Low-temperature thermochronology of the Black and Panamint mountains, Death Valley, California: Implications for geodynamic controls on Cenozoic intraplate strain

Tandis S. Bidgoli¹, Erika Amir², J. Douglas Walker¹, Daniel F. Stockli³, Joseph E. Andrew¹, and S. John Caskey²

¹DEPARTMENT OF GEOLOGY UNIVERSITY OF KANSAS, LAWRENCE, KANSAS 66045, USA
²DEPARTMENT OF EARTH AND CLIMATE SCIENCES, SAN FRANCISCO STATE UNIVERSITY, SAN FRANCISCO, CALIFORNIA 94132, USA
³JACKSON SCHOOL OF GEO SCIENCES, UNIVERSITY OF TEXAS, AUSTIN, TEXAS 78712, USA

ABSTRACT

We use apatite and zircon (U-Th)/He thermochronometry to evaluate space-time patterns and tectonic drivers of Miocene to Pliocene deformation within the Death Valley area, eastern California. Zircon He ages from the footwall of the Amargosa–Black Mountains detachment in the Black Mountains record continuous cooling and exhumation from 9 to 3 Ma. Thermal modeling of data from the central Black Mountains suggests that this cooling took place during two intervals: a period of rapid footwall exhumation from 10 to 6 Ma, followed by slower (<5 mm/yr) exhumation since 6 Ma. Cumulative exhumation is estimated to be 10–16 km. Paleodepth reconstruction of cooling ages from the footwall of the Panamint-Emigrant detachment, in the central Panamint Range, also show two periods of cooling. Zircons record late Miocene cooling, whereas apatite He ages show punctuated exhumation at ca. 4 Ma. The results suggest the Panamint Range experienced a minimum of 7.2 km of exhumation since ca. 12 Ma. The new data, when evaluated within the context of published fault timing data, suggest that the transition from Basin and Range extension to dextral transtension is spatially and temporally distinct, beginning at ca. 11–8 Ma in ranges to the east and north of the Black Mountains and migrating westward into eastern Death Valley at 6 Ma. Initiation of dextral transtension was coincident with a major change in plate-boundary relative motion vectors. Data from Panamint Range and several ranges to the west of Death Valley indicate transtension initiated over a large area at ca. 3–4 Ma, coeval with proposed lithospheric delamination in the central and southern Sierra Nevada Range. Our results suggest that the transition from extension to dextral transtension may reflect an evolution in tectonic drivers, from plate-boundary kinematics to intraplate lithospheric delamination.

INTRODUCTION

Plate motions may be accommodated across broad zones of diffuse and variable-style deformation within continental lithosphere (e.g., England, 1987). One of the best-known examples of a diffuse zone is the Pacific–North American plate boundary, where ~25% of the current plate motion is accommodated far inboard of the San Andreas transform fault (Minster and Jordan, 1987; Dokka and Travis, 1990; Bennett et al., 2003). Geodetic data from across western North America show that most of this intraplate strain is focused in the Eastern California shear zone (also the Walker Lane belt), a system of active, mostly northwest-striking, strike-slip faults that account for ~9–12 mm/yr of displacement of the Sierran microplate relative to the eastern Great Basin (Fig. 1; Dokka and Travis, 1990; Dixon et al., 1995; Bennett et al., 2003).

Global circuit reconstructions of the Pacific plate relative to North America suggest that at ca. 10–8 Ma, the plate boundary changed from NW oblique to dominantly coast-parallel motion (Atwater, 1970; Atwater and Stock, 1998). It is proposed that this motion change initiated the change from Basin and Range–style deformation to the transcurrent Eastern California shear zone and attendant structures (e.g., Dokka and Travis, 1990). (Plate-boundary and intraplate deformation patterns are shown in the animations of Atwater and Stock [1998], available at http://emvc.geol.ucsb.edu/download/napc.php, and McQuarrie and Wernicke [2005]). However, timing data from individual structures within the Eastern California shear zone range from middle Miocene to late Pleistocene (see Burchfiel et al., 1987; Hodges et al., 1989; Holm and Dokka, 1991, 1993; Holm et al., 1992; Hoisch and Simpson, 1993; Snow and Lux, 1999; Snyder and Hodges, 2000; Niemi et al., 2001; Monastero et al., 2002; Stockli et al., 2003; Guest et al., 2007; Lee et al., 2009; Mahan et al., 2009; Beyene, 2011; Walker et al., 2014), suggesting that the transition from intraplate extension to intraplate dextral transtension may not have been simply related to plate-boundary kinematics, and that other geodynamic factors may have played a role in the temporal and spatial pattern of deformation. One possible factor is lithospheric delamination, which is proposed to have occurred in the central and southern parts of the Sierra Nevada at ca. 3.5 Ma (Manley et al., 2000; Jones et al., 2004; Zandt et al., 2004; Gilbert et al., 2007).

In this paper, we present new zircon and apatite (U-Th)/He thermochronologic data from the Black and Panamint mountains bordering Death Valley in eastern California (Fig. 1). Death Valley lies within a region that has experienced both Basin and Range extension (e.g., Stewart, 1983; Snow and Wernicke, 2000) and more recent dextral transtension related to the Eastern California shear zone and Walker Lane belt (e.g., Dixon et al., 1995; Reheis and Sawyer, 1997; Bennett et al., 2003; Frankel et al., 2003; McQuarrie and Wernicke, 2005).
GEOLOGIC BACKGROUND

The Black Mountains are located on the eastern margin of Death Valley (Fig. 1). The range is host to the Amargosa–Black Mountains detachment, a normal fault system that exposes 1.7 Ga gneiss and late Precambrian metasedimentary rocks intruded by the 11.6 Ma Willow Springs pluton (Asmerom et al., 1994) and 10.4 Ma Smith Mountain Granite (Miller et al., 2004). Published $^{39}$Ar/$^{39}$Ar and zircon and apatite fission-track ages from the Black Mountains show that exhumation and cooling along the Amargosa–Black Mountains detachment began at ca. 12 Ma in the southern Black Mountains; however, major unroofing of the northern and central parts of the range took place between ca. 8 and 6 Ma (Holm et al., 1992; Holm and Dokka, 1993). The sedimentological record of the lower part of the adjacent Furnace Creek basin matches the timing of exhumation recorded in the thermochronology data; however, a significant portion of the basin shows rapid deposition beginning at 6 Ma, suggesting a major reorganization of the basin at that time (Wright et al., 1999, and references therein for details on the Furnace Creek basin).

The Panamint Range, on the western flank of Death Valley, is the relatively intact hanging wall to the Amargosa–Black Mountains detachment. The range hosts two major Cenozoic structures: the Eastern Panamint fault system and the Panamint-Emigrant detachment (Fig. 1). These structures expose a core of 1.7 Ga gneiss, middle and late Precambrian metasedimentary rocks, and Cretaceous and Cenozoic plutons. The Eastern Panamint fault system is a low-angle normal fault system, exposed in the eastern part of the range. The timing of motion on this fault system is poorly constrained, but it likely postdates...
intrusion of the 10.6 Ma Little Chief Stock in the center of the range, and most of the Trail Canyon volcanic sequence (ca. 10.5–9.4 Ma), exposed on east side of the range (McKenna and Hodges, 1990; Hodges et al., 1990). The Trail Canyon volcanic sequence is tilted 20°–40°, indicating significant eastward tilting of the Eastern Panamint fault system and range since ca. 9 Ma (McKenna and Hodges, 1990).

The Panamint-Emigrant detachment, exposed on the west side of the Panamint Range, includes the Emigrant and Towne Pass faults, and the Panamint detachment. Timing constraints for the Panamint-Emigrant detachment come from the sedimentary succession of the Nova Formation preserved in its hanging wall, and they suggest fault initiation and basin development after ca. 12 Ma (Hodges et al., 1989; Snyder and Hodges, 2000). However, the bulk of the Nova Formation was deposited rapidly between ca. 4.4 and 3.0 Ma, indicating that much of the activity related to this fault system is Pliocene in age (Snyder and Hodges, 2000). These sedimentologic observations are consistent with a palinspastic restoration of basalt flows across northern Panamint Valley that also suggests significant post–4 Ma fault motion (Burchfiel et al., 1987).

(U-Th)/He THERMOCRONOMETRY

We analyzed 48 samples from the footwalls of the Amargosa–Black Mountains detachment and Panamint-Emigrant detachment using zircon and apatite (U-Th)/He thermochronometry (Fig. 1). Two additional samples were also analyzed: one from the western base of the Nopah Range and another from the northern base of the Avawatz Mountains (Fig. 1). Samples represent a range of units, including Proterozoic gneiss and metasedimentary rocks, Cretaceous gneiss and leucogranite, and Cenozoic diorite and granite. Laboratory and analytical work was performed at Isotope Geochemistry Laboratories at the University of Kansas, the (U-Th)/He Geo- and Thermochronometry Laboratory at the University of Texas at Austin, and the (U-Th)/He Thermochronology Laboratory at the University of California, Santa Cruz. Data tables, descriptions of analytical procedures, and error reporting are given in Tables DR1 and DR2 and Appendix DR1 in the GSA Data Repository.1

He AGE RESULTS

Black Mountains

Cross-section A–A′ (Fig. 2) is oriented east-west and shows the geometry of the Amargosa–Black Mountains detachment and the projected positions of our thermochronology samples from Sheep Canyon in the central Black Mountains. Zircon (U-Th)/He mean ages range from 5.4 ± 0.6 Ma to 9.3 ± 3.9 Ma and systematically increase with increasing elevation (Figs. 2 and 3; Table DR1 [see footnote 1]). Samples also systematically increase in age eastward across the range (Fig. 2). A similar pattern of cooling ages is observed from the footwall of the Amargosa–Black Mountains detachment in Confidence Wash in the southern Black Mountains (cross-section B–B′ in Fig. 2). Zircon (U-Th)/He mean ages range from 5.4 ± 0.2 Ma to 8.5 ± 1.4 Ma. Mean ages from this transect also systematically increase from west to east; however, the age-elevation relationship is much subdued when compared with data from the central Black Mountains (Figs. 2 and 3).

In addition to these transects, we analyzed several samples from along the range front of the Black Mountains (Fig. 1). Zircon (U-Th)/He mean ages span from 3.3 ± 0.3 Ma to 5.5 ± 0.3 Ma, with most samples clustering at around 4 Ma (Fig. 1). These samples also show a modest correlation between mean age and elevations (Fig. 3).

Panamint Mountains

Cross-section C–C′ (Fig. 2) shows the geometry of the Miocene to Pliocene faults in the Panamint Range and projected positions of our thermochronology samples from the footwall of the Panamint-Emigrant detachment in Surprise Canyon and Pleasant Canyon in the central part of the range. Zircon (U-Th)/He mean ages range from 6.4 ± 1.0 Ma to 45.3 ± 4.9 Ma and systematically increase with increasing elevation (Table DR1 [see footnote 1]). Samples also increase in age eastward across the range. In contrast, mean apatite (U-Th)/He ages from these transects appear to cluster at ca. 3–4 Ma. The exception is our structurally highest sample, which had a mean age of 19.4 ± 0.3 Ma.

THERMAL MODELING AND PALEODEPTH RECONSTRUCTION

In order to evaluate possible cooling histories and apparent exhumation rates, we modeled footwall transects from the central Black Mountains and Panamint Range using the numerical modeling software HeMP (Hager and Stockli, 2009). The software searches for viable thermal histories for multisample transects by modeling He production, stopping, and diffusión for randomly generated temperature-time paths using algorithms and goodness-of-fit tests described in Ketcham (2005). Details of the required model inputs and constraints are given in Appendix DR1 (see footnote 1).

The modeling results for the central Black Mountains are shown in Figure 4. The models show continuous exhumation since ca. 10 Ma and a distinct change in the slope of model fits at ca. 6 Ma. This change is also reflected in exhumation rates, with rates as high as 10–5 mm/yr for segments of the thermal history prior to 6 Ma. By contrast, exhumation rates are consistently lower (<5 mm/yr) after 6 Ma. The cumulative exhumation from our best-fit models (30 °C/km geothermal gradient) ranges from 9 to 16 km, which is similar to earlier geobarometric estimates for the Willow Springs pluton (Holm et al., 1992). The modeling results also show that most of the model fits correspond to reasonable geothermal gradients between 20 and 50 °C/km, although model fits with geothermal gradients as high as ~140 °C/km were not excluded by the analysis.

In contrast, thermal models for the Panamint Range are best satisfied by model fits at very high geothermal gradients (100+ °C/km; Fig. 4). Both intrusion of the Little Chief Stock at 10.6 Ma (Hodges et al., 1990) prior to fault initiation and isotherm advection during rapid exhumation could elevate geothermal gradients in the area, but these transient effects would not be representative of time-averaged geothermal gradients. Another possible explanation for the high geothermal gradients in our models is tilting or horizontal-axis rotation of our samples, which would narrow the vertical distance between samples and, consequently, paleotherms. Such a scenario seems likely given that 20°–40° of tilting is documented for the range (McKenna and Hodges, 1990). To further evaluate the data and account for this rotation, we restored samples to their middle Miocene paleodepths using the unconformity below the middle Miocene surface, consistent with

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1GSA Data Repository Item 2015194, Table DR1 (summary of [U-Th]/He data), Table DR2 ([U-Th]/He data), and Appendix DR1 (analytical procedures, error reporting, and thermal modeling inputs and constraints), is available at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
Figure 2. Geologic cross sections across the central Black Mountains (A–A'), southern Black Mountains (B–B'), and central Panamint Range (C–C'). Thermochronology samples, shown as dots, are projected into the plane of each cross section. In this projected view, samples may lie above or below the topography of the section line. Mean zircon (black diamonds) and apatite (white boxes) (U-Th)/He ages and errors (1σ standard deviation) are shown above each sample. Strip maps below each cross section show sample locations with respect to the line of the section. Cross section locations are shown in Figure 1. Geology is from Drewes (1963), Hunt and Mabey (1966), and the compilation of Workman et al. (2002). ABMD—Amargosa–Black Mountain detachment; PED—Panamint-Emigrant detachment; EPFS—East Panamint fault system.
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Figure 3. (A) Plot of (U-Th)/He age versus elevation for the Black Mountains showing a strong age-elevation relationship for the Sheep Canyon data, while data from Confidence Wash show a more modest correlation. (B) (U-Th)/He age versus elevation plot for the Panamint Range. The zircon (Zr) data show a strong age versus elevation relationship, while apatite (Ap) data are mostly elevation invariant.

Figure 4. (A) Modeled temperature-time (T-t) paths (acceptable fits) for the Sheep Canyon transect, central Black Mountains. Most of the modeled paths have an inflection point or change in slope and cooling rate at ca. 6 Ma. Black boxes show the model constraints based on biotite and hornblende 40Ar/39Ar ages from Holm et al. (1992) and an assumed mean annual surface temperature. (B) Exhumation rates from modeled (t-T) histories that satisfy a 30 °C/km geothermal gradient (1000 fits). Results suggest that rates have decreased since 6 Ma. Inset chart shows the number of acceptable fits for geothermal gradients ranging from 10 °C to 200 °C. (C) Modeled (T-t) paths (acceptable fits) for the Panamint Range. Black boxes show the model constraints based on muscovite and hornblende K-Ar ages from Lanphere (1962) and an assumed mean annual surface temperature. (D) Exhumation rates from modeled (t-T) histories colored according to geothermal gradient. Inset chart shows the number of acceptable fits for geothermal gradients ranging from 10 °C to 200 °C. ZHe—zircon helium; PRZ—partial retention zone.
crystallization pressures estimated for the stock (McDowell, 1974).

The resulting paleodepth reconstruction (Fig. 5) shows two distinct periods of cooling. The structurally lowest zircon ages overlap within errors and show a period of late Miocene cooling. Samples above 7.5 km then steadily increase in age with decreasing paleodepth, defining a zircon He partial retention zone. The shallowest zircon samples cluster at ca. 45 Ma and are not reset, defining the top of the partial retention zone. In contrast,apatite ages from these same samples are invariant at ca. 4 Ma, consistent with rapid exhumation at that time.

Assuming a mean surface temperature of 10 °C, our paleodepth reconstruction indicates that the Panamint Range has experienced a minimum of 180 °C of cooling since the late Miocene. The estimated pre-extensional geothermal gradient from our reconstruction is ~25 °C/km, which translates to ~7.2 km of vertical exhumation. However, our structurally deepest sample resides 1.2 km below the approximate position of the 190 °C isotherm in our paleodepth reconstruction. Therefore, the total vertical exhumation since the late Miocene is probably closer to 8.4 km.

DISCUSSION AND CONCLUSIONS

The new data from the Black Mountains, combined with earlier thermochronologic constraints from the range (Holm et al., 1992; Holm and Dokka, 1993), show a continuous exhumation history that begins at ca. 12 Ma. A marked change in the thermal history and inferred exhumation rate occurred at ca. 6 Ma, which is coincident with a major change in the character of sediment and depositional rates within the Furnace Creek basin (Wright et al., 1999, and references therein). The Panamint Range similarly shows two periods of exhumation: one in the late Miocene and the other in the Pliocene. The Pliocene cooling coincides with a period of rapid sedimentation within the adjacent Nova basin (Snyder and Hodges, 2000), suggesting a major structural reorganization at that time.

Timing constraints for the major faults within the Eastern California shear zone are variable. Faults located east and north of the Black Mountains (e.g., Stateline fault, Boundary Canyon detachment, Furnace Creek fault, Northern Death Valley–Fish Lake Valley fault) initiated between 11–8 Ma, around the time of the plate-boundary change (Fig. 1; Holm and Dokka, 1991, 1993; Hoisch and Simpson, 1993; Reheis and Sawyer, 1997; Snow and Lux, 1999; Niemi et al., 2001; Mahan et al., 2009; Beyene, 2011; Ferrill et al., 2012). It is unclear if these structures initiated at the onset of regional extension or dextral transtension, a problem that is compounded by the fact that some of the published data are maximum ages rather than well-defined fault initiation ages (e.g., Reheis and Sawyer, 1997; Snow and Lux, 1999; Niemi et al., 2001). However, timing data across much of the Eastern California shear zone suggest that extension and transtension occurred in discrete phases (see summary in Norton, 2011). The Northern Death Valley–Fish Lake Valley fault system, for example, initiated at ca. 10 Ma, but reorganized at ca. 6 Ma, similar to the Black Mountains (Reheis and Sawyer, 1997; Stockli et al., 2003). Like the Panamint Range, the Slate Range, and Inyo and White mountains show two phases of rapid exhumation: one in the middle Miocene and another at ca. 3–4 Ma (Fig. 1; Walker et al., 2014; Lee et al., 2009; Stockli et al., 2003). The earlier of these events is linked to Basin and Range extension, while the latter is linked to the initiation of dextral transtension (Stockli et al., 2003; Lee et al., 2009; Walker et al., 2014). A two-phase history is also supported by differences in the timing, composition, and volume of suites of igneous rocks in the region, with copious intermediate to felsic magmatism during the middle to late Miocene giving way to small-volume mafic eruptions during the Pliocene to Quaternary (e.g., Asmerom et al., 1994). (Space-time patterns are well expressed in the palinspastic reconstruction of the North American Volcanic Database by McQuarrie and Oskin [2010].)

The new thermochronology data, when placed within the context of published fault timing data, demonstrate that the very eastern part of the Eastern California shear zone experienced a transition to dextral transtension that was coincident with and likely triggered by the plate-boundary kinematic change at 10–8 Ma, while areas to the west lagged this change by several million years. A westward progression in fault initiation is predicted by and may support a rolling hinge model for the structural development of the greater Death Valley area (e.g., Stewart, 1983; Wernicke et al., 1988; Snow and Wernicke, 2000; Niemi et al., 2001; Ferrill et al., 2012), but given the two-phase pattern of deformation documented by this and other studies (e.g., Stockli et al., 2003; Lee et al., 2009; Walker et al., 2014), such a model may be too simplistic. As an alternative, the westward progression of fault initiation could reflect changes in crustal strength that closely follow the locus of earlier extension and crustal thinning (Fridrich and Thompson, 2011). In this case, the earlier pattern of strain, which may have been controlled by the migration of a rolling hinge or some other mechanism, and its impact on crustal rheology are the dominant controls on the initiation of dextral transtension.

Although both of these models adequately describe the westward progression in fault initiation, neither model explains the near-simultaneous inception of the Eastern California shear zone west of Death Valley at 3–4 Ma, suggesting that other dynamic drivers may need to be considered. One factor that may be imparting a control on the temporal and spatial pattern of intraplate strain is lithospheric delamination, which is interpreted to have occurred in the central and southern Sierra Nevada at ca. 3.5 Ma (Manley et al., 2000; Jones et al., 2004; Zandt et al., 2004; Gilbert et al., 2007). Mantle tomographic studies have identified a large, dense lithospheric body (the Isabella anomaly) spreading out from the base of the crust into the asthenosphere beneath the western Sierras and Great Valley, while the topographically high eastern Sierras are made up of relatively thin crust (~35 km) and low-velocity mantle (Gilbert et al., 2012, and references therein). Aside from the geophysical evidence for delamination, garnet-rich xenoliths, present in 12–8 Ma basalts, are conspicuously
missing from eruptions younger than ca. 4 Ma, suggesting that a portion of the lithosphere was removed during the intervening interval (Duca and Saley, 1996, 1998). The timing of delamination is inferred from a brief pulse of alkaline volcanism at ca. 3.5 Ma, interpreted to have been caused by asthenospheric upwelling in the wake of lithospheric removal (Manley et al., 2000; Farmer et al., 2002; Jones et al., 2004).

The similar timing of lithospheric delamination and the development of the Eastern California shear zone west of Death Valley suggests these events are linked. Such a connection has been postulated and modeled by a number of authors (e.g., Jones et al., 2004; Oldow et al., 2008; Le Pourhiet et al., 2006; Saley et al., 2012), but major gaps in fault timing constraints have hindered the relationship between the two ambiguous. Data from this study, combined with published fault timing constraints (Holm and Dokka, 1991; 1993; Hoisch and Simpson, 1993; Reheis and Sawyer, 1997; Snow and Lux, 1999; Niemi et al., 2001; Stockli et al., 2003; Lee et al., 2009; Mahan et al., 2009; Beyene, 2011; Ferrill et al., 2012; Walker et al., 2014), indicate that the initiation of dextral transtension occurred as a westward-migrating wave, with transtensional structures initiating in the east at ca. 11–8 Ma, in Death Valley and Fish Lake Valley at 6 Ma, and in areas west of Death Valley at 4–3 Ma. This pattern may be explained by an evolution in geodynamic drivers, from plate-boundary kinematics to intraplate factors like lithospheric delamination.

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