Cenozoic exhumation of the northern Sierra Nevada, California, from (U-Th)/He thermochronology

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ABSTRACT

Apatite and zircon (U-Th)/He ages from a 100-km-long range-perpendicular transect in the northern Sierra Nevada, California, are used to constrain the exhumation history of the range since ca. 90 Ma. (U-Th)/He ages in apatite decrease from 80 Ma along the low western range flanks to 46 Ma in the higher elevations to the east. (U-Th)/He ages in zircon also show a weak inverse correlation with elevation, decreasing from 91 Ma in the west to 66 Ma in the east. Rocks near the range crest, sampled at elevations of 2200–2500 m, yield the youngest apatite helium ages (46–55 Ma), whereas zircon helium ages are more uniform across the divide. These data reveal relatively rapid cooling rates between ca. 90 and 60 Ma, which are consistent with relatively rapid exhumation rates of 0.2–0.8 km/m.y., followed by a long period of slower exhumation (0.02–0.04 km/m.y.) from the early Paleogene to today. This is reflected in the low-relief morphology of the northern Sierra Nevada, where an Eocene erosional surface has long been identified. A long period of slow exhumation is also consistent with well-documented, widespread lateritic paleosols at the base of Eocene depositional units. Laterites preserved in the northern Sierra Nevada are the product of intense weathering in a subtropical environment and suggest an enduring, soil-mantled topography. We interpret this exhumation history as recording a Late Cretaceous to early Cenozoic period of relatively rapid uplift and unroofing followed by tectonic quiescence and erosional smoothing of Sierran topography through the Neogene. Well-documented recent incision appears to have had little effect on (U-Th)/He ages, suggesting that less than ~3 km has been eroded from the Sierra Nevada since the early Cenozoic.

Keywords: Sierra Nevada, tectonics, exhumation, paleotopography, thermochronology.

INTRODUCTION

Knowledge of the thermal and exhumation histories of mountain belts can provide important constraints on their tectonic and geomorphic evolution. Low-temperature thermochronology has emerged as a particularly useful means for constraining the cooling history of mountain ranges and the movement of crustal masses through shallow isotherms. Fission-track analyses and (U-Th)/He methods are being used to link geodynamic and tectonic processes to landscape development and change (e.g., Burbank et al., 1996; Stockli et al., 2003; House et al., 2001; Ehlers and Farley, 2003).

The Sierra Nevada is one of the highest topographic features in North America, yet its development as an orogenic belt throughout the Late Cretaceous and the early Cenozoic is somewhat enigmatic (Jones et al., 2004). In addition to having peak elevations of 2–4 km today, the Sierra Nevada was most likely a high mountain range during the Late Cretaceous as well, when it was an active magmatic arc. While the mean Cretaceous elevation of the Sierra Nevada cannot be precisely quantified, contractional thrust belt features (Dunne and Walker, 2004) and patterns of forearc sedimentation (Mansfield, 1979) are consistent with range-wide crustal shortening and uplift during that time. In spite of this, documented early Cenozoic apatite He cooling ages suggest that the Sierra has experienced less than 3 km of erosion during the last ~60 m.y. (Dumitru, 1990; House et al., 1997, 1998, 2001; Clark et al., 2005). This is atypical of regions of large-scale relief, like large continental mountain ranges, which are positively correlated with high rates of mechanical denudation (Pinet and Souriau, 1988). There are few geologic clues, such as preserved stratigraphy, that can help us decipher the Cenozoic evolution of the Sierra Nevada. Several divergent conceptual models for the Cenozoic development of Sierran morphology have been proposed (see a recent review by Jones et al., 2004), but none has gained widespread acceptance. Further complicating matters is our continuing inability to clearly distinguish tectonic from climatic signatures in the landscape (Molnar and England, 1990).

Given the lack of information available in the geologic record—the Sierra Nevada is composed of mostly pre-Cenozoic crystalline and metamorphic basement rocks—low-temperature thermochronology has emerged as an important means of interpreting the morphology of the range. Several pioneering thermochronologic studies have been carried out in the southern Sierra Nevada (Dumitru, 1990; House et al., 1997, 1998, 2001); these studies unambiguously document the slow Cenozoic unroofing of the range. The few Cenozoic stratigraphic and geomorphologic remnants present in the range, however, are present only in the northern Sierra Nevada (Bateman and Wahrhaftig, 1966), where no low-temperature thermochronologic studies have been conducted. Basement rocks in the

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north are capped by a series of early Cenozoic fluvial deposits and Neogene volcanic units, and an Eocene erosional surface is preserved. Although an Eocene "remnant landscape" has been identified in the south, the southern Sierra lacks much of the Cenozoic stratigraphy present in the north, and it is unclear whether the northern and southern parts of the range had similar Cenozoic geomorphic histories (Clark et al., 2005).

In this paper, we estimate exhumation rates of the northern Sierra through time by using apatite and zircon (U-Th)/He thermochronometry. The purpose of this study is twofold: (1) to compare the cooling and exhumation history of the northern and southern Sierra Nevada, and (2) to provide additional constraints on the Late Cretaceous and Cenozoic uplift and exhumation of the range. We use both zircon and apatite He dating on the same samples in order to gain information about the earlier cooling history of these rocks, not long after their emplacement as part of the magmatic arc. The closure temperatures of the (U-Th)/He system in zircon and apatite are low, ~170–190 °C (Reiners et al., 2004) and ~65–70 °C (Farley, 2000), respectively, so ages can reveal important information about the cooling histories of rocks that can be interpreted as vertical movements through shallow crustal isotherms. Exhumation rates were relatively high (averaging ~0.5 km/m.y.) during and immediately following the formation of the Mesozoic Sierra Nevada batholith, but tapered off to ~0.03 km/m.y. in the Tertiary. Available data suggest that the entire Sierra Nevada had achieved its overall size and morphology in the early Cenozoic, and it has not changed significantly since then.

GEOLOGIC SETTING

The Sierra Nevada is ~100 km wide, extending approximately north-south for 600 km along California's eastern border (Fig. 1). Together with the Great Valley, it behaves as a rigid microplate bounded to the west by the Coast Ranges and to the east by the Basin and Range Province (Argus and Gordon, 1991). The development of the Sierra Nevada as a continental arc began in the latest Triassic, with magmatism and building of the arc continuing through the Late Cretaceous (Ducea, 2001). Basement rocks exposed in the Sierra Nevada consist mainly of Jurassic to Late Cretaceous tonalites and granodiorites, as well as deformed Paleozoic continental margin sediments (Bateman and Wahrhaftig, 1966). Batholithic rocks of the Sierra have been exhumed anywhere from 3 to 20 km, and the greatest paleodepths are exposed in the southernmost part of the range (Ague, 1997; Saleeby, 1990). Whereas there is little Cenozoic cover present in the southern Sierra, Tertiary sedimentary and volcanic units are preserved throughout much of the northern part of the range. Thick deposits of Eocene fluvial gravels, which include coarse, auriferous units at the base, outline large, westward-draining paleoriver systems (Lindgren, 1911; Yeend, 1974). A series of late Oligocene to Pliocene volcanics were later erupted over a large portion of the northern Sierra Nevada topography, burying the river gravels and virtually inundating the landscape (Bateman and Wahrhaftig, 1966; Christensen, 1966). The nature and thickness of the Eocene gravels, together with the great lateral extent and morphology of the volcanic flows, indicate that the northern Sierra had achieved a gentle topography of modest relief by the mid-Tertiary (Bateman and Wahrhaftig, 1966; Wakabayashi and Sawyer, 2001).

Studies have also interpreted the Tertiary river gravels and volcanic flows as representing some 2 km of surface uplift of the high Sierra, probably accompanied by westward tilting of the Sierran block, in the last 3–5 m.y. (Huber, 1981; Christensen, 1966). This is supported by evidence of recently renewed river incision in

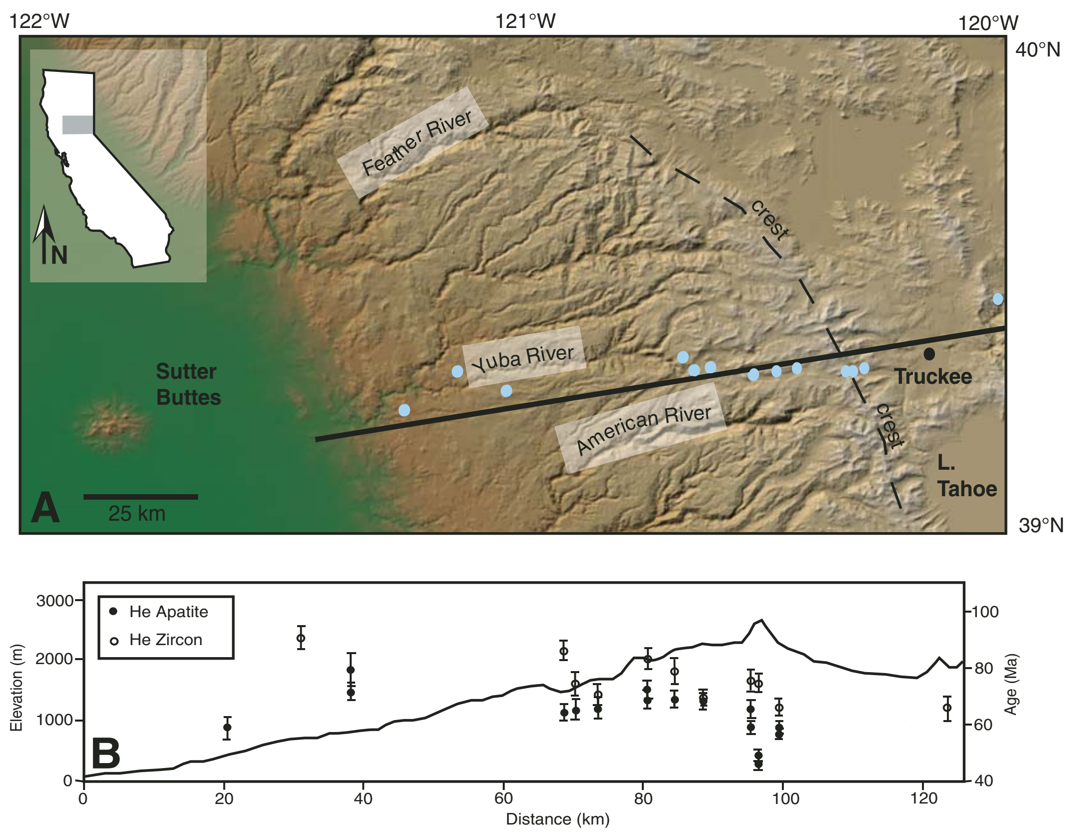

Figure 1. (A) Geographic and topographic setting of the northern Sierra Nevada. Note the broad, low-relief surfaces between major drainages. The black line marks the location of the study transect. Sample locations are shown in blue. The gap in sampling at mid-range elevations on the west side is due to a lack of suitable granodioritic rocks. (B) Topographic profile of transect with sample ages superimposed (all reported errors are 2σ).

the southern Sierra Nevada (Stock et al., 2004, 2005), progressive tilting of Great Valley sediments (Unruh, 1991), and a recent increase in Great Valley sedimentation (Wakabayashi and Sawyer, 2001). Based on the lack of a crustal root beneath the Sierra Nevada (Wernicke et al., 1996), a tectonic mechanism involving the convective removal of a dense arc residue and its replacement with buoyant asthenosphere has been invoked to explain the proposed uplift (Ducea and Saleeby, 1996, 1998). A climate-driven mechanism, in which accelerated erosion at the range crest leads to flexural isostatic rebound of the high elevations, has also been suggested (Small and Anderson, 1995). Regardless of the mechanism involved, exhumation associated with surface uplift or with Pliocene and younger river incision (i.e., Stock et al., 2004, 2005) has a maximum range of 1–2 km and therefore is not reflected in apatite He data.

The (U-Th)/He work carried out in the southern Sierra Nevada, however, has demonstrated the antiquity of some of the major canyons (the San Joaquin and the Kings), and has prompted the hypothesis that the Sierra Nevada experienced a gradual lowering of relief and mean elevation throughout the Cenozoic (House et al., 1998, 2001; Braun, 2002). This is also supported by the $\delta^{18}O$ values of authigenic minerals to the east of the southern Sierra, which indicate the presence of a Miocene rain shadow (Poage and Chamberlain, 2002). A fundamental problem in this debate is that most stratigraphic and geomorphic evidence, which led workers to suggest recent crestal uplift, is present in the northern part of the range, whereas data supporting or contradicting the uplift models have come from the southern Sierra, which may have had a different morphological evolution. It is important, therefore, to perform similar thermochronologic studies in the north, so that cooling and exhumation histories can be compared to those reconstructed in the south.

SAMPLES AND RESULTS

Samples were collected along an ~100 km east-west transect ranging in elevation from ~350 m near the Great Valley to ~2300 m at the crest of the Sierra Nevada (Fig. 1B). All samples were collected from Sierra Nevada batholith granodiorites and tonalites, which have crystallization ages ranging from 95 to 165 Ma (Saleeby et al., 1989; Snoke et al., 1982; Evernden and James, 1964), as well as from the Devonian Bowman Lake batholith (364–385 Ma; Hanson et al., 1988) (Table 1). The gap in the sample transect marks a north-south–trending belt of Paleozoic metasedimentary rocks (the Shoo Fly and Calaveras complexes), which did not yield apatite or zircon grains suitable for analysis. Samples were later crushed and both apatites and zircons were removed using standard heavy liquid and magnetic separation techniques at the University of Arizona.

Mineral separates were then analyzed for (U-Th)/He thermochronometry at Yale University. Preparation included selection of grains for euhedral shape, appropriate size, and, in the case of apatites, absence of inclusions. Single-crystal aliquots of apatite and zircon were then wrapped in Pt and Nb foils, respectively, and degassed by laser heating. He abundances were measured using ^{3}He isotope dilution and quadropole mass spectrometry (see Reiners et al. [2003] for methods). The same degassed aliquots were then dissolved, and U and Th parent concentrations were measured by isotope dilution using an ELEMENT 2 sector inductively coupled plasma–mass spectrometry (ICP-MS). Finally, an α-ejection correction was applied to account for the energetic release and long-stopping distance of the daughter nuclide (Farley et al., 1996; Reiners, 2005) to derive the corrected (U-Th)/He age. We report 16 apatite (U-Th)/He ages, ranging in age from 46 to 80 Ma, and 11 zircon (U-Th)/He ages, ranging in age from 64 to 86 Ma, determined from 13 rock samples (Table 2). Age uncertainties reported in Table 2 are propagated 2σ analytical uncertainties for each single-grain analysis. Multiple replicate analyses were only performed for four apatite pairs (Table 2). In all cases, zircon cooling ages are systematically older than apatite ages from the same rock sample. Both apatite and zircon ages show a weak inverse correlation with elevation (Fig. 2).

ESTIMATION OF EXHUMATION RATES

Compared to the southern Sierra, suitable locations for vertical sampling are less numerous in the north, where local topographic relief tends to be lower. As a result, estimated exhumation rates presented here are determined from multiple systems ([U-Th]/He in apatite and zircon) with different closure temperatures within a given rock sample, as well as from modeling of the apatite He ages. We assume that exhumation is steady state and that cooling rates are entirely the result of unroofing, which is a reasonable assumption given that pluton ages are older than measured He ages (Table 1) and samples were not collected near volcanic sites. Because the He system in zircon closes at relatively higher temperatures (170–190 °C), it is often the case that magmatic cooling, in addition to unroofing, partly controls the estimated cooling rate. In the northern Sierra Nevada, however, the youngest reported crystallization age is 95 Ma (Table 1),

TABLE 1. SAMPLE LOCATION, ROCK TYPE, AND PREVIOUSLY REPORTED AGES

Sample	Longitude (°W)	Latitude (°N)	Elevation (m)	Other reported age: Rock type	(Ma)	Source
52501	121.1108	39.3141	542	Bi-Hb tonalite	159 ± 2	Saleeby et al. (1989)
52602	121.2170	39.2361	393	Quartz diorite	–	–
52603	120.6563	39.3456	1699	Bowman Lake tonalite	364–385	Hanson et al. (1988)
52702	120.5996	39.3241	1725	Two-pyroxene diorite	163	Snoke et al. (1982)
52703	120.5154	39.3095	1768	Granodiorite	95–112†	Evernden and James (1964)
52704	120.4276	39.3207	1878	"	"	"
52705	120.3275	39.3165	2166	"	"	"
52706	120.3155	39.3180	2038	"	"	"
52707	120.0079	39.4611	1559	"	"	"
52708	120.2915	39.3226	1815	"	"	"
60401	120.4696	39.3149	1832	"	"	"
60402	120.6336	39.3209	1562	Two-pyroxene diorite	164 ± 1	Saleeby et al. (1989)
60403	121.0134	39.2704	804	Bi-Hb granodiorite	159 ± 2	"

†All previously reported ages are from U-Pb in zircon, with the exception of the granodiorites dated by Evernden and James (1964), who used K-Ar in biotite. (All K-Ar ages are corrected ages.)

TABLE 2. ZIRCON AND APATITE (U-Th)/He ANALYTICAL DATA

Sample	Age (Ma)	2σ error (Ma)	U (ppm)	Th (ppm)	^{4}He (nmol/g)	Mass (μg)	F_t†
Apatite							
052602A	58.4	4.29	6.49	34.2	3.34	3.14	0.710
052603B	64.3	2.58	26.3	41.8	8.01	1.06	0.633
052702B	64.6	3.53	11.6	17.4	3.59	1.25	0.644
052703A	68.4	2.39	21.2	42.4	7.97	2.22	0.682
052703B	72.6	2.54	82.5	125	27.4	1.06	0.620
052704A	69.6	2.57	21.6	47.1	7.82	1.45	0.632
052705A	64.8	2.78	51.5	62.0	13.2	0.57	0.565
052705B	59.0	2.25	41.3	52.6	10.8	1.14	0.625
052706A	49.1	1.67	45.4	79.7	13.2	6.44	0.769
052706B	46.0	1.64	43.8	70.1	10.2	1.86	0.676
052708A	57.8	2.13	47.8	96.9	13.2	1.12	0.595
052708B	56.3	1.94	53.9	103	15.7	1.63	0.653
060401A	69.0	2.49	133	128	38.0	1.20	0.622
060401B	72.6	2.77	117	110	32.0	0.70	0.570
060403A	74.5	3.16	12.0	24.6	4.98	1.99	0.685
060403B	79.5	5.62	8.87	12.3	3.29	1.16	0.639
Zircon							
052501A	91.0	4.01	658	226	234	1.12	0.667
052603A	86.0	3.64	354	220	140	4.14	0.740
060401A	79.0	3.52	893	218	306	4.60	0.757
060402A	74.8	3.31	119	55.8	36.4	1.53	0.682
052702A	71.0	3.09	546	171	157	2.22	0.697
052703A	83.3	3.48	615	397	260	14.3	0.811
052704A	69.3	2.85	385	308	130	4.72	0.760
052705A	75.3	3.18	338	171	106	1.73	0.685
052706A	74.6	3.07	505	358	178	4.66	0.746
052707A	65.9	3.40	702	344	239	24.3	0.856
052708A	65.8	3.01	1000	500	289	4.21	0.727

†F_t is the correction factor for alpha-ejection loss (after Farley, 2002; Reiners, 2005).

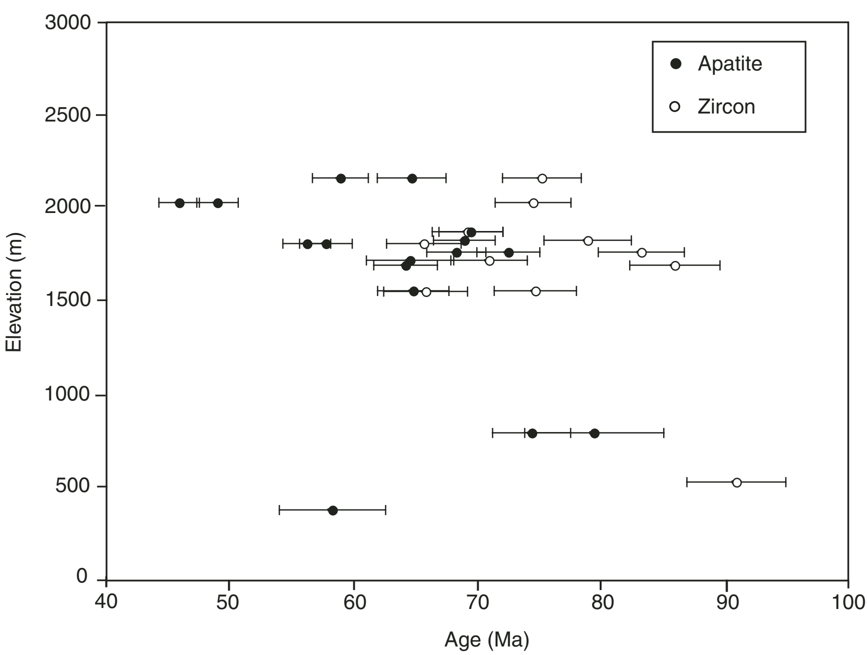

Figure 2. (U-Th)/He ages versus sample elevation. Both apatite and zircon ages decrease with elevation. The youngest reported apatite ages (ca. 50 Ma) were sampled from highest-elevation rocks of the range crest, while samples yielding the oldest ages were collected at low elevations along the range flank.

which is ~10 m.y. older than the oldest zircon He age reported here. It is therefore unlikely that magmatic cooling has had a significant effect on zircon He ages.

Two distinct estimates of exhumation rates are presented. The first was made by dividing the difference in depth to closure of the apatite and zircon thermochronometers by the difference in their cooling ages, and it describes the rate of unroofing of the Sierran batholith between ca. 90–60 Ma. These relatively high rates range between 0.2 and 0.8 km/m.y. (Fig. 3) and were determined assuming a range of geothermal gradients between 20 and 25 °C/km and closure temperatures of 65 °C and 173 °C for apatite and zircon, respectively. However, exhumation rates approaching 1 km/m.y. should be considered approximate because rapid exhumation can cause significant advection of heat to the surface, driving up the geothermal gradient and simultaneously lowering mineral closure depths (Mancktelow and Grasemann, 1997). A marked increase in geothermal gradient would have the effect of lowering unroofing rate estimates, although such a change would be relatively minor compared to the order of magnitude difference in rate through time reported here.

The other exhumation rate presented was estimated using only apatite cooling ages, and it describes the rate of unroofing since ca. 66 Ma. The technique used for converting apatite cooling ages to exhumation rates was adapted from Brandon et al. (1998) and has been applied to He thermochronology by Reiners et al. (2003) and Ducea et al. (2004). In this case, exhumation rate is the depth to closure of He in apatite divided by the apatite cooling age. Depth to closure of a given system is determined by its closure temperature, which in turn was estimated using Dodson's (1973) method. In making these estimates, we assumed a geothermal gradient of 25 °C/km and a mean surface temperature of 10 °C. He diffusion parameters for apatite and zircon were taken from Farley (2000) and Reiners et al. (2004), respectively, and effective cooling radii (or grain sizes) of ~38 μm for apatite and ~40 μm for zircon were used.

Depth to closure is also a function of the difference between the elevation at which a sample is collected and the mean elevation of the local topography that controls the closure isotherm depth. Since shallow isotherms follow the broadest wavelengths of topography (Braun, 2002), the effective closure depth used in Brandon et al.'s (1998) algorithm is measured with respect to that same broad wavelength topography, a surface that we mimicked by filtering digital elevation data to remove wavelengths of less than 20 km. This was accomplished by averaging all elevation data within a 10 km radius of a given sample location. Closure temperatures determined using this method range between 64 and 69 °C, and effective closure depths range between 1.8 and 2.3 km. Exhumation rates estimated using just apatite cooling ages ranged from ~0.02 to 0.04 km/m.y., which are an order of magnitude lower than those estimated using both zircon and apatite data (Fig. 3).

SIGNIFICANCE OF EXHUMATION RATES

The data presented here show a marked change in long-term exhumation rate from relatively high exhumation rates associated with development of an early, or ancestral Sierra Nevada in the Late Cretaceous to earliest Cenozoic to much lower average rates in the middle to late Cenozoic. This trend in decreasing exhumation rate is consistent with early Cenozoic decreases in Great Valley sediment accumulation rate and Sierran erosion rates. Wakabayashi and Sawyer (2001) documented high (~0.2–0.5 km/m.y.) sedimentation rates in the San Joaquin Valley from 100 to 57 Ma, followed by low (<0.1 km/m.y.) sedimentation rates beginning in the latest Paleocene. Long-term erosion rates for the time period between 100 and 57 Ma follow the same trend. Those rates, which were estimated using the difference in age between pluton crystallization (ca. 100 Ma) and deposition of Eocene units (ca. 57 Ma) and the depth at which those plutons formed (11–15 km; Ague and Brimhall, 1988), are between 0.26 and 0.35 km/m.y. (Wakabayashi and Sawyer, 2001). We interpret our high Late Cretaceous–early Cenozoic exhumation rates as representing a pulse of erosional denudation following the emplacement of the batholith and thickening of Sierran crust due to orogenic shortening. Average late Cenozoic erosion rates, however, are significantly lower, ranging from ~0.01 to 0.02 km/m.y. on summit flats to a maximum of 0.3 km/m.y. in the Pliocene associated with stream incision (Small et al., 1997; Stock et al., 2005). These values are consistent with our estimated middle to late Cenozoic average exhumation rates of 0.02–0.04 km/m.y., which we interpret to be the result of slow, erosional unroofing associated with tectonically quiescent regions.

The distribution of apatite (U-Th)/He ages along the transect is similar to that of He ages previously measured in the southern Sierra Nevada (Fig. 4) (see House et al., 2001, for a review). Several areas in the North American Cordillera, including parts of California, have undergone episodes of significant, tectonically driven exhumation. In these areas, unroofing led to the exposure of bedrock that yielded young apatite He ages (e.g., Blythe et al., 2000; Stockli et al.,

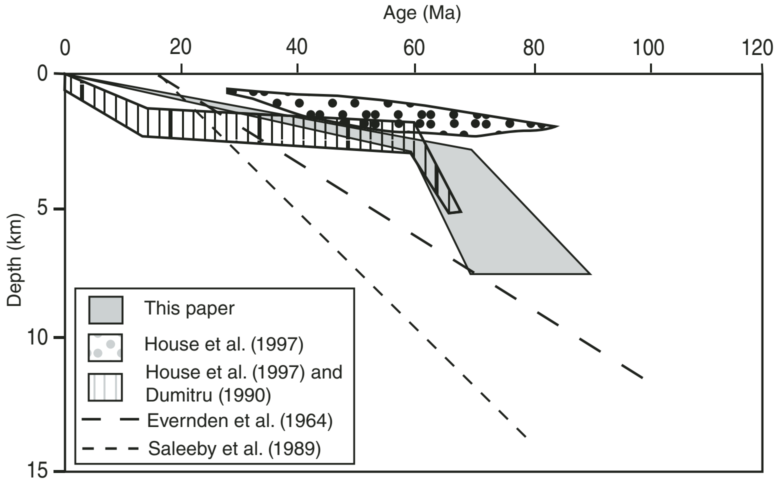

Figure 3. Various Sierra Nevada exhumation histories from available thermochronologic data. The shaded path was constructed from data presented in this paper and shows a marked decrease in exhumation at ca. 60 Ma. The dotted path was constructed using apatite (U-Th)/He age–elevation profiles from House et al. (1997) and shows little change in exhumation rate through time. The vertically striped path represents apatite fission-track modeling (see House et al., 1997) and shows a decrease in exhumation rate at ca. 60 Ma, as well as a renewed increase in that rate at ca. 15 Ma. Dashed lines represent long-term steady-state cooling rates derived from Sierra Nevada pluton cooling ages.

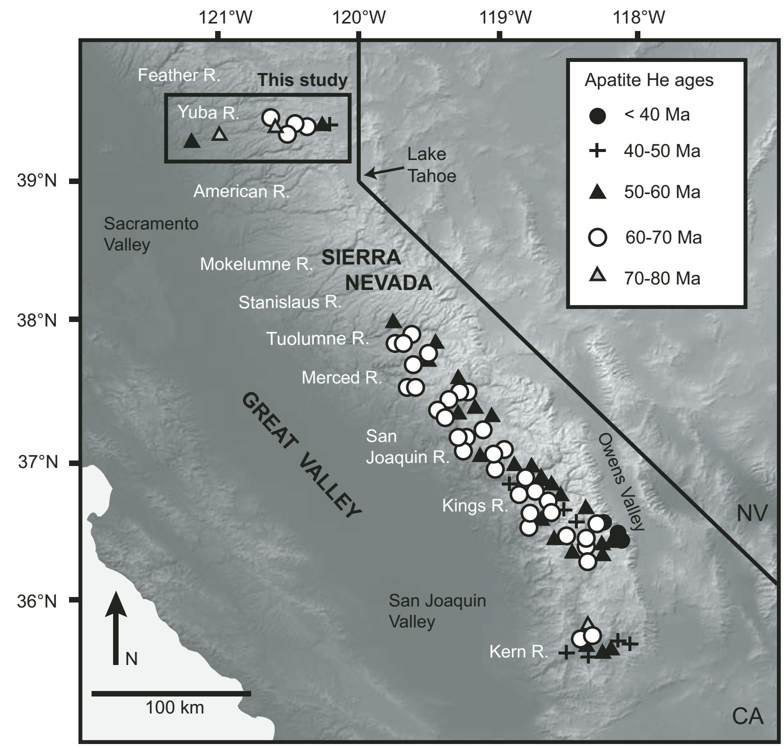

Figure 4. Plot of reported apatite He ages from this study as well as from House et al. (1997, 1998, 2001), Dumitru (1990), and Clark et al. (2006). Data are superimposed on a digital elevation model of the Sierra Nevada and surrounding area. No helium thermochronometric data have been reported for rocks of the central Sierra Nevada (between latitudes 38°N and 39°N). Apatite helium ages presented in this study are in the same range as those documented in the southern Sierra, with ages averaging ca. 60 Ma in both areas.

2000; Spotila et al., 2001; Farley et al., 2001; Ducea et al., 2003). In contrast, the (U-Th)/He ages in the Sierra Nevada are mostly ca. 60 Ma, suggesting that no more than ~3 km of bedrock has been removed since the early Cenozoic. The first implication of our results is that we do not observe a major difference between the northern and the southern Sierra with respect to the age of that isotherm. Overall, the consistency of a ca. 60 Ma surface throughout the Sierra Nevada (with the exceptions explained in the papers by House et al., 2001) is indicative of an early Cenozoic long-wavelength topography that was broadly similar to that of today. The existence of Tertiary sedimentary and volcanic cover in the north, and the absence of such a cover in the south, is most likely due to a greater degree of recent (post-Pliocene) erosion in the southern Sierra. The Cenozoic cover present in the north, however, is relatively thin (≤300 m; Yeend, 1974), such that its absence in the south does not necessarily imply a significantly greater degree of exhumation there. In fact, a recent study by Clark et al. (2005) has shown that remnants of an Eocene erosion surface are preserved at mid-altitudes in the southern Sierra Nevada as well.

New and previously published (U-Th)/He thermochronology data for the Sierra Nevada (see House et al., 2001, for a review) show that a surface that existed ~60 million years ago parallels the modern topographic surface throughout the range, perhaps except from some of the deep canyons. The limited amount of erosion from what was most likely an orogenic belt in the early Cenozoic is puzzling and requires some explanation. An orogenic plateau can explain low erosion rates, but (U-Th)/He apatite ages (House et al., 1998; this study) suggest that the Sierra Nevada had a relief that is inconsistent with a flat, plateau-like surface. In addition, the Sierra Nevada was in a forearc position and close to the Farallon–North America trench for much of the Cenozoic. It is arguably very difficult to maintain a plateau-like morphology in such a tectonic framework. Cenozoic marine sediments of the Great Valley sequence (Dickinson and Rich, 1972) and paleoflora from near-sea-level environments in the westernmost foothills of the Sierra Nevada (Wolfe et al., 1998) indicate the range's close proximity to the continental margin. In order for the Sierra Nevada to have had a broad, low-relief surface, a steeply dipping western flank, which is inconsistent with analyses of Eocene river gradients, would be necessary.

While the Eocene erosional surface in the northern Sierra Nevada is typically viewed as the result of low-elevation planation (Huber, 1981), climatic controls and precipitation patterns can also create and maintain low- to moderate-relief surfaces, independent of their elevation (Gregory and Chase, 1994). It has long been recognized that the early Cenozoic was a time of higher global temperature and higher regional humidity (Robert and Chamley, 1991; Wolfe, 1994). Paleoflora of the interior of the western United States indicate not only a warmer, wetter, and less variable climate in the late Paleogene (Wilf, 2000), but also the presence of high altitudes in the western United States (Wolfe et al., 1998). The widespread abundance of kaolinite found near the Paleocene-Eocene boundary and overlying crystalline basement rocks also indicates heightened precipitation and temperature in continental interior uplands (Robert and Chamley, 1991). Tropically weathered lateritic and kaolinitic horizons are preserved at the base of Eocene river gravels and have been well documented throughout the northern Sierra Nevada (Allen, 1929; Bateman and Wahrhaftig, 1966). In fact, along the western margin of the northern Sierra, Eocene fluvial and deltaic deposits are consistently found overlying a thick, deeply weathered lateritic soil, indicating a subtropical to tropical climate during the range's early history that persisted until at least Eocene time (Allen, 1929). Such a climatic regime is markedly different than that of today and may have influenced the development of Sierran topography in the early Cenozoic.

Trying to interpret the widespread occurrence of lateritic horizons and low exhumation rates in the northern Sierra Nevada in terms of the interplay between climate and tectonics is a chicken or egg dilemma. Did a specific climatic regime create a thick soil mantle and indirectly slow erosion or has slowed erosion softened relief and allowed for the development of thick soils? Recent studies of erosion in mountainous terrains indicate that erosion rate is primarily a function of tectonism and is only slightly affected by changes in climatic factors, such as precipitation and mean annual temperature (Riebe et al., 2001a, 2001b). Those studies addressing the relative influence of climate versus tectonics, however, are necessarily conducted within the context of modern Quaternary climate (Riebe et al., 2001a). Although present-day temperature and precipitation regimes may be locally highly variable, that variation might not accurately represent differences in climate between the more stable and tropical Eocene conditions and the stormier and more variable conditions prevalent today.

Unraveling the climatic and tectonic effects on the Cenozoic evolution of the Sierra Nevada has a significant bearing on models proposed for the growth and decay of mountain belts. While the hypothesis that Sierran landscape development was controlled by a shift to an Eocene subtropical climate does not influence predictions regarding the absolute elevation of the Sierra Nevada through the Cenozoic, it does aim to explain low erosion rates for a range that had at least ~1500 m of relief in the Late Cretaceous (House et al., 2001). However, recent research looking at the relative controls of physical (tectonic) versus chemical (climatic) weathering suggests that chemical weathering is incapable of accomplishing such a marked decrease in erosion rates (Riebe et al., 2001b). Furthermore, stream chemistry studies indicate that mechanical weathering, as a result of tectonic uplift, has a much greater impact on bedrock erosion than chemical weathering, which is more selective and less effective in silicate surfaces (Jacobson et al., 2003). A more complete investigation into the nature and extent of lateritic horizons is needed in order to better assess controls on landscape evolution in the northern Sierra. Our preliminary observations and discussions with colleagues working in the area (Saleeby, Clark, 2005, personal commun.) suggest that lateritic surfaces are common throughout the Sierra Nevada.

CONCLUSION

When coupled with the large-scale morphology of the northern Sierra Nevada, the thermochronologic data presented here provide further evidence for antiquity of the overall form of the modern range. Our data document exhumation rates during the Late Cretaceous that are typical of an eroding orogenic belt, but which slow considerably in the early Cenozoic. We show that the unroofing history of the northern Sierra is similar to that of the intensely studied area south of Yosemite. There appears to be a correlation between the puzzling low Cenozoic exhumation rates in the Sierra Nevada and the presence of an Eocene highly weathered, lateritic soil profile. Whether that profile is the cause of low erosion (and exhumation) rates, or the result of them, remains to be worked out. Recent studies suggest that climatic changes and chemical weathering is insufficient to dampen erosion rates to such an extent (Riebe et al., 2001a, 2001b; Jacobson et al., 2003). Geomorphic modeling, however, does indicate that an early Cenozoic climate, characterized by numerous, low-magnitude storms (Gregory and Chase, 1994), together with a thick subtropical vegetation cover for much of the Cenozoic, could have restricted the amount of material being stripped off the landscape and kept erosion rates low.

Further evaluations of the lateritic soils, as well as additional independent tests of paleoaltitude, are needed in order to accurately piece together the Cenozoic evolution of the northern Sierra Nevada.

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