0.12           | 4.62                   | 0.13            |          |                |          |                      |
| 824-03        | ROAD 1_03 | 4.70          | 0.14           | 4.67                   | 0.13            |          |                |          |                      |
| 824-04        | ROAD 1_04 | 4.94          | 0.11           | 5.09                   | 0.34            |          |                |          |                      |
| 824-05        | ROAD 1_05 | 4.622         | 0.044          | 4.61                   | 0.12            |          |                |          |                      |
| 825-01        | RO 108_01| 34.56         | -111.637       | W. Clear Creek Canyon (5) | 6.25         | 0.15     | 6.18            | 0.14     | Top of volcanic sequence |
| 825-02        | RO 108_02| 6.35          | 0.19           | 6.28                   | 0.13            |          |                |          |                      |
| 825-03        | RO 108_03| 6.25          | 0.19           | 6.30                   | 0.13            |          |                |          |                      |
| 825-04        | RO 108_05| 6.67          | 0.18           | 6.62                   | 0.26            |          |                |          |                      |
| 825-06        | RO 108_06| 6.24          | 0.19           | 6.30                   | 0.16            |          |                |          |                      |
| 827-01        | RO 104_01| 35.017        | -111.739       | Oak Creek Canyon (4)    | 4.774          | 0.066    | 4.736           | 0.075    | 4.760                | 0.100    | Basalt flow in canyon |
| 827-02        | RO 104_02| 4.751         | 0.038          | 4.763                  | 0.052            |          |                |          |                      |
| 828-01        | RO 85_01  | 34.421        | -111.592       | Fossil Springs (3)     | 13.02          | 0.12     | 12.5            | 1.2      | 14.66                | 0.25     | Lava flow capping conglomerate 30 m above creek |
| 828-02        | RO 85_02  | 13.09         | 0.23           | 12.89                  | 0.43            |          |                |          |                      |
| 830-01        | RO 81_01  | 34.82         | -111.715       | Lee Mountain (2)       | 15.44          | 0.16     | 15.3            | 1.5      | 15.45                | 0.47     | Lava flow capping conglomerate |
| 830-02        | RO 81_02  | 15.44         | 0.16           | 15.45                  | 0.47            |          |                |          |                      |

Note: Detailed plateau age plots are in the Supplemental File [text footnote 1]. SD—standard deviation.
presumably surface volcanics are both exposed at the bottom of the modern canyon, it follows that either a canyon at least as deep as the modern Oak Creek Canyon had already been carved before 26.7 Ma, or these deposits were downdropped on faults to their current position. If the canyon was carved to its modern depth before 26.7 Ma, it must have filled with at least 250 m of gravels to fill the canyon to the top of the conglomerate at Thomas Point. Subsequent eruption of lava flows would have buried this conglomerate, but incision from a presumably south-flowing river must have removed all evidence of such a deep paleocanyon. The other possibility to explain the modern geology is a polarity change in fault kinematics, consistent with the history of the Oak Creek fault (Holm and Cloud, 1990) (Fig. 7D). It is possible that the fault block that forms the floor of Surveyor Canyon, which is a graben at present, was a horst at the time of conglomerate deposition and volcanism. Holm and Cloud (1990) showed that the Oak Creek fault was a reverse fault during Laramide compression. If the rocks forming the modern canyon floor were previously much higher, the conglomerate at the canyon bottom could have been continuous with the conglomerate at Thomas Point, our favored interpretation (Fig. 7D).

**Dry Beaver Creek Canyon**

The cross section of Dry Beaver Creek Canyon, combined with sedimentary data and radiometric ages, allows a detailed reconstruction of the unconformity at different time intervals (Fig. 5B). Cenozoic conglomerates recording different depositional episodes and up to 150 m of volcanic rocks rest on an irregular surface eroded into the Paleozoic strata. The general geologic structure is gently west-dipping Paleozoic strata cut by steep normal faults. Faults in the eastern part of this canyon mainly have down-to-the-northeast movement, whereas faults at the mouth of the canyon have down-to-the-southwest movement. The net displacement along the entire southern canyon wall is 135 m down to the east. The Paleozoic–Cenozoic unconformity rises from the canyon mouth ~1000 m to the Colorado Plateau (Table 3). Adding the 135 m down-to-the-east displacement by faults to this relief results in 1135 m relief on this surface at present. Figure 6 illustrates that ~640 m of this relief was caused by erosion, and the remaining 495 m are due to the gentle westward tilt of the Paleozoic strata. The geometry of the restored unconformity is shown in Table 3. SUMMARY OF DIFFERENT FACTORS CONTRIBUTING TO THE RELIEF ON THE TERTIARY–PALEOZOIC UNCONFORMITY

| Canyon                | Total relief on Tertiary–Paleozoic unconformity (m) | Erosion (m) | Faulting (m) | Dip of layers (m) | Average incision rates (m/m.y.) |
|-----------------------|-----------------------------------------------------|-------------|--------------|-------------------|-------------------------------|
| Sycamore Canyon       | 920                                                 | 460         | 30           | 0                 | 15–5 Ma: 17 Since 5 Ma: 65    |
| Dry Beaver Creek Canyon | 990                                                 | 640         | –135         | 485               | Since 5.4 Ma: 47 Since 6 Ma: 83 |
| Wet Beaver Creek Canyon | 670                                                 | 205         | 210          | 255               | –                             |
| West Clear Creek Canyon | 970                                                 | 470         | 290          | 210               | Since 8 Ma: 45               |
| Fossil Creek Canyon   | 945 (710)                                           | 945 (710)   | ?           | 0                 | Since 8 Ma: 48               |

**Note:** In Fossil Creek Canyon, the values for the north rim are bracketed.
The reconstructed surface exhibits a gentle slope on what is today the Colorado Plateau. This slope is linked to the west limb of the Mormon Mountain Anticline (Weir et al., 1989). Farther west, two major breaks in slope can be seen. The first one is eroded into the Toroweap and Coconino sandstone with a relief of more than 300 m. The second is less steep and carved into the Upper Supai Formation with another ~300 m of relief. Sediments with different ages are deposited on this unconformity; the lower sediments deposited on this surface are part of the Beavertail Butte Formation. This deposit changes upsection from a locally derived conglomerate transported mainly southwest (parallel to the profile) to a mature sediment with distant source areas and transport in southeastern direction (perpendicular to the profile), mostly devoid of volcanic clasts (Holm, 2001). The overlying sediments deposited on this surface are dominated by angular clasts from the Kaibab Formation with varying content of Cenozoic basalt incorporated and composition very similar to the overlying lava flows. The transport direction is mainly south-southeast (perpendicular to profile). The 640 m of erosional relief must have been established by the time the lower, older conglomerate was deposited. The distribution of published K-Ar ages from Dry Beaver Creek Canyon (Fig. 5B) indicates...

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an average incision rate of 47 m/m.y. since the Pliocene. Less than 200 m of postvolcanic incision below the Paleozoic-Cenozoic unconformity show moderate relief generation since their emplacement.

Lee Mountain

We dated two lava flows north of Dry Beaver Creek Canyon at the top of Lee Mountain and Lookout Mountain below the Mogollon Rim. The resulting ages are 14.604 ± 0.066 and 15.44 ± 0.16 Ma, approximately coeval despite an elevation difference of 540 m. From the geologic map, one can estimate ~50 m of down-to-the-west movement along a fault (Weir et al., 1989). The remaining 490 m of elevation difference can be attributed to erosional relief at the time of lava flow emplacement (Fig. 8), again possibly having retreated to this position following an earlier period of faulting to the southwest. The dashed line in the inset of Figure 8 is the projection of the base of lava flows in the lower part of Dry Beaver Creek Canyon (see Fig. 5B). The base of the Middle Miocene lava flow dated in this study is the same as for the Late Miocene lava flows in Dry Beaver Creek Canyon, indicating a stable period without incision between 15 and 6 Ma. This is similar to the contemporaneous low incision rates we found in Sycamore Canyon.

Wet Beaver Creek Canyon

Wet Beaver Creek Canyon is located 12 km southeast of Dry Beaver Creek Canyon and carved into Permian strata with Tertiary conglomerates and volcanic sequences up to 250 m thick (Fig 9A). In Wet Beaver Creek Canyon, the total relief on the Paleozoic–Tertiary unconformity is ~670 m within a distance of 25 km from the mouth of the canyon. Figure 9A illustrates that only ~205 m of the 670 m rise of the unconformity result from erosion in the Cenozoic. About 210 m of relief are accumulated by normal faults with down-to-the-west movement that offset the Tertiary conglomerates and volcanics. The remaining 255 m of relief probably result from the dip of the east limb of the Mormon Mountain anticline mapped by Twenter and Metzger (1963). Uncertainty remains in the eastern part of the canyon where the river does not cut down to the unconformity, and no information about faults can be gained. Two faults are inferred from Weir et al. (1989), but their throw is uncertain, and more faults might be present leaving ambiguity about the geometry of the unconformity. Therefore, the relief on the prevolcanic land surface might be less than indicated in Figure 9A. The reconstructed unconformity is very gentle with ~210 m of relief related to prevolcanic erosion and without an
ancestral Mogollon Rim. About 150 m of the post–Middle Miocene incision into the Paleozoic rocks show a moderate relief increase of up to 50%, similar to Dry Beaver Creek.

**West Clear Creek Canyon**

West Clear Creek Canyon is 35 km long, and the geology of the canyon walls exposes the longest section of the Paleozoic–Cenozoic unconformity in the Verde Valley. The age of the unconformity is constrained by one published K-Ar and two new Ar/Ar ages from lava flows presented in this study (Fig. 9B). The canyon cuts through Paleozoic strata overlain by up to 450 m of volcanic rocks. The relief on the Paleozoic–Cenozoic unconformity is ~945 m in total. Figure 9B reveals that ~470 m of the relief on this unconformity can be attributed to erosion, whereas at least 290 m are the product of normal faulting. About 210 m of relief on the unconformity result from the dip of sedimentary strata on the eastern limb of the Mormon Mountain Anticline. All the faults in this canyon cut the volcanic rocks and therefore must be postvolcanic. Subtraction of the fault movement results in a highly irregular surface, which

![Figure 9](http://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/14/4/1690/4265559/1690.pdf)
should roughly correspond to the prevolcanic erosion surface, assuming a Laramide age of the Mormon Mountain Anticline (Twenter and Metzger, 1963). The reconstruction of the prevolcanic erosion surface illustrates that a major escarpment was present before the volcanic rocks were emplaced (Fig. 9B). This escarpment is carved into the Coconino sandstone, has a relief of more than 200 m, and is located ~15 km east of the modern-day Mogollon Rim. The lava flows buried this part of the ancestral Mogollon Rim ca. 10 Ma, and it took ~3.5 m.y. to accumulate the 355-m-thick volcanic sequence at the sampled location (Fig. 9B). Subsequently, the more than 500-m-deep canyon was cut (primarily re-incising through the volcanic fill) at an average rate of 77 m/m.y. since ca. 6.6 Ma. Paleozoic rocks in the lower reach are incised only ~60 m, showing that postvolcanic incision barely increased canyon depth.

Fossil Creek Canyon

Fossil Creek exposes a steep drop and 945 m of relief of the Paleozoic-Cenozoic unconformity (Figs. 4C and 9C). Twenter (1962) first described an ancestral Mogollon Rim with volcanic rocks accumulating against it. Peirce et al. (1979), Peirce (1987), and Holm (2001) also discuss different erosional episodes at Fossil Creek Canyon. In the northeast, thin basalt flows cover the Paleozoic strata at elevations up to 2070 m. The altitude of the Paleozoic–Cenozoic unconformity drops from 2070 m at Five Mile to 1280 m at Fossil Springs and even more farther downstream where the unconformity has not been exposed by post-Miocene incision (Fig. 9C). In Figure 4, an oblique view of the unconformity drop on northeastern canyon wall is shown, from ~1850 m at Pocket Point Tank to 1280 m 6 km downstream. Since the unconformity has not been exposed farther downstream, only a minimum estimate of paleorelief can be inferred. From Fossil Springs to the Irving power plant at 1120 m, no major faults were observed; this elevation can be used as a minimum estimate for the base of the erosional surface. Therefore, at least 945 m of relief were present before the onset of volcanism. As noted above, this “erosional relief” may reflect erosional retreat of an earlier tectonic escarpment, possibly associated with slip on the Diamond Rim fault (a major normal fault southeast of the canyon). The Diamond Rim fault is not mapped to Fossil Creek but projects to a point downstream of the paleoescarpment now buried under lava and was an active down-to-the-south normal fault between 25 and 15 Ma (Mayer, 1979). Therefore, seemingly erosional relief might be a combination of erosional and prevolcanic tectonic relief in this area. Conglomerates and gravel deposits of different ages are found at many different elevations in Fossil Creek. At the base of the volcanic pile, thick Valley gravel (as evidenced by entrained basalt clasts [Holm, 2001] confirmed by our field study) channels with deposit thicknesses up to 70 m are exposed. Additionally, conglomerates of similar appearance are exposed at intermediate elevations (1675 and 1525 m) on the unconformity at the sharp break in slope (Fig. 9C). We dated a basalt flow 30 m above Fossil Creek to 13.02 ± 0.12 Ma and a flow from the top sequence to 7.95 ± 0.16 Ma. The 13 Ma date is a minimum age constraint for the cutting (potentially enhanced by earlier faulting) of ~945 m of prevolcanic relief at Fossil Springs and shows that the more than 400-m-thick volcanic sequence accumulated in ~3.5–4.5 m.y. Subsequently, the K-Ar age and Ar/Ar age from the top of the sequence reveal an average incision rate of 54 m/m.y. since 8 Ma. The fact that Fossil Creek has not incised all the way through conglomerates below the ancestral rim shows that all of the relief was already generated before the Middle Miocene volcanism.

DISCUSSION

Cenozoic lava flows and sediments and their relationship to the Paleozoic rocks of the Verde Valley provide important constraints on the incision history of this region. We first discuss age constraints on Plateau and Valley gravels closely related to the timing of drainage reversal and first episode of relief formation along the Mogollon Rim and incision. Subsequently, we explore interpretation of the geometry of the Paleozoic–Tertiary unconformity and incision rates from the cross sections and lava flow ages to see if these require young Colorado Plateau uplift. Finally, we discuss the evolution of landscape morphology within the context of local base-level history.

Timing of Early Relief Formation from Age Constraints on Plateau and Valley Gravels

The canyon cross sections show that a significant fraction of modern-day relief already existed in the Miocene Verde Valley landscape. The timing of relief formation can be estimated by constraining the ages of conglomerates below and above the Mogollon Rim. The minimum age of valley gravels is constrained by the age of overlying lava flows, while the maximum age can be constrained by the composition of Valley gravels and the relationship to the Plateau gravels. Our Ar/Ar ages from overlying basalt flows at Lookout Mountain, West Clear Creek Canyon, and Fossil Creek Canyon show that the Valley gravels in the study area must have been deposited before the early Middle Miocene (14.6–13.0 Ma) emplacement of the lava flows. This is in agreement with published K-Ar ages from Black Mountain, House Mountain, Beavertail Butte, and the mouth of Wet Beaver Canyon (Fig. 1), where the Valley gravels are overlain by 15.4–13.4 Ma lava flows. Sullivan Butte latite clasts can be found only in some Valley gravels and could be an indicator for deposition after the volcanic activity at Sullivan’s Butte 27–21 Ma ago (Krieger et al., 1971). Reworking of Plateau gravels containing Sullivan Butte’s latite seems unlikely since these clasts can only be found in upper Valley gravels with more distant source areas and are absent in the underlying locally derived Valley gravels considered here. Holm (2001) reported rare basalt cobbles in Valley gravels (Fossil Creek Canyon, and Black Mountain), an observation confirmed by our field work. The presence of basalt in the Valley gravels and absence of them in Plateau gravels together show that the Valley gravels must be younger be-
cause they were deposited after the onset of volcanism at ca. 27 Ma. Moreover, imbrication measurements by Holm (2001) showed that the Valley gravels are consistent with deposition in a southeasterly-flowing drainage system, contrary to general northeasterly transport of Plateau gravels—an observation also confirmed by our field measurements.

Our cross sections illustrate that the Valley gravels were deposited below an erosional escarpment (or erosional retrograded tectonic escarpment), which requires drainage reversal prior to deposition. In conclusion, the valley gravels have been deposited after the deposition of Plateau gravels and after drainage reversal and the formation of an ancestral Mogollon Rim but before mid-Miocene. Since Valley gravels were deposited below an ancestral Mogollon Rim, they must have been deposited in a south-flowing stream network, moving the timing of drainage reversal and first episode of relief generation in central Arizona to between the end of Plateau gravel deposition (after 33.3 Ma; Potochnik, 2001) and the beginning of Valley gravel deposition (27–15 Ma).

The observations from Surveyor Canyon place an additional constraint on the timing of Plateau gravel deposition in the region. Evidence of a surface eruption and conglomerates consistent with a north-flowing drainage system are found in the bottom of the modern canyon and therefore suggest either a switch in fault polarity or a deep north-flowing paleocanyon filled by conglomerates now being re-excavated. The switch in fault polarity seems more likely than a deep paleocanyon for three reasons. (1) There is no independent supporting evidence for significant incision in this region before ca. 25 Ma. (2) If an ancestral Oak Creek Canyon was carved to its modern depth and filled with gravels and capped by lava flows, it is unlikely that all gravel remnants would have been removed. (3) There is no evidence in other canyon walls that a canyon of this size (more than 500 m wide and 250 m deep) could have continued farther north or south. Thus we conclude that the Surveyor Canyon graben structure was a horst until the Oak Creek fault was reactivated as a normal fault after the volcanism in the region, and that the conglomerate found at the bottom of the modern canyon is part of the Plateau gravels deposited here before the minette vent erupted 26 m.y. ago in a north-flowing drainage system, consistent with other age estimates of Plateau gravels in the region. Potochnik (2001) dated a basalt flow overlying Plateau gravels at Blue Ridge 65 km SE of Surveyor Canyon to 33 Ma.

Pre–Middle Miocene Relief on the Mogollon Rim, Incision Rates, and Colorado Plateau Uplift

Canyons cut into the Verde Valley expose the Paleozoic–Cenozoic unconformity and reveal information about the time before the sedimentary strata were covered by lava flows. All over the Verde Valley, volcanic activity mainly took place in the Middle and Late Miocene, and therefore erosion surfaces from different canyons can be roughly correlated. Accounting for fault movement and dip of sedimentary strata to estimate the amount of erosion and relief prior to volcanism involves the assumption that during the formation of the erosion surface, the strata were not faulted but were already tilted. Most faults in the study area displace the Cenozoic volcanic rocks and can therefore be assumed to have been activated during or after the emplacement of the volcanic rocks. Moreover, the tilt of sedimentary strata in the field region is mainly caused by the Mormon Mountain Anticline, which is believed to be a Laramide structure (Twenter and Metzger, 1963) similar to others on the Colorado Plateau. Prevolcanic relief can then be used to estimate the timing of Colorado Plateau uplift (Fig. 3).

The reconstructions of the unconformity with fault displacement restored reveal that the prevolcanic erosion surfaces covered by Miocene lavas already exhibited substantial relief in the Verde Valley region in the Middle Miocene. Depending on the timing of the tilting associated with the Mormon Mountain Anticline, the average relief on the unconformity ranges from ~730 m (if tilting predates the erosion surfaces) to 540 m (if tilting postdates the erosion surfaces) (see Table 3). Since the last known folding of Paleozoic rocks occurred during the Laramide orogeny, a Laramide age for this Anticline seems most plausible, and we assume an average Middle Miocene relief of ~700 m. The erosion surface at Fossil Creek shows that maximum prevolcanic relief had to be nearly 1000 m, similar to Dry Beaver Creek Canyon. However, southeast of Fossil Creek Canyon, the Diamond Rim fault was active between 25 and 15 Ma (Mayer, 1979) with ~400–600 m normal slip (S. Reynolds, 2017, personal commun.). If this fault continues below the volcanic infill of the Fossil Creek area, the prevolcanic relief might be explained by relief generation by normal faulting and subsequent erosional escarpment retreat. Contemporaneous normal faulting may have contributed to relief generation throughout the Verde Valley. Almost the entire modern relief in the southeastern Verde Valley had already been established in Middle Miocene, and the Colorado Plateau elevation must therefore have been a minimum of ~1 km, assuming the floor of the Verde Valley was not dropped below sea level. This substantial amount of prevolcanic relief requires that half of the Colorado Plateau uplift must have been accomplished before Middle Miocene (Fig. 3).

Subsequent emplacement of Middle Miocene and Late Miocene lava flows must have interrupted the stream system and might be responsible for low rates of incision as documented by the 16 m/m.y. incision average observed in Sycamore Canyon and in the Lee Mountain area between 15 and 6 Ma. Thereafter, incision rates accelerated substantially toward the present and reached average rates of 50–80 m/m.y. since 6–8 Ma everywhere in the valley. Because the Verde Valley was occupied by a lake until ~2.5 m.y. ago (Bressler and Butler, 1978), incision rates in the Quaternary were probably a lot higher; streams draining to the Verde Valley likely experienced a base-level rise during accumulation of the Verde Formation between 7.5 and 2.5 Ma. It is likely that much of the incision has occurred since the base-level drop associated with the breaching of the Lake Verde basin. This is supported by the removal of at least 300 m of lake sediments since the breaching event (House, 1994). This base-level drop is sufficient to explain canyon re-excavation and deepening and therefore does not require young Colorado Plateau uplift. Oak Creek Canyon marks an exception in this context because the dated basalt flow in the middle of the canyon is only ~1.5–3 m.y. younger than basalt.
flows from the base of the volcanic sequence dated farther downstream on the eastern canyon wall (Fig. 6). Assuming that it took more than 1 m.y. to fill the entire canyon with lava flows, which seems reasonable considering the duration of volcanic infilling in Fossil Creek and West Clear Creek Canyon (Fig. 9), there must have been rapid downcutting at the head of the canyon to create 200 m of relief on the base of the lava flow dated to 4.75 Ma. We speculate that weakness of the local bedrock caused by the Oak Creek fault allowed the canyon to maintain an excavated flow path during the period of volcanism while other canyons were choked by lava flows.

Figure 10 shows how deeply the different canyons have cut below the unconformity after emplacement of the Middle Miocene lava flows. The amount of incision below the unconformity steadily decreases from northwest to southeast and reaches zero at Fossil Creek Canyon, where the Paleozoic–Cenozoic unconformity is still buried in the lower reaches of the canyon. This illustrates that despite significant Middle Miocene paleorelief, post-Miocene erosion progressively increased relief to the northwest, upstream of the breach of the Lake Verde, reinforcing the argument that most of the postvolcanic incision has been driven by local base-level fall and does not require young Colorado Plateau uplift.

Evolution of the Modern Verde Valley Landscape

As noted earlier, the morphology of the Mogollon Rim changes greatly in the Verde Valley from steep cliffs in the north to gentler vegetated slopes in the southeastern part of the Valley. This seems to be linked with erosion induced by

Figure 10. The amount of incision below the Paleozoic–Cenozoic unconformity after the emplacement of Middle and Late Miocene lava flows. The canyons are plotted from northwest to southeast, and the measured locations are indicated in the respective cross sections (Figs. 5, 6, and 9) by dashed white lines and are all placed close to the respective canyon mouth. Note the decrease of incision below the unconformity toward the southeast.

Figure 11. Map showing the distribution of Verde Formation in the Verde Valley (yellow), weak shales of the Hermit Formation (brown), and major faults indicating the steep and gentler parts of the Mogollon Rim escarpment. The white contour represents the elevation of the highest large remnant of Verde Formation on House Mountain (1430 m). The blue contour corresponds to the level of high remnants of Verde Formation mapped by Karlstrom et al. (1983), mainly scattered limestone pebbles and encrustations but confirmed in our field observations.
the southern margin of the Valley close to the Verde fault and the geophysically imaged deep part of the graben (Langenheim et al., 2005); whereas in the east, there is a roughly 3–4-km-wide swath between the contour lines and the first occurrence of Verde Formation. In the northern Verde Valley, this surface devoid of Verde Formation widens to more than 10 km. Figure 11 shows that the soft shales of the Hermit Formation are mainly exposed in this northern part of the Valley, where the Verde Formation is missing and the escarpment is the steepest. Either higher paleotopography in the north since removed by scarp retreat restricted the northward extent of the lake, or any deposits of lake sediments in the northern part of the valley have been removed by erosion, also probably associated with scarp retreat. In either case, this erosion and scarp retreat was probably facilitated by the weak shales of the Hermit Formation exposed at the base of the modern escarpment (Koons, 1955). Incision into this weak layer, and the subsequent undermining of stronger rock units above (Forte et al., 2016), probably also helped to steepen the northern part of the valley, thereby rejuvenating the appearance of the escarpment that retreated slowly beforehand.

The Hermit Formation could also have been exploited for fast rim retreat and escarpment steepening in the Miocene. The reconstructions of the Paleozoic–Cenozoic unconformity show that the steepest preserved, ancestral Mogollon Rim with by far the most relief is exposed at Fossil Creek Canyon, where the prevolcanic erosion was able to cut down to the Hermit Formation. The only other place where we have evidence for prevolcanic erosion cutting to such deep stratigraphic levels is close to Lee Mountain, where we also have evidence for a steep ancestral escarpment with ~500 m of relief. At the other canyons where the Hermit Formation is not exposed, we do not find ancestral escarpments with more than 200 m relief. Potentially the Hermit shale allowed Miocene escarpments that were initially formed by faulting to retreat quickly and keep a sharp morphology until the preservation by lava flows, analogous to the findings of Mayer (1979) just southeast of the field area.

**Geologic Evolution of the Region**

Figure 12 shows the Cenozoic geologic evolution of the region. The conglomerate found at Surveyor Canyon predates the minette vent and shows that conglomerates preserved from the northeast-directed drainage must be older than 26 Ma. This is in agreement with similar findings from other areas on the Colorado Plateau indicating a northeast-directed drainage system in the Eocene and potentially Oligocene (Fig. 12A). Reconstructions of the Paleozoic–Cenozoic unconformity show that gravels with young basalt clasts partly buried by Middle Miocene lavas have been deposited below erosional,
or tectonically generated and subsequently erosionaly retreated, relief of an ancestral Mogollon Rim after drainage reversal (Fig. 12B). The amount of relief present by the Middle Miocene shows that the Colorado Plateau had already reached half of its present elevation. The cross sections through the canyons show how Middle and Late Miocene lava flows drape across this relief, preserve it, and inhibit incision. Enhanced normal faulting after 10 Ma leads to the formation of a closed basin and deposition of lake sediments (Fig. 12C). Integration of the Verde River system following breaching of Lake Verde ~2.5 m.y. ago induces a base-level fall that causes incision rates to increase dramatically, forming new and excavating and deepening preexisting canyons (Fig. 12D) without the need for post–mid-Miocene uplift of the Colorado Plateau.

CONCLUSIONS

In this study, erosional surfaces and the composition and geomorphic position of Cenozoic sediments were combined with 15 new Ar/Ar ages from nine lava flows in order to address the Cenozoic incision history of the Verde Valley, with implications for uplift of the Colorado Plateau. Throughout the Paleocene, Eocene, and potentially in the Oligocene, the Mogollon Highlands south of the transition zone were higher than the ancestral Colorado Plateau to the north-east. This led to a northeast-directed drainage system and the deposition of Plateau gravels on the surface of the Colorado Plateau. A minette vent in Surveyor Canyon shows that these Plateau gravels were deposited before 26.7 Ma in the Verde Valley region, consistent with constraints from elsewhere along the southwestern margin of the Colorado Plateau (Peirce et al., 1979; Potochnik, 1989; Elston and Young, 1991; Potochnik, 2001; Young, 2014). Some combination of plateau uplift and tectonic lowering of the base level to the south, probably related to Basin and Range extension, caused the formation of an ancestral Mogollon Rim and initiation of deposition of the Verde Valley gravels in the Late Oligocene or Early Miocene. These deposits filled a northwest-southeast-trending valley below the escarpment. The prevolcanic mid-Miocene landscape had substantial relief with an average of ~700 m (assuming the Mormon Mountain Anticline is a Laramide structure). The minimum of 945 m of prevolcanic relief at Fossil Creek Canyon reveals that the Colorado Plateau must have experienced at least 1 km uplift by Middle Miocene time, fully consistent with evidence that the SW Colorado Plateau was already at modern elevations by 16 Ma (Huntington et al., 1979). Middle and Late Miocene lavas filled the canyons and probably disrupted the drainage network significantly. Incision rates from this time period are less than 20 m/m.y. Ar/Ar ages from top and bottom sections of volcanic infills show that most canyons were filled by lavas over a time period from 3 to 4 Ma. Subsequently, from the Late Miocene to modern day, incision rates accelerated substantially and reached averages of ~50–80 m/m.y. since 5–8 Ma. Incision rates during the Quaternary are likely to have been a lot higher since the base level of rivers dropped significantly after internal drainage and lake formation ended ca. 2.5 Ma. The re-incision of canyons may have all occurred since 2.5 Ma at average rates of 100–160 m/m.y. The 300–500 m base-level drop documented by erosional removal of Verde Formation sediments is fully sufficient to account for observed post-volcanic incision amounts. In the northern part of the Verde Valley, the enhanced erosion since 2.5 Ma might have driven fast rim retreat and steepening of the escarpment due to undermining at the contact with the underlying weak Hermit shale formation. Canyons incision in this region seems to be dictated by the base-level history, Early-Middle Miocene extensional faulting, and later breaching of Lake Verde. Therefore, although Late Miocene to present Colorado Plateau uplift cannot be excluded, no uplift is required to explain canyon incision in the Verde Valley.

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