Sciencexpress Reports

Apatite $^4He/^3He$ and (U-Th)/He Evidence for an Ancient Grand Canyon

R. M. Flowers[1]* and K. A. Farley[2]

[1]Department of Geological Sciences, University of Colorado at Boulder, 2200 Colorado Avenue, UCB 399, Boulder, CO 80309, USA. [2]Division of Geological and Planetary Sciences, California Institute of Technology, MS 170-25, Pasadena, CA 91125, USA.

*To whom correspondence should be addressed. E-mail: rebecca.flowers@colorado.edu

Grand Canyon is one of the most dramatic features on Earth, yet when and why it was carved have been controversial for more than 150 years. We present apatite $^4He/^3He$ thermochronometry data from Grand Canyon basement that tightly constrain the near-surface cooling history associated with canyon incision. $^4He/^3He$ spectra for eastern Grand Canyon apatites of differing He date, radiation damage, and U-Th zonation yield a self-consistent cooling history that substantially validates the He diffusion kinetic model applied here. Similar data for western Grand Canyon provide evidence that it was excavated to within a few hundred m of modern depths by ~70 million years ago (Ma), in contrast to the conventional model in which the entire canyon was carved since 5-6 Ma.

The very existence of Grand Canyon (Arizona, USA) (Fig. 1) inspires questions about why rivers sometimes carve canyons, how drainage systems and landscapes evolve, and how these processes relate to continental elevation gain. The prevailing view is that canyon carving occurred after 5-6 Ma, when detritus derived from the upstream reaches of the Colorado River system first appeared in Grand Wash Trough at the river's western exit from the Colorado Plateau (*1*–*3*). Many consider the absence of such diagnostic deposits prior to 6 Ma as evidence that Grand Canyon was not yet excavated (*4*, *5*), with most recent debate focused on how river integration occurred (*5*–*7*). This interpretation assumes that establishment of the integrated Colorado River drainage requires coeval canyon carving.

However, a puzzling array of data hints that the canyon's origin is more complex and could predate integration. Direct geochronologic constraints demanding post-6 Ma formation of the entire canyon do not exist. Dated volcanic rocks drape western Grand Canyon ≤75 m above modern river level (*8*), constraining only the most recent ~8% of the total ~1000 m of canyon incision here. For the eastern canyon, dated basalts, travertines, and alluvium are ≤0.5 Ma and <200 m above river level (*4*, *9*–*11*), and resolve <20% of total incision. Speleothem dates may extend this record (*12*), but their interpretation as incision constraints is debated because it relies on unproven paleohydraulic assumptions (*4*, *13*). A western canyon speleothem date 290 m above river level suggests that the lower ~30% of western canyon carving occurred after ~3.9 Ma (*12*). Thus, the upper ~70% of western Grand Canyon lacks any direct geochronologic constraint on when it was carved. In the eastern part of the canyon, 2.19-3.72 Ma speleothems located ~900 m above the river (*12*) imply the majority of the 1500 m of incision here occurred after 6 Ma, again subject to paleo-groundwater table assumptions.

Other observations imply an older origin for at least parts of the canyon. Deeply incised paleochannels on the Colorado Plateau's southwestern edge support an extensive northeastward flowing paleodrainage system that included portions of a paleo-Grand Canyon in the early Tertiary (*14*–*17*). Substantial canyon incision between 17 and 6 Ma was inferred from 19 Ma lavas on the plateau surface (*15*, *18*, *19*) and from speleothem dates (*12*), but the latter are controversial owing to their distal locations from the canyon (*13*, *20*). If an older canyon existed it is possible that a smaller drainage basin in largely carbonate lithologies explains the absence of pre-6 Ma Colorado River clastics in Grand Wash Trough (*19*, *21*). Grand Canyon history is further complicated by the possibility that its eastern and western segments evolved independently and later merged into the modern configuration. As discussed below, our work supports an east-west dichotomy in incision history, and our data are presented accordingly.

Apatite (U-Th)/He (AHe) thermochronometry can document canyon incision because of its unique sensitivity to topographically-induced temperature variations in the shallow crust (*22*). Rocks cool as they approach the Earth's surface by erosion, and AHe data record this cooling history. Prior application of this method to eastern Grand Canyon suggested incision of a km-scale paleocanyon by 55 Ma, with subsequent downcutting of this canyon below the modern plateau surface in late Tertiary time. This history is compatible with the suggestion that incision of much of the eastern canyon occurred after 6 Ma (*23*). In contrast, AHe data from western Grand Canyon suggested excavation to within several hundred meters of the canyon's modern depth by ~70 Ma, in direct conflict with the young canyon model (*21*).

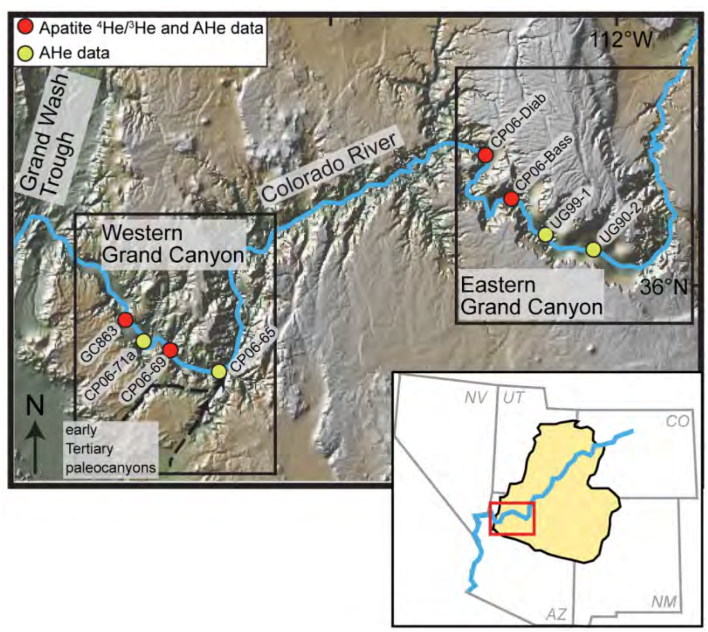

Fig. 1. Grand Canyon shaded relief map showing locations of canyon-bottom samples with apatite $^4He/^3He$ and apatite (U-Th)/He (AHe) data. Inset marks location of study area (red rectangle), the Colorado Plateau (yellow shading), and Colorado River (blue) in the southwestern United States.

Downloaded from www.sciencemag.org on November 30, 2012

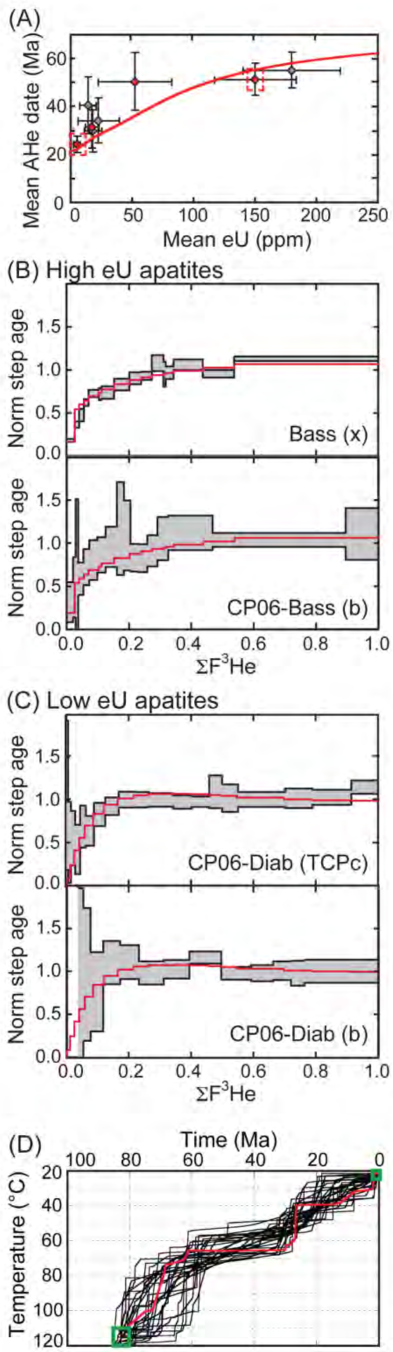

Fig. 2. Results for eastern Grand Canyon. (**A**) Mean sample AHe date versus mean apatite eU for eight samples (errors at ± 1σ standard deviation). Dashed red boxes mark the two samples with apatite $^4He/^3He$ data. Samples with apatite U-Th zonation data are indicated with diamonds, with their AHe dates corrected for α ejection using the mean FTZ (*26*) values of grains with U-Th zonation data. Red line is predicted date-eU correlation from best-fit thermal history in (D). Normalized $^4He/^3He$ step age plots for (**B**) two high eU apatites and (**C**) two low eU apatites, with 1σ uncertainties. Red curves are profiles predicted by best-fit thermal history in (D). (**D**) Thermal histories that satisfy the AHe dates for the four samples of variable eU marked by red diamonds in (A) (G = 0.3) and the four normalized step age profiles in (B) and (C) (G = 0.15). G is a goodness of fit parameter defined in (*30*). Red line is best-fit thermal history. Green boxes are thermal history constraints.

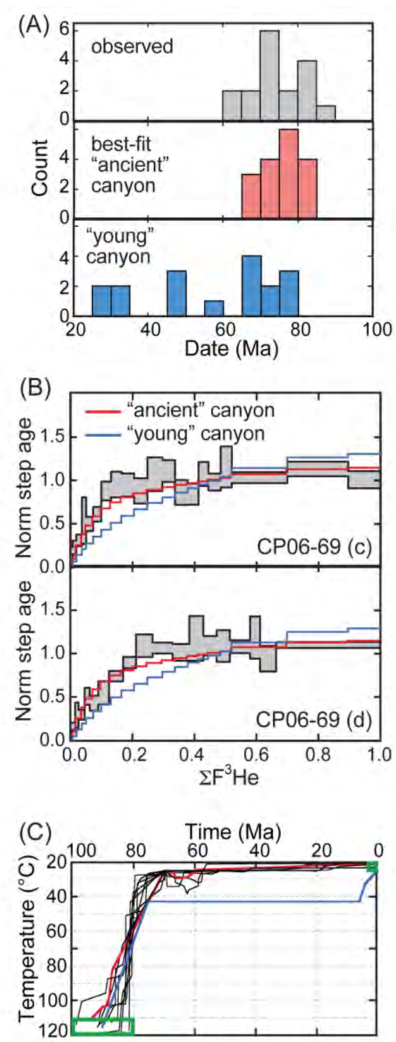

Fig. 3. Results for western Grand Canyon. (**A**) Distribution of measured AHe dates for multiple replicates of four samples (upper panel) compared with AHe dates predicted by the best-fit thermal history from the inverse modeling suggesting an "ancient" Late Cretaceous canyon [middle histogram, using red cooling path in (C)], and those predicted by the conventional "young" post-6 Ma canyon model [bottom histogram, using blue path in (C)]. (**B**) Normalized $^4He/^3He$ step age plots for two apatites from CP06-69. Red and blue curves are profiles predicted by the best-fit and young canyon thermal histories in (C), respectively. (**C**) Thermal histories that satisfy the bulk AHe data in (A) (G = 0.3) and the two normalized step age profiles in (B) (G = 0.32). Red line is best-fit thermal history. Blue line is conventional post-6 Ma incision history based on ref. (*4*) as described in (*30*), and yields a substantially poorer fit to the $^4He/^3He$ spectra in (B) (G < 0.06). Green boxes are thermal history constraints.

Downloaded from www.sciencemag.org on November 30, 2012

The unexpected implications of this initial Grand Canyon AHe work motivated the apatite ^{4}He/^{3}He and U-Th zonation study presented here.

The apatite ^{4}He/^{3}He method provides even greater sensitivity to canyon incision by constraining cooling histories down to ~30°C from the spatial distribution of radiogenic ^{4}He in the crystal (*24*). Successful interpretation of both AHe dates and ^{4}He/^{3}He spectra demands accurate understanding of He behavior in apatite. While the role of radiation damage in retarding apatite He diffusion and the superposition of U-Th zonation effects on ^{4}He/^{3}He spectra have recently been characterized (*25*–*27*), verification of the methodology is limited. Because eastern Grand Canyon yields AHe dates generally consistent with previous models of late Tertiary canyon incision, we use this region as a test case for the ^{4}He/^{3}He method. Our goal is to assess whether the ^{4}He/^{3}He results from this suite, which includes apatites of variable He date, degree of radiation damage, and U-Th zonation, yield mutually consistent thermal histories using a recent He diffusion kinetic model (*28*). Fulfillment of this expectation validates application of the method to a similar data set from western Grand Canyon to test the "young" versus "ancient" canyon models.

From two eastern canyon-bottom samples we acquired ^{4}He/^{3}He spectra on apatites having a large difference in effective uranium concentration (eU) (*29*) and mean AHe date (Fig. 2, fig. S1, and tables S1 and S2). These two samples were selected from a suite in which He dates are correlated with eU, diagnostic of the effects of radiation damage on He diffusivity (*23*) (Fig. 2A). We mapped U and Th concentrations in these apatites plus those from two other samples in the suite (fig. S2 and tables S3 and S4). We performed inverse modeling to find time-temperature paths that simultaneously satisfy the mean AHe dates and the ^{4}He/^{3}He spectra (*30*) (table S5).

Thermal histories were forced through 110-120°C peak temperatures at 80-85 Ma as suggested by complete annealing of apatite fission tracks at this time (*31*), and cooling to 20-25°C surface temperature by present-day. Statistically acceptable paths (*30*) are characterized by a distinctive two-stage cooling trajectory, impose tight constraints on the ~90°C to 30°C thermal history experienced by the eastern gorge, and are consistent with but more restrictive than the history inferred from the AHe dates alone (*28*) and apatite fission-track (AFT) data from the same area (*32*) (Fig. 2D). This history records a distinct late Tertiary cooling phase, permissive of substantial post-6 Ma incision. Importantly, the agreement among samples with differing eU provides compelling evidence that the He diffusion kinetic model we used is appropriate for simulation of Grand Canyon AHe and ^{4}He/^{3}He data.

Given this validation, we examined a similar suite of data from western Grand Canyon (Fig. 1). Late Cretaceous AHe dates for four canyon-bottom samples (*23*, *26*) show no correlation with apatite eU, consistent with a single-phase cooling history also indicated by AFT data (*32*) (tables S1 and S6). Apatite ^{4}He/^{3}He data were obtained from two of these samples (Fig. 3, fig. S1, and tables S1 and S2). Duplicate ^{4}He/^{3}He spectra for one sample (CP06-69) are similar, and apatites from this sample are characterized by similar U-Th zonation (fig. S2 and tables S3 and S4). In contrast, the 11 apatite ^{4}He/^{3}He spectra for sample GC863 have diverse shapes, which arise from extreme U-Th zoning heterogeneity in this sample (*26*) (figs. S1 and S2). Because we do not have U-Th zonation data for each apatite with ^{4}He/^{3}He data, this extreme zonation precludes use of the GC863 ^{4}He/^{3}He results for inverse modeling.

Consequently, we used the ^{4}He/^{3}He spectra from CP06-69 and the AHe dates from all four basement samples (table S5) to constrain statistically acceptable thermal histories for western Grand Canyon (*30*). We used the same thermal history constraints as eastern Grand Canyon, differing only in broader age bounds of 100-80 Ma for the peak temperature, owing to the older AHe dates here. Statistically acceptable paths (*30*) require rapid cooling to <30°C by ~70 Ma (Fig. 3). Assuming a 20-25°C/km geothermal gradient and a 25°C surface temperature (*21*, *30*), this result implies carving of western Grand Canyon to within several hundred meters of modern depths (70-80% of total incision) by 70 Ma. This history is compatible with the volcanic and speleothem data within the western gorge (*8*, *12*).

We explicitly tested the young canyon model against our ^{4}He/^{3}He spectra and bulk AHe dates for these same samples using a time-temperature path constructed from a popular description of post-6 Ma incision (*4*, *30*). The predicted distribution of AHe dates is much broader and includes dates younger than observed (Fig. 3). The fits of the predicted ^{4}He/^{3}He spectra to the measurements are similarly statistically unacceptable (Fig. 3B). These conclusions are insensitive to reasonable assumptions about the geotherm and surface temperature and to alternative diffusivity parameters (*30*) (fig. S3A). The young canyon model also yields a qualitatively poorer fit than the ancient canyon model to the ^{4}He/^{3}He spectra of the strongly eU-zoned sample GC863 (*30*) (fig. S3B).

The western Grand Canyon ^{4}He/^{3}He and AHe data demand a substantial cooling event at 70-80 Ma, and provide no evidence for the strong post-6 Ma cooling signal predicted by the young canyon model. Thus, when applying our best understanding of apatite He diffusion kinetics derived from recent work (*25*, *28*), apatite He data support carving of most of western Grand Canyon by ~70 Ma and are inconsistent with the conventional view that the entire canyon was cut after 6 Ma (*4*). Moreover, the results imply a dichotomy in eastern and western canyon carving, characterized by coeval excavation of an eastern paleocanyon (*23*) and substantial carving of the modern western gorge by 70 Ma (*21*), followed by substantial late Tertiary incision restricted to the eastern canyon. This history supports a model (*21*) in which much of Grand Canyon incision was accomplished by an ancient Cretaceous river that flowed eastward from western highlands, with Tertiary reversal of the river's course as topography rose in the east and collapsed in the west, and thus has profound implications for the evolution of topography, landscapes, hydrology, and tectonism in the North American Cordillera.

References and Notes

1. E. Blackwelder, Origin of the Colorado River. *Geol. Soc. Am. Bull.* **45**, 551 (1934).
2. C. R. Longwell, How old is the Colorado River? *Am. J. Sci.* **244**, 817 (1946). doi:10.2475/ajs.244.12.817
3. I. Lucchitta, Early history of the Colorado River in the Basin and Range Province. *Geol. Soc. Am. Bull.* **83**, 1933 (1972). doi:10.1130/0016-7606(1972)83[1933:EHOTCR]2.0.CO;2
4. K. E. Karlstrom, R. Crow, L. J. Crossey, D. Coblentz, J. W. Van Wijk, Model for tectonically driven incision of the younger than 6 Ma Grand Canyon. *Geology* **36**, 835 (2008). doi:10.1130/G25032A.1
5. J. L. Pederson, The mystery of the pre–Grand Canyon Colorado River—Results from the Muddy Creek Formation. *GSA Today* **18**, 4 (2008). doi:10.1130/GSAT01803A.1
6. J. E. Spencer, P. A. Pearthree, in *Colorado River Origin and Evolution*, R. A. Young, E. E. Spamer, Eds. (Grand Canyon Association, Grand Canyon, AZ, 2001), pp. 215–222.
7. I. Lucchitta, R. F. Holm, B. K. Lucchitta, A Miocene river in northern Arizona and its implications for the Colorado River and Grand Canyon. *GSA Today* **21**, 4 (2011). doi:10.1130/G119A.1
8. K. E. Karlstrom *et al.*, ^{40}Ar/^{39}Ar and field studies of Quaternary basalts in Grand Canyon and model for carving Grand Canyon: Quantifying the interaction of river incision and normal faulting across the western edge of the Colorado Plateau. *Geol. Soc. Am. Bull.* **119**, 1283 (2007). doi:10.1130/0016-7606(2007)119[1283:AAFSOQ]2.0.CO;2
9. J. Pederson, K. Karlstrom, W. Sharp, W. McIntosh, Differential incision of the Grand Canyon related to Quaternary faulting—Constraints from U-series and Ar/Ar dating. *Geology* **30**, 739 (2002). doi:10.1130/0091-7613(2002)030<0739:DIOTGC>2.0.CO;2
10. S. W. Davis *et al.*, in *Colorado River Origin and Evolution*, R. A. Young, E. E. Spamer, Eds. (Grand Canyon Association, Grand Canyon, AZ, 2001), pp. 135–139.

Downloaded from www.sciencemag.org on November 30, 2012

11. I. Lucchitta, G. H. Curtis, M. E. Davis, S. W. Davis, B. Turrin, Cyclic aggradation and downcutting, fluvial response to volcanic activity, and calibration of soil-carbonate stages in the Western Grand Canyon, Arizona. *Quat. Res.* **53**, 23 (2000). doi:10.1006/qres.1999.2098
12. V. Polyak, C. Hill, Y. Asmerom, Age and evolution of the Grand Canyon revealed by U-Pb dating of water table-type speleothems. *Science* **319**, 1377 (2008). doi:10.1126/science.1151248 Medline
13. J. Pederson, R. Young, I. Lucchitta, L. S. Beard, G. Billingsley, Comment on "Age and evolution of the Grand Canyon revealed by U-Pb dating of water table-type speleotherms". *Science* **321**, 1634b (2008). doi:10.1126/science.1158019
14. R. A. Young, Laramide deformation, erosion and plutonism along the southwestern margin of the Colorado Plateau. *Tectonophysics* **61**, 25 (1979). doi:10.1016/0040-1951(79)90290-7
15. D. P. Elston, R. A. Young, Cretaceous-Eocene (Laramide) landscape development and Oligocene-Pliocene drainage reorganization of Transition Zone and Colorado Plateau, Arizona. *J. Geophys. Res.* **96**, 12389 (1991). doi:10.1029/90JB01978
16. A. R. Potochnik, in *Colorado River Origin and Evolution*, R. A. Young, E. E. Spamer, Eds. (Grand Canyon Association, Grand Canyon, AZ, 2001), pp. 17–22.
17. R. A. Young, in *Colorado River Origin and Evolution*, R. A. Young, E. E. Spamer, Eds. (Grand Canyon Association, Grand Canyon, AZ, 2001), pp. 7–16.
18. R. A. Young, in *Geology of Grand Canyon, Northern Arizona*, D. P. Elston, G. H. Billingsley, R. A. Young, Eds. (American Geophysical Union, 28th International Geological Congress Fieldtrip Guidebook T115/315, Washington, DC, 1989), pp. 166–173.
19. R. A. Young, in Late Cenozoic Drainage History of the Southwestern Great Basin and Lower Colorado River Basin: Geologic and Biologic Perspectives, M. C. Reheis, R. Hershler, D. M. Miller, Eds. (Geological Society of America Special Paper, 2008), vol. 439, pp. 319–333.
20. P. A. Pearthree, J. E. Spencer, J. E. Faulds, P. K. House, Comment on "Age and evolution of the Grand Canyon revealed by U-Pb dating of water table-type speleotherms". *Science* **321**, 1634c (2008). doi:10.1126/science.1158862
21. B. Wernicke, The California River and its role in carving Grand Canyon. *Geol. Soc. Am. Bull.* **123**, 1288 (2011). doi:10.1130/B30274.1
22. M. A. House, B. P. Wernicke, K. A. Farley, Dating topography of the Sierra Nevada, California, using apatite (U-Th)/He ages. *Nature* **396**, 66 (1998). doi:10.1038/23926
23. R. M. Flowers, B. P. Wernicke, K. A. Farley, Unroofing, incision and uplift history of the southwestern Colorado Plateau from apatite (U-Th)/He thermochronometry. *Geol. Soc. Am. Bull.* **120**, 571 (2008). doi:10.1130/B26231.1
24. D. L. Shuster, K. A. Farley, ^{4}He/^{3}He thermochronometry. *Earth Planet. Sci. Lett.* **217**, 1 (2004). doi:10.1016/S0012-821X(03)00595-8
25. K. A. Farley, D. L. Shuster, E. B. Watson, K. H. Wanser, G. Balco, Numerical investigations of apatite ^{4}He/^{3}He thermochronometry. *Geochem. Geophys. Geosyst.* **11**, Q10001 (2010). doi:10.1029/2010GC003243
26. K. A. Farley, D. L. Shuster, R. A. Ketcham, U and Th zonation in apatite observed by laser ablation ICPMS, and implications for the (U-Th)/He system. *Geochim. Cosmochim. Acta* **75**, 4515 (2011). doi:10.1016/j.gca.2011.05.020
27. D. L. Shuster, R. M. Flowers, K. A. Farley, The influence of natural radiation damage on helium diffusion kinetics in apatite. *Earth Planet. Sci. Lett.* **249**, 148 (2006). doi:10.1016/j.epsl.2006.07.028
28. R. M. Flowers, R. A. Ketcham, D. L. Shuster, K. A. Farley, Apatite (U-Th)/He thermochronometry using a radiation damage accumulation and annealing model. *Geochim. Cosmochim. Acta* **73**, 2347 (2009). doi:10.1016/j.gca.2009.01.015
29. R. M. Flowers, D. L. Shuster, B. P. Wernicke, K. A. Farley, Radiation damage control on apatite (U-Th)/He dates from the Grand Canyon region, Colorado Plateau. *Geology* **35**, 447 (2007). doi:10.1130/G23471A.1
30. Materials and methods are available as supplementary materials on *Science* Online.
31. T. A. Dumitru, I. R. Duddy, P. F. Green, Mesozoic-Cenozoic burial, uplift, and erosion history of the west-central Colorado Plateau. *Geology* **22**, 499 (1994). doi:10.1130/0091-7613(1994)022<0499:MCBUAE>2.3.CO;2
32. S. A. Kelley, C. E. Chapin, K. Karlstrom, in *Colorado River Origin and Evolution*, R. A. Young, E. E. Spamer, Eds. (Grand Canyon Association, Grand Canyon, AZ, 2001), pp. 37–42.
33. D. L. Shuster, K. A. Farley, J. M. Sisterson, D. S. Burnett, Quantifying the diffusion kinetics and spatial distribution of radiogenice ^{4}He in minerals containing proton-induced ^{3}He. *Earth Planet. Sci. Lett.* **217**, 19 (2004). doi:10.1016/S0012-821X(03)00594-6
34. K. A. Farley, R. A. Wolf, L. T. Silver, The effects of long alpha-stopping distances on (U-Th)/He ages. *Geochim. Cosmochim. Acta* **60**, 4223 (1996). doi:10.1016/S0016-7037(96)00193-7
35. K. A. Farley, P. W. Reiners, W. Nenow, An apparatus for high-precision helium diffusion measurements from minerals. *Anal. Chem.* **71**, 2059 (1999). doi:10.1021/ac9813078
36. D. L. Shuster, K. A. Farley, in *Reviews in Mineralogy and Geochemistry: Low-Temperature Thermochronology: Techniques, Interpretations, and Applications*, P. W. Reiners, T. A. Ehlers, Eds. (Mineralogical Society of America, 2005), vol. 58, pp. 181–203.
37. R. A. Ketcham, in *Reviews in Mineralogy and Geochemistry: Low-Temperature Thermochronology: Techniques, Interpretations, and Applications*, P. W. Reiners, T. A. Ehlers, Eds. (Mineralogical Society of America, 2005), vol. 58, pp. 275–314.
38. R. A. Ketcham, R. A. Donelick, M. L. Balestrieri, M. Zattin, Reproducibility of apatite fission-track length data and thermal history reconstruction. *Earth Planet. Sci. Lett.* **284**, 504 (2009). doi:10.1016/j.epsl.2009.05.015
39. J. D. Nations, in *Geology of Arizona*, J. P. Jenny, S. J. Reynolds, Eds. (Arizona Geological Society Digest, Tucson, AZ, 1989), pp. 435–446.
40. J. Zachos, M. Pagani, L. Sloan, E. Thomas, K. Billups, Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science* **292**, 686 (2001). doi:10.1126/science.1059412 Medline

Acknowledgments: This work was supported by NSF grant EAR-1019896 to K.A.F. The data reported in this paper are tabulated in the supplementary materials. We thank B. Wernicke for discussion.

Supplementary Materials
www.sciencemag.org/cgi/content/full/science.1229390/DC1
Materials and Methods
Figs. S1 to S3
Tables S1 to S6
References (*33–40*)

27 August 2012; accepted 7 November 2012
Published online 29 November 2012
10.1126/science.1229390

Downloaded from www.sciencemag.org on November 30, 2012