ABSTRACT. New apatite (U-Th)/He ages from the central Sierra Nevada, California, place limits on the morphology and evolution of longitudinal profiles of major transverse river drainages developed in the Late Cretaceous. Helium ages from a new orogen-parallel, constant-elevation sample transect are relatively uniform (~60 Ma) and not correlated with topography, unlike those from a similar, lower elevation transect approx 15 km to the west. We interpret the marked difference in the two orogen-parallel profiles to reflect a headward decrease in long-wavelength, transverse relief at the time of cooling, consistent with either a concave-up stream gradient, typical of those observed near the headwaters of modern Sierran trunk streams, or a convex gradient like those found along slope breaks of eroding plateau edges. From the San Joaquin drainage we obtained a new helium age-versus-elevation profile, which has a comparable slope to those previously reported for the Yosemite Valley, Kings Canyon, and Mt. Whitney areas. This new profile yields slightly older ages at a given elevation as expected from its position adjacent to the largest major drainage. The age versus elevation profiles imply that the mean denudation rate of the region in the Cenozoic was about 0.04 to 0.05 mm/yr. We show that long-wavelength (~70 km) relief inferred from longitudinal helium age variations is a strong function of erosion rate, such that even relatively subdued relief is detectable with helium age profiling provided that denudation rates were low. Using the rate implied by Sierran age-versus-elevation profiles, we infer long-wavelength relief of 1500 ± 500 m in the Late Cretaceous. By analogy with modern orogenic plateaus, this value of long-wavelength relief suggests a Cretaceous interior Cordilleran plateau lay at an elevation of at least 3000 m.

INTRODUCTION

Recent advances in low-temperature thermochronometry coupled with an improved understanding of the influence of topographic relief on the thermal architecture of the shallow crust (<5 km depth) provides a means to relate cooling histories to landscape evolution. Analytical and numerical models suggest that topographic relief influences the thermal path of a rock as it is exhumed through the Earth’s uppermost crust (Stiwe, White, and Brown, 1994; Mancktelow and Grasemann, 1997), imparting variations in mineral cooling ages that can be used to quantify the magnitude of past relief. This effect was first employed for detecting paleo-relief in a study of the central and southern Sierra Nevada, California, where spatial variations in apatite (U-Th)/He ages suggested the largest modern transverse drainages in the region formed as early as the Late Cretaceous (House, Wernicke, and Farley, 1998). Simple thermal models suggest that the scale of the relief indicated by the age variations is comparable to that of the modern Andes, implying that the average elevation of the Late Cretaceous Sierras was higher than the modern range and has decreased through Cenozoic time. Other workers have come to similar conclusions regarding the region extending from the Sierra Nevada eastward into western Nevada, using geomorphologic arguments.
(Small and Anderson, 1995), basin reconstructions (Gilbert and Reynolds, 1973), and various paleoclimatological proxies for elevation (Wolfe and others, 1997; Chamberlain and Poage, 2000). These results collectively suggest that the Sierra Nevada is a long-lived mountain range and, by analogy with the modern Andes (Masek and others, 1994) may have occupied a position at the edge of an elevated plateau spanning the Cordilleran interior during Late Cretaceous times (Coney and Harms, 1984; Wolfe, Forest, and Molnar, 1998).

Our original study only provided insight into topography along a single range-parallel transect, and our estimate of paleorelief was based on a simple denudation model with constant relief during cooling (steady-state topography and an average denudation rate estimated at 0.1 mm/yr on the basis of thermobarometry of Sierran plutons; Ague and Brimhall, 1988a,b). Here we report new helium age data from a second horizontal sample profile that provide a first glimpse of the longitudinal profile of the Sierra paleo-drainages. We also report new helium ages from a vertical profile adjacent to the San Joaquin River Valley, the largest modern drainage in the Sierra Nevada. Our earlier results suggested that this drainage was also the largest feature during the Late Cretaceous, whereas Yosemite Valley to the north showed little age effect and was thus a relatively minor feature at the time of cooling. Comparison of the vertical age-elevation profiles from these two regions and from the Mount Whitney area provides insight into how the Cenozoic cooling history varied between deeply incised valleys (the San Joaquin samples) and intervening ridges and adjacent highlands (Yosemite and Whitney areas, respectively). Using these vertical profiles, we estimate valley and ridge denudation rates through the Cenozoic and evaluate the influence of denudation rate on the inference of paleo-relief from apatite helium ages.

HELICUM THERMOCRONOLGY AND TOPOPGRAPHIC RELIEF

The influence of topographic relief on the thermal structure of the shallow crust has been known for many years from studies of crustal heat flow (Birch, 1950; Lachenbruch, 1968; Bodmer and others, 1979; Blackwell, Steele, and Brott, 1980; Saltus and Lachenbruch, 1991; Rybach and Pfister, 1994). Long wavelength (λ) topographic relief (relief = 2ho, where ho = amplitude) perturbs shallow crustal isotherms such that, at depths less than 1 to 2 characteristic depths λ/2π, the geothermal gradient beneath valleys is substantially higher than that beneath intervening ridges (fig. 1; Turcotte and Schubert, 1982; Stüwe, White, and Brown, 1994; Mancktelow and Grasemann, 1997; Kohl, 1998). Figure 1 shows schematically that, as rocks are denuded (either erosionally or tectonically) and pass through the shallow crust, the presence of topography influences their cooling histories. This effect is significant enough to be detected in the spatial distribution of low-temperature thermochronometric ages. For example, a suite of isostructural samples (originating at the same depth below sealevel or any other reference surface) that are denuded at a constant rate beneath flat topography will have the same cooling paths. However, periodic topography with amplitude ho distorts the time-temperature paths of these rocks as they pass through the upper crust so that rocks denuded beneath paleo-ridges will cool more slowly (that is, are hotter at any given time) than those originating at the same depth below sealevel but exhumed beneath or adjacent to paleo-valleys (fig. 1). In general, greater relief and slower denudation will produce larger variations in the cooling histories between ridges and valleys and therefore increase the critical depth above which the effect might be detectable.

If the divergence in cooling histories described above can be detected, it can provide limits on the wavelength and amplitude of topography at the time of cooling. For periodic topographic relief like that found in most orogenic belts (λ = 20-70 km, and ho = 0.5-2 km; Hovius, 1996) and conditions of slow denudation (~0.1 mm/yr), topographic perturbations are damped at depths greater than ~4 to 12 km, typically
Fig. 1. Schematic diagrams illustrating the relationship between topography, temperature, and time (after House, Wernicke, and Farley, 1998). (A) The influence of idealized topography on near surface isotherms. Topography is generally sinusoidal (dashed line) with small wavelength ($\lambda < 10$ km) features superimposed. The shape of the isotherms is controlled by long wavelength relief (Stu¨we, White, and Brown, 1994; Mancktelow and Grasemann, 1997). The positions of hypothetical sub-interfluve and sub-valley samples prior to denudation are indicated by filled circles. (B) Idealized time-temperature histories that result from slow denudation (approx 0.1 mm/yr) beneath steady-state topography shown in (A). At a given time ($t_1$), samples exhumed beneath or adjacent to valleys will be cooler than those located beneath paleo-ridges. (C) Theoretical sample transect and the corresponding helium age patterns that would be produced by the denudation history and topography shown in (A) and (B). The difference in helium ages obtained for samples exhumed beneath valley and ridge axes (V and R, respectively) is larger than that between ridge samples and those adjacent to valleys (R1 or R2).
corresponding to temperatures <120°C assuming nominal geothermal gradients in the range of 10° to 30°C/km (House, Wernicke, and Farley, 1998). Thus, topographically distorted cooling histories are best detected using a very low-temperature thermochronometer like (U-Th)/He ages in apatite.

The closure temperature for helium diffusion in apatite is lower than for other techniques: the transition between complete diffusive loss and quantitative retention of helium occurs over the temperature interval of 45° to 75°C for crystals of ~125 micron prism diameter (Wolf, Farley, and Silver, 1996; Farley, 2000). This temperature interval, referred to as the helium partial retention zone (HePRZ), corresponds to depths of 2 to 4 km for a nominal ~20°C/km geothermal gradient and lies well within the region of the crust most susceptible to topographically induced thermal effects. As a result, regional patterns of helium ages are sensitive to the presence of topography because the HePRZ is compressed beneath valleys and expanded beneath ridges (fig. 1A; House, Wernicke, and Farley, 1998); the absolute depth of the HePRZ is also distorted in accordance with higher sub-valley geothermal gradients and lower sub-interfluve gradients. This distortion in the HePRZ, and consequent divergence in time-temperature histories means that samples exhumed beneath or adjacent to paleo-valleys will yield older helium ages than isostructural samples exhumed at the same rate beneath paleo-ridges (fig. 1C).

It is important to emphasize that collecting a profile of isostructural or nearly isostructural samples may be possible by exploiting short-wavelength topography, such that “valley” samples are collected from local peaks near the river valley, and “ridge” samples are collected from local valleys positioned on interfluves between drainages (fig. 1A). For example, a sample near Glacier Point in Yosemite Valley collected at 2000 m would be isostructural with a sample collected at the bottom of a local valley in the high country between the Yosemite and San Joaquin River valleys. The thermal effects of these short-wavelength features are small compared to those imposed by the periodic major drainages (House, Wernicke, and Farley, 1998). For example, the modern Yosemite Valley is approx 5 km wide. Its characteristic depth ($\lambda/2\pi$) is only ~800 m, therefore its effect on temperature at depth would not be detectable below ~2000 m. Despite the locally high amplitude of the short-wavelength variations, they have little effect on cooling histories of samples at temperatures less than 50 °C, yet make it possible to sample horizontally across long-wavelength (30-70 km) topography. Finally, even if the topography does not permit a perfectly horizontal profile, ages can be corrected to a common datum using the local age versus elevation gradient.

The difference in helium ages for samples along isostructural profiles ($\Delta t_{He} = Age_{Valley,x} - Age_{Ridge,x}$, where x is a reference elevation) reflects the amplitude of relief during cooling and to a lesser extent its wavelength (House, Wernicke, and Farley, 1998). As discussed below, the rate of denudation is another important factor but was not considered earlier (House, Wernicke, and Farley, 1998). The difference in helium ages ($\Delta t_{He,x}$) measured on a given isostructural profile will be largest when samples collected from the axes of ridges and valleys are compared ($\Delta t_{He} = Age_{Valley,x} - Age_{Ridge,x}$; fig. 1C). In many cases, samples located precisely over the valley axis have long been eroded away, but samples are collected as close to the valley axis as possible. In this case, $\Delta t_{He}$ may be an underestimate of the value that would be obtained if the axial samples were available.

The value of $\Delta t_{He}$ that results from topographic effects can be forward modeled to estimate $h_0$ during denudation, provided the overall geothermal gradient and the rate of denudation during the time of interest can be estimated (House, Wernicke, and Farley, 1998).
The Sierra Nevada is a west-tilted crustal block situated on the western edge of the Basin and Range province (fig. 2). Presently exposed basement rocks are predominantly 125 to 80 Ma granite and granodiorite plutons of the Sierran magmatic arc and metamorphic country rocks (Evernden and Kistler, 1970; Stern and others, 1981; Chen

BEDROCK GEOLOGY AND ROCK UPLIFT OF THE SIERRA NEVADA

The Sierra Nevada is a west-tilted crustal block situated on the western edge of the Basin and Range province (fig. 2). Presently exposed basement rocks are predominantly 125 to 80 Ma granite and granodiorite plutons of the Sierran magmatic arc and metamorphic country rocks (Evernden and Kistler, 1970; Stern and others, 1981; Chen
and Moore, 1982; Saleeby and Busby-Spera, 1992). Thermobarometric data suggest crystallization pressures of most of these plutons (~80-100 Ma) at 100 to 300 MPa or about 4 to 12 km depth, with the deepest rocks exposed in the southern Sierra Nevada and in the western foothills (Ague and Brimhall, 1988a,b).

It is generally agreed that a large component of bedrock uplift was accomplished by westward tilting through most of the Cenozoic (Huber, 1981; Unruh, 1991), although the implications for associated changes in the average elevation of the Sierra Nevada remain in debate (Small and Anderson, 1995; House, Wernicke, and Farley, 1998). Constraints on the post-50 Ma rate and magnitude of tilting are relatively well-known from tilted strata preserved in the eastern Great Valley and correlations to uplifted terraces and remnants of basalt flows in some of the larger Sierran rivers such as the American, Mokulemne, and San Joaquin (Diment and Urban, 1981; Huber, 1981; Unruh, 1991). Evidence for such tilting, combined with some paleobotanical evidence (Axelrod, 1962) has been inferred to indicate an increase in average Sierran elevation since Miocene times (Huber, 1981; Unruh, 1991). Various models have been presented which seek to explain this episode of bedrock uplift (Chase and Wallace, 1988; Small and Anderson, 1995; Wernicke and others, 1996), but considerable debate still remains as much of this evidence is re-examined (for example, Small and Anderson, 1995; Wolfe and others, 1997).

The chronology and magnitude of Late Cretaceous-Early Eocene bedrock uplift and denudation are known poorly due to the scarcity of direct geologic constraints of the appropriate ages. Available evidence suggests that bedrock uplift and presumably denudation may have been non-uniform during this time, beginning with extremely rapid rates during the last stage of arc magmatism but slowing considerably in parts of the Sierra Nevada after ~70 Ma. Rapid cooling and decompression coeval with the emplacement of 81 to 95 Ma plutons in the central Sierra Nevada coincided with rapid sedimentation in the adjacent Great Valley fore-arc basin and deposition of Late Cretaceous sediments directly onto basement rocks near the present day Sierra-Great Valley boundary, suggesting that significant denudation had occurred by ~75 Ma (Evernden and Kistler, 1970; Mansfield, 1979; Dumitru, 1990; Renne, Tobisch, and Saleeby, 1993). Apatite fission-track and helium ages from basement rocks within the range imply that basement rocks in the vicinity of Yosemite and Kings River canyons and elsewhere within the range were at depths of ~3 to 4 km at ~70 Ma (Naeser and Dodge, 1969; Dumitru, 1990; House and others, 1997). Geological constraints on rates of continued denudation in the central Sierra Nevada are sparse, but Eocene marine sediments preserved in some locations along the southern Sierra-Great valley boundary were deposited directly onto 80 Ma plutons of the southern Sierras, indicating that at least some presently exposed basement rocks in the western foothills were originally exposed at the surface by ~37 to 58 Ma (Saleeby, Sams, and Tobisch, 1986). Thermochronometric data indicate that rocks within the range to the east remained at depths of 3 to 4 km, however (House and others, 1997; House, Wernicke, and Farley, 1998).

Constraints on the geomorphology of the range during the Early Cenozoic are even rarer than limits on denudation rates. Cobbles of Sierran granite in Eocene channel deposits in the northern Sierra and the western Great Valley indicate the presence of Early Tertiary drainage systems (Bateman and Wahrhaftig, 1966; Christiansen, 1966; Mansfield, 1979), and more recently, helium thermochromometric data indicate the presence of significant canyons incised by ~70 Ma and possibly persisting until ~40 Ma. A large range of helium ages (40-85 Ma) from samples collected along a single structural datum (along a transect parallel to the axis of Cenozoic tilting), which should have experienced similar cooling histories in the absence of topographic relief, is spatially correlated with the modern topography (House, Wernicke, and Farley,
1998). The older ages are from samples on local topographic highs within the Kings and San Joaquin river drainages, whereas younger ages are systematically from samples collected in local valleys within highlands between the major drainages. No large differences in age adjacent to the Merced (Yosemite Valley) or Tuolumne (Hetch-Hetchy Valley) drainages were observed, however.

Qualitatively, the large range in helium ages collected along the orogen parallel transect and their spatial correlation with the modern drainages suggest that large topographic relief existed when Sierra basement rocks cooled through the HePRZ. Simple models of slow denudation (~0.1 mm/yr) in the presence of steady-state topography were used to relate the range in helium ages observed along the transect to the amplitude of the relief present during cooling (House, Wernicke, and Farley, 1998). The models predict that denudation beneath topography with wavelengths of 35 to 70 km and amplitudes of 1 to 2 km (2-4 km of net long-wavelength relief) will produce differences in helium ages ($\Delta$He = Age_{valley} - Age_{ridge}) that approach the observed range in the Sierra of ~20 to 30 my. On the basis of these results, House, Wernicke, and Farley (1998) concluded that (1) the average elevation of the Late Cretaceous Sierra Nevada may have approached that of the modern Andes and, if so, (2) that the average elevation and relief has decreased over time. The latter would require that the erosion rate of ridges was on average higher than that in valleys in Cenozoic times. The single horizontal profile provided little insight into the longitudinal character of the drainages suggested by the large differences in helium age, nor did our analysis attempt to use the helium data to constrain the denudation history or evaluate the sensitivity of age variation to denudation rate.

**apaTite (U-Th)/He ages: sampling strategy and results**

We collected 33 samples from a new transect, parallel to the original but 500 m higher in elevation. This transect (T2) is an average of 15 km east of T1 and extends from Yosemite Valley area in the north to the upper Kern River/Mt. Whitney area in the south (fig. 2). If the long-wavelength transverse drainages recorded by the T1 profile were of significant amplitude where crossed by the second profile, then they should produce a variation in cooling ages like that observed in the T1 transect.

At least one of the modern drainages, that of the Merced River, lacked significant helium age variations, suggesting that either the predecessor to this drainage was relatively small at the time basement rocks were exhumed through the HePRZ, or that the drainage may be a young topographic feature created later in the evolution of the range (House, Wernicke, and Farley, 1998). In either case, one might expect the relationship between helium age and elevation from a near-vertical sample transect from this drainage to contrast with those collected from regions exhumed beneath the inferred ancient valleys (the San Joaquin and Kings River drainages), because near-surface isotherms in the latter case would be more compressed at the time of cooling, producing higher ages at a given elevation for the valley sites. With this effect in mind, we collected twelve new samples from a near-vertical elevation transect along the northern rim of the San Joaquin Canyon (spanning the south face of Shuteye Peak; fig 2.) for comparison with previously published vertical transects from the Yosemite Valley, Kings River Canyon, and Mt. Whitney areas (House and others, 1997). Because the slope of an age-elevation curve is sensitive to denudation rate, these comparisons may provide insight into spatially or temporally varying erosion rates that would be of use in refining previous estimates of paleo-relief.

**Analytical approach.**—For each sample, we analyzed aliquots of 5 to 15 grains (about 75 micrograms) of apatite that were carefully selected to be of good crystal form and free of mineral inclusions. Good crystal form is necessary to measure accurately grain dimensions for correction of alpha ejection effects (Farley, Wolf, and Silver, 1996) and for estimation of closure temperature (Farley, 2000). Freedom from
inclusions is important because even small inclusions of U- and Th-rich phases (most commonly zircon and monazite) can compromise age measurements, particularly in the case of apatites with low U and Th concentrations (around 1 ppm; House and others, 1997). We therefore inspected all grains prior to analysis using a high-power binocular microscope under crossed nicols. In general, problematic phases have much higher birefringence than apatite, and hence most are readily detected by this technique.

After inspection and size measurement, the grains were heated in vacuum to 950 °C for 20 min. The evolved helium was spiked with an accurately known amount of 3He, concentrated and purified using a cryogenic cold trap cycling between 16 and 34 K, and analyzed using a quadrupole mass spectrometer. Blanks were run before and re-extraction steps after each sample and were typically in excellent agreement. When re-extract steps yield helium contents above the expected blank, the most common cause is thought to be undetected mineral inclusions releasing helium at higher temperatures than apatite. Such analyses are rejected, and a new aliquot of the sample analyzed until the re-extract step yields helium at blank levels. The outgassed grains were then retrieved from the furnace, dissolved, and spiked with enriched 235U and 230Th and analyzed on a Finnigan Element inductively-coupled plasma mass spectrometer. Results are shown on tables 1 and 2.

Most samples yielded replicate ages that were within analytical uncertainty (3 percent at 1 σ; tables 1 and 2). When replicate analyses were obtained, we report an average age with a standard deviation of 6 percent (1 σ) that is determined from the average standard deviation of the entire data set. Where there was only enough material for a single aliquot the resulting ages are assigned a 6 percent (1 σ) uncertainty and plotted with the averaged ages; such samples are indicated on tables 1 and 2. This uncertainty is larger than the analytical value but reflects the effects of slight grain size differences among replicate aliquots, uncertainties in correction for alpha-ejection, and potential grain to grain differences in helium diffusivity (House and others, in press). Neither the T2 samples, nor those from the San Joaquin vertical profile display a systematic relationship between age and grain size or grain size and position along the profile. The average mass-weighted prism diameter for both groups of samples is 130 ± 30 µm, corresponding to a closure temperature of roughly 68° to 75°C (assuming a cooling rate of 10 °C/my; Farley, 2000).

Results.—Helium ages from the San Joaquin vertical profile generally increase with increasing elevation. Ages range from ~45 to 76 Ma over ~1300 m elevation (table 1; fig. 3). The scatter in the profile exceeds that expected from analytical uncertainties alone but is only slightly greater than that expected from the 6 percent uncertainty assigned based on reproducibility. We explore some of the causes of scatter along the profile in the following section.

Helium ages from the T2 profile range from 70.6 to 44.8 Ma, with the exception of one sample (MH97-K9), which yields a much younger age of 31.6 Ma. This extremely young age is reproducible yet anomalously younger than nearby samples. In light of its position at the extreme southern limit of the transect in a region, combined with the likelihood that this region may have been influenced by Neogene volcanism and possibly motion on the nearby Kern Canyon fault, we exclude this sample in the following discussion and figures.

Computing denudation rates from vertical profile data

As outlined above, geological limits on Cenozoic denudation rates in the Sierra Nevada are broad estimates due to a lack of direct geological constraints during the times of interest and the scarce outcrop distribution of units of interest. In lieu of these limits, thermochronometric data from vertical elevation profiles may provide an estimate of the rate of denudation (Farley, Rusmore, and Bogue, 2001), provided the
<table>
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<tr>
<th>Sample (elevation, longitude, latitude)</th>
<th>Radius (±σ)</th>
<th>Length (μm)</th>
<th>[U] (ppm)</th>
<th>[Th] (ppm)</th>
<th>$[^{3}He]$ (nmol/g)</th>
<th>Age (Ma) Raw</th>
<th>Age (Ma) Corrected†</th>
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<tbody>
<tr>
<td>MH95-2 (2073 m, 119°26'1&quot;, 37°22'47&quot;)</td>
<td>0.81</td>
<td>62</td>
<td>210</td>
<td>19</td>
<td>34</td>
<td>0.56</td>
<td>56.6 70.0(2.1)</td>
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<tr>
<td>MH96-10 (1049 m, 119°19'2&quot;, 37°19'29&quot;)</td>
<td>0.80</td>
<td>60</td>
<td>221</td>
<td>33</td>
<td>69</td>
<td>0.49</td>
<td>46.2 57.7(2.4)</td>
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<tr>
<td>MH96-11 (1037 m, 119°18'42&quot;, 37°19'21&quot;)</td>
<td>0.81</td>
<td>57</td>
<td>212</td>
<td>31</td>
<td>58</td>
<td>0.54</td>
<td>41.7 51.7(2.2)</td>
</tr>
<tr>
<td>MH96-12 (1146 m, 119°19'42&quot;, 37°20'10&quot;)</td>
<td>0.80</td>
<td>60</td>
<td>220</td>
<td>56</td>
<td>93</td>
<td>0.60</td>
<td>30.0 37.4(2.2)S</td>
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<tr>
<td>MH96-13 (1195 m, 119°20'33&quot;, 37°21'56&quot;)</td>
<td>0.88</td>
<td>92</td>
<td>245</td>
<td>26</td>
<td>24</td>
<td>1.09</td>
<td>39.6 45.2(1.9)</td>
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<tr>
<td>MH96-14 (1415 m, 119°21'33&quot;, 37°23'18&quot;)</td>
<td>0.89</td>
<td>108</td>
<td>286</td>
<td>34</td>
<td>22</td>
<td>1.59</td>
<td>50.4 56.6(3.4)S</td>
</tr>
<tr>
<td>MH96-15 (1439 m, 119°20'33&quot;, 37°23'42&quot;)</td>
<td>0.88</td>
<td>83</td>
<td>239</td>
<td>47</td>
<td>34</td>
<td>1.23</td>
<td>42.4 49.2(2.1)</td>
</tr>
<tr>
<td>MH96-16 (1354 m, 119°23'3&quot;, 37°22'53&quot;)</td>
<td>0.82</td>
<td>66</td>
<td>240</td>
<td>37</td>
<td>77</td>
<td>0.48</td>
<td>56.3 68.6(2.9)</td>
</tr>
<tr>
<td>MH96-17 (1512 m, 119°23'3&quot;, 37°21'48&quot;)</td>
<td>0.82</td>
<td>62</td>
<td>225</td>
<td>41</td>
<td>65</td>
<td>0.64</td>
<td>47.3 58.0(2.3)</td>
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<td>MH96-18 (1585 m, 119°23'3&quot;, 37°20'51&quot;)</td>
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<td>63</td>
<td>227</td>
<td>91</td>
<td>85</td>
<td>1.07</td>
<td>53.0 65.5(2.8)</td>
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<td>53</td>
<td>193</td>
<td>21</td>
<td>33</td>
<td>0.62</td>
<td>52.8 66.4(2.8)</td>
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<td>MH96-21 (2000 m, 119°24'53&quot;, 37°19'46&quot;)</td>
<td>0.76</td>
<td>47</td>
<td>195</td>
<td>24</td>
<td>37</td>
<td>0.65</td>
<td>57.6 75.8(2.3)</td>
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<td>MH96-22 (2049 m, 119°26'3&quot;, 37°20'10&quot;)</td>
<td>0.78</td>
<td>52</td>
<td>206</td>
<td>22</td>
<td>36</td>
<td>0.62</td>
<td>56.7 72.7(2.2)</td>
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<tr>
<td>MH96-24 (2341 m, 119°25'3&quot;, 37°21'40&quot;)</td>
<td>0.78</td>
<td>44</td>
<td>149</td>
<td>10</td>
<td>23</td>
<td>0.45</td>
<td>59.2 80.0(3.4)S</td>
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<th>Sample (elevation, latitude, longitude)</th>
<th>z_{t}</th>
<th>Radius Length</th>
<th>[U]</th>
<th>[Th]</th>
<th>[He]</th>
<th>Raw</th>
<th>Corrected</th>
<th>Final††</th>
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<td>MH97-Y2 (2439 m, 119°38'4&quot;, 37°51'9&quot;)</td>
<td>0.86</td>
<td>82 232</td>
<td>27 40</td>
<td>10.62</td>
<td>53.6</td>
<td>62.7</td>
<td>63.3(2.7)</td>
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<tr>
<td>MH97-Y3 (2598 m, 119°29'0&quot;, 37°48'1&quot;')</td>
<td>0.85</td>
<td>77 223</td>
<td>23 36</td>
<td>7.99</td>
<td>46.6</td>
<td>55.2</td>
<td>57.9(2.3)</td>
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<tr>
<td>MH97-Y4 (2720 m, 119°27'50&quot;, 37°46'13&quot;)</td>
<td>0.87</td>
<td>91 274</td>
<td>25 42</td>
<td>7.42</td>
<td>38.7</td>
<td>44.8</td>
<td>44.6(1.9)</td>
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<tr>
<td>MH97-F1 (2549 m, 119°16'26&quot;, 37°34'8&quot;)</td>
<td>0.86</td>
<td>77 223</td>
<td>13 13</td>
<td>4.45</td>
<td>51.2</td>
<td>59.5</td>
<td>63.5(2.6)</td>
<td></td>
</tr>
<tr>
<td>MH97-F1.5 (2377 m, 119°15'0&quot;, 37°30'0&quot;)</td>
<td>0.77</td>
<td>57 211</td>
<td>39 82</td>
<td>15.33</td>
<td>48.4</td>
<td>62.7</td>
<td>68.1(2.7)</td>
<td></td>
</tr>
<tr>
<td>MH97-F3 (2329 m, 119°15'50&quot;, 37°28'50&quot;)</td>
<td>0.85</td>
<td>79 240</td>
<td>25 45</td>
<td>10.50</td>
<td>53.5</td>
<td>63.3</td>
<td>68.2(2.7)</td>
<td></td>
</tr>
<tr>
<td>MH97-F4 (2470 m, 119°49'32&quot;, 37°22'25&quot;)</td>
<td>0.74</td>
<td>45 155</td>
<td>34 79</td>
<td>12.44</td>
<td>43.4</td>
<td>59.0</td>
<td>61.7(2.5)</td>
<td></td>
</tr>
<tr>
<td>MH97-F5 (2439 m, 119°51'15&quot;, 37°19'28&quot;)</td>
<td>0.76</td>
<td>50 182</td>
<td>32 77</td>
<td>10.94</td>
<td>39.8</td>
<td>52.4</td>
<td>57.1(2.2)</td>
<td></td>
</tr>
<tr>
<td>MH97-F6 (2500 m, 119°6'40&quot;, 37°16'50&quot;)</td>
<td>0.77</td>
<td>- -</td>
<td>42 22</td>
<td>11.08</td>
<td>43.0</td>
<td>55.8</td>
<td>56.2(2.0)</td>
<td></td>
</tr>
<tr>
<td>MH97-F7 (2439 m, 119°7'2&quot;, 37°13'59&quot;)</td>
<td>0.83</td>
<td>54 223</td>
<td>39 36</td>
<td>13.06</td>
<td>50.4</td>
<td>60.8</td>
<td>60.0(2.6)</td>
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</tr>
<tr>
<td>MH97-F7.5 (2610 m, 119°7'18&quot;, 37°10'46&quot;)</td>
<td>0.74</td>
<td>45 156</td>
<td>12 25</td>
<td>5.47</td>
<td>52.0</td>
<td>70.6</td>
<td>63.8(2.4)</td>
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</tr>
<tr>
<td>MH97-F8 (2530 m, 118°53'30&quot;, 37°53'36&quot;)</td>
<td>0.77</td>
<td>51 171</td>
<td>14 37</td>
<td>5.41</td>
<td>43.2</td>
<td>56.1</td>
<td>54.6(2.4)</td>
<td></td>
</tr>
<tr>
<td>MH97-F9 (2524 m, 118°57'51&quot;, 37°43'2&quot;)</td>
<td>0.73</td>
<td>42 145</td>
<td>60 51</td>
<td>18.77</td>
<td>47.3</td>
<td>65.3</td>
<td>63.6(2.8)</td>
<td></td>
</tr>
<tr>
<td>MH97-F9.5 (2363 m, 118°57'49&quot;, 37°3'19&quot;)</td>
<td>0.70</td>
<td>50 150</td>
<td>13 32</td>
<td>4.79</td>
<td>42.4</td>
<td>60.1</td>
<td>60.8(3.6)</td>
<td></td>
</tr>
<tr>
<td>MH97-F11 (2661 m, 118°55'47&quot;, 36°50'46&quot;)</td>
<td>0.78</td>
<td>54 177</td>
<td>41 64</td>
<td>13.09</td>
<td>42.3</td>
<td>54.7</td>
<td>48.0(2.3)*</td>
<td></td>
</tr>
<tr>
<td>MH97-K1 (2622 m, 118°46'34&quot;, 36°56'11&quot;)</td>
<td>0.75</td>
<td>50 146</td>
<td>22 40</td>
<td>9.14</td>
<td>51.8</td>
<td>51.7</td>
<td>51.6(2.9)</td>
<td></td>
</tr>
<tr>
<td>MH97-K1.5 (2398 m, 118°46'16&quot;, 36°53'53&quot;)</td>
<td>0.83</td>
<td>79 241</td>
<td>7 14</td>
<td>2.96</td>
<td>52.8</td>
<td>63.7</td>
<td>66.7(2.7)</td>
<td></td>
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<tr>
<td>MH97-K2 (2439 m, 118°41'50&quot;, 36°51'27&quot;)</td>
<td>0.80</td>
<td>51 194</td>
<td>12 34</td>
<td>4.58</td>
<td>42.6</td>
<td>53.6</td>
<td>57.7(1.6)</td>
<td></td>
</tr>
<tr>
<td>MH97-K2.5 (2537 m, 118°39'7&quot;, 36°49'30&quot;)</td>
<td>0.78</td>
<td>51 172</td>
<td>23 20</td>
<td>5.85</td>
<td>39.2</td>
<td>50.6</td>
<td>53.7(2.1)</td>
<td></td>
</tr>
<tr>
<td>MH97-K3 (2427 m, 118°43'22&quot;, 36°46'17&quot;)</td>
<td>0.82</td>
<td>71 263</td>
<td>62 80</td>
<td>23.25</td>
<td>52.0</td>
<td>63.8</td>
<td>63.1(2.0)</td>
<td></td>
</tr>
<tr>
<td>MH97-K5 (2413 m, 118°38'19&quot;, 36°45'55&quot;)</td>
<td>0.77</td>
<td>52 182</td>
<td>68 78</td>
<td>19.31</td>
<td>40.6</td>
<td>52.7</td>
<td>56.3(3.2)*</td>
<td></td>
</tr>
<tr>
<td>MH97-K5 (2622 m, 118°35'34&quot;, 36°44'16&quot;)</td>
<td>0.83</td>
<td>66 211</td>
<td>51 70</td>
<td>16.21</td>
<td>44.1</td>
<td>53.2</td>
<td>53.8(1.6)</td>
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</tr>
<tr>
<td>MH97-K5.5 (2732 m, 118°36'23&quot;, 36°42'16&quot;)</td>
<td>0.84</td>
<td>74 227</td>
<td>38 59</td>
<td>14.91</td>
<td>52.2</td>
<td>62.1</td>
<td>58.4(2.6)</td>
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<tr>
<td>MH97-K6 (2512 m, 118°34'13&quot;, 36°40'19&quot;)</td>
<td>0.88</td>
<td>94 354</td>
<td>31 26</td>
<td>8.86</td>
<td>43.1</td>
<td>49.0</td>
<td>50.1(2.9)*</td>
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</tr>
<tr>
<td>MH97-K6.5 (2668 m, 118°31'55&quot;, 36°39'27&quot;)</td>
<td>0.84</td>
<td>70 253</td>
<td>73 71</td>
<td>19.28</td>
<td>39.0</td>
<td>46.7</td>
<td>46.0(2.0)</td>
<td></td>
</tr>
<tr>
<td>MH97-K7 (2690 m, 118°25'39&quot;, 36°34'48&quot;)</td>
<td>0.82</td>
<td>65 251</td>
<td>23 49</td>
<td>7.19</td>
<td>38.4</td>
<td>46.8</td>
<td>47.6(2.0)</td>
<td></td>
</tr>
<tr>
<td>MH97-K8 (2576 m, 118°28'42&quot;, 36°28'59&quot;)</td>
<td>0.81</td>
<td>66 213</td>
<td>10 25</td>
<td>3.48</td>
<td>41.5</td>
<td>51.4</td>
<td>47.7(2.2)</td>
<td></td>
</tr>
<tr>
<td>MH97-K9 (2561 m, 118°25'1&quot;, 36°27'56&quot;)</td>
<td>0.85</td>
<td>81 225</td>
<td>10 24</td>
<td>2.24</td>
<td>36.8</td>
<td>31.6</td>
<td>30.5(1.3)**</td>
<td></td>
</tr>
<tr>
<td>MH97-K9.5 (2634 m, 118°25'11&quot;, 36°25'35&quot;)</td>
<td>0.81</td>
<td>65 168</td>
<td>16 34</td>
<td>5.18</td>
<td>39.7</td>
<td>49.0</td>
<td>44.0(1.6)</td>
<td></td>
</tr>
<tr>
<td>MH97-K10 (2476 m, 118°23'30&quot;, 36°20'55&quot;)</td>
<td>0.84</td>
<td>78 204</td>
<td>12 27</td>
<td>4.75</td>
<td>47.6</td>
<td>57.1</td>
<td>52.4(2.4)*</td>
<td></td>
</tr>
</tbody>
</table>

† Corrected for alpha-ejection after Farley, Wolf, and Silver (1996). Ages based on single aliquots; all others are averages of multiple aliquots. Errors in parentheses are one standard deviation. †† Adjusted for deviation from 2500 m and tilting. ** Excluded on plots. * Adjusted according to 2000 m reference line. m Mass-weighted value.
The geothermal gradient has remained relatively stable and the rate of denudation is not extremely high (>5 mm/yr; Mancktelow and Grasemann, 1997). If so, the slope of the resulting age-elevation profile can provide a limit on the rate of denudation during the time span of the ages along the profile. For example, the slope of a suite of samples with ages ranging from ~40 to 60 Ma might be inferred to reflect the rate of denudation during that time interval. Changes in denudation rate may be detected from a distinct change in slope along the profile as shown by Stockli, Farley, and Dumitru (2000); the timing for the change in rate would be inferred from the ages that correspond to that change in slope. Note that this approach does not require estimation of a geothermal gradient, only that it be relatively constant during the period of interest. In this section, we evaluate denudation rates indicated by our new profile from the San Joaquin River valley and the vertical sample profiles reported by House and others (1997). We then discuss possible causes for sample age scatter along the profiles.

Denudation rates from vertical profiles.—The helium age-elevation profile from the San Joaquin River vertical transect displays a considerable amount of scatter that must
be resolved in order to estimate a denudation rate from these data. Some of this scatter may reflect the fact that the samples were collected over a relatively large map area rather than along a single linear transect and is partially removed when a minor correction for westward tilting is applied. Note that we employ a correction for 2° of westward tilting about a northwest-trending tilt-axis that passes through the eastern Great Valley (Huber, 1981; Unruh, 1991; House and others 1997; House, Wernicke, and Farley, 1998).

Despite this correction for tilting, a transition to a lower slope at low elevations (corresponding to ages less than ~55 Ma) persists in the San Joaquin vertical transect. The apparent transition to a lower slope may reflect the fact that the lower samples are sufficiently far removed from the others to have experienced a slightly different cooling history: the samples with younger ages were collected ~3 km farther to the east than the others (near Mammoth Pool Reservoir) in an area with more subdued local relief (fig. 2).

If the western, higher elevation samples are considered alone, they yield a denudation rate of 0.04 mm/yr (or 0.05 mm/yr after correction for tilting). This value is similar to the slopes of previously reported vertical sample profiles from the Sierra Nevada which extend to ages as young as ~22 Ma (House and others, 1997). Thus, the apparent change in slope may reflect a slowing of denudation rate, but more likely is an artifact of sampling geometry. Helium ages from Yosemite Valley yield an apparent denudation rate of 0.05 mm/yr (0.06 mm/yr after correction for tilting), and a profile from the Kings River Canyon indicates denudation at a rate of 0.05 mm/yr (0.05 mm/yr after correction for tilting). A transect along the east side of Mt. Whitney suggests a rate of 0.05 mm/yr (0.04 mm/yr after tilt correction).

**Sources of scatter in vertical elevation profiles.**—Scatter among samples along the age versus elevation profiles from some of the vertical transects approaches 5 to 10 my, which limits the precision of denudation rates determined from these data. Sources of the scatter in the Kings Canyon profile have been attributed to the effects of U- and Th-bearing inclusions on apatites of low U and Th content (House and others, 1997). Closure temperature variations and sample transect geometry may add additional scatter.

The closure temperatures for radiometric dating techniques depend on cooling rate (Dodson, 1973). The slow denudation rates indicated by the vertical elevation transects can be translated to a cooling rate by assuming a geothermal gradient; this cooling rate can in turn be used to estimate the helium closure temperature for the Sierran rocks. Although this calculation requires the assumption of a constant and known geothermal gradient, it provides a reasonable measure of the closure temperature of the system. This analysis may explain some of the scatter among different samples in the vertical elevation profiles, as well provide insight into the limitations of helium data.

A nominal geothermal gradient of 20°C/km was chosen for this study because it is consistent with both apatite fission-track and helium ages from Yosemite Valley, the Kings River Canyon, and Mt. Whitney (Dumitru, 1990; House and others, 1997). These data are inconsistent with a dramatic shift to extremely low geothermal gradients (approx 10°C/km) near 70 Ma proposed by Dumitru (1990) and suggest values in the range of ~15°-25°C/km. This range of values is consistent with estimates of modern heat flow values in the western Sierra Nevada (Saltus and Lachenbruch, 1991). It is probable that the geotherm was higher during denudation following final emplacement of the batholith at around 80 Ma, but the general cooling history of the Sierra is not consistent with a high geothermal gradient after 70 Ma.

The slow denudation rates indicated by the data (approx 0.05 mm/yr) and a paleo-geothermal gradient of ~15° to 25°C/km implies a cooling rate of ~0.8° to
1.3°C/My. This cooling rate corresponds to a closure temperature of ∼54° to 57°C, indicating that these samples passed through depths of roughly 1.7 to 2.5 km between ∼40 and 80 My ago. This very slow cooling rate may explain some of the scatter in the ages from the vertical profiles because even modest variations in closure temperature or geotherm can yield large age differences under these circumstances. Such variations in closure temperature may be related to grain size differences (House and others, in press) or to presently unknown characteristics of apatite (Farley, 2000).

Compounding these uncertainties is the fact that since none of the profiles is a perfect vertical transect, the cooling history of any particular sample may be slightly different from that of its nearest-elevation neighbors. This is particularly true if the geothermal gradient was spatially variable, as would be expected if denudation occurred in the presence of topographic relief (Stüwe, White, and Brown, 1994; Mancktelow and Grasemann, 1997). As a result, the level of precision with which Sierran helium ages may be interpreted may be no better than ∼5 to 10 My, the range indicated by scatter in the San Joaquin elevation transect. In other words, the scatter in the data set may be an inherent feature in vertical profiles collected from natural, slowly cooled settings because topographic effects on the cooling path and grain size variations in helium diffusivity are amplified at slow cooling rates (House and others, in press).

Comparison of computed denudation rates to geological estimates.—As discussed earlier, direct geological limits on denudation rates after ∼70 Ma are not available for much of the Sierra Nevada. Although Early Cretaceous plutons and metamorphic wallrocks near the axis of Cenozoic tilting were completely denuded by Eocene times, available thermochronometry from the interior of the range suggests that these rocks were more slowly denuded. Average Late Cretaceous denudation rates computed for rocks overlain by Eocene sediments are in the range of 0.05 to 0.15 mm/yr during the interval between 100 and 45 Ma. These rates are somewhat higher than those indicated from thermochronometric data as described above and based on the analyses of House and others (1997) and Dumitru (1990). These slightly discrepant rates can be reconciled if denudation rates were not uniform during this interval but were more rapid earlier (100-70 Ma) and then decreased after 70 Ma. In lieu of more detailed information on rocks directly beneath early Tertiary unconformities, we use rates deduced from our thermochronometric data described above in the following calculations but recognize that rates may have been somewhat higher during the early Cenozoic.

Comparison of constant-elevation profiles

One of our objectives is to compare the results along the two orogen parallel transects in order to constrain the longitudinal shape of trans-Sierran drainages. However, the modern relative positions of samples collected along the T1 and T2 transects have been modified by Cenozoic tilting of the range (Huber, 1981). In order to remove these effects from the data sets, we applied two geographic corrections to the profiles (fig. 4). This approach represents a modification of our original study (House, Wernicke, and Farley, 1998), so we summarize the effects of our final correction relative to uncorrected data on both transects in figure 4.

The first geographic correction accounts for sample scatter about the reference elevation and effectively shifts the samples to a constant reference horizon (2000 m for the T1 transect and 2500 m for the T2 transect). This correction was originally applied to the T1 samples to remove elevation-related age variations, although a slightly higher correction factor was used here: the uncorrected average age-elevation gradient of 0.05 mm/yr from the vertical profiles. Sample elevations along the T2 transect range from 2329 to 2756 m, corresponding to maximum age corrections of +3.4 and −5.1 Ma, respectively.
We apply a second geographic correction designed to remove the effects of Late Cenozoic tilting on relative positions of T1 and T2 sample transects. Present locations (T1 samples shown by open circles; T2 shown by filled circles) are centered about 2000 and 2500 m elevations, respectively, and are projected onto profile orthogonal to those shown on figure 2. Rotation into pre-tilt configuration (removal of 2° of westward tilt about a northwest trending axis parallel to profiles shown in figure 2 and centered in the eastern great Valley, at Friant (Huber, 1981; Unruh, 1991; House and others, 1998), are shown by group labeled “prior to tilting”. (B) The first geographic correction to helium ages adjusts sample ages in order to account for differences between sample elevations and the reference elevations (2900 m for T1 and 2500 m for T2). Open circles are schematic sample locations along orogen-parallel profile; dashed line is the reference elevation. Using a value of 0.05 mm/yr from the observed elevation/age gradients of vertical profiles, elevation-adjusted helium ages are calculated: elevation-adjusted age = [Ft corrected observed age] + [Δy/(0.05 mm/yr)], where Δy = reference elevation – observed elevation. (C) The second geographic correction adjusts the sample ages according to 2° of westward tilting. Following geographic correction 1, samples are now effectively at their reference elevation (shown by gray circles on profile parallel to the tilt-direction). Tilting produces a change in elevation (Δy,tilt) that varies as the sample distance from the reference profile (black circle). Using the same correction factor used for correction 1: tilt-corrected age = elevation-adjusted age + [(Δy,tilt)/(0.05 mm/yr)]. (D) Magnitude of corrections for T1 and T2 profile. Filled circles are original, Ft-corrected ages; open circles show the final corrected ages. The maximum age correction that results is about 12 my.

In order to account for tilting we correct ages along each profile using the age-elevation gradient implied by the vertical profiles from the western Sierra Nevada (again, using 0.05 mm/yr as described above). A final tilt-corrected age for each sample can be calculated from the change in elevation due to tilting and the age-elevation gradient (fig. 4). The samples along the T1 profile were also corrected...
of the Sierra Nevada, California, from (U-Th)/He ages in apatite

**Correction One**

- Reference elevation
- \( \Delta y \)
- Elev. corr. age = obs. age + \( \Delta y / (0.05 \text{ km/my}) \)
- Distance along range-parallel transect

**Correction Two**

- \( \Delta y, \text{tilt} \)
- Final adj. age = (adj. age) + (\( \Delta y, \text{tilt} / (0.05 \text{ km/my}) \))
- Distance along range-orthogonal transect

**Graphs**

- **C.**
  - Age (Ma)
  - Distance (km)
  - T1
    - Ft corrected age
    - Tilt-corrected age
  - T2
    - Ft corrected age
    - Tilt-corrected age
using this second correction procedure. The magnitude of this adjustment is small for samples within each profile as shown on figure 4.

After correcting for the difference between sample elevations and the 2500 m reference elevation and for late Cenozoic tilting (as described in above), the T2 ages are entirely within the range of values for the T1 profile (fig. 5). Helium ages and the three-sample moving average along the original T1 profile exhibit a pronounced variation in age that is roughly correlated with modern topography (fig. 5). In contrast, helium ages along T2 are nearly invariant across the Kings drainage but systematically younger in association with the higher topography toward the southern end of the profile (Great Western Divide area; figs. 2, 5). Ages in the region approaching the San Joaquin River canyon are somewhat higher than those elsewhere along the transect, but there is no systematic age variation like that seen on the T1 transect.

**Analysis and interpretation of horizontal age profiles**

Helium ages along a constant elevation transect are much more sensitive to topographic amplitude than to wavelength, suggesting that $\Delta_{\text{He}}$ may be used as an indicator of paleo-topographic relief (House, Wernicke, and Farley, 1998). In our previous study, we assumed an erosion rate of 0.1 mm/yr, a rough estimate for the average Late Cretaceous to Recent rate in the Sierra Nevada, as discussed above. However, the slopes of the age versus elevation profiles throughout the Sierra Nevada, including the Shuteye Peak transect, suggest that denudation during this time may have been a factor of two slower ($\sim 0.02-0.05$ mm/yr). Below, we consider the effect of denudation rate on estimates of paleorelief from helium age data.

**Models of denudation beneath steady state topography.**—We modeled $\Delta_{\text{He}}$ values for a range of denudation rates and topographic amplitudes in order to evaluate how uncertainty in denudation rate affects estimates of paleo-relief. We have also investigated how the assumed geothermal gradient influences these factors as well. In these models, the time-temperature history of hypothetical samples R (sub-interfluve or ridge) and V (sub-valley) were constructed assuming a constant rate of denudation under steady-state topography (Mancktelow and Grasemann, 1997). From the resulting model histories, $\Delta_{\text{He}}$ was computed for apatites (radius of 60 microns) using diffusion parameters for Durango apatite (Farley, 2000) and the numerical method of Wolf, Farley, and Kass (1998).

Parameters used in these models (shown in table 3) are nominal values that are widely applied to the Sierra Nevada, corresponding to a Cenozoic geothermal gradient of $\sim 20^\circ$C/km; a wavelength of 70 km was assumed in all cases. As discussed above, this nominal geothermal gradient was chosen, because it is consistent with both apatite fission track and helium ages from Yosemite Valley, the Kings River Canyon, and Mt. Whitney (Dumitru, 1990; House and others, 1997), as well as estimates of modern heat flow values in the western Sierra Nevada (Saltus and Lachenbruch, 1991). Exploration of a slightly wider range of geothermal gradients ($15^\circ$-$30^\circ$C/km) reveals only minor effects on our results, as discussed below and shown on figure 6.

Our calculations show that, in addition to being sensitive to amplitude, $\Delta_{\text{He}}$ is a strong function of denudation rate (fig. 6) such that an overestimate will produce an overestimate in paleo-relief. The relationship between denudation rate, topographic amplitude, and $\Delta_{\text{He}}$ shown in figure 6 is the product of two effects. First, $\Delta_{\text{He}}$ reflects the time elapsed between the cooling of valley and ridge samples through the HePRZ. The computed value of $\Delta_{\text{He}}$ can therefore also be estimated from the depth of the closure isotherm (here we refer to the $60^\circ$C isotherm), $\Delta z(60^\circ C) = z(60^\circ C)_{\text{valley}} - z(60^\circ C)_{\text{ridge}}$, divided by the denudation rate, $e$, such that $\Delta_{\text{He}} = \Delta z/e$. This relationship produces the nearly linear relationship that we obtained for denudation rates $>0.04$ mm/yr. At very slow rates, $<0.04$ mm/yr, however, the closure temperature is lower: a denudation rate of 0.02 mm/yr would translate to a $0.3^\circ$ to $0.5^\circ$C/my cooling rate,
Fig. 5. Final tilt-corrected helium ages for the T1 and T2 transects. (A) Final tilt-corrected helium ages from the 2000 m transect (T1; House, Wernicke, and Farley, 1998), plotted on top of running three sample average. Lower panel shows sample positions projected onto T1 topographic profile in figure 2. Note that one sample from the original T1 transect (MH95–5) is located closer to the T2 transect and so was included in T2 when correcting for Cenozoic tilting and in calculating the average age curves. Similarly, two samples from the T2 transect, MH97-F11 and MH97-K10, lie closer to the T1 transect and so are included in this profile and in the calculation of the average curve. Errors are 1σ. (B) Final tilt-corrected helium ages from the 2500 m transect (T2), plotted on top of running three sample average. Lower panel shows sample positions projected onto T2 topographic profile in figure 2.
assuming a geothermal gradient of 16° to 25°C/km and a closure temperature of ∼48° to 51°C). As the closure temperature is reduced, the depth at which the helium age locks in becomes shallower and increasingly occupies regions of the upper crust that are more strongly affected by the overlying topography (fig. 6).

Uncertainty in the geothermal gradient during denudation produces a small effect at denudation rates higher than ∼0.02 mm/yr. In general, slightly higher Δ_tHe’s are predicted for higher geothermal gradients, but this effect is relatively minor for the range of parameters examined here (15°-30°C/km; fig. 6). This effect would be larger

Table 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>K, thermal conductivity</td>
<td>2.4 W/mK</td>
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<td>A_v, volumetric heat flow</td>
<td>2.2 x 10^3 W/m³</td>
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<td>h_0, length scale of rad. decay</td>
<td>10 km</td>
</tr>
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<td>T_0, T at y = -h_0</td>
<td>15 °C</td>
</tr>
<tr>
<td>L, depth to base of lithosphere</td>
<td>100 km</td>
</tr>
<tr>
<td>T_1, temperature at base of lithosphere</td>
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<tr>
<td>β, soil lapse rate</td>
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</tbody>
</table>

Fig. 6. Relationship between helium age differences (Δ_tHe), denudation rate, and amplitude, h_0, based on models of denudation beneath steady-state topography. Helium age differences (Δ_tHe) were computed between samples denuded at a constant rate beneath the axes of ridges and valleys of a periodic topography with a wavelength of 70 km; samples are spaced 35 km apart (λ/2). Thermal histories were constructed following Mancktelow and Grasemann (1997) with parameters shown in table 3. Each curve represents the predicted relationship between (Δ_tHe) and denudation rate for a given amplitude of relief assuming a geothermal gradient of 20°C/km. The light gray band shows the Δ_tHe range observed in the Sierra T1 transect (fig. 4). Open circles show results computed using a higher geothermal gradient (30°C/km); gray circles show results computed using a lower gradient (15°C/km).
at higher geothermal gradients (>30°C/km) but is not considered here because available evidence from the Sierra Nevada suggests that the Cenozoic geothermal gradient lies within the 15°-30°C/km range (see above).

For rapid rates of erosion (>0.1 mm/yr), values of \( \Delta t_{\text{He}} \) predicted for a wide range of amplitudes become indistinguishable given the analytical uncertainty in the dating technique. In cases of extremely rapid denudation, like that proposed for tectonically active regions such as the Southern Alps of New Zealand (Tippett and Kamp, 1995) or Nanga Parbat (Schneider and others, 1999), \( \Delta t_{\text{He}} \) may ultimately approach zero.

**Limits on Sierran paleo-relief from steady-state models.**—The observed difference in helium ages along the original T1 sample transect is generally in the range of 20 to 30 my (fig. 5; House, Wernicke, and Farley, 1998). Assuming that the erosion rate was roughly 0.04 to 0.05 mm/yr, as indicated by the slopes of the age versus elevation transsects from the Sierras, a range of amplitudes \( h_o \) between 0.6 and 1.2 km is suggested (fig. 6). Although significantly lower than our earlier estimate of 2 to 4 km of total relief \( h_o = 1-2 \) km based on the average post-emplacement denudation rate of 0.1 mm/yr, these figures nonetheless suggest long-wavelength relief of \( \sim 1.0 \) to 2.4 km along the T1 transect during cooling.

The overall lack of topographically correlated age variations on the T2 transect suggests that the thermal effect of the topographic relief that existed at the time of cooling was greatly reduced along this transect relative to that along the T1 transect. We interpret this reduced thermal effect to indicate a simple reduction in long-wavelength relief: our sensitivity analyses of helium ages computed from models of denudation beneath steady-state topography indicate that amplitudes less than \( \sim 0.2 \) km (at 20-70 km wavelengths) will impart no detectable \( \Delta t_{\text{He}} \) for most denudation rates (fig. 6; House, Wernicke, and Farley, 1998). However, assuming the overall scatter in the ages of \( \sim 5 \) to 10 my at any given location (as opposed to the smaller error in a particular age) is an upper limit of age variation that might go undetected (see for example the scatter along the San Joaquin age profile, fig. 3), then a somewhat higher amplitude may go undetected at higher erosion rates, perhaps as high as 0.5 km.

Alternatively, the thermal effects of topographic relief along the T2 profile may have been counteracted by the effects of secondary topographic features oriented either parallel or transverse to the trend of the range. To assess the effects of such features requires a landscape evolution model more complex than that considered here. Thus, we cannot rule out the possible effects of such features on our data, but we can assess the possible magnitude of such effects by examining the modern topography of the range. The density of lower-order features is known to increase (Hovius, 1996), and the periodic nature of long-wavelength relief is reduced toward orogenic crests as apparent in the topography of the Sierra Nevada today (fig. 2). The topography along the T1 and T2 transects shows that at wavelengths less than \( \sim 20 \) km which typify such lower-order features, relief is generally less than 0.5 km \( (h_o = 0.25 \) km). Our analysis indicates that the contribution of such local topography would be less than 7 to 10 my even at very low erosion rates, which is within the noise of the data (fig 6.). The presence of features of a scale sufficient to dampen the effects of long-wavelength topography along the T1 and T2 transects implies that the topography along the T1 transect was even larger than we estimate above and that relief along the T2 transect was of lower amplitude than we suggest. Alternatively, if such features positively reinforced the long-wavelength effects, then we may be over-estimating the relief along T1 and T2. Again, we reiterate that more complex landscape and thermal models are required to assess these effects.

**INDEPENDENT ESTIMATES OF RELIEF FROM VERTICAL TRANSECTS**

House and others (1998) suggested that the long-wavelength topography in the proto-Yosemite Valley region was subducted \( (h_o < 0.2 \) km) at the time of cooling.
Therefore, thermochronometric ages from the vertical sample transect from this valley may be considered to represent the cooling history beneath an interfluve. In contrast, transects from the Kings Canyon and the San Joaquin drainages, which appear to have been large features throughout the Cenozoic, should record cooling in response to denudation beneath large paleo-valleys. As a result, helium ages from the Yosemite Valley transect should be systematically younger than those from the Kings Canyon and San Joaquin transects at a given elevation. Indeed, the helium ages along the San Joaquin profile are generally older than those from the Yosemite profile (both before and after tilt correction), consistent with earlier cooling beneath a paleo-valley. However, this relationship is not observed in the Kings River Canyon transect, where high analytical uncertainties and the possibility of contamination problems complicate the interpretation of helium ages (House and others, 1997).

The Mt. Whitney profile is consistently younger than any of the western profiles at a given elevation, both in its present position and in its reconstructed position prior to tilting. Because the Whitney profile is located well to the east of the others, the younger ages may be partly or wholly due to a higher geotherm to the east at the time of cooling. Alternatively, the younger Whitney ages may indicate that the Mt. Whitney transect records delayed cooling beneath a paleo-interfluve, with the lowest elevation samples exposed by Late Cenozoic faulting and erosion along the Sierra Nevada-Owens Valley boundary (House and others, 1996). If the cooling ages along the Mt. Whitney transect represent the thermal structure beneath an interfluve rather than east-west variations in the thermal structure from other causes, then the difference in helium ages between the Whitney profile and those of the sub-valley profiles may be used as an estimate of the magnitude of relief during cooling that is independent of the vertical elevation profiles. The difference in helium ages at a given elevation, \( \Delta t_{\text{He}} \), is \( \sim 35 \) my when the profiles are compared in their present orientations; the difference is reduced after correction for tilting to \( \sim 20 \) my. These estimates are similar to those along the T1 transect, suggesting that the difference may reflect the amplitude of the overlying topography.

One of the corollaries of our new interpretation of the Sierra helium data is that an overall reduction in relief during the Cenozoic is likely but not required, because the modern topography has an amplitude near 0.5 km at a 70 km wavelength. If relief reduction is accomplished by an increase in the rate of interfluvial erosion relative to that in valleys after maximum relief is attained (Davis, 1899), then it would presumably be accompanied by more rapid cooling rates at interfluvial sites and departure from steady-state topography.

The age of the onset of relief reduction in the Sierras is not known, but if it occurred prior to or during denudation of the rocks of the central Sierra Nevada through the HePRZ, then its effects may be apparent in the slopes of vertical elevation profiles. In particular, comparison of the ages of samples from vertical profiles cooling beneath paleo-interfluves with those of samples collected from vertical profiles that cooled beneath paleo-valleys may provide insight into whether there was a significant difference in denudation rate at these sites during cooling. Thus, we might expect the slopes of the Yosemite and Mt. Whitney profiles to be higher than that of the San Joaquin profile.

This effect is schematically shown in figure 7. Denudation beneath steady-state topography will produce parallel but offset profiles, with the offset (\( \Delta t_{\text{He}} \)) reflecting the denudation rate and topographic amplitude present during denudation. However, cooling during a period of relief reduction that is accomplished by accelerated denudation at interfluves relative to valleys may produce different effects depending on the trade-off between denudation rate and relief during cooling. Similar slopes would be produced if a higher ridge denudation rate is exactly balanced by a lower...
geothermal gradient under the ridge (fig. 7A). Alternatively, a lower apparent denudation rate for the ridge profile would result in the case of a very large topographically induced reduction in interfluve geotherm (fig. 7B). Finally, if topography is minor, imparting only a small effect on the near surface geotherm, then the apparent denudation rate of the ridge profile will more closely reflect the denudation rate and might be higher than that of the valley (fig. 7C).

As discussed above, we do not discern a clear difference in slope among the vertical profiles. This observation, coupled with possibly ambiguous results in vertical transects as described above, suggests that if relief reduction did occur, it must have either largely post-dated cooling of the samples through the HePRZ, or it may have occurred at a slow rate. The same is true for any periods of relief production.

**Implications for Late Cretaceous Geomorphology of the Sierra Nevada**

Our helium results combined with other limits on paleo-elevation from the region (Small and Anderson, 1995; Wolf and others, 1997; Chamberlain and Poage, 2000) suggest that the Sierra Nevada is a long-lived mountain range and may once have occupied the edges of a large orogenic plateau that extended across the Cordilleran interior (Coney and Harms, 1984; Wolfe, Forest, and Molnar, 1998; Sonder and Jones, 1999).

The long wavelength relief at the longitude of deepest incision may be used to estimate summit elevations of the paleo-mountain range by analogy with modern ones (House, Wernicke, and Farley, 1998). Short-wavelength topography, especially in the early stages of incision, may be a large fraction of or even greater than the long-wavelength signal. For example, local relief is routinely >500 m, and values in excess of 1000 m are not uncommon in the Sierras. Further, relief at the longitude of deepest incision is only about 70 percent of that for the range as a whole. Using these assumptions and an estimated range of $h_o = 0.6$ to 1.2 km, the height of the mountain range would be $1.3(2h_o + 500$ m) or 2 to 3.8 km. The lower part of this range is much lower than the 4.5 km estimated by House and others (1998) assuming $h_o = 1.5$ km but agrees well with recent paleobotanical estimates from Miocene strata in western Nevada (see below).
The absence of age variations across the drainages for the T2 profile suggests that the overlying relief at the time of cooling was smaller than that overlying the T1 transect. Only helium ages adjacent to the San Joaquin drainage hint at the presence of significant relief during cooling. The data suggest that the relief along the T2 transect was <0.5 km, significantly smaller than values of ~2 to 4 km along the T1 transect, or that if it were at all larger, the signal may have been offset or counteracted in some way by the three-dimensional pattern of paleodrainages.

The decrease in relief that we infer from these data is consistent with a headward increase in the stream gradient or the transition in relief such as might be found approaching the headwaters of an orogenic plateau (fig. 8; Masek and others, 1994; Montgomery, 1994). Stream gradients increase non-linearly with proximity to the trunk stream source such that a large decrease in relief can occur over a very short distance in the upper reaches of the drainage (Ahnert, 1984; Masek and others, 1994; Montgomery, 1994). This transition is also accompanied by a reduction in drainage spacing as more tributaries are encountered with an overall reduction in long-wavelength relief (fig. 2; Montgomery, 1994). Thus, the horizontal age variations for T1 and T2 appear to indicate that by 70 to 80 Ma, the margins of the Cordilleran orogen were deeply incised, but deep incision had not eroded headward from the locus of the T1 transect by more than about 50 to 60 km. If the Sierra Nevada occupied a position at the edge of a large plateau, the long profiles of the streams would likely have been convex-upward at this time (fig. 8). Since the modern drainages, in particular the San Joaquin, extended east of the modern crest of the range at 10 Ma (Huber, 1981), the average headward erosion rate of the drainages from 80 to 10 Ma would have been at least 0.7 mm/yr.

Many authors have alluded to the possibility of a plateau such as that postulated here based on the analogy of the modern Andes and the Late Cretaceous Cordillera (for example, Sonder and others, 1987; Wernicke and others, 1996; Jones, Sonder, and Unruh, 1998; Sonder and Jones, 1999). The Basin and Range has also been suggested to reflect a mature version of the Tibetan plateau (Molnar and Chen, 1983). These comparisons are supported by paleo-botanical data suggesting the region stood at altitudes of 2 to 3 km during the Early to Middle Cenozoic (Forest, Molnar, and Emmanuel, 1995; Gregory-Wodzicki, 1997; Wolfe and others, 1997; Wolfe, Forest, and Molnar, 1998). Several other lines of evidence suggest that in the vicinity of the Sierra Nevada, these elevated regions were of moderately low relief (Marchand, 1971; Gilbert and Reynolds, 1973).

In order to better understand the tectonic setting and geomorphic significance of the Late Cretaceous mountain belt that we infer on the basis of helium data, more information regarding paleo-elevations of inland regions are needed (Sonder and Jones, 1999). Indeed, our helium data do not require the existence of such a plateau but are consistent with the evidence outlined above. Carefully designed helium sample transects targeted at regions to the east (for example, the White Mountains) may further elucidate the paleogeomorphology of the region.

**CONCLUSIONS**

New (U-Th)/He ages in apatite from the central and southern Sierra Nevada illustrate the importance of strategic sampling profiles in estimating denudation rates and paleorelief based on differences in helium ages. In the case of the Sierras, vertical elevation profiles constrain denudation rates that are in turn necessary for refining paleo-relief estimates from horizontal profile data.
The simple thermal models discussed here demonstrate the sensitivity of paleo-relief estimates to helium age differences and denudation rate and show that for fast denudation, relief may go undetected. Clearly, much remains to be learned regarding the geomorphologic significance of helium age data. While important first order limits are available from the approach we employ here, more detailed investigations of these relationships will require more complex models of landscape evolution and the resulting topographic effects on cooling histories than those employed here.

Fig. 8. Illustration of possible Sierra paleo-topography consistent with helium data. Top panel shows relative positions of T1 and T2 sample transects now, with a smoothed average longitudinal profile of major transverse drainages (Montgomery, 1994). Lower panel shows the relative positions of sample profiles beneath ancient Sierran topographic relief. Prior to tilting, the profiles are at similar structural positions, but valleys are deeper over T1 samples than over T2. Two longitudinal profiles are suggested by heavy (concave up) and light (convex up) dashed lines.

The simple thermal models discussed here demonstrate the sensitivity of paleo-relief estimates to helium age differences and denudation rate and show that for fast denudation, relief may go undetected. Clearly, much remains to be learned regarding the geomorphologic significance of helium age data. While important first order limits are available from the approach we employ here, more detailed investigations of these relationships will require more complex models of landscape evolution and the resulting topographic effects on cooling histories than those employed here.
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