Constraints on exhumation and extensional faulting in southwestern Nevada and eastern California, U.S.A., from zircon and apatite thermochronology

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ABSTRACT

Eastern California and southwestern Nevada represent an area of Tertiary and Quaternary extensional and dextral transtensional deformation. We used zircon and apatite fission-track thermochronology to study the distribution and timing of tectonic exhumation resulting from extensional and transtensional detachment faulting in this area. Sampling efforts were focused on Paleozoic and Precambrian clastic sedimentary and metasedimentary rocks. Sixty-nine new apatite and zircon fission-track cooling ages from 50 samples, analyzed in conjunction with published fission-track data from the region, indicate a distinct population of young (Miocene) fission-track ages and a population of irregularly distributed older (pre-Miocene) fission-track ages. Miocene (young population) fission-track ages become younger toward the west—indicating westward migration of the cooling front, consistent with well-documented Miocene extension of the Basin and Range Province. The younging pattern is also consistent with west-northwest displacement of the hanging wall of a crustal-scale extensional fault system and consequent progressive footwall exhumation. The active trailing edge of the hanging wall of this system generally coincides with Death Valley. Migration rates of the cooling front in the footwall of this system are on the order of 10–11 mm/yr. Based on the distribution of the Miocene fission-track ages, we interpret that the crustal faults that defined the eastern edge of the detachment system originated as separate normal faults that were linked by the formation of a transfer fault. Extrapolation of apatite fission-track closure ages from two transects across the eastern margin of the Death Valley region suggests that exhumation along the eastern margin of the system continues beneath Death Valley today.

INTRODUCTION

Oblique motion between the Pacific and North American plates produces a transtensional tectonic regime in the Basin and Range Province of eastern California and southern Nevada (Harrall, 1971; Atwater, 1970; Frisch et al., 2011). Active deformation in this region is manifested by an interconnected network of large-scale, north-south–striking normal faults and north-west-trending strike-slip faults, an area Stewart (1988) referred to as the Walker Lane belt (Fig. 1). Although there is debate about the total amount of extension in the region (e.g., Serpa and Pavlis, 1996) and the details of fault block definition and displacement style (e.g., Snow and Wernicke, 2000), there is consensus that rapid and continuing displacement on this network of basin-controlling faults has generated starved basins (where rate of subsidence exceeds rate of sedimentation) with several kilometers of structural and topographic relief. Most of these active basins have developed since the late Miocene (e.g., MIT 1985 Field Geophysics Course and Biehler, 1987; Snow and Wernicke, 2000), although there is also evidence of Eocene, Oligocene, and early Miocene basin development in the region (Axen et al., 1993). Along the eastern margin of this region of active and rapid basin formation, there lies the Death Valley–Furnace Creek fault system. East of this fault system, displacement on normal faults initiated in the Miocene and has exhumed rocks from depths of 10–15 km (Hodges et al., 1987; Hoisch and Simpson, 1993; Hoisch et al., 1997; Holm and Dokka, 1993, 1991). Exhumation of deep footwall rocks during deformation led to progressively more brittle overprinting of previously formed ductile deformation features at the northern end of the Panamint Range (Hodges et al., 1989), the Black Mountains (Cowan et al., 2003; Miller and Pavlis, 2005; Hayman, 2006), and the Funeral Mountains (Hoisch and Simpson, 1993). Isostasy is presumed to have produced uplift of footwalls relative to hanging walls, placing rocks from 10 to 15 km depths at the same elevation as uppermost crustal rocks (e.g., Wernicke and Axen, 1988; Asmerom et al., 1990; King and Ellis, 1990; Wernicke, 1992). Analog modeling that simulates brittle deformation of the upper crust above more ductile lower crustal material has reproduced many of the key structural elements seen in the region (Brun et al., 1994).

The purpose of this paper is to summarize fission-track cooling ages and related distribution and timing of fault-related exhumation of crustal rocks in the vicinity of Yucca Mountain, Nevada. The original motivation for this work was to provide constraints on tectonic models of the Yucca Mountain area, which was under evaluation as the potential site for a high-level radioactive waste repository. We use fission-track ages from apatite and zircon as a basis for interpreting the distribution and timing of exhumation for pre-Miocene rocks in southwest Nevada.
Fission-Track Thermochronology

Nevada and eastern California. We present 69 new apatite and zircon fission-track ages collected from Paleozoic and Precambrian rocks throughout the study area. The fission-track ages indicate exhumation ages of the sample host rocks as these rocks cooled through the fission-track closure temperatures of apatite and zircon. Our results define an area of Miocene crustal extension exhumed by normal faulting. Spatial distribution of the fission-track ages is also used to infer the original configuration of crustal faults that define the detachment system.

Fission-Track Thermochronology

Fission tracks are linear damage zones caused by spontaneous fission of uranium atoms in U-bearing minerals such as apatite and zircon. U-238 decay occurs at a known rate unaffected by temperature or pressure, and the number of fission tracks per unit area of crystal in conjunction with the uranium concentration gives a measure of the time since track accumulation began (Wagner and Van den Haute, 1992). Fission tracks are not permanent features of a crystal and are subject to healing or annealing if the crystal is heated above its closure temperature for a period of ~10^6 yr (Tagami and O’Sullivan, 2005). While at temperatures above the closure temperature, rates of fission-track formation within the crystal are balanced by rates of annealing, and there is no net fission-track accumulation. Below the closure temperature, however, annealing is inhibited, and fission tracks accumulate within the crystal. Thus, a fission-track age is a measure of the time elapsed since the latest cooling of the crystal through its closure temperature. If the rock in which the mineral sample resides has been buried to depths at which the ambient temperature was greater than the fission-track closure temperature for that mineral, then the fission-track age also represents the time at which the rock was exhumed by erosion, extensional faulting, or a combination of these processes (additional background is provided in Appendices A and B).

Sampling and Methods

Samples were collected from outcrops around Yucca Flat and Frenchman Flat (on the Nevada Test Site), the Striped Hills, Mount Stirling, Resting Spring Range, Bare Mountain (Spivey et al., 1995; Ferrill et al., 1996b), Bullfrog Hills, and the eastern margin of the Funeral Mountains (Figs. 1 and 2). Sampling sites were selected to expand upon previous fission-track results that concentrated on mountain ranges along the eastern margin of Death Valley, the Bullfrog Hills, and the northwest corner of Bare Mountain. To constrain timing of exhumation associated with crustal-scale normal faulting, we focused our sampling efforts on Paleozoic and Precambrian clastic sedimentary and metasedimentary rocks of the Stirling Quartzite, Wood Canyon Formation, Zabriskie Quartzite, Eureka Quartzite, and Eleana Formation (see Tables 1 and 2 and Fig. 3 for details on sampled rock types).

In a few cases, we sampled younger igneous rocks to provide an independent check of dating results and additional geochronologic constraints. For these purposes, samples were collected from Cretaceous granite and Tertiary diorite and latite dikes at Bare Mountain, Mesozoic monzogranite of the Climax Stock (northwest Yucca Flat), and Rainier Mesa tuff from the Bullfrog Hills. In total, 50 new samples were collected for dating. Apatite and zircon mineral separates were isolated from each sample following procedures outlined in Dumitru (2000) using standard gravimetric and magnetic mineral separation techniques. Theapatite mineral separates consist of fluorine-rich apatite. Apatite fission-track ages were measured at Apatite to Zircon, Inc., by Raymond A. Donelick (analyst RAD; see Appendix A) using the external detector method (e.g., Gleadow, 1981). Zircon grains from 16 samples were analyzed using zircon fission-track thermochronology techniques (e.g., Wagner and Van den Haute, 1992). Eleven of the zircon fission-track age analyses were performed at the University of California at Santa Barbara by Ann E. Blythe (analyst AEB), and five were performed at Apatite to Zircon, Inc. (analyst RAD; see Appendix B). All analyses were performed using the external detector method.
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(Research)

Gleadow, 1981). Fission-track analyses are detailed in Appendices A and B.

APATITE FISSION-TRACK THERMOCHRONOLOGY RESULTS

Except for the Miocene silicic porphyry dikes at Bare Mountain (apatite fission-track ages 10.9–16.0 Ma; Monsen et al., 1992), the Rainier Mesa Tuff from the Bullfrog mine (apatite fission-track age 21.3 Ma; Maldonado, 1990), and the Climax Stock (apatite fission-track age 76 Ma; Naeser and Maldonado, 1981) in northern Yucca Flat (Fig. 1), all apatite fission-track ages reported here (Table 1) are significantly younger than the host rocks. Of the 53 ages reported here (including two duplicates and one combined), 50 exhibit Dpar (mean etch pit diameter measured parallel to crystallographic c axis) values less than or equal to 2 μm, indicating that the apatites can be treated as fast annealing for interpretation purposes. In general, fission-track ages that are younger than the host rock indicate heating above the temperatures required for total fission-track annealing after deposition or crystallization of the host rocks. Thus, the ages are not inherited (e.g., from rocks of a previously eroded terrain); rather, they represent cooling of the host rocks through the fluorine-rich apatite closure temperature, presumably during exhumation. In addition to our 53 new ages, we include 10 published ages from the Black Mountains (Holm and Dokka, 1993), the Funeral Mountains (Holm and Dokka, 1991; Hoisch and Simpson, 1993), and the Bullfrog Hills and northwest corner of Bare Mountain (Hoisch et al., 1997).

Apatite fission-track ages fall into a population of diverse pre-Miocene ages and a population of Miocene and younger ages (Fig. 4). Pre-Miocene ages generally lie to the east of Miocene ages at a given latitude in the study area and range from 25 to 115 Ma. To assess spatial variation of the Miocene and younger ages, we subdivided these ages into three groups: (1) early Miocene (16.6–23.7 Ma), (2) middle Miocene (11.2–16.6 Ma), and (3) late Miocene (5.3–11.2 Ma) and younger (Fig. 4). The youngest ages are found along the eastern margin of Death Valley in the Funeral Mountains and Black Mountains. Miocene cooling ages generally get younger to the west or northwest. The Funeral Mountains and Bare Mountain include ages belonging to both the Miocene and pre-Miocene populations, which allow us to delineate these age transitions in bedrock within these ranges.

ZIRCON FISSION-TRACK THERMOCHRONOLOGY RESULTS

Sixteen samples were processed for zircon fission-track analysis (Table 2). Most of the zircon fission-track ages are much younger than the ages of their host rocks, indicating that the host rocks were heated above the total fission-track annealing temperature of zircon after deposition. With two exceptions, the zircon fission-track ages reflect resetting of the host mineral grains and cooling of the host rocks, presumably during exhumation, through the zircon fission-track closure temperature, rather than being inherited from a previously eroded terrain or recording primary cooling.

One exception is the sample from the silicic porphyry dike (BME-2; Table 2) sampled from Bare Mountain, which yields a zircon fission-track age of 11.9 ± 1.2 Ma, concordant with the
TABLE 1. APATITE FISSION-TRACK DATA

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<th>σ</th>
<th>Mean length (μm)</th>
<th>NT</th>
<th>NT Mean length (Ma)</th>
<th>Mean age (Ma)</th>
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<th>Mean length (μm)</th>
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<th>NT Mean length (Ma)</th>
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(continued)
TABLE 1. APATITE FISSION-TRACK DATA (continued)

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Previously published
- CC-61 Pelitic schist (H&S 93)
- 900008 Muscovite granite (H&D 91)
- IHI-BIO Precambrian basement (H&D 93)
- DKH-IH2 Precambrian basement (H&D 93)
- DKH-JP Precambrian basement (H&D 93)
- 968-25 Gabbro diorite (H&D 93)
- 89-MP Precambrian basement (H&D 93)
- BM-TH-14ab Schist (H etal 97)
- BF-TH-9AB Amphibolite (H etal 97)
- BF-TH-10 Schist (H etal 97)

Note: Easting and Northing are UTM (Zone 11, NAD 27) locations in meters. All errors are reported at 1σ; zeta calibration factor for analyst RAD of 113.8 ± 2.9 (e.g., Hurford and Green, 1983) relative to CN-1 dosimeter glass (39 ppm natural uranium) was determined using Durango and Fish Canyon Tuff apatite standards irradiated with these samples; mean spontaneous track lengths for Durango and Fish Canyon Tuff apatite standards are 14.47 ± 0.06 µm, and 15.35 ± 0.06 µm, respectively. Rock types are defined in Monsen et al. (1992). Values of $\rho_s$, $\rho_i$, and $\rho_d$ are spontaneous, induced, and dosimeter fission tracks, respectively, given in units of 10$^6$ tracks per cm$^2$; Ns, Ni, and Nd are the number of spontaneous, induced, and dosimeter fission tracks, respectively; grains is the number of apatite grains; Q is the probability that $\chi^2$ value would be greater than reported for a population of apatite grains having a common history and common kinetic response to that history; $\chi^2$ test, P (pass) for Q 0.05, F (fail) for Q <0.05; Dpar is the mean etch pit diameter parallel to the crystallographic c-axis for the grains measured (Dpar <1.75 typical of near-end-member fluorapatite); pooled age is the fission-track age based on sum total of spontaneous and induced tracks for all grains measured (reliable when $\chi^2$ test is P, indicated by bold font) given in Ma; mean age is the arithmetic mean of the individual grain ages (reliable when $\chi^2$ test is F, indicated by bold font) given in Ma; NT is the number of track lengths measured; mean length is average track length in µm; $\sigma$ is one standard deviation about the mean of the track length measurements; U is the concentration of uranium in ppm; n.a. is not applicable. H&S 93—Hoisch and Simpson (1993); H&D 91—Holm and Dokka (1991); H&D 93—Holm and Dokka (1993); H etal 97—Hoisch et al. (1997).
Table 2. Zircon Fission-Track Data

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Note: Explanations of table headings are the same as in Table 1. Ages were determined using zeta calibration factor of 335 ± 20 relative to SRM 962a dosimeter glass (analyst AEB) or 135.0 ± 3.8 relative to CN-1 dosimeter glass (analyst RAD). The age for sample BFH-2, which failed the $\chi^2$ test, is the mean age instead of the pooled age. H&D 91—Holm and Dokka (1991); H&D 93—Holm and Dokka (1993); H et al. 97—Hoisch et al. (1997).
Apatite fission-track age of 12.3 ± 2.2 Ma. A conventional K/Ar age of 13.8 ± 0.2 Ma was measured from biotite from this dike (Monsen et al., 1992). Based on data from Marvin et al. (1989), Noble et al. (1991), Monsen et al. (1992), and Weiss (1996), conventional K/Ar and 40Ar/39Ar dates from the silicic porphyry dikes along eastern Bare Mountain, of which this is part, range from 14.9 to 13.8 Ma. However, textural features and K/Ar dates from alunite indicate epithermal and hydrothermal activity contemporaneous with the later stages of silicic volcanism (ca. 11.0–12.5 Ma), especially associated with altered margins of the silicic porphyry dikes. Our apatite and zircon fission-track ages are consistent with resetting due to epithermal or hydrothermal activity, or the fission-track ages can be considered concordant with the conventional K/Ar biotite age.

The second exception is Eureka Quartzite (DFM-2) sampled from the south side of Frenchman Flat at Mercury Ridge, which yielded a fission-track age of 13.8 ± 0.2 Ma (Monsen et al., 1992; Monsen et al., 1992). Gray areas show gaps in the geologic record due to nondeposition, faulting, or erosion.
Uplift generated by displacement of the hanging wall causes the footwall and its associated population ofapatites and zircons to move toward Earth’s surface and down the geothermal gradient to progressively cooler conditions. The fission-track ages represent the time elapsed since the mineral passed through its closure temperature on its way to Earth’s surface. Apatite and zircon grains deeper than their corresponding annealing depths are progressively unroofed and cooled, resulting in accumulation of fission tracks and younging of fission-track ages in the direction of hanging-wall transport. Rocks exposed in the exhumed footwall will contain mineral grains that exhibit a variety of cooling-age patterns, depending upon the depth to detachment of the major fault system, the geothermal gradient during exhumation, and the depth of erosion following footwall uplift. Because the unroofing process is progressive, and at large scale directional, the pattern of cooling ages in the exposed footwall will show a pattern of decreasing ages in the direction of hanging-wall transport (Fig. 6B). Fault slivers stranded on the footwall will contain fission-track younging patterns broadly similar to the fundamental footwall (Fig. 6C). Structural complexities, such as the stranding of a hanging-wall fault sliver, may partially occlude the broad footwall pattern and produce local anomalies in the regional younging pattern (Fig. 6C). Based on this model, Bare Mountain, the Bullfrog Hills, the Funeral Mountains, and the Black Mountains were all unroofed differentially during the Miocene (Maldonado, 1990; Holm and Dokka, 1991; Hoisch and Simpson, 1993; Serpa and Pavlis, 1996), and this interpretation is in accord with large-scale structural relationships and small-scale deformation features, including brittle extensional structures that overprint ductile extensional deformation fabrics (Wernicke and Axen, 1988; Wernicke, 1995, 1992).
The eastern half of Bare Mountain exhibits pre-Miocene cooling through 250 °C, followed by Miocene cooling through 130–146 °C (Figs. 4 and 5). Northwest Bare Mountain cooled through both 250 °C and 130–146 °C since the beginning of the Miocene. South and east of Bare Mountain, including the southeastern Funeral Mountains and the Resting Spring Range but excluding the Black Mountains, apatite closure ages are pre-Miocene. West of this broadly defined line, apatite ages show a consistent younging trend to the west.

We interpret Miocene and younger apatite and zircon cooling ages to indicate exhumation of the rocks through the 130–146 °C (apatite) and 250 °C (zircon) closure temperatures in response to the west-northwest–directed tectonic removal of overlying crust. The initiation of the breakaway at Bare Mountain occurred at ca. 13 Ma (this work; Hoisch et al., 1997). Our fission-track results do not indicate tectonic exhumation east of Bare Mountain, which refutes earlier interpretations by Hamilton (1988, 1987) and Scott (1990) that a shallow regional detachment extends beneath and east of Yucca Mountain. We interpret that the Death Valley–Furnace Creek fault zone (Fig. 2) represents the current position of the easternmost surface trace of the west-northwestward–moving hanging wall (consistent with Stewart, 1983; Serpa and Pavlis, 1996).

If we project the apatite age data horizontally and parallel to the traces of the extensional fault segments onto transects that are parallel to the regional extension direction over the last 12 m.y. (represented by the Furnace Creek fault trace; McQuarrie and Wernicke, 2005), we can create graphs that illustrate the sharp break between older (pre-Miocene) ages to the east-southeast and younger (Miocene) ages to the west-northwest (Figs. 7B and 7C). Considering only the Miocene and younger ages, Figures 7B and 7C show a consistent younging trend to the west.
and 7C reveal a relatively simple west-northwest younging trend that results from migration of the apatite cooling front, consistent with the conceptual model shown in Figure 6B. Notably, there is no repetition of lateral younging trends, which would be expected to appear as a sawtooth pattern on Figures 7B and 7C, if extension had been accomplished by a series of tilted normal-fault blocks or fault slivers (e.g., Fig. 6C).

Migration of the apatite cooling front was comparable in the Bare Mountain–Bullfrog Hills area (10 mm/yr; Fig. 7B) and in the Black Mountains (11 mm/yr; Fig. 7C). If we assume that the migration of the apatite cooling front represents the horizontal (extension) component of normal fault displacement, then this represents crustal extension at a rate of 10–11 mm/yr. This rate is in accord with rates for the “Death Valley extensional belt” (between the Spring Mountains and Sierra Nevada; Wernicke et al., 1988) derived from palinspastic reconstruction, with extension initiating between 14 and 16 Ma and a rate of ~2 mm/yr, increasing to a maximum rate of ~16.5 mm/yr between 6 and 8 Ma, and declining to a present-day rate of ~11.5 mm/yr (see fig. 12 in Snow and Wernicke, 2000). Our study area represents a subset of the Death Valley extensional belt as described by Snow and Wernicke (2000), and the timing and rate of deformation should be expected to differ from the regional average pattern. Geodetic global positioning system (GPS)-derived rates indicate ~13 mm/yr for the Eastern California shear zone north of the Garlock fault (Miller et al., 2001), of which ~3–5 mm/yr are concentrated along the Death Valley fault zone (Bennett et al., 1997; Gan et al., 2000; Miller et al., 2001). Collectively, these data suggest a decreasing extension rate at Death Valley.

Projection of the Black Mountain apatite fission-track data eastward to 13 Ma indicates that the location of the breakaway in that area was just to the west of the Resting Spring Range (Fig. 7A). This also agrees with Stewart’s (1983) placement of the Panamint Mountains prior to faulting, and subsequent restored positions of the Panamint Range interpreted by Snow (1994), Serpa and Pavlis (1996), and Snow and Wernicke (2000).

South of Bare Mountain, the position of the breakaway is constrained between the location for our sample locality RJBD1 along the northeastern margin of the Funeral Mountains (mean apatite age of 69.1 Ma), and samples CC-61 (apatite age of 5.6 Ma; Hoisch and Simpson, 1993) and 900008 (apatite age of 6.6 Ma; Holm and Dokka, 1991). From here, the trace must step laterally to pass to the east of the late Miocene ages from the Black Mountains and west of the 89.3 Ma apatite fission-track age from the Resting Spring Range. This step corresponds to the surface trace of the Furnace Creek fault. The precise location of the footwall cutoff in the vicinity of the Funeral Mountains is not well constrained by our data. However, although Workman et al. (2002) showed the geologic location from which we collected sample RJBD1 as being separated from the main Funeral Mountains by a fault, more detailed geologic mapping by Wright and Troxel (1993) shows that the geologic layers and layer orientations (including marker beds and folds) at RJBD1 correlate with geology along strike in the Funeral Mountains. We have, therefore, chosen to link the footwall cutoff trace directly to the Furnace Creek fault zone as shown in Figure 7A, but there may be more complexity than this indicates.
Constraints on exhumation and extensional faulting from thermochronology

**Figure 7.** (A) Digital shaded relief map illustrating the interpreted position of the breakaway fault, interpretation of domains with respect to detachment system, and location of transects in (B) and (C). Squares are horizontally projected onto the northern transect line (Fig. 7B) along an azimuth of 190°, diamonds are horizontally projected onto the southern transect line (Fig. 7C) along an azimuth of 170°. (B) Transect along azimuth 123°, parallel to the Furnace Creek fault zone showing apatite fission-track cooling ages plotted against distance along transect. Color coding as in (A)). Gray area represents range of best-fit lines within ±1 standard deviation from the mean. Least-squares best-fit line to the Miocene and younger data is provided. The southeastern projection to 13 Ma coincides with the inferred trace of the footwall cutoff of the detachment system. The northwestward projection to 0 Ma indicates that rocks at the far northwest end of the transect, at the appropriate depth, are currently passing through the apatite closure geotherm. The inverse slope of the best-fit line is 10 mm per year. (C) Transect along azimuth 123° (parallel to the Furnace Creek fault zone), apatite fission-track cooling ages are plotted against distance along transect. The inverse slope of the best-fit line is 11 mm/yr.
Our interpretation of detachment faulting related to crustal exhumation in the Death Valley region is consistent with Figure 6. Exhumed footwall rocks adjacent to the surface trace of the breakaway fault, which were initially shallower in the crust than the apatite fission-track closure temperature geotherm, exhibit pre-exhumation ages for both apatites and zircons. Within the footwall and in the direction of transport of the hanging wall, there will be a zone in which apatite will yield exhumation cooling ages but zircon will not. Finally, there is a zone in which both zircon and apatite yield exhumation cooling ages. Fission-track ages for a given mineral will be younger in the direction of transport of the hanging wall, reflecting progressive exhumation (e.g., Holm and Dokka, 1993, 1991; Hoisch and Simpson, 1993; Hoisch et al., 1997). Complications to this general pattern arise if slivers of the hanging wall are left on the exhumed footwall (e.g., Fig. 6c; Wernicke and Axen, 1988; Wernicke, 1992)—each sliver, however, represents a small version of the overall footwall pattern.

Our interpreted configuration of the footwall and hanging-wall cutoffs of the Death Valley–Furnace Creek regional detachment system places Crater Flat basin immediately adjacent to the footwall cutoff and in the footwall of the system (Fig. 7A). Yucca Mountain lies at the eastern edge of Crater Flat basin and is a series of cuestas formed by west-dipping normal faults with displacements on the order of a few hundreds of meters (e.g., Ferrill et al., 1999; Ferrill and Morris, 2001; Morris et al., 2004). Crater Flat basin is a half graben controlled by displacement on the east-dipping Bare Mountain fault, which has a maximum displacement of 3–5 km (Faulds et al., 1994; Ferrill et al., 1996a; Brocher et al., 1998). Faulting at Yucca Mountain and on the Bare Mountain fault was at least in part contemporaneous with Miocene tuff emplacement (Carr, 1990; Monsen et al., 1992), began ~13 m.y. ago, and has continued into the Quaternary (Ferrill et al., 1997, 1996a). Fault displacements and associated extensions within the Bare Mountain–Crater Flat–Yucca Mountain system are one to two orders of magnitude less than those faults in the Bullfrog Hills (just north and west of Bare Mountain) and within the Death Valley–Furnace Creek detachment system. Fault slivers within the Bullfrog Hills contain a highly extended sequence of Miocene volcanic rocks (Maldonado, 1990). The Bare Mountain–Crater Flat–Yucca Mountain system likely represents footwall damage that developed at the same time as the large Miocene displacement on the Death Valley–Furnace Creek detachment system and its consequent footwall uplift.

CONCLUSIONS

Apatite and zircon fission-track cooling ages from the Death Valley region of southern Nevada show the following. (1) There is a belt of Miocene ages and a broad region of pre-Miocene ages in the area. (2) The belt of Miocene ages corresponds to an area of large-magnitude crustal extension by normal faulting and is segmented, with an area of Miocene fission-track ages in the Bare Mountain–Funeral Mountains area and in the Black Mountains. (3) The eastern edge of Miocene fission-track ages is mapped in Bare Mountain and the Funeral Mountains and then steps eastward (to the south) to east of the Black Mountains and west of the Resting Spring Range. (4) Fission-track ages within the belt of Miocene exhumation get younger westward, suggesting progressive westward or northwestward progression of exhumation.

We interpret that early Miocene apatite ages are near the breakaway (footwall cutoff) of the regional detachment faulting and that the original crustal faults that defined the edge of the detachment system may have originally been separate normal faults linked by a transfer zone, similar to fault system architecture in the Panamint Valley–Saline Valley region today. Migration rates of the cooling front in the footwall of this system are on the order of 10–11 mm/yr. Extrapolation of apatite fission-track cooling ages from two transects across the eastern margin of the Death Valley region suggests that exhumation along the eastern margin of the system continues beneath Death Valley today. East of the footwall cutoff of this system, extensional basins, such as the Crater Flat basin, either did not experience enough extension in the last 13 m.y. to produce footwall exhumation sufficient to be recorded in cooling ages or Miocene basin filling with volcanic and alluvial material occurred too rapidly for isostatic footwall uplift to occur.

APPENDIX A—APATITE FISSION-TRACK THERMOCHRONOLOGY

The estimated closure temperature for fast-anneling, typical Ca-F-rich apatite, is estimated to be 130–146 °C for a cooling rate of 100 °C/m.y. (Ketcham et al., 1999). For slow annealing, often times Cl-rich and possibly Mn-, Fe-, and/or rare earth element (REE)—rich apatite, the closure temperature is estimated to be as high as 172 °C for a cooling rate of 100 °C/m.y. (Ketcham et al., 1999). Fast-anneling apatites are typically less soluble in the nitric acid used to reveal the tracks for observation and measurement. The mean diameter of fission-track etch pits (Dpar) on the apatite surface being studied is usually less than 2 µm for the etching conditions used in this study (e.g., Carlson et al., 1999; Donelick et al., 2005). Assuming an average surface temperature of 15 °C and a constant geothermal gradient of 30 °C/km (Ferrill et al., 1995, 1996b), a
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