

# Calibration of the apatite (U-Th)/He thermochronometer on an exhumed fault block, White Mountains, California

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## ABSTRACT

**This study provides an empirical calibration of the apatite (U-Th)/He thermochronometer using the thermal structure derived from an extensive apatite fission-track study of an exhumed, normal-fault–bounded crustal block in the White Mountains in the western Basin and Range province. This fault block has been tilted ~25° to the east during extension, exposing a continuous section of rocks previously buried to ~7 km. Apatites yield (U-Th)/He apparent ages of ca. 50–55 Ma at shallow pre-extensional crustal levels that decrease systematically to ca. 12 Ma at >4.5 km paleodepth. The ages exhibit a well-defined exhumed apatite He partial retention zone over a pre-extensional temperature range of ~40–80 °C and are completely reset above 80 °C, as calibrated from the apatite fission-track data. This pattern is in good agreement with He diffusion behavior predicted by laboratory experiments. The (U-Th)/He and fission-track methods yield concordant estimates for the timing of the onset of extensional faulting in the White Mountains ca. 12 Ma. Given the partially overlapping temperature-sensitivity windows, the (U-Th)/He and fission-track thermochronometers are highly complementary and may be used together to reconstruct thermal histories over the temperature window of ~40–110 °C.**

**Keywords:** (U-Th)/He dating, fission-track dating, thermochronology, extensional faulting, White Mountains.

## INTRODUCTION

(U-Th)/He dating of the mineral apatite has attracted considerable interest as a potential low-temperature thermochronometer (e.g., Zeitler et al., 1987; Lippolt et al., 1994; Wolf et al., 1996). Laboratory He-diffusion experiments suggest that this system should be sensitive to crustal temperatures of ~40–80 °C (Wolf et al., 1996, 1998), lower than any other known thermochronometer. Assuming a mean annual surface temperature of  $10 \pm 5$  °C and a geothermal gradient of 25 °C/km, this temperature range is equivalent to depths of ~1.2–3 km. Thus the system can potentially be applied to investigate a variety of geologic processes in the uppermost part of the crust, such as mountain building, neotectonics, and landscape development (e.g., House et al., 1997; Spotila et al., 1998).

Before the (U-Th)/He system can be applied with confidence, however, it is essential to demonstrate that the laboratory-derived temperature sensitivity is properly calibrated and that measured (U-Th)/He ages reliably date cooling events. Warnock et al. (1997) and House et al. (1999) compared laboratory-derived He-diffusion data with He ages obtained on samples collected from deep wells with reasonably well-known downhole temperatures. These studies broadly confirm the

expected decrease in apparent age with increasing downhole temperature, but exhibit considerable scatter. Possible explanations for this scatter include uncertainties in the thermal history of the borehole, excess He from U- and Th-bearing mineral inclusions such as zircon, possible inheritance of He in detrital apatite, and the effects of grain-size variations on the closure temperature.

Another approach for testing the (U-Th)/He thermochronometer is to apply it to exhumed rocks, the time-temperature histories of which have been determined by independent thermochronometers that have fundamentally different principles and uncertainties. In this paper we apply (U-Th)/He methods to the White Mountains in eastern California (Fig. 1), where the thermal history has been established by extensive apatite fission-track dating (Stockli, 1999). The northern White Mountains compose a virtually intact range-scale crustal block that has been tilted eastward by ~25° during Miocene extension. This tilting has exhumed and exposed rocks that were at paleodepths of 0 to ~7 km before extension began (Stockli, 1999). This near-ideal setting permits (U-Th)/He and fission-track samples to be analyzed from a range of pre-extensional paleodepths (and thus paleotemperatures), to characterize the in situ behavior of the (U-Th)/He system.

## WHITE MOUNTAINS FAULT BLOCK

The Basin and Range province is a broad area of Tertiary extension in the western United States. Many areas of the province exhibit a distinctive

structural style in which the individual ranges consist of more or less intact, exhumed, crustal-scale footwall blocks that are bounded along one flank by major high-angle normal faults and that have been tilted during major fault offset (e.g., Stewart, 1980). The White Mountains are an excellent example of such a block, having undergone substantial eastward tilting that was accommodated by normal displacement along the White Mountains fault zone (Fig. 1). Detailed mapping and structural analyses suggest that the interior of the White Mountains is essentially undeformed and rigid. A sequence of pre-extensional Cenozoic volcanic rocks (ca. 12–15 Ma) unconformably overlies basement rocks on the eastern flank of the range and records ~25° of eastward tilting since the middle Miocene (Fig. 1) (Stockli, 1999).

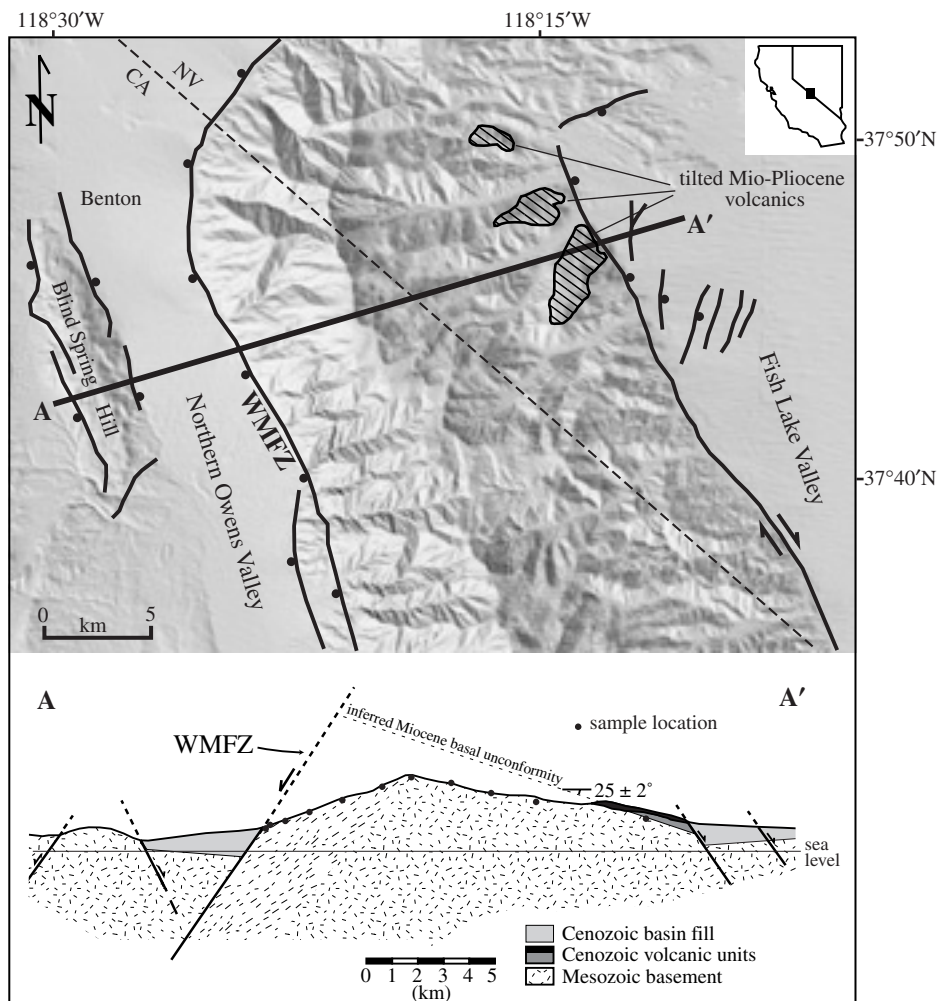
## THERMOCHRONOLOGY ON EXHUMED FOOTWALL ROCKS

Pre-exhumation fission-track and (U-Th)/He ages are expected to vary systematically with depth and thus burial temperature in the stable crust (Green et al., 1989; Wolf et al., 1996, 1998; Dumitru, 2000). The increase in depth and temperature results in a measurable reduction of apparent ages by thermally induced annealing of fission tracks and diffusive loss of He. Figure 2 shows a schematic structural model of the exhumation and cooling of extensional crustal fault blocks. If fault slip has been rapid and of sufficient magnitude to exhume samples from the zero-retention zones, (U-Th)/He and fission-track ages will directly date the timing of faulting and footwall exhumation (e.g., Fitzgerald et al., 1991; Miller et al., 1999). At increasingly shallow paleodepths, apparent ages will become older, because the isotopic clocks at least partially accumulate before exhumation commences. The observed (U-Th)/He ages and fission-track data in these exhumed partial-retention zones may be used to estimate the pre-extension paleotemperatures of samples from various depths.

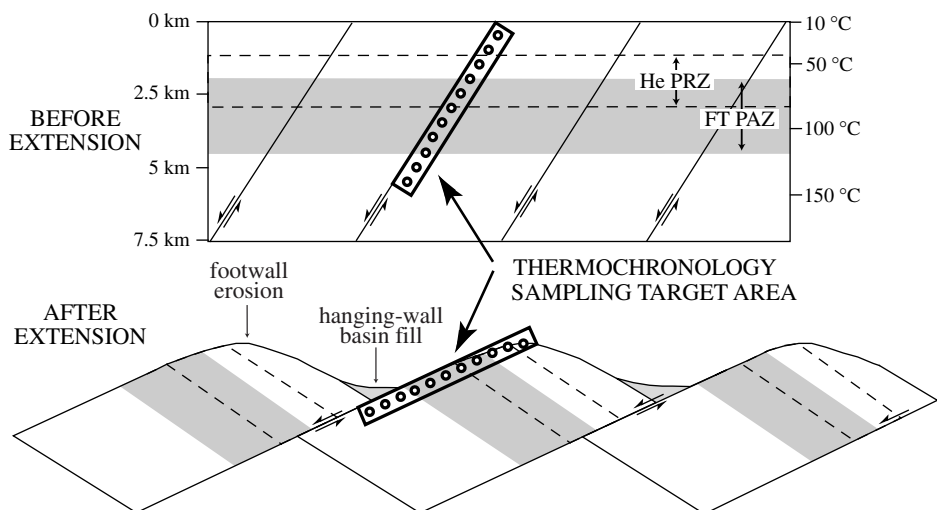
## APATITE (U-Th)/He AND FISSION-TRACK THERMOCHRONOLOGY

Fission-track dating of apatite is based on the decay of trace  $^{238}\text{U}$  by spontaneous nuclear fission (e.g., Fleischer et al., 1975; Dumitru, 2000). The use of apatite fission-track methods for thermochronologic analysis depends on the fact that tracks are partially or entirely annealed

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**Figure 1.** Shaded relief map and cross section (A–A') of northern White Mountains, east-central California and west-central Nevada, illustrating geometry of east-tilted White Mountains fault block. Tilt block is structurally controlled by west-dipping White Mountains fault zone (WMFZ), which accommodates ~8–9 km of normal displacement, resulting in ~25° of eastward tilt as recorded by Tertiary volcanic sequences along eastern flank of range.



**Figure 2.** Simplified model illustrating exhumation of footwall rocks during extension. Apatite fission-track (FT) and (U-Th)/He sampling transects are devised to obtain samples from largest possible range of pre-extensional paleodepths exposed in intact, tilted fault blocks. PRZ—partial retention zone.

(erased) by thermally induced recrystallization at elevated temperatures, causing reductions in both the lengths of individual tracks and the fission-track ages. Fission tracks are shortened and partially erased by annealing in about the temperature range of 60–110 °C, termed the partial-annealing zone (PAZ); essentially no annealing occurs at lower temperatures, and total erasure occurs at higher temperatures (e.g., Laslett et al., 1987; Green et al., 1989).

(U-Th)/He dating is based on the  $\alpha$ -decay of  $^{235}\text{U}$ ,  $^{238}\text{U}$ , and  $^{232}\text{Th}$  series nuclides. Extrapolation of laboratory volume-diffusion kinetic parameters to geologic time scales indicates that He is completely expelled from apatite above ~80 °C and almost totally retained below ~40 °C (Wolf et al., 1996, 1998). Diffusion experiments further suggest that the apatite (U-Th)/He system has a closure temperature of ~65–75°C, assuming a constant cooling rate of 10 °C/m.y. (Farley, 2000). He diffusivity correlates with the physical dimensions of Durango apatite, indicating that the diffusion domain is the grain itself, so grain size has a small effect on the closure temperature (Farley, 2000).

#### APATITE SAMPLES AND METHODS

We collected 15 samples of Cretaceous granitic basement along an east-west transect across the northern White Mountains; these rocks effectively sample the entire exposed structural section of the crustal block (Fig. 1). Experience has shown that the biggest hurdle to accurate and reproducible He age determinations is isolation of apatite grains that are free of U-, Th-, and He-bearing impurities, in particular zircon microlites and fluid inclusions (e.g., Warnock et al., 1997; House et al., 1997). In order to eliminate suspect grains, every apatite was inspected prior to analysis under a binocular microscope at 125 $\times$  magnification. Unrecognized zircon inclusions could be detected by a re-extraction process incorporated within the standard He furnace degassing procedure (House et al., 1999). All analyzed apatite grains in this study were euhedral with a nearly invariant grain size of  $\sim 170 \pm 20 \mu\text{m}$  in length and  $\sim 70 \pm 10 \mu\text{m}$  in radius. The selection of a uniform grain size should minimize differences in diffusion behavior related to grain size (Farley, 2000). These measurements were also used to correct for  $\alpha$  emission (Farley et al., 1996).

The 10 crystals analyzed from each sample show that all apatites are monocompositional fluorapatite with Cl contents of <0.02 wt% (Table 1<sup>1</sup>). Qualitative optical inspection of induced fission-track distributions on external

<sup>1</sup>GSA Data Repository item 2000102, Thermochronological and compositional data and methodology, is available on request from the Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2000.htm.

detectors from irradiated fission-track samples suggests that U zoning in all apatite grains is minimal. Thus  $\alpha$ -emission corrections, which assume homogeneous U and Th distributions, will be accurate in these rocks (Farley et al., 1996).

### APATITE (U-Th)/He AND FISSION-TRACK RESULTS

The fission-track age and mean track length data outline a well-defined exhumed PAZ (Fig. 3; Table 2 [see footnote 1]). The observed patterns correspond well with expected apparent age versus depth patterns (e.g., Gleadow et al., 1986; Green et al., 1989) and with predicted apparent age versus paleodepth patterns (e.g., Miller et al., 1999). Fission-track ages decrease systematically with increasing structural depth from  $59.3 \pm 3.8$  Ma at  $\sim 1.7$  km to  $12.1 \pm 1.5$  Ma at  $\sim 6.2$  km (Fig. 3). Below the base of the PAZ at  $\sim 6.2$  km depth ( $T > \sim 110^\circ\text{C}$ ), fission-track ages are invariant ca. 12 Ma, indicating the timing of rapid exhumation of the White Mountains. The vertical separation between the base of the PAZ ( $T \sim 110^\circ\text{C}$ ) and the Miocene basal unconformity yields a paleogeothermal gradient of  $15 \pm 2^\circ\text{C}$ , assuming a mean annual surface temperature of  $\sim 10 \pm 5^\circ\text{C}$ . This reconstruction of the pre-extensional thermal state of the crust provides a thermal reference frame for evaluating the (U-Th)/He thermochronometer.

Apparent (U-Th)/He ages similarly decrease with increasing paleodepth, from  $57.5 \pm 0.9$  Ma to  $12.1 \pm 1.1$  Ma, defining a well-developed partial retention zone (PRZ) (Fig. 3; Table 3 [see footnote 1]). A marked inflection point in the age versus depth profile marks the base of the PRZ at  $\sim 4.5$  km. The apparent age behavior is consistent with theoretically predicted apparent age versus depth or temperature profiles (e.g., Wolf et al., 1998) and borehole studies (Warnock et al., 1997; House et al., 1999). Below the PRZ, (U-Th)/He ages are essentially invariant, clustering ca. 12 Ma. At the deepest structural levels exposed in this area, the (U-Th)/He results trend toward younger ages as a reflection of renewed Pliocene faulting (Stockli, 1999). Apparent (U-Th)/He ages are consistently equal to or younger than apatite fission-track ages from the same sample, with two exceptions.

1. Sample 96BR217 (Table 3; see footnote 1) from the western range front exhibits anomalously old (U-Th)/He ages. Three analyses yielded ages ranging from 45 to 93 Ma, substantially older than the corresponding fission-track age of 26 Ma. Re-extraction data do not point to U- or Th-bearing inclusions as the probable explanation for these anomalously old ages. Optical examination of grains at  $1250\times$  revealed the presence of abundant elongate, minute fluid inclusions. The presence of  $^4\text{He}$  in fluid inclu-

sions might represent a feasible explanation, but in-vacuum crushing experiments would be required to test this possibility.

2. One granitic basement sample was collected  $\sim 4$  m below the Tertiary basal unconformity, which is overlain by  $\sim 200$  m of Miocene andesite dated as  $5.70 \pm 0.04$  Ma (Stockli, 1999). The apatite fission-track age of  $6.9 \pm 1.2$  Ma is concordant with the  $^{40}\text{Ar}/^{39}\text{Ar}$  age of the andesite. However, two (U-Th)/He analyses yielded apparent ages of  $11.2 \pm 0.8$  and  $11.6 \pm 1.4$  Ma, distinctly older than the  $^{40}\text{Ar}/^{39}\text{Ar}$  age of the overlying andesite. Whereas the fission-track system apparently dates the heating and subsequent cooling of the basement during andesite emplacement, He loss was only partial. This discrepancy arises from the fact that the rate of diffusive loss of He depends on both the diffusivity and the concentration gradient. As diffusion proceeds and the concentration gradient becomes shallower, the rate of loss drops dramatically. For example, on the basis of diffusion measurements (Wolf et al., 1996), 45% of the He in a Durango apatite ( $180 \mu\text{m}$  diameter) will be lost in 3.3 h at  $360^\circ\text{C}$ ; losing the next 45% requires almost an order of magnitude more time. In contrast, essentially all fission tracks disappear in Durango apatite in just 1 hr at the same temperature. The effect of short-term heating on apatite (U-Th)/He and fission-track ages warrants further investigation, but laboratory observations and this

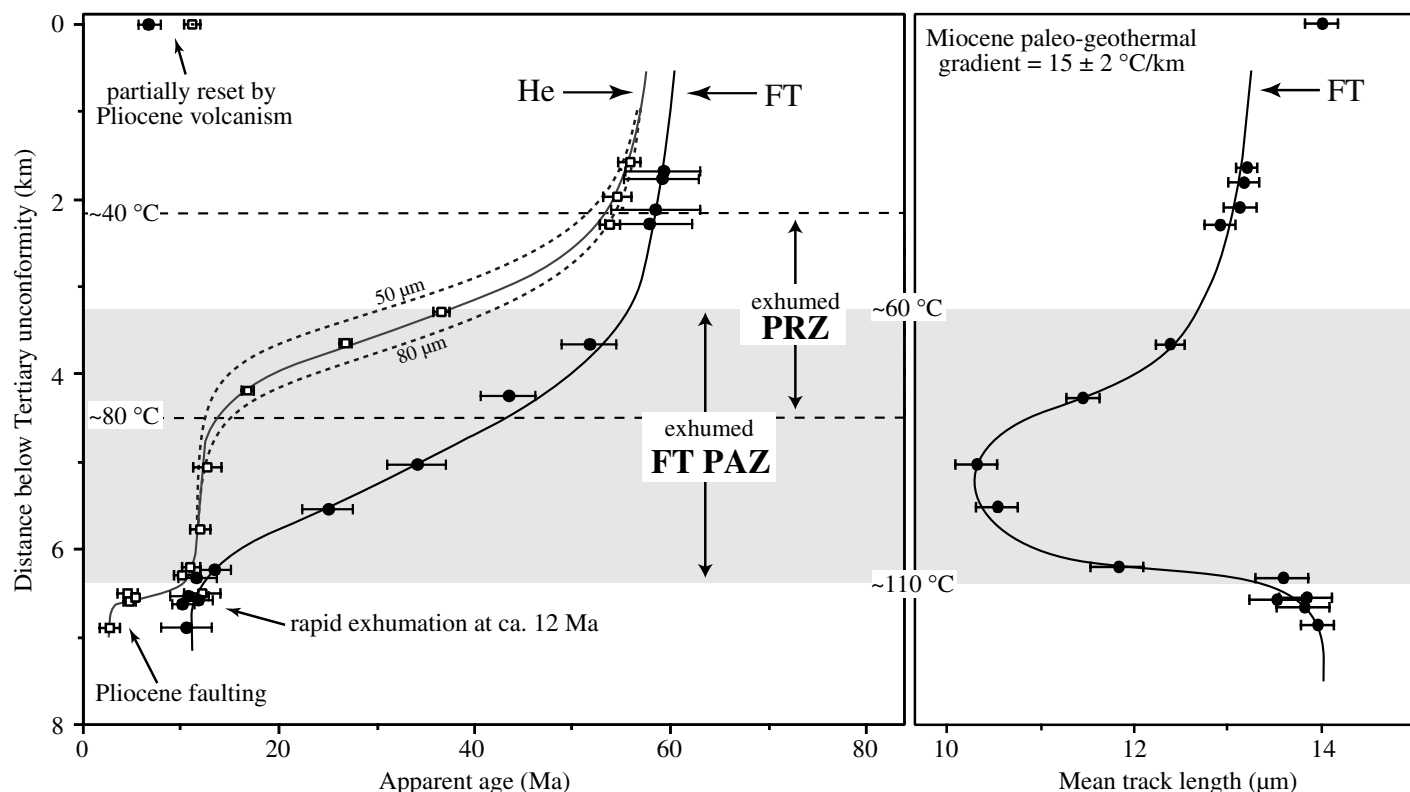


Figure 3. Summary diagram of integrated apatite (U-Th)/He and fission-track (FT) data from northern White Mountains. Apatite fission-track data establish thermal reference system that allows for empirical calibration of (U-Th)/He thermochronometer. Observed partial retention zone (PRZ) is in excellent agreement with forward-modeled PRZ for range of grain sizes (50–80  $\mu\text{m}$  radii, dashed curves), assuming isothermal holding for 43 m.y. prior to rapid exhumation at 12 Ma. Samples from below exhumed PRZ are invariant in age and directly date time of inception of footwall cooling and extensional faulting.



White Mountains sample suggest that fission-track ages younger than He ages will occur when the duration of heating is short compared to radiogenic ingrowth.

## DISCUSSION AND CONCLUSIONS

This study confirms that He diffusion parameters derived from laboratory experiments can be extrapolated to geologic time scales. The reconstruction of the pre-extensional thermal state of the crust using the apatite fission-track system confirms that the (U-Th)/He thermochronometer is characterized by a partial retention zone between ~40 and 80 °C (Fig. 3). This result is in good agreement with the ~40–80 °C range derived from forward modeling results of the He PRZ (Fig. 3) and represents robust geologic evidence that the temperatures calculated for the (U-Th)/He partial retention zone from laboratory data are correct. This study also intercalibrates apatite fission-track and (U-Th)/He thermochronology and shows that the two low-temperature thermochronometers yield consistent estimates for the time of onset of rapid footwall exhumation of the White Mountains fault block as well as for the pre-extensional paleogeothermal gradient. Compared to the first geologic calibration studies using borehole data (Warnock et al., 1997; House et al., 1999), these data yield well-behaved apparent-age versus depth profiles with relatively little scatter (Fig. 3). This behavior can be attributed in part to recent advances in analytical procedures such as the detection of zircon inclusions as well to the nature of the apatite samples. In this study, only plutonic, inclusion-free, monocompositional, and unzoned (at least in U) apatite grains with a uniform grain size were used to minimize differences in diffusion behavior.

In interpreting (U-Th)/He apparent ages, it must be recognized that they represent total gas ages, much like K/Ar ages. During nonmonotonic cooling or isothermal periods, partial diffusive loss and retention of <sup>4</sup>He substantially reduces the age of a sample that resided at temperatures between ~40 and 80 °C. Such apparent (U-Th)/He ages cannot generally be interpreted as directly dating when a sample cooled through a specific closure temperature (Dodson, 1973). In this case study, only 5 of 15 (U-Th)/He samples directly date the timing of cooling and footwall exhumation at 12 Ma, whereas most samples yield apparent ages that do not directly date a specific cooling event. At this point, proper interpretation of a given (U-Th)/He age from a single sample is possible only with corroborating evidence, such as apatite fission-track data from the same sample and/or (U-Th)/He versus paleodepth sample arrays.

This study demonstrates that the apatite (U-Th)/He thermochronometer provides a means to reliably quantify thermal histories between 40 and 80 °C. A wide variety of important geologic processes in the upper ~1–5 km of the crust can

potentially be investigated by (U-Th)/He dating methods and by integrated apatite (U-Th)/He and fission-track studies. Given their partially overlapping sensitivity windows of ~40–80 °C and 60–110 °C, the apatite (U-Th)/He and fission-track thermochronometers are complementary and can be used together to robustly define low-temperature thermal histories.

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