Unroofing of the southwestern Colorado Plateau from (U-Th)/He apatite thermochronometry

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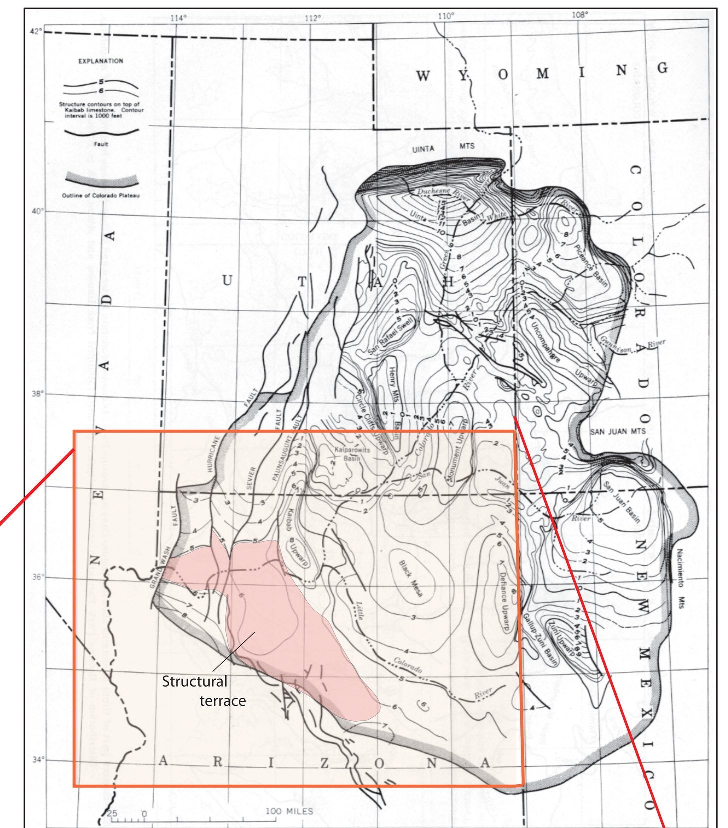
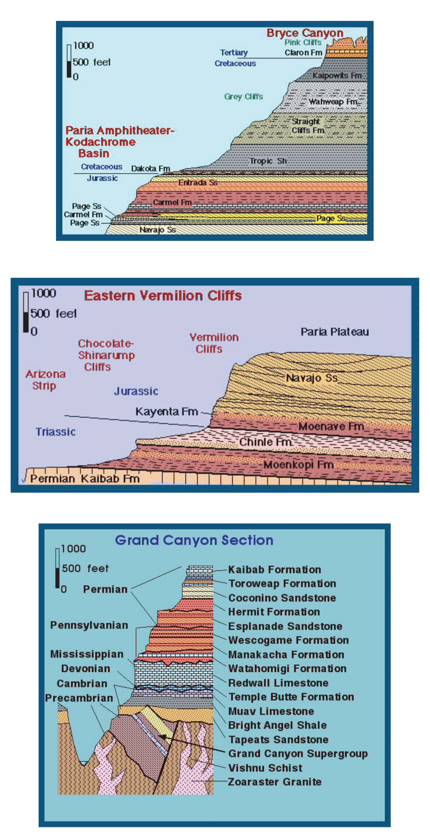
ABSTRACT

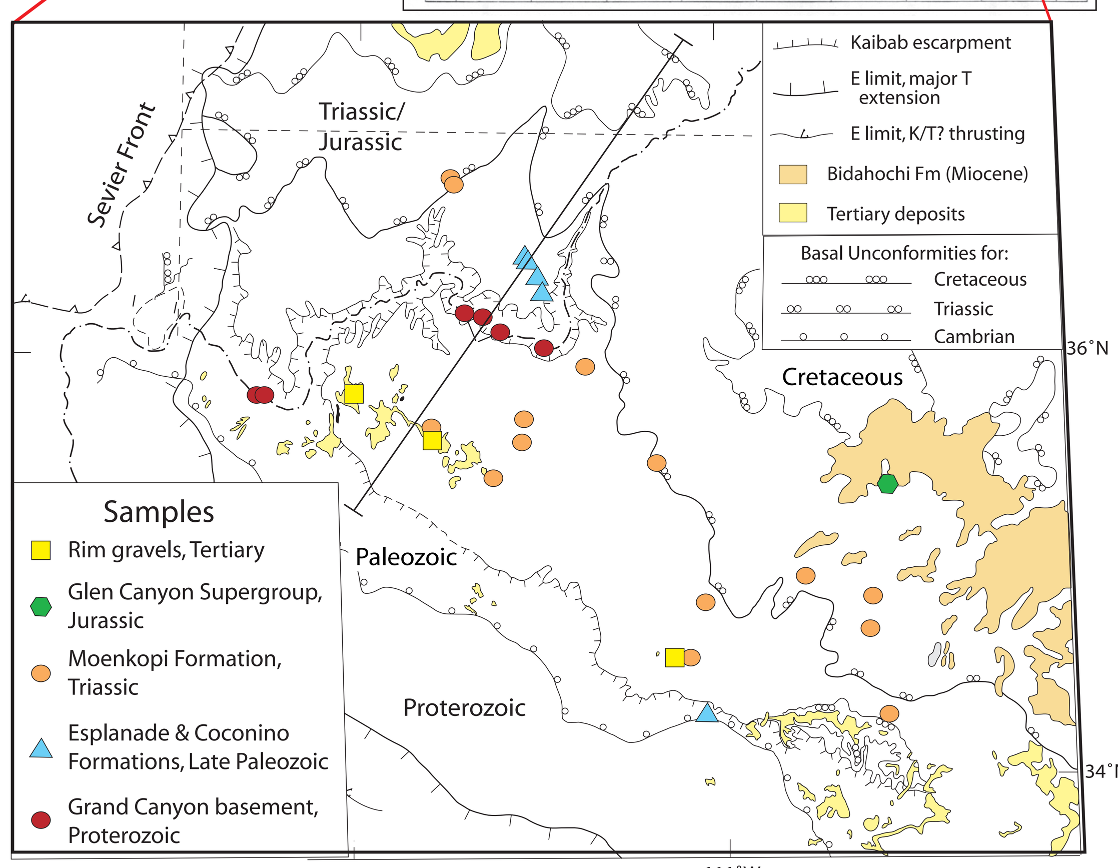
The timing and mechanism of uplift of the Colorado Plateau by ~1.9 km since the Cretaceous is a major question in Cordilleran tectonics. Resolving when the Colorado Plateau was unroofed can provide some insight into this problem, because erosional denudation commonly is linked with uplift. New (U-Th)/He apatite data constrain post-Cretaceous denudational patterns in the Grand Canyon region of the southwestern Colorado Plateau.

(U-Th)/He dates for individual detrital apatites from fourteen Moenkopi sandstone samples across this area 1) are significantly younger than the depositional age of the unit, indicating partial to complete He loss following deposition, and 2) display dates that are younger with increasing distance from the plateau margin, reflecting an overall pattern of southwest to northeast stripping of the overlying sedimentary package. Individual apatites from five Tertiary rim gravel samples did not undergo significant He loss following deposition, such that the distributions of dates reflect the denudation of source regions and impose a maximum timing constraint on gravel deposition following unroofing to the modern plateau surface. Our results suggest that the current plateau margin was buried by > 1.5 km of Cretaceous sediments prior to pulses of denudation in the Laramide and mid-Tertiary (40-35 Ma) that may be linked with uplift episodes at these times. Each denudational pulse was followed by rim gravel aggradation. A component of unroofing ca. 30-20 Ma is likely associated with drainage reversal across the Mogollon rim. Significant late-Tertiary unroofing and scarp retreat is most simply explained by integration of the Colorado River at 6 Ma that provided a mechanism to efficiently remove large sediment volumes from the plateau. A mid-Tertiary ancestral Colorado River in the eastern Grand Canyon is permissible by the current dataset, and $^4He/^3He$ thermochronometry on basement samples is underway to better resolve the timing of canyon incision.



Stratigraphic Section



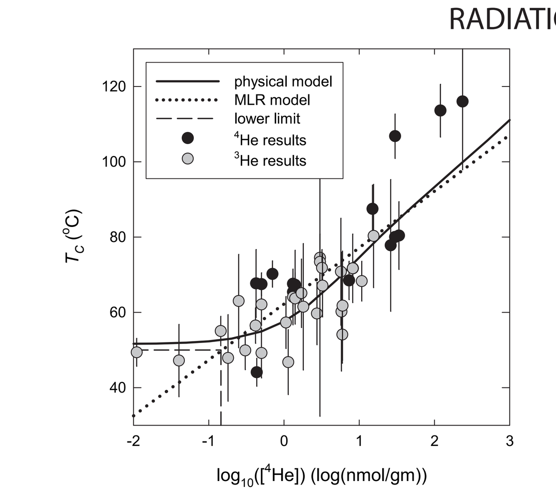


GRAND CANYON REGION OF THE COLORADO PLATEAU

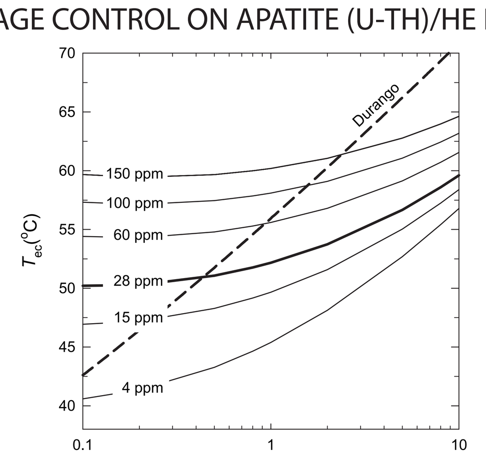
The southwestern portion, or Grand Canyon region, of the Colorado Plateau is characterized by a broad (~15,000 km2) gently NE-dipping structural terrace that is interrupted by the N-trending Kaibab uplift. The plateau surface resides at an elevation of 1500 to 2000 m, is underlain by the resistant Permian Kaibab limestone, and preserves discontinous 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 "Great Rock Staircase". To the west, the plateau edge is structurally delineated by major normal faults of the Basin and Range Province. The Colorado River currently drains the Colorado Plateau to the southwest, forming the Grand Canyon where it cuts across the topographically high southwestern plateau and incises to depths as great as 1600m.

The Mogollon rim, extending 500 km in a northwest trend across Arizona, is primarily an erosional feature that separates the Colorado Plateau from Precambrian basement of the Transition Zone (e.g. Peirce, 1979). Tertiary Rim gravels are preserved immediately north of the Mogollon Rim, and record northeastward transport and unroofing of the Laramide Mogollon highlands to the southwest (Young, 1979; Potochnik, 1989). Locally, in the extreme western Grand Canyon, deeply incised channels containing preserved Rim gravels have >1200 m of relief (Young, 1989, 2001; Elston and Young, 1991; Billingsley et al., 1999). Drainage reversal across the Mogollon rim is inferred to have occurred ca. 30-20 Ma. The thin (~100 m) areally extensive Bidahochi Formation records fluvial and lacustrine aggradation from ~16 to 6 Ma (Dallege et al., 2001).

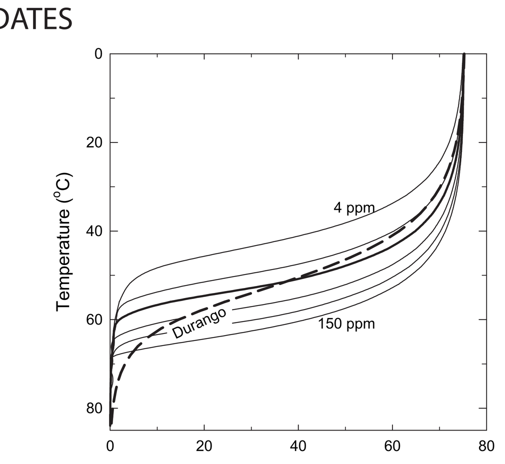
RADIATION DAMAGE CONTROL ON APATITE (U-TH)/HE DATES



Apatite helium closure temperature (Tc) versus the log of the ^4He concentration., for stepwise degassing experiments on 39 different apatite samples. Tc is positively correlated with [He] and is interpreted to be a proxy for accumulated radiation damage. Values of Tc were calculated for a cooling rate of 10 C/m.y. Figure 1, Shuster et al., 2006.

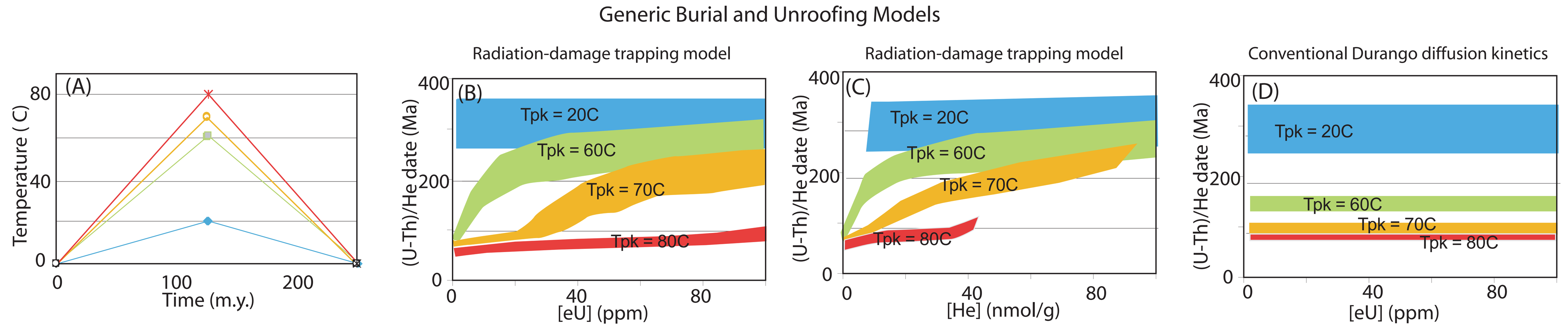


Effective closure temperature (Tec) as a function of cooling rate and [eU] computed from the radiation-damage trapping model. Results for conventional Durango diffusion kinetics are also shown. Figure 5, Shuster et al., 2006.



The He partial retention zone calculated for apatites of differing [eU] that are held at the indicated temperatures for 75 m.y. for the radiation-damage trapping model and conventional Durango diffusion kinetics. Figure 6, Shuster et al., 2006.

Generic Burial and Unroofing Models

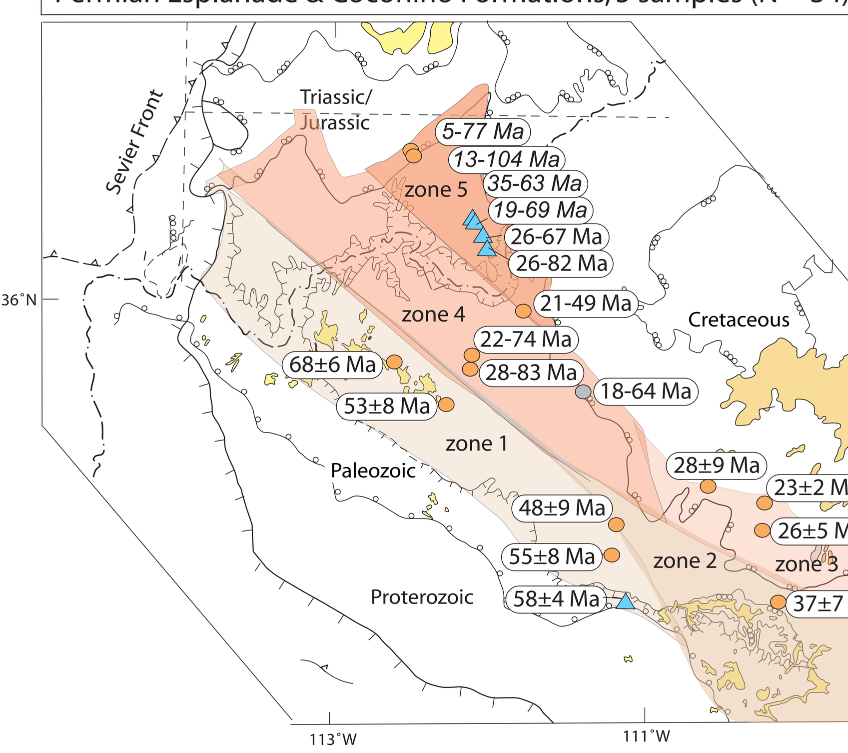


The radiation-damage trapping model incorporates He diffusion kinetics that evolve with temperature and [He]. We simulated distributions of dates expected for detrital grains of uniform diameter (100 um) characterized by an arbitrary but reasonable range of [eU] (2-100 ppm) and (U-Th)/He provenance dates (AHe date of the apatite when deposited, AHedep) from 5 to 100 Ma. We first consider monotonic heating and cooling (A), and display the results in (B) and (C). For comparison we show the results for a model that assumes conventional Durango apatite He diffusion kinetics (D).

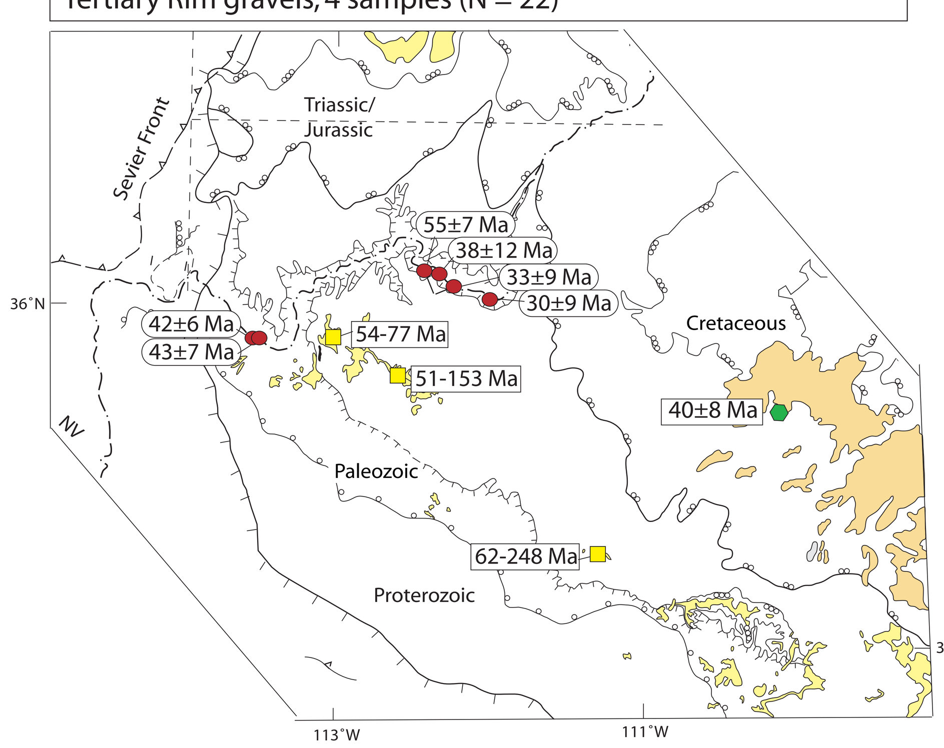
A Tpk of 20 °C is insufficient to cause He loss from any of the apatites, such that the final distribution of dates mimics the provenance distribution, and is independent of [eU]. For Tpk of 60 °C, apatites with the lowest [eU] (least radiation damaged and lowest Tec) undergo complete He loss and thus yield the youngest dates, while apatites with higher [eU] (more radiation damaged and higher Tec) are incompletely reset under the same conditions and so yield older dates. Increasing Tpk to 70 °C induces greater resetting of apatites with higher [eU]. A Tpk of 80 °C causes nearly complete He loss in all apatites, thereby generating a fairly uniform population of dates. Thus, burial and unroofing simulations characterized by no resetting show no correlation between date and [eU], and those affected by complete resetting yield dates that cluster fairly tightly. Only those simulations that include an episode of partial He loss can generate broad distributions of AHe dates that correlate with [eU] and [He], due to divergence of He retentivities in the apatite suite prior to partial resetting.

(U-Th)/He RESULTS

Triassic Moenkopi Formation, 14 samples (N = 114)
Permian Esplanade & Coconino Formations, 5 samples (N = 34)



Proterozoic Grand Canyon basement, 6 samples (N = 25)
Tertiary Rim gravels, 4 samples (N = 22)

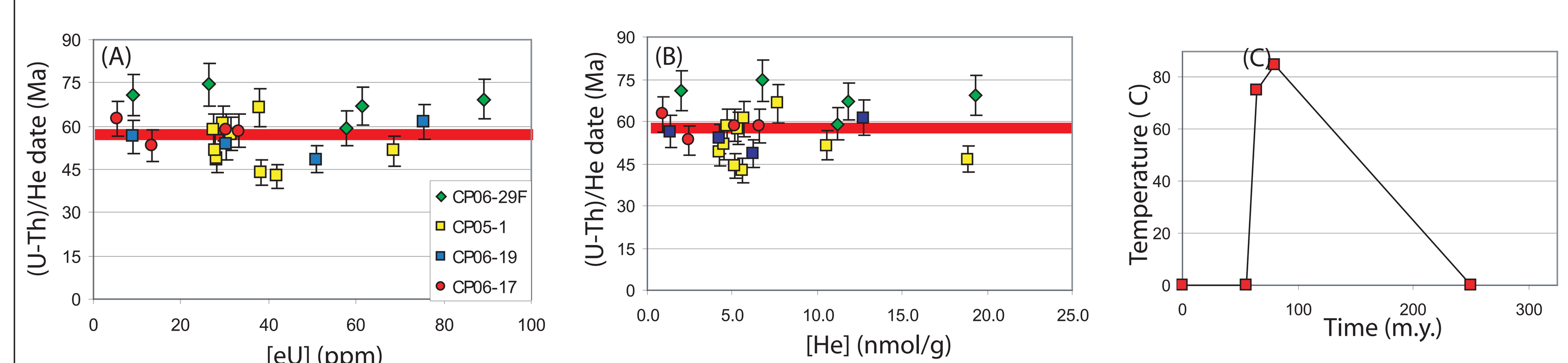


Three clear patterns emerge from the AHe dataset. First, the apatite dates are younger to the northeast with increasing distance from the Mogollon rim and in closer proximity to the modern scarp formed by the Mesozoic and Cenozoic units. Second, dates along the southeastern Mogollon rim (zone 2) are younger than those along its northwestern segment (zone 1). Third, apatites along the Mogollon rim (zones 1, 2, 3) yielded more consistent dates than apatites to the northeast (zones 4, 5). For this reason, results for the former are reported as weighted mean dates, while the span of dates is reported for the latter samples. Zone 5 samples are characterized by large ranges of dates correlated with [eU] and [He], and can be explained by the effect of radiation damage on He retentivity (see below).

Grand Canyon basement - We targeted crystalline basement from the Upper and Lower Granite Gorges because these rocks typically are characterized by more abundant apatite than the sedimentary units that are exposed elsewhere in the canyon. With the exception of one sample characterized by high [eU], apatites from the other samples yield younger dates in the eastern than in the western Grand Canyon.

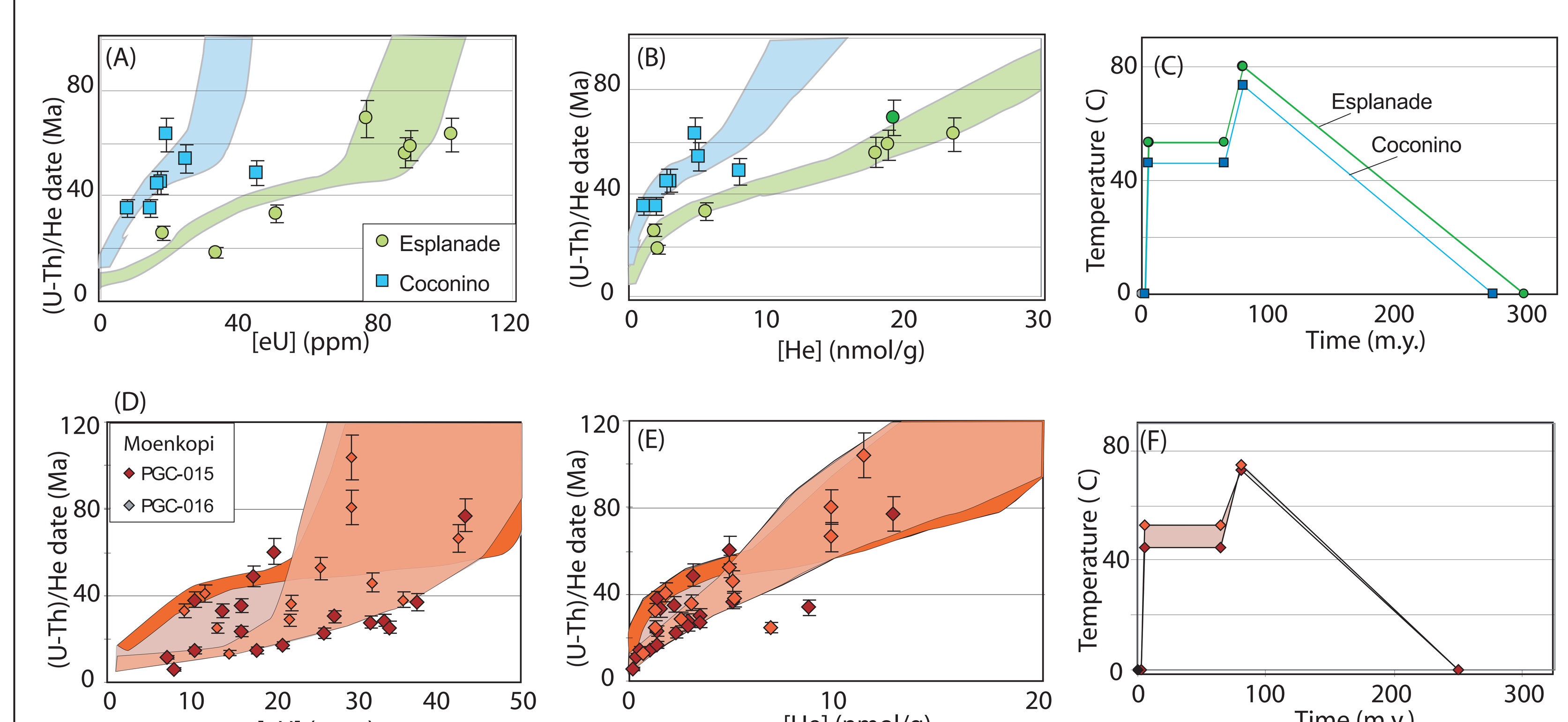
Tertiary rim gravels - The heterogeneous dates, including results significantly older than the Tertiary depositional age of the unit, indicate that the apatites did not undergo significant He loss following deposition. The youngest AHe dates of ca. 50 Ma provide a maximum constraint on gravel aggradation.

Zone 1 - Detrital Apatite Data



(A) (B) Individual detrital AHe dates (symbols) as a function of [eU] and [He]. (C) Simulated thermal history, with simulated distributions of dates using the radiation damage trapping model depicted as shaded fields in (A) and (B). Samples from zones 1 can be explained by a single pulse of Laramide cooling/unroofing. These samples show fairly uniform dates, despite broad [eU] and [He] variation. This is most simply explained by peak temperatures in zone 1 that were higher and/or were maintained longer than those in zone 5, and induced complete He loss from all the apatites. We attribute these higher temperatures to the proximity of zone 1 samples to magmatic and orogenic activity in the Sevier and Mogollon orogenic systems.

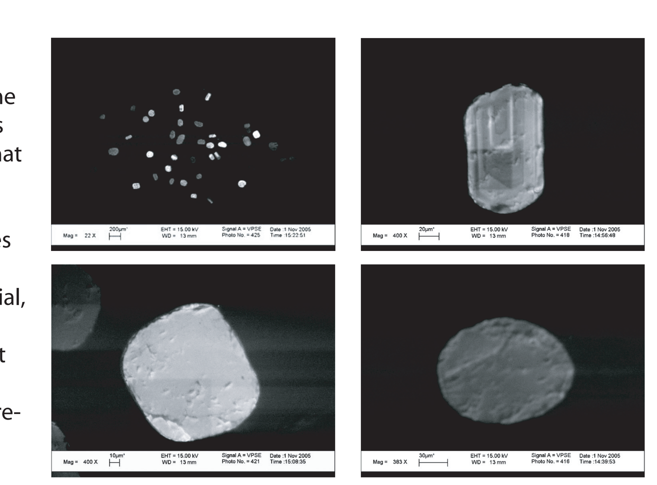
Zone 5 - Detrital Apatite Data



Individual detrital AHe dates (symbols) as a function of [eU] and [He]., for the Esplanade and Coconino samples (A) and (B), and Moenkopi samples (D) and (E). (C) Simulated thermal histories used to reproduce the Esplanade and Coconino data distributions using the radiation damage trapping model, with simulated distributions depicted as shaded fields in (A) and (B). (F) Simulated thermal histories used to reproduce the Moenkopi data using the radiation damage trapping model. with simulated distributions of dates depicted as shaded fields in (D) and (E). A single thermal history does not generate the entire spread of data, so we depict endmember thermal histories that together encompass the fan of data. Two endmember simulated distributions are depicted as separate, but overlapping, shaded fields in (D) and (E). The distributions of dates in all six samples analyzed from zone 5 can be explained by a two-pulse exhumation model involving episodes of cooling in the Laramide and Miocene (Flowers et al., in review). In contrast to the samples in zone 1, we infer that these apatites underwent incomplete He loss during burial.

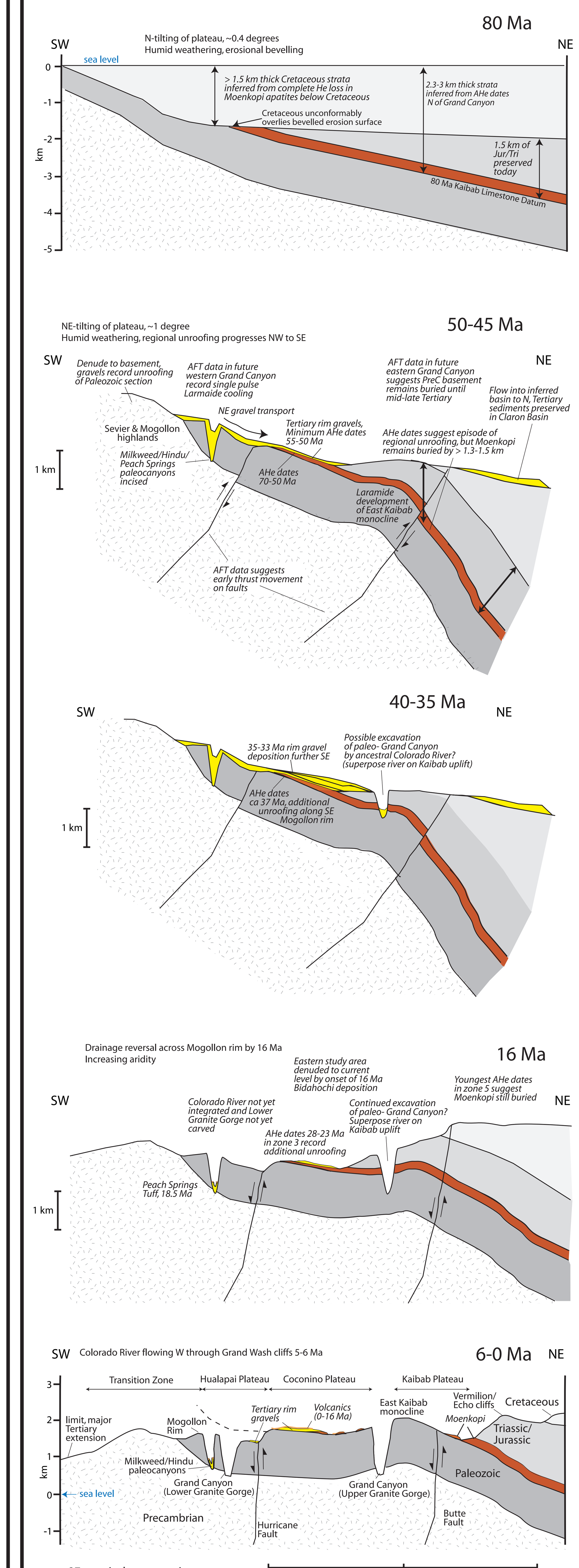
RADIATION DAMAGE CONTROL ON (U-Th)/He APATITE DATES FROM THE SOUTHWESTERN COLORADO PLATEAU

Our results from zone 5 of the Grand Canyon region of the Colorado Plateau suggest that the increase in apatite He retentivity due to radiation damage, implied by laboratory diffusion data, is important for the interpretation of data in certain geological settings. Forward models predict that the effect of radiation damage on He retentivity will be manifested in suites of apatites with a range of [eU] that underwent a history in which the apatite He diffusion kinetics had sufficient time to diverge prior to an episode of partial resetting. A common geological history that satisfies these requirements is one like that in the Grand Canyon region involving 1) deposition of compositionally diverse apatites with variable provenance dates in sedimentary units, and 2) burial, partial He loss, and subsequent exhumation. The data suggest that in some situations, a span of AHe dates positively correlated with [eU] is geologically meaningful. Our simulations predict that the correlations between AHe date, [He] and [eU] can be very sensitive to the thermal history. Thus, it may be possible to extract additional information regarding the details of the temperature-time path from these relationships than would be possible in a sample characterized by a uniform distribution of apatite dates.



CL images of apatites from Moenkopi sample PGC-015 that display variable brightness and zoning characteristics.

UNROOFING THE COLORADO PLATEAU



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