Where does sediment come from? Quantifying catchment erosion with detrital apatite (U-Th)/He thermochronometry

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ABSTRACT

We present a new method for tracing sediment using detrital apatite (U-Th)/He (AHe) thermochronometry, and use this to quantify the spatial distribution of catchment erosion in the eastern Sierra Nevada, California. Well-developed age-elevation relationships permit detrital AHe ages to track the elevations where sediment grains were shed from bedrock. We analyzed sediment exiting nonglaciated Inyo Creek and adjacent (formerly) glaciated Lone Pine Creek. Statistical comparison of measured AHe age probability density functions (PDFs) with predicted PDFs based on catchment hypsometries suggests that Inyo Creek is eroding uniformly, consistent with field observations of weathered hillslopes tightly coupled to the fluvial system. In contrast, significant mismatch between measured and predicted PDFs from Lone Pine Creek reveals that sediment derives primarily from the lower half of the catchment. The dearth of older ages is likely due to sediment storage in cirques and moraines and/or focused erosion at intermediate elevations, both potential consequences of glacial modification. Measured PDFs can also improve cosmogenic nuclide-based erosion rates by more accurately scaling nuclide production rates. Our results demonstrate the utility of detrital AHe thermochronometry for quantifying erosion in fluvially and glacially sculpted catchments.

Keywords: detrital thermochronometry, apatite (U-Th)/He, cosmogenic nuclides, erosion, Sierra Nevada.

INTRODUCTION

Quantifying catchment erosion is fundamentally important for understanding how tectonic and climatic forces shape mountain topography. Sediment collected from the mouth of a catchment is particularly useful for this purpose, because it spatially integrates erosion information. Where does sediment exiting a catchment come from? In some cases, unique mineralogy or detrital provenance studies can identify which rock units are contributing sediment, but even these usually do not yield specific elevation information, key to understanding surface processes acting in the catchment and for calculating spatially averaged erosion rates from cosmogenic nuclides. Most detrital studies assume that sediment derives uniformly from across catchments. In reality, this assumption is difficult to test beyond basic field observations, and may be invalid because multiple geomorphic processes can operate with different rates and magnitudes across a catchment.

We present a new method for tracing sediment using detrital apatite (U-Th)/He (AHe) thermochronometry. Previous detrital thermochronometry studies have focused on sediment provenance or mixing with zircon U-Pb ages (e.g., Ross and Bowring, 1990; Amidon et al., 2005) and orogen-scale erosion rates with muscovite $^{40}Ar/^{39}Ar$ (e.g., Carrapa et al., 2003; Brewer et al., 2003; Ruhl and Hodges, 2005) and apatite or zircon fission track ages (e.g., Brandon and Vance, 1992; Garver et al., 1999; Bernet et al., 2001). We use detrital AHe ages as markers to quantify the spatial distribution of erosion at the catchment scale. The technique relies on the observation that mineral cooling ages in bedrock samples often increase with elevation. In detrital settings, this relationship has been proposed as a means of estimating paleorelief (Stock and Montgomery, 1996), and, by inversion, catchment erosion rates (Brewer et al., 2003; Ruhl and Hodges, 2005). Detrital mineral cooling ages can also be used to determine the elevation from which sediment grains were dislodged from bedrock. AHe has the lowest closure temperature (~70 °C) of the commonly used thermochronometers and generally records cooling by exhumation (Ehlers and Farley, 2003), yielding well-developed age-elevation relationships. This is not always the case with higher-temperature thermochronometers (e.g., $^{40}Ar/^{39}Ar$, zircon fission track), which may record pluton crystallization ages or differential depths to closure isotherms, and thus not display clear age-elevation relationships.

Detrital thermochronometry is subject to several potentially complicating factors, including variable mineral concentrations in bedrock, differential mineral preservation, and low single-grain age precision. Detrital AHe is subject to additional complications associated with the reproducibility of ages (e.g., inclusions, U-Th zonation; Farley, 2002) and age resetting by wildfires (Mitchell and Reiners, 2003). In order to explore the use of detrital AHe, we dated apatites in sediment exiting two adjacent catchments with properties that tend to reduce these complicating factors. In addition, because these catchments have highly contrasting geomorphic histories, AHe age distributions reveal how different surface processes affect spatial variations in catchment erosion.

QUANTIFYING SPATIALLY VARIABLE CATCHMENT EROSION

We describe the distribution of detrital AHe ages in terms of measured probability density functions (PDFs), defined as the normalized summation of the individual cooling ages and their associated Gaussian uncertainties (Appendix 1[1]). The spatial distribution of erosion is quantifiable with a statistical comparison between measured PDFs and predicted PDFs. Predicted PDFs are constructed by convolving catchment hypsometry (frequency distribution of elevations) with the local AHe age-elevation relationship (Fig. 1A), such that each elevation in a digital elevation model (DEM) is assigned a model AHe age. If erosion occurs in proportion to surface area (catchment erosion is spatially uniform), and sediment exiting the catchment records that proportion in high fidelity, then the measured PDF should exactly match the predicted PDF (Fig. 1B; Ruhl and Hodges, 2003). Deviations document nonuniform erosion, and either indicate focused erosion in certain parts of the catchment, perhaps due to rock falls, landslides, or glacial modification (Fig. 1B), or indicate sediment storage.

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[1]GSA Data Repository item 2006152, Appendix 1, sample preparation and analytical techniques; Tables DR1–DR4, AHe ages, Kuiper test statistics, and ^{10}Be data; Figure DR1, Apatite photomicrographs; and Figure DR2, U concentration vs. AHe age, is available online at www.geosociety.org/pubs/ft2006.htm or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, Colorado, 80301–9140, USA.

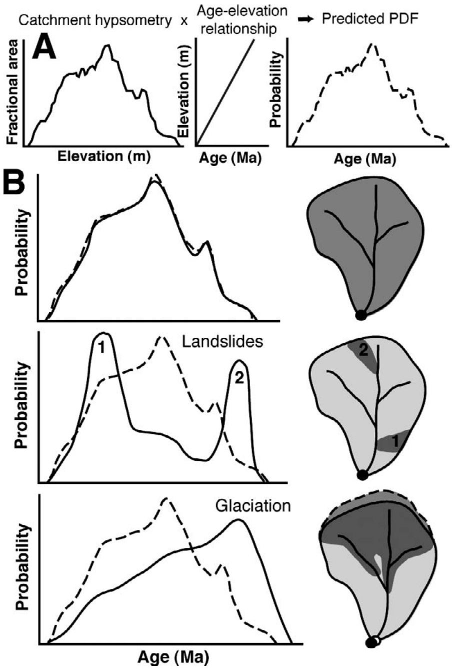

Figure 1. Construction and utility of cooling age probability density functions (PDFs). A: Construction of predicted PDF (dashed line) based on catchment hypsometry and age-elevation relationship, assuming no lateral age variation (Brewer et al., 2003; Ruhl and Hodges, 2005). B: Effect of spatially and temporally variable erosion on measured PDF. If catchment is eroding uniformly (top panel), measured PDF (solid) should match predicted PDF (dashed); if not (middle), there will be mismatch. In small catchments, cirque glaciation (bottom) shifts hypsometry toward higher elevations (Brocklehurst and Whipple, 2004), thus shifting measured PDF toward older ages.

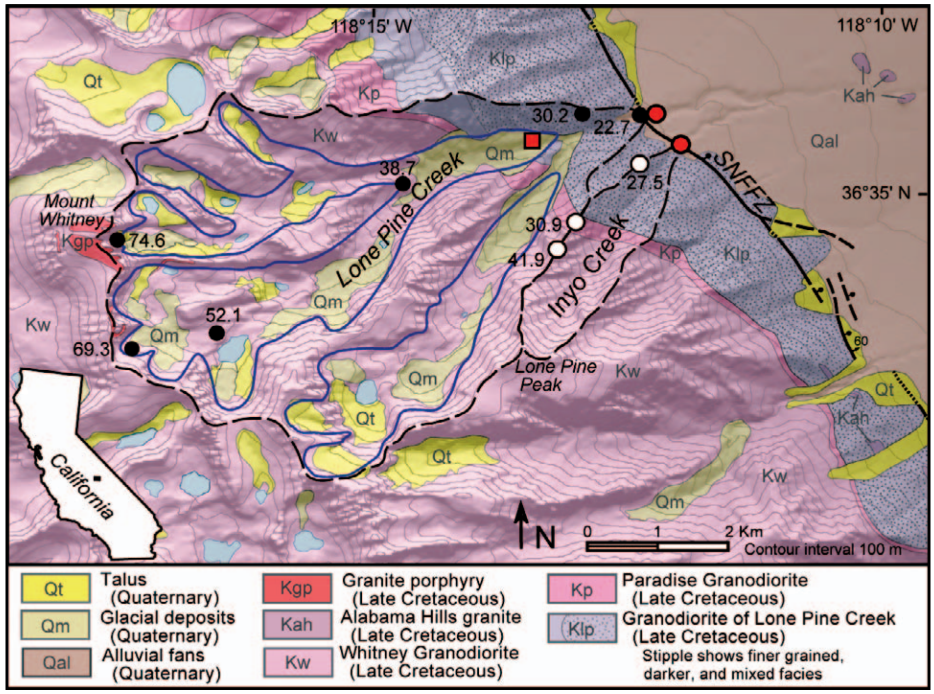

Figure 2. A: Geology and topography of Inyo Creek and Lone Pine Creek catchments. Geology is modified from Stone et al. (2000) and Moore (1981). Bedrock apatite (U-Th)/He (AHe) samples are shown by black (House et al., 1997) and white (this study) circles (ages in Ma). Red circles show detrital samples, red square shows moraine sample. Dashed black lines show catchment boundaries, blue lines show approximate Last Glacial Maximum glacier extent. SNFFZ—Sierra Nevada frontal fault zone.

FIELD SETTING

We investigated Inyo and Lone Pine Creeks, adjoining catchments draining the steep eastern escarpment of the Sierra Nevada, California (Fig. 2). Previous bedrock AHe transects up the escarpment display linear cooling age-elevation relationships, reflecting slow, steady exhumation of the Sierra Nevada between 80 and 20 Ma (House et al., 1997; Clark et al., 2005). Subsequently, vertical offset along the normal Sierra Nevada frontal fault zone (SNFFZ) created the escarpment ca. 2–8 Ma (Pinter and Keller, 1995; Bachman, 1978). Although isotherm bending beneath topography can occur (Ehlers and Farley, 2003), in this case the thermal structure recorded by bedrock AHe ages predates creation of the modern topography.

Inyo and Lone Pine Creeks have cut into a nearly uniform lithology, the Whitney, Paradise, and Lone Pine Creek granodiorites (Fig. 2; Stone et al., 2000). Both catchments are sparsely vegetated, reducing the potential for wildfire resetting of AHe ages but not eliminating it entirely (Bierman and Gillespie, 1991). Inyo Creek is a small first-order catchment with total relief of 1905 m and a contributing area of 3.1 km^2. Inyo Creek preserves no evidence of Pleistocene glaciation, a fact reflected in its hypsometry and concave longitudinal profile (Fig. 3; Brocklehurst and Whipple, 2004). The Inyo Creek channel contains virtually no stored sediment. In contrast, Lone Pine Creek is a much larger fifth-order catchment with total relief of 2423 m and a contributing area of 30.7 km^2. This catchment was fully glaciated during the Pleistocene (Fig. 2). Glacial modification has skewed the catchment hypsometry toward higher elevations, reflecting the greater surface area of high elevation cirques and basins, and created a stepped longitudinal profile characteristic of glacial valleys (Fig. 3; Brocklehurst and Whipple, 2004). Moraine and talus deposits are widespread (Fig. 2).

METHODS AND RESULTS

We dated 106 apatites in modern sediment from Inyo and Lone Pine Creeks where they cross the SNFFZ (Fig. 2; Table DR2 [see footnote 1]). Although analytical uncertainty for AHe dating is typically 2%–3% (1σ), the total uncertainty depends on reproducibility of replicate bedrock samples, which is often much poorer (Farley, 2002). As replicate analyses are not possible in detrital studies, we delimited the total age uncertainty by dating 14 apatites from 3 bedrock samples (4–5 replicates from each sample) of the plutons contributing sediment to the catchments (Fig. 2). The mean reproducibility of these bedrock samples is 11% (Table DR1), which we assign as the uncertainty in the detrital AHe ages. We constructed predicted PDFs using our bedrock AHe ages and those of House et al. (1997) (Fig. 4A), and assume no lateral age variation over this small field area.

AHe ages from the Inyo Creek catchment (n = 52) range from 23.6 to 63.4 Ma (one grain age of 77.4 Ma). The measured PDF has a peak centered ca. 33 Ma, very close to the ca. 31 Ma peak in the predicted PDF (Fig. 4B). The shapes of the measured and predicted PDFs appear similar, but are they statistically indistinguishable? We compared the two distributions using Monte Carlo simulations in which n ages are selected randomly from the predicted PDF and compared with the measured PDF using the Kuiper equality test (Table DR3; Ruhl and Hodges, 2005). Results of 10,000 simulations indicate that the measured and predicted PDFs for the Inyo Creek catchment are statistically indistinguishable, i.e., there is a 99% probability that the two distributions are the same at the 95% confidence level. In contrast, AHe ages from Lone Pine Creek (n = 54) range from 27.1 to 86.8 Ma (with two ages younger than 20 Ma). The measured PDF peak is centered ca. 41 Ma, substantially younger than the ca. 62 Ma peak

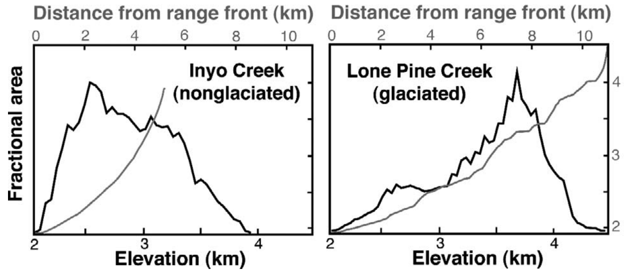

Figure 3. Hypsometries (black) and longitudinal profiles (gray) of nonglaciated Inyo Creek and fully glaciated Lone Pine Creek. Asymmetric hypsometry and stepped profile of Lone Pine Creek catchment reflect high-elevation cirques and basins.

in the predicted PDF (Fig. 4C). In this case the Monte Carlo statistical tests indicate a 97% probability that the predicted and measured PDFs of the Lone Pine Creek catchment are different at the 95% confidence level.

DISCUSSION

The similarity between the predicted and measured PDFs for the Inyo Creek catchment (Fig. 4B) suggests that it is eroding uniformly. This may seem surprising given the very steep nature of this catchment. However, much of the bedrock is grussified, likely resulting from lack of glaciation, and sediment in the Inyo Creek channel consists mostly of grus. Steep hillslopes are tightly coupled to the channel so that grus shed from hillslopes is quickly mobilized by the fluvial system. We propose that erosion is uniform because sediment delivery occurs grain by grain from bedrock weathering, rather than by mass-wasting processes. If mass-wasting processes are operating, they apparently do so uniformly across the catchment.

In contrast, Lone Pine Creek shows a statistically significant mismatch between the predicted and measured PDFs (Fig. 4C), indicating spatially nonuniform erosion. We consider three possibilities for this mismatch: (1) older (higher elevation) grains were destroyed in this much larger glaciated catchment before reaching the range front, (2) these grains are currently stored in the catchment, and (3) modern erosion rates are more rapid at intermediate elevations. We are not able to exclude the first possibility, given that apatite is not a particularly robust mineral in detrital settings (Kowalewski and Rimstidt, 2003). However, the presence of several old (older than 70 Ma) apatites suggests that at least some have traveled the entire length of the catchment (~11 km). Furthermore, abundant datable apatites in moraine sediment (Fig. DR1; see footnote 1) diminish the argument that glacial abrasion destroyed older apatites. More likely, sediment from higher elevations is stored within the catchment. Field observations highlight abundant sediment sinks, including tarns, moraines, and extensive talus deposits (Fig. 2). As in Inyo Creek, steep hillslopes in the lower part of the Lone Pine Creek catchment are tightly coupled to the stream channel. However, hillslopes at the top of the catchment, though even steeper and thus more likely to produce sediment, are not as tightly coupled, e.g., detritus shed from cirque headwalls falls onto broad cirque floors and is not readily transported by the low-gradient, low-discharge streams draining these areas. The few old apatites exiting the catchment may be reworked from moraines (Fig. 2). The mismatch may result from more rapid erosion at intermediate catchment elevations, perhaps due to oversteepened walls where glaciers converged and became more entrenched. However, glaciation of eastern Sierra Nevada catchments has skewed hypsometries toward higher elevations, suggesting greater erosion there (Brocklehurst and Whipple, 2004). In any case, our results suggest caution when assuming uniform erosion for formerly glaciated catchments.

Several factors associated with detrital AHe dating could alter the shape of the PDFs and thus our interpretations. First, have we analyzed a sufficient number of grains? Although >100 analyses are needed to be 95% confident that no fraction ≥5% of the population is missed (Vermeesch, 2004), previous studies have suggested that 40–50 analyses are often sufficient to adequately capture the distribution (Ruhl and Hodges, 2005; Stock and Montgomery, 1996). Additional Monte Carlo simulations (n = 20,000) (Figs. 4B, 4C) indicate that the statistical results of our PDF comparisons would not change with additional measurements.

Do the three plutons contributing sediment have uniform concentrations of datable apatites? Variations in mineral concentration can significantly bias a detrital signal (e.g., Amidon et al., 2005; Spiegel et al., 2004). Because apatites must be selectively handpicked for AHe dating, quantifying the number of datable grains from bedrock samples is difficult. We partially address this problem by studying catchments with nearly uniform lithologies. In addition, we detected no variation in apatite size, quality, or abundance between the three plutons that would bias our selection of grains for analysis (Fig. DR1; see footnote 1).

Do AHe ages have sufficient precision to resolve discrete elevation information? AHe ages in these catchments span ~60 m.y., a result of slow Cenozoic cooling and substantial catchment relief. Because of this large age range there is sufficient precision to identify unique elevation ranges even with the relatively large single-grain age uncertainty. For example, a 50 Ma AHe age with 11% uncertainty identifies an elevation range of 3290 ± 226 m. Less precision should be expected for catchments with lower relief, smaller age ranges, and/or greater age uncertainty.

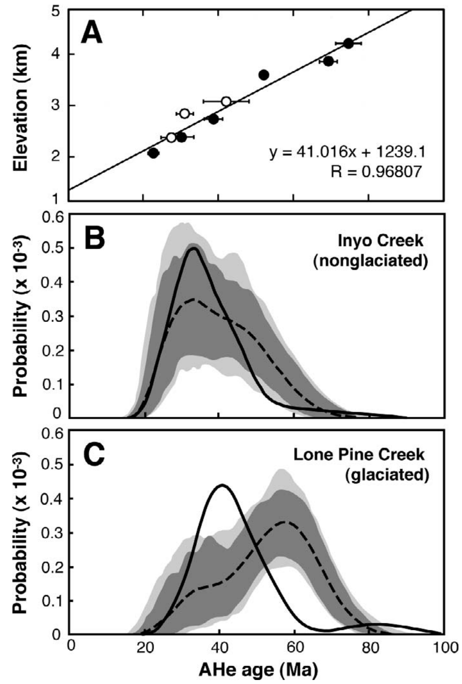

Figure 4. Statistical comparison of measured and predicted probability density functions (PDFs). A: Apatite (U-Th)/He (AHe) age-elevation relationship upon which predicted PDFs are based. Black circles are data from House et al. (1997), white circles are from this study. B: Predicted PDF (dashed) and measured PDFs (solid) for Inyo Creek, with area under curve normalized to 1. Smoothing results from 11% uncertainty. Shaded areas represent Monte Carlo simulations of predicted PDFs based on 52 (light) and 100 (dark) randomly selected predicted ages. Predicted and measured PDFs are statistically indistinguishable, indicating uniform catchment erosion. C: Similar plot for Lone Pine Creek showing statistically different predicted and measured PDFs, indicating nonuniform catchment erosion.

ESTIMATING CATCHMENT EROSION RATES

Assuming steady-state conditions, catchment erosion rates can be derived by dividing observed detrital cooling age ranges into catchment relief (Ruhl and Hodges, 2005). For Inyo and Lone Pine Creeks, this yields erosion rates of 0.04–0.05 mm/yr. However, because bedrock, and thus detrital, AHe ages in the eastern Sierra Nevada predate creation of the modern topography, these do not accurately capture catchment erosion rates. Shorter time scale erosion rates must be determined by other means, but the measured PDFs derived from detrital AHe ages still prove useful. Previous work has shown that concentrations of cosmogenic nuclides in detrital sediment record catchment erosion rates (e.g., Granger et al., 1996; Schaller et al., 2001). Calculating erosion by this method requires a spatially averaged nuclide production rate, determined by averaging production rates, scaled for altitude, latitude, and topographic shielding, for each pixel of the catchment DEM. However, this assumes spatially uniform catchment erosion; if instead, sampled sediment derives from point-source erosion, for example a landslide at low elevations (e.g., Niemi et al., 2005), then the estimated catchment production rate and resulting erosion rate will be erroneously high. In such instances, the measured PDF can be used to correct the production rate for the specific elevation ranges where sediment is produced.

In the case of nonglaciated Inyo Creek, the measured PDF validates the uniform erosion assumption. We measured the concentration of cosmogenic ^{10}Be in quartz extracted from the same Inyo Creek sample analyzed for detrital AHe. The ^{10}Be concentration indicates a catchment erosion rate of 0.24 ± 0.03 mm/yr (Table DR4; see footnote 1). This rate is much faster than those estimated using detrital AHe ages, but is supported by identical vertical slip rates along the SNFFZ (0.2–0.4 $\pm$ 0.1 mm/yr; Le, 2004) and adjacent Fish Springs fault (0.24 ± 0.04 mm/yr; Zehfuss et al., 2001).

CONCLUSIONS

In high-relief catchments with well-developed age-elevation relationships, thermochronometers identify the elevations where sediment is produced. This information can be used to quantify the spatial distribution of catchment erosion and can be integrated with cosmogenic nuclides to determine catchment erosion rates. Our results from the eastern Sierra Nevada suggest that sediment production in two adjacent catchments varies from uniform (Inyo Creek) to highly nonuniform (Lone Pine Creek). Although potential complexities with detrital AHe thermochronometry (e.g., apatite concentrations, lateral age variations, wildfires) likely increase with catchment size, our results demonstrate the utility of this technique to quantify erosion in fluvially and glacially sculpted catchments. Integrated detrital studies of sedimentary archives may be particularly useful for investigating the temporal evolution of catchment erosion, relief, and hypsometry.

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