Late Cenozoic denudation, bedrock and surface uplift rates in the Santa Lucia Mountains, California

3719 words

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Abstract

Apatite U-Th/He ages from a vertical transect from the Santa Lucia Mountains, central California Coast Ranges are used to reconstruct the history of exhumation, and bedrock and surface uplift in this region since ~6 Ma. We find an overall increase in topographic elevation between ~6 and ~2 Ma, coincident with denudation rates of ~0.35 mm/yr. The topographic growth of the Santa Lucia Range is consistent with the appearance of granitic clasts of Salinian origin that are found in the Temblor Range at this time. The onset of bedrock uplift and exhumation at ~6 Ma follows a change in plate motion at ~8 Ma. The apparent time lag in response to this change in relative plate motion may be due to the fact that the increased shortening was accommodated by structures elsewhere in the Coast Ranges. After 2 Ma, denudation rates increased substantially (>1 mm/yr) and far outpaced rates of bedrock uplift, contributing to an overall decrease in elevation. The transition in denudation rates at ~2 Ma is not matched by detectable changes in the plate motion record, but may be related to partitioning of strain within the Coast Ranges. The post-2 Ma denudation rate is about one order of magnitude higher than independently
constrained river erosion rates in the area. We suggest that this discrepancy indicates that exhumation of the steep western slopes of this segment of the Coast Ranges has been dominated by mass wasting via landslides, rather than fluvial erosion, since ~2 Ma.
Introduction

The Santa Lucia Mountains define one of several topographically distinct transpressional ranges within the Coast Ranges province (Figure 1). Oblique strike-slip faulting along the boundaries of these ranges, coincident with folding and reverse faulting in response to transpression across the San Andreas system have resulted in the Late Cenozoic topographic rise of many of these ranges, as well as pronounced episodes of denudation (e.g. Burgmann et al., 1994; Dumitru, 1991). In some regions, the topographic growth or denudation of a particular range has been shown to be directly related to the obliquity of the local plate boundary (Anderson, 1990).

The stratigraphic record and deformational history of young sedimentary rocks in the Santa Lucia Range indicate that most recent deformation in this range is Plio-Pleistocene in age (Compton, 1966; Page et al., 1998). However, there are few constraints on bedrock uplift during this time (e.g. Compton, 1966) and existing thermochronometric data provide little insight into the coincident history of denudation and bedrock uplift. Late Cretaceous apatite fission track (AFT) cooling ages from the region limit the total amount of denudation in much of the range during the Cenozoic to less than 3-4 km (Naeser and Ross, 1976), although more significant denudation may have occurred locally.

In this paper we estimate the average post-Miocene denudation rates in the Santa Lucia Mountains using (U-Th)/He apatite thermochronometry. The low closure temperature of this system (~70°C, Farley, 2000) makes it possible to constrain the recent history of denudation in this region, while the record of marine sedimentation in
the region permits us to reconstruct the history of bedrock and surface uplift coincident with denudation. These estimates are then used to (1) track the topographic evolution of the mountain range (2) assess the relative contribution of principal mechanisms of erosion in the area, and (3) address the relationships between the exhumation history and the plate tectonic record.

Geologic setting

The Santa Lucia Range of the southern Coast Ranges, California, extends along the California coast from Monterey Bay approximately 140 miles south where it merges with the San Rafael Mountains (Figure 1). The range is bounded on the west by the Sur-Nacimiento fault zone and to the northeast by the Rinconada-Reliz fault (Hall, 1991). Basement rocks exposed in the western part of the range include Late Cretaceous magmatic arc intrusive rocks (100-80 Ma; Mattinson and James, 1985, Kistler and Champion, 2001) and amphibolite to granulite facies metasediments (7-8 kbar; Hansen and Stuk, 1993). These rocks, representing the deepest exposure of the now-dissected Salinian arc (Ross, 1978), are unconformably overlain by a sequence of Latest Cretaceous (Maastrichtian) and Cenozoic sedimentary rocks predominantly exposed on the northeastern and southern limits of the range (Lawson, 1893; Christensen, 1965; Compton, 1966).

Northward translation of Salinian basement and the overlying Late Cretaceous sedimentary sequence of the Santa Lucia Mountains were largely accomplished by Cenozoic movement along the San Andreas and related faults, including the San Gregorio-Hosgri, Rinconada-Reliz, and Sur-Nacimiento faults (Ross, 1978; Graham,
Northward translation was accompanied by episodic compressional deformation and considerable vertical motion within and adjacent to the Santa Lucia Mountains. At least 4 distinct episodes of Late Cenozoic compressional deformation have been identified in the region, at least two of which are attributed to the change in the relative plate motions between Pacific and North America from a mostly strike-slip to a more compressive vector in the last ~8 Ma (Atwater and Stock, 1998; Page et al., 1998; Tavarnelli, 1998; Tavarnelli and Holdsworth, 1999). In the northern Santa Lucia range, increased compression culminated in Plio-Pleistocene high-angle reverse faulting and folding, which removed much of the Cenozoic sedimentary cover and deeply eroded Salinian basement rocks (Compton, 1966; Page et al., 1998).

Compressional deformation and structural inversion of the Santa Lucia Mountains since the Late Miocene stripped much of the sedimentary cover especially on the western flank of the central Santa Lucia Mountains (Compton, 1966; Page et al., 1998). Patterns of AFT cooling ages in basement rocks and the topographic asymmetry of the range suggest that total denudation along the northwestern and western limits of the range has been greater than in the east and southeast. Stratigraphic relationships and Late Cretaceous AFT cooling ages from the Southern Santa Lucia range limit both the amount of Cenozoic burial and subsequent exhumation to less than 2-4 km (Compton, 1966; Naeser and Ross, 1976). In contrast, a single Miocene AFT cooling age from the northern Santa Lucia Mountains suggests more extreme denudation.

Samples and Results
Apatite helium ages were measured on seven samples from the Cone Peak area, ranging in elevation from 152 to 1510 meters along Hare Canyon, as well as one sample from about 30 km to the north of Cone Peak (SUR-1) (Figure 1). We chose this transect because its relief (~1400 m in one of the steepest topographic segments of coastal North America) and it is largely underlain by granitic basement rocks suitable for (U-Th)/He thermochronometry. The samples analyzed here consist of Salinian basement rocks, tonalites and diorites that occupy the hanging wall of the steeply-dipping Nacimiento fault (Dickinson, 1983; Hall, 1991) which runs approximately parallel to the coast; the footwall Franciscan rocks were not sampled for this study (Figure 1). Upper Cretaceous sedimentary rocks as well as all major Cenozoic stratigraphic units of the Coast Ranges also crop out in the vicinity of Cone Peak (Compton, 1966). Although several Plio-Pleistocene reverse faults have been mapped around Cone Peak, there are no mapped Cenozoic faults within the sampled transect (Compton, 1966, our unpublished field mapping).

Helium age determinations were made using the analytical approach described by House et al. (2002). For each helium age determination, we analyzed aliquots consisting of 5-15 grains in the 88-200 µm size-range with an average grain size of 130 microns. Despite the wide range in radii, the corresponding closure temperatures range is between only 71-82°C, with a closure temperature of 76°C corresponding to the mean grain size (Wolf et al., 1996; Farley, 2000). Results for the samples are shown in Table 1.

Helium ages range from 2.3 to 9.9 Ma and are strongly correlated with elevation (Figure 2). With one exception, replicate ages obtained on four samples agree within the estimated analytical uncertainty described above. Only sample 3 (700 m) yields ages that
fall outside of this range, but these appear to be correlated with grain size: two aliquots with grain radii of 46 and 74 microns yield ages of 2.7 and 4.2 Ma, respectively. Assuming a cooling rate of 10°C/my, the mean radii of these two aliquots (46 and 74 microns) yield closure temperatures of 71 and 78°C, respectively, which may account for some of the range in the measured ages (Reiners and Farley, 2001).

Within the Hare Canyon suite, helium ages generally increase with increasing elevation. The highest elevation sample yields a much older cooling age that falls off of the trend defined by the other samples and is suggestive of the base of a helium partial retention zone (Figure 2). These data, therefore, qualitatively suggest that relatively slow cooling of the region was followed by rapid cooling between 6-2 Ma. By comparison, the cooling age from the SUR-1 sample, 30 km to the north, is roughly 2 my older than ages at the corresponding elevation in the Hare Canyon transect.

**Interpretation of helium results**

The systematic pattern of cooling ages that we obtained in the Santa Lucia samples suggests that these data record cooling in response to denudation. That is, removal of overburden either by erosion or by some tectonic action like normal faulting causes rocks to cool through the helium closure temperature. Assuming no structural modification of the Hare Canyon sample transect subsequent to the locking in of these ages (i.e. regional tilting or faulting that offsets the samples; Compton, 1966; Montgomery, 1993), we can use the correlation between cooling age and elevation to calculate the exhumation rate that produced the pattern of cooling ages that we observe.
Regression of the data from the Hare Canyon transect yields a slope that corresponds to a steady exhumation rate of \(0.35 \pm 0.06\) mm/yr for the period 6.1 to 2.3 Ma.

In addition to this information, the data may also be used to constrain the more recent exhumation history. Assuming a geothermal gradient of 25°C/km and a mean annual surface temperature of 10°C, the helium closure isotherm corresponding to the grain size range of the Hare Canyon samples (~76°C) should lie at a depth of 2640 meters below the Earth’s free cooling surface, which we assume here to be sea level (Farley et al., 2001). However, the regression line yields a zero age intercept at a depth of 640 ± 249 meters below sea level. If exhumation proceeded at the rate indicated by the regression (0.35 mm/yr) to the present day, this intercept thus predicts that a zero helium age, and the closure isotherm, would lie at this depth. The 2000 meter discrepancy between the zero age depth from the regression and that based on the geothermal gradient can be explained by an acceleration in exhumation after ~2.3 Ma. Assuming the acceleration initiated at 2.3 Ma, the ensuing rate would have been 1.2 mm/yr, and higher if the shift occurred after that time. Factors like climatic cooling, or a progressive increase in the geothermal gradient since ~2.3 Ma may contribute to an apparent increase in denudation rate, but are unlikely to explain the full acceleration indicated by the data.

While folding and faulting of Plio-Pleistocene sediments are common, there are no data suggesting large-scale block rotations of this part of the Santa Lucia Mountains in the Plio-Quaternary (Compton, 1966). Pleistocene tilting of the Hare Canyon transect could have several implications for our interpretation of the data above. If tilting occurred about an axis parallel to the trend of the profile, it would have no effect on the resulting denudation rates computed above but it would explain the shift in ages between the Hare
Canyon transect and the SUR-1 sample to the north. However, this sense of tilting is distinctly different from that indicated by geomorphic features in the adjacent Gabilan range (e.g. Christensen, 1965), as well as evidence for southward tilting in the Santa Lucia region in general (e.g., Compton, 1966; Page et al., 1998). Furthermore, the apparent offset in cooling ages is also consistent with either earlier denudation to the north.

Alternatively, tilting around an axis parallel to the range (and the trend of the range-bounding Nacimiento fault to the south) could impact the rates of denudation computed above significantly. East directed tilting would compress the current elevation range of the samples relative to that at the time of cooling, resulting in a calculated thermochronometric denudation rate that is lower than the actual value (e.g. House et al., 1997). Furthermore, the post-2.3 Ma rate may have been even higher than the value calculated above. Alternatively, westward tilting after cooling would act to expand the elevation range of the Hare Canyon suite, resulting in overestimates of denudation rates. Without reliable marker horizons on which to base estimates of tilting, however, it is difficult to resolve the effect of tilting on calculated denudation rates. Nevertheless, it is important to recognize these limitations in the following discussion.

**Estimates of bedrock and surface uplift**

In addition to the rate of exhumation, helium age data can also be used to estimate total bedrock uplift, provided a number of assumptions are satisfied. If the significantly older cooling age of the highest elevation sample represents the base of a helium partial
retention zone, then we may obtain an estimate of the amount of bedrock uplift that has occurred since ~6.1 Ma.

The helium partial retention zone (HePRZ; Wolf et al., 1998) refers to a temperature window in the upper crust in which helium is neither quantitatively retained nor lost. In the case of no denudation, helium ages within this thermal window, typically considered to span ~40-80°C (Wolf et al., 1998), decrease sharply with increasing temperature so that zero ages are encountered at the base (quantitative loss) and maximum ages, corresponding to the time since samples last cooled through the HePRZ are encountered at the top (quantitative retention). The relationship between helium age and temperature has been shown theoretically (Wolf et al., 1998), and documented in modern boreholes (House et al., 1997). Examples of fossil HePRZ’s have been observed in many fault-bounded blocks where the distinctive morphology of the HePRZ has been used to estimate the total amount of bedrock uplift (Stockli et al., 2000).

The base of the helium partial retention zone falls in the 75-85°C temperature range for the apatites grain-sizes in the Hare Canyon suite. In order to convert this information to an estimate of bedrock uplift, we must assume a geothermal gradient and mean annual surface temperature; here we will assume 25°C/km and 10°C, respectively. We must also define the reference elevation against which we will measure bedrock uplift (typically the average elevation); here we will assume the average elevation is sea level.

Using these parameters, the closure isotherm at the base of the HePRZ (76°C) would lie at a depth of 2640 m below sea level today. The fact that this horizon is
currently at an elevation of 1500 m above sea level implies roughly 4140 m of bedrock uplift since 6.1 Ma.

Changes in surface elevation (or surface uplift) can be estimated if bedrock uplift and exhumation are known (Molnar and England, 1990). In the Santa Lucia Mountains, contours of uplifted sedimentary contacts have been used to estimate total bedrock uplift in the last 2-3 Ma (600-900 m; Christensen, 1965). These values can be combined with constraints from the helium data above to reconstruct how relief has evolved in this part of the Coast Ranges over time. These constraints, combined with our geochronologic data allow us to break up the history of the region into two segments: 6.1-2.3 Ma and 2.3-0 Ma. Values and calculations used in this analysis are shown in Table 2.

Bedrock uplift between 6.1-2.3 Ma (3390 m) surpassed total denudation (1330 m), leading to a net increase in surface elevation of ~2060 m (Table 2). In contrast, denudation during the 2.3-0 Ma interval exceeded the estimated amount of bedrock uplift during this time (750 m average; Christensen, 1965), leading to a net reduction in surface elevation.

**Discussion and Conclusions**

Where plate motion is oblique to major transform systems, rapid denudation and bedrock uplift has been reported on the basis of thermochronometric analyses (e.g. Dumitru, 1991; Burgmann et al., 1994; Spotila et al., 1998). Within these zones of transpression, rapid bedrock uplift is accommodated by oblique slip on high angle transform faults (Spotila et al., 1998). In response to the bedrock uplift, enhanced denudation acts to reduce the surface uplift rate below that of rock uplift, effectively
decreasing the average elevation of a particular range (e.g. Anderson, 1994). This relationship has been observed in the Santa Cruz Mountains to the north of the Santa Lucia Mountains, where the pattern of bedrock uplift and denudation depends in part on the local geometry of faults adjacent to a small restraining bend in the San Andreas fault (Anderson, 1990; Anderson, 1994; Burgmann et al., 1994). Overall, patterns of younger AFT cooling ages (~4.6 Ma) are reported in topographically steeper parts of the range on the northeastern side of the San Andreas, while significantly older (Late Cretaceous) cooling ages are reported to the southwest of the fault. The topographic growth and demise of the Santa Cruz Mountains is correlated to its position relative to the local restraining bend in the San Andreas, as well as the denudational response to passage of the range past this bend (Anderson, 1994).

We observe a similar temporal correlation between episodes of rapid bedrock uplift, enhanced denudation and a reduction in surface uplift in the Santa Lucia Mountains. This correlation suggests that bedrock uplift between ~6 and 2 Ma may be a response to the local plate boundary geometry as well as potential changes in relative plate motions across this section of the Pacific-North American plate boundary beginning at ~8 Ma (Atwater and Stock, 1998) and possibly between 5-3 Ma (Cox and Engebretson, 1985; Pollitz, 1986; Harbert, 1991). The approximately 2 Myr lag between increased convergence at ~8 Ma and the onset of enhanced bedrock uplift at ~6 Ma indicated by our analysis of the data may reflect the fact that shortening was initially accommodated on structures elsewhere along the Coast Ranges and only initiated in the Santa Lucia Mountains once a sufficient amount of shortening accumulated.
Alternatively, the onset of bedrock uplift at ~6 Ma may be a direct response to a more recent plate reorganization that is not recognized by the most recent reconstruction of Atwater and Stock (1998). Earlier reconstructions suggested additional increases in compression across the Pacific-North American plate boundary at various times ranging from ~3.4 to ~5 Ma (Cox and Engebretson, 1985; Pollitz, 1986; Harbert, 1991). These recent episodes of increased compression have been cited as the cause of enhanced compression and uplift in the Coast Ranges (Page and Engebretson, 1984; McCulloch, 1989; Tavarnelli and Holdsworth, 1999), and while not confirmed by the reconstruction of Atwater and Stock (1998), they are permissible given the uncertainty of their reconstruction.

The data indicate that surface uplift exceeded denudation in the Santa Lucia Mountains during the interval between ~6 and 2 Ma as a result of enhanced bedrock uplift. The resulting topographic growth of the range during this interval is consistent with the fact that the Santa Lucia Mountains, along with the Santa Cruz Mountains and the Gabilan Range, have been suggested to be source regions for granitic clasts in Late Miocene conglomerates of the Temblor Range (Compton, 1966; Fletcher, 1967; Huffman, 1972). The helium results indicate that basement rocks were actively eroding and that positive relief was present in the Santa Lucia Mountains at this time, thus they may have served as a source for the Temblor conglomerates.

Enhanced denudation after ~2 Ma may reflect the denudational response to the accumulation of bedrock uplift and positive topographic relief during the prior interval (Anderson, 1994). Denudation rates of order ~1 mm/yr indicated by the helium data are approximately one order of magnitude greater than fluvial erosion rates measured in the
range today (~0.05-0.1 mm/yr; Griggs and Hein, 1980). While it is possible that the short-term fluvial erosion rates are not representative for longer timescales, Reneau (1988) and Montgomery (1993) convincingly make the case that in the central Coast Ranges the river erosion rates could not have been higher in the Pleistocene than they are in the Holocene and suggest that the average Quaternary fluvial erosion rate in the Central Coast Ranges is no more than about 0.1 mm/yr.

The apparent mismatch between these rates may be explained by the fact that hill-slope processes like land-sliding may be more important agents of denudation in the Santa Lucia Mountains (e.g. Anderson, 1994), particularly following the accumulation of ~3 km of bedrock uplift and ~2 km of surface uplift during the 6-2 Ma interval (Table 2). The modern Santa Lucia Mountains is characterized by extremely steep western, Pacific-facing slopes, many of which are near the rock angle of repose (25-30°) and rockslides are a constant phenomenon in the area. Our fieldwork indicates that most of the western slopes of the Santa Lucia Mountains in the study area are covered with paleo-landslide debris. Moreover, offshore geologic data also indicates that rather large Plio-Quaternary landslides are very common (Greene et al., 2001). We suggest that land-sliding is and was a much more efficient mechanism for denudation on the western slopes of the Santa Lucia Range and could account for the difference between the estimated river erosion rates and thermochronologic denudation rates during the last 2 Myrs.

Finally, the pattern of denudation and the asymmetric topographic relief suggests that bedrock uplift was more pronounced in the western and northwestern limits of the Santa Lucia Mountains and may be accommodated by structures bounding the range to the west. Candidate structures responsible for this bedrock uplift include the Sur-
Nacimiento fault system and the San Gregorio-Hosgri fault (Compton, 1966; Page, 1970; Graham, 1978). Although nominally strike-slip faults, these faults may have accommodated some component of reverse motion as well. Similar relationships between denudation and topographic asymmetry observed in other distinct segments of the Coast Ranges suggest that compression is widely accommodated by this type of deformation. Thus, if the evolution of individual ranges within the Coast Ranges province can be resolved more completely, we may ultimately arrive at a better understanding of how these complex plate margins evolve.

**Acknowledgments**

Discussion and field excursions with William Dickinson, Graham Greene, Lew Rosenberg, Leslie Perg, Yulia Goreva and Jon Pelletier helped stimulate this work. We wish to thank John Smiley for hosting us at the University of California Big Creek Reserve and providing valuable information regarding the natural history of the region. Alisa Miller is thanked for help with sample collection.
Table 1. (U-Th)/He data from the Cone Peak transect, Santa Lucia Range, CA.

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<thead>
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<th>Sample</th>
<th>Latitude (North)</th>
<th>Longitude (East)</th>
<th>Elev. (m)</th>
<th>Age* (Ma)</th>
<th>[U] (ppm)</th>
<th>[Th] (ppm)</th>
<th>[4He] (nmol/g)</th>
<th>Mass (µg)</th>
<th>F&lt;sub&gt;t&lt;/sub&gt;</th>
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<td>152</td>
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*Corrected using F<sub>t</sub> parameter after method of Farley et al. (1996). Estimated analytical errors are 3% at 2 sigma. Aliquots consist of multiple grains (5-15 crystals) with an analyzed using furnace gas extraction method described by House et al. (2002). Replicate analyses indicated by “R” after sample ID.
Table 2. Denudation, bedrock uplift and surface uplift calculations

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<th>Denudation (m)</th>
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</tbody>
</table>

Calculations assume a surface temperature, $T_s$, of 10 °C and a geothermal gradient, $dT/dz$, of 25 °C/km. The closure isotherm, $T_c$, and base of HePRZ is 76°C (for 65 micron grain radius, 10 °C/my cooling rate; Farley, 2000). *The calculated slope of the age-elevation profile is 0.35 ± 0.06 mm/yr, corresponding to the denudation rate between 6.1-2.3 Ma; the zero age intercept, $z(t=0)$, is -640 ± 250 meters below sea level. **The total amount of bedrock uplift since 2-3 Ma is 600-900 meters (Christensen, 1965); use average an average value of 750 meters in these calculations. Closure isotherm depth, $z(T_c)$ = $(T_c-T_s)/(dT/dz) = 2640$ meters; discrepancy between closure isotherm depth and zero age intercept, $|z(T_c) – z(t=0)| = 2000$ meters. Calculated parameters shown with equations used to compute them: [1] slope*(time interval); [2] $0.35 + [z(T_c) – z(t=0)]$; [3] denudation (6.1-2.3) + denudation(2.3-0); [4] denudation/interval; [5] abs($z(T_c)$) + elevation of uplifted HePRZ; [6] bedrock uplift(6.1-0) – bedrock uplift(2.3-0); [7] bedrock uplift (interval) – denudation (interval).
References


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**Figures**

1. Figure 1. a. Location map of the study area within California; b. simplified geologic map of the Hare Canyon-Limekiln Creek transect; filled diamond symbols denote sample locations; c. topographic profile though Hare Canyon (A-A’) and the Limekiln Creek-Hare Canyon inter-fluvial ridge reaching Cone Peak.

2. Helium ages from the Santa Lucia Mountains. Errors are 2 sigma analytical uncertainty. Denudation rate computed for samples represented by open circles yields a slope of 0.35 mm/yr (± 0.06 mm/yr) and an intercept depth of 640.3 meters below sea level (± 248.7 m). Two samples, indicated by grey circles that are not included in this regression are SUR-1 (located approximately 40 km from
the others) and sample 7 (which most likely falls within the Helium partial retention zone, HePRZ). Overall, these samples indicate monotonic denudation between ~2 and 6 Ma.
Figure 1. a. Location map of the study area within California; B. simplified geologic map of the Hare Canyon-Limekiln Creek transect; filled diamond symbols denote sample locations; c. topographic profile though Hare Canyon (A-A') and the Limekiln Creek-Hare Canyon interfluvial ridge reaching Cone Peak.
Figure 2