Two-phase Neogene extension in the northwestern Basin and Range recorded in a single thermochronology sample

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ABSTRACT

We use a combination of apatite ^{4}He/^{3}He, (U-Th)/He, and fission-track thermochronology to date slip on the Surprise Valley fault in northeastern California by analyzing a single sample from the Warner Range in the footwall of the fault. This sample, a granitic clast from a conglomerate, yielded a fission-track age of 11.6 ± 2.8 Ma and a (U-Th)/He age of 3.02 ± 0.52 Ma. Geologic relationships indicate that this sample was buried to a depth of ~3.3 km prior to exhumation during slip on the Surprise Valley fault. Fission-track age and length data indicate that the sample was fully reset (>120 °C) prior to exhumation, which began sometime after 14 Ma. A single aliquot of nine apatite grains was step-heated for ^{4}He/^{3}He analysis; modeling of the resulting ^{4}He distribution indicates that cooling from >80 °C to ~20 °C occurred between 3 and 1 Ma. Interconsistent time-temperature (*t-T*) solutions to the combined ^{4}He/^{3}He, (U-Th)/He, and fission-track data require two distinct periods of cooling, consistent with noncontinuous slip on the Surprise Valley fault. Early cooling and fault slip took place between 14 and 8 Ma, followed by more recent fault slip ca. 3 Ma. This timing is consistent with both local geologic relationships and with the regional timing of faulting along the western margin of the Basin and Range Province. These data demonstrate the resolving power of combined fission-track, (U-Th)/He, and ^{4}He/^{3}He thermochronometric data to extract low-temperature *t-T* information from a single sample close to Earth's surface.

Keywords: ^{4}He/^{3}He thermochronology, (U-Th)/He dating, fission-track analysis, Surprise Valley fault.

INTRODUCTION

Fission-track and (U-Th)/He thermochronology of apatite are effective and widely applied tools for dating the exhumation of rocks within a few kilometers of Earth's surface. Because individual fission-track and (U-Th)/He ages do not correspond to unique thermal histories (time-temperature paths), successful application of these methods usually requires multiple samples from a range of elevations or structural positions that record different portions of the overall cooling history (e.g., Ehlers, 2005; Stockli, 2005). Fission-track length analysis can constrain the time-temperature path of a single sample under favorable circumstances, but it is less useful for young samples with very few tracks, and it is not sensitive to cooling below ~60 °C (e.g., Tagami and O'Sullivan, 2005). In practice, fission-track and (U-Th)/He dating have been applied most successfully to areas with abundant apatite-bearing rocks exhumed from depths greater than 3–4 km. Although many areas meet these criteria, there remain many locations where it is not possible to obtain detailed cooling information due to a lack of apatite-bearing rocks, insufficient exhumation and cooling, or both.

The recent development of ^{4}He/^{3}He thermochronology has made it possible to extract the cooling history of a single apatite grain or grains through very low temperatures (80–20 °C; e.g., Shuster et al., 2005). By combining this method with fission-track and (U-Th)/He analyses, it is possible to obtain the thermal history of a single apatite sample from ~120 °C to 20 °C. Here, we apply these methods to the Warner Range in northeastern California, a geologically well-characterized fault block exhumed in the footwall of the Surprise Valley fault (Fig. 1). In most respects, it is an ideal candidate for dating fault slip with low-temperature thermochronology, but it contains no apatite-bearing rocks save for very rare granitic clasts locally preserved in conglomerate beds near the base of the range. Our combined apatite fission-track, (U-Th)/He, and ^{4}He/^{3}He analysis of a single granitic clast from the Warner Range reveals two distinct periods of slip on the Surprise Valley fault. Early cooling (and inferred fault slip) took place between 14 and ca. 8 Ma and was followed by rapid Pliocene (ca. 3 Ma) fault slip, which is not apparent in the fission-track data but is well constrained by ^{4}He/^{3}He analysis. This study demonstrates the potential for obtaining detailed information about the recent thermal—and tectonic—history of an area where apatite-bearing rocks are rare.

GEOLOGIC SETTING

The Warner Range (Fig. 1) forms the western margin of the Basin and Range Province in northeastern California and exposes over 3 km of Tertiary rocks. The lower part of this section consists of over 1.5 km of Eocene and Oligocene volcaniclastic rocks (Fig. 2); the depth to pre-Cenozoic basement is unknown (Duffield and McKee, 1986). Volcaniclastic rocks are overlain by up to 1 km of intermediate lava flows and rhyolite tuffs erupted at 26–17 Ma, which are capped by up to 1 km of 16–14 Ma basalt flows and interbedded tuffs (Fig. 2; Duffield and McKee, 1986). This section is tilted 15–25°W and bounded by the down-to-the-east Surprise Valley fault. A seismic-reflection profile 20 km north of section A–A′ (Fig. 1) imaged the Surprise Valley fault dipping 35°E beneath ~2 km of fill in Surprise Valley (Egger et al., 2007). The fault is inferred to have formed with an initial dip of ~55–60° and rotated to its present orientation, accumulating ~8 km total slip and exhuming the Tertiary section in the Warner Range. Although no rocks younger than 14 Ma are directly cut by the Surprise Valley fault, late Miocene to Pliocene (8–4 Ma) basalt flows (Fig. 1) are cut and tilted by normal faults on the east side of Surprise Valley (Carmichael et al., 2006). Slip on the Surprise Valley fault and exhumation of the

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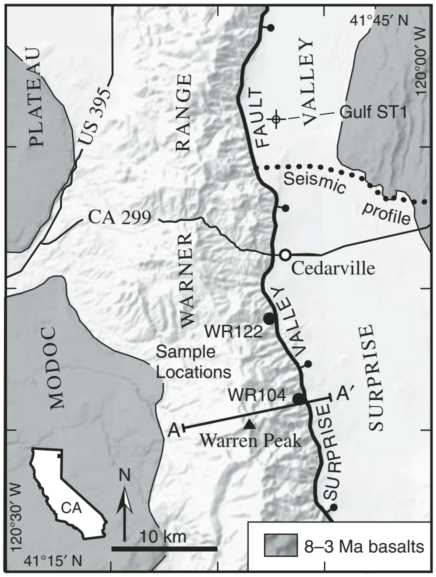

Figure 1. Shaded-relief map of Warner Range and Surprise Valley, showing sample locations, line of section A–A′ (Fig. 2), and other features discussed in text. Distribution of Pliocene basalt flows is from Carmichael et al. (2006).

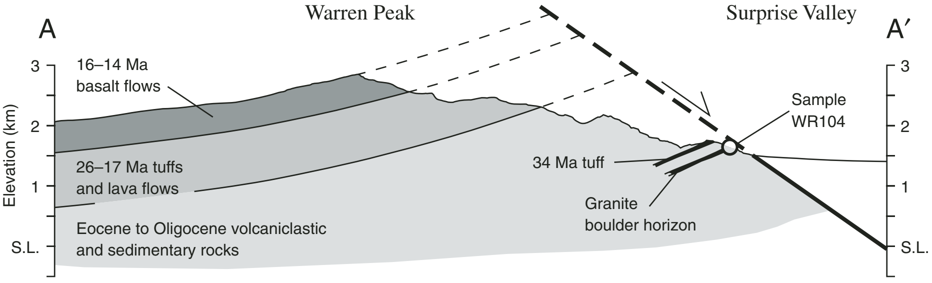

Figure 2. Geologic cross section of central Warner Range, showing position of sample WR104. Geology was modified from Duffield and McKee (1986). S.L.—sea level.

Warner Range therefore began sometime after 14 Ma, and at least some—possibly all—fault slip has taken place more recently than 4 Ma.

We collected a transect of 20 samples from Tertiary volcaniclastic rocks in the Warner Range and attempted to extract apatite from two matrix samples and four representative clasts. None yielded any apatite. However, very rare granitic clasts can be found in conglomerate lenses near the base of the section in the central Warner Range (Fig. 2), and one of these clasts (WR104) yielded abundant, high-quality apatite grains. Zircons from this sample yielded a U-Pb sensitive high-resolution ion microprobe (SHRIMP) age of 109.5 ± 1.0 Ma (2σ). Duffield and McKee (1986) obtained a 34 Ma (K-Ar, hornblende) age from a tuff located 200–300 m upsection from the conglomerate horizon sampled in this study (Fig. 2). Sample WR104 thus crystallized in the Cretaceous and then was exhumed (probably in the Late Cretaceous or earliest Tertiary, e.g., Colgan et al., 2006), eroded, and deposited in a basin during the Eocene. By 14 Ma, it had been buried to a depth of ~3.3 km, based on the present thickness of the overlying section (Fig. 2).

APATITE FISSION-TRACK AND (U-Th)/He ANALYSIS

Sample WR104 yielded an apparent fission-track age (i.e., the nominal time over which tracks accumulated) of 11.6 ± 2.8 Ma (2σ). To determine if this sample was fully reset (all tracks erased) prior to Miocene exhumation, we modeled the complete thermal history of the sampled boulder using fission-track age and length data (Table DR1 in the GSA Data Repository[1]) with the HeFTy search algorithm (Ketcham, 2005). With the crystallization and depositional age of the sample known from the geologic constraints presented previously (modeled, but not shown, in Fig. 3), the model was allowed to reheat anywhere from 60 °C to 160 °C at the time of maximum burial (14–15 Ma). With these constraints, the fission-track data require a Miocene (pre-exhumation) temperature hot enough (at least 120 °C) to erase any tracks that accumulated between early Tertiary exhumation and Miocene burial. Assuming a surface temperature of ~10 °C, this indicates a Miocene geothermal gradient of at least 34 °C/km—high, but comparable to the modern gradient in Surprise Valley, where an exploration well (Gulf ST-1, Fig. 1) has yielded a geothermal gradient of 43 °C/km (from 1.5 to 2.0 km depth) (Benoit et al., 2005). We therefore conclude that WR104 was sufficiently hot at 14 Ma for fission-track and (U-Th)/He data to record only subsequent exhumation during slip on the Surprise Valley fault.

Six single apatite grains from WR104 (average radius of 50 µm) were analyzed by conventional (U-Th)/He methods (e.g., Farley, 2002) and yielded a weighted-mean age of 3.02 ± 0.52 Ma (2σ). Assuming a temperature >120 °C at 14 Ma and a modern surface temperature of 10 ± 10 °C, the combined fission-track and (U-Th)/He data are consistent with cooling at a relatively constant rate of ~7 °C/m.y. from ca. 14 to 3 Ma and a more rapid cooling (~15 °C/m.y.) from 3 Ma to the present (Fig. 3). These data effectively rule out complete exhumation of the Warner Range more recently than 4 Ma (as permitted by the geologic relationships), but they suggest a single protracted episode of fault slip, with more rapid slip sometime after 3 Ma, possibly as recently as 1–2 Ma.

APATITE ^{4}He/^{3}He ANALYSIS

The ^{4}He/^{3}He thermochronometer is a powerful complement to the (U-Th)/He dating method because it has the potential to provide quantitative constraints on the time-temperature history of apatite grains at very low temperatures (80 °C to ~20 °C) (Shuster and Farley, 2005). Apatite grains were first irradiated with energetic protons to produce a uniform distribution of ^{3}He throughout the crystal (Shuster et al., 2004). Irradiated grains were then step-heated to measure the distribution of radiogenic ^{4}He within the crystal(s) relative to the proton-induced ^{3}He. The conventional (U-Th)/He age of the sample was determined both on separate grains of similar size and shape, and on the actual grains used in ^{4}He/^{3}He analysis (Table DR2). The measured ^{4}He/^{3}He ratios and the shape of the ^{4}He concentration profile

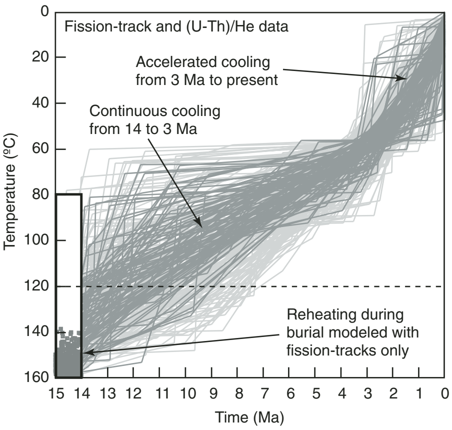

Figure 3. Modeled time-temperature (*t-T*) path from apatite fission-track and (U-Th)/He data for WR104. Black box is user-defined constraint from geologic relationships; additional constraints not shown are >160 °C at 110 Ma and <20 °C at 34 Ma. Gray points are model-generated inflection points in the *t-T* path; note that all paths require heating to >140 °C at 14–15 Ma. Shaded lines are statistically "good" (dark gray, >50%) and "acceptable" (light gray, >5%) *t-T* paths from 14 Ma to the present. Model is not sensitive above 120 °C. Paths were generated with HeFTy (Ketcham, 2005).

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[1] GSA Data Repository item 2008153, analytical data and description of methods, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

(Fig. 4) then constrained the time-temperature (*t-T*) path corresponding to the measured (U-Th)/He age (Shuster and Farley, 2004; Shuster and Farley, 2005). Because critical information about the ^{4}He distribution is preserved near the edges of the crystal, the apatite grains used in ^{4}He/^{3}He analysis were carefully selected to be of similar size, euhedral, and intact (without chipped faces or broken ends).

Nine apatite grains from WR104 (average radius of 52 μm) were packaged together and analyzed in a single multigrain ^{4}He/^{3}He analysis (Fig. 4). These grains were subsequently recovered and analyzed for U, Th, and Sm analysis, yielding a conventional bulk (U-Th)/He age of 3.03 ± 0.30 Ma. A second packet of five grains (Fig. DR4) yielded a similar, but less precise, result (due to lower ^{4}He abundance) and was not used in the following modeling. Representative *t-T* paths that are consistent with the (U-Th)/He age and fission-track data (from Fig. 3) are shown in Figure 4A, and corresponding ^{4}He/^{3}He ratio evolution diagrams are shown in Figure 4B. A subset of these paths is clearly precluded by the ^{4}He/^{3}He data, notably the recent (<1–2 Ma) cooling from ~50 °C (paths 2a, 2b, and 2c) permitted by the (U-Th)/He and fission-track data (Fig. 3). We consider path 1 (monotonic cooling from 80 °C to 10 °C beginning ca. 5 Ma) to be barely consistent with the data, and, therefore, it places a lower bound on the cooling rate below 80 °C. Paths 3a, 3b, and 3c (cooling at different rates beginning ca. 3–4 Ma) are the best fits to the data, with residual sum of squares (RSS) values <0.03, compared to RSS values >1.17 for paths 2a–2c (Fig. 4).

To obtain the highest-resolution thermal history from WR104, we used the HeFTy search algorithm (Ketcham, 2005) to find the internally consistent *t-T* solution space to the fission-track data, the (U-Th)/He age, *and* the ^{4}He/^{3}He data. To exclude histories incompatible with the ^{4}He/^{3}He data, we ran the algorithm with the same parameters as Figure 3 but added the constraints indicated by the three gray boxes in Figure 4A. The combined data set requires two distinct periods of cooling (Fig. 5) that are not readily apparent in the fission-track and helium data alone (Fig. 3). An early period of cooling between ca. 14 and 8 Ma (from >120 to ~80 °C) was apparently followed by a period of relative thermal stability at 80–90 °C that lasted until ca. 4 Ma. Final cooling from ~80–20 °C began at 3–4 Ma and was essentially over by 1–2 Ma.

TIMING OF FAULT SLIP AND EXHUMATION

We interpret the cooling history of WR104 to reflect two distinct episodes of slip on the Surprise Valley fault. Although our data alone cannot rule out the possibility of local reheating (and subsequent cooling), there is no geologic evidence for this in the vicinity of WR104, either in the form of Pliocene lava flows and/or dikes (which are abundant and distinctive elsewhere in the region; Fig. 1), or the extensive fracture networks required for hydrothermal fluids to circulate through the low-permeability country rocks. Furthermore, another granite clast from ~10 km north of WR104 (WR122, Fig. 1) yielded a similar 2.2 ± 0.8 Ma (U-Th)/He age (the U-content—and thus ^{4}He—of this sample was too low for reliable ^{4}He/^{3}He analysis) (Table DR2). Together, these data are consistent with Pliocene exhumation being a major event that affected much or all of the Warner Range.

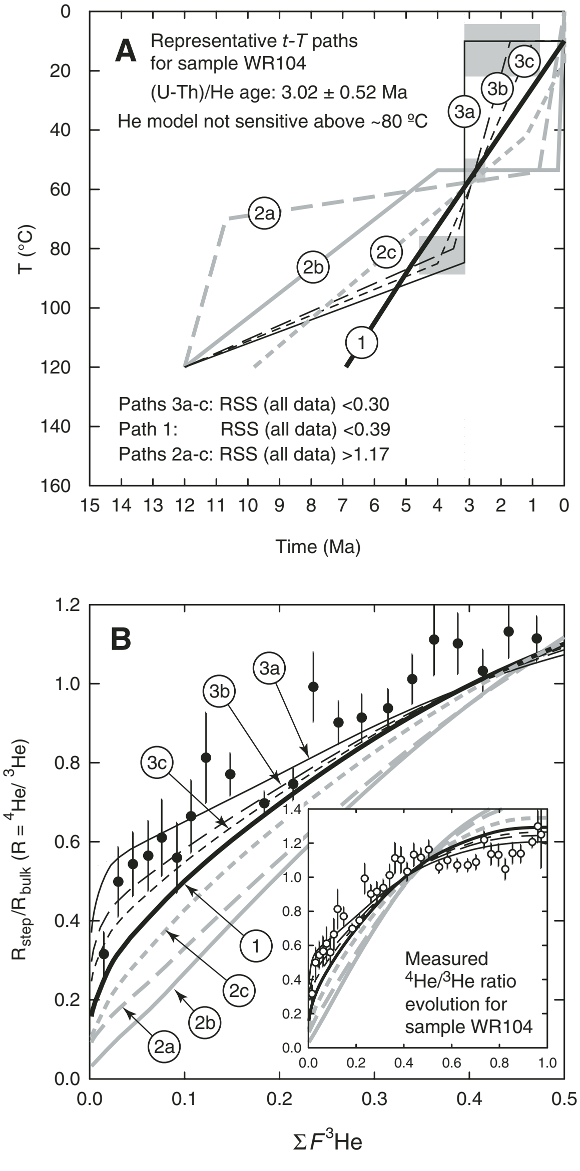

Figure 4. ^{4}He/^{3}He thermochronometry. A: Representative time-temperature (*t-T*) paths for WR104 consistent with observed (U-Th)/He age and fission-track data (Fig. 3). Path 1 is monotonic cooling from 7 Ma to present. Paths 2a, 2b, and 2c are early cooling followed by late (<1–2 Ma) cooling from 60 °C to 20 °C. Paths 3a, 3b, and 3c are cooling (at different rates) at ca. 3 Ma. Gray boxes are constraints used in Figure 5. B: Plot of measured ^{4}He/^{3}He ratios (with 2σ errors) versus cumulative ^{3}He release fraction (ΣF^3He). Curves are modeled ^{4}He/^{3}He ratios of corresponding *t-T* paths in A. RSS—residual sum of squares.

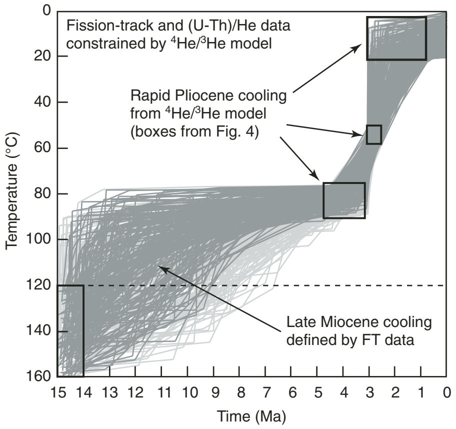

Figure 5. Modeled post–14 Ma time-temperature (*t-T*) path from apatite fission-track (FT) and (U-Th)/He data for WR104, with lower-temperature (<80 °C) section constrained by ^{4}He/^{3}He model. Black boxes are user-defined constraints (same as gray boxes in Fig. 4A). Shaded lines are statistically "good" (dark gray, >50%) and "acceptable" (light gray, >5%) *t-T* paths. Model is not sensitive above 120 °C. Paths were generated with HeFTy (Ketcham, 2005).

Late Miocene slip on the Surprise Valley fault took place between ca. 14 and 8 Ma (Fig. 5). The data do not constrain exactly when or how fast faulting took place within this window, but it overlaps with a widespread episode of late Miocene extensional faulting that began ca. 12 Ma over a large area of the western Basin and Range (e.g., Colgan et al., 2006; Stockli et al., 2003; Henry and Perkins, 2001). Exhumation of the modern Warner Range was completed during a distinct, younger period of faulting that began ca. 3–4 Ma and continued until 1–2 Ma (Fig. 5), equivalent to a slip rate of 1–2 km/m.y. (assuming a geothermal gradient of ~40 °C/km). Some additional fault slip is required after 1–2 Ma to exhume sample WR104 from a depth equivalent to ~20 °C to its present elevation of 150 m above the floor of Surprise Valley, consistent with Quaternary fault scarps in Surprise Valley (Hedel, 1984).

Basalt flows ranging from ca. 8 to 3 Ma are exposed on both sides of the Warner Range (Fig. 1) but are absent at higher elevations in the range itself, consistent with their eruption after initial (ca. 14–8 Ma) uplift of the range. The bulk of the dated flows is ca. 4–5 Ma in age, and flows as young as 4.2 Ma are tilted up to 12–15°W (Carmichael et al., 2006), consistent with eruption shortly before—and subsequent tilting during—Pliocene slip on the Surprise Valley fault. Miocene faulting followed by renewed extension ca. 3–4 Ma has also been documented in the White Mountains of eastern California (Stockli et al., 2003), the Reno, Nevada, area (Henry and Perkins, 2001), and the Wassuk Range in western Nevada (Stockli et al., 2002), suggesting that this two-phase history of faulting may have taken place along ~400 km of the western margin of the Basin and Range Province (including the Surprise Valley fault).

CONCLUSIONS

Integrated fission-track, (U-Th)/He, and ^{4}He/^{3}He dating of a single apatite sample from the Warner Range reveal a two-stage cooling history that we infer to record late Miocene and Pliocene episodes of slip on the Surprise Valley fault, consistent with both local and regional geologic relationships. This result demonstrates that the ^{4}He/^{3}He method can be a powerful complement to fission-track and (U-Th)/He methods when dating recent, low-temperature cooling. More importantly, this study demonstrates the feasibility of obtaining relatively detailed cooling histories from areas where apatite-bearing rocks are very rare. Transects or suites of samples are—and will remain—more robust and desirable, but they need not be a prerequisite for dating tectonic events with low-temperature thermochronology.

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