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Two-phase westward encroachment of Basin and Range extension into the northern Sierra Nevada

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[1] Structural, geophysical, and thermochronological data from the transition zone between the Sierra Nevada and the Basin and Range province at latitude ∼39°N suggest ∼100 km westward encroachment of Basin and Range extensional deformation since the middle Miocene. Extension, accommodated primarily by east dipping normal faults that bound west tilted, range-forming fault blocks, varies in magnitude from <2% in the interior of the Sierra Nevada crustal block to >150% in the Wassuk and Singatse Ranges to the east. Geological and apatite fission track data from exhumed upper crustal sections in the Wassuk and Singatse Ranges point to rapid footwall cooling related to large magnitude extension starting at ∼14–15 Ma. Farther to the west, geological and thermochronological data indicate a younger period of extension in the previously unextended Pine Nut Mountains, the Carson Range, and the Tahoe-Truckee depression initiated between 10 Ma and 3 Ma, and incipient post-0.5 Ma faulting to the west of the Tahoe-Truckee area. These data imply the presence of an extensional breakaway zone between the Singatse Range and the Pine Nut Mountains at ∼14–15 Ma, forming the boundary between the Sierra Nevada and Basin and Range at that time. In addition, fission track data imply a Miocene preextensional geothermal gradient of 27 ± 5°C km^{-1} in the central Wassuk Range and 20 ± 5°C km^{-1} in the Singatse Range, much higher than the estimated early Tertiary gradient of 10 ± 5°C km^{-1} for the Sierra Nevada batholith. This might point to a significant increase in geothermal gradients coupled with a likely decrease in crustal strength enabling the initiation of extensional faulting. Apatite fission track, geophysical, and geological constraints across the Sierra Nevada-Basin and Range transition zone indicate a two-stage, coupled structural and thermal westward encroachment of the Basin and Range province into the Sierra Nevada since the middle Miocene. *INDEX TERMS:* 8109 Techtonophysics: Continental tectonics—extensional (0905), 8015 Structural geology: Local crustal structure, 8035 Structural geology: Pluton emplacement, 5134 Physical properties of rocks: Thermal properties; *KEYWORDS:* extension, geochronology, Basin and Range, Sierra Nevada, fission track, structure

1. Introduction

[2] The eastern escarpment of the Sierra Nevada is one of the most prominent topographic and geologic boundaries in the Cordillera, separating the unextended Sierra Nevada crustal block on the west from the highly attenuated crust of the northern Basin and Range province on the east. However, closer examination of the region near Lake Tahoe (39°N) reveals a relatively broad structural transition zone between the northern Sierra Nevada and the northern Basin and Range province, where the magnitude of extension and the amount of westward tilting of individual extensional fault blocks increase from west to east, as the style of extensional faulting increases in complexity (Figure 1). Although the structural and thermal nature of the transition between the two physiographic provinces has been investigated in the southern Sierra Nevada [e.g., *Jones and Dollar*, 1986; *Saltus and Lachenbruch*, 1991; *Jones et al.*, 1994; *Ducea and Saleeby*, 1996; *Park et al.*, 1996; *Wernicke et al.*, 1996], the structural and thermal evolution of the northern transition zone at 39°N has not been previously studied in detail.

[3] Several workers [e.g., *Best and Hamblin*, 1978; *Wernicke*, 1992] have suggested that throughout the Basin and Range, localized areas of large magnitude extension gave way to later, more distributed extension in adjacent, less extended areas. Near latitude ∼39°N, *Dilles and Gans* [1995] hypothesized a ∼100 km westward migration of extensional deformation into the northern Sierra Nevada since ∼15 Ma on the basis of the spatial distribution and age of synextensional deposits. The concentration of contemporary seismicity along normal and right lateral faults which define the western margin of the Basin and Range province [e.g., *Eaton*, 1982; *Eddington et al.*, 1987] supports the inference that deformation associated with the Basin and Range is encroaching westward into relatively unextended areas [e.g., *Best and Hamblin*, 1978; *Christiansen and McKee*, 1978; *Jones and Dollar*, 1986; *Saltus and Lachenbruch*, 1991; *Jones et al.*, 1992; *Wernicke*, 1992]. Thus the transition zone between the provinces in the northern Basin and Range province provides an excellent opportunity to study the temporal and spatial evolution of extensional faulting, from a region of highly extended crust in the east to unextended crust in the west.

[4] Individual exhumed fault blocks across the transition zone (Figures 1 and 2) expose virtually intact sections of the preextensional granitic upper crust and thus allow us to study the timing of fault block exhumation and the thermal history of that crust using apatite fission track thermochronology [e.g., *Dumitru*, 1990; *Fitzgerald et al.*, 1991; *Howard and Foster*, 1996; *Miller et al.*, 1998; *Stockli et al.*, 2000]. The objective of this paper is to describe geologic, geophysical, and thermochronologic data that constrain both the timing of exhumation of individual tilted fault blocks and the spatial distribution of faulting through time as well as the thermal structure of the upper crust at the onset of extensional faulting.

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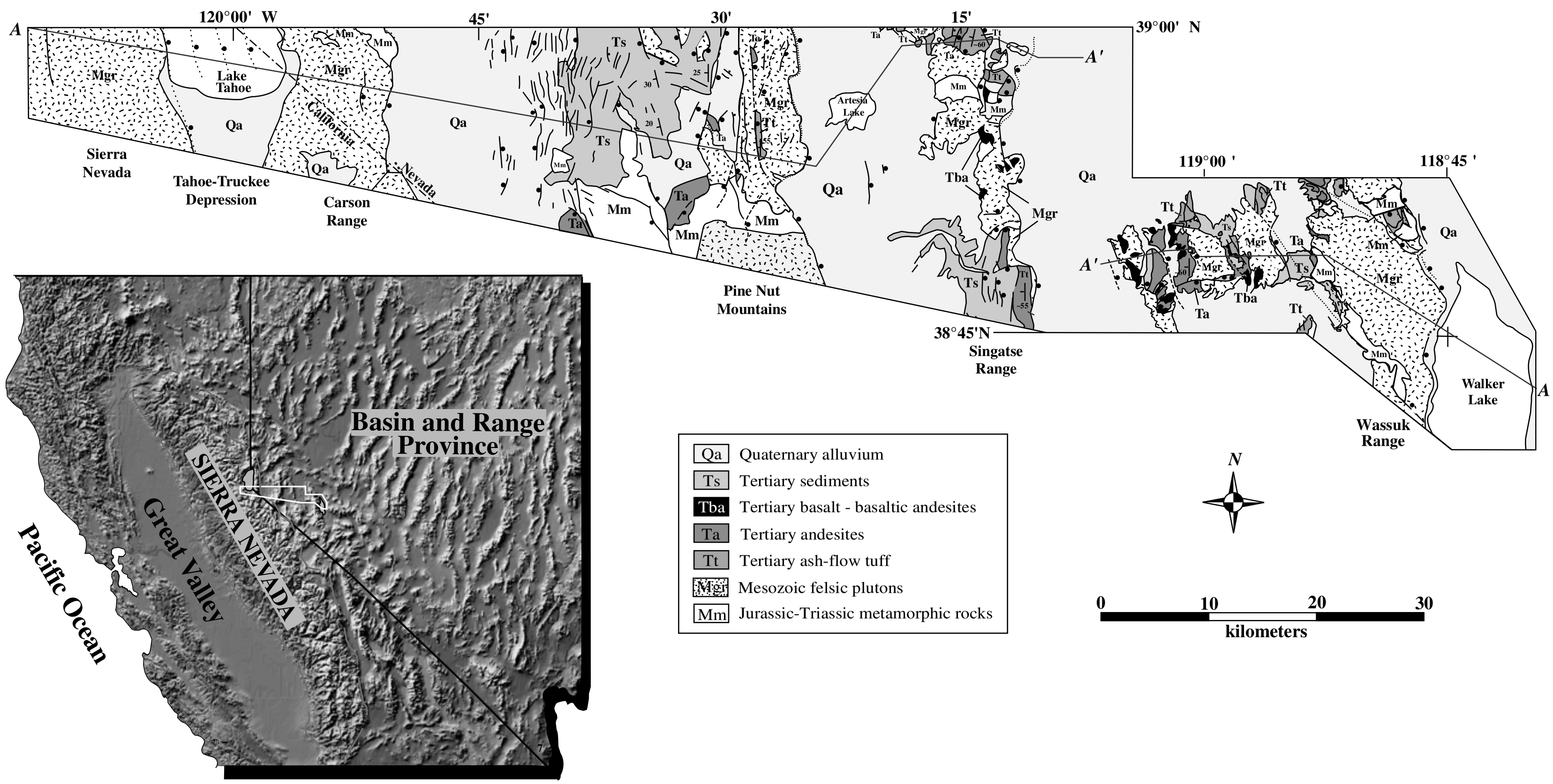

Figure 1. Geologic strip map of the northern Sierra Nevada-Basin and Range transition zone with digital relief map of California and Nevada. This is the geologic base map for the composite geological and geophysical cross section shown in Figure 2. Geologic data sources are as follows: Wassuk Range, *Bingler* [1978], *McIntyre* [1990], and *Surpless* [1999]; Singatse Range, *Proffett and Dilles* [1984] and *Stewart and Dohrenwend* [1984]; Pine Nut Mountains, *Moore and Archbold* [1969], *Stewart et al.* [1984] and *Stanford Geological Survey* [1986]; Carson Range, *Pease* [1979], *Armin and John* [1983], *Stewart et al.* [1984], and *Grose* [1985, 1986]. Boxed area on digital relief map is map area shown above. [The full size Figure 1 is available at http://www.agu.org/journals/tc.]

2. Geological and Geophysical Setting of the Sierra Nevada-Basin and Range Transition Zone

[5] The distinctive topography of the northern Sierra Nevada-Basin and Range province transition zone consists of several N-S trending mountain ranges and intervening basins (Figures 1 and 2) that are primarily the result of westward tilting of discrete, upper crustal fault blocks during Cenozoic time. From east to west, these fault-controlled structures are the Wassuk Range, the Singatse Range, the Pine Nut Mountains, the Carson Range, and the Tahoe-Truckee depression (Figures 1 and 2). These range-forming tilted fault blocks are predominantly composed of Middle Jurassic and Cretaceous granodiorite to granite with lesser amounts of thermally metamorphosed sedimentary and volcanic wall rocks of the former Sierran magmatic arc [e.g., *Dilles and Wright*, 1988]. Oligocene and later Cenozoic volcanic and sedimentary rocks unconformably overlie Mesozoic igneous and metamorphic basement and can be used to determine the timing of fault motion, the magnitude and direction of tilting associated with faulting, and displacements across individual normal faults. Differences in the magnitude and style of extensional faulting in mountain ranges within this transition zone result in variations in the maximum structural relief of exposure of the preextensional upper crust. In areas of large magnitude extension, such as the Wassuk and Singatse Ranges, near cross-sectional views of preextensional upper crust are now exposed ($\sim$8.4 km in the Wassuk Range and $\sim$7 km in the Singatse Range). In the west, where extension appears to be just beginning, such as in the Carson Range and the Tahoe-Truckee area, the magnitudes of fault offsets are considerably less, and footwall exhumation is not sufficient to expose thick sections of the preextensional upper crust.

[6] Geophysical features characteristic of extended continental crust are recognizable in the western Basin and Range province (Figure 2). These characteristics include subhorizontal reflectivity in the lower crust [e.g., *Klemperer et al.*, 1986; *Knuepfer et al.*, 1987; *McCarthy and Thompson*, 1988], low-relief topography of the Moho discontinuity, and a relatively thin crust [e.g., *Klemperer et al.*, 1986; *Allmendinger et al.*, 1987; *Fliedner et al.*, 1996]. The total lithospheric thickness beneath the transition zone increases to the west from <60 km below the Wassuk Range to >80 km beneath the Tahoe-Truckee area [e.g., *Mavko and Thompson*, 1983], and the depth of earthquake foci across the transition zone suggests an increase in thickness of the seismogenic, or brittle, crust beneath the Sierra Nevada relative to the northern Basin and Range province. In addition, heat flow values across the transition zone decrease to the west, from $\sim$90 mW m^{-2} to <40 mW m^{-2} in the unextended Sierra Nevada, with most of this decrease occurring between the Pine Nut Mountains and the western margin of the Tahoe-Truckee depression [e.g., *Blackwell et al.*, 1991]. All of these documented geophysical characteristics of the crust and lithosphere point to a transitional boundary between the two provinces, as suggested by upper crustal deformation (Figure 2).

3. Apatite Fission Track Thermochronology and the Thermal Histories of Exhumed Fault Blocks

[7] Apatite fission track thermochronology has been used extensively to determine the timing of cooling and exhumation of rocks in structurally intact, exhumed footwalls of major extensional fault systems [e.g., *Foster et al.*, 1990; *Fitzgerald et al.*, 1991; *Foster et al.*, 1994; *Howard and Foster*, 1996; *Miller et al.*, 1998; *Stockli et al.*, 2000]. Fission track dating of apatite is based on the decay of trace ^{238}U by spontaneous nuclear fission [e.g., *Fleischer et al.*, 1975; *Dumitru*, 2000]. The use of this method for thermochronologic analysis depends on the fact that fission tracks are partially or entirely annealed (erased) at elevated temperatures, causing reductions in both the lengths of individual tracks and the fission track ages. Fission tracks are shortened and partially annealed at subsurface temperatures between $\sim$60°–110°C, termed the partial annealing zone (PAZ); essentially, no annealing occurs at lower temperatures, and total erasure occurs at temperatures higher than $\sim$110°C [e.g., *Laslett et al.*, 1987; *Green et al.*, 1989].

[8] Preexhumation apatite fission track ages are expected to vary systematically with depth and thus burial temperature in the stable crust [*Green et al.*, 1989; *Dumitru*, 2000]. In the footwalls of normal faults, rocks are exhumed from substantial depths, and if fault slip has been rapid and of sufficient magnitude to exhume samples from below the PAZ, apatite fission track ages will directly date the timing of faulting and footwall exhumation [e.g., *Miller et al.*, 1998; *Stockli et al.*, 2000]. At increasingly shallow paleodepths, apparent ages become progressively older because fission tracks accumulate prior to the onset of exhumation. The observed PAZ may also be used to estimate the preextension paleotemperatures of samples from various depths and allow for the reconstruction of the preextensional thermal state of the crust.

4. Sampling Methodology

[9] Thirty-three thermochronology samples were collected primarily from Mesozoic quartz monzonite plutons along a $\sim$100 km E-W transect (Figures 1 and 2). In all cases, 5–10 kg thermochronologic samples were taken from outcrops of fresh, unaltered plutonic rocks sufficiently distant from exposed dikes to avoid thermal effects. Samples were collected along transects parallel to the extensional direction across individual exhumed fault blocks covering the maximum exposed preextensional structural relief. Fission track sample localities, counting, and age data for the Wassuk Range, the Singatse Range, the Pine Nut Mountains, and the Carson Range are displayed in Table 1. All Wassuk Range sample localities, paleodepth, counting data, and fission track age and length data are discussed by D. F. Stockli et al. (Thermochronological constraints on the timing and magnitude of Miocene and Pliocene extension in the central Wassuk Range, western Nevada, submitted to *Tectonics*, 2001, hereinafter cited as D. F. Stockli et al., submitted manuscript, 2001).

5. Miocene and Younger Evolution of the Wassuk Range and the Singatse Range

[10] Fault blocks in the central Wassuk Range and the Singatse Range are primarily composed of Jurassic and Cretaceous quartz monzonites unconformably overlain by Oligocene silicic ash flow tuffs (Figure 1). Extension in both ranges was large in magnitude (>150%) and was accommodated primarily by a first generation of east dipping normal faults initiated at high angles in the uppermost crust [*Proffett*, 1977; *Proffett and Dilles*, 1984; *Dilles and Gans*, 1995; *Surpless*, 1999]. Major extension was immediately preceded

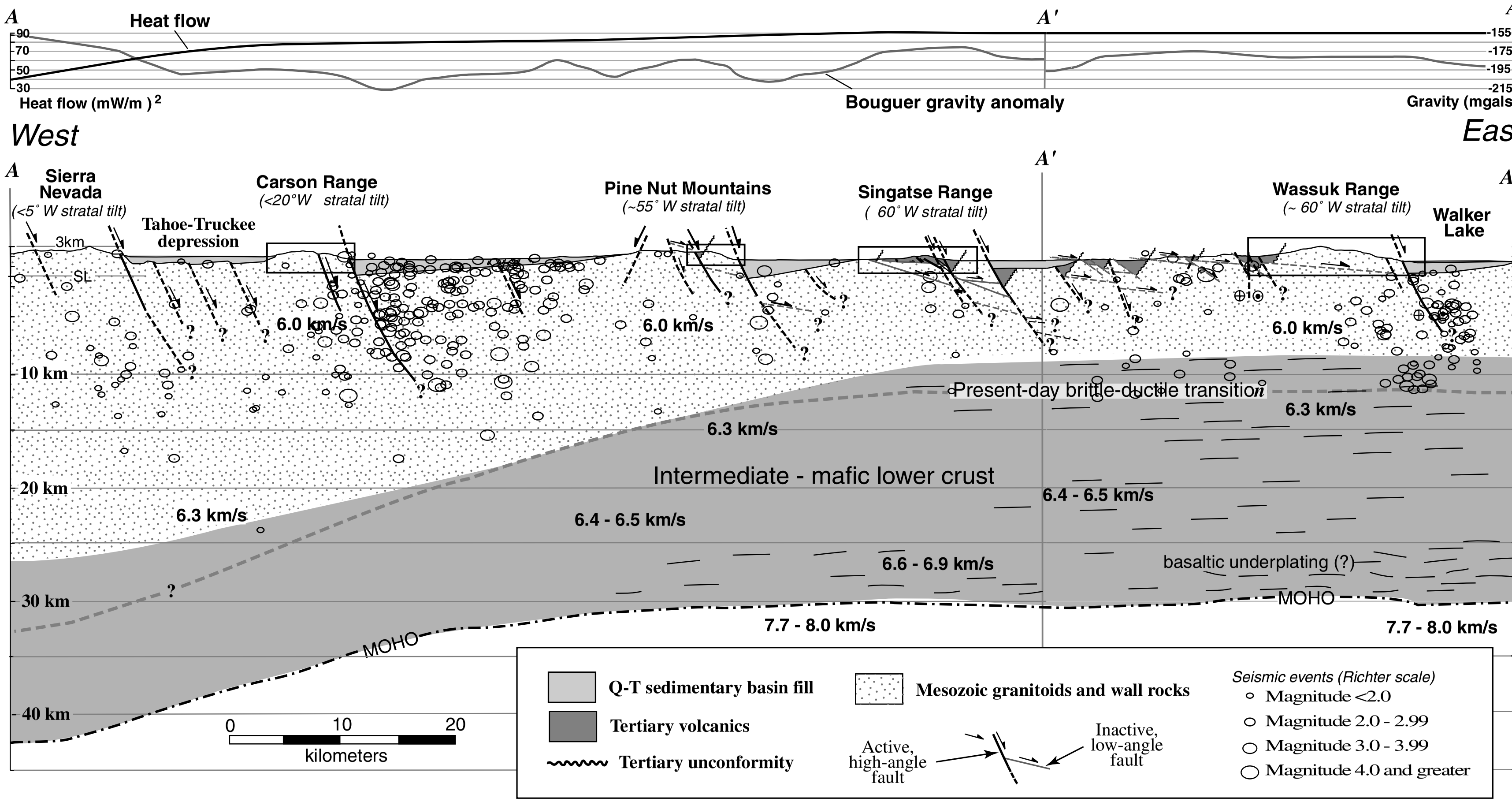

Figure 2. Composite geological and geophysical cross section of the northern Sierra Nevada-Basin and Range transition zone. Geological base map for this cross section is shown in Figure 1. The evolution of normal faulting across the transition zone has resulted in greater stratal tilts and greater structural complexity with increasing distance from the Sierra Nevada. Heat flow and seismicity data indicate a gradual thermal transition that coincides with the structural transition. The depth to the brittle-ductile transition (~350°C) is 10–15 km beneath the Basin and Range and deepens to over 30 km beneath the Sierra Nevada (on the basis of the assumption that the deepest seismic events define the thickness of the brittle upper crust), and the decrease in heat flow values accompanies a decrease in the magnitude of extension. Boxed areas are cross sections shown in Figures 3 and 5. (Sources of data for cross section are as follows: Moho depth, reflectivity, and relief, *Klemperer et al.* [1986]; velocity structure, *McCarthy and Thompson* [1988]; depth of seismicity/brittle-ductile transition, *Vetter et al.* [1983], *Hill et al.* [1991], Northern California Earthquake Data Center (NCEDC), and Council of the National Seismic System (CNSS) for the years 1950–1996 (between latitudes 38°30′ N and 39°15′ N); heat flow data, *Blackwell et al* [1991]; depth of sedimentary basins, calculated from gravity data: depth = $g_{max}/2\pi G\rho T$ [e.g., *Blakely*, 1995]; basaltic underplating, e.g., *Jarchow and Thompson* [1993]. [The full size Figure 2 is available at http://www.agu.org/journals/tc.]

by the eruption of Lincoln Flat hornblende andesite flows dated in the Wassuk Range by $^{40}Ar/^{39}Ar$ analyses of hornblende at 14.8–15.1 Ma [*Surpless*, 1999] and dated in the Singatse Range at 15.0–13.8 Ma [*Dilles and Gans*, 1995].

[11] In the Wassuk Range a single synextensional basaltic andesite flow dated by $^{40}Ar/^{39}Ar$ whole rock analysis at 14.4 ± 0.1 Ma [*Surpless*, 1999] constrains the magnitude of westward fault block tilt to ~25°–30° between ~15 Ma and 14.4 Ma (Figure 3). Between 14.4 Ma and 7 Ma, the evolution of extension is not well recorded by geologic relationships. During this latter period, synextensional deposition of the Tertiary Wassuk Group occurred in localized pull-apart basins bounded on the west by a second generation of east dipping normal to normal-dextral oblique-slip faults, which now dip 25°–40° to the east. The next major structural markers constraining the tilt history are 7 Ma basaltic andesite flows that now dip 8°–12° to the west [*McIntyre*, 1990; *Surpless*, 1999] (Figure 3). Extensional events in the central Wassuk Range have caused up to 60° of cumulative westward fault block tilt and have exposed ~8.4 km of the preextensional upper crust (Figures 2 and 3).

[12] In the Singatse Range, rapid extension continued until sometime before 13.0–12.6 Ma and caused 40°–45° of westward tilt, based on volumetrically minor andesite dikes of this age which crosscut previously active fault surfaces [*Dilles and Gans*, 1995; J. Dilles, personal communication, 1998]. Further tilt of the fault surfaces to subhorizontal occurred in conjunction with motion across younger normal faults that accommodated an additional 10°–15° westward tilt [*Proffett*, 1977; *Proffett and Dilles*, 1984; J. Dilles, personal communication, 1998]. Since the early episode of large magnitude extension, only minor extension has taken place in the Singatse Range. Documented extension has resulted in present-day westward fault block tilts of ≥60° and has exposed ~7 km thick sections of the preextensional upper crust (Figure 3).

6. Apatite Fission Track Thermochronology

[13] In the major fault blocks of both the central Wassuk Range and the Singatse Range, fission track apparent ages of samples from the exposed upper crustal section systematically decrease with increasing preextensional depth in the crust as measured structurally downward from the Tertiary unconformity (Figure 3). This systematic decrease in apparent ages is expected in the exhumed footwalls of major normal faults [e.g., *Foster et al.*, 1990; *Fitzgerald et al.*, 1991; *Foster et al.*, 1994; *Howard and Foster*, 1996; *Miller et al.*, 1998; *Stockli et al.*, 2000]. Sample data from middle to lower structural levels in both ranges display unimodal and narrow track length distributions, long mean track lengths (>13 μm), and apparent fission track ages that are essentially invariant with depth (Figures 3 and 4 and Table 1). The portion of the apparent age-paleodepth curve defined by these samples (samples 95BS-11.2 through 97BS-11.4b in the Wassuk Range and samples TDY-9 and TDY-10 in the Singatse Range) corroborates structural data that suggest a rapid cooling event at ~15 Ma in the Wassuk Range and ~14 Ma in the Singatse Range (Figure 4). This middle Miocene event exhumed rocks that formerly resided at or structurally below the top of the apatite total annealing zone (all samples >110°C [e.g., *Gleadow et al.*, 1986; *Green et al.*, 1989]).

[14] The apparent age-paleodepth curves for samples in the middle and upper structural levels display inflections at ~3.5 km paleodepth in the Wassuk Range (D. F. Stockli et al., submitted manuscript, 2001) and at ~5.0 km paleodepth in the Singatse Range (Figures 3 and 4). The structural depth of these inflections defines the paleodepth of the 110°C isotherm at the onset of the cooling event. This paleodepth suggests a geothermal gradient of 27° ± 5°C km^{-1} at the onset of extension in the central Wassuk Range (D. F. Stockli et al., submitted manuscript, 2001) and a geothermal gradient of 20° ± 5°C km^{-1} in the Singatse Range, assuming a mean annual surface temperature of 10° ± 5°C.

[15] Following this large magnitude extensional event, lower rates of extension prevailed in both ranges. In the Wassuk Range, the impressive relief across the east flank of the range, the concentration of seismicity (Figure 2), and (U-Th)/He data (D. F. Stockli et al., submitted manuscript, 2001) all suggest a lesser magnitude, but significant post-5 Ma cooling and exhumation event [*Surpless*, 1999]. This later episode of extension may be related to motion across the Walker Lane dextral shear zone, a major structure thought to accommodate a portion of the relative motion between the Pacific plate and the North American craton [e.g., *Stewart*, 1993].

[16] Thus geologic and thermochronologic data from both the Singatse Range and the Wassuk Range outline an episode of large magnitude middle Miocene extension accommodated along east dipping normal faults. This event was nearly synchronous in the two ranges, and the timing of extension is roughly similar to Basin and Range extensional faulting documented farther to the east throughout the central portion of the northern Basin and Range [e.g., *Stockli*, 1999] and to the southeast in southern ranges of the northern Basin and Range province [e.g., *Fitzgerald et al.*, 1991; *Wernicke and Snow*, 1998; *Stockli*, 1999]. Since that early event in the Wassuk and Singatse Ranges, much slower rates of extension appear to have prevailed across the eastern portion of the transition zone, now dominated by deformation associated with the Walker Lane Belt [e.g., *Oldow*, 1993; D. F. Stockli et al., submitted manuscript, 2001].

7. Miocene and Younger Evolution of the Pine Nut Mountains, the Carson Range, and the Tahoe-Truckee Graben

[17] The Pine Nut Mountains, the Carson Range, and the Tahoe-Truckee depression constitute the westernmost structural and topographic expressions of Basin and Range deformation at ~39°N latitude (Figures 1 and 2). These ranges are composed primarily of Cretaceous granodiorite to granite and are unconformably overlain by very minor Tertiary volcanics. The total magnitude of extension recorded in these western mountain ranges is substantially smaller than in the highly extended Singatse and Wassuk Ranges.

[18] The eastern flank of the Pine Nut Mountains is bound by an east dipping, high-angle normal fault (Figures 1 and 5). The only significant structural marker is the Oligocene Hartford Hill silicic ash flow tuff, which unconformably overlies Mesozoic quartz monzonite in the central part of the range and dips westward at attitudes of ~55° [*Moore and Archbold*, 1969; J. Dilles, personal communication, 1997] (Figures 1, 2, and 5). The thickness of preextensional upper crust now exposed in the Pine Nut Mountains is loosely constrained at 1.5–3.0 km because of the uncertainty in the overall attitude of the Hartford Hill tuff and the possibility of minor fault repetition of the section.

[19] Although the lack of structural data prevents a quantitative estimate of cumulative extension across the Pine Nut Mountains,

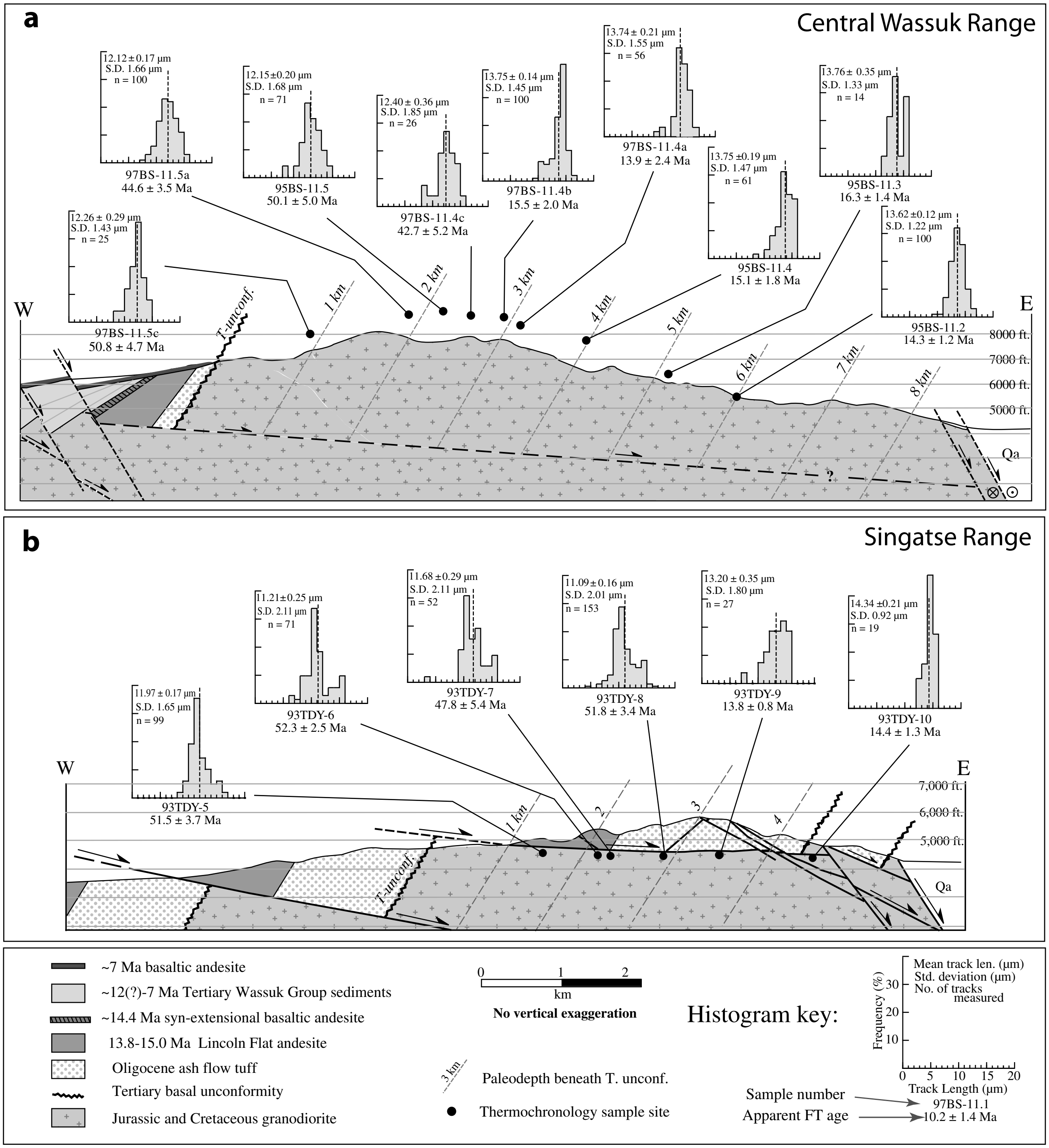

Figure 3. Simplified geological cross section of (a) the central Wassuk Range and (b) the Singatse Range, with apatite fission track apparent age and track length data. Key structural markers are illustrated schematically on these cross sections to help demonstrate the evolution of westward tilting in both ranges. The widespread ~60° west dipping Tertiary unconformity (T-unconf.) was used to establish an approximate preextensional horizontal beneath which preextensional structural depth was measured for each sample. Thermochronology samples are projected onto the line of section. Fission track data from the Wassuk Range are from D. F. Stockli et al. (submitted manuscript, 2001), and fission track data from the Singatse Range are in Table 1.

Table 1. Fission Track Sample Localities, Counting, and Age Data for the Singatse Range, the Pine Nut Mountains, and the Carson Range[a]

Sample	Latitude, North	Longitude, North	Elev, m	PD, km	Xls	Spontaneous		Dosimeter		$P(\chi^2)$, %	Rho-D	ND	Age, Ma	Length (n)
						Rho-S	NS	Rho-I	NI					
Singatse Range Apatite Samples														
93TDY-5	38°58′29″	119°15′49″	5440	3.65	8	0.6878	230	4.465	1493	83	1.738	5079	51.5 ± 3.7	11.97 ± 0.17 (99)
93TDY-6	38°58′32″	119°15′19″	5620	4.25	30	0.4781	646	3.048	4118	1.9	1.738	5079	52.3 ± 2.5	11.21 ± 0.25 (71)
93TDY-7	38°58′35″	119°15′17″	5640	4.3	9	0.1592	91	1.125	643	98	1.756	5079	47.8 ± 5.4	11.68 ± 0.29 (52)
93TDY-8	38°58′37″	119°14′49″	6020	4.6	29	0.4898	430	3.252	2855	3.3	1.756	5079	51.8 ± 3.4	11.09 ± 0.16 (153)
93TDY-9	38°58′43″	119°14′05″	5730	5.35	32	0.0812	327	2.018	8123	74	1.775	5079	13.8 ± 0.8	13.20 ± 0.35 (27)
93TDY-10	38°57′54″	119°13′42″	5280	6.55	26	0.0914	175	2.168	4147	13	1.775	5079	14.4 ± 1.3	14.34 ± 0.21 (19)
Pine Nut Mountains Apatite Samples														
95PN-1	38°53′44″	119°24′56″	1570	-	25	0.5356	616	4.023	4627	20.3	1.773	5090	41.3 ± 2.1	11.85 ± 0.14 (150)
95PN-2	38°53′51″	119°25′40″	2035	-	30	0.5984	395	3.847	2539	17.1	1.779	5090	48.1 ± 3.0	12.44 ± 0.15 (100)
95PN-3	38°54′02″	119°26′17″	2280	-	30	0.6619	424	3.856	2470	85.7	1.786	5023	53.6 ± 2.9	13.03 ± 0.14 (100)
95PN-4	38°54′26″	119°26′55″	2270	-	25	0.5416	497	3.45	3166	86.5	1.792	5023	49.0 ± 2.5	12.88 ± 0.15 (120)
Carson Range Apatite Samples														
97BS-CR-1	38°56′15″	119°50′52″	1524	-	25	0.5853	854	3.918	5717	44.1	1.608	4786	42.6 ± 1.7	12.38 ± 0.13 (100)
97BS-CR-2	38°56′18″	119°51′22″	1720	-	25	0.5882	852	3.927	5688	80	1.608	4786	42.7 ± 1.7	12.97 ± 0.15 (100)
97BS-CR-3	38°55′54″	119°52′01″	1890	-	25	0.5979	601	3.45	3468	96.6	1.618	4786	49.7 ± 2.3	12.76 ± 0.14 (100)
97BS-CR-4	38°55′48″	119°53′33″	2073	-	25	1.795	684	9.164	3492	74.6	1.618	4786	56.2 ± 2.5	13.39 ± 0.14 (100)
97BS-CR-5	38°55′35″	119°52′42″	2220	-	25	0.6371	537	3.993	3365	40.1	1.629	4786	46.1 ± 2.2	13.10 ± 0.12 (100)
97BS-CR-6	38°56′20″	119°52′30″	2390	-	25	1.31	810	7.265	4492	10.5	1.629	4786	52.4 ± 2.5	13.09 ± 0.16 (100)
97BS-CR-7	38°55′03″	119°54′03″	3040	-	25	0.8493	644	4.131	3132	76.5	1.64	5007	59.7 ± 2.7	13.63 ± 0.13 (100)
97BS-CR-8	38°55′00″	119°54′44″	2835	-	25	1.252	13-41	5.377	5760	75.4	1.64	5007	67.6 ± 2.3	13.70 ± 0.13 (100)
97BS-CR-9	38°55′30″	119°55′03″	2615	-	25	1.169	915	5.414	4237	53.1	1.651	5007	63.1 ± 2.5	13.82 ± 0.10 (100)
97BS-CR-10	38°55′27″	119°56′06″	2378	-	25	0.9123	886	4.057	3940	35.6	1.651	5007	66.0 ± 2.8	13.72 ± 0.11 (100)
97BS-CR-11	38°55′45″	119°56′17″	2220	-	25	1.055	791	4.619	3462	29.6	1.656	5007	66.8 ± 3.1	13.65 ± 0.12 (100)
97BS-CR-12	38°55′56″	119°56′30″	2073	-	25	1.021	670	4.967	3259	100	1.672	5007	60.9 ± 2.7	13.49 ± 0.13 (100)

[a]Abbreviations are as follows: Elev, sample elevation; PD, paleodepth below preextensional surface with calculated 2.0 km overburden in the Singatse Range; Xls, number of individual grains dated; Rho-S, spontaneous track density ($\times 10^6$ tracks per square centimeter); NS, number of spontaneous tracks counted, Rho-I, induced track density in external detector (muscovite) ($\times 10^6$ tracks per square centimeter); NI, number of induced tracks counted; $P(\chi^2)$, χ^2 probability [*Galbraith,*1981; *Green,*1981]; Rho-D, induced track density in external detector adjacent to dosimetry glass ($\times 10^6$ tracks per square centimeter); ND, number of tracks counted in determining Rho-D. Age is the sample central fission track age; central age given [*Galbraith and Laslett,* 1983] and calculated using zeta calibration method [*Hurford and Green,*1983]. Length is the average track length, and n is the number of fission tracks measured. The following is a summary of key laboratory procedures. Samples were analyzed by D. Stockli (samples 95PN-1 through 95PN-4 and samples 97BS-CR-1 through 97BS-CR-12) and T. Dumitru (samples 93TDY-5 through 93TDY-10). All apatites were etched for 20 s in 5 N nitric acid at room temperature. Grains were dated by external detector method with muscovite detectors. The CN5 dosimetry glass was used as a neutron flux monitor. Zeta calibration factors were as follows: 356.0 (D. Stockli) and 389.5 (T. Dumitru). Samples were irradiated in well-thermalized positions at the Oregon State University reactor. External detectors were etched in 48% HF. Tracks were counted with Zeiss Axioskop microscope with 100× air objective, 1.25× tube factor, 10× eye piece, transmitted light with supplementary reflected light as needed; external detector prints were located with Kinetek automated scanning stage [*Dumitru*, 1993]. Only grains with *c* axes subparallel to slide plane were dated. Confined track lengths were measured only in grains with *c* axes subparallel to slide plane; only horizontal tracks measured (within ± 5° – 10°), following protocols of *Laslett et al.* [1982]. Lengths were measured with computer digitizing tablet and drawing tube, calibrated against stage micrometer [e.g., *Dumitru*, 1993].

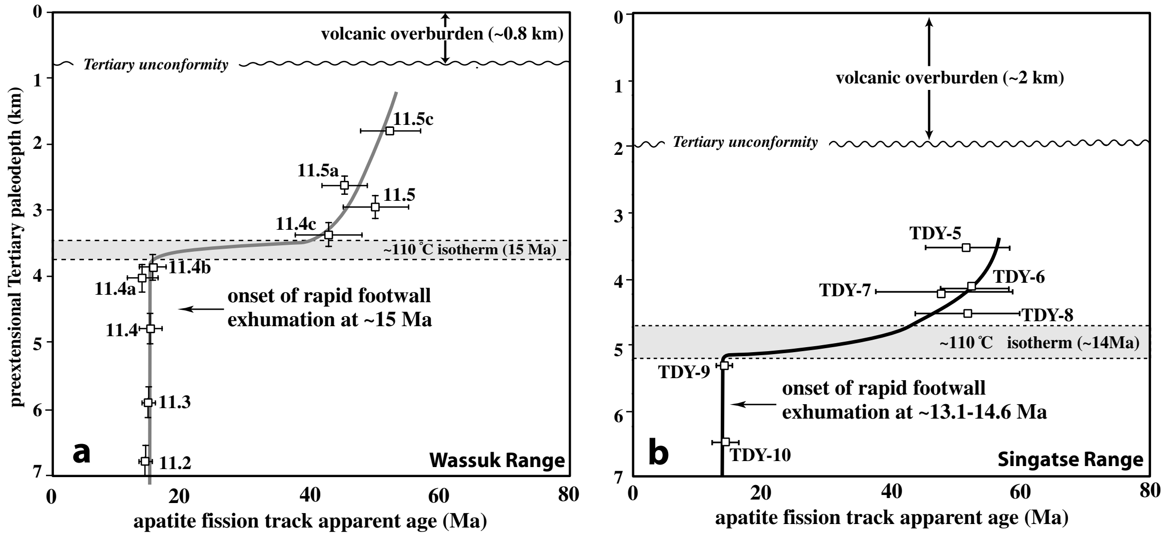

Figure 4. Apparent apatite fission track ages from the central Wassuk Range and the Singatse Range, plotted against preextensional paleodepth. Errors shown are $\pm 2\sigma$. (a) In the Wassuk Range, fission track data suggest a $\sim$15 Ma cooling event related to footwall exhumation. The apparent age-paleodepth curve indicates a geothermal gradient of $27 \pm 5°C\ km^{-1}$ prior to exhumation. (b) In the Singatse Range, fission track data suggest a cooling event at $\sim$13.1–14.6 Ma related to footwall exhumation. The apparent age-paleodepth curve indicates a geothermal gradient of $20 \pm 5°C\ km^{-1}$ prior to exhumation. Fission track data from the Wassuk Range are from D. F. Stockli et al. (submitted manuscript, 2001), and fission track data from the Singatse Range are listed in Table 1.

the $\sim$55° westward dip in Oligocene tuff within the central range suggests the possibility of large magnitude extension, and the much more shallowly dipping 15°–35° tilts of early Miocene strata on the west flank of the Pine Nut Mountains [*Moore and Archbold*, 1969; L. Garside, personal communication, 1998] suggest a poorly exposed middle Miocene fault zone immediately west of the exposure of the Oligocene tuff (J. Oldow, personal communication, 1997; L. Garside, personal communication, 1998; Figures 1, 2, and 5).

[20] West of the Pine Nut Mountains the Carson Valley is considered the alluviated backslope of the Pine Nut Mountains tilted fault block (Figures 1 and 2). Gravity data indicate that the floor of bedrock beneath the Carson Valley is tilted to the west, with the thickest section of valley fill considerably west of the center of the valley [e.g., *Moore and Archbold*, 1969; *Plouff*, 1984]. West tilting of the valley was caused by normal motion along the range-bounding fault on the east side of the Carson Range and has continued to the present, causing the Carson River to flow on the west side of the valley rather than in its center [e.g., *Moore and Archbold*, 1969].

[21] The planar, east dipping, high-angle Genoa frontal fault system [*Pease*, 1979] bounds the Carson Range on the east and has accommodated <10% extension (Figure 2). It is characterized by significant contemporary seismicity, indicating continued uplift and extension in the area, with a minor component of dextral motion [e.g., *Pease*, 1979; *Surpless*, 1999]. The fault displays dip-slip normal separation on the order of 3–3.5 km on the basis of gravity data, but only 1–1.5 km of the preextensional granitic upper crust is exposed owing to burial by Tertiary and Quaternary sediments (Figure 2).

[22] The timing of faulting that formed the Tahoe-Truckee depression is only loosely constrained. *Henry and Perkins* [2001] showed evidence for a small magnitude extensional episode to the north of the Tahoe-Truckee area at $\sim$12 Ma, and crosscutting relationships of faults and basalt flows loosely bracket the inception of significant extensional faulting in the area between 7 Ma and 2 Ma [*Dalrymple*, 1964]. This later extensional episode most likely postdated the extrusion of nearly flat-lying andesite flows in the Sierra Nevada that unconformably overlie granitic rocks at the heads of several major canyons. The youngest of these units has been dated at 3.6 Ma [*Saucedo and Wagner*, 1992], which agrees with *Henry and Perkins*' [2001] evidence for the onset of extensional faulting just to the north of the Carson Range and Tahoe-Truckee area at $\sim$3 Ma.

7.1. Apatite Fission Track Thermochronology

[23] The small sections of preextensional upper crust exposed in the Pine Nut Mountains and the Carson Range (1.5–3.0 km and 1.0–1.5 km, respectively) and the poorly constrained sample paleodepths prevent detailed thermochronologic analysis of these fault blocks (Figure 5). However, the structurally deepest samples in both mountain ranges (samples PN-1, PN-2, and PN-3 in the Pine Nut Mountains and samples 97CR-1, 97CR-2, and 97 CR-3 in the Carson Range) display decreasing mean track length, decreasing age, and an increase in spread of track length distribution with increasing structural depth (Figure 5). These features suggest exhumation of the upper portion of the apatite PAZ. A likely mechanism for exhumation of these samples is normal motion across east dipping range-bounding faults along the east flanks of the Pine Nut Mountains and the Carson Range (Figures 1, 2, and 5).

[24] In addition to constraining the timing of faulting and the thermal evolution, the sampling transect across the Carson Range fault block was devised to quantify the amount of westward fault

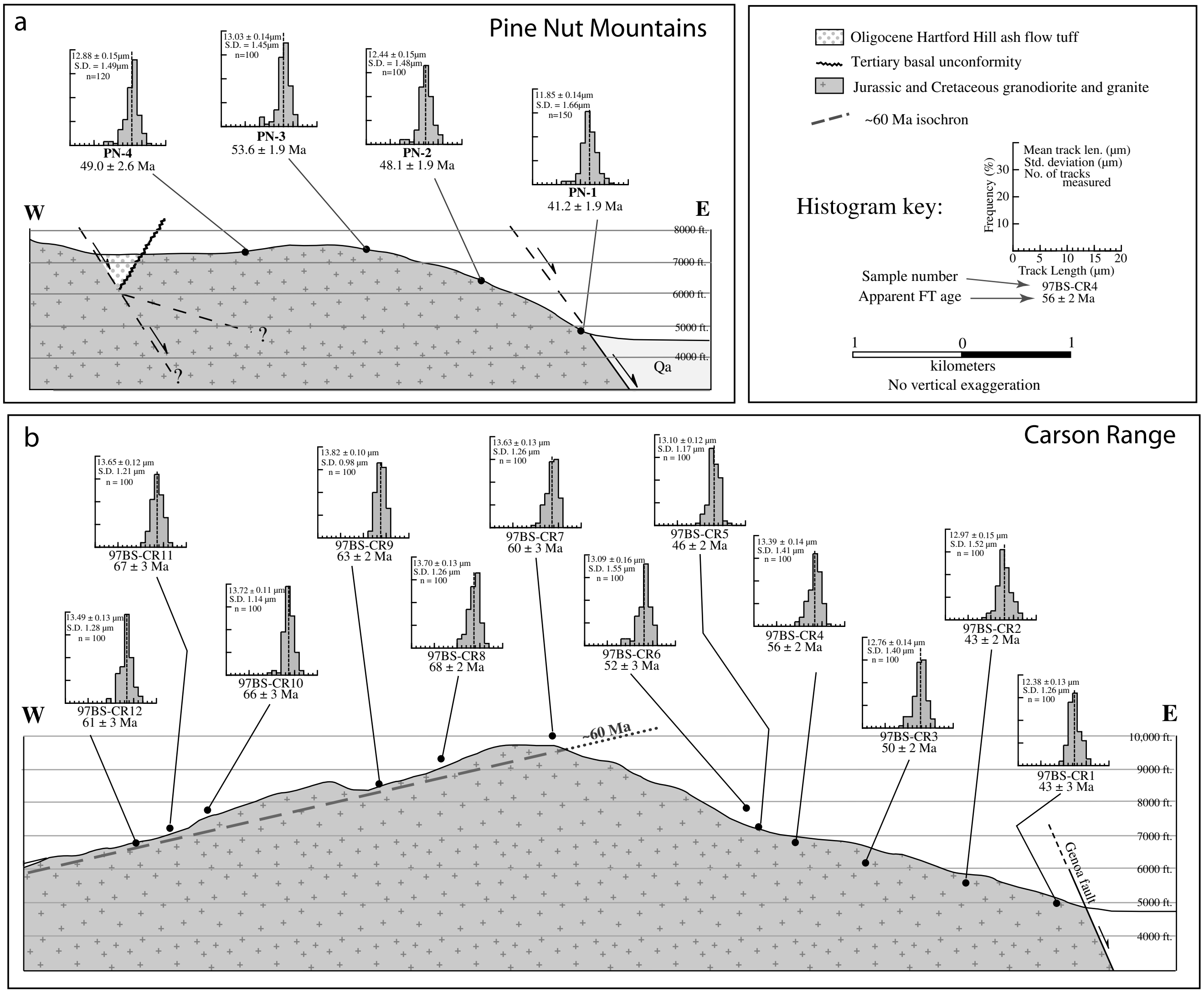

Figure 5. Structural and thermochronological cross sections of the east flank of (a) the Pine Nut Mountains and (b) the central Carson Range, with apatite fission track apparent age and track length data. Fission track data are listed in Table 1.

block tilting. Samples 97BS-CR-7 through 97BS-CR-12 all display long mean track lengths (>13.4 μm) and apparent ages between ∼60 Ma and ∼70 Ma (Figure 5). These data delineate a 60 Ma isochron that dips at ∼15° to the west, roughly following the present-day slope of the west flank of the Carson Range (Figure 5). The west slope of the Carson Range bounds the eastern margin of Lake Tahoe, but no systematic trend in fission track data could be detected attributable to west dipping normal faults, which would be expected in the classic model of symmetric graben formation [e.g., *Birkeland*, 1963]. These data suggest that the Carson Range is a west tilted fault block and strongly support *Lahren and Schweickert*'s [1995] reinterpretation of the Tahoe-Truckee depression as an asymmetric half graben bound by major east dipping faults on the western margin of the depression. This 15° westward tilt requires significant motion along an east dipping fault surface located on the west flank of the Tahoe-Truckee depression; this structure is likely the West Tahoe fault, which displays a minimum of 1280 m of down to the east displacement [*Lahren and Schweickert*, 1995]. This asymmetric model for basin formation is consistent with the structural style of faulting on the western margin of the Basin and Range at this latitude.

7.2. Apatite Fission Track Length Modeling

[25] The magnitude of fault slip along the Pine Nut Mountains and the Carson range bounding faults is not sufficient to expose rocks that resided below the base of the apatite fission track PAZ, so the onset of faulting cannot be dated directly with the methods used in the Wassuk Range and the Singatse Range. Instead, track-length distributions and age data were modeled using the Monte Trax program of *Gallagher* [1995]. The stochastic modeling program utilizes a Monte Carlo-type approach with a genetic algorithm. Partially annealed apatite fission track apparent age and length data were used to constrain the thermal (T < 110°C)

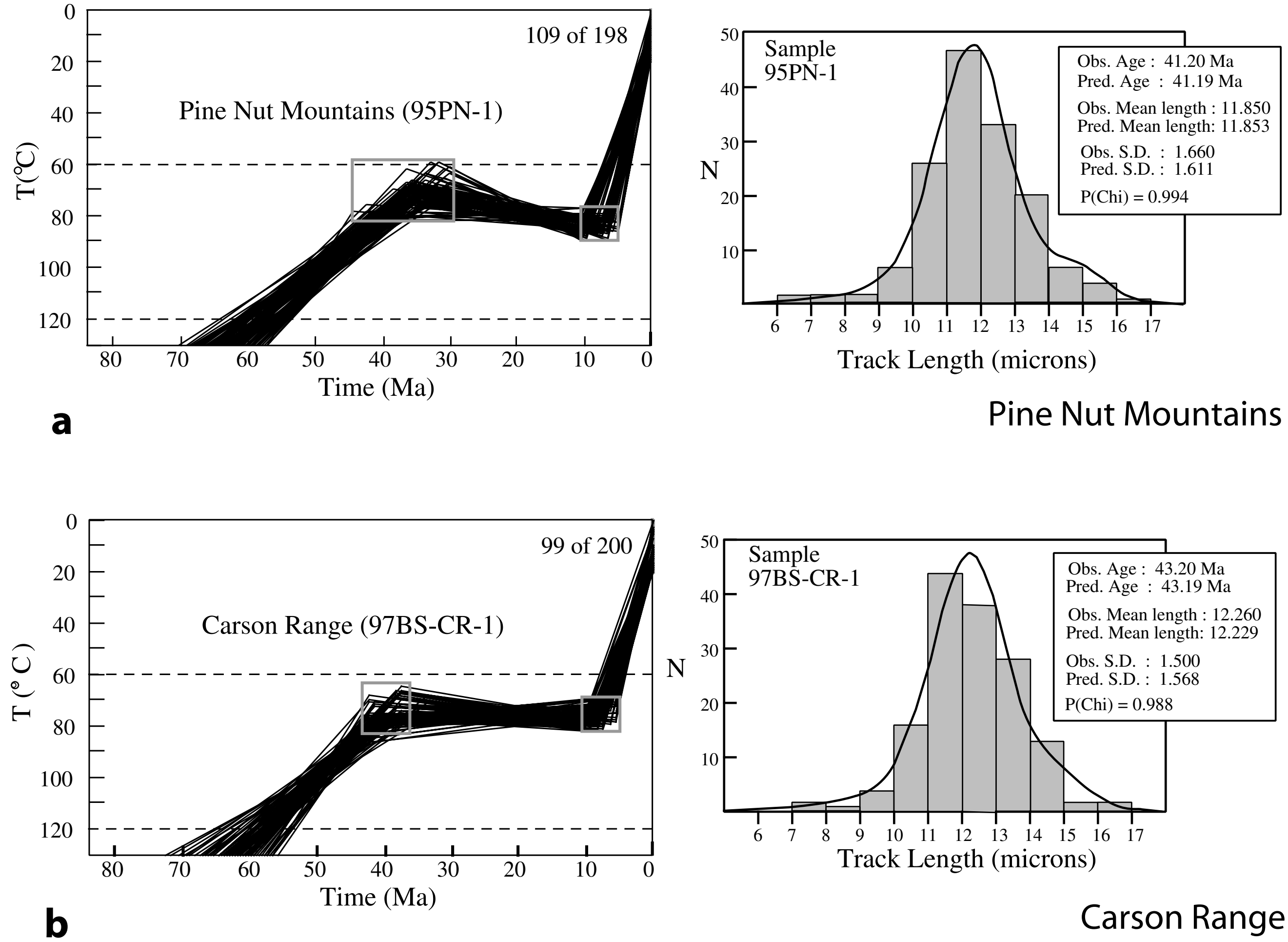

Figure 6. Time-temperature plots displaying "best-run" model thermal histories for samples from (a) the Pine Nut Mountains and (b) the Carson Range. These samples were chosen because they are the structurally deepest samples from each mountain range and should therefore retain the most thermal information. Black lines represent the thermal histories that produce data that best fits the observed fission track parameters. The outlined boxes (left diagrams) enclose the nodes of all thermal histories and in both ranges suggest cooling related to footwall uplift at between 10 and 3 Ma. For the Pine Nut Mountains sample, the best 109 of 198 thermal models are shown, and for the Carson Range sample, the best 99 of 200 model runs are shown. Modeling was completed using the program Monte Trax [*Gallagher*, 1995].

evolution of single samples from the extensional footwall blocks of the Pine Nut Mountains and the Carson Range. These model runs constrain the pre-Miocene cooling history of these samples and also define temporal aspects of cooling related to younger fault motion (Figure 6). These model thermal histories produce predicted apparent ages, track-length distributions, and standard deviations that are compatible with the observed fission track parameters (Figure 6).

[26] Fission track modeling suggests an early period of protracted uplift beginning at ~70 Ma to ~60 Ma and continuing until between ~45 Ma and ~30 Ma in both ranges, which is consistent with Late Cretaceous-Early Tertiary erosional denudation due to crustal thickening [e.g., *Coney and Harms*, 1984; *Smith et al.*, 1991]. This event resulted in a widespread Tertiary unconformity across much of the Basin and Range province. In the Pine Nut Mountains, eruption of the Oligocene Hartford Hill ash flow tuff marks the end of this period of erosion. The modeled thermal histories suggest relative tectonic quiescence in the Pine Nut Mountains and Carson Range until the late Cenozoic, when these fault flocks underwent rapid cooling and exhumation (Figure 6). This event is most likely related to fault block tilting and footwall exhumation in both the Pine Nut Mountains and the Carson Range between ~10 and ~3 Ma (Figure 6).

8. Extensional Deformation Within the Sierra Nevada Block

[27] The Sierra Nevada has long been considered a fairly rigid crustal block that was uplifted and tilted westward during late Cenozoic time [e.g., *Christensen*, 1966; *Hamilton and Myers*, 1966; *Chase and Wallace*, 1988]. Stratigraphic relations of tilted

river channel sediments suggest that Cenozoic uplift of the Sierran block by extensional faulting along its eastern flank probably began at a slow rate at ~25 Ma and has accelerated since ~10 Ma [*Huber*, 1981; *Unruh*, 1991]. Although the cause of this uplift remains controversial [e.g., *Small and Anderson*, 1995], recent xenolith, magnetotelluric, refraction, and reflection studies in the southern Sierra Nevada at latitude 36°–37°N do reveal possible thinning of the mantle lithosphere beneath both the eastern Sierra Nevada and the adjacent Basin and Range by a factor of 2 since ~20 Ma [*Jones et al.*, 1994; *Park et al.*, 1996; *Wernicke et al.*, 1996]. In the Tahoe-Truckee area and Carson Range, faulting has resulted in shallow westward dips in late Cenozoic volcanic rocks [e.g., *Grose*, 1986]. We consider the Carson Range as the westernmost Basin and Range fault block, and thus argue that the fault system that bounds the western margin of the Lake Tahoe basin represents the present-day boundary between the Sierra Nevada block and the northern Basin and Range province at 39°N latitude.

[28] However, encroachment of normal faulting into the region west of the Tahoe-Truckee half graben appears to continue today. Down to the east normal fault motion, and consequent westward tilting of fault blocks, has been documented in the Sierra Nevada north and west of the Tahoe-Truckee half graben, at ~40° N latitude, with the most recent documented offsets of volcanic units occurring since 0.5 Ma (J. Wakabayashi, personal communication, 1998). *Sawyer et al.* [1993] have also documented a decrease in dip-slip fault displacements with increasing distance from the Sierran escarpment, confirming the probability of incipient faulting and westward migration of Basin and Range extensional deformation into the main Sierra Nevada block.

9. Conclusions

[29] Geological, thermochronological, and geophysical data from range-forming, tilted fault blocks across the Sierra Nevada-Basin and Range transition zone support a probable two-stage westward encroachment of extensional deformation into the former Sierran magmatic arc since the middle Miocene. The timing of the onset of extensional faulting and rapid exhumation of fault-bound upper crustal blocks constrained by both thermochronological and geological data appears to be nearly synchronous in the central Wassuk Range and the Singatse Range, with the onset of extension beginning at ~15 Ma in the Wassuk Range and propagating west at 14.6–13.1 Ma in the Singatse Range. In both the Wassuk and the Singatse Ranges, the eruption of the Lincoln Flat andesite appears to immediately precede the onset of major extension. The similarities in timing of magmatism, extension, and structural style suggest a large magnitude mid-Miocene extensional event characterized by westward tilt of fault blocks along more than one generation of eastward dipping normal faults producing ≥150% extension across this region.

[30] This timing of extension in the Wassuk and Singatse Ranges agrees with the onset of normal faulting in mountain ranges of the central Basin and Range province farther to the east [*Stockli*, 1999]. The western limit, or breakaway zone, of this major extensional faulting event appears to be to the west of the highly extended Singatse Range and east of the Pine Nut Mountains. We argue that this breakaway zone represented the boundary between the highly extended Basin and Range province and the almost unextended Sierra Nevada in middle Miocene times. Although the structural evolution of the Pine Nut Mountains is not well studied, geological data and modeling of fission track data suggest a ≤10 Ma onset of significant extension in the Pine Nut Mountains, which supports our temporal and spatial position of the breakaway zone and might indicate formation of a new breakaway zone to the west of the Pine Nut Mountains at ≤10 Ma. At the western end of the transect in the Carson Range and the Tahoe-Truckee depression (Figures 1 and 2), extension is of distinctly lesser magnitude and is accommodated by single sets of high-angle normal faults. Thermochronologic and geologic data suggest that the onset of significant extensional faulting is younger than 10 Ma in these areas, with most extension in the Tahoe-Truckee asymmetric half graben accommodated along east dipping faults after 5 Ma, which appears to be similar to geological data to the north [*Henry and Perkins*, 2001]. Since the onset of extension in the Wassuk and Singatse Ranges at ~14–15 Ma, the eastern escarpment of the Sierra Nevada has migrated from east of the Pine Nut Mountains to its present position on the western margin of the Tahoe-Truckee depression, and very recent (<0.5 Ma) incipient faulting to the north and west of the West Tahoe fault suggests that the westward encroachment of extension continues today.

[31] Thermochronologic data and thermal modeling of data sets from the less extended areas in the west suggest a period of protracted cooling beginning at ~70 Ma to ~60 Ma and continuing until between ~45 Ma and ~30 Ma. The data are compatible with a history of earlier crustal thickening [e.g., *Coney and Harms*, 1984; *Smith et al.*, 1991] followed by erosional unroofing of the Sierran batholith, culminating with the development of the Tertiary unconformity exposed across the transition zone today (Figures 1 and 2). This long period of cooling broadly coincides with the time of Laramide-age shallow-angle subduction [e.g., *Bird*, 1988] that was also responsible for establishing low geothermal gradients across the present-day transition zone and much of the western United States [e.g., *Dumitru et al.*, 1991]. The low geothermal gradient of the present-day Sierran block is considered a transient effect of the conductive cooling by the subducted ocean slab [e.g., *Dumitru*, 1991], and prior to dissection of the area by Basin and Range extension, it is likely that the entire transition zone was part of this reduced heat flow province.

[32] The middle Miocene geothermal gradients established by fission track data in the Wassuk and Singatse Ranges (27° ± 5°C km^{-1} and 20° ± 5°C km^{-1}, respectively) document an increase in upper crustal temperatures at the onset of large magnitude extension. In the Wassuk Range the large volume of andesites extruded immediately prior to extension suggests significant advective heating of cooler crust, a potential trigger for the documented extensional event. The high modern geothermal gradients in the eastern part of the transition zone required by heat flow values, seismicity, and seismic reflection data are in part the result of crustal thinning due to extension and theorized magmatic underplating [e.g., *Jarchow and Thompson*, 1993]. A hot, low-velocity upper mantle beneath the western Basin and Range [*Mavko and Thompson*, 1983] also contributes to the high geothermal gradient in the area.

[33] Today, the region characterized by geothermal gradients that are on the order of those estimated for the Singatse and Wassuk Ranges in the middle Miocene lies farther to the west, likely beneath the seismically active Carson Range (Figures 1 and 2),

suggesting a westward migration of heating of the upper crust over the last 15 m.y. As *Saltus and Lachenbruch* [1991] documented in the southern Sierra Nevada, a thermal pulse may have preceded the westward encroachment of Basin and Range extensional faulting into the former Sierran magmatic arc at the latitude of Lake Tahoe. In our model, a thermal pulse weakens the formerly cold crust of the Sierran crustal block to a critical value at which the local stress field causes failure in the form of brittle faulting. Although this model is not original [e.g., *Kuznir and Park*, 1987], it explains the existing geological, stratigraphic, geophysical, and thermochronological data exceedingly well. Our data provide evidence that changes in the thermal structure and thus the strength of the crust may be essential to the onset of large magnitude extension and the growth of extensional provinces, and in the case of the northern Sierra Nevada-Basin and Range transition zone, our data document a two-phase westward encroachment of Basin and Range extensional faulting into the Sierra Nevada crustal block.

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