Middle Miocene to recent exhumation of the Slate Range, eastern California, and implications for the timing of extension and the transition to transtension

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ABSTRACT

New mapping combined with fault-slip and thermochronological data show that Middle Miocene to recent extension and exhumation of the Slate Range, eastern California, is produced by the active Searles Valley fault system and the Slate Range detachment, an older Middle Miocene low-angle normal fault. Offset Middle Miocene rocks record a combined ~9 km of west-directed extension over the past ~14 m.y. for the fault zones. (U-Th)/Heapatite cooling ages of samples from the central and southern Slate Range indicate that footwall cooling began ca. 14 Ma; we interpret this as the age of initiation of motion on the Slate Range detachment. This timing is consistent with inferences made using stratigraphic and structural criteria. Data from the northern Slate Range show that rapid fault slip began along the Searles Valley fault ca. 4 Ma; data from the central and southern Slate Range can be interpreted as indicating cooling at 5–6 Ma. This timing correlates to the results of nearby studies, suggesting a strain transition in the surrounding area between ca. 6 and 3 Ma. The data collected are most consistent with a westward migration in the locus of transtensional deformation, and show that the initiation of that deformation commonly lags the timing predicted by plate reconstructions by a few million years.

INTRODUCTION

The Miocene Basin and Range extensional province and the latest Miocene to recent eastern California shear zone–Walker Lane transtensional belt at the latitude of Las Vegas, Nevada, may have been stretched as much as 300% since ca. 16 Ma (e.g., Wernicke et al., 1988; Niemi et al., 2001). The earlier deformation resulted in primarily east-west extension across the region (Wernicke et al., 1982, 1988), initiating ca. 15 Ma, as inferred by the ages of early basin deposits of the Panuga (Snow and Lux, 1999) and Eagle Mountain formations (Niemi et al., 2001) of the northern Death Valley area, and of the Panamint Valley volcanic sequence in the Argus, Panamint, and Slate Range region (Fig. 1; Andrew and Walker, 2009). Peak extension, however, probably occurred after 15 Ma (Snow and Wernicke, 2000, p. 687) and lasted until Late Miocene time; the locus of the major deformation is interpreted to be east of Panamint Valley.

Later deformation is primarily transtensional in character, expressed as dextral-oblique normal faults and strike-slip faults active in the region from the Spring Mountains to the eastern flank of the Sierra Nevada. At this latitude, this later deformation belt is variably referred to as the eastern California shear zone or Walker Lane belt, and affects the western half of the older Basin and Range extensional province.

Atwater and Stock (1998) interpreted a change in plate motions ca. 10 Ma, from a more westward to a more northward motion of the Pacific plate relative to North America, and associated this change to the transtensional deformation. Geological evidence indicates a more complex deformational history. Mahan et al. (2009) suggested initiation of dextral transtension along the State-line fault in southern Nevada ca. 5 Ma (Fig. 1). Wernicke et al. (1988; and subsequently Snow and Wernicke, 2000; McQuarrie and Wernicke, 2005) considered the Furnace Creek fault to be active from ca. 9 to 5 Ma, and that this fault is a component of the dextral regime (Fig. 1). Snow and Lux (1999) interpreted the change to dextral deformation in Death Valley to have started ca. 11 Ma (Fig. 1). Other studies that focus on different areas interpret younger ages for this change to transtension. Hodges et al. (1989) placed the transition as ca. 3.7 Ma in Panamint Valley (Fig. 1). Monastero et al. (2002) considered this transition to have occurred ca. 3–2 Ma in the Indian Wells Valley based on mostly subsurface stratigraphic data. Bellier and Zoback (1995) considered the transition to have occurred in the past 300 k.y. using Holocene fault scarp slip data. In Stockli et al. (2003), a general westward migration of the transition was reported, starting at 6 Ma and progressing westward to 4 Ma, based on fault kinematic and thermochronometric data from the Fish Lake Valley–White Mountain area. Thus, the precise timing and associated spatial patterns of the onset of significant dextral deformation remain uncertain. The transition from east-west extension to northwest-directed oblique extension is apparently complex in both timing and location. The resolution of this problem requires more complete documentation of the age of transtensional slip on specific structures.

This paper aims to more closely bracket the initiation of extension and to better define the age of the transition from extension to transtensional deformation for the Slate Range and adjacent Searles Valley, which are west of Panamint and Death Valleys (Fig. 1). To do this we present new structural interpretations tied to three thermochronologic transects from the northern, central, and southern Slate Range. The northern transect (approximately along cross-section...
Slate Range extension and transtension

A–A’ in Fig. 2) trends east-west across the northern Slate Range, near where the south-west-striking Manly Pass fault joins the north-striking Searles Valley fault; the central transect (along cross-section B–B’ in Fig. 2) crosses the Slate Range just north of Tank Canyon; and the southern transect (cross-section C–C’ in Fig. 2) parallels Layton Canyon. This work complements studies of late Cenozoic deformation in the southern and northern Slate Range (Walker et al., 2005; Numelin et al., 2007; Andrew and Walker, 2009).

GEOLOGIC SETTING

The Slate Range trends north-south and the southern two-thirds of the range is bound on its western flank by a west-dipping, low- to moderate-angle normal fault zone (Fig. 2; Moore, 1976; Smith et al., 1968; Walker et al., 2005; Numelin et al., 2007). Pre-Cenozoic rocks along the northern transect consist of 100 Ma Stockwell diorite, 159 Ma Copper Queen alaskite, and 166 Ma Isham Canyon granite (Moore, 1976; Dunne and Walker, 2004) containing pendants of Paleozoic and Mesozoic metasedimentary rocks. The central and southern transects cross Jurassic plutonic rocks that contain pendants of Jurassic metavolcanic and metaepiclastic rocks (Smith et al., 1968; Dunne and Walker, 2004). These assemblages represent portions of the Mesozoic Sierran magmatic arc and the Paleozoic continental passive margin. There is an ~85 m.y. time gap between the youngest Cretaceous intrusive rock and Middle Miocene sedimentary-volcanic units, marked by an extensive erosion surface (Moore, 1976; Andrew and Walker, 2003, 2009). A similar volcanic and sedimentary sequence is also found to the northwest in the Argus Range (Moore, 1976; Andrew and Walker, 2003, 2009), to the east in the Panamint Range (Johnson, 1957; Andrew and Walker, 2009) and Owlshead Mountains (Davis, 1988; Davis and Fleck, 1977; Luckow et al., 2005), and to the southeast in the Quail Mountains (Muehlberger, 1954; Andrew, 2002), although thicknesses vary greatly between the sections to the east and south of the study area.

The relatively uniform nature of the Miocene sections in the Slate Range and nearby areas implies that the basal nonconformity was relatively planar (Andrew and Walker, 2009), although the thickness of the lowest Miocene sedimentary deposits varies from 0 to 30 m. The thickest sections were deposited against lava flows, pumaceous epiclastic rocks, and andesitic to dacitic laharc deposits (Smith et al., 1968; Andrew and Walker, 2003, 2009; Didericksen, 2005).
Figure 2. Simplified geologic map of the Slate Range with locations of major fault systems and zones. Black dots correspond to the locations of our thermochronology samples. Arrows with corresponding orientations show the locations of the northward projection of the Miocene nonconformity (2σ orientations) used in calculating extension magnitudes (see text for discussion). Geology from this study, Smith et al. (1968), Walker et al. (1994, 2002), Andrew (2002), Dunne and Walker (2004), and Andrew and Walker (2009).
STRUCTURAL SETTING

The structural geology presented here is based on detailed geologic mapping and previous work by Moore (1976) and Smith et al. (1968). Structural interpretations come mostly from the mapping of Andrew and Walker (2009; see also Walker et al., 2005) for the northern Slate Range, and Didericksen (2005) and Numelin et al. (2007) for the central Slate Range.

There are two Tertiary-age extensional fault systems in the Slate Range: the Slate Range detachment fault and the active Searles Valley and Manly Pass faults (Fig. 2). The Searles Valley and Manly Pass fault zones constitute a younger, segmented fault system (Walker et al., 2005; Numelin et al., 2007) that we refer to as the Searles Valley fault zone (SVFZ). The Slate Range detachment is the older structure, because it is variably exposed in the footwall and hanging wall of the Slate Range fault and the hanging wall of the Manly Pass fault (Fig. 2; Andrew, 2005; Andrew and Walker, 2009; Didericksen, 2005). Geologic relationships from the Layton Canyon area indicate that collectively the Searles Valley fault and the Slate Range detachment accommodate a minimum of ~9 km of horizontal extension in an apparent westward direction (Fig. 3; Didericksen, 2005).

The geometry and kinematics of these faults are critical to establishing paleodepth estimates for thermochronology samples and are examined in more detail in the following.

Faulting History of the Central Slate Range

The Slate Range detachment is currently inactive, rotated to near horizontal dips, and is offset across the Searles Valley fault zone (Figs. 2 and 3). The fault is interpreted to have initiated as a roughly north-to-northwest-striking normal fault that dipped westward between 25° and 50° (Didericksen, 2005). The interpreted initial dip is derived from its apparent 25° cutoff angle with Miocene strata east of the breakaway in the footwall (Fig. 4A); it cannot be any steeper than 50°, the cutoff angle of Miocene rocks in fault horses in the hanging wall. The Slate Range detachment probably initiated during Miocene deposition because the volcanic sequences (ca. 12–15 Ma) contain interbedded rock avalanche deposits, some basal conglomerates, and locally consist almost entirely of footwall-derived clasts, indicative of significant topographic relief (see additional discussion in Andrew and Walker, 2009). Definitive Pliocene and younger rocks are not found in the hanging wall of the Slate Range detachment, suggesting that the fault was uplifted and inactive before Pliocene volcanism began in the nearby Argus Range (Andrew and Walker, 2009). In the central Slate Range, Middle Miocene units in the hanging wall dip eastward as much as 50° into a 2–3-m-thick zone of fault gouge, which grades into brecciated Jurassic basement (Figs. 2 and 4B). The detachment in the northern Slate Range is exposed west of the Manly Pass fault; there are several fault spays that dip 5°–10° westward, cutting Mesozoic plutonic rocks. A several-meter-thick gouge zone separates the Mesozoic plutonic rocks from hanging wall faulted and brecciated Miocene basaltic-andesite lava flows and an overlying carbonate-cemented footwall-derived fanglomerate (Fig. 4C). This fanglomerate is undated, but the deformed nature of it along with poorly exposed but east-tilted bedding suggest that it is older than the nearby 4–5 Ma relatively untilted basalt flows in the Argus Range (Andrew and Walker, 2009).

The Searles Valley fault zone as defined in Walker et al. (2005) is a curvilinear fault zone striking 155°–180° and dipping 15°–35° to the west-southwest in the southern and central Slate Range (Fig. 2). The dip steepens to ~50° as the fault is traced northward into the north-central Slate Range. Fault-slip data for the southern and central Slate Range, measured along the fault zone in the Mesozoic bedrock, indicate that overall motion is west directed (Didericksen, 2005). This structure extends to the northern portion of the central Slate Range, where it was mapped as the Manly Pass fault by Moore (1976). As noted herein, we consider the Manly Pass and Searles Valley faults to constitute a single segmented fault system. South of cross-section line A′–A′ (Fig. 2), the Manly Pass fault is indistinguishable from the Searles Valley fault; north of A′–A′ it bends to the northeast, dips moderately to gently northwest, and has left-lateral oblique normal motion (Walker et al., 2005; Andrew and Walker, 2009). The fault continues northeastward into Panamint Valley, where it intersects with the southern Panamint Valley fault zone and the Panamint detachment (Walker et al., 2005; Andrew and Walker, 2009).

We interpret these relationships to indicate that the Slate Range detachment is an older structure related to Middle Miocene, west-directed extension in the Death Valley region. The Searles Valley fault zone is a younger structure related to transtension because it (1) clearly cuts the Slate Range detachment; (2) appears to be moving with active fault systems (Walker et al., 2005; Numelin et al., 2007); and (3) is coincident with arrays of earthquake foci (e.g., Unruh and Hauksson, 2009).

In the following section we present preextensional paleodepth estimates for our rock samples, which are critical to properly evaluating the thermal histories of the Slate Range detachment and Searles Valley fault systems. These estimates are independent of the cooling ages, which are discussed herein. The thermochronologic data better delineates the timing of initiation and exhumation of structures described here.

Preextensional Paleodepth Estimates

The preextensional paleodepths of rock samples in the Slate Range are essential to placing the thermochronologic data into a cooling history (Stockli, 2005). Middle Miocene sedimentary
Figure 3 (Continued on following page). Cross sections across the Slate Range based on work of Smith et al. (1968), Andrew and Walker (2009), and this study. (A) Northern. (B) Central. (C) Southern. Samples, shown as black dots, are projected in the plane of the cross section. In the projected view, samples may be above or below topography of the section line. Number above each sample corresponds to sample numbers referred to in Tables 2 and 3. Green dashed lines show the projected Miocene nonconformity (lower) and preextensional surface datum (upper). Dashed orange line is the approximate base of the Miocene and/or Pliocene partial retention zones (hachured areas). Mean (U-Th)/He ages are plotted as a function of horizontal distance above each cross section. Errors shown at 1σ standard deviation. PRZ-M—Miocene partial retention zone; PRZ-P—Pliocene zone; SRD—Slate Range detachment; SVFZ—Searles Valley fault zone. Locations of section lines are shown in Figure 2.
and volcanic rocks nonconformably overlie basement along the eastern flank of the Slate Range, providing a preextensional paleohorizonal datum (Fig. 4A). However, the topography of the nonconformity, thickness of volcanic and sedimentary overburden, and potential errors in post–14 Ma tilt corrections need to be considered in order to accurately estimate the paleodepths of thermochronology samples (e.g., Stockli et al., 2002). The thickness of basal sediments overlying the nonconformity provides evidence for only minor, short-wavelength topographic relief (~30 m) prior to the deposition of the remainder of the Middle Miocene sedimentary and volcanic sequence. It is unlikely that these small-amplitude variations perturbed the thermal structure (e.g., Stockli, 2005).

The orientation of the paleohorizonal and/or nonconformity surface in the footwall block of the Slate Range detachment and Searles Valley fault zone was calculated as the mean of 11 measurements made in Miocene units on the east-central flank of the central Slate Range, yielding a strike of 349° ± 16° and dip of 24° ± 6° (2σ) (Fig. 5; Table 1). The preextensional volcanic and sedimentary overburden above the Miocene nonconformity at the onset of faulting was estimated based on the preserved stratigraphic thickness. Our observations and those of Smith et al. (1968) suggest the basal sandstones and limestones could collectively be as much as 50 m thick, and conglomerate sections could be <30 m thick; overlying pyroclastic rocks may be as thick as ~30 m; and the capping basaltic and andesitic volcanic section is commonly >50 m thick and locally may be as thick as 100 m. Thus, an overburden value of ~200 m is added to all sample paleodepths. This thickness is at the high end of measurements in Andrew and Walker (2009), in which values of ~100–200 m for the section in the northern Slate Range were presented. A difference of 100 m, however, has little effect on the reconstructions, and is minor compared to the other uncertainties. Although not seen or preserved in the Slate Range sections, correlative rocks thicken to >700 m to the south and east in the southern Panamint Range and Brown Mountains areas.

These values and orientations bracket paleodepths in the central and southern Slate Range relatively well (Figs. 2 and 3) because Miocene strata directly overlie the basement rocks in the line of section. Assuming an ~25° dip for this surface gives paleodepth values ranging from 0.3 to 3.2 km. This estimate is possible because the range can be considered a simple tilted fault block, thus eliminating the need to consider the hinge position for tilting (e.g., Armstrong et al., 2003). These depths apply to the area in Middle Miocene time since they are computed using the Miocene nonconformity. The removal of hanging-wall rocks by the Slate Range detachment as well as possible footwall tilting makes estimates of depths for later Miocene to recent time less certain as most of the samples are below the detachment (Figs. 3 and 6). We assume that the main eastward tilting of this section occurred during the Pliocene due to recent motions on the Searles Valley and Panamint Valley fault systems, although it is possible that some tilting accompanied movement on the detachment: we present information herein that supports former interpretation for timing of the tilting.

For the northern Slate Range, the paleohorizonal and/or nonconformity reference plane was projected northward to the latitude of the thermochronologic transect as Miocene units are not present to the east of the Manly Pass fault in this area (Figs. 2 and 3). The projection was made in the direction of mean strike from the northernmost exposure of the nonconformity (Fig. 2) at an elevation of ~510 m. In addition, there are three small faults that cut across or project into the area. These were initially ignored in estimating the paleodepths.

For all three areas, paleodepth estimate errors are primarily a function of the uncertainty in the timing and amount of eastward footwall tilting and, for the northern transect, the projection of
the paleohorizontal surface northward ~6 km. Timing of tilting is important as rotation of the block changes the estimated depths. If tilting is prior to cooling age, then depth estimates would become shallower. Uncertainties for tilt correction of the central (B–B') and southern (C–C') transects mainly result from the variation in dip of the nonconformity and the assumption that the block behaves in a rigid manner, and only amount to a few hundred meters for this transect (with probable uncertainty of 500 m for the deepest samples). For the northern transect, projection uncertainties are computed using the extreme high and low values for dip and strike of the section. This results in a possible variation of as much as 1.5 km of depth (2σ). (This uncertainty is not plotted in any figures but is included in the paleogeothermal gradient calculation.) Because the sample locations are mostly adjacent to or east of the projected breakaway for the Slate Range detachment (Figs. 3 and 6), we assume that tilting was minor prior to movement on the Searles Valley fault zone. Structural reconstructions based on interpretations of the thermochronologic data will help evaluate this uncertainty. The paleodepth estimates for samples 1, 2, 8, and 37 (located in the hanging wall of the Searles Valley fault zone) were not calculated. Thermochronologic data give some information about their possible reconstructed positions (Fig. 6; see the following detailed discussions for how positions were determined).

(U-Th)/He THERMOCHRONOMETRY

To better understand the timing and magnitude of fault motion, we analyzed 43 samples from the Slate Range using (U-Th)/He

Figure 4. (A) Miocene volcanic rocks cropping out over Jurassic granite and metavolcanic rocks on the eastern flank of the Slate Range north of Layton Pass. The tilted nonconformity here appears to be a rotated gentle erosional surface with beds steepening upsection to higher dips in the dark volcanic rocks. Field of view is ~800 m. Panamint Range is in background. Panoramic view is toward the northeast. (B) Slate Range detachment west-southwest of Layton Pass. Miocene strata dip ~45° at top of hill, an ~2-m-thick ground zone is beneath (tan layer), and brecciated Jurassic metaplutonic rocks are at base. White box is next to ~2-m-tall person for scale. (C) Slate Range detachment fault and splay faults in the hanging wall of the Searles Valley normal fault, just north of Copper Queen Canyon.
thermochronometry (Fig. 2). The (U-Th)/He method is a well-established and effective technique for directly dating the exhumation and cooling of footwalls of major normal faults (e.g., Axen et al., 2000; Stockli et al., 2000; Ehlers et al., 2003; Armstrong et al., 2004), as well as the initiation of transpressional structures (e.g., Stockli et al., 2003; Lee et al., 2009; Mahan et al., 2009). The method is based on the production of $^4$He through the decay of $^{238}$U, $^{235}$U, $^{232}$Th, and $^{142}$Sm. However, $^4$He retention in minerals is temperature dependent. In apatite, $^4$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., 1999; Stockli et al., 2000). For zircon, helium is retained over a higher temperature range, from 190 to 130 °C (Reiners et al., 2002, 2004). These temperatures define thermal sensitivity windows or partial retention zones (PRZs) (Wolf et al., 1998) that can be used to reconstruct temperature-time paths or apparent age.

Paleodepth and/or elevation trends for a range of geologic studies (e.g., Foster and Stockli, 2001; Stockli et al., 2000). For zircon, helium is retained over a higher temperature range, from 190 to 130 °C (Reiners et al., 2002, 2004). These temperatures define thermal sensitivity windows or partial retention zones (PRZs) (Wolf et al., 1998) that can be used to reconstruct temperature-time paths or apparent age.

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Figure 6. Reconstructed sample positions for the thermochronology transects. (A) Northern. (B) Central. (C) Southern. Abbreviations and line coloring are as in Figure 3. Sample numbers refer to Tables 2 and 3. MP—Manly Pass.
12LC09, and 12LC13) are single grain ages; therefore, we show the error in the mean age as the standard error.

RESULTS

The results for the northern, central, and southern thermochronology transects are discussed separately because of structural and age differences between them.

Northern Transect

The northern transect crosses the Manly Pass fault and consists of 15 samples of medium-grained Stockwell diorite from both the footwall and hanging wall (Figs. 2 and 3). Hanging-wall rocks are complicated in that they come from the footwalls of the Searles Valley fault and consist of 14 samples of medium-grained Stockwell diorite from both the footwall and hanging wall (Figs. 2 and 3). Only one sample was collected from the hanging wall of the fault zone; all other samples are from the footwalls of the Searles Valley fault and Slate Range detachment.

Table 2 shows that apatite (U-Th)/He mean ages from the northern transect range from as young 4.2 Ma to as old as 51.8 Ma, but no systematic relationship between cooling age and elevation is observed. The youngest cooling ages along this transect are located in the footwall immediately east of the Manly Pass fault, clustering at ca. 4 Ma (Table 2; Fig. 3A). The samples increase in apparent age to east (Table 2; Fig. 3A). Some of the oldest apparent ages are located west of the fault, ranging from 28.8 to 51.8 Ma (Table 2; Fig. 3A).

Central Transect

The central transect crosses the Searles Valley fault and consists of 14 samples of Copper Queen alaskite and Jurassic metadiorite (Figs. 2 and 3). Only one sample was collected from the hanging wall of the fault zone; all other samples are from the footwalls of the Searles Valley fault and Slate Range detachment.

Table 2 shows that apatite (U-Th)/He mean ages from the central transect range from as young 6.0 Ma to as old as 50.1 Ma. Like the northern transect, no systematic relationship between cooling age and elevation is observed (Table 2). Samples with the youngest cooling ages come from the western part of the transect (Table 2; Fig. 3B). The three westernmost samples from the Searles Valley fault footwall have ages varying from ca. 6 to 9 Ma. Higher in the range, 2 samples give consistent ages of ca. 14 Ma. Samples then increase in apparent age eastward over the range (Table 2; Fig. 3B). The oldest apparent ages are located on the eastern slope, from samples located only a few hundred meters beneath the projection of the Miocene nonconformity, and have ages of ca. 45–50 Ma (Table 2; Fig. 3B).

Southern Transect

The southern transect crosses the Searles Valley fault and consists of 14 samples of Jurassic diorite, leucogranite, and metavolcanic rocks (Figs. 2 and 3). Two samples were collected from the hanging wall of the fault zone; all other samples are from the footwall of both the Searles Valley fault and Slate Range detachment.

Although there are 14 samples in the southern transect, only 7 contained inclusion-free apatite grains. Table 2 shows that the resulting mean ages range from as young 5.2 Ma to as old as 26.0 Ma.

TABLE 2. SUMMARY OF (U-TH)/HE APATITE DATA FOR THE SLATE RANGE

<table>
<thead>
<tr>
<th>Sample</th>
<th>Longitude (W)</th>
<th>Latitude (N)</th>
<th>Elevation (m)</th>
<th>Mass (µg)</th>
<th>Ft* (ppm)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>Sm (ppm)</th>
<th>Th/U</th>
<th>He (ncc/mg)</th>
<th>Mean Age (Ma)</th>
<th>St.Dev.† (Ma)</th>
<th>Replicates</th>
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<td>Northern Transect (section A–A')</td>
<td>117.2627</td>
<td>35.4875</td>
<td>840</td>
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<td>0.61</td>
<td>15.1</td>
<td>32.8</td>
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<td>35.4896</td>
<td>1310</td>
<td>3.09</td>
<td>0.67</td>
<td>7.5</td>
<td>21.0</td>
<td>–</td>
<td>2.84</td>
<td>108.0</td>
<td>10.8</td>
<td>1.4</td>
<td>3</td>
</tr>
<tr>
<td>BD04CSR-48</td>
<td>117.2124</td>
<td>35.4805</td>
<td>1300</td>
<td>1.20</td>
<td>0.63</td>
<td>5.4</td>
<td>34.5</td>
<td>–</td>
<td>2.50</td>
<td>35.1</td>
<td>9.0</td>
<td>0.9</td>
<td>3</td>
</tr>
<tr>
<td>Southern Transect (section C–C)</td>
<td>117.1936</td>
<td>35.7459</td>
<td>1320</td>
<td>0.60</td>
<td>0.56</td>
<td>36.6</td>
<td>125.6</td>
<td>–</td>
<td>3.27</td>
<td>138.0</td>
<td>27.0</td>
<td>6.0</td>
<td>6</td>
</tr>
</tbody>
</table>

Note: Individual analyses are given in Tables DR1 and DR2 in the Supplemental File and on-line (see text footnote 1); dash—not measured.

*Ft is the alpha ejection correction of Farley et al. (1996).
†St. Dev.—standard deviation.
Like the other transects, no systematic relationship between apparent age and elevation is observed (Table 2). Samples with the youngest cooling ages come from the western part of the transect, east of the both the Searles Valley fault and Slate Range detachment, ranging from 5.2 to 6.8 Ma (Table 2; Fig. 3C). Farther east, 2 samples give consistent ages of ca. 13 Ma (Table 2; Fig. 3C). The oldest apparent age is from a sample located a few hundred meters below the projection of the Miocene nonconformity (Table 2; Fig. 3C).

Zircon (U-Th)/He mean ages from the southern transect are shown in Table 3. Only 11 of the 14 samples had useable zircon grains. The mean ages range from as young as 44.6 Ma to as old as 56.6 Ma; most samples cluster around 51 Ma. No systematic relationship between the age of samples and their elevation was observed in the data.

**INTERPRETATION OF THE (U-Th)/He THERMOCRONOLOGIC DATA**

Plotting the apparent (U-Th)/He ages against paleodepth provides a basis for interpreting the cooling and exhumation history of the Slate Range with respect to the mapped faults and faulting history of the area (Fig. 6). It is important to note that the paleodepth interpretations come from basic structural mapping of the area, whereas the temperature and PRZ interpretations come solely from the (U-Th)/He age data. Thus, the two data sets are independent, although we use the apparent age data to make some adjustments to the depths in the northern profile.

**Northern Transect**

The northern transect is somewhat complicated in that three mapped faults cross or project into the footwall of the Searles Valley fault zone (Fig. 3A). The amount slip on these structures is unknown. An additional complication for this transect is that three of the oldest (U-Th)/He samples are found within the hanging wall of the fault (Fig. 3A). Clearly, any offsets from faults within the cross section must be accounted for in order to restore all of the samples to their true preextensional paleodepths. Our initial interpretations ignored footwall faults, restoring samples to paleodepths relative to our projection of the Miocene nonconformity. This yielded a clear trend of age with depth, but resulted in a somewhat jagged PRZ. We then made small adjustments to the paleodepths by using the cooling ages to create a smooth PRZ to infer offset across these structures (Figs. 3A, 6A, and 7). Our interpretation based on cooling ages is that the western 2 faults have ~125 and ~150 m of down-to-the-west throw, and the eastern fault has ~300 m of down-to-the-east throw at the eastern flank of the northern-central Slate Range (Fig. 3A); therefore, the down-to-the-east and down-to-the-west components are essentially the same. This means that these faults have little effect on our depth estimates in the western part of the transect, and the relatively minor offsets restored on these structures do not quantitatively affect our conclusions. However, samples in the hanging wall of the Manly Pass fault are particularly important, as they can be used to constrain Pliocene slip on that structure and the top of the Pliocene PRZ. These samples (1, 2, 3, and 8) were restored by adjusting the depths of the sample until they intersected the extrapolated trend of data from the footwall of the Manly Pass fault, through the Pliocene PRZ (Fig. 7).

After restoring the samples to their paleodepths, the apatite (U-Th)/He data from the northern Slate Range exhibit systematic apparent age versus paleodepth patterns indicative of rapid footwall exhumation of a shallow crustal block (House et al., 1999; Reiners et al., 2000; Armstrong et al., 2003; Stockli et al., 2005; Stockli et al., 2000, 2002). Apparent ages decrease with increasing paleodepths from 51.8 to 4.3 Ma at ~2.3 km paleodepth (Fig. 7). Invariant ages at the structurally deepest paleodepths record rapid exhumation ca. 4 Ma. Based on the proximity of these samples to the Manly Pass fault (Figs. 3A and 6A), these invariant (U-Th)/He ages are interpreted to be related to fault slip along that structure. The invariant ages indicate that fault slip was significant enough to cool samples from just below the zero retention isotherm (≥~80 °C) to <40 °C. We therefore interpret the Manly Pass segment of the Searles Valley fault zone to have initiated ca. 4 Ma. Progressively older apparent ages at structurally shallower depths record residence in the apatite He PRZ prior to early Pliocene exhumation (Fig. 7). Exhumation and cooling directly attributed to the earlier Slate Range detachment is not observed in the data. The projected north-northwest strike of the Slate Range detachment and structural reconstructions suggests that the breakaway for this fault was west or above most samples in this transect (Fig. 6A). This may indicate that the effect of motion on this structure was not in a position to cause a significant change in the thermal structure.

Based on our paleodepth reconstructions, the relative position of the 80 °C isotherm is constrained to be between 1.8 and 2.0 by samples 6 (shallowest Pliocene sample) and 7 (deepest Miocene sample). Although the relative position is tightly determined, our structural restoration (using all estimated errors) places the preextensional depth of the 80 °C isotherm at 1.8 ± 1.5 km. Using an assumed mean annual surface temperature of 10 ± 5 °C (Stockli et al., 2000), the preextensional geothermal gradient is 40 ± 30 °C/km. The uncertainty based on absolute paleodepths is obviously quite large, but it is the most precise estimate that can be obtained with the available structural data.

The ~40 °C/km geothermal gradient is elevated compared to average continental geothermal gradients of ~25 °C/km; however, local volcanic activity supports high heat flow and an elevated geothermal gradient in the Late Miocene and Pliocene Slate Range (Andrew and

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**TABLE 3. SUMMARY OF (U-TH)/HE ZIRCON DATA FOR THE SLATE RANGE**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Longitude (W)</th>
<th>Latitude (N)</th>
<th>Elevation (m)</th>
<th>Mass (µg)</th>
<th>F\textsuperscript{t}*</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>Sm (ppm)</th>
<th>Th/U</th>
<th>He (nmol/g)</th>
<th>Mean age (Ma)</th>
<th>St.Dev.\textsuperscript{1} (Ma)</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern Transect (section C-C\textsuperscript{2})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>12LC01</td>
<td>117.2191</td>
<td>35.6778</td>
<td>675</td>
<td>6.12</td>
<td>0.77</td>
<td>659.4</td>
<td>253.5</td>
<td>5.7</td>
<td>0.39</td>
<td>151.8</td>
<td>50.1</td>
<td>5.8</td>
<td>3</td>
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<tr>
<td>12LC02</td>
<td>117.2159</td>
<td>35.6784</td>
<td>700</td>
<td>2.88</td>
<td>0.76</td>
<td>683.6</td>
<td>257.2</td>
<td>5.0</td>
<td>0.38</td>
<td>147.2</td>
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<td>12LC03</td>
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<td>35.6787</td>
<td>700</td>
<td>4.79</td>
<td>0.75</td>
<td>771.4</td>
<td>225.8</td>
<td>1.0</td>
<td>0.30</td>
<td>149.2</td>
<td>44.6</td>
<td>8.4</td>
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</tr>
<tr>
<td>12LC04</td>
<td>117.2092</td>
<td>35.6798</td>
<td>750</td>
<td>5.90</td>
<td>0.76</td>
<td>644.5</td>
<td>355.5</td>
<td>0.7</td>
<td>0.56</td>
<td>135.4</td>
<td>45.3</td>
<td>2.6</td>
<td>3</td>
</tr>
<tr>
<td>12LC07</td>
<td>117.1985</td>
<td>35.6792</td>
<td>800</td>
<td>6.00</td>
<td>0.76</td>
<td>171.5</td>
<td>312.8</td>
<td>0.8</td>
<td>0.26</td>
<td>257.4</td>
<td>50.7</td>
<td>7.0</td>
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<td>12LC09</td>
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<td>14.93</td>
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<td>433.1</td>
<td>146.5</td>
<td>0.6</td>
<td>0.34</td>
<td>113.8</td>
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<td>117.1880</td>
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<td>45.8</td>
<td>35.7</td>
<td>0.5</td>
<td>0.76</td>
<td>11.7</td>
<td>51.3</td>
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<td>12LC11</td>
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<td>367.8</td>
<td>125.3</td>
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<td>81.6</td>
<td>51.0</td>
<td>2.0</td>
<td>3</td>
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<tr>
<td>12LC12</td>
<td>117.1812</td>
<td>35.6782</td>
<td>950</td>
<td>7.17</td>
<td>0.78</td>
<td>190.8</td>
<td>221.3</td>
<td>1.0</td>
<td>1.19</td>
<td>46.4</td>
<td>46.1</td>
<td>3.5</td>
<td>3</td>
</tr>
<tr>
<td>12LC15</td>
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<td>1070</td>
<td>5.63</td>
<td>0.76</td>
<td>381.4</td>
<td>114.4</td>
<td>0.7</td>
<td>0.31</td>
<td>92.4</td>
<td>55.2</td>
<td>3.1</td>
<td>3</td>
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<tr>
<td>12LC16</td>
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<td>1000</td>
<td>4.35</td>
<td>0.75</td>
<td>195.9</td>
<td>135.6</td>
<td>0.7</td>
<td>0.69</td>
<td>52.5</td>
<td>56.6</td>
<td>2.9</td>
<td>3</td>
</tr>
</tbody>
</table>

Note: Individual analyses are given in Tables DR1 and DR2 in the Supplemental File and online (see text footnote 1).

\*F\textsuperscript{t} is the alpha ejection correction of Farley et al. (1996).

\textsuperscript{1}St. Dev.—standard deviation.
It is interesting that this value is similar to estimates of the geothermal gradient in the Wassuk Range (Stockli et al., 2002) and to modern geothermal gradients of ~35 °C/km in the western Basin and Range province (e.g., Lachenbruch and Sass, 1980). Unfortunately, uncertainties in our data make drawing conclusions about the thermal structure of the Slate Range preextensional upper crust difficult.

Using the cooling ages, we can estimate the throw, fault slip, and west-directed heave or extension on the Manly Pass segment over the past ~4 m.y. Our principal estimate using sample 2 does not directly rely on paleodepth, but rather restoration of cooling ages in cross section. The dip slip estimated here is ~1.5 km. This is the amount of offset of sample 2 to restore it to the appropriate age horizon of the PRZ. This estimate is similar to the ~2 km magnitude of the dip slip estimated across section A–A′ by restoring the Middle Miocene rocks in the hanging wall along the fault to the projected Middle Miocene nonconformity in the footwall (although this interpretation is complicated by uncertain effects of the Slate Range detachment). The present dip of the Manly Pass fault is ~50° to the west in the northern-central Slate Range. This dip constrains the amount of heave on the fault over the past 4 m.y. to ~1 km. This yields an average west-directed extension rate of ~0.25 mm/yr since the early Pliocene on the basal fault of the system. This rate is the same as the slip rate of 0.21–0.35 mm/yr inferred for the Searles Valley fault to the south by Numelin et al. (2007) over latest Pleistocene to Holocene time. Because that fault dips shallowly, it slip rate is approximately the same as the east-west extension rate. For this reason, it appears that the modern and time-averaged rates on the Searles Valley fault zone are similar along its extent. It is important to note that this estimate applies to the basal fault strand of the Searles Valley fault zone. There is significant distributed faulting in the hanging wall of this structure (not sampled by this estimate or that of Numelin et al., 2007) that probably amounts to ~3.5 km of additional regional extension (Andrew and Walker, 2009).

Central and Southern Transects

Paleodepth reconstructions of (U-Th)/He ages from the central and southern transects are somewhat simpler than for the northern one because almost all of the samples reside within the minimally faulted footwall to the Searles Valley fault zone and Slate Range detachment (Figs. 3, 6B, and 6C). However, interpretation of the reconstructed cooling ages is significantly more complicated. Zircon (U-Th)/He ages from the southern transect cluster at ca. 51 Ma, suggesting that there was an exhumation event at that time (Fig. 8; Table 2). While this exhumation event is significantly older than the Miocene and Pliocene fault history, this age is an important constraint for interpreting the apatite data (see following).

Apatite (U-Th)/He apparent ages increase with decreasing paleodepth from ca. 5 Ma to ca. 51 Ma (Fig. 8). The oldest apatite samples from the central transect (samples 27–30, 38, and 39) are similar in age to zircons from the southern transect, suggesting that these relatively old apatite samples resided near the top of a PRZ, and are either unset or only minimally reset. Below 1.0 km (depth of sample 39), apatite ages get progressively younger. Figure 8 shows a possible interpretation of data, where a PRZ is identified between 0.4 and 2.5 km. Below 2.5 km, (U-Th)/He ages form a cluster at ca. 6 Ma, suggesting rapid exhumation at that time (Fig. 8). Using this paleodepth reconstruction, the relative position of the 80 °C isotherm is constrained to be between 2.2 and 2.5 km by sample 12LC11, the shallowest ca. 6 Ma sample, and sample 35, the deepest sample definitively within the PRZ. Using an assumed mean annual surface temperature of 10 ± 5 °C (Stockli et al., 2000), the calculated Late Miocene geothermal gradient is 30 ± 4 °C/km.

Although the pattern of cooling ages and calculated geothermal gradient, using the above interpretation, are broadly similar to those of the northern transect (Fig. 7), it implies that exhumation along Searles Valley fault zone initiated at 6 Ma in the central and southern parts of the Slate Range, and at 4 Ma in the north. Fault initiation at 6 Ma is not improbable, because extension is known to have occurred in the Death Valley area at that time (e.g., Topping, 1993; Snow and Lux, 1999). However, Pliocene cooling and fault histories are much more common for this part of the Basin and Range (e.g., Hodges et al., 1989; Snyder and Hodges, 2000; Monastero et al., 2002; Stockli et al., 2003; Andrew and Walker, 2009; Lee et al., 2009). The interpretation shown in Figure 8 also ignores a group of samples between 1.7 and 2.2 km that cluster between 12 and 14 Ma, coincident with the timing of initiation for the Slate Range detachment (Andrew and Walker, 2009). For these reasons, we prefer an alternative interpretation of our reconstructed samples, shown in Figure 9.
interpretation, two PRZs are identified from the data. The first is evident between 0.4 and 1.6 km (Fig. 9). Below 1.6 km, ages cluster between 12 and 14 Ma, recording an exhumation event at that time (Fig. 9). We interpret these samples to record cooling related to motion on the Slate Range detachment (consistent with the work of Andrew and Walker, 2009). While these samples were exhumed and cooled through the aplitie He PRZ in the Miocene, structurally deeper samples yield younger apparent ages (between ca. 5 and 9 Ma). Although the data are somewhat clustered, they show inconsistent age to paleodepth scatter. We therefore interpret these rocks to have resided in a second PRZ during Late Miocene to early Pliocene time; they were then exhumed and cooled during Pliocene motion on the Searles Valley fault. We accept the ca. 4 Ma age from the Manly Pass segment to be the most reliable time of initiation of faulting. For the central transect, motion on the fault was probably not sufficient to expose rocks that were originally below the PRZ for the Pliocene (Figs. 3, 6, and 9). In contrast, paleodepth reconstructions of the data from the southern transect suggest that samples 12LC03 and 12LC04 resided below the Pliocene PRZ (Fig. 6C). Unfortunately this could not be confirmed because inclusion-free aplitie grains were not identified within these samples.

Structural restoration using our preferred interpretation places the preextensional depth of the Middle Miocene 80 °C isotherm at 1.6 ± 0.2 km (Fig. 8). Based on an assumed mean annual surface temperature of 10 ± 5 °C (Stockli et al., 2000), the preextensional geothermal gradient is 45 ± 9 °C/km. The 45 °C/km geothermal gradient is elevated compared to average continental geothermal gradients of ~25 °C/km and significantly higher than the ~15 °C/km geothermal gradient documented for the nearby Inyo (Lee et al., 2009) and White Mountains (Stockli et al., 2003). Although local volcanic activity is consistent with relatively high heat flow and an elevated geothermal gradient during the Miocene in the Slate Range (Andrew and Walker, 2009), the high magnitude of the geothermal gradient suggests that there may be a problem with our absolute paleodepths. This is confirmed when evaluating the position of the 40 °C isotherm in both Figures 8 and 9 at 0.4 km, which is an unrealistically shallow depth. This suggests there was additional overburden in the central and southern parts of the Slate Range not accounted for in our reconstructions. Miocene sections to the east in the Panamint Range are typically 500 m thicker; if this is applied to the central and southern transects, then the 40 °C isotherm would have been at a more reasonable depth of ~1 km.

Extension across the central and southern transects is somewhat larger; we see the effects of both the Miocene and Pliocene to recent fault systems. In the Layton Canyon area, we estimate a minimum of ~9 km of east-west extension; 4 km of this is from the Slate Range detachment (the distance between the westmost klippe and its likely footwall equivalent to the east) and 5 km is from the Searles Valley fault (see Andrew and Walker, 2009). A significant component of the apparent horizontal displacement across the central Slate Range results from the post-Miocene tilting of a moderately dipping Slate Range detachment fault to low dips. This tilting appears to have occurred during initiation of the SVFZ; it occurred after the slip on the Slate Range detachment and before 4 Ma, the age of uniltled basalt flows in the nearby Argus Range (Andrew and Walker, 2009). If there is a general westward-moving wave of the initiation of transtensional deformation, then extensional faults in the Death Valley extensional system may have been active before transtension began in the Slate Range (ca. 11 Ma; Snow and Lux, 1999; ca. 8 Ma; Topping, 1993). The Death Valley extensional fault system dips to the west beneath the Panamint Range and probably also below the Slate Range; therefore, displacement on these systems could have led to similar amounts and orientations of tilted Miocene units of the hanging walls of the Panamint and Slate ranges before transtensional deformation began in this area.

**DISCUSSION**

Our age of ca. 4 Ma for cooling of the Searles Valley fault zone footwall rocks provides an

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![Graph](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/10/2/276/3332756/276.pdf)
important regional constraint on the timing of transition to transtensional deformation. Comparing the work of Mahan et al. (2009) and Monastero et al. (2002) with this study would indicate that the onset of dextral transtensional deformation was younger westward at this latitude, from ca. 5 Ma in southern Nevada, to 4 Ma in Searles Valley–southern Panamint Valley, to 3–2 Ma in Indian Wells Valley. These data therefore support the idea (presented in Stockli et al., 2003) of a westward progression in initiation of dextral transtension.

It is interesting that our ca. 4 Ma age is somewhat older than the 2.8 ± 0.7 Ma age for renewed motion on the eastern Inyo fault zone and start of motion on the Hunter Mountain fault (Fig. 1; Lee et al., 2009). This is significant in that motion on the Hunter Mountain fault is interpreted to transfer slip from the Panamint Valley fault zone onto the eastern Inyo fault zone in Saline Valley (e.g., Burchfiel et al., 1987; Lee et al., 2009), implying that the Panamint system started ca. 3 Ma (see Fig. 1 for structures and locations). Alternatively, in Walker et al. (2005) the Searles Valley fault zone and Panamint Valley fault zones were interpreted to be an integrated system of structures accomplishing dextral transtensional deformation in the region, implying a somewhat older age of initiation. This leads to several possible options for resolving this difference in age. (1) Uncertainties on the ages interpreted from the analytical data are underestimated, and the ages would overlap if larger and/or more reasonable errors were assigned. (2) The rapid cooling evident in age-depth profiles does not record the onset of faulting, but is imparted at somewhat different times. (3) Slip along the Panamint-Searles system did not initially link along the Hunter Mountain fault into Saline Valley, but rather continued northward through the Towne Pass area between the Panamint and Cottonwood mountains. Although all these scenarios are possible, we favor the last for several reasons. First, the errors seem reasonably computed and the ages are reproducible. Second, other studies show that rapid cooling is associated with fault initiation (see Stockli, 2005). Third, there is evidence for significant deformation in the Towne Pass area at the time motion began on the Searles system. Snyder and Hodges (2000) reported a large increase in the sedimentation rate for the Nova basin starting ca. 4 Ma and continuing to ca. 3 Ma; they also reported that faulting in the area is distributed in a complex manner between the Emigrant detachment and other structures over this time interval. Thus, it is our interpretation that the Panamint-Searles system initiated ca. 4 Ma, and that for the first 1 m.y. of its history fault deformation northward through the Emigrant and Towne Pass systems. This ceased ca. 3 Ma when deformation in northern Panamint Valley was transferred northwestward into Saline Valley via the Hunter Mountain fault.

If these interpretations are correct for the timing of extension and the initiation of transtension in the Slate Range, then regionally there may not be a change from local extension to transtension, but instead there is a spatial wave of the local initiation of major transtensional deformation structures that overprint an earlier discrete east-west extensional event, active only in the Middle to Late (?) Miocene. This idea may resolve the issue of comparing timing data derived from fault studies versus from plate tectonic data. The plate tectonic data indicate that transtensional deformation should have begun at 8–10 Ma (Atwater and Stock, 1998) after a period of east-west extension. Transtension in Death Valley seems to have begun at this time (Wernicke et al., 1988; Topping, 1993; Snow and Lux, 1999); but areas to the west (i.e., the Panamint and Slate Ranges) were not undergoing significant deformation until ca. 4 Ma (Hodges et al., 1989). Transtensional deformation then migrated westward in a series of jumps to structures farther west (Hodges et al., 1989; Andrew, 2005; Monastero et al., 2002). Transtensional faulting then began ca. 4 Ma in the Slate Range by the initiation of the Searles Valley fault zone.

CONCLUSIONS

Our new mapping and thermochronological data give important insights to the exhumation and extension of the Slate Range, California. The range is currently part of the eastern California shear zone and Walker Lane belt and is undergoing transtension on the Searles
Walker et al.

Valley fault zone. Transtensive activity started ca. 4 Ma when footwall rocks of the Searles Valley fault zone cooled below the apatite (U-Th)/He PRZ.

Apatite data from the central and southern Slate Range indicate that cooling started ca. 14 Ma. This is probably related to motion on the Slate Range detachment. This fault currently has a flat dip, but probably initiated with a dip closer to 25° to 50°, the dip of footwall Miocene strata and the cutoff angle of similar strata in the hanging wall, respectively. Overall extension during this phase was west directed, and has a minimum value of 4 km; this is the offset distance between Miocene strata in the hanging wall from the footwall nonconformity beneath coeval rocks. Assuming that extension is similar between the northern and central Slate Range, this gives a combined total extension in the range of ~9 km.

The timing of extension fits well with regional patterns. The beginning of transtensive deformation is somewhat older than that in Indian Wells Valley, but somewhat younger than in southern Nevada, suggesting that transtension is progressively younger westward.

ACKNOWLEDGMENTS

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