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

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ABSTRACT

Apatite (U-Th)/He ages from a vertical transect through the Santa Lucia Mountains, central California Coast Ranges, are used to reconstruct the history of exhumation and of bedrock and surface uplift in this region since ca. 6 Ma. We find a direct correlation between (U-Th)/He ages and elevation, which we interpret to correspond to denudation rates of ~0.35 mm/yr between 6 and 2 Ma. The onset of bedrock uplift and exhumation ca. 6 Ma followed a change in plate motion ca. 8 Ma. After 2 Ma, denudation rates increased substantially (~0.9 mm/yr). This is a rare instance in which long-term average bedrock (~0.85 mm/yr) and surface (~0.20 mm/yr) uplift can be calculated from denudation rates and stratigraphic data. The post–2 Ma denudation rate is about one order of magnitude higher than independently determined 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, at least since ca. 2 Ma. We also show that the bedrock uplift is predominantly tectonic, not isostatic.

Keywords: denudation, uplift, transpression, California.

INTRODUCTION

The Santa Lucia Mountains, California, define one of several topographically distinct transpressional ranges within the Coast Ranges province (Fig. 1). Oblique strike-slip faulting along the boundaries of these ranges in response to transpression across the San Andreas system resulted in the late Cenozoic topographic rise and episodic denudation of many of these ranges (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 Mountains indicate that the most recent deformation in this range is Pliocene–Pleistocene in age (Compton, 1966; Page et al., 1998). However, there are few data on bedrock uplift during this time, and existing thermochronometric data provide little insight into the preceding or coincident history of denudation and bedrock uplift.

In this paper we estimate the average post-Miocene denudation rates in the Santa Lucia Mountains by using (U-Th)/He apatite thermochronometry. The low closure temperature of this system (~70–75 °C, Farley, 2000) allows us to determine the recent history of unroofing in this region, and the record of marine sedimentation in the region makes it possible to infer the surface and bedrock uplift. We propose that the main denudation mechanism in the area during recent time is mass wasting by landsliding. It has been long recognized that landsliding may be an important erosional mechanism in actively deforming areas. However, because landslides are sporadic events, it is extremely difficult to calculate their contribution to erosion. Overall, this paper exemplifies the applicability of the (U-Th)/He thermochronologic technique to some of the key unresolved goals of tectonic geomorphology, i.e., (1) determining long-term rates of denudation and uplift, (2) sorting out mechanisms of erosion of mountain ranges, and (3) linking tectonic causes to the development of topography.

GEOLOGIC SETTING

The Santa Lucia Mountains of the southern Coast Ranges extend along the California coast from Monterey Bay ~140 km south where they merge with the San Rafael Mountains (Fig. 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 intrusive rocks (Mattinson and James, 1985; Kistler and Champion, 2001) and amphibolite to granulite facies metasedimentary rocks (Ross, 1978). These rocks, representing the deepest exposure of the now-dissected Salinian arc (Ross, 1978), are unconformably overlain by Upper Cretaceous–Cenozoic sedimentary rocks predominantly exposed on the northeastern and southern limits of the range (Christensen, 1965; Compton, 1966). Stratigraphic relationships and Late Cretaceous apatite fission-track cooling ages from the southern Santa Lucia Range limit both the amount of Cenozoic burial and subsequent exhumation to <3–4 km (Compton, 1966; Naeser and Ross, 1976). The transition from marine to terrestrial sedimentation is marked in the upper Cenozoic stratigraphy by the upper boundary of the marine Santa Maria Formation with the overlying continental gravels of the Paso Robles Formation. This transition is generally estimated to have occurred ca. 4 ± 0.2 Ma, on the basis of the age of a tuff near the base of the Paso Robles Formation (Sarna-Vojcicki et al., 1991). The local late Cenozoic stratigraphy indicates that the rocks currently exposed in the Santa Lucia Mountains were in a near coastal environment for much of the Tertiary (Page et al., 1998).

Northward translation and uplift of Salinian basement rocks within the Santa Lucia Range was accomplished by movement along the

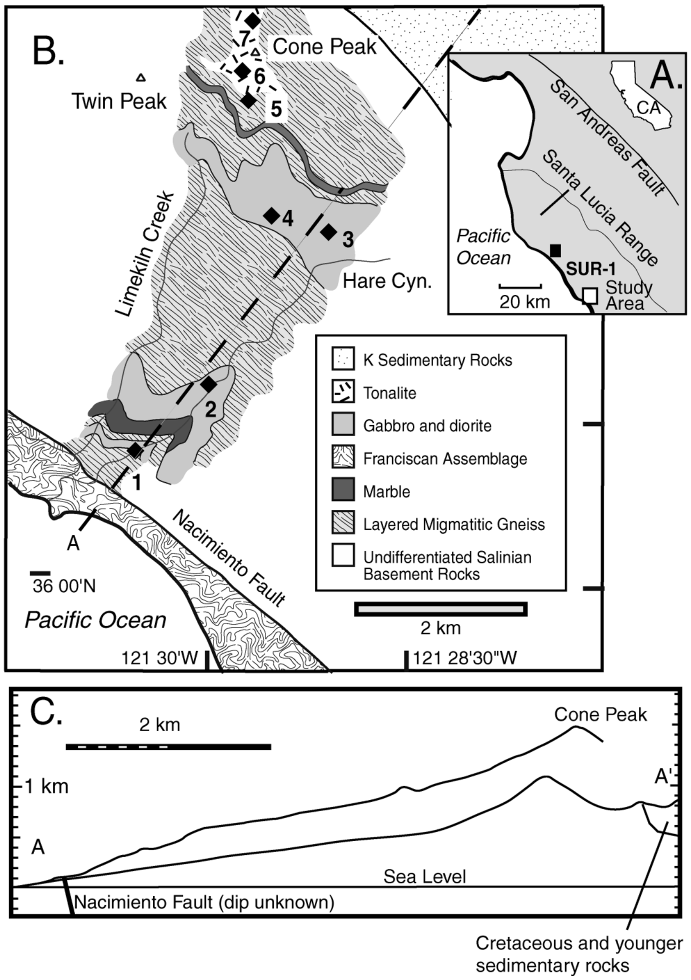

Figure 1. A: Location map of study area within California. B: Simplified geologic map of Hare Canyon–Limekiln Creek transect; diamonds denote sample locations. C: Topographic profile though Hare Canyon (A-A′) and Limekiln Creek–Hare Canyon interfluvial ridge reaching Cone Peak.

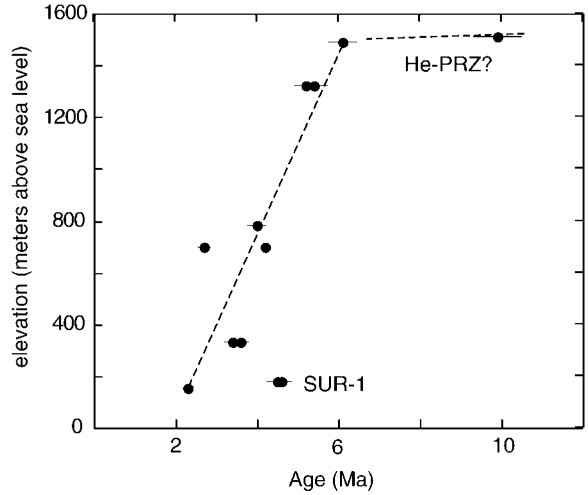

Figure 2. Helium ages from Santa Lucia Mountains. Errors are 2 sigma analytical uncertainty. Denudation rate computed for samples represented by open circles yields slope of 0.35 mm/yr (±0.06 mm/yr) and intercept depth of 640.3 m below sea level (±248.7 m). Two samples that are not included in this regression are SUR-1 (located ~40 km from others) and sample 7 (interpreted as base of helium partial retention zone, HePRZ).

San Andreas and related faults, including the San Gregorio–Hosgri and Sur-Nacimiento faults (Ross, 1978; Graham et al., 1989). At least four distinct episodes of late Cenozoic compressional deformation have been identified in the Santa Lucia region, 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 since ca. 8 Ma (Atwater and Stock, 1998; Page et al., 1998; Tavarnelli and Holdsworth, 1999). For example, increased compression led to Pliocene–Pleistocene reactivation of the dominantly strike-slip Sur-Nacimiento fault system as an east-dipping high-angle reverse fault (Compton, 1966) and high-angle reverse faulting and folding in the northern Santa Lucia Range (Compton, 1966; Page et al., 1998). The resulting compressional deformation and structural inversion of the Santa Lucia Range has stripped away much of the sedimentary cover, especially on the western flank of the mountains (Compton, 1966; Page et al., 1998).

SAMPLES AND RESULTS

Apatite helium ages were measured on seven samples from the Cone Peak area, ranging in elevation from 152 to 1510 m along Hare Canyon, as well as one sample from ~30 km to the north of Cone Peak (SUR-1) (Fig. 1). We chose this transect because of its significant relief (~1400 m). The samples analyzed here consist of Salinian basement rocks, tonalites, and diorites that occupy the hanging wall of the steeply dipping Nacimiento fault (Hall, 1991), which extends approximately parallel to the coast; the footwall Franciscan rocks were not sampled for this study. 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 Pliocene–Pleistocene reverse faults have been mapped around Cone Peak, there are no mapped Cenozoic faults within the sampled transect (Compton, 1966).

Helium age determinations were made using the analytical approach described by House et al. (2002). Results for the samples are shown in Table 1[1]. Helium ages range from 9.9 to 2.3 Ma and are strongly correlated with elevation (Fig. 2). 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 the trend defined by the other samples and is suggestive of the base of a helium partial-retention zone (Fig. 2). However, more data are required to firmly establish the existence of a helium partial retention zone within the higher parts of the transect. These data therefore qualitatively suggest that slow cooling of the region was followed by relatively rapid cooling between 6 and 2 Ma. By comparison, the cooling age from the SUR-1 sample, 30 km to the north, is ~2 m.y. older than the ages at the corresponding elevation in the Hare Canyon transect.

ESTIMATES OF DENUDATION RATES AND BEDROCK UPLIFT

The systematic pattern of cooling ages obtained in the Santa Lucia samples suggests that these data record cooling in response to denudation. Although there are no reliable marker horizons on which to base estimates of tilting along the Hare Canyon transect, Pliocene–Pleistocene sedimentary rocks in the neighboring Junipero Serra area, ~5 km northeast of Cone Peak, show no evidence for bed tilting (Compton, 1966). Extrapolation of these relationships into the vicinity of the sample transect indicates that there was little or no structural modification of the Hare Canyon sample transect subsequent to the locking in of the helium cooling ages (i.e., regional tilting or faulting that offsets the samples; Compton, 1966; our field mapping). Thus, the

[1]GSA Data Repository item 2003011, Table 1, (U-Th)/He analytical data, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

correlation between cooling age and elevation can be used to estimate the exhumation rate that produced the pattern of cooling ages. Regression of the data from the Hare Canyon transect yields a slope that corresponds to a steady exhumation rate of 0.35 ± 0.06 mm/yr for the period 6.1–2.3 Ma. Analytical errors were included in the regression.

The helium data may also be used to determine the more recent exhumation history of the region. If a geothermal gradient of 25 °C/km and a mean annual surface temperature of 10 °C are assumed, the helium closure isotherm corresponding to the grain-size range of the Hare Canyon samples (~76 °C) should be at a depth of 2640 m below Earth's free cooling surface, assumed here to be sea level (Farley et al., 2001). The closure temperature was calculated using the classic Dodson (1973) formulation, relevant diffusion parameters from Farley (2000), and an average grain size of 66 μg. However, the regression line yields a zero-age intercept at a depth of 640 ± 250 m 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 be at this depth. The ~2000 m discrepancy between the zero-age depth from the regression and that based on the geothermal gradient can be explained by accelerated exhumation after ca. 2.3 Ma. The ensuing Quaternary rate would have been 0.9 mm/yr, or higher if the shift occurred after that time. Alternatively, a progressive increase in the geothermal gradient may contribute to an apparent increase in denudation rate, but dramatic crustal-scale changes in heat flow via heat conduction take place over time scales of tens of millions of years. There are no young magmatic products in the area or any other evidence to suggest that heat advection could have played a factor in transporting heat in this region during the Quaternary.

Helium age data in combination with stratigraphic information can be used to estimate bedrock uplift. Geologic data indicate that the last major transition from submarine to subaerial sedimentation took place in the Santa Lucia Mountains ca. 4 Ma, as marked by the beginning of the deposition of the Paso Robles gravels. For a geothermal gradient of 25 °C/km, a mean annual surface temperature of 10 °C, and sea level chosen as a reference elevation, the (U-Th)/He closure isotherm for apatite (76 °C) would be at a depth of 2640 m below sea level at 4 Ma. That this horizon is currently at an elevation of 800 m above sea level (interpolated from the age versus elevation profile, Fig. 2) implies ~3440 m of bedrock uplift since 4 Ma. The corresponding surface-uplift rate (Molnar and England, 1990) since 4 Ma is ~0.2 mm/yr. Changes in sea level between 4 Ma and the present day are tens of meters (Vail and Hardenbol, 1979) and have not been included in these calculations.

CAUSES OF UPLIFT IN THE SANTA LUCIA MOUNTAINS

It has been argued that uplift in narrow transpressional ranges is tectonic and that the topographic features are not isostatically compensated (e.g., Spotila et al., 1998; Spotila and Sieh, 2000). In order to check this hypothesis for the Santa Lucia Mountains, we compared the total Pliocene–Pleistocene bedrock uplift to the independently estimated component of tectonic uplift in the area. The total bedrock uplift (U) can be expressed as the sum of a tectonic (U_t) and an isostatic (U_i) component ($U = U_t + U_i$; Burbank and Anderson, 2001). Unfortunately, there are very few places in the world where it is practical to sort out these components (e.g., Abbott et al., 1997). The Santa Lucia range represents a notable exception because of the availability of data on (1) the long-term bedrock-uplift rate estimated in this paper and (2) the amount of shortening for the same time period (Compton, 1966). Crustal thickness is ~20–25 km beneath the Santa Lucia Mountains and the mountain has no crustal root (Howie et al., 1993). This relatively narrow mountain range is therefore not in isostatic equilibrium and thus the bedrock uplift should be predominantly tectonic. The Pliocene–Pleistocene (~3 m.y.) shortening estimated by Compton (1966) for the Junipero Serra Quadrangle is ~10%–12%; most of the shortening is accommodated by high-angle reverse faults. For a 30-km-wide orogen like the central Santa Lucia Mountains, a 10%–12% shortening applicable to the entire 20–25-km-thick crust would result in 2.2–2.7 km of bedrock uplift, corresponding to a 0.7–0.9 mm/yr tectonic component of the bedrock uplift. This number is virtually identical to the bedrock uplift deduced from thermochronometry. These data confirm that the tectonic component is the principal cause of bedrock uplift in the studied area.

Rapid bedrock uplift may be accommodated by oblique slip on high-angle transform faults within the oblique San Andreas system (Spotila et al., 2001). In this case, the episode of bedrock uplift that we deduce between ca. 6 and 2 Ma may be a direct result of the local plate-boundary geometry and the potential changes in relative plate motions across this section of the Pacific–North American plate boundary beginning ca. 8 Ma (Atwater and Stock, 1998). Earlier reconstructions suggested additional increases in compression across the Pacific–North American plate boundary at various times ranging from ca. 3.5 to ca. 5 Ma (Cox and Engebretson, 1985; Harbert, 1991), but were not confirmed by the reconstruction of Atwater and Stock (1998) and are not apparent in our helium age results. The ~2 m.y. lag between increased convergence ca. 8 Ma and the onset of enhanced bedrock uplift ca. 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 was initiated in the Santa Lucia Mountains once a sufficient amount of shortening accumulated. Alternatively, exhumation may have been initiated earlier than ca. 6 Ma in the Santa Lucia Mountains, but is not detected when using helium thermochronometric data alone and might require a technique with a higher closure temperature to document its onset.

Another possible driving force for uplift of the Santa Lucia Range is the passage of the Mendocino triple junction. The ensuing development of a slab window may have induced short-term heating and crustal-thickening effects that would produce local uplift that could drive the denudation that we detect thermochronometrically (Furlong and Govers, 1999). However, the Santa Lucia Mountains were located at least 150 km southeast of the northward-migrating Mendocino triple junction at any time between the Pliocene and present, and were unlikely to be subject to such transient signals related to the triple junction.

The (U-Th)/He data suggest significantly higher Quaternary unroofing rates compared to the Pliocene. Structural evidence for the Santa Lucia Mountains argues strongly for a tectonic cause of this enhanced denudation; several late Pliocene–Quaternary episodes of deformation have been recognized in the area (Page et al., 1998). Unfortunately, the (U-Th)/He data do not have the resolution to sort out the relative importance of different deformation events within the Quaternary. Complementary techniques focusing on shorter time scales, such as cosmogenic radionuclide chronometry on marine terrace deposits, have the potential to further define the Quaternary evolution of the Santa Lucia Mountains.

DENUDATION MECHANISMS—THE ROLE OF LANDSLIDES

Enhanced unroofing after ca. 2 Ma may reflect the response to the accumulation of bedrock uplift and positive topographic relief during the prior interval (Anderson, 1994). Denudation rates of ~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). Although it is possible that the short-term fluvial erosion rates are not representative for longer time scales, Montgomery (1993) argued that in the central Coast Ranges the river erosion rates could not have been higher in the Pleistocene, and suggested that the average Quaternary fluvial erosion rate in the central Coast Ranges was no more than ~0.1 mm/yr.

The apparent mismatch between these rates may be explained by the fact that hillslope processes like landsliding may be more important agents of denudation in the Santa Lucia Mountains. Extremely steep Pacific-facing slopes, many of which are near the rock angle of repose, characterize the modern Santa Lucia Mountains, and rockslides are a common phenomenon in the area. Our field work and previously published data (Hall, 1991) indicate that most of the western slopes of the Santa Lucia Mountains in the study area are covered with paleolandslide debris. Moreover, offshore geologic data also indicate that large Pliocene–Quaternary landslides are common (Greene et al., 2001). We suggest that landsliding is and has been a much more efficient mechanism for denudation on the western slopes of the Santa Lucia Range over time scales of ~1 m.y. and could account for the order of magnitude difference between the estimated river erosion rates and thermochronologic denudation rates during the past 2 m.y.

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