Low-temperature thermochronologic constraints on the kinematic histories of the Castle Cliffs, Tule Springs, and Mormon Peak detachments, southwestern Utah and southeastern Nevada

Tandis S. Bidgoli¹, Daniel F. Stockli² and J. Douglas Walker¹
¹Department of Geology, University of Kansas, Lawrence, Kansas 66045, USA
²Jackson School of Geosciences, University of Texas, Austin, Texas 78712, USA

ABSTRACT

We use apatite and zircon (U-Th)/He thermochronometry to evaluate the timing, magnitude, and spatial pattern of Miocene strain within the Beaver Dam Mountains, Tule Springs Hills, and Mormon Mountains of southwestern Utah and southeastern Nevada (USA). The region is host to three major low-angle structures, the Castle Cliffs, Tule Springs, and Mormon Peak detachments, the origin and role of which in regional extension are vigorously debated. We analyzed 36 samples collected from Precambrian basement gneisses and Paleozoic to Jurassic siltstones and sandstones exposed in the footwalls of these detachments. Zircon He ages from the footwall of the Castle Cliffs detachment record rapid footwall exhumation ca. 18–17 Ma. At structurally higher positions, apparent ages become progressively older, defining a zircon He partial retention zone. Paleodepth reconstructions of the data using published cross sections suggest 180°C, or greater, of cooling or 6.5–8.2 km of total exhumation, yielding a maximum of ~13 km of extension across this detachment. In contrast, zircon and apatite ages from the footwall of the Mormon Peak record rapid exhumation at 14–13 Ma and 5.8–7.1 km of vertical exhumation. Using a range of restored fault dips (20°–28°) for the Mormon Peak detachment, the thermochronometry data record 10.9–19.5 km horizontal extension. Data from the Tule Springs detachment also show a similar timing of exhumation and indicate that there has been 5.0–6.8 km of vertical exhumation and a minimum of ~5 km of extension. The results demonstrate that extension initiated in the east along the Castle Cliffs detachment and migrated westward with time. Although our data indicate that existing extension estimates across this system of detachment faults are too high (40 km versus 54 km), the pattern of cooling ages and protracted cooling history recorded in these ranges is inconsistent with rootless gravity slide interpretations and low-magnitude extension models.

INTRODUCTION

The Basin and Range province of the western United States is host to some of the best examples of low-angle normal faults (LANFs) or detachment faults (e.g., Whipple detachment, Davis et al., 1980; Snake Range, Bartley and Wernicke, 1984; Sevier Desert detachment, Allmendinger et al., 1983). Although these structures are now widely recognized in continental and oceanic rift systems, there is still significant debate surrounding these faults. The controversy is in large part due to an apparent conflict between well-documented examples of LANFs that are interpreted to have originated and slipped at low dips and fault mechanical theory. According to such theory, only steep normal faults should form within the brittle part of the crust and faults that dip <30° should be frictionally locked (Anderson, 1942, 1951). Consequently, slip on LANFs can only occur by invoking some special circumstance, such as reactivation of a preexisting weakness (e.g., Morley, 2009), rotation of the stress field (e.g., Yin, 1989), and/or high pore-fluid pressures (e.g., Collettini and Barchi, 2002). The lack of convincing seismological evidence for large earthquakes on LANFs is also frequently used as an argument against their mechanical feasibility (Jackson, 1987; Jackson and White, 1989; Thatcher and Hill, 1991; Collettini and Sibson, 2001).

This controversy is typified by the geology of the Beaver Dam Mountains–Tule Springs Hills–Mormon Mountains area of southeastern Nevada and southwestern Utah, where three of the best-documented LANFs occur (Fig. 1). Detailed geologic mapping and cross-section reconstructions of the Castle Cliffs, Tule Springs, and Mormon Peak detachments convincingly show that they formed and slipped at low angles and accommodated significant extension across this portion of the province (Wernicke, 1982; Wernicke et al., 1985; Axen et al., 1990; Axen, 1993). Others, however, have questioned a rooted LANF interpretation for these structures. Carpenter and Carpenter (1994a) provided some of the earliest criticism, suggesting instead that the low-angle dislocation surfaces in these ranges form the bases to catastrophically emplaced rootless gravity slide blocks. A gravity slide interpretation was suggested by Anders et al. (2006), based on similarities between breccias found along the Mormon Peak detachment and deposits found at the bases of known gravity slide blocks (e.g., Heart Mountain; Beutner and Gerbi, 2005). Inconsistencies in the orientations of kinematic indicators measured along the Mormon Peak detachment have also been cited as evidence of mass wasting (Walker et al., 2007). These workers, alternatively, suggest that extension in these ranges is much more modest and has been accomplished by high-angle range-bounding faults that have been imaged in subsurface seismic reflection profiles (e.g., Carpenter and Carpenter, 1994a) and interpreted from geophysical anomaly maps (e.g., Blank and Kucks, 1989).

The debate over the origin of low-angle features in these ranges stems in part from uncertainties in the magnitude, timing, and spatial pattern of strain. Cross-section–based restorations by Wernicke et al. (1985) and Axen et al. (1990) suggest that these structures collectively accommodated >50 km of extension. Although extension estimates for the Mormon Peak and Tule Springs detachments are fairly well con-
strained, much of the Castle Cliffs detachment is buried beneath the Virgin River Valley, representing a significant source of uncertainty in the total extension across this system of faults. The timing of fault motion has only been loosely bracketed by crosscutting relationships between faults and the volcanic units of the Kane Springs Wash caldera (ca. 17.4–13.5 Ma; Scott et al., 1995; Wernicke et al., 1985; Axen et al., 1990; Axen, 1993; Walker, 2008). Thermochronology data are also lacking in the region. The exception is the Beaver Dam Mountains, where fission track studies have provided some constraint on the exhumation history of the range (O’Sullivan et al., 1994; Stockli, 1999). Thermochronology determines ages that can be linked to specific temperatures and thus can be used to reconstruct the time-temperature history of a mountain range (e.g., Foster and John, 1999). When integrated with structural and stratigraphic data, these methods can provide information about a diverse range of tectonic and geomorphic processes (e.g., timing, magnitude, and rate of faulting; geothermal gradients; degree of tilting or rotation of crustal blocks; magnitude and rate of erosion; see summaries in Ehlers, 2005; Spotila, 2005; Stockli, 2005).

In this paper we present new zircon and apatite (U-Th)/He thermochronologic data that better constrain the deformational histories of the Castle Cliffs, Tule Springs, and Mormon Peak detachments. Paleodepth reconstructions of the (U-Th)/He data, using published cross sections,
are evaluated to test competing models for the development of these low-angle structures and exhumation in the area. The results provide new constraints on the timing of fault initiation and the magnitude of extension. Our results suggest that earlier extension estimates may be too high; however, a gravity slide origin for low-angle structures in these ranges is inconsistent with the pattern of cooling ages and the protracted cooling history evident in the data.

GEOLOGIC BACKGROUND

The Beaver Dam Mountains, Tule Springs Hills, and Mormon Mountains are located within the eastern part of the central Basin and Range province (sensu Wernicke, 1992; Figs. 1 and 2), in a region that has undergone both Mesozoic contraction and Cenozoic extension (Tschanz and Pampeyan, 1970; Wernicke et al., 1985; Hintze, 1986; Axen et al., 1990; Axen, 1993). Mesozoic contractional structures are part of the dominantly east-directed Sevier orogenic belt (Armstrong, 1968), a northeast-trending décollement-style thrust system, active between the mid-Cretaceous and early Tertiary (Longwell, 1949; Fleck, 1970; Bohannon, 1983; Carpenter, 1989; Axen et al., 1990; Carpenter and Carpenter, 1994b). The principal thrust belt structure is the Mormon–Tule Springs thrust, which has a well-characterized flat-ramp-flat geometry (Wernicke et al., 1985; Axen et al., 1990; Axen, 1993) (Fig. 2). This fault and its associated folds place important constraints on Miocene reconstructions (Wernicke et al., 1985; Axen et al., 1990; Axen, 1993).

Mesozoic contractual structures in the region are overprinted by low-angle and high-angle normal faults that formed during two major pulses of extension: one in the early to middle Miocene (Anderson and Barnhard, 1993a, 1993b). The kinematics and timing of these faults are not well known; however, cross-cutting relationships with detachment faults and detachment-related structures, as well as with Pliocene (Axen, 1993). High-angle range-bounding faults have also been identified on the west side of the Mormon Mountains and Beaver Dam Mountains in seismic reflection profiles (e.g., Carpenter and Carpenter, 1994a) and gravity and magnetic anomaly maps (e.g., Blank and Kucks, 1989) (Fig. 2). The timing of these structures is not known, but they also probably postdate detachment faulting.

Castle Cliffs Detachment

The Castle Cliffs detachment (CCD), exposed in the Beaver Dam Mountains, is the easternmost detachment within the Las Vegas system (Figs. 1 and 2). The fault forms the eastern edge of Basin and Range province, separating a region of moderately to highly extended crust on the west from the stable and relatively undeformed Colorado Plateau on the east (Fig. 1). Where exposed, the detachment dips 10°–20° westward, but geometric reconstructions suggest that the fault had an initial dip of 32° (Wernicke and Axen, 1988; Axen et al., 1990; Axen, 1993). The present low dip of the fault reflects a combination of detachment-related tilting or unloading (Wernicke and Axen, 1988; Axen et al., 1990; Axen, 1993) and possible tilting related to an inferred range-front fault (Hintze, 1986; Blank and Kucks, 1989).

The footwall of the CCD contains the so-called Beaver Dam anticline, a large-scale monocline that exposes Precambrian basement gneisses and Paleozoic through Mesozoic carbonate and clastic strata (Fig. 3). The fold was interpreted by Wernicke and Axen (1988) to have formed by flexural unloading of the footwall of the detachment during Miocene slip. The fold has also been interpreted as a Laramide-age, basement-involved contractual structure (Hintze, 1986; Carpenter and Carpenter, 1994a; Christie-Blick et al., 2007); however, tilted mid-Tertiary strata on the east flank of the monocline (Wernicke and Axen, 1988; Axen and Wernicke, 1989; Axen, 2004) and published fission track ages (O’Sullivan et al., 1994; Stockli, 1999) from the footwall of the detachment support fold formation during the Miocene.

The hanging wall of the CCD consists of Paleozoic carbonates, principally Mississippian Redwall Limestone and Pennsylvania Callville Limestone, preserved as klippen on Precambrian basement rocks. These klippen were initially thought to be remnants of the hanging wall of the Castle Cliffs thrust (Dobbins, 1939), which is now interpreted to be a normal fault based on the younger-over-older relationship between geologic units (Wernicke and Axen, 1988; Axen, 2004). These klippen were also interpreted by Cook (1960) and Christie-Blick et al. (2007) as gravity slide blocks. Part of the difficulty in finding a satisfactory interpretation for the klippe is that similar blocks of Paleozoic strata are found in contact with Tertiary conglomerate at the Beaver Dam range front (Cook, 1960; Hintze, 1986). However, these known landslide deposits and underlying sediment were interpreted by Axen (2004) to have formed above the CCD, and thus record Neogene motion on the detachment.

Tule Springs Detachment

The Tule Springs detachment (TSD), exposed in the Tule Springs Hills, is the middle of the three detachments within the study area (Fig. 2). The detachment is one of the earliest documented examples of a LANF that originated and slipped at low dips, and one of the best examples of a LANF with a ramp-flat geometry. The description below follows Axen (1993).

Exposures of the TSD are currently subhorizontal, but geometric reconstructions show that the detachment ramp began with a moderate west dip and that the detachment flat reactivated a portion of the former Tule Springs thrust. Structural arguments indicate that this part of the fault initiated with a 3°–15° dip to the west.

The footwall of the TSD is folded into a large-scale asymmetric syncline called the Abe-Steer Flat syncline. At the surface, the east limb of the syncline is made up of subhorizontal Jurassic Kayenta Formation, whereas the west limb comprises east-tilted Triassic and younger stratigraphic units. Like the Beaver Dam anticline, the Abe-Steer Flat syncline is also interpreted to have formed by flexural unloading of the footwall of the detachment during Miocene slip. The hanging wall of the TSD is made up of klippen of middle Cambrian to Carboniferous carbonates and minor Tertiary strata. These klippen are cut by closely spaced, low- and high-angle normal faults with as much as 3 km of stratigraphic throw. Most of these faults are interpreted to be synkinematic upper plate faults of the TSD because they either terminate at or merge with the detachment. Crosscutting relationships between these faults and poorly dated Tertiary volcanic and sedimentary units suggest that the TSD was active from the middle to late Miocene. Pliocene (?) calcrites deposited on
Figure 2. Simplified geologic map of the study area showing the locations of the Castle Cliffs, Tule Springs, and Mormon Peak detachments. Red dots correspond to the locations of our thermochronology samples. Geology simplified from compilation by Felger and Beard (2010).
He is epilepsy by alpha translocation currently dip 5°–10° and form a broad enclines and small-scale groove and mullion structures, are common along the detachment, although the movement direction determined by them locally contrasts with the west-southwest extension direction determined by Wernicke et al. (1988; see Walker et al., 2007). Above the detachment is a thick (2–3 m) carbonate gouge and breccia. Anders et al. (2006) documented a number of similarities between the breccia and deposits found at the base of known gravity slide blocks, providing the strongest evidence in support of a gravity slide interpretation for the MPD. However, the origin and significance of these deposits need additional investigation.

**Mormon Peak Detachment**

The Mormon Peak detachment (MPD) is the westernmost detachment within the study area (Fig. 2), and perhaps the most controversial of structures in the region. Exposures of the detachment currently dip 5°–10° and form a broad dome over the Mormon Mountains; however, the detachment is interpreted to have initiated with a dip of 20°–28° westward (Wernicke et al., 1985; Axen, 2004). This range in initial dip was determined by reconstructing the cut-off angle between the fault and lower plate stratigraphy (17°–20°) and by allowing for some modest westward tilting (3°–8°) beneath the load of the preextensional fold-thrust belt (Wernicke et al., 1985; Axen, 2004). The restored dip is also supported by hanging-wall reconstructions of the fold-thrust structure, between the Mormon Mountains and the Meadow Valley Mountains to the west, relative to the detachment footwall (Wernicke et al., 1985; Axen et al., 1990; Axen, 1993). The hanging wall of the MPD is made up of erosional remnants of Paleozoic and Tertiary strata that are extensively faulted and brecciated. These remnants are bounded at their base by the detachment, which is a sharp and planar structure. Kinematic indicators, including slick-enlines and small-scale groove and mullion structures, are common along the detachment.

**Figure 3. Summary of Paleozoic through Mesozoic stratigraphy for the study area.**

| Symbol | Age   | Lithology       | Name                    | Thickness (m) |
|--------|-------|-----------------|-------------------------|---------------|
| Mz     | Jurassic | Navajo Sandstone | 610–760                 |               |
|        |        | Kayenta Formation | 655                    |               |
|        |        | Moenave Formation | 60                     |               |
|        | Triassic | Chinle Formation | 275–325                 |               |
|        |        | Moenkopi Formation | 535–705                |               |
| P      | Permian | Kaibab Formation | 100–200                 |               |
|        |        | Toroweap Formation | 120–260                |               |
|        |        | Queantoweap Sandstone | 460–610               |               |
|        |        | Pakoon Dolomite  | 215–275                 |               |
|        |        | Calville Limestone | 460–610                |               |
|        | Mississippian | Redwall Limestone | 260–280                 |               |
|        |        | Muddy Peak Dolomite | 210–215               |               |
|        | Devonian | Pogonip Group | 265                     |               |
|        | Ordovician | Nopah Formation | 100–400                 |               |
|        | Cambrian | Bonanza King Formation | 760–770             |               |
|        |        | Bright Angel Shale | 75–140                 |               |
|        |        | Tapeats Sandstone | 145–365                 |               |
|        | Precambrian | Basement (gneiss, schist, pegmatite) | 460–610         |               |

(U-Th)/He THERMOCRONOMETRY

(U-Th)/He thermochronometry is a powerful dating technique that is increasingly being applied to extensional settings. It is one of the few methods that can expressively date the exhumation and cooling of a footwall of a major normal fault in the upper crust (e.g., Axen et al., 2000; Stockli et al., 2000; Ehlers et al., 2003; Armstrong et al., 2004). These types of data can also be used to estimate geothermal gradients within the crust prior to and during extension (e.g., Fitzgerald and Gleadow, 1990; Howard and Foster, 1996; Miller et al., 1999; Stockli et al., 2002). The (U-Th)/He method is based on the decay of 235U, 238U, 232Th, and 147Sm by alpha (He nucleus) emission. However, He retention in minerals is temperature dependent and controlled principally by mineralogy; grain size (e.g., Farley, 2000; Reiners and Farley, 2001), cooling rate (e.g., Dodson, 1973), and damage to the crystal lattice (e.g., Shuster et al., 2006) also play important roles.

Apatite is one of the most commonly used (U-Th)/He thermochronometers, in part because it records cooling at low temperatures: He is completely lost by thermally activated volume diffusion above ~80 °C and mostly retained below ~40 °C (Wolf et al., 1996, 1998; House et al., 2002). The (U-Th)/He method is based on the decay of 235U, 238U, 232Th, and 147Sm by alpha (He nucleus) emission. However, He retention in minerals is temperature dependent and controlled principally by mineralogy; grain size (e.g., Farley, 2000; Reiners and Farley, 2001), cooling rate (e.g., Dodson, 1973), and damage to the crystal lattice (e.g., Shuster et al., 2006) also play important roles.

(After Bidgoli et al., 2015, Geosphere, June 2015)
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et al., 1999; Stockli et al., 2000). These temperatures define thermal sensitivity windows or partial retention zones (PRZs; Wolf et al., 1998) that can be used to reconstruct temperature-time histories or apparent age-paleodepth/elevation trends (summary in Stockli, 2005).

Zircon is also widely used as a (U-Th)/He thermochronometer in extensional settings (e.g., Reiners et al., 2000, 2002; Lee et al., 2009). Zircon retains helium over a higher temperature range, from ~130 °C to as high as ~200 °C (Reiners et al., 2002, 2004; Wolfe and Stockli, 2010), but the zircon helium PRZ is not as well determined because diffusion kinetics in zircon are complicated by a number of factors, the most significant being the impact of radiation damage on He diffusion and (U-Th)/He ages. Several studies have shown that zircon (U-Th)/He ages can be considerably affected by radiation damage to the crystal lattice (e.g., Hurley, 1952; Reiners et al., 2002, 2004; Nasdala et al., 2004; Reich et al., 2007). The damage is mainly produced by recoil of heavy isotopes during alpha emission, but spontaneous fission events and ejected \(^{4}\)He nuclei also contribute to the total lattice damage. Radiation damage to grains is generally recognized by a strong correlation (positive or negative; Guenther et al., 2013) between (U-Th)/He ages and both He concentration [He] and effective U concentration [Ue]. The [Ue] is calculated as [U] + 0.235 [Th] + 0.005 [Sm], which is concentration of U, Th, and Sm within the grain weighted for each isotopes productivity. A positive correlation between dates and [Ue] typically develops at low levels of radiation damage, suggesting a decrease in He diffusivity or trap-like behavior, similar to radiation-damaged apatite (Guenther et al., 2013; Shuster et al., 2006; Flowers et al., 2009). Conversely, a negative correlation between dates and [Ue] typically develops as higher levels of radiation damage, as damage zones become interconnected, forming fast networks or pathways for He diffusion within the grain (Nasdala et al., 2004; Reiners, 2005; Guenther et al., 2013).

Sample Collection

We collected 49 samples from the study area; however, only 36 samples (Fig. 2) yielded usable apatite and zircon. Samples from the Beaver Dam Mountains and Mormon Mountains were collected previously (Stockli, 1999); samples from the Tule Springs Hills were collected during the course of this study. Where possible, we collected samples systematically, in horizontal transects, parallel to the known extensional fault slip direction (west-southwest; Wernicke et al., 1985; Axen et al., 1990). Although our sample transects are tightly spaced (~500 m) and cover the exposed range of structural depths in the footwalls of the detachments, sample gaps occur where we cross Paleozoic carbonate rock. This was particularly problematic for the Mormon Mountains, where much of the exposed rock is carbonate.

Analytical Procedures

We used standard mineral separation techniques to isolate and concentrate apatite and zircon from our rock samples. From our separates, individual grains were inspected, measured, and photographed using a 180x Nikon stereo microscope with crossed polarizers and mounted digital camera. When possible, we selected nearly euhedral grains, >70 µm in width, that appeared inclusion free. These guidelines increase the accuracy and reproducibility of (U-Th)/He ages by minimizing the effects of (1) U- and Th-bearing inclusions that may incompletely dissolve, producing parentless He and anomalously older apatite He ages (House et al., 1999; Farley and Stockli, 2002), and (2) the alpha-ejection (Ft) correction, a standard morphometric age correction that accounts for the loss of alpha particles near the edge of a grain (Farley et al., 1996). Each single grain was then loaded into a 1 mm platinum packet and heated using a continuous-mode laser. Apatite grains were heated for 5 min at 1070 °C; zircon grains were heated for 10 min at 1300 °C. The extracted He gas was spiked with \(^{3}\)He, purified using a gettering and cryogenic 

Paleodepth Reconstructions

In order to properly evaluate the thermal structure of the crust within the study area, it is necessary to restore our thermochronology samples to their preextensional paleodepths. In this study, we restore samples using cross sections of Axen et al. (1990). Alternative interpretations for the structures in the region have been suggested (e.g., Anderson and Barnhard, 1993a; Carpenter and Carpenter, 1994a; Anders et al., 2006; Walker et al., 2007); however, Axen et al. (1990) contains the only set of balanced cross sections across these specific ranges and is the most widely accepted interpretation.

These cross sections and, consequently, our paleodepth reconstructions make several assumptions about the preextensional thrust belt structure; the most important is that Paleozoic through Mesozoic strata in the footwall of the detachments were roughly horizontal prior to extension. This assumption is supported by the fact that the strata are part of the thrust autocline, in the frontal portion of the Mesozoic Sevier thrust belt, and are therefore unlikely to have been significantly deformed prior to extension, although some modest westward tilting is expected (~3°–8°; for detailed discussions, see Wernicke et al., 1985; Axen et al., 1990). This interpretation is also supported by the fact that there is little angular discordance (<5°) between Oligocene–Miocene strata and the footwall stratigraphy of the thrust (Wernicke et al., 1985; Wernicke and Axen, 1989; Axen et al., 1990).

For the Beaver Dam Mountain transect, we use the nonconformity between the Precambrian basement and Cambrian sedimentary rocks as our paleohorizontal datum, although

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1Supplemental File. Supplemental Table 1 (Zircon (U-Th)/He data) and Supplemental Table 2 (Apatite (U-Th)/He data). The data are also available through www.geochron.org at http://dx.doi.org/10.1594/IEDA/100520. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GE01083.1 or the full-text article on www.gsapubs.org to view the Supplemental File.
TABLE 1. ZIRCON AND APATITE (U-Th)/He DATA

| Sample                          | Latitude (°N) | Longitude (°E) | Mass (ppm) | Effective U Concentration | Replicates |
|---------------------------------|---------------|----------------|------------|---------------------------|------------|
| Beaver Dam Mountains zircon data | 37.084900     | 113.911868     | 1250       | 5.88                      | 3          |
| 95BR104                         | 37.086105     | 113.908644     | 1300       | 5.59                      | 3          |
| 95BR104                         | 37.084152     | 113.903273     | 1330       | 3.58                      | 3          |
| 95BR105                         | 37.090440     | 113.896418     | 1450       | 4.18                      | 3          |
| 95BR106                         | 37.089592     | 113.893245     | 1420       | 4.27                      | 3          |
| 95BR109                         | 37.084821     | 113.886668     | 1340       | 6.27                      | 3          |
| 95BR110                         | 37.086551     | 113.881132     | 1335       | 4.19                      | 3          |
| 95BR111                         | 37.089775     | 113.875986     | 1140       | 4.25                      | 3          |
| 95BR112                         | 37.087679     | 113.870691     | 1335       | 5.37                      | 3          |
| 95BR113                         | 37.086700     | 113.867590     | 1405       | 4.40                      | 3          |
| 95BR115                         | 37.094251     | 113.853044     | 1400       | 5.26                      | 3          |
| 95BR119                         | 37.131019     | 113.811933     | 1315       | 8.93                      | 3          |
| 95BR120                         | 37.134219     | 113.817980     | 1320       | 3.21                      | 3          |
| 95BR124                         | 37.244919     | 113.778249     | 1025       | 6.80                      | 3          |
| Tule Springs Hills zircon data  | 37.019740     | 114.211914     | 1065       | 3.74                      | 3          |
| 1TTS01                          | 37.022479     | 113.240961     | 1040       | 10.33                     | 3          |
| 1TTS04                          | 37.065468     | 113.252700     | 980        | 5.41                      | 3          |
| 1TTS06                          | 37.057649     | 113.268647     | 1005       | 7.44                      | 3          |
| 1TTS08                          | 37.055451     | 113.258261     | 975        | 8.25                      | 3          |
| 1TTS09                          | 37.058329     | 113.224719     | 1040       | 2.35                      | 3          |
| 1TTS03                          | 37.072333     | 113.239118     | 1060       | 1.64                      | 3          |
| 1TTS06                          | 37.036999     | 113.252700     | 980        | 1.26                      | 3          |
| 1TTS07                          | 37.036999     | 113.237554     | 1060       | 0.39                      | 3          |
| 1TTS09                          | 37.055451     | 113.258261     | 975        | 0.30                      | 3          |
| Mormon Mountains zircon data    | 36.915615     | 114.277625     | 930        | 2.73                      | 3          |
| 96BR003                         | 36.949433     | 114.286667     | 945        | 5.03                      | 3          |
| 96BR006                         | 36.970822     | 114.299497     | 935        | 4.48                      | 3          |
| 96BR008                         | 36.938966     | 114.293648     | 1030       | 3.93                      | 3          |
| 96BR009                         | 36.923159     | 114.454233     | 1700       | 4.35                      | 3          |
| 96BR102                         | 36.920278     | 114.451065     | 1660       | 3.58                      | 3          |
| 96BR111                         | 36.917119     | 114.439676     | 1540       | 8.30                      | 3          |
| 96BR102                         | 36.917132     | 114.544837     | 1290       | 4.93                      | 3          |
| 96BR104                         | 36.973663     | 114.555490     | 1170       | 3.68                      | 3          |
| 96BR106                         | 36.975915     | 114.563448     | 1110       | 4.49                      | 3          |
| Mormon Mountains apatite data   | 36.946503     | 114.283040     | 915        | 1.91                      | 3          |
| 96BR004                         | 36.949433     | 114.286667     | 945        | 1.29                      | 3          |
| 96BR006                         | 36.970822     | 114.299497     | 935        | 0.24                      | 3          |
| 96BR009                         | 36.923159     | 114.454233     | 1700       | 1.78                      | 3          |
| 96BR102                         | 36.920278     | 114.451065     | 1660       | 0.72                      | 3          |
| 96BR113                         | 36.972881     | 114.555490     | 1170       | 1.30                      | 3          |
| 96BR104                         | 36.973663     | 114.555490     | 1170       | 0.90                      | 3          |

**Note:** Individual aliquot analyses are given in the Supplemental File (see text footnote 1). [U]e—effective U concentration. St. dev.—standard deviation.

*Ft is the alpha ejection correction of Farley et al. (1996).
any of the Paleozoic unit boundaries could have been selected because the stratigraphic thickness of these intervals does not change by any significant degree over the study area. All other samples are referenced relative to the sub-Tertiary unconformity, a regional marker that is important for restoring cross sections and for determining paleotopographic patterns in the area. The sub-Tertiary unconformity was chosen because there is a small degree of westward tilting (5°) to the fold-thrust structure and the nonconformity above the Precambrian basement across the Tule Springs Hills and Mormon Mountains (Wernicke et al., 1985; Axen et al., 1990; Axen, 1993).

These paleohorizontal references were selected because there are only limited exposures of Tertiary strata within the study area, making overburden and true paleodepth estimates difficult. Because we rely on published cross sections to restore samples to their preextensional configuration, it is difficult for us to quantify our paleodepth uncertainties. A steeper tilt to the fold-thrust structure across the study area would shift the positions of our samples downward, particularly for areas west of the Beaver Dam Mountains (the Beaver Dam Mountains are unlikely to be affected because they are located at the very frontal portion of the thrust belt where tilt is expected to be low). For the Tule Springs Hills and East Mormon Mountains a steeper tilt (to 8°) could amount to a shift of ~1.5 km; for the western Mormon Mountains, the steeper tilt could result in a shift of >2 km. Although these shifts are large, the relative positions of our samples and reconstructed isotherms are unlikely to be significantly changed.

Geothermal Gradient Estimates

To estimate preextensional geothermal gradients, we follow Stockli et al. (2002) and use the difference in temperature and depth between paleoisotherms that bound our apatite and zircon He PRZs and the apatite fission-track partial annealing zone from Stockli (1999). The positions of these paleoisotherms are defined by inflection points in the age versus paleodepth profiles. For our calculations, we assume 40 °C and 80 °C for the apatite He PRZ, 130 °C and 190 °C for the zircon He PRZ, and 60 °C and 110 °C for the apatite fission track partial annealing zone. Although these temperatures are approximately known from both laboratory step-heating experiments and borehole studies, uncertainties associated with grain size, cooling rate, and radiation damage can add significant uncertainty to these estimates (House et al., 1999; Farley, 2001; Farley et al., 2002; Reiners et al., 2004; Wolfe and Stockli, 2010). Therefore, geothermal gradient estimates using this approach should be taken with some caution and evaluated, where possible, for consistency between different pairs of isotherms and across a region.

THERMOCRONOLOGY RESULTS

Table 1 shows our resulting (U-Th)/He mean ages and associated errors (1σ). For most samples (N = 38), 3 or more replicates were used to calculate the mean; however, 6 of the 44 reported ages were calculated using fewer than 3 replicates. These samples contained single-grain analyses that were excluded from our calculated mean ages. For apatite, outliers were determined as dates that were >2 standard deviations from the mean. Analyses with a large number of reextractions during laser He degassing were also excluded from the determined means, as this can indicate that there are unseen mineral or fluid inclusions within the grain (House et al., 1999). Of the 40 single-grain apatite analyses completed, 9 (~22%) were excluded (see the Supplemental File [see footnote 1]).

Although most of our mean ages were calculated with an appropriate number of replicates, many of the reported standard deviations in Table 1 are large (>20%) and show that there is a wide spread of dates captured by our mean (U-Th)/He ages, particularly for zircon. Upon closer inspection, it appears that individual zircon dates for most of our samples are negatively correlated with both [He] and [U]e, a strong indication that radiation damage is a likely factor (Fig. 4; Reiners et al., 2002, 2004; Nasdala et al., 2004; Reich et al., 2007; Guenther et al., 2013). The data also reveal that there is a wide range in [U]e for our samples, from <50 ppm to >1600 ppm (Table 1). Thus, the outlier analysis approach we used for apatite could not be applied to the radiation-damaged zircon. Of the 148 single-grain zircon analyses, 8 (5%) were excluded. Excluded analyses had zircon (U-Th)/He dates that were younger than the apatite (U-Th)/He age for the same sample. Radiation damage and its effects on our zircon (U-Th)/He dates and interpretations are discussed in more detail herein.

Beaver Dam Mountains

Zircon (U-Th)/He Data

Cross-section B–B’ (Fig. 5) is oriented west-southwest and shows the geometry of the Beaver Dam monoclone and the projected positions of our thermochronology samples. We analyzed 16 samples from the footwall of the CCD. The samples were collected from a large portion of the footwall section, including Precambrian gneiss and granite, Cambrian sandstone (Tapeats Sandstone), and Permian through Jurassic sandstone and conglomerate (Quaintowep Sandstone; Chinle and Kayenta Formations; and Navajo Sandstone; Figs. 2–4). A sample gap occurs where our transect crosses Cambrian through Mississippian miogeoclinal carbonates (Figs. 2–4). Reported zircon He ages range from as old as 650 ± 350 Ma to as young as 171 ± 1.9 Ma, but no systematic relationship between cooling age and elevation is observed in the data (Table 1; Fig. 5). The youngest mean ages, with the exception of sample 95BR111, are located in the very western part of the transect, collected just east of the detachment, clustering near 18 Ma (Figs. 2 and 4). The samples increase in apparent age eastward, and the eastern half of the transect contains the oldest apparent ages, with ages older than 200 Ma (Table 1; Fig. 5).

Paleodepth Reconstruction and Interpretations

To evaluate the samples further, we restored samples to their preextensional paleodepths (Fig. 6). Depths in Figure 6 are referenced to a datum at the basal nonconformity, not the interpreted depth. The paleodepth reconstruction reveals that, although the samples were collected from within a few hundred meters of elevation (1035–1450 m), they capture an ~7-km-thick crustal section. The structurally lowest and deepest samples (95BR102, 95BR103, and 95BR104) are invariant near 18–17 Ma, recording rapid exhumation at that time. These ages overlap (within error) with apatite fission track ages (in Stockli, 1999) analyzed from the same samples (Fig. 6). At structurally shallower depths, the samples form a broad grouping, with mean ages ranging from ca. 75 to 18 Ma (Fig. 6). These samples appear to define a zircon He PRZ. Ages dramatically increase above the PRZ (above sample 95BR115); mean ages for these samples are, in most cases, older than the depositional ages of the units, suggesting that they have not been thermally reset (Table 1; Fig. 6).

The thermochronology data can also be used to evaluate the Miocene preextensional geothermal gradient. This is accomplished by using the relative positions of the top (~130 °C) and base (~190 °C) of the zircon He PRZ in our paleodepth reconstruction (Fig. 7). The position of 130 °C isotherm is constrained between 0.35 and 0.20 km by samples 95BR115 (shallowest Tertiary age) and 95BR116 (deepest Paleozoic age; Fig. 7). Using a similar approach, the position of the 190 °C isotherm is constrained between ~2.1 and ~1.6 km below the nonconformity (Fig. 7). The vertical difference between these isotherms is 1.9–2.4 km, resulting in a preextensional geothermal gradient of
Alternatively, we can calculate the geothermal gradient by using the difference between the base of apatite fission track partial annealing zone (~110 °C; from Stockli, 1999) and the base of our zircon He PRZ (~190 °C) (Fig. 7). Although the base of the zircon He PRZ is fairly well constrained, the base of the apatite fission track partial annealing zone is uncertain where our traverse crosses middle Cambrian to lower Permian carbonates (Fig. 7). Factoring uncertainties, the difference between these isotherms ranges from as little as 1.9 km to as high as 4.9 km, resulting in a geothermal gradient of $28 \pm 3 \, ^\circ\text{C/km}$ (Fig. 7).

**Mormon Mountains and Tule Springs Hills**

**Zircon and Apatite (U-Th)/He Data**

We analyzed 7 samples from the footwall of the MPD, collected from exposures of Precambrian gneiss and Cambrian Tapeats Sandstone in the western and central Mormon Mountains (Fig. 2). Zircon (U-Th)/He ages are shown in cross-section C–C’ (Fig. 8), ranging from 85 ± 150 to 13.4 ± 1.0 Ma. In the western part of the range, zircon ages systematically increase to the east, from 14.3 ± 2.1 Ma to 24.7 ± 10.9 Ma. A similar pattern is present in the central Mormon Mountains where two samples cluster at 14–13 Ma. The next sample to the east, however, increases in apparent age to 84 ± 78 Ma. The cross section also shows that a similar eastward increase in apparent ages occurs in the footwall of the TSD. In contrast, apatite (U-Th)/He ages from the MPD footwall range from 13.7 ± 2.2 to 7.6 ± 2.5 Ma.

Cross section D–D’ (Fig. 9) is a deformed state cross section across the Mormon Mountains and Tule Springs Hills, showing the projected positions of 13 samples collected from the footwall of the TSD. Samples from the East Mormon Mountains were collected from Precambrian gneiss and Cambrian Tapeats Sandstone (Fig. 2). Samples from the Tule Springs Hills were collected from sandstones and siltstones of the Jurassic Kayenta Formation (Fig. 2). Zircon (U-Th)/He mean ages range from 348 ± 172 to 21.6 ± 1.0 Ma (Fig. 9). No systematic relationship between apparent age and elevation is evident in the data (samples are collected from within 150 m in elevation; Table 1; Fig. 9). Instead, the youngest cooling ages occur in the western part of the transect, within the East Mormon Mountains, and the oldest cooling ages occur to the east, across the Tule Springs Hills (Fig. 9). Apatite (U-Th)/He ages from the same transect range from 27.6 ± 6.2 to 13.4 ± 0.8 Ma (Fig. 9). The youngest apatite cooling ages occur in the western part of the transect, clustering near 14–13 Ma; ages are progressively older to the east (Fig. 9).

Three of the Tule Springs Hills zircon ages (11TS04, 11TS06, and 11TS09) shown in Table 1 have been excluded from the cross section and our paleodepth reconstruction. These samples have very young dates (younger than our apatite He dates) and very high [U]e when compared with other samples from the transect and study area (Table 1). We believe that these grains may have leaked He at relatively low temperatures and therefore may not reflect the cooling history of the TSD. Alternatively, the samples may have undergone localized hydrothermal resetting, but given the relationship between dates and [U]e, we think that scenario is unlikely.

![Figure 4.](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/11/3/850/3338037/850.pdf)
Low-temperature thermochronologic constraints

Paleodepth Reconstructions and Interpretations

Paleodepth reconstruction of the footwall of the MPD reveals that the preextensional depths of our samples are within a narrow range, spanning ~2 km. Figure 8 shows that most of our apatite ages and the structurally deepest zircon sample have similar cooling ages, ca. 14–13 Ma. This implies that these samples cooled through both the zircon He PRZ and apatite He PRZ, indicative of rapid exhumation at that time. Zircon cooling ages systematically increase at shallower depths, a pattern consistent with residence in a PRZ prior to the mid-Miocene. The base of the zircon He PRZ (~190 °C) is well constrained between our shallowest partially reset sample (96BR014) and our deepest 14–13 Ma sample (96BR016); however, the top of the PRZ is uncertain in this reconstruction (Fig. 8).

The restored positions of the samples in cross-section D–D’ are shown in Figure 9. The paleodepth reconstruction reveals that samples from the TSD footwall span ~5 km of preextensional crust. Zircon (U-Th)/He ages form two groups: a broad cluster of dominantly Tertiary ages between 5.5 and 6.2 km, and a broad cluster of Jurassic and older ages between 2.0 and 2.4 km (Figs. 8 and 9; depths in this case are relative to the basal Tertiary unconformity). The deeper cluster shows a fairly systematic increase in apparent age with depth, characteristic of a PRZ. However, the positions of the top and base of the zircon He PRZ are uncertain. The shallower cluster has zircon ages that are either close to or older than the depositional age of the sampled unit. These samples probably resided above the zircon He PRZ and are not thermally reset. Apatite (U-Th)/He ages also form two groups (Figs. 8 and 9). The first includes a group of invariant samples at 14–13 Ma. The second group shows a somewhat orderly increase in apparent age with shallowing depth, suggestive of an apatite He PRZ, although its geometry is uncertain. Our best estimate is that the base of this zone resides between samples 11TS09, our shallowest partially reset sample, and 11TS07, the age of which overlaps with 14–13 Ma samples that record the timing of exhumation.

Paleodepth reconstructions of our data from Mormon Mountains, East Mormon Mountains, and Tule Springs Hills indicate that the footwalls of the MPD and TSD underwent rapid cooling at the same time (ca. 14–13 Ma). The close proximity of these faults and the similarity in their cooling histories indicates that the preextensional thermal structure across the region was relatively smooth. Figure 10A shows the combined data set and the approximate position of the zircon He PRZ. Figure 10B shows the same data rescaled to show the interpreted shape and position of the apatite He PRZ. The combined paleodepth reconstruction can be used to evaluate the Miocene preextensional geothermal gradient. To do this, we use the relative positions of the base of the apatite He PRZ (~80 °C) and the base of the zircon He PRZ (~190 °C) (Fig. 10B). The vertical difference between these isotherms is 3.6–4.8 km, which yields a preextensional geothermal gradient of 27 ± 4 °C/km (Fig. 10B).

DISCUSSION

Radiation Damage Effects

The strong correlation between our (U-Th)/He dates and the [U]e suggests that radiation damage effects may be modifying the diffusive behavior of He within our grains and closure temperatures, raising a question about the reliability of our zircon data and paleodepth interpretations. However, several factors make us believe that the
data are still reliable despite obvious radiation damage effects. In the Beaver Dam Mountains, the timing of exhumation from our (U-Th)/He ages is within error of apatite fission track data (from Stockli, 1999) on these same samples, and compatible with the timing of exhumation regionally (e.g., Fitzgerald et al., 1991, 2003, 2009; Reiners et al., 2000, 2002; Bernet et al., 2002; Reiners, 2005; Quigley et al., 2010). The youngest ages are also consistently between 18 and 17 Ma. If grains were sufficiently leaky at ambient temperatures, we might expect an age reversal, with (U-Th)/He ages being younger than the published fission track ages. Similar observations can be made in the Mormon Mountains and Tule Springs Hills, where most of our zircon (U-Th)/He ages are the same (within error) as the apatite (U-Th)/He ages. The exceptions are 11TS04, 11TS06, and 11TS09 (Table 1), which were excluded from our palaeodepth reconstructions because they had younger cooling dates than apatite grains analyzed from the same samples and very high [U].

The geothermal gradients calculated from our thermochronology data also seem to suggest that radiation damage effects are at a minimum. The geothermal gradients determined from our data are reasonable (23–31 °C), invariable across the study area, and similar to the average continental geothermal gradient (~25 °C) and published geothermal gradients from the region (e.g., Reiners et al., 2002; Fitzgerald et al., 1991, 2009; Karlstrom et al., 2010). This implies that the temperatures at the top and base of zircon He PRZ may close to their expected values.

Figure 11 illustrates the overall shape of the zircon He PRZ using our data from the Beaver Dam Mountains. The size of each He date symbol is scaled to the [U], and the approximate shape of the PRZ is shown at high (>600 ppm) and low (<200 ppm) [U]. In general, the PRZs are sigmoidal in shape, similar to what would be expected for a typical zircon without significant radiation damage (e.g., Fish Canyon Tuff). However, at high [U] the PRZ is steep and abruptly flattens towards the ~130 °C isotherm. The shape of this PRZ, particularly its steepness, shows that zircon (U-Th)/He dates are younger over a wide range of temperatures. The PRZ shape also shows that dates are younger at lower temperatures, consistent with a reduction in He retentivity in radiation-damaged zircon. In contrast, the shape of the low [U]e PRZ appears relatively flat at higher temperatures, where zircon (U-Th)/He dates are older, suggesting that undamaged zircons or those with lower levels of radiation damage have higher retention of He.

Our results seem to suggest that, although there are clear radiation damage effects on our zircon cooling ages, the data can still be interpreted in a robust way. This may be explained by the fact that our data capture a wide range of [U], minimizing uncertainties in the positions of paleoisotherms at the top and base of the PRZ. However, a more quantitative study of radiation damage and its impact on He diffusivity in our samples is required to properly evaluate this claim (e.g., Nadasa et al., 2004, 2011; Shuster et al., 2006; Guenthner et al., 2013).

**Temporal and Spatial Patterns**

The new thermochronology data allow us to place constraints on the timing and spatial pattern of strain across the study area. The structurally lowest (deepest) zircon (U-Th)/He ages from the footwall of the CCD are invariant at 18–17 Ma and overlap (within error) with apatite fission track ages in Stockli (1999). This implies that samples rapidly cooled from below the zircon He PRZ and to above the apatite fission track partial annealing zone at that time. Thus, we interpret the onset of rapid cooling and exhumation ca. 17 Ma as marking the timing of initiation of the CCD.

The timing of initiation for the CCD is similar to that of other structures that are along the western margin of the Colorado Plateau. Thermochronology studies of the Virgin Mountain anticline (Quigley et al., 2010), and of the South Virgin–White Hills detachment in the Gold Butte block (Fitzgerald et al., 1991, 2009; Reiners et al., 2000; Bernet et al., 2002; Reiners, 2005), Lost Basin Range (Fitzgerald et al., 2009), and northern White Hills (Fitzgerald et al., 2003, 2009) also show rapid cooling at 19–17 Ma. Sedimentological constraints from the region show a similar, but slightly younger age (ca. 16.5 Ma) for fault initiation and basin development based on the conglomerates within the lower Horse Springs Formation (Beard, 1996; Blythe et al., 2010; Lamb et al., 2010). This may imply that there is a lag between fault activity and the first appearance of sediment in catchments. It is also possible that the earliest
Low-temperature thermochronologic constraints

Figure 7. (A) Mean zircon (U-Th)/He ages (black diamonds) versus distance from the nonconformity above the Precambrian basement. Error bars are 1σ standard deviations. Sample numbers refer to Table 1. Apatite fission track (AFT) ages (red squares) and exhumed partial annealing zone (PAZ) in Stockli (1999) are also shown. Shaded area corresponds to the approximate position of the zircon He partial retention zone (ZPRZ). Hachured area shows uncertainty in position of the ~190 °C isotherm. Given the uncertainty, the distance between the top and base of the PRZ may be from 1.9 to 2.4 km, resulting in a geothermal gradient of 28 ± 3 °C/km. (B) The same paleodepth reconstruction can be used to calculate the distance between the base of the apatite fission track partial annealing zone (~110 °C isotherm) in Stockli (1999) and the base of ZPRZ (~190 °C isotherm). However, the high degree of uncertainty in the position of the isotherms (hachured areas), results in anywhere from 1.9 to 4.9 km between paleoisotherms and a geothermal gradient of 29 ± 3 °C/km.

Our paleodepth reconstruction (Fig. 7) indicates that the Beaver Dam Mountains have undergone a minimum of 180 °C of cooling since ca. 17 Ma. This value is determined by our thermochronologically based interpretations for the timing of fault initiation indicate that the MPD and TSD are younger than the CCD by as much as 5 Ma. This implies that extension and exhumation began at the eastern margin of the central Basin and Range and migrated westward with time. This is a somewhat surprising result because field relations between the detachments suggest that these structures young in an eastward direction; faults in the hanging wall of the TSD cut the MPD, and faults in the hanging wall of the CCD cut the TSD. The apparent paradox may be resolved, however, if activity along these structures ceased from west to east. If correct, it suggests that the CCD is a relatively long-lived structure, with its activity spanning more than 10 m.y. Such a lengthy tectonic history may imply that this structure serves as a fundamental boundary at the edge of this diffusely deforming province.

Vertical Exhumation and Magnitude of Extension

In addition to providing critical timing constraints, the thermochronology data may be used to estimate vertical exhumation and pre-extensional overburden, and can provide an independent test of cross-section–based extension estimates. It is important to note that the cross sections and consequently our paleodepth interpretations come from detailed geologic map data, whereas the PRZs and temperature estimates come entirely from the thermochronology data.

Our paleodepth reconstruction (Fig. 7) indicates that synkinematic strata are poorly dated, not well preserved, or not sampled because they are buried by younger strata.

Zircon and apatite (U-Th)/He ages from the footwalls of the MPD and TSD are invariant at 14–13 Ma, indicating that samples cooled by as much as ~150 °C at that time. We interpret this rapid cooling as marking the onset of slip along these detachments. This interpretation is supported by crosscutting relationships with regionally distributed ash-flow tuffs, which indicate that detachment faulting postdates the 18.2 ± 0.2 Ma Hiko Tuff (Rowley et al., 1995) and at least some of the tuffs of the Kane Springs Wash caldera (ca. 17.4–13.5 Ma; Scott et al., 1995), although tentative correlations between volcanic units in these ranges and source calderas have not been made (Wernicke et al., 1985; Axen, 1993; Walker, 2008).

Our thermochronologically based interpretations for the timing of fault initiation indicate that the MPD and TSD are younger than the CCD by as much as 5 Ma. This implies that extension and exhumation began at the eastern margin of the central Basin and Range and migrated westward with time. This is a somewhat surprising result because field relations between the detachments suggest that these structures young in an eastward direction; faults in the hanging wall of the TSD cut the MPD, and faults in the hanging wall of the CCD cut the TSD. The apparent paradox may be resolved, however, if activity along these structures ceased from west to east. If correct, it suggests that the CCD is a relatively long-lived structure, with its activity spanning more than 10 m.y. Such a lengthy tectonic history may imply that this structure serves as a fundamental boundary at the edge of this diffusely deforming province.

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Our paleodepth reconstruction (Fig. 7) indicates that the Beaver Dam Mountains have undergone a minimum of 180 °C of cooling since ca. 17 Ma. This value is determined by assuming a mean surface temperature of 10 °C, although a slightly warmer or cooler tempera-
temperature (±5 °C) may be used. Using our best estimate of the geothermal gradient (28 ± 3 °C/km), this translates to 5.8–7.2 km of vertical exhumation. However, our structurally deepest sample resides almost 1 km below the approximate position of the 190 °C isotherm in our reconstruction. Therefore, the total vertical exhumation is between 6.8 and 8.2 km. The estimated vertical exhumation indicates that the total overburden above current exposure levels in the Beaver Dam Mountains never exceeded ~1.5 km.

The thermochronology data from the Beaver Dam Mountains can also be used to evaluate extension across the CCD. To do this, we trigonometrically convert the vertical exhumation (throw) to horizontal extension (heave) assuming a planar fault geometry. Using the restored fault dip of 32° from Axen et al. (1990), the estimated vertical exhumation results in a net extension, or heave, of 10.9–13.1 km. It is important to note that our estimate assumes that all of the exhumation is related to slip on the CCD, which is an unlikely scenario. A small component of the exhumation may be attributed to erosion and to buried faults at the Beaver Dam range front. Therefore, these estimates for exhumation related to detachment faulting should be considered maximums.

Using a similar set of assumptions, we can determine the vertical exhumation and horizontal extension along the MPD. Figure 10 shows that the Mormon Mountains have undergone a maximum of 180 °C of cooling since ca. 14 Ma. Using our calculated geothermal gradient (27 ± 4 °C/km), this translates to 5.8–7.1 km of vertical exhumation, which suggests that the total overburden there never exceeded ~1 km. Using the range of restored fault dips (20°–28°) from Wernicke et al. (1985), we estimate from 10.9 to 19.5 km of extension along the MPD. This calculation assumes that all of the exhumation is related to slip on the MPD. Any exhumation associated with buried faults on the west side of the Mormon Mountains or related to erosion would reduce this estimate.
A similar set of calculations can be made for the TSD. Because the deepest sample from the TSD footwall is 0.3–0.8 km shallower than the 190 °C isotherm, we estimate that the total vertical exhumation is 5.0–6.8 km (Fig. 10). Using the restored fault dip for the ramping portion of the fault in cross-section D–D’ (50°), we estimate a minimum of 4.2–5.7 km of horizontal extension. Calculations for the TSD, however, are complicated because it is in the footwall of the MPD, which makes determining its thermal history difficult. It is also difficult to accurately estimate the heave on the fault because much of the fault is subhorizontal where it follows a footwall flat of the former Tule Springs thrust.

Cross-section–based reconstructions suggest that there has been ~54 km of extension between the Beaver Dam and Meadow Valley.
Figure 10. (A) Mean zircon and apatite (U-Th)/He ages from the footwalls of the Mormon Peak detachment (MPD) and Tule Springs detachment (TSD) plotted against distance from the Tertiary unconformity. Error bars are 1σ standard deviations. Sample numbers refer to Table 1. Shaded area corresponds to the approximate position of the zircon He partial retention zone (ZPRZ). Hachured area shows uncertainty in position of the ~190 °C isotherm. (B) The same paleodepth reconstruction rescaled to only show samples younger than 40 Ma. Shaded area corresponds to the approximate position of the apatite He partial retention zone (APRZ). Hachured areas show uncertainties in position of the ~80 °C and 190 °C isotherms.

Mountains (Wernicke et al., 1985, 1988; Axen et al., 1990; Axen, 1993). These reconstructions assign 24 km of extension to the CCD, 7 km to the TSD, and 23 km to the MPD (Wernicke et al., 1985; Axen et al., 1990; Axen, 1993). These values have been challenged by a number of studies (e.g., Anderson and Barnhard, 1993a; Carpenter and Carpenter, 1994a; Anders et al., 2006; Anderson et al., 2010), with those authors preferring more modest extension across these ranges. Our data suggest that extension estimates for at least two of the detachments may be too high. At a minimum, ~3 km may be eliminated from the MPD, and ~11 km from the Castle Cliffs, making the net extension across this system of faults closer to 40 km, ~25% lower than earlier estimates.

A lower value for extension across the CCD is not entirely surprising because cross-section reconstructions across the Virgin River Valley are largely unconstrained, with earlier extension errors of ±10 km cited for the CCD (Axen et al., 1990; Axen, 1993). However, the lower range of extension estimates for the MPD, determined by our data, seems unlikely given that the Meadow Valley syncline necessarily formed above the Mormon Valley thrust ramp (Axen et al., 1990). It would be difficult to remove more than a few kilometers of heave given this fairly tight geological constraint. Reconciling the fold-fault relationship with our thermochronology results means that the range of fault dips proposed by Wernicke et al. (1985) and used in our calculations may be too wide and that the initial fault dip was probably closer to 20°.

LANFs or Gravity Slide Blocks?

Although our data do not allow us to determine definitively the origin of low-angle structures in these ranges, we can say that the thermochronology data make good sense in the context of a LANF interpretation. In particular, the pattern of cooling ages seems to support such an interpretation, as samples systematically young in the presumed slip direction of the fault. The youngest samples are consistently from what would be the deepest and most recently exhumed parts of the footwall, while the oldest samples are along the eastern portions of our transects.

Proponents of a gravity slide interpretation for low-angle structures in these ranges prefer more modest extension models, and have suggested that uplift and exhumation was accomplished by high-angle normal faults inferred at the range fronts of the Beaver Dam and Mormon Mountains (e.g., Carpenter and Carpenter, 1994a; Anders et al., 2006; Christie-Blick et al., 2007; Walker, 2008). However, our thermochronology data indicate that there may be problems with such interpretations. First, there is no systematic cooling age–elevation relationship observed in our data, as might be expected for exhumation along a high-angle fault (Stockli, 2005). Instead, samples collected from very similar elevations have vastly different cooling ages, a strong indication that paleoisotherms have been tilted or rotated. An interpretation that invokes exhumation along a high-angle normal fault would narrow the distance between paleoisotherms and produce
unreasonably high geothermal gradients. Second, models invoking extension along high-angle range-front faults would also require very deep basins west of the Beaver Dam and Mormon mountains, as our data demonstrate ~6–8 km of vertical exhumation. However, geophysical data gathered over these basins suggest that they are shallow. For example, gravity modeling across the Meadow Valley Wash indicates that basement is only ~1.5 km below the surface (Scheirer et al., 2006), consistent with seismic reflection data that show the top of basement at shallow two-way traveltimes (Carpenter and Carpenter, 1994a; Scheirer et al., 2006). Gravity data from the central and southern Virgin River Valley support the interpretation of a deep (~8 km) basin there, but the magnitude of the gravity anomaly diminishes significantly to the north, suggesting that the portion of the basin adjacent to the Beaver Dam Mountains is relatively shallow, inconsistent with the high-angle fault interpretation (Blank and Kucks, 1989).

CONCLUSIONS

The new apatite and zircon (U-Th)/He thermochronometric data provide important insights into the kinematic histories of the CCD, TSD, and MPD. Paleodepth reconstructions of the basin along a LANF. Our thermochronologically based interpretations indicate that extension estimates for detachments in the region are too high (e.g., Wernicke et al., 1988; Axen et al., 1990); however, ~40 km of extension is allowed from our data, compatible with earlier assertions of large-magnitude extension between these ranges. Although we cannot rule out a gravity slide interpretation for low-angle structures in these ranges, the protracted cooling history, magnitude of exhumation, and pattern of cooling ages are most consistent with exhumation along a LANF.

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