Influence of wildfires on apatite and zircon (U-Th)/He ages

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ABSTRACT

Low closure temperatures of the apatite and zircon (U-Th)/He thermochronometers allow valuable constraints on timing and rates of bedrock exhumation through shallow crustal depths, but raise the possibility that shallow-level processes other than exhumation-related cooling may also influence He ages. A simple He diffusion model predicts that wildfires can completely or partially reset apatite He ages as much as 3 cm below rock surfaces and partially reset zircon He ages in the outermost 1 cm. Measured He ages in bedrock and sediments from the Washington Cascades that were exposed to extensive wildfires in 2001 show strong agreement with these model predictions. Apatite He ages decrease from a regionally consistent age of 19.5 ± 1.2 Ma at a distance >3 cm from the rock surface to as low as 1.9 Ma in the outermost 1 cm, whereas zircon He ages decrease from 65 to 55 Ma over the same distance. Thin (<3 cm) flakes shed from a nearby boulder during or after the most recent fire have apatite He ages ranging from 9.7 ± 0.6 to 17.2 ± 1.0 Ma. The partial-resetting profiles are best explained by model thermal histories involving at least one short-duration (~5–10 min), high-temperature (575–650 °C) event and at least one longer (30–40 min), lower-temperature (350–450 °C) event. Age-depth profile data may be useful in determining wildfire intensities or locations and also suggest that He ages of detrital apatites from some environments may be subject to bias from the thermal effects of wildfires.

Keywords: helium, diffusion, geochronology, wildfires, apatite, zircon.

INTRODUCTION

Helium is produced in apatite and zircon by radioactive decay of uranium and thorium, but is diffusively lost over geologic time scales at temperatures above ~65–70 and 180 °C, respectively, allowing use of these systems as low-temperature thermochronometers (e.g., Zeitler et al., 1987; Farley, 2000; Reiners et al., 2002a; 2003). The thermal sensitivity of these systems, particularly apatite, suggests that they may be susceptible to transitory thermal events once they are exposed at Earth's surface; e.g., Wolf et al. (1998) suggested that a short (10 min), high-temperature (600 °C) surface-heating event can cause >30% He loss in apatite crystals on rock surfaces, but that loss is negligible at depths of >3 cm. Using a model of He diffusion similar that of Wolf et al. (1998), we found that a thermal event of this type results in >90% He loss in the outermost 1 cm, suggesting that wildfire-related He loss may be a critical consideration when collecting bedrock or sediment samples.

The potential for wildfire-induced He loss is important for a number of reasons. First, it could affect interpretations of the timing and rate of exhumation of bedrock based on (U-Th)/He ages, because such ages are typically interpreted as a duration of time elapsed since monotonic cooling of the rock through relevant isotherms or depths beneath the Earth's surface. For bedrock sampling, this problem may be avoided by removing the outer few centimeters of rock as part of the sample preparation. However, using He ages measured from detrital grains as a means of determining basin-average exhumation rates could give highly compromised results, particularly if sediment is generated from the erosion of exposed rock surfaces. From a different perspective, the pattern and extent of He loss from bedrock samples may help delineate burned regions and resolve durations and intensities of wildfires. Here we first show modeled effects of heating on He loss. Next, we present apatite He and zircon He data collected from bedrock and colluvium located in a recently burned region of central Washington State. Finally, we use the data and model to constrain the thermal history of our bedrock sample.

He DIFFUSION

We used a simple model of He diffusion to investigate the potential extent of He loss from apatite and zircon in the outermost few centimeters of rock exposed to different durations and temperatures of heating at the surface. In the absence of surface heating, all crystals in an otherwise undisturbed, unfaulted outcrop on the scale of ~100 m would, in theory, be expected to have identical He ages, reflecting the time of exhumation through closure isotherms. An exception to this prediction is crystal size vs. age correlations for very slowly cooled rocks (e.g., Reiners and Farley, 2001); we show that grain size is only a minor consideration for short-time-scale events like wildfire-induced heating.

We modeled wildfire at the rock surface by forcing heat pulses of given temperature and duration. These pulses lead to time-varying thermal histories for crystals at different depths below the surface, which we modeled by one-dimensional finite difference (details of this and other aspects of the model are available in the GSA Data Respository[1]). The model then determines the fraction of He diffusively lost by each crystal for each thermal history, following previous approaches assuming spherical and isotropic domains (e.g., Wolf et al., 1998; Farley, 2000). He diffusion was modeled using activation energies and frequency factors from Farley (2000) and Reiners et al. (2003). Thermal histories were used to generate time-varying diffusion coefficients (e.g., Gillespie et al., 1982; McDougall and Harrison, 1999), and degrees of

[1]GSA Data Repository item 2003155, description of He diffusion model, analytical procedures, and field photos, is available online at www.geosociety.org/pubs/ft2003.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

He age resetting were calculated using the fractional-loss approximations of McDougall and Harrison (1999).

Temperatures and heating durations reached on the ground surface from wildfires are poorly known. They are determined by fuel available, wind conditions, and position of the rock relative to fuel and, as such, can be highly variable even within a single burn area (e.g., Agee, 1993). Some approximate values can be estimated by considering previous observations, however. Blackwelder (1927) investigated conditions necessary for the exfoliation that often results from wildfires, and determined that rapid temperature increases to >350 °C are required. Gillespie et al. (1989) measured temperatures >700 °C in rocks subjected to a controlled, non-forced-draft bonfire. During a controlled fire in maquis (thick, scrubby underbrush in Mediterranean areas), Molina and Llinares (2001) measured peak temperatures >500 °C at the soil surface, and temperatures above 100 °C for >35 min. On the basis of direct observations of fire dwell times, Bierman and Gillespie (1991) suggested that sagebrush fires in Owens Valley likely reached temperatures of ~600 °C and had dwell times of ~3–5 min.

Using these estimates as constraints, we modeled fractional He loss resulting from several different surface-heating scenarios, such as 5–20 min at 600 °C and 40 min at 400 °C (Fig. 1). In addition, we modeled repeated heating events to simulate fire recurrence. Model results for both single and multiple events suggest that if wildfires heat rock surfaces to the degree suggested by previous observations, they should have clearly measurable effects on apatite He ages in exposed rocks to depths of ~3 cm. These results, although technically in agreement with those presented by Wolf et al. (1998), suggest that He loss from apatite resulting from short, hot events could be much more significant in the outermost few centimeters of rock than previously implied. Wildfires are likely to cause only minimal He loss in zircon, however, with measurable resetting requiring temperatures >550 °C and lasting >5 min. In all these models, fractional loss depends relatively weakly on crystal size, and important features of the resetting profiles are not changed for reasonable crystal size variations (Fig. 1).

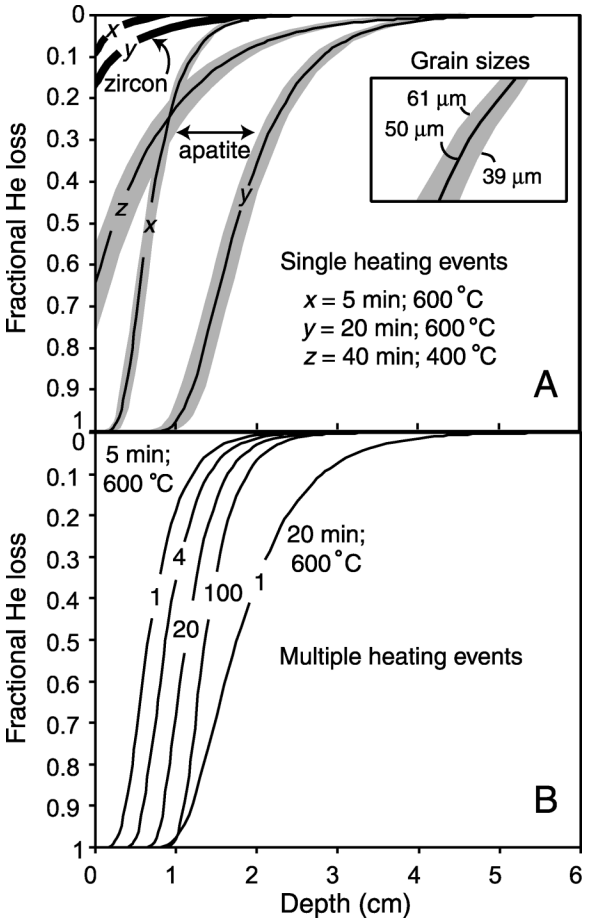

Figure 1. Example apatite and zircon fractional He loss profiles for different surface-heating histories. A: Bold lines are profiles for 50 μm (half-width) zircon grains; fine lines with gray shading are He loss profiles for different-sized apatite grains (50 ± 11 μm radius). Short-time, high-temperature events fully reset apatites at surface while causing negligible resetting deeper than 2 cm, whereas longer, cooler events do not reset grains at surface, but cause partial resetting at 2 cm depth. Zircons are less sensitive to He loss. B: Effects of multiple, 5 min, 600 °C heating events on fractional He loss from 50 μm apatites. Parallel lines to left show fractional He loss for 1, 4, 20, and 100 successive heating events; line to right shows fractional He loss for single, 20 min, 600 °C event. Numbers embedded in lines represent numbers of events: 100, 5 min, 600 °C heating events resulted in less He loss at almost all depths than a single, longer-duration event.

STUDY AREA

We collected samples of granodiorite of the Mount Stuart batholith from the Icicle Creek drainage, on the east side of the central Washington Cascades (Tabor et al., 1987). Our two sample areas were within 1 km of each other, at an elevation of ~700 m above sea level, and in a region that was subject to a wildfire in August 2001. The average apatite He age of the Mount Stuart batholith within 4 km of this area and at similar elevation is 20.2 ± 3.4 Ma; zircon He ages from the batholith are 74–54 Ma (Reiners et al., 2002b).

The forest in this area consists mainly of ponderosa pine and Douglas fir, a forest type that, in this climate and without human interference, will experience fires every 15–25 yr on average (Everett et al., 2000; Agee, 1993). In the immediate area of each sample location, the bases of the trees were charred, undergrowth had been burned out, and there was a layer of soot and ash on the ground surface (photographs of sample sites are available; see footnote 1). Neither area appeared to have experienced burns intense enough to kill the larger ponderosa pines. However, some stumps and fallen trees in these areas appeared to have burned thoroughly, indicating that in places the fire burned for relatively long periods of time.

METHODS

Our first sample was an ~3 kg block of bedrock collected from a vertical rock face, ~0.3 m from a charred tree base. The flat outer surface of the rock was sooty and retained a burned odor. The preservation of soot on the rock surface suggests negligible erosion since the most recent fire—this is important because erosion of even 1 cm of rock from the surface would remove the majority of highly depleted apatites and virtually all depleted zircons (Fig. 1). Because He loss should be depth dependent, we cut the bedrock sample into four subsamples: three 1-cm-thick, surface-parallel slabs, and the remaining inner ''core'' (rock from 3 to 6 cm beneath the surface). The second sample was an amalgamation of thin (<3 cm) chips of rock found <1 m from the base of a flaking boulder. These pieces likely broke off the boulder during or shortly following the most recent fire, as there were no other large rocks nearby, the pieces looked very fresh, and their shape suggested that they had not traveled far (for photographs of samples, see footnote 1).

Single-grain apatite and zircon He ages were measured by standard procedures involving laser heating, cryogenic purification, and isotope-dilution quadrupole mass spectrometry for He and isotope-dilution sector inductively coupled plasma–mass spectrometry for U-Th (details are available; see footnote 1). Alpha ejection corrections of Farley (2002) were applied to all crystals.

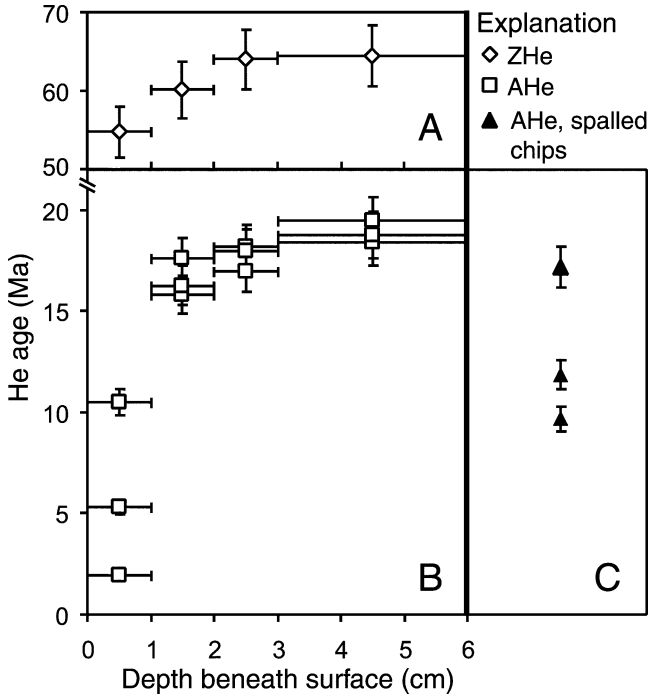

Figure 2. (U-Th)/He ages from bedrock samples as function of depth. A: Zircons. B: Apatites. For all bedrock samples, shallowest three subsamples are 1 cm thick, and deepest samples include grains from 3 to ~6 cm depth. A—apatite; Z—zircon. C: (U-Th)/He ages from apatites from <3-cm-thick chips found near spalling boulder. Expected apatite He age from rocks in this area and at this elevation is ca. 20 Ma.

RESULTS AND DISCUSSION

Apatite He ages in the bedrock sample vary systematically with depth; ages were young (10.5–1.9 Ma) in the upper centimeter, but increased to 19.5 Ma >3 cm below the surface (Fig. 2). As predicted by the model, a wide range in ages is found in the uppermost centimeter. There is no consistent relationship between age and crystal radius in these samples. The degree of He loss in the zircon grains is much less than in the apatite grains, with zircon He ages of 64.5 ± 3.9 Ma in the deepest subsample, decreasing to 54.7 ± 3.3 Ma in the outermost 1 cm (Fig. 2). The three apatite He ages from the fire-spalled chips have ages of 9.7 ± 0.6, 11.9 ± 0.7, and 17.2 ± 1.0 Ma (Fig. 2; Table DR-1 presents U, Th, He, and grain-size data [see footnote 1]).

These results demonstrate that He ages, particularly of apatite, can vary significantly within a single rock at the hand-sample scale. Moreover, ages vary systematically as a function of distance from the surface; extremely young apatite He ages are measured in the outermost 1 cm, and there is a hyperbolic increase to 19–18 Ma ages in the interior of the rock (>3 cm deep), consistent with the regional age for apatite He determined by Reiners et al. (2002b). Similarly, zircon He ages are lower, but only slightly so, in the outermost 1 cm. Both of these He age profiles are consistent with He loss expected from temporary surface-heating pulses and are consistent with the duration and temperature of heating expected from a wildfire. Thus, wildfire-induced He loss may account for some of the scatter seen in apatite He age replicates in other studies, because ages are generally measured from grains separated from whole-rock samples, and inclusion of near-surface, depleted grains can result in erroneously low ages from a single rock if the outer rim is not removed. It is also possible that this kind of surface-heating phenomenon can affect cosmogenic ^{3}He concentrations (Bierman and Gillespie, 1991) or other low-temperature thermochronometers such as apatite fission-track dating. Therefore, our data show that removing the outer 3–5 cm of samples from fire-prone regions before mineral separation is essential to avoid scatter in apatite He ages (i.e., House et al., 1998; Wolf et al., 1998).

Our apatite He data also show that apatites in sediments shed from exposed bedrock can experience substantial fire-induced He loss. Unlike bedrock sampling, in which the outermost 3–5 cm of a hand sample can be removed, it is possible that a substantial proportion of detrital apatites, transported from bedrock downslope into alluvial and sedimentary systems, may have resided in the outermost 3 cm of exposed bedrock for sufficiently long periods of time to be susceptible to wildfire-induced degassing. In some regions, fire-induced exfoliation itself may produce a significant amount of sediment; e.g., Zimmerman et al. (1994) determined that the median thickness of material spalled from exposed boulder surfaces during and immediately following a Wyoming fire was 0.4 mm per fire, or ~1 kg of sediment per square meter of exposed rock per fire. By using their rate of 0.4 mm per fire, we estimate that if wildfires occur in a particular area once every 20–30 yr, they could be responsible for 0.013–0.02 km of erosion per m.y., or ~10%–20% of the overall erosion rate for our study area since the mid-Tertiary (Reiners et al., 2002b). In such areas, detrital apatite He age distributions can at best only provide minimum ages of bedrock sources, and will not represent exhumation ages as normally conceived. Depending on the proportion of sediment generated from exposed rock surfaces, detrital apatite He ages in fire-prone areas could have a wide scatter or be too low. Detrital zircons are much less sensitive to resetting, and may be preferable to apatites for detrital (U-Th)/He investigations in wildfire-prone regions.

Given some assumptions, we can place some constraints on the duration and temperature of the heating events that affected our bedrock sample. We calculated fractional He loss of each apatite and zircon grain and compared the profile to various He loss profiles generated by using our model (Fig. 3). For these calculations, we assume that the regionally consistent He ages of the oldest grains (19.5 ± 1.2 Ma and 64.5 ± 3.9 for apatite and zircon, respectively) represent unreset ages. Fractional apatite He loss ranges from 70% to 90% in the uppermost 1 cm, but decreases to <10% in the deepest sample (Fig. 3). Although the He ages vary between the 2–3 cm aliquot and the >3 cm aliquot, the difference is slight, suggesting that most of the He depletion is limited to the outermost 2–3 cm. Similarly, fractional He loss from zircon is ~15% in the uppermost 1 cm, but decreases to 0% in samples >2 cm below the surface.

Clearly, the precision and spatial resolution of our data and the uncertainty in the number, timing, and duration of heating and previous erosion events preclude determination of a unique thermal history. We have limited our family of potential solutions to single and multiple heating events of constant temperature. Because our bedrock sample had a sooty surface and no obvious indications of recent erosion, we assume that the rock retains the effects of at least one fire, and therefore do not consider the effects of postfire erosion. Temperature histories had to create fractional-loss profiles that fit within the error bounds of both the zircon and apatite fractional-loss data.

We determined that a thermal history equivalent to a single heating pulse of 5–10 min at 575–650 °C is a minimum required for the observed He loss in the zircon grains, whereas durations at those temperatures longer than 10 min result in too much He loss from apatite in the outermost 1 cm (Fig. 3). However, a single short ~600 °C event does not sufficiently deplete apatites 2–3 cm from the surface. Adding a longer-duration, lower-temperature heating event (30–40 min at 350–475 °C) can increase the He loss in the deeper apatites without excessively depleting the He in the samples <1 cm from the surface (Fig. 3). However, this longer-duration, lower-temperature event alone, while resulting in the observed He loss in apatite, does not reset the zircon He ages to the degree observed. Thus, we prefer a multievent thermal history that includes both a short, high-temperature event and a longer, lower-temperature event.

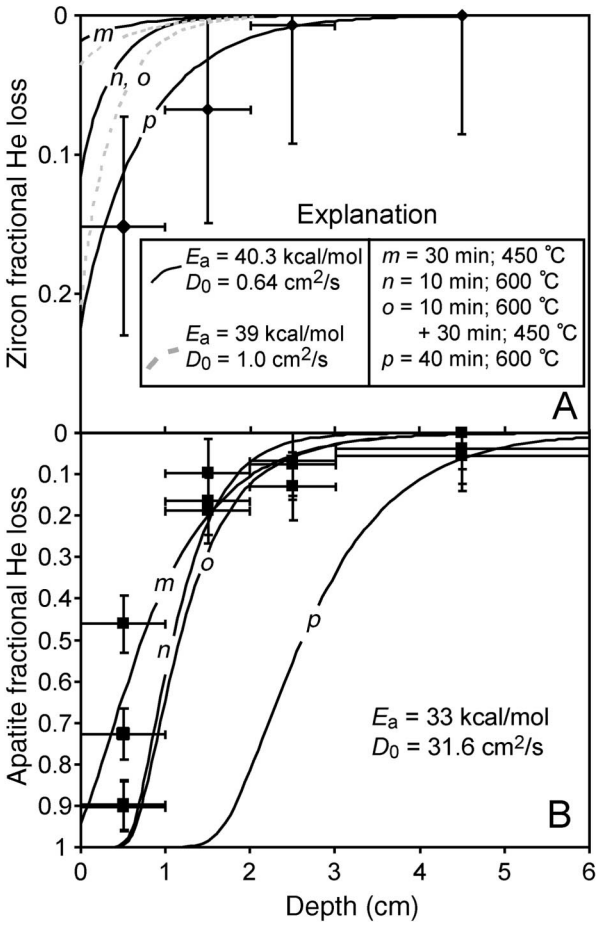

Figure 3. Fractional He loss as function of depth in (A) zircon grains (diamonds) and (B) apatite grains (squares) from bedrock samples, compared to models of He loss (lines). Modeled thermal histories are denoted by letter embedded in line. Because diffusion parameters are less well constrained for zircon than for apatite, we show fractional losses based on two sets of E_a and D_0 estimates (gray dashed lines vs. solid black lines; see text footnote one) (Reiners et al., 2002a; 2003). Modeling shows that 40 min at 450 °C results in sufficient He loss from apatite but not from zircon grains, whereas 40 min at 600 °C results in relatively good fit to zircon grains but excessively depletes He in apatite grains. Models represent He loss from 50 μm grains.

These temperature and duration constraints for this ponderosa pine–Douglas fir forest seem plausible for a burn region that had both quick-burning undergrowth and long-burning logs as fuel sources (Agee, 1993). However, the possibility that wildfires can burn longer than 30 min and hotter than 600 °C (Gillespie et al., 1989; Agee, 1993) suggests that, in some cases, the extent and depth of wildfire-induced He loss may exceed those observed here.

CONCLUSIONS

We present the first field evidence that wildfires can cause 10%–90% He loss from apatites in the upper 2–3 cm of exposed bedrock and 15% He loss from zircons in the outermost 1 cm. Although these losses could potentially explain some types of poor reproducibility or anomalously low ages in some apatite He data, our results show that such effects should be avoidable by not analyzing material from within 3 cm of the exposed rock surface. In addition, the potential for wildfire-induced He loss raises questions about the suitability of detrital apatites for determining basin-averaged exhumation rates in fire-prone regions. By measuring apatite and zircon He loss profiles in exposed bedrock samples, one can constrain surficial thermal histories, potentially identifying or delineating wildfire zones, and constraining fire temperatures and dwell times in regions where these parameters are unknown.

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