Unroofing, incision, and uplift history of the southwestern Colorado Plateau from apatite (U-Th)/He thermochronometry

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ABSTRACT

The source of buoyancy for the uplift of cratonic plateaus is a fundamental question in continental dynamics. The ~1.9 km uplift of the Colorado Plateau since the Late Cretaceous is a prime example of this problem. We used apatite (U-Th)/He thermochronometry (230 analyses; 36 samples) to provide the first single-system, regional-scale proxy for the unroofing history of the southwestern quadrant of the plateau. The results confirm overall southwest to northeast unroofing, from plateau margin to plateau interior. A single phase of unroofing along the plateau margin in Late Cretaceous to Early Tertiary (Sevier-Laramide) time contrasts with multiphase unroofing of the southwestern plateau interior in Early and mid- to Late Tertiary time. The Early Cretaceous was characterized by northeastward tilting and regional erosion, followed by aggradation of ≥1500 m of Upper Cretaceous sediments along the eroded plateau margin. Sevier-Laramide denudation affected the entire southwestern plateau, was concentrated along the plateau margin, and migrated from northwest to southeast. Following a period of relative stability of the landscape from ca. 50–30 Ma, significant unroofing of the southwestern plateau interior occurred between ca. 28 and 16 Ma. Additional denudation north of the Grand Canyon took place in latest Tertiary time.

Mid-Tertiary dates from the Grand Canyon basement at the bottom of the Upper Granite Gorge limit significant incision of the modern Grand Canyon below the Kaibab surface to <23 Ma. Modeling the age distributions of samples from the basement and Kaibab surface nearby suggests that the gorge and the plateau surface had similar Early to mid-Tertiary thermal histories, despite their >1500 m difference in vertical structural position. If these models are correct, they indicate that a "proto–Grand Canyon" of kilometer-scale depth had incised post-Paleozoic strata by the Early Eocene. Evidence for kilometer-scale mid-Tertiary relief in northeast-flowing drainages along the plateau margin, as well as the mid-Tertiary episode of plateau interior unroofing, imply that the southwestern plateau interior had attained substantial elevation by at least 25–20 Ma, if not much earlier. These observations are inconsistent with any model calling for exclusively Late Tertiary uplift of the southwestern plateau.

Sevier-Laramide plateau surface uplift and incision thus result from one or more processes that enhanced the buoyancy of the plateau lithosphere, expanding the Cordillera's orogenic highlands into its low-standing cratonic foreland. The onset of the Laramide slab's demise at ca. 40 Ma and the major pulse of extension in the Basin and Range from ca. 16–10 Ma appear to have had little influence on the denudation history of the southwestern plateau. In contrast, the post-Laramide unroofing episodes may be explained by drainage adjustments induced by rift-related lowering of regions adjacent to the plateau, without the need to otherwise modify the plateau lithosphere. Our data do not preclude a large component of post–Early Eocene elevation gain (or the geodynamic mechanisms it may imply), but they do point toward Laramide-age buoyancy sources as the initial cause of significant surface uplift, ending more than 500 m.y. of residence near sea level.

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INTRODUCTION

Like most of the North American craton, the Colorado Plateau remained near sea level for 500 m.y. during slow subsidence and deposition of Paleozoic and Mesozoic sediments (Hunt, 1956). However, unlike most of the craton, the plateau was uplifted to its current elevation of ~1.9 km with little internal upper crustal strain (<1%), requiring the acquisition of significant lithospheric buoyancy, sometime after widespread deposition of Upper Cretaceous marine sediments.

Models of how this buoyancy was acquired are numerous (e.g., McGetchin et al., 1980; Morgan and Swanberg, 1985), and can be broadly subdivided into three groups on the basis of the predicted timing of uplift. Late Cretaceous to Early Tertiary uplift mechanisms related to Sevier-Laramide contractional deformation (80–40 Ma) include crustal thickening due to channel flow (e.g., McQuarrie and Chase, 2000), convective removal of lithospheric mantle (England and Houseman, 1988), or chemical modification of the lithosphere by volatile addition from the Laramide flat slab (Humphreys et al., 2003). Mid-Tertiary buoyancy addition (40–20 Ma), perhaps driven by the demise of the Laramide flat slab, could be due to partial removal of the plateau lithosphere and replacement with hot asthenosphere (Spencer, 1996), or post-Laramide chemical modification through melt extraction along the plateau margins (Roy et al., 2004). Late Tertiary uplift models (post–20 Ma) associated with regional extensional tectonism involve heating the lithosphere from below (Thompson and Zoback, 1979) possibly aided by a mantle plume (Parsons and McCarthy,

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1995), or convective removal of the lithospheric mantle (Bird, 1979; Humphreys, 1995).

Resolving when the Colorado Plateau rose to its present elevation is key to determining the mechanism(s) that drove its rise. However, resolving the timing and magnitude of continental uplift is a central challenge in tectonics. Thermochronologic data and geologic observations that constrain the past magnitude of relief in a landscape provide minimum estimates on past surface elevation (e.g., Elston and Young, 1991; House et al., 1998). Methods that decipher cooling during regional unroofing can be used to infer surface uplift, if denudation was a direct response to elevation gain, but in reality this relationship is complicated by the potential for unroofing to lag behind surface uplift, given the substantial variation in the effectiveness of erosive agents as a function of climate, drainage configuration, and other factors. Post-Cretaceous erosional unroofing of the plateau ranges from as much as 4.5 km in the Grand Canyon, to zero in early Tertiary basins on the plateau's perimeter (e.g., Dumitru et al., 1994; Pederson et al., 2002). We use apatite (U-Th)/He data to constrain the development of significant relief and the patterns of regional exhumation in the structurally highest, southwestern portion of the plateau (Fig. 1), and consider the implications for the timing of uplift.

TECTONIC SETTING

In the foreland of the Cordilleran orogen, the Colorado Plateau was affected by relatively mild Phanerozoic deformation compared to adjacent foreland regions that were more severely disturbed by late Paleozoic ancestral Rockies deformation, Late Cretaceous–Early Tertiary Sevier-Laramide contraction, and Late Tertiary Basin and Range–Rio Grande rift extension (Fig. 1). The plateau is underlain by Proterozoic basement, blanketed by Paleozoic strata 1–1.5 km thick, and overlain by Mesozoic strata up to 2–3 km thick (Hintze, 1993). Cretaceous units deposited during inundation by the western interior seaway are variably preserved (Nations, 1989). Late Cretaceous–Lower Tertiary strata are up to several thousand meters thick along the northern (Uinta and Piceance Basins), western (Markagunt-Sevier-Table Cliffs plateau), and eastern (San Juan Basin) margins of the plateau (e.g., Dickinson et al., 1989; Goldstrand, 1992; Goldstrand and Eaton, 2001). In contrast, along the southern (Rim gravels) and southeastern (Baca basin) margins, age-equivalent strata typically have maximum preserved thicknesses of only a few hundred meters (e.g., Koons, 1945; McKee and McKee, 1972; Young and McKee, 1978; Cather et al., 1987; Potochnik, 1989; Elston and Young, 1991). Extensive Oligocene and younger volcanism occurred on the plateau margins, while isolated silicic Oligocene to Miocene plutons intruded its interior (e.g., Hunt, 1956).

The northern plateau is characterized by a dome-and-basin structural pattern, with typical wavelengths of 100–150 km and amplitudes of 1.5–2.0 km (Fig. 1). Amplitudes range up to 3 km adjacent to the larger Laramide uplifts of the Rocky Mountains. Structural relief diminishes southwestward. Within the southwestern quadrant of the plateau, in northern and eastern Arizona, structural relief on pre-Laramide strata is less than ±1.0 km across the Defiance and Kaibab uplifts. Within 100 km of the southwestern plateau rim, relief is less than ±0.6 km (Fig. 1).

To first order, the structure of the southwestern portion of the Colorado Plateau (Fig. 2A) is a NE-dipping homocline with an average dip of ~0.4° across a strike length of 500 km. In the vicinity of the Grand Canyon, the homocline is interrupted by a broad (~15,000 km^2) structural terrace residing at an elevation of 1500–2000 m (Fig. 1), underlain by the resistant Permian Kaibab Limestone, and discontinuous exposures of fluvial sandstone of the Triassic Moenkopi Formation. To the northeast, progressively younger Mesozoic and Cenozoic formations are exposed in a series of cuestas known as the "Grand Staircase," beginning with the Vermilion and Echo Cliffs. To the west, the plateau edge is structurally delineated by major normal faults of the Basin and Range province adjacent to the Grand Wash trough (Brady et al., 2000; Faulds et al., 2001). The Colorado River currently drains the Colorado Plateau to the southwest (Fig. 2A), forming the Grand Canyon where it cuts across the topographically high southwestern plateau and incises to depths as great as 1600 m.

The southwest boundary of the physiographic plateau, defined by the southwesternmost exposures of Permian limestone, includes the Mogollon Rim and equivalent southwest-facing topographic escarpments in northwestern Arizona (Fig. 2A). Southwest of the boundary, the Precambrian basement rises quickly to the surface, forming a roughly 100-km-wide belt of exposure, referred to as the Transition Zone, which separates the Colorado Plateau from the Basin and Range province (e.g., Peirce et al., 1979). In this manuscript, we will refer to the southwestern boundary of the plateau as the "plateau rim" or "rim." We refer to that portion of the plateau that is within ~50 km of the rim as the "plateau margin." We refer to that portion of the plateau in northern Arizona that is greater than 50 km from the rim as the "southwestern plateau interior" or "plateau interior."

Tertiary Rim gravels are discontinuously exposed along the plateau margin, and record northeastward transport and unroofing of the Laramide Mogollon highlands to the southwest (Young, 1979; Potochnik, 1989, 2001). Locally, in the western Grand Canyon region near the plateau rim where the modern erosion surface cuts southwestward across the Paleozoic section, deeply incised paleochannels (coincident with the modern Milkweed and Peach Springs canyons) with >1200 m of relief preserve Rim gravels (Young, 1989, 1999, 2001; Elston and Young, 1991). In the Transition Zone of east-central Arizona, a similar paleocanyon (coincident with the modern Salt River) preserves 850–1400 m of relief, and contains a record of regional drainage reversal across the Mogollon Rim (Potochnik and Faulds, 1998; Potochnik, 2001). A plateau rim with up to 600 m of relief was present by the mid-Tertiary, with the former Mogollon highlands to the southwest becoming topographically lower than the region that is now the Colorado Plateau, implying drainage reversal toward the southwest at or subsequent to this time (e.g., Peirce et al., 1979). The thin (~100-m) areally extensive Bidahochi Formation (Fig. 2A) records fluvial and lacustrine aggradation from ca. 16–6 Ma (Dallegge et al., 2001). Along the western boundary of the plateau, the Transition Zone is absent, and a sharp boundary between the plateau rim and the highly extended central Basin and Range province is present along the Grand Wash cliffs (Wernicke et al., 1988; Brady et al., 2000). In the ranges north and west of Lake Mead, the easternmost décollement thrust faults of the Sevier orogenic belt are preserved (Fig. 2).

TIMING CONSTRAINTS ON COLORADO PLATEAU UPLIFT, INCISION, AND UNROOFING

Timing Constraints on Uplift

In this manuscript, we refer to "rock uplift" as the vertical displacement of rock relative to sea level, to "unroofing" as the thickness of rock removed through erosion or tectonism, and to "surface uplift" or simply "uplift" as the increase in surface elevation (in the sense described in England and Molnar, 1990). The widespread occurrence of Upper Cretaceous marine sediments on the plateau marks the last time it was known to be at sea level. In the southwestern plateau, these units are preserved in the Black Mesa area and along the Mogollon Rim (Fig. 2A). Estimates of when the plateau reached its current elevation are generally based on the record of events preserved within the southwestern plateau. These events include the

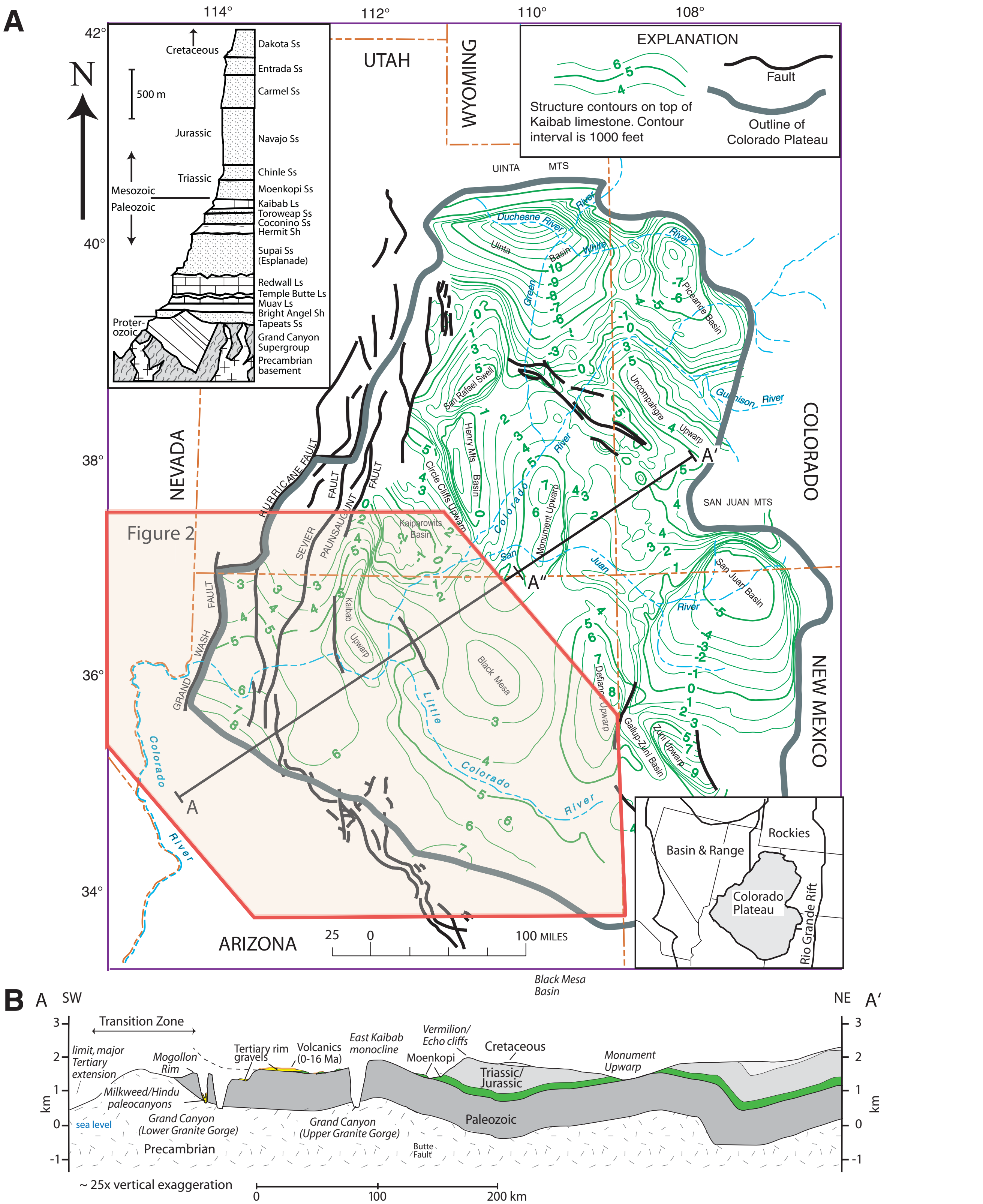

Figure 1. (A) Map from Hunt (1956) showing geomorphic outline of the Colorado Plateau and structure contours on top of the Permian Kaibab limestone and equivalents. Contour interval is 1000 ft. Location of map in Figure 2 is shown. A stratigraphic section for the southwestern plateau is included for reference. (B) Cross section through Colorado Plateau. Section line is A–A′ in (A). Section line A–A″ marks the location of the cross-sectional reconstructions in Figure 8. Features such as the Lower Granite Gorge are projected onto the cross-section line to more effectively depict the development and evolution of these features in our models.

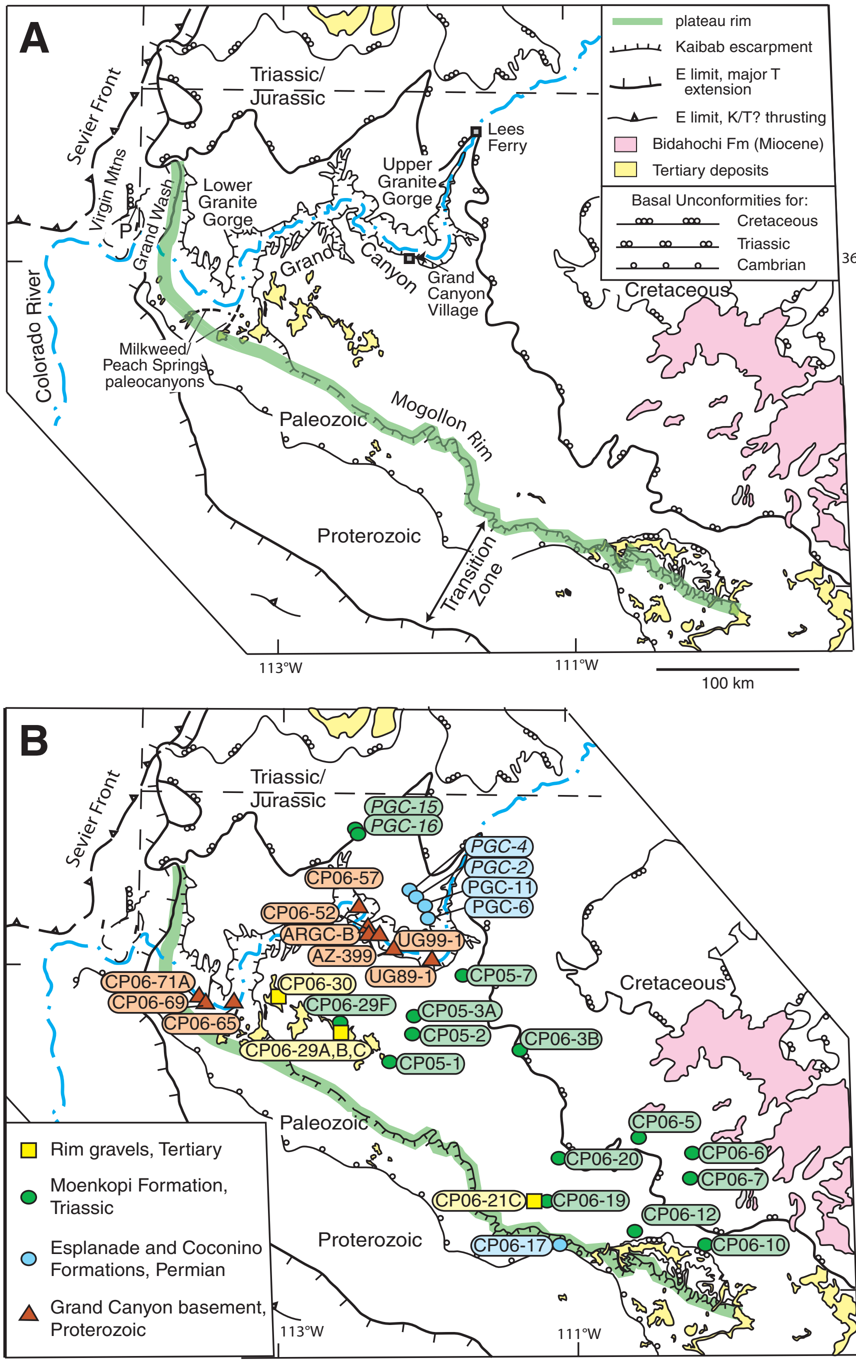

Figure 2. (A) Map showing selected tectonic elements of the southwestern Colorado Plateau. "P" indicates position of the southward pinchout of Mesozoic strata below sub-Oligocene unconformity in Virgin Mountains described in text. (B) Sample types, names, and locations.

reversal of drainage along the Mogollon Rim at 40–20 Ma induced by mid-Tertiary extension in central Arizona (e.g., Elston and Young, 1991), the abrupt truncation of the western plateau edge by extension from 16 to 11 Ma (e.g., Brady et al., 2000; Faulds et al., 2001), the appearance of the first Colorado River sediments in the Grand Wash trough after deposition of the Hualapai limestone near 6 Ma Hualapai limestone (e.g., Spencer et al., 2001), and the timing of incision of a Grand Canyon with kilometer-scale relief (e.g., Young, 1979; Lucchitta, 1979). A proposed marine origin for the upper Miocene Hualapai Limestone immediately west of the Grand Wash Cliffs and the Bouse Formation (preserved well downstream) along the lower reaches of the Colorado (Blair, 1978) suggested 800 m (the modern elevation of the youngest Hualapai Limestone) of plateau uplift since 6 Ma (Lucchitta, 1979). However, geochemical and physical evidence for a lacustrine origin of the Hualapai and Bouse makes this interpretation questionable (Spencer and Patchett, 1997; House et al., 2005). The only direct paleoaltimetry estimate for the southwestern portion of the plateau is based on the size distribution of vesicles in young basalts that suggests a general acceleration of uplift through the Tertiary (Sahagian et al., 2002), but this interpretation is also controversial (Libarkin and Chase, 2003; Sahagian et al., 2003). Thus, despite decades of debate, the timing of uplift of the southwestern Colorado Plateau is still only bracketed between ca. 80 Ma and the present, with little consensus on the details.

Timing Constraints on Incision

The timing and mechanisms of incision of the Grand Canyon, and the paleohydrology of the Colorado River, are highly controversial. From studies of the sedimentary record in the Grand Wash Trough where the Colorado River currently exits the western margin of the Colorado Plateau, it appears clear that the Colorado River did not become integrated into its modern course until after the 5.97 ± 0.07 Ma deposition of the Hualapai limestone (Longwell, 1946; Lucchitta, 1979, 1989; Faulds et al., 2001; Spencer et al., 2001). However, the course of the river from 16 to 5 Ma is problematic, resulting in a remarkable diversity of proposals for the pre-Pliocene paleohydrology of the southwestern plateau. A major topic of debate is whether lake spillover led to top-down river integration (e.g., Spencer and Pearthree, 2001; House et al., 2005) or headward erosion led to capture of an ancestral northward flowing Colorado River (e.g., Lucchitta 1979; Lucchitta et al., 2001). Another important uncertainty involves the role of pre-Pliocene paleocanyons in controlling the subsequent course of the river. The presence of the deeply incised Peach Springs and Salt River paleocanyons along the plateau margin, mentioned above, has led some workers to propose an extensive ancestral northeastward-flowing drainage system that may have included portions of the Grand Canyon (e.g., Potochnik, 2001; Young 2001, 2008). Quaternary Grand Canyon incision rates appear insufficient to carve the entire canyon in 6 m.y., indicating either that incision rates have decreased or that the modern river exploited paleocanyons that were present prior to river integration (e.g., Pederson et al. 2002; Karlstrom et al., 2007).

Timing Constraints on Regional Unroofing

Stratigraphic relationships suggest that variable thicknesses of Mesozoic and Cenozoic strata covered the entire plateau (Hunt, 1956). Five important unconformities within the southwestern plateau put important constraints on the timing of denudation. The first is the mid-Cretaceous unconformity in east-central Arizona near the Mogollon rim. Throughout the Colorado Plateau region, mid-Cretaceous strata disconformably overlie Middle or Upper Jurassic (e.g., Hunt, 1956; Pipiringos and O'Sullivan, 1978). In east-central Arizona, Late Cenomanian-Turonian (ca. 93 Ma) strata unconformably overlie Paleozoic units, indicating erosional removal of Triassic, Jurassic, and even some Permian strata prior to this time (e.g., Nations, 1989; Potochnik, 1989, 2001). In northwestern Arizona, significant erosion along the plateau margin may have occurred in the Early Cretaceous, but the mid-Cretaceous unconformity is not preserved on this portion of the plateau (Fig. 2A). Overall, the mid-Cretaceous unconformity indicates greater unroofing along the plateau margin than within the interior during the Early Cretaceous. The second unconformity is preserved in northwestern Arizona, where Rim gravels (Music Mountain Formation) are paleontologically dated as Paleocene or early Eocene in age, indicating the plateau margin was unroofed to the top of the Paleozoic by this time (e.g., Elston and Young, 1989; Elston et al., 1989; Potochnik, 1989; Young, 1999). In east-central Arizona, rim gravels contain ash beds with $^{40}Ar/^{39}Ar$ dates of 35–34 Ma (Potochnik and Faulds, 1998), and therefore appear to be wholly younger than the Rim gravels in northwest Arizona. The third unconformity is located in northeastern Arizona and northwestern New Mexico (to the northeast of the map area in Fig. 2), where the 32–25 Ma Chuska Formation unconformably overlies the Mesozoic section (Scarborough, 2001). These strata appear to record aggradation in the plateau interior at about the same time as deposition of the southeastern Rim gravels. The fourth unconformity occurs within the plateau interior in northeastern Arizona, where the ca. 16–6 Ma Bidahochi Formation unconformably overlies Mesozoic units, indicating unroofing there by 16 Ma, with little subsequent net unroofing or erosion. Finally, Oligocene through Recent volcanic strata overlie the plateau surface and young toward the plateau interior (e.g., Wenrich et al., 1995).

Along the west-central margin of the plateau in the Lake Mead region to the east of the Sevier front, two important stratigraphic relationships that also bear on the unroofing history of the plateau are preserved within tilted fault blocks in the central Basin and Range province (Fig. 2A). The first is the preservation in the North Muddy Mountains of at least 1200 m of Upper Cretaceous (Albian and younger) foreland basin deposits that lie unconformably on Lower Jurassic strata, indicating perhaps modest (?) Late Jurassic or Early Cretaceous erosion followed by significant Late Cretaceous aggradation (Bohannon, 1983), similar to the history in east-central Arizona described above. The second is the character of the basal Tertiary unconformity on the cratonic section in the Virgin Mountains and environs (Fig. 2A). Toward the north, strata of late Oligocene age (Rainbow Gardens Member of the Horse Spring Formation, $^{40}Ar/^{39}Ar$ dates ca. 26–18 Ma; Beard, 1996; Lamb et al., 2005) disconformably overlie the Lower Jurassic. Over a distance of ~10 km, the unconformity cuts downsection, such that in the southern part of the range, the Rainbow Gardens rests on Permian. The southward pinch-out of the Mesozoic below this unconformity tightly constrains the ca. 25 Ma position of the southern limit of preserved Triassic and Lower Jurassic units along the western boundary of the plateau (Fig. 2A).

Existing thermochronological data sets for the Grand Canyon region include a horizontal transect of apatite fission-track (AFT) dates at Colorado River level (Naeser et al., 1989, 2001; Kelley et al., 2001) and a vertical AFT profile in the Grand Canyon Village area (Naeser et al., 1989; Dumitru et al., 1994). The river transect displays generally decreasing ages from ca. 70–90 Ma within the Lower Granite Gorge to ca. 30–40 Ma at Lees Ferry, consistent with southwest to northeast removal of the overlying cover (Naeser et al., 1989, 2001; Kelley et al., 2001). The vertical Grand Canyon transect indicates complete apatite annealing and the attainment of temperatures >110 °C in the basement at the bottom of the canyon, while apatite in strata from the canyon rim were interpreted to have been partially annealed at temperatures >80–90 °C (Dumitru et al., 1994; Kelley et al., 2001). These data suggest that following their deposition, currently exposed upper Paleozoic and lower Mesozoic sedimentary units in the Grand Canyon region were buried by several kilometers of Mesozoic and Cenozoic strata.

APATITE (U-Th)/He THERMOCHRONOMETRY

We acquired 230 single-grain apatite (U-Th)/He dates for 36 samples from the southwestern quadrant of the Colorado Plateau; the samples include Proterozoic basement from the Grand Canyon, Triassic and Permian sandstone, and Tertiary Rim gravels. Single crystals of apatite were selected based on morphology, clarity, and lack of inclusions using a binocular microscope with crossed polars. Sample locations are marked in Figure 2B, and results are shown in Figures 3A and 3B. Data for each sample are summarized in Table 1, analytical results for individual apatites are reported in GSA Data Repository Tables DR1 to DR3[1], and analytical methods are described in the data repository.

Conventionally, He diffusion in apatite is assumed to be sensitive to temperatures from ~70–30 °C (Wolf et al., 1998; Farley, 2000). However, recent studies demonstrated that He retentivity increases with the accumulation of He and associated radiation damage in the apatite crystal, such that an apatite's effective closure temperature evolves through time (Farley, 2000; Shuster et al., 2006). Forward models predict that for some thermal histories and apatite suites, the radiation-damage effect will be manifested as a span of (U-Th)/He dates positively correlated with both He concentration [He] and effective U concentration [eU]. The latter parameter weights the decay of U and Th for their He productivity, and is computed as ([U] + 0.235 × [Th]). The positive correlation between date and [eU] develops because an apatite with higher [eU] and more radiation damage has a higher closure temperature than a lower [eU] apatite with less radiation damage, despite experiencing the same thermal history (Shuster et al., 2006; Flowers et al., 2007). Flowers et al. (2007) reported several samples from the southwestern region of the Colorado Plateau that display variations in dates that can be explained by the effects of radiation damage on He mobility. The significance of these and additional samples that manifest this phenomenon will be discussed further below.

Apatite (U-Th)/He dates (N = 51) were obtained for 11 Precambrian crystalline basement samples from the Grand Canyon (Fig. 3A). Results are reported as the sample mean and sample standard deviation. Three samples from the Lower Granite Gorge of the western Grand Canyon along the plateau margin range from 71 ± 3 Ma to 89 ± 7 Ma. Mean dates for eight samples from the Upper Granite Gorge of the eastern Grand Canyon, within the southwestern plateau interior, range from 55 ± 7 Ma to 23 ± 3 Ma. For apatites from the Upper Granite Gorge, the mean dates are positively correlated with both [He] and [eU].

[1]GSA Data Repository Item 2008027, apatite (U-Th)/He data tables and the description of analytical methods, is available at www.geosociety.org/pubs/ft2008.htm. Requests may also be sent to editing@geosociety.org.

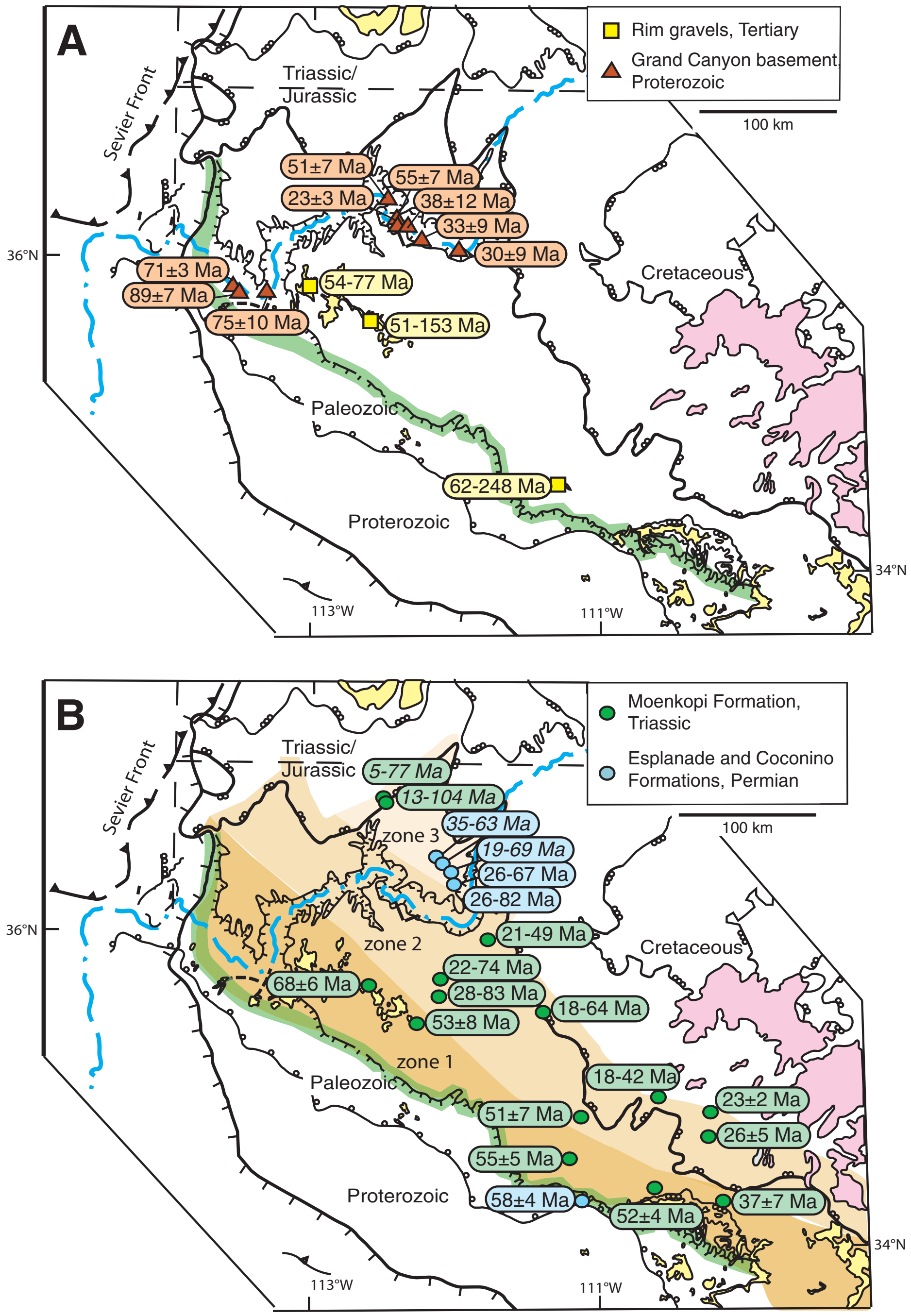

Figure 3. (A) Apatite (U-Th)/He dates for Grand Canyon crystalline basement and Rim gravel samples. The sample mean and standard deviation are reported for the basement samples. The span of dates is reported for the Rim gravel samples. (B) Apatite (U-Th)/He dates for Moenkopi, Esplanade, and Coconino sandstone samples. Dates for samples in italics were previously reported in Flowers et al. (2007). For samples that yielded dates with ≤20% standard deviation (type A), the mean dates and standard deviations are reported. For samples that yielded dates with >20% standard deviation (type B), the range of dates is reported. Zone 1 samples are type A, and yielded the oldest consistent detrital apatite dates. Zone 3 samples are type B, and show a positive correlation of date with [eU]. Zone 2 samples include both sample types, with type B sample dates not always correlated with [eU].

Apatite (U-Th)/He data (N = 152) were acquired from 15 samples of Triassic Moenkopi sandstone and five samples of Permian Esplanade and Coconino sandstone (Fig. 3B). The Moenkopi Formation was targeted because it is distributed as erosional remnants on the Kaibab surface throughout much of the southwestern plateau, commonly contains abundant detrital apatites, and provides a datum with which we can assess the relationship between net erosion and structural position. The Esplanade and Coconino Formations are not as widely exposed but locally provide important constraints, relative to the Moenkopi datum, on unroofing at lower levels of the stratigraphic column. In all studied samples, the apatite dates are significantly younger than the unit's depositional age, indicating significant post-depositional He loss from the apatites. The sample results can be subdivided into two types. Type A samples yielded dates with ≤20% standard deviation, and results are reported as the sample mean and sample standard deviation (Fig. 3B, Table 1). Type B samples yielded dates characterized by >20% standard deviation, and the results are reported as the range of dates (Fig. 3B, Table 1). Type B samples commonly display a positive correlation of apatite date with [eU] and [He], while type A samples lack such a relationship (Fig. 5). Using this characterization system, the results suggest subdivision of the study area into three zones (Fig. 3B). Along the plateau margin, samples are entirely type A, which we define as zone 1. Within the southwestern plateau interior, samples are entirely type B and are all positively correlated with broad [eU] (>40 ppm) variation, which we define as zone 3. Between the interior and the rim, the results may be used to define zone 2, including samples that are either type A or type B, with type B apatite dates not always correlated with [eU].

We acquired apatite (U-Th)/He data (N = 27) for five samples of Rim gravels (Fig. 3A) (Elston et al., 1989; Young, 1999, 2001). The samples include: a coarse arkose near Frazier Wells; three samples from a single outcrop at Long Point consisting of a coarse arkose, a suite of granitic clasts, and a suite of volcanic clasts; and an indurated conglomerate containing angular to subrounded cm-scale clasts of limestone, sandstone, and granite from the Blue Ridge gravel locality (Elston et al., 1989). The samples from Frazier Wells and Long Point are assigned to the Music Mountain Formation (Young, 1999). These samples are characterized by a broad span of dates not correlated with [eU], and are thus reported as a span of sample dates (Fig. 3A). Apatites (N = 16) from the Frazier Wells arkose and the clasts at Long Point yielded dates from 153 to 48 Ma, with 12 of 16 apatites <90 Ma. Apatites (N = 6) from

TABLE 1. SUMMARY TABLE FOR SAMPLE (U-Th)/He APATITE DATA

Sample	Number of analyses	Mean date (Ma)	Span (Ma)	Standard deviation (Ma)	Standard deviation (%)	Mean [eU] (ppm)	Range [eU] (ppm)	Youngest date (Ma)
Grand Canyon crystalline basement (N = 51)								
Lower Granite Gorge								
CP06-65: Diamond Creek pluton	4	75	61–81	10	13	38	16	61
CP06-69: Separation Point batholith	5	89	83–100	7	8	12	3	83
CP06-71A: 245-mile pluton	4	71	68–75	3	4	9	9	68
Upper Granite Gorge								
CP06-57: Diabase	4	23	19–28	3	15	5	2	19
CP06-52: Ruby Creek pluton	4	51	42–57	7	13	150	67	42
UG89-1: Pipe Creek pluton	3	30	22–40	9	30	18	14	22
UG99-1: Tuna Canyon granodiorite	4	33	26–45	9	27	17	12	26
AZ399: Elves Chasm gneiss	5	38	26–53	12	31	21	36	26
ARGC-B: Bass granodiorite	4	55	44–60	7	14	180	47	44
UG90-2, Horn pluton	7	54	35–66	12	22	52	76	35
UG91-1, Trinity gneiss	7	41	23–53	12	29	14	17	23
Moenkopi, Esplanade, and Coconino sandstones (N = 152)								
Zone 1								
CP06-29F, Moenkopi	5	68	59–75	6	8	49	80	59
CP05-1, Moenkopi	10	53	43–66	8	15	47	110	43
CP06-19, Moenkopi	4	55	48–61	5	10	41	67	48
CP06-12, Moenkopi	5	52	47–57	4	8	83	146	47
CP06-20, Moenkopi	7	51	41–58	7	13	59	93	41
CP06-10, Moenkopi	7	37	30–46	7	18	42	76	30
CP06-17, Esplanade	4	58	53–63	4	7	21	28	53
Zone 2								
CP06-5, Moenkopi	8	28	18–42	9	31	30	146	18
CP06-6, Moenkopi	5	23	20–25	2	9	29	18	20
CP06-7, Moenkopi	4	26	21–33	5	20	22	27	21
CP05-2, Moenkopi	9	46	28–83	16	36	31	14	28
CP05-3A, Moenkopi	8	39	22–74	17	43	38	55	22
CP06-3B, Moenkopi	6	34	18–64	17	50	49	63	18
CP05-7, Moenkopi	8	32	21–49	9	30	26	19	21
Zone 3								
PGC-011, Esplanade	7	49	26–67	14	28	47	146	26
PGC-006, Esplanade	9	44	26–82	10	23	62	69	26
PGC-002, Esplanade	7	47	19–69	20	43	77	89	19
PGC-004, Coconino	7	47	35–63	10	21	34	42	35
PGC-015, Moenkopi	19	31	5–77	17	57	26	52	13
PGC-016, Moenkopi	13	45	13–104	25	56	35	80	5
Tertiary rim gravels (N = 27)								
CP06-29A: Long Point volcanic clasts	5	75	51–115	26	34	35	29	51
CP06-29C: Long Point granitic clasts	5	98	60–153	39	40	27	12	60
CP06-29B: Arkose matrix	5	34	20–58	16	46	45	38	20
CP06-30: Arkose	6	65	48–77	12	18	90	195	48
CP06-21C: Blue Ridge gravel	6	142	62–248	81	57	23	46	62

the Blue Ridge sample locality in general are older, with dates from 248 to 62 Ma, and only two of six apatites <90 Ma. The heterogeneous dates, including results significantly older than the unit's Tertiary age, suggest that the apatites did not undergo significant post-depositional He loss. In contrast, detrital apatites (N = 5) from the coarse arkose at Long Point yielded three anomalously young dates from 26 to 21 Ma, >22 m.y. younger than the youngest apatite from cobbles of igneous rock in the same outcrop. Variations in [eU] and accumulated radiation damage cannot explain the results. These data are inconsistent with other geological and thermochronological constraints in the region. Although we do not fully understand the significance of these younger dates, a late Tertiary basalt flow that caps the outcrop ~20 m above the stratigraphic level of the sample may have contributed to post-depositional open system behavior in the arkose apatites.

RADIATION DAMAGE CONTROL ON APATITE (U-Th)/He DATES

The radiation damage trapping model, in which He diffusion is impeded by becoming incorporated within radiation damage "traps," uses He diffusion kinetics that are a function of temperature and the apatite [He] (Shuster et al., 2006). For some thermal histories, this model predicts distributions of dates that are positively correlated with [eU] and [He]. This correlation generally is not linear. On the southwestern Colorado Plateau, both igneous apatites from Grand Canyon basement samples, as well as detrital apatites from Moenkopi, Esplanade, and Coconino sandstone samples, locally display such patterns of dates. We reproduce the dates in these suites of samples using the radiation damage trapping model and present these results below. Although our basic models attempt to distinguish episodicity in the unroofing history, the inferred temperature-time paths may be characterized by rounded edges and low slopes between episodes.

Complicating factors such as micro-inclusions with high [eU], fluid inclusions, and He implantation from external phases may induce scatter in (U-Th)/He data sets, but these effects are not predicted to produce a distribution of (U-Th)/He dates positively correlated with [eU] as observed in our samples. Apatites from the Moenkopi sandstone are typically characterized by high clarity and subrounded prism morphologies such that identification of inclusions is straightforward. Apatites from the Esplanade and Coconino samples are commonly more rounded. Representative apatites from each sandstone were imaged by backscatter and cathodoluminescence techniques, and the major-element and trace-element compositions were determined by electron microprobe and inductively coupled plasma–mass spectrometer (ICP-MS) analysis

(Flowers et al., 2007; see footnote 1). This study did not reveal high [eU] micro-inclusions that could interfere with data interpretation.

Uncertainties remain regarding the role of radiation damage trap annealing on the He diffusion kinetics of apatite. In reality, [He] is not a perfect proxy for radiation damage, because radiation damage can accumulate at temperatures too high for He to be retained in the crystal. An alternative is to utilize He diffusion kinetics that are a function of the total He, and thus the total radiation damage, generated in the apatite throughout its thermal history. However, this model is clearly inappropriate, because the radiation damage traps appear to be annealed at temperatures comparable to those required for significant shortening and annealing of apatite fission-tracks (~110–60 °C) (Farley et al., unpublished data). We more rigorously tracked trap accumulation and annealing and evaluated the effect on our thermal histories by utilizing the Ketcham (2005) annealing model in HeFTy to compute the evolution of the fission-track date, used the fission-track date as a proxy for the evolution of the total radiation damage accumulated in the apatite crystal, and for any given time step in the He production-diffusion model used this radiation damage value to compute the apatite He diffusion kinetics. We applied this approach to the Grand Canyon basement samples and the Esplanade and Coconino samples on the plateau surface nearby. For both basement and sandstone samples, the predicted thermal histories are 4–5 °C hotter than those predicted by utilizing diffusion kinetics that are a function of the [He]. For a 25 °C/km geothermal gradient, this small temperature difference results in only a 200-m increase of the inferred overburden, a result that is well within the uncertainty of the geothermal gradients. This exercise suggests that incorporation of trap annealing will not significantly modify the first-order conclusions we draw from our data set.

Grand Canyon Proterozoic Basement

Igneous apatites from Grand Canyon crystalline basement samples in general have little intra-sample variation in [eU] but display significant [eU] variation among samples. The thermal models described below use a temperature of 120 °C at 80 Ma, based on prior AFT data that indicate the… the fission-track dates for the basement were completely annealed during Sevier-Laramide time (e.g., Naeser et al., 1989; Kelley et al., 2001). Samples from the Lower Granite Gorge along the plateau margin yield (U-Th)/He dates from ca. 70–90 Ma that do not display a correlation with [eU]. These results are best explained by a model in which the samples underwent a single relatively rapid pulse of cooling following complete He loss during the attainment of peak temperatures. In contrast, the mean sample apatite (U-Th)/He dates for eight samples from the Upper Granite Gorge within the plateau interior range from 23 ± 3 Ma to 55 ± 7 Ma, and collectively they exhibit a strong positive correlation with mean sample [eU], which ranges from 5 to 180 ppm (Fig. 4A). Using the radiation damage trapping model, the distribution of dates is consistent with a restricted suite of thermal histories characterized by complete resetting during peak temperatures near the end of Cretaceous sedimentation, followed by pulses of cooling in the Laramide and mid-Late Tertiary (Fig. 4B). The best-fit thermal histories that include an extended duration in the Early and mid-Tertiary at temperatures from ~45–61 °C can generate the spread of apatite dates. A phase of cooling at ca. 20–25 Ma to temperatures below ~32 °C appears required to reproduce the youngest ca. 23 Ma dates. The single phase cooling history of the Lower Granite Gorge contrasts with the multiphase cooling history of the Upper Granite Gorge. This is consistent with a similar interpretation derived from modeling of apatite fission-track length data for basement samples in the two areas (Kelley et al., 2001).

Triassic and Permian Moenkopi, Esplanade, and Coconino Sandstones

Detrital apatites from Moenkopi, Esplanade, and Coconino sandstones have broad intra-sample variations in [eU], and likely were characterized by broad variations of (U-Th)/He date at the time of deposition. Apatites from the plateau margin samples (type A samples, zone 1) show uniform dates despite broad [eU] variation (Fig. 5), and are best explained by complete resetting of apatites at peak temperature followed by a single phase of cooling. In contrast, apatites from the plateau interior samples (type B samples, zone 3), yield broad spans of dates (from 104 to 5 Ma) positively correlated with the large range of [eU] (from 8 up to 115 ppm) (Fig. 6) (Flowers et al., 2007). Given apatites with the observed range of [eU]

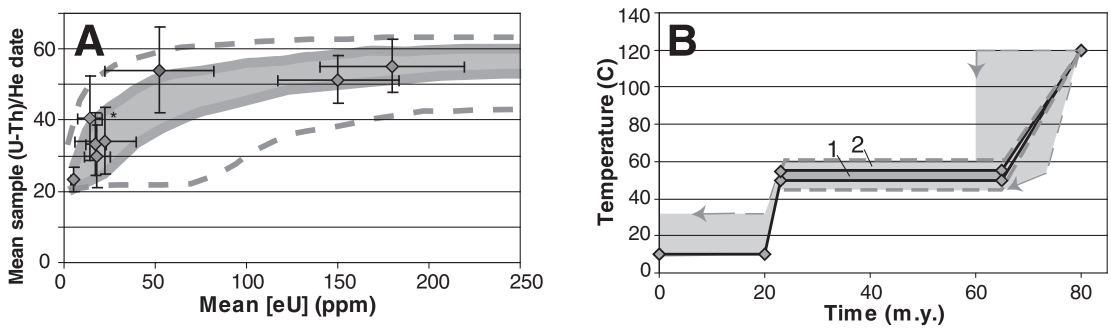

Figure 4. (A) Apatite data from Upper Granite Gorge crystalline basement samples, plotted as mean sample apatite (U-Th)/He date versus mean sample [eU]. The errors shown are the standard deviation of the mean (1 sigma). Asterisk (*)—one aliquot excluded. (B) Simulated thermal histories for Upper Granite Gorge crystalline basement samples. The shading represents the region where certain (but not all) thermal histories can generate a distribution of dates that falls within the shaded region in (A) using the radiation damage trapping model. For example, the two solid T-t paths in (B) represent two thermal histories that bracket the data, the deviation between the two histories is shown as the dark-gray field 1, and the predicted distributions of dates are depicted as solid bands in (A). The two dashed T-t paths in (B) represent thermal histories that differ from the better-fit paths by ±5 °C in the 65–20 Ma time interval, the deviation between the two histories is shown as field 2, and the predicted distributions of dates are depicted as the dashed lines in (A).

and initial (U-Th)/He dates at the time of deposition from 5 to 100 Ma (for the Esplanade and Coconino samples) and 5–200 Ma (for the Moenkopi samples) and using a thermal history similar to that described above for the basement samples, we can reasonably reproduce these age distributions using the radiation damage trapping model. The large range in (U-Th)/He date at the time of deposition results in a large range of accumulated radiation damage and closure temperature in the apatite suite, and therefore the simulated results plot as a fan-shaped field on a plot of date versus [eU]. In our simulations, only a restricted set of thermal histories can reproduce the distributions of dates in the samples. Satisfactory thermal histories must include (1) partial, rather than complete, He loss in the higher [eU] apatites to generate the oldest dates, (2) a major pulse of either Oligocene or Miocene cooling, depending on location, to yield the youngest dates, and (3) extended residence in the apatite He partial retention zone after peak temperature attainment to generate the large spread of dates (Fig. 6). Incomplete resetting of apatites from the plateau interior indicates that the peak temperatures in this region were lower and/or briefer than those along the plateau margin where apatites were completely reset. The data from detrital apatites near the Kaibab surface also corroborate the finding based on nearby basement samples that the plateau margin underwent a single phase of Sevier-Laramide cooling, whereas the interior underwent a two-stage history of cooling in Sevier-Laramide and mid-Late Tertiary time.

UNROOFING OF THE SOUTHWESTERN COLORADO PLATEAU AND IMPLICATIONS FOR UPLIFT

Regional Unroofing Patterns

Incorporation of our results into a model for the regional unroofing history must take into account three primary observations about the data, explained further below. First, in general, dates are systematically older along the plateau margin than within the southwestern plateau

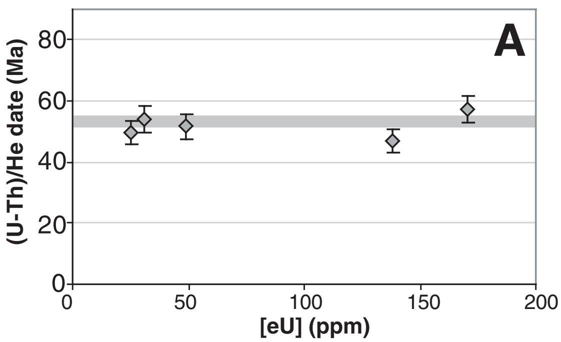

Figure 5. Apatite data from a representative Moenkopi sample from zone 1, plotted as date versus [eU]. Estimated analytical errors for individual analyses are plotted as 8% (2 sigma). (B) Simulated thermal history for the Moenkopi sample, with the distribution of dates predicted by the radiation damage trapping model depicted as the gray band in (A). Simulations use an initial distribution of (U-Th)/He dates at the time of deposition from 5 to 100 Ma. The pre-deposition segment of the temperature-time path is depicted as a dotted line.

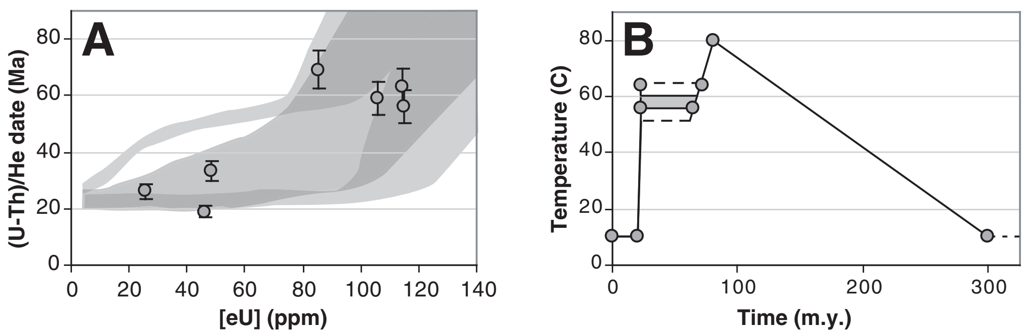

Figure 6. (A) Apatite data from Esplanade sample from zone 3, plotted as date versus [eU], from Flowers et al. (2007). Estimated analytical errors for individual analyses are plotted as 8% (2 sigma). (B) Simulated thermal histories for the Esplanade sample. The two solid T-t paths in (B) represent the two thermal histories that encompass the data, with distributions of dates predicted by the radiation damage trapping model depicted as the darker gray field in (A). In (B), the shaded region indicates where the two thermal histories differ. The two dashed T-t paths in (B) represent thermal histories that differ from the better-fit paths by ±5 °C in the 65–20 Ma time interval, with the predicted distributions of dates depicted as the lighter gray fields in (A). Simulations use an initial distribution of (U-Th)/He dates at the time of deposition from 5 to 100 Ma. The pre-deposition segment of the T-t path is depicted as a dotted line.

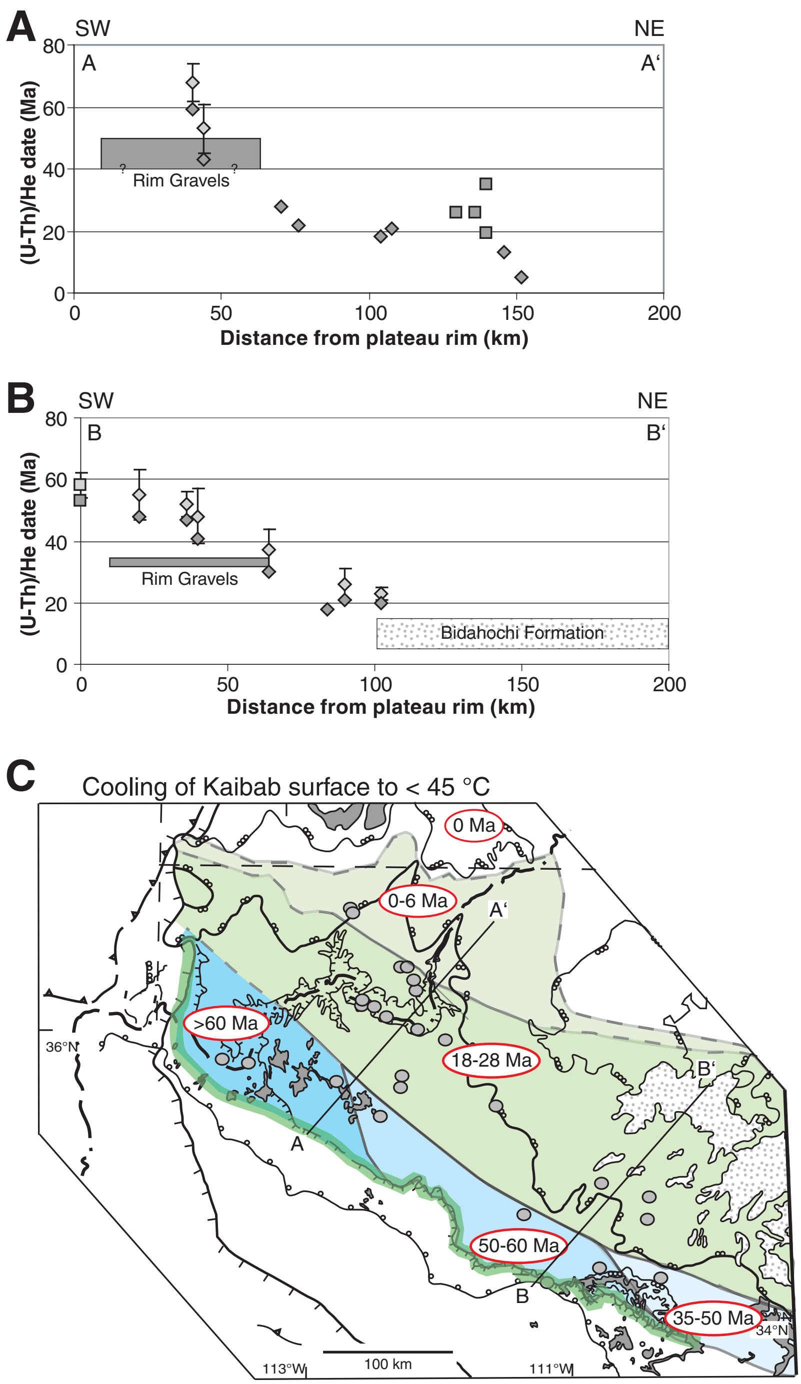

Figure 7. Apatite (U-Th)/He date versus distance from the plateau rim margin for cross sections through (A) northwestern study area, A–A′, and (B) southeastern study area, B–B′. Locations of cross-section lines indicated in (C) Diamonds represent data for Triassic Moenkopi sandstones, and squares represent data for Permian Esplanade and Coconino sandstones. For type A samples, the sample mean and standard deviation is plotted. For all samples, the youngest date is plotted (see text for additional explanation). The location and timing constraints for deposition of the Rim gravels and Bidahochi Formation are also shown. (C) Map showing the time at which the Kaibab surface is inferred to have cooled below 45 °C. Time periods not shown are intervals during which the landscape was relatively stable. Dashed lines indicate regions less constrained by data.

interior, confirming an overall pattern of southwest to northeast denudation. Second, models that reproduce the distributions of sample dates indicate a single dominant phase of Laramide unroofing along the plateau margin, in contrast to multiphase unroofing that denuded the southwestern plateau interior. Third, regional data patterns suggest significant differences in the migration of unroofing between Sevier-Laramide time and mid- to Late Tertiary time. Apatites from Lower Granite Gorge basement proximal to the plateau rim are older (Late Cretaceous) than those from Upper Granite Gorge basement samples from the southwestern plateau interior (mid-Tertiary), and the youngest apatite dates from the Triassic and Permian sandstones systematically young from the margin (Early Tertiary) to the interior (mid-Late Tertiary) (Fig. 7). The youngest apatite dates for the detrital sandstones are significant, because they have the lowest effective closure temperatures, and therefore yield dates that are most sensitive to the final removal of Mesozoic to Tertiary overburden. Although it is impossible to know whether we obtained the youngest date in each sample, the coherent regional pattern strongly supports the interpretation of southwest to northeast removal of overburden (Fig. 7). Toward the northwest, in northwestern Arizona (Figs. 3B and 7A), the data record (1) Sevier-Laramide unroofing along the plateau margin, with denudation to the Kaibab surface by the time of deposition of the Rim gravels at ca. 50 Ma, (2) mid-Tertiary unroofing (28–18 Ma) recorded both on the Kaibab surface and in the basement of the Grand Canyon, indicating this was a significant denudational phase, and (3) Late Tertiary unroofing (<16 Ma) north of the Grand Canyon. Toward the southeast, in east-central Arizona (Figs. 3B and 7B), the data indicate (1) Sevier-Laramide unroofing along the plateau margin, with denudation to the Kaibab surface by the time of deposition of the Rim gravels at 35 Ma, and (2) mid-Tertiary unroofing (28–18 Ma) to the Kaibab surface prior to the onset of deposition of the Bidahochi Formation at 16 Ma.

The temperature-time paths that best explain our data set imply that the entire Kaibab surface exposed in the study area cooled below 65–70 °C in Early Tertiary time. We constructed a map showing the inferred time at which the Kaibab surface cooled below 45 °C (Fig. 7C). We interpret a diachronous single phase of unroofing along the plateau margin, as implied by the uniform dates within individual samples that are younger southeastward along the plateau margin (Figs. 5 and 7). The northeastward advance of the second phase of unroofing within the southwestern plateau interior is inferred from our modeled distributions of sample dates (Figs. 6

and 7). The data define significant differences in the timing of unroofing as a function of position along the regional tectonic strike (NW-SE). Along the plateau margin, the data strongly suggest that Laramide unroofing migrated from northwest to southeast. Cooling of the Kaibab surface below 45 °C occurred prior to 60 Ma in the western Grand Canyon region, and from 60 to 35 Ma in the Mogollon Rim region. In contrast, the mid-Tertiary phase of denudation occurred in a swath roughly parallel to the plateau margin, suggesting a southwest to northeast progression of unroofing.

Implications for an Early Tertiary "Proto–Grand Canyon"

The distribution of dates for samples from the Upper Granite Gorge basement and samples nearby ~1500 m stratigraphically higher in the section indicate that significant incision of the Grand Canyon below the Kaibab surface did not occur until after 23 Ma, and raise the possibility that a significant "proto–Grand Canyon" may have been carved in post-Paleozoic sediments during Early Tertiary time. The youngest dates from the Upper Granite Gorge basement constrain substantial incision of the modern Grand Canyon below the Kaibab surface to post–23 Ma, because our models require temperatures >45 °C prior to this time to generate the distributions of dates in the basement samples (Fig. 4). Assuming a moderate geothermal gradient of 25 °C/km and a surface temperature of 10 °C, this would indicate pre–23 Ma thicknesses of overburden ≥1.4 km, comparable to the stratigraphic separation between the basement and Kaibab surface. In addition, the distributions of dates for samples from the Upper Granite Gorge basement (Fig. 4) and for Esplanade and Coconino samples >1200 m stratigraphically higher in the section from the Kaibab monocline (Fig. 6) suggest Early to mid-Tertiary residence at similar temperatures of ca. 45–61 °C. The youngest dates for Moenkopi samples on the Kaibab surface south and east of the Grand Canyon are 21–22 Ma, indistinguishable within error from the youngest basement dates, and indicative of mid-Tertiary temperatures >45 °C. Similar Early through mid-Tertiary temperatures in samples now separated by as much as 1500 m in both elevation and stratigraphic position imply that a kilometer-scale proto–Grand Canyon was carved in post-Paleozoic sediments during Early Tertiary time in the Upper Granite Gorge region. If significant relief in this area were absent, then a moderate geothermal gradient of 25 °C/km would instead imply a temperature difference of 30–38 °C for samples stratigraphically separated by 1200–1500 m. Additional study is currently under way to more firmly constrain temperatures in basement and sedimentary samples in order to more fully evaluate this hypothesis.

Unroofing Model

We combine our new data with previous stratigraphic and thermochronologic studies to develop a self-consistent model of tilting, erosion, and aggradation of the southwestern Colorado Plateau from mid-Cretaceous to Holocene time. We present our model as individual cross-sectional reconstructions drawn across the Grand Canyon region from the Transition Zone well into the plateau interior (Fig. 1, cross-section line A–A″, Fig. 8), and we show the evolution of the erosion surface relative to the datum of the Kaibab Formation (Fig. 9). For the pre–50 Ma history, we note that the mid-Cretaceous unconformity in the North Muddy Mountains described earlier indicates erosion of Middle and Upper Jurassic strata just off the western margin of the plateau, and therefore we assume that the Transition Zone in northwestern Arizona experienced the same broad Early Cretaceous erosion as east-central Arizona (Fig. 8A). Recognizing the along-strike contrasts in unroofing history discussed above, a somewhat different reconstruction would result from a section in east-central Arizona, particularly considering differences in the post–16 Ma interval described above (Figs. 8D–8E). The reconstruction assumes (except where otherwise noted) a nominal Tertiary geothermal gradient of 25 °C/km (e.g., Fitzgerald et al., 1991; Reiners et al., 2000), a surface temperature of 10 °C, and the thermal histories shown in Figure 7.

Important uncertainties in the model include both spatial and temporal variations in the shallow crustal geothermal gradient. In the Jurassic and Cretaceous, there was likely a northeastward decrease in the geothermal gradient due to the existence of the Cordilleran arc to the southwest (e.g., Foster et al., 1990). In the Tertiary, the geothermal gradient may have increased from a relatively low value during flat slab subduction to higher values after the demise of the slab (e.g., Dumitru et al., 1994). Although these effects introduce errors in the estimated amount of denudation, they do not markedly affect the overall unroofing pattern. We consider these errors in the discussion below.

Aggradation and Maximum Burial in Cretaceous Time

In our model, pre-mid Cretaceous, northward plateau tilting and regional erosion was followed by the accumulation of ≥1500 m of Upper Cretaceous sediments along the plateau margin (Fig. 8A). In eastern Arizona, the mid-Cretaceous unconformity cuts downsection toward the southwest at an angle of ~0.4° across ~1.5 km of Upper Jurassic to Permian strata. In southwesternmost exposures, ~170 m of late Cenomanian (ca. 94 Ma) strata rest on Permian (e.g., Nations, 1989; Potochnik, 1989). Apatite (U-Th)/He dates from Moenkopi sandstone underlying the Cretaceous are 37 ± 7 Ma, and those to the northwest along the plateau margin range from 68 ± 6 Ma to 51 ± 7 Ma. As mentioned earlier, these dates, all younger than the age of the overlying Cretaceous, imply complete He loss from the Moenkopi apatites after erosion of the Triassic and Jurassic units, development of the mid-Cretaceous unconformity, and deposition of Upper Cretaceous units. Even under the assumption that Late Cretaceous arc magmatism elevated the upper crustal geothermal gradient in the cratonic backarc region to as high as 45 °C/km, at least 1500 m of Upper Cretaceous overburden would be required to induce the ≥80 °C temperatures required by our models to completely reset the apatites. Therefore, our reconstruction at 80 Ma (Fig. 8A) shows a net thickness of 1500 m of Upper Cretaceous strata, although we recognize that this is a minimum thickness. Elsewhere on the southern Colorado Plateau, in the Black Mesa, San Juan, and Kaiparowits basins, up to 2350 m of Upper Cretaceous strata are preserved (Molenaar, 1983), and are consistent with our minimum estimated thickness along the plateau margin. Given the sparse preservation of Cretaceous strata along the southwestern quadrant of the plateau, it is noteworthy that such a large thickness of Late Cretaceous strata were present and removed not long after deposition. As noted by earlier workers, the Colorado Plateau in Utah, Colorado, and New Mexico was generally an area of substantial subsidence in Late Cretaceous, pre-Maastrichtian time, even in uplifted areas now devoid of Cretaceous strata (Hunt, 1956). Our results confirm that a similar Late Cretaceous history extends at least as far southwestward as the plateau rim in northern Arizona. Whether there was continuity between the "plateau basin" and widespread exposures of Late Cretaceous volcanic and sedimentary rock southwest of the Transition Zone remains an open question.

Unroofing in Late Cretaceous–Early Tertiary Time

The reconstruction depicts renewed northeastward tilting, profound denudation of the plateau margin, and more modest denudation of the southwestern plateau interior from ca. 80–50 Ma (Fig. 8B). Although not depicted in our cross-sectional reconstructions, the southeastward migration of both unroofing and the transition to aggradation is striking (Fig. 7C). Whatever

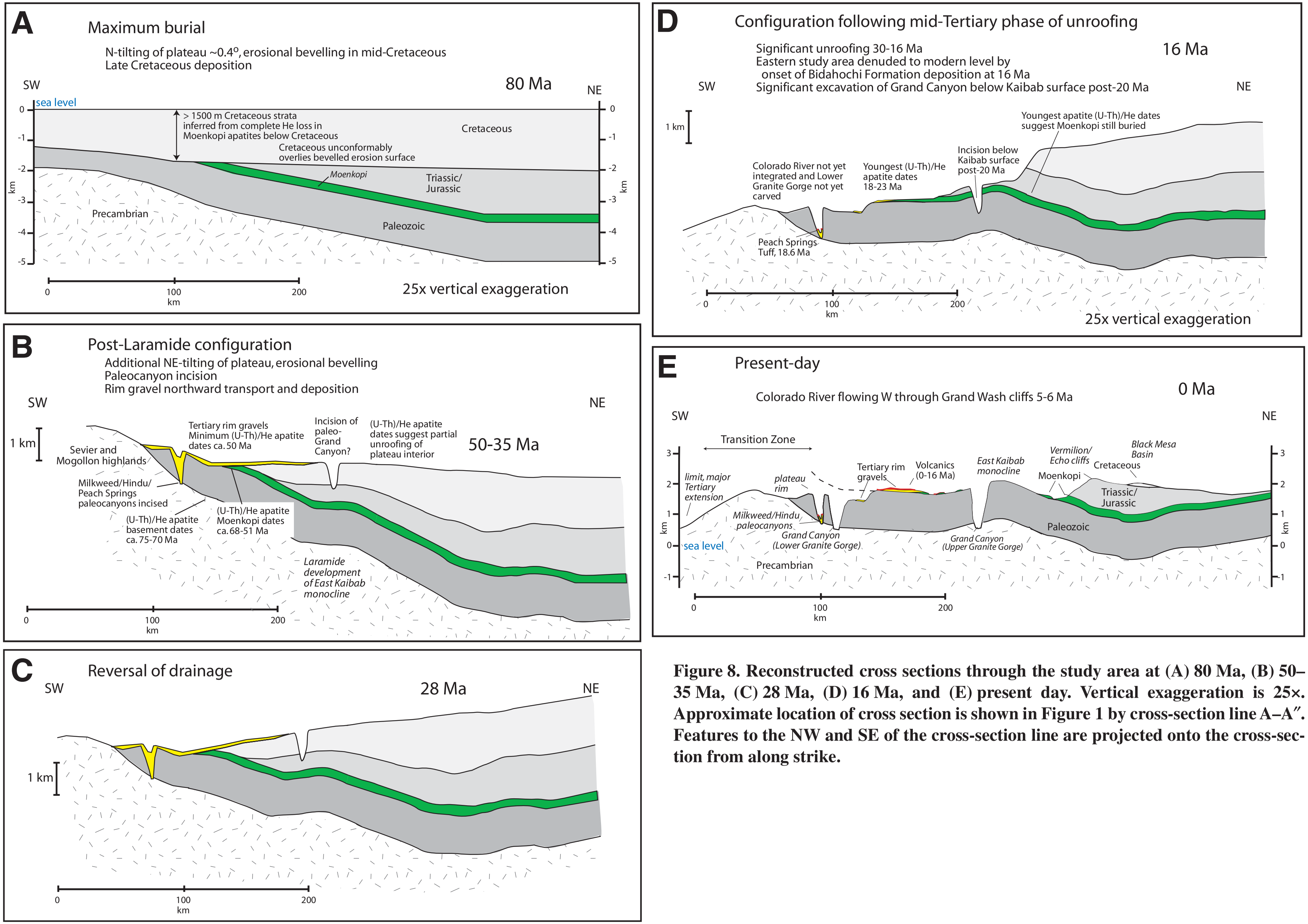

Figure 8. Reconstructed cross sections through the study area at (A) 80 Ma, (B) 50–35 Ma, (C) 28 Ma, (D) 16 Ma, and (E) present day. Vertical exaggeration is 25×. Approximate location of cross section is shown in Figure 1 by cross-section line A–A″. Features to the NW and SE of the cross-section line are projected onto the cross-section from along strike.

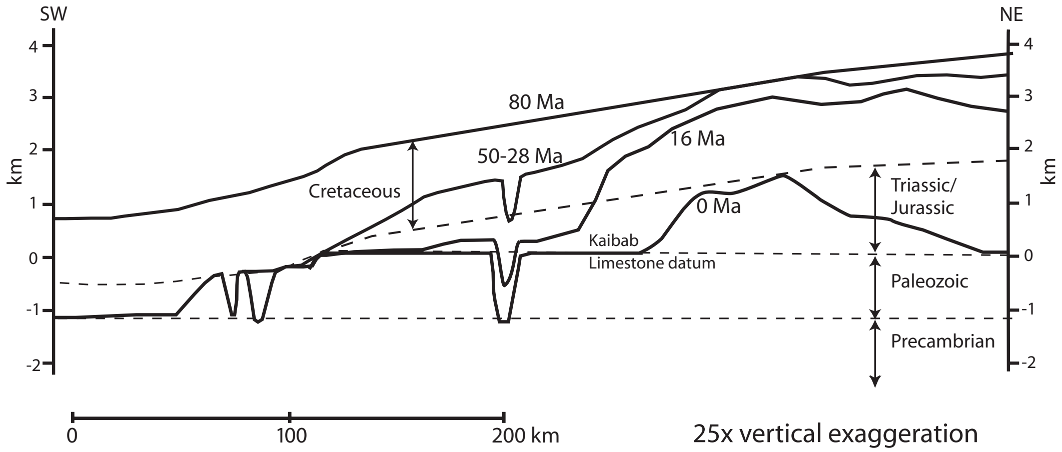

Figure 9. Reconstructed sedimentary thicknesses at the selected times depicted in the cross sections in Figure 9, relative to the horizontal Kaibab limestone datum. Dashed lines represent contacts between major rock packages of different age. Vertical exaggeration is 25×.

the cause of this migration, we note that the Sevier orogeny affected the western margin of the plateau well before the onset of the Laramide tectonism that affected the eastern margin, and therefore it seems likely that the diachronism in unroofing is in some way related to the diachronism in mountain building on either side of the plateau (Sevier versus Laramide). Denudation was followed by northeastward transport and aggradation of Rim gravels starting in the early Eocene in northwest Arizona, and starting in the late Eocene in east-central Arizona (Potochnik and Faulds, 1998). Assuming that the apatite (U-Th)/He apatite dates for the Music Mountain Formation reflect unroofing of their source regions, the youngest clast dates of ca. 50 Ma provide a maximum age for deposition, consistent with (1) apatite (U-Th)/He apatite dates from the underlying Moenkopi Formation as young as ca. 53 Ma, (2) a 64 Ma K-Ar date for the youngest dated volcanic clast at the base of the Long Point section (Elston et al., 1989), (3) the occurrence of upper Paleocene or lower Eocene freshwater gastropods in the Long Point section (Young, 2001), and (4) the identification of Eocene charophytes in the section (Young, 2006, personal commun.). Collectively, these data indicate that the plateau margin was topographically higher than the southwestern plateau interior, and had developed a net structural relief of at least 5500 m on the basal Cambrian unconformity by Early Tertiary time. According to our model, ca. 2300 m of this relief had developed by ca. 94 Ma (Late Cenomanian) (Fig. 8A), and an additional 3200 m developed at some time between ca. 80 and 50 Ma (Fig. 8B). Although we cannot constrain absolute elevations, evidence for kilometer-scale relief at the head of the Milkweed and Peach Springs paleocanyons and within the Upper Granite Gorge area imply that kilometer-scale uplift had affected both the plateau margin and at least a portion of the plateau interior by 50 Ma. If such a paleocanyon existed, then the Milkweed and Peach Springs drainages would presumably have been tributary to a northeast-flowing ancestral Colorado River.

We emphasize that our constraints on uplift and canyon incision are derived from samples from the Upper Granite Gorge in the eastern Grand Canyon, and need not apply to the western Grand Canyon or east central Arizona. In the westernmost segment of the Grand Canyon just downstream from the intersection of Peach Springs Wash and the Colorado, early Miocene basalts (19 Ma) appear to have flowed across a deeply incised southern tributary (Spencer Canyon), strongly suggesting this reach of the canyon was carved from a Miocene surface of low relief. An Early to mid-Tertiary proto–Grand Canyon may have extended from Peach Springs Canyon to the Upper Granite Gorge, but need not have had the precise form, course, or dimensions of the modern canyon. Rather an ancestral canyon may have been modified and subsequently exploited during the integration of the modern river post–6 Ma (e.g., Potochnik, 2001; Young, 2001), perhaps accounting for the inadequacy of Quaternary incision rates to carve the entire canyon in 6 m.y. (Pederson et al., 2002; Karlstrom et al., 2007).

Drainage Reversal and Unroofing in Mid-Tertiary Time

The southwestern plateau appears to have been characterized by a relatively stable landscape (Figs. 8B–8C) with either slow erosion or aggradation from ca. 50–30 Ma. In the mid-Tertiary (28–16 Ma), a significant phase of unroofing coincides with the initiation of major extensional tectonism in the Basin and Range province, which is presumably the cause of drainage reversal across the Mogollon Rim recorded in the Salt River region (Potochnik, 2001) (Figs. 8C–8D). Relatively little is known about this time interval on the plateau from geological relationships, because there are few preserved deposits of this age. Toward the southeast (Fig. 7B), (U-Th)/He dates of ca. 26–18 Ma for Moenkopi samples record unroofing at this time, prior to the onset of aggradation of the Bidahochi Formation at 16 Ma. Toward the northwest (Fig. 7A), the youngest (U-Th)/He dates from the Moenkopi samples on the Kaibab surface, Coconino and Esplanade samples from the Kaibab uplift, and crystalline basement samples from the Grand Canyon are 28–19 Ma. The dates in this range are laterally persistent in a northwest-trending band ~75 km wide (Fig. 7A), suggesting a pulse of erosion of the plateau interior at this time. The youngest dates of ca. 23 Ma from the Grand Canyon basement indicate that significant incision of the Upper Granite Gorge below the Kaibab surface could not have begun until after this time. Our model maintains kilometer-scale relief in the Upper Granite Gorge area from 25 Ma to 16 Ma, with the bottom of the channel cut in Lower Jurassic strata at 25 Ma and Mississippian strata at 16 Ma (Figs. 8C–8D). Our data do not allow us to determine whether relief increased or decreased through this interval in the Upper Granite Gorge area. However, in contrast to the westernmost portion of the canyon below Peach Springs Canyon, the data do not support carving of the Upper Granite Gorge into a surface of low relief cut on or near the Kaibab Formation.

Unroofing in Late Tertiary Time

Substantial post-Laramide unroofing of the southwestern plateau interior north of the Grand Canyon occurred in latest Miocene to Pliocene time, recorded by samples containing (U-Th)/He dates <18 Ma, and as young as 5 Ma (Figs. 7A and 8E). These youngest dates are consistent with apatite (U-Th)/He apatite results even farther north in southern Utah suggesting accelerated erosion <10 Ma (Stockli, 2005). On the basis of widespread Pliocene river gravels along the lower part of the Colorado River derived in part from central Utah, there is strong consensus that a through-going Colorado River existed at least as far back as 5 Ma (e.g., Spencer et al., 2001). Rapid, young denudation of the interior portions of the southwestern plateau supports the hypothesis that river integration induced the latest phase of plateau unroofing by providing a mechanism to efficiently remove large sediment volumes from the plateau interior (Pederson et al., 2002).

Implications for the Relationship between Unroofing, Incision, and Surface Uplift in the Upper Granite Gorge Region

Our new results impose important constraints on the controversial timing of uplift and incision of the southwestern Colorado Plateau, especially in the Upper Granite Gorge region of the plateau interior. In this section, we describe and evaluate two endmember models for the relationship between these processes (Fig. 10). We note that although these endmembers echo the views of many geologists since the time of John Wesley Powell's exploration of the canyon, neither precisely describes the views of any particular investigator or period of investigation. Concise, modern overviews of the complex evolution of ideas relating to this topic may be found in Ranney (2005) and Powell (2005). In one endmember, regional unroofing to the Kaibab surface occurred prior to Late Tertiary incision of the Grand Canyon and coeval uplift of the plateau, implying that regional unroofing of the Mesozoic (Dutton's Great Denudation) is genetically unrelated to uplift and incision of the Grand Canyon (Dutton's Great Erosion) (Fig. 10, model #1). In the opposite endmember, canyon incision and plateau uplift in Early Tertiary time preceded regional unroofing, such that regional unroofing is a direct consequence of these processes (Fig. 10, model #2). In this extreme, a high-relief Early Tertiary "equilibrium" landscape lowers itself largely unchanged onto the present landscape, such that the carving of the modern Grand Canyon from Kaibab down to basement was accompanied by equivalent lowering of the plateaus on the canyon's rim from Cretaceous down to Permian.

In support of the general viability of the low-relief denudation of model #1, we cite the pre-mid Cretaceous erosion of ~1500 m of Lower Triassic through Upper Jurassic units (~0.03 mm/yr for ~56 m.y.), followed by deposition of Late Cretaceous marine sediments (Fig. 8A). Deposition on either side of the low-relief, basal Cretaceous erosion surface occurred at or near sea level (e.g., Blakely, 1989), and therefore it is difficult to envisage the growth and demise of kilometer-scale topographic relief during this erosional event. This particular example does not specifically support either of the models in Figure 10, which apply only to post–mid-Cretaceous unroofing. Rather, it cautions us not to presume that unroofing is a direct proxy for surface uplift, or that erosional unroofing at moderate rates requires the development of kilometer-scale relief.

Our data indicate significant denudation of the southwestern plateau interior during the mid-Tertiary (28–16 Ma), most likely due to drainage reversal across the plateau rim. The question of whether this unroofing was associated with elevation gain of the plateau interior is difficult to address on the evidence for unroofing alone. Along the plateau margin, substantial topographic relief had developed by the mid-Tertiary in the Salt River Canyon (850–1400 m) and along the Mogollon Rim (~600 m). Because regional drainage had reversed such that the plateau interior was now the source region for gravels deposited in these areas, the southwestern plateau interior presumably had attained significant elevation by this time (Peirce et al., 1979; Potochnik, 2001). Uplift of at least a portion of the plateau interior may have occurred as early as the Early Tertiary, when the plateau margin was topographically higher than the plateau interior and the area had developed a net structural relief of >5500 m. If our models for the thermal histories of samples from the Upper Granite Gorge region are correct, they would imply that a significant proto–Grand Canyon had incised post-Paleozoic strata by the early Eocene, therefore indicating kilometer-scale elevation gain of at least this part of the plateau during Sevier-Laramide time. These results are inconsistent with models for the rise of the entire plateau from near sea level during Late Tertiary time (Fig. 10, model #1), and indicate that at least part of the uplift was decoupled from the integration of a southwest-flowing Colorado River in latest Miocene time. Rather, the data suggest a scenario more similar to model #2 (Figs. 9 and 10), in which canyon incision and substantial plateau uplift in Early Tertiary time preceded the mid- and Late Tertiary unroofing episodes that denuded the plateau interior. Clearly, however, our data do not preclude a significant component of elevation

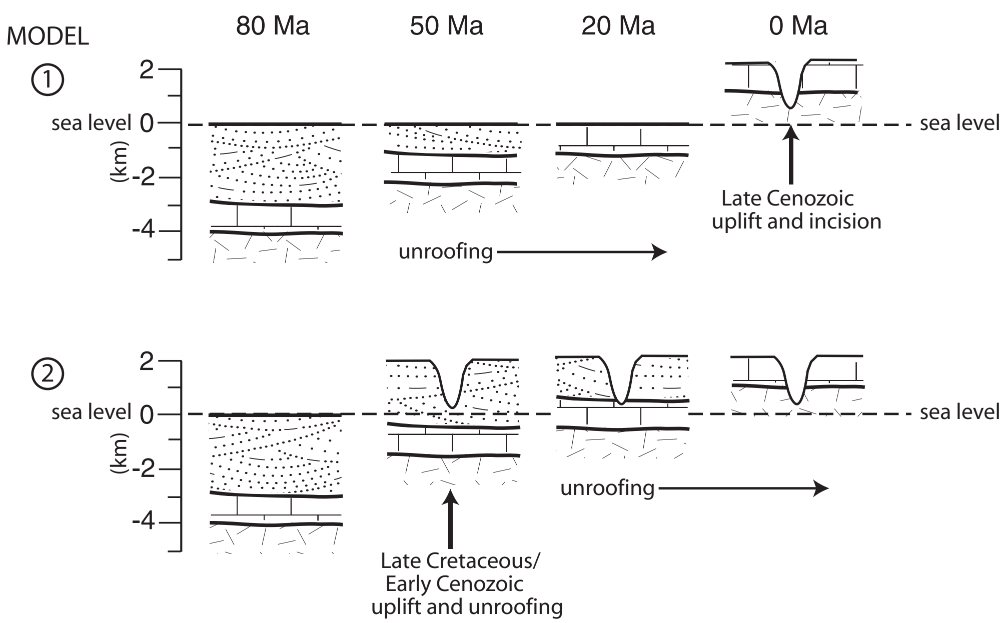

Figure 10. Endmember models for the uplift, incision, and unroofing history of the plateau interior in the Upper Granite Gorge region of the Grand Canyon.

gain of the plateau in Late Tertiary time (e.g., Lucchitta, 1979; Lucchitta et al. 2001; Sahagian et al., 2002).

Early to mid-Tertiary elevation gain is consistent with paleoaltimetry estimates based on leaf physiognomy and stable isotope techniques in the adjacent Rocky Mountain and Basin and Range provinces that generally support the idea of high elevation (2000 m or more) throughout the Tertiary (Gregory and Chase, 1992; Wolfe et al., 1997; Wolfe et al., 1998; Poage and Chamberlain, 2002, Horton et al., 2004; Horton and Chamberlain, 2006). In addition, although controversial, a number of studies suggest that the Sierra Nevada existed as a major topographic feature (≥1.5 km elevation) throughout the Cenozoic (e.g., Wernicke et al., 1996; House et al., 1998; Poage and Chamberlain, 2002; Clark et al., 2005; Mulch et al., 2006). Thus, significant Early Tertiary uplift of at least part of the Colorado Plateau would be compatible with its location in the middle of an inferred Early Tertiary high-elevation Cordilleran orogen.

CONCLUSIONS

Our data provide the first single-system proxy for the unroofing history of the southwestern Colorado Plateau, and confirm overall southwest-northeast denudation from plateau margin to plateau interior. Our reconstructions incorporate the constraints from prior geological studies that indicate significant denudation of the plateau margin in the mid-Cretaceous (e.g., Nations, 1989; Potochnik, 2001), and plateau margin uplift, unroofing, paleocanyon incision, and Rim gravel aggradation in the Early Tertiary (e.g., Young, 1979; Elston and Young, 1991; Young, 2001; Potochnik, 2001). Our (U-Th)/He results, and by extension our model, are also consistent with prior apatite fission-track thermochronological data from the Grand Canyon basement indicating a single phase of Laramide unroofing in the Lower Granite Gorge (Kelley et al., 2001), and multiphase Early and mid-Tertiary unroofing of the southwestern plateau interior (Naeser et al., 1989; Dumitru et al., 1994; Kelley et al., 2001).

Our model includes four significant new features. First, the reconstructions depict the accumulation of at least 1500 m of Late Cretaceous strata along the southwestern plateau margin following the development of the mid-Cretaceous unconformity and prior to Sevier-Laramide unroofing. This thick package of Cretaceous overburden is the simplest means of explaining complete post-Cretaceous He loss of apatites from the plateau margin. Elsewhere, the plateau preserves thick Cretaceous deposits near its rim but did not experience the development of kilometer-scale structural relief and unroofing. The implied Sevier-Laramide history is therefore a dynamic one of major erosion and aggradation, followed by a second major erosional event that left the structurally highest portion of the plateau largely devoid of Late Cretaceous strata.

Second, the model indicates that the younger of the two Sevier-Laramide unroofing episodes (ca. 80–50 Ma) was characterized by northeastward plateau margin tilting, regional erosion, and a northwest to southeast progression of denudation. This accounts for greater Early Tertiary denudation of the plateau margin than the interior, and patterns of dates that young from northwest to southeast along the plateau margin.

Third, the reconstructions depict the Early Tertiary incision into post-Paleozoic strata of a proto–Grand Canyon of similar dimensions to the modern canyon in the Upper Granite Gorge area. This feature of the model appears necessary to account for the similar thermal histories of samples from the crystalline rocks in the bottom of the canyon and sedimentary rocks on the Kaibab surface nearby. This result is somewhat counterintuitive because the high-relief escarpment along the modern rim of the Grand Canyon strongly suggests a disequilibrium landscape that should be rapidly changing its overall form. The strong contrast in power of erosive agents within the canyon (incision by a major river and attendant mass wasting acting on a high-relief landscape) and on the plateau (small perennial streams acting on a nearly featureless landscape) would seemingly require that the canyon widen with time, with the steep escarpment wasting laterally away from the river. However, our data do not require that the proto–Grand Canyon was identical to the current canyon in its shape and course, and do not preclude widening, smoothing, and some reduction in relief prior to the development of the modern canyon.

Fourth, the reconstruction shows that a 75-km-wide, 500-km-long, northwest-trending swath, and locally at least 1500 m of vertical section, was unroofed in the mid-Tertiary (28–16 Ma) in a high-relief landscape, and included the relatively rapid northeastward retreat of cuestas similar to today's "Great Rock Staircase." The timing of this event also indicates the earliest time possible for significant incision of the modern canyon below the Kaibab surface. This explains the uniformity of the youngest dates across this region in a band roughly parallel to the plateau margin, and the youngest dates of ca. 23 Ma in the Upper Granite Gorge basement.

The evidence for substantial unroofing and the creation of high relief during Sevier-Laramide time (80–50 Ma), contrasts with the stability of the landscape from ca. 50–30 Ma, a time period that includes the onset of removal of the Laramide slab at ca. 40 Ma (e.g., Coney and Reynolds, 1977). Any model of the geodynamic effects of Laramide slab removal, such as dramatic increases in lithospheric buoyancy, would be required to maintain a relatively stable landscape across both the margin and interior of the southwestern plateau. The most visible phase of denudation and creation of topographic relief occurred during Sevier-Laramide time, which overall records a northeastward expansion of Cordilleran highlands from latest Jurassic (ca. 145 Ma) to Eocene time (ca. 50 Ma), across a terrain that experienced little or no horizontal tectonism of the upper crust. Therefore, this history supports models wherein buoyancy is added to the cratonic lithosphere in Sevier-Laramide time. This might include buoyancy-driven lateral flow of deep crust along the lines suggested by McQuarrie and Chase (2000). Indeed, the southeastward progression of unroofing along the plateau margin appears to support this hypothesis. Alternatively, models that invoke pre-Laramide convective removal of the lower lithosphere, or models wherein a Laramide slab rarefies the cratonic lithosphere through the introduction of volatiles from below, may also explain our proposed patterns of unroofing and uplift.

The resumption of unroofing at ca. 28 Ma coincides closely with the timing of drainage reversal and the onset of significant crustal extension southwest of the Transition Zone. The interval from 16 to 6 Ma was a period of little net erosion or deposition in east-central Arizona, and our data from the Grand Canyon region permit a relatively stable landscape in northwestern Arizona. Therefore, the effect of drainage reversal on erosion of the southwestern plateau interior appears to have been limited in both space and time. It is noteworthy that the profound extension in the central Basin and Range from ca. 16–6 Ma that occurred where the modern Colorado exits the plateau appears to have had little effect on the evolution of the plateau landscape. In contrast, the opening of the Gulf of California at ca. 6 Ma (Oskin and Stock, 2003) and the coeval integration of a west-flowing Colorado River drainage induced renewed unroofing of the plateau interior in northwestern Arizona and probably large portions of eastern Utah centered on the Colorado and Green Rivers. Thus, in regard to post-Laramide time, the primary cause of unroofing is the relative lowering and attendant drainage reorganization associated with rifting adjacent to the plateau, which does not require topographic uplift of the plateau itself. If erosion were the only process affecting plateau lithosphere in post-Laramide time, then the Great Denudation would have the effect of modestly lowering average elevation, perhaps 200–300 m.

We conclude by noting that only one of the four primary unroofing episodes we have identified from Late Jurassic through Recent time, the ca. 80–50 Ma unroofing of the plateau margin, has direct evidence for a link to the rise of the plateau. Thus the overall history presented above suggests much caution in the presumption that unroofing events faithfully record topographic uplift and the dynamic processes it implies.

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