Exhumation of the southern Sierra Nevada–eastern Tehachapi Mountains constrained by low-temperature thermochronology: Implications for the initiation of the Garlock fault

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ABSTRACT

New apatite and zircon fission-track and apatite (U-Th)/He data from nine samples collected on a north-south transect across the southern Sierra Nevada–eastern Tehachapi Mountains constrain the cooling and exhumation history over the past ~70 m.y. The four northernmost samples yielded zircon and apatite fission-track ages of ca. 70 Ma, indicating rapid cooling from ~250 °C to <60 °C (6–8 km of exhumation) at that time. Four of the five southernmost samples yielded slightly younger zircon fission-track ages (57–46 Ma) and apatite fission-track ages (21–18 Ma); the fifth southern sample (from a lower elevation) yielded an apatite fission-track age of ca. 11 Ma. Eight of the nine samples yielded apatite (U-Th)/He ages; these ranged from 60 to 9 Ma, with the youngest ages from the southernmost samples. Inverse thermal history models developed from the data reveal two major stages of cooling for the area, with an initial major cooling event ending at ca. 70 Ma, followed by 50 m.y. of thermal stasis and a second major cooling event beginning at 20 Ma and continuing to the present. The data are consistent with northward-directed tilting and exhumation beginning at 20 Ma, probably as the result of north-south extension in the Mojave Desert on an early strand of the Garlock fault with down-to-the-south offset. A third minor phase of rapid exhumation beginning at ca. 10 Ma is suggested by the data; this may indicate the beginning of left-lateral slip on the Garlock fault.

INTRODUCTION

The Tehachapi Mountains trend southwestward from the southern Sierra Nevada Range to the San Emigdio Range, which lies adjacent to the San Andreas fault in central California (see Fig. 1). Both the Tehachapi Mountains and Sierra Nevada expose plutonic rocks that were emplaced as part of the Sierra Nevada batholith as the Farallon plate was subducted beneath western North America during Mesozoic time (Hamilton, 1969; Stern et al., 1981; Chen and Moore, 1982; Saleebey et al., 2008). Although the plutonic rocks in the Tehachapi Mountains are genetically related to the batholiths of the Sierra Nevada complex, they appear to have different postemplacement histories, with the Tehachapi Mountains having undergone a substantially greater amount of exhumation since emplacement (Pickett and Saleebey, 1993; Saleebey et al., 2007). One of the puzzles in trying to understand the differences in exhumational histories of the Tehachapi Mountains and the Sierra Nevada is the nature of the bounding faults: the Sierra Nevada is tilted to the west along the Sierra Nevada escarpment, a late Miocene down-to-the-east and right-lateral normal fault system (e.g., Unruh et al., 2003), whereas the major structure bounding the Tehachapi Mountains on the southeastern margin is the Garlock fault, a major left-lateral strike-slip fault (Davis and Burchfiel, 1973). The timing of the initiation and the evolution of the Garlock fault are not well constrained. In this study, we have obtained detailed low-temperature thermal history and (U-Th)/He data from a north-south transect of the southeastern Sierra Nevada as it transitions into the Tehachapi Mountains. These data provide us with new insights into the timing and evolution of the southernmost Sierra Nevada and allow us to propose a model for the initiation of the Garlock fault.

GEOLOGICAL SETTING

Rocks now at the surface in the Tehachapi Mountains have been exhumed from much greater depths than rocks in the rest of the Sierra Nevada. Detailed pressure-temperature-time (P-T-t) analyses of rocks in the Tehachapi Mountains document pluton emplacement between 115 and 99 Ma at depths of 24–35 km (Pickett and Saleebey, 1993; Saleebey et al., 2007). In the Sierra Nevada to the north of the Tehachapi Mountains, the maximum depth of exhumation decreases over a distance of ~100 km before reaching an average maximum depth of 5–12 km for the remainder of the Sierra Nevada (Evernden and Kistler, 1970; Ague and Brimhall, 1988).

The difference in exhumation between the Tehachapi Mountains and Sierra Nevada is attributed to the formation of a lateral ramp in the subduction zone beneath the southern Sierra Nevada in Late Cretaceous time (e.g., Saleebey, 2003). To the south of this lateral ramp, the subduction zone fault flattened and remained shallow, whereas to the north, it maintained a steeper trajectory into the mantle. As the result of flat-slab subduction in the south, tectonic erosion of the mantle lithosphere occurred (Ducea and Saleebey, 1996, 1998), followed by underplating of a subduction zone accretionary assemblage (Jacobson et al., 2007, and references therein). In the Tehachapi Mountains, the Rand schist, a remnant of the accretionary assemblage, occurs in fault contact with the base of the lower-crustal plutonic rocks (Sharry, 1981; Ross, 1989; Wood, 1997). Rapid exhumation of the Rand schist to depths of ~12 km had occurred by 80 Ma (Saleebey et al., 2007). Much of the
postemplacement exhumation of the eastern Tehachapi Mountains may have been accommodated on a Late Cretaceous–Paleocene detachment fault in the western Tehachapi Mountains that appears to be related to the southern Sierra detachment system (Wood and Saleeby, 1997; Chapman et al., 2010).

The northern and central Sierra Nevada, along with the Central Valley to the west, presently behave as a coherent microplate (e.g., Argus and Gordon, 1991; Wernicke and Snow, 1998; Dixon et al., 2000) bounded on the east by the Sierra Nevada escarpment and on the west by the San Andreas fault. Westward tilting and exhumation of the Sierra Nevada microplate occurred along a series of down-to-the-east normal faults of the Sierra Nevada escarpment (Bateman and Wahrhaftig, 1966). The Sierra Nevada escarpment is commonly recognized as the westernmost edge of the Basin and Range Province. The normal faults forming the escarpment appear to have become active in the past ~10–5 m.y., although constraints on the exact timing are poor (Unruh, 1991; Wakabayashi and Sawyer, 2001; Monastero et al., 2002). Faults of the Sierra Nevada escarpment also accommodate right-lateral slip on the Eastern California shear zone, a component of the North American–Pacific plate boundary with 20%–25% of the total plate motion (e.g., Bennett et al., 2003).

In the southern Sierra Nevada and Tehachapi Mountains, basement faulting is more complicated, probably as the result of being located above the lateral ramp in the Late Cretaceous subduction zone (Saleeby et al., 2009). The north-striking Kern Canyon fault bisects the southern Sierra Nevada and has active down-to-the-east motion, controlling the western tecton of the southern Sierra Nevada (Saleeby et al., 2009; Nadin and Saleeby, 2010). The northern margin of the Tehachapi Mountains is bounded by the northeast-trending White Wolf fault (see Fig. 1), which has left-lateral and down-to-the-west offsets (Davis and Lague, 1988; Saleeby et al., 2012). Structures mapped within the Tehachapi Mountains include north-vergent reverse faults and folds with minor shortening, as well as two sets of Neogene–Quaternary normal faults striking north and northwest (Ross, 1989; Malin et al., 1995; Mahé et al., 2009). The southeast side the Tehachapi Mountains is bounded by the active left-lateral northeast-trending Garlock fault (Davis and Burchfiel, 1973), which has accumulated up to 64 km of offset (Smith, 1962). The best estimates for the timing of initiation of strike-slip offset on the Garlock fault come from paleomagnetic studies and correlations of volcanic rocks that suggest it occurred between ca. 17 and 14 Ma (Burbank and Whistler, 1987; Monastero et al., 1997).

The timing of surface uplift of the Sierra Nevada is the subject of much debate, with geomorphic evidence suggesting that the range has reached its highest elevation in the past 10 m.y. (e.g., Huber, 1981; Unruh, 1991; Wakabayashi and Sawyer, 2001; Figueroa and Knott, 2010), and other lines of evidence (primarily apatite [U-Th]/He analyses and stable isotope paleoelevation data) suggesting that the range was substantially higher during the Late Cretaceous–early Cenozoic than it is now (e.g., House et al., 1998, 2001; Mulch et al., 2006; Cassel et al., 2009). Geomorphic studies also suggest that there is a greater amount of late Cenozoic surface uplift in the southern part of the Sierra Nevada (e.g., Clark et al., 2005; Figueroa and Knott, 2010) than farther to the north. Recent modeling of low-temperature thermochronology from the southern Sierra Nevada suggests that the region was higher during the Late Cretaceous, lost elevation through the Tertiary, but has undergone ~2 km of surface uplift in the past 20 m.y. (McPhillips and Brandon, 2012).

Previous studies of the Sierra Nevada documented cooling and exhumation events predating the formation of the Sierra Nevada frontal fault system and the Garlock fault. Apatite fission-track (AFT) and zircon fission-track (ZFT) and apatite (U-Th)/He analyses from the central and northern Sierra Nevada ranged from 91 to 30 Ma, bracketing batholith emplacement and cooling, as well as exhumation associated with the Laramide orogeny (Dumitruc, 1990; House et al., 1998; Cecil et al., 2006). Zircon and apatite (U-Th)/He ages from the southern Sierra Nevada were similar (ca. 85–31 Ma), with the exception of three younger apatite ages of ca. 15, 17, and 28 Ma, which were interpreted to have been reset via thermal blanketing by sediments in local basins (Mahé et al., 2009; Chapman et al., 2012). The southern Sierra Nevada and Tehachapi fission-track and (U-Th)/He analyses we present here are younger, clearly documenting exhumation resulting from post-Laramide tectonic events.
METHODS

Nine samples were collected for this study from a 10-km-long north-south transect across the Tehachapi Mountains (see Fig. 2). Eight of the samples were collected very close to the north-south line; the northernmost sample was collected a few kilometers to the west of the line of transect. The elevation of the samples increased from north to south: the two southernmost samples are from the tops of the highest peaks, Double Mountain and Tehachapi Mountain, at elevations of ~2450 m. The total elevation spanned for the nine samples was ~800 m.

Fission-track and (U-Th)/He thermochronology were used to evaluate the low-temperature cooling history of the nine samples. These two methods, when applied to the minerals zircon and apatite, can document sample cooling history from ~250°C to 40°C. For a region with a geothermal gradient of ~25–28°C/km depth (Brady et al., 2006), this range of temperatures is equivalent to depths between ~10 and 1 km, assuming a mean annual surface temperature of ~10–15°C.

Fission tracks are linear zones of damage in crystals or glass formed by the spontaneous fission of 238U. The tracks are visible and can be counted under an optical microscope if they are etched with acids or bases. Fission tracks are unstable at elevated temperatures, and the crystal lattice repairs itself, which is manifested as a shortening in length of the fission tracks. This process is referred to as annealing (e.g., Naeser, 1979). The range of temperatures over which annealing occurs is dependent on the mineral, and in the case of the most commonly used mineral, apatite, the chemical composition. At cooling rates of ~10°C/m.y., newly formed tracks in fluorine-rich apatites (~95% of all apatites) shorten and disappear at temperatures >120°C, and they remain long at temperatures <60°C (e.g., Ketcham et al., 1999). Between 120 and 60°C, the tracks shorten in length at a rate proportional to the temperature; this range is referred to as the partial annealing zone (Gleadow and Fitzgerald, 1987). The "age" of the sample and its distribution of track lengths can be used to reconstruct the thermal history of the sample within the partial annealing zone (e.g., Ketcham, 2005).

For the mineral zircon, fission tracks will begin to anneal at temperatures of ~180°C and will be totally annealed at ~350°C at average geologic cooling rates (Tagami, 2005, and references therein), but variations in annealing rate occur in different zircons, possibly as the result of damage by alpha particles in older zircons with high U concentrations (e.g., Garver, 2002). A generic closure temperature of ~250 ± 50°C is commonly used to interpret zircon fission-track ages.

(U-Th)/He thermochronometry is based on the release of He in the crystal lattice during the decay of U and Th. As with the retention of fission tracks, He accumulation in the crystal lattice is dependent on ambient temperature. At average geologic cooling rates, He is retained in apatites at temperatures <40°C and completely lost at temperatures >80°C; this range of temperatures corresponds to the helium partial retention zone (Wolf et al., 1996, 1998; Farley, 2002). A closure temperature of 70°C is generally used to interpret apatite (U-Th)/He ages (Farley, 2002).

FIGURE 2. Digital elevation model of the southern Sierra Nevada and Tehachapi Mountains, showing sample locations (yellow stars), and zircon fission-track, apatite fission-track, and (U-Th)/He ages, respectively. The elevation profile for line A-B is shown below the map, with sample locations and elevations projected onto the line.

Table 1 is a summary of all thermochronometric ages obtained for the nine study samples. Complete analytical data can be found in Tables A2 (AFT and ZFT), and A3 (apatite [U-Th]/He) in the supplemental materials (GSA Data Repository).1 The data, which consist of seven zircon and nine apatite fission track and He analyses, show a distinct pattern with respect to sample location, generally becoming younger to the south, and younger with increasing elevation (see Fig. 3A).

The four northernmost samples (TK-1 through 4) yielded three ZFT and four AFT ages, ranging from 71.2 (~7.5f5/4) to 67.9 (~12.7f5/10) Ma.

1GSA Data Repository Item 2013181, data tables with zircon and apatite fission-track analyses, (U-Th)/He analyses, and He/fruit model inputs, is available at www.geosociety.org/pubs/fl2013.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
Table 1. Summary of Zircon and Apatite Fission-Track and Apatite (U-Th)/He Analyses for the Tehachapi Mountain Transect

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Lat. (°N)</th>
<th>Long. (°W)</th>
<th>Elev. (m)</th>
<th>ZFT</th>
<th>AFT</th>
<th>AHe</th>
</tr>
</thead>
<tbody>
<tr>
<td>TK-1</td>
<td>35°05'37&quot;</td>
<td>118°33'05&quot;</td>
<td>1646</td>
<td>-</td>
<td>62.4 (±6.9)</td>
<td>48.5 (±0.59)</td>
</tr>
<tr>
<td>TK-2</td>
<td>35°04'45&quot;</td>
<td>118°29'41&quot;</td>
<td>1737</td>
<td>68.0 (±5.0)</td>
<td>71.2 (±4.0)</td>
<td>59.6 (±1.77)</td>
</tr>
<tr>
<td>TK-3</td>
<td>35°03'58&quot;</td>
<td>118°29'11&quot;</td>
<td>1890</td>
<td>70.8 (±5.0)</td>
<td>71.0 (±5.0)</td>
<td>32.8</td>
</tr>
<tr>
<td>TK-4</td>
<td>35°03'46&quot;</td>
<td>118°28'48&quot;</td>
<td>2012</td>
<td>68.4 (±5.0)</td>
<td>67.9 (±5.0)</td>
<td>33.8 (±0.24)</td>
</tr>
<tr>
<td>TK-5</td>
<td>35°02'28&quot;</td>
<td>118°29'00&quot;</td>
<td>2286</td>
<td>56.6 (±5.0)</td>
<td>19.1 (±5.0)</td>
<td>12.9 (±2.60)</td>
</tr>
<tr>
<td>TK-6</td>
<td>35°02'03&quot;</td>
<td>118°29'11&quot;</td>
<td>2225</td>
<td>-</td>
<td>11.1 (±5.0)</td>
<td>12.6 (±4.20)</td>
</tr>
<tr>
<td>TK-7</td>
<td>35°01'59&quot;</td>
<td>118°29'08&quot;</td>
<td>2438</td>
<td>46.2 (±5.0)</td>
<td>20.2 (±5.0)</td>
<td>10.0 (±0.05)</td>
</tr>
</tbody>
</table>

Figure 3. (A) Individual sample ages for all zircon and apatite fission-track and apatite (U-Th)/He analyses are plotted with respect to their location along north-south line A-B. HeFTy thermal models are shown for samples: (B) TK-1, (C) TK-2, (D) TK-4, (E) TK-5, (F) TK-6, and (G) TK-7. The black triangles and squares on these plots are the measured apatite (U-Th)/He and fission-track ages, respectively, for each sample. Table A4 (supplementary data [see text footnote 1]) lists the model inputs used. The shaded regions on the plots represent envelopes of thermal histories with “acceptable” (light-gray) and “good” (medium-gray) statistical fits. The black line represents the “best” statistical fit. See text for further discussion.
All fission-track errors quoted are 95% confidence intervals. The AFT and ZFT ages are statistically the same, which is consistent with rapid cooling from ~250 °C to 110 °C at ca. 70 Ma. In general, theapatite (U-Th)/He ages from these samples were slightly younger, ranging from 58.9 to 33.5 Ma.

The five southern samples (TK-5 through 9) yielded consistently younger ages. Four of the five samples yielded ZFT ages, which ranged from 56.6 (+5.4/–4.9) to 46.2 (+5.2/–4.7) Ma. All five of the samples yielded AFT ages; four of the AFT ages were tightly clustered, with ages ranging from 20.5 (+2.3/–2.0) to 18.2 (+2.5/–2.2) Ma. A single sample, from the lowest elevation of the five southern samples, yielded a younger AFT age of 11.1 (+5.2/–3.4) Ma. Four of these samples yielded apatite (U-Th)/He ages, which ranged from 21.4 ± 2.36 Ma to 9.0 ± 1.27 Ma; these ages became progressively younger toward the south.

Six samples yielded AFT and (U-Th)/He ages as well as >100 AFT length analyses. For these samples, thermal history models were derived using HeFTy (Ketcham, 2005). HeFTy is an inverse modeling program that uses both AFT and (U-Th)/He analyses to calculate the range of possible thermal histories permitted by the data. For individual samples, AFT length and Dpar (diameter of tracks measured parallel to crystallographic c-axis on the exposed apatite surface) measurements are entered, as well as individual grain track count measurements and crystallographic c-axis orientations. The user specifies initial constraints on the thermal history (as boxes spanning a range of times and temperatures), and the program compares the measured values of sample ages and track length distributions with those predicted by individual cooling paths for statistical fit. The time-temperature histories for individual samples are shown in Figures 3B–3G.

INTERPRETATION

The data obtained in this study are consistent with two separate major periods of exhumation-induced cooling, the first at ca. 70 Ma and the second beginning at ca. 20 Ma and continuing through the present, as well as an overall tilting of the range to the north. The ca. 70 Ma cooling phase is seen predominantly in the northern part of our field area, and the ca. 20 Ma phase is observed in the southern part. The northernmost samples document nearly 200 °C of cooling at ca. 70 Ma (Figs. 3B and 3C). These data are consistent with the results of Saleeby et al. (2007) from the central to western Tehachapi Mountains (a few kilometers west of our study area) that indicated substantial cooling from >700 °C beginning at ca. 95 Ma through ~150 °C by 80 Ma. The data presented here indicate that this regional cooling event continued until ca. 70 Ma, when temperatures of ~60–40 °C were reached. We interpret this cooling to have been a continuation of the rapid exhumation associated with the removal of the mantle lithosphere and subsequent underplating of the Rand schist in response to Laramide flat-slab subduction.

The thermal models indicate that the area then remained stable (with no significant heating or cooling) from ca. 70 to 20 Ma. An increase in cooling rate at 20 Ma is indicated by both the pattern of AFT ages (see Fig. 3A) and the thermal models for samples TK-5 and TK-7 (Figs. 3D and 3E). This distinct 20 Ma cooling event has not been documented previously in low-temperature thermochronometric data from the Tehachapi Mountains or Sierra Nevada. The total amount of cooling at 20 Ma for the southern part of the region was ~60–70 °C, which corresponds to ~2.1–2.8 km of exhumation for a geothermal gradient of ~25–28 °C/km depth.

Regional tilting is interpreted to explain the patterns seen in the HeFTy thermal models (for example, TK-2 was substantially cooler at 20 Ma than TK-4), as well as the apatite (U-Th)/He ages, which become progressively younger to the south. The difference in temperature at 20 Ma for the northern and southernmost samples is ~100 °C (compare Figs. 3B and 3D). If the modern geothermal gradient of ~25–28 °C/km depth is assumed to have been stable over the past 20 m.y., the ~100 °C temperature variance is equivalent to ~3.6–4 km of differential exhumation. This pattern is consistent with tilting of a fault block to the north around a horizontal east-west axis, with greater erosion occurring in the south, thereby exposing sample sites with younger thermochronometric ages, as would be expected in the footwall of an east-west–striking normal fault.

North-south extension was previously documented in the Mojave Desert between ca. 24–22 and 18 Ma (e.g., Glazner et al., 2002, and references therein), but it appeared to be relatively restricted to an area to the northwest of Barstow, California (~100 km east from our study area). Recent work, however, suggests that extension may have occurred over a wider area. Early to middle Miocene extension and rapid subsidence have been documented in the Maricopa subbasin on the northern flank of the Tehachapi Mountains (e.g., Goodman and Malin, 1992). Immediately to the south and north of the field area (see Fig. 1), Neogene–Quaternary north-west-striking normal faults were recognized (Mahéo et al., 2009, and references therein). In a paleoseismic study (McGill et al., 2009), an active normal fault was documented within a few hundred meters of the Garlock fault ~35 km to the northeast of our field area, and inferred to be the range-bounding structure.

Based on our data, we suggest that the normal fault responsible for the 20 Ma exhumational event in our study lies to the south of our study area and may be coincident with the active Garlock fault in this region, making it difficult to recognize. We suggest that north-south extension occurred on a proto–Garlock fault. We speculate that the restricted location of extension in this region controlled the location of the Garlock fault as it transitioned into a through-going strike-slip fault. A schematic model for this scenario is shown in Figure 4A.

Finally, there is weak evidence for a renewed pulse of cooling at ca. 12–10 Ma. This evidence suggests that this cooling could have been induced by Laramide subduction. The initiation of Garlock Fault

Figure 4. Proposed tectonic evolution for the southern Sierra Nevada–Tehachapi Mountains, showing (A) north-south extension at 20 Ma, and (B) the initiation of the Garlock fault at ca. 12 Ma. SAF—San Andreas fault; SGF—San Gabriel fault. The black lines with hachures are proposed normal faults with the northern Mojave faults idealized from Glazner et al. (2002).
includes the four apatite (U-Th)/He ages from the southernmost part of the transect, which ranged from 12.9 to 9.0 Ma, as well as the 11.1 Ma AFT age from TK-8; the overlap of these five ages suggests a more rapid pulse of cooling, although in general, the samples were at temperatures that were too low at this time to accurately bracket this event. We suggest that isolated strands of the Garlock fault, with normal offsets on them, linked together and became a through-going strike-slip fault at that time (see Fig. 4B).

CONCLUSIONS

The low-temperature thermochronometric data presented here, from the eastern Southern Sierra and Tehachapi Mountain transect, are in general significantly younger than ages obtained in previous studies from the Tehachapi Mountains to the west and the Sierra Nevada to the north (Mahéo et al., 2009; Saleebey et al., 2007; Clark et al., 2005). Two very distinct phases of cooling are evident in the data. The earliest cooling phase, at ca. 70 Ma, documented by the northern four samples, appears to be a continuation of the major exhumation and cooling event associated with emplacement of the Sierra Nevada batholith and flattening of the subduction zone beneath the southern Sierra and Tehachapi Mountains. The second phase of cooling, at ca. 20 Ma, is robustly documented by the southernmost samples from the study area, and is attributed to >2 km of exhumation associated with extension along an east-west normal fault along the southern boundary of the sample area. The data also appear to suggest a third, less-distinct cooling event at 10 Ma, which may represent the time at which the Garlock fault transitioned to being a through-going left-lateral strike-slip fault.

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