Tectonics of Pliocene removal of lithosphere of the Sierra Nevada, California

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ABSTRACT

Pliocene (ca. 3.5 Ma) removal of dense eclogitic material under the Sierra Nevada has been proposed from variations in the petrology and geochemistry of Neogene volcanic rocks and their entrained xenoliths from the southern Sierra. The replacement of eclogite by buoyant, warm asthenosphere is consistent with present-day seismologic and magnetotelluric observations made in the southern Sierra. A necessary consequence of replacing eclogite with peridotite is that mean surface elevations and gravitational potential energy both increase. An increase in potential energy should increase extensional strain rates in the area. If these forces are insufficient to significantly alter Pacific–North American plate motion, then increased extensional strain rates in the vicinity of the Sierra must be accompanied by changes in the rate and style of deformation elsewhere. Changes in deformation in California and westernmost Nevada agree well with these predictions. Existing geologic evidence indicates that a period of rapid uplift along the Sierran crest of more than ~1 km occurred between 8 and 3 Ma, most likely as a consequence of removal of lower lithosphere. About this same time, extensional deformation was initiated within ~50 km of the eastern side of the Sierra (5–3 Ma), and regional shortening began to produce the California Coast Ranges (5–3 Ma). We suggest that these events were induced by the >1.2 × 10^{12} N/m increase of gravitational potential energy generated by the Sierran uplift. Evidence for Pliocene uplift, adjoining crustal extension, and shortening in directly opposing parts of the Coast Ranges is found along nearly the entire length of the Sierra Nevada and implies that lithosphere was removed beneath all of the present-day mountain range. The uplifted area lies between two large, upper-mantle, high-P-wave-velocity bodies under the south end of the San Joaquin Valley and the north end of the Sacramento Valley. These high-velocity bodies plausibly represent the present position of material removed from the base of the crust. Lithospheric removal may also be responsible for shifting of the distribution of transform slip from the San Andreas Fault system to the Eastern California shear zone, a prediction that awaits better-defined slip histories on both faults. Overall, the late Cenozoic deformational history of the Sierra Nevada and vicinity illustrates that locally derived forces can influence deformation kinematics within plate-boundary zones.

Keywords: Sierra Nevada, Cenozoic, tectonics, delamination, orogeny.

INTRODUCTION

An enduring mystery of California tectonics has been the creation of the modern Sierra Nevada range, which currently rises to mean elevations of 2800 m above sea level. The results of the 1993 Southern Sierra Continental Dynamics project clearly demonstrated that the southern Sierra Nevada lacks a thick crustal root and is instead supported by upwelling, low-density asthenosphere (e.g., Wernicke et al., 1996). Geochemical studies of late Cenozoic volcanic rocks and their entrained lower-crustal and upper-mantle xenoliths further suggest that the mantle upwelling was triggered by late Cenozoic foundering of the dense, mafic-composition underpinnings of the Sierra Nevada batholith (Ducea and Saleeby, 1996; Farmer et al., 2002). This event most likely occurred at or just prior to a short-lived pulse of potassic magmatism that took place in the southern Sierra Nevada at ca. 3.5 Ma (Manley et al., 2000). Seismological experiments conducted in 1997 revealed substantial seismic anisotropy under both Quaternary and Miocene volcanic vents, supporting the inference that garnet-rich, seismically isotropic lithologies were indeed removed and replaced with mantle geophysically similar to peridotite xenoliths entrained in Quaternary volcanic rocks farther south and east in the Sierra (Fig. 1).

The xenolith studies suggest that the garnet-bearing rocks were removed between ca. 8 and 3 Ma. However, age and geochemical data from Pliocene volcanic rocks in the southern Sierra Nevada reveal that highly potassic magmatism occurred only during a short-lived episode centered at ca. 3.5 Ma (Farmer et al., 2002; Manley et al., 2000). This magmatism apparently originated in a phlogopite-rich part of the mantle lithosphere not involved in magmatism at any other time in the Cenozoic. Farmer et al. (2002) proposed that the Pliocene volcanism was triggered by sudden heating of the uppermost mantle, which resulted from removal of the underlying lithosphere at or near the time of the magmatism.

Removal of a significant thickness of dense rocks from the base of the Sierran lithosphere leads predictably to several potentially observable physical consequences. First, as asthenosphere moves into the gap, the isostatic column decreases in weight, and the overlying rocks must rise buoyantly. Thus, one prediction is uplift of the Sierra at or slightly before 3.5 Ma. Second, emplacement of more buoyant material and associated uplift will increase the total gravitational potential energy of the lithosphere, thus increasing the extensional strain rates in the area affected (e.g., Molnar and Lyon-Caen, 1988). So a second prediction is that there should have been increased extensional deformation in the Sierra at ca. 3.5 Ma. Presumably, an increase in buoyancy force in this region would be insufficient to reorient Pacific–North American plate motion; indeed, recent plate-circuit calculations show that the last change in Pacific–North American plate motions was

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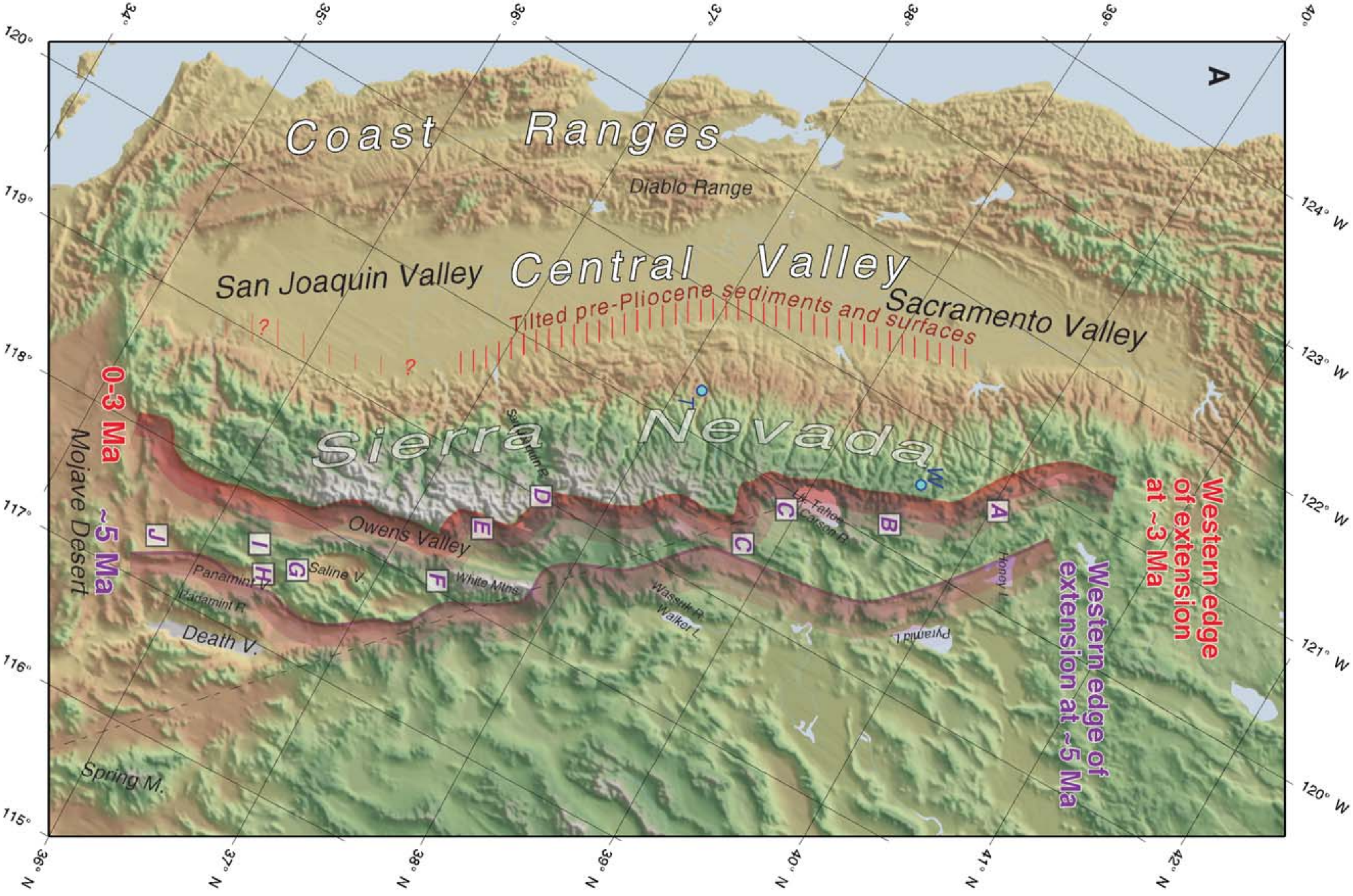


Figure 1. (A) Shaded elevation map and (B) shaded relief map of the Sierra Nevada and environs. Localities in text are labeled in A with locations (keyed to Table 1) where estimates have been made of the timing of initial extension, the western edge of extension at ca. 5 Ma (thick purple line) and ca. 3 Ma (thick red line), the location of floras showing possible uplift (blue dots: T—Table Mountain and W—Webber Lake localities of Wolfe et al. [1998, 1997]), and the extent of tilted Miocene sedimentary rocks along the Sierra/Great Valley margin (hatched area). The geology in the Sierra is shown in B (after Wakabayashi and Sawyer, 2000) along with the location of the ancestral Yuba River channel plotted in Figure 3 (thin red line) and the positions (bold letters) of other paleochannels plotted in Figure 3: M—Mokelumne River; S—Stanislaus River; and T—Tuolumne River. The position of the Gorda plate's southern edge relative to the Sierra at different times in the past lies along the green lines (from Atwater and Stock, 1998) assuming the Snow and Wernicke (2000) reconstruction of the Sierra relative to the Colorado Plateau. The yellow dots show the position of the Mendocino Fracture Zone/continental margin intersection carried back on the Pacific plate relative to North America. Neogene volcanic fields (VF) of the southern Sierra are the orange-tinged areas, Quaternary centers are yellow-tinged. Map view of the extent of the high-P-velocity anomalies at ~200 km depth is shown in purple (Benz and Zandt, 1993; Jones et al., 1994).

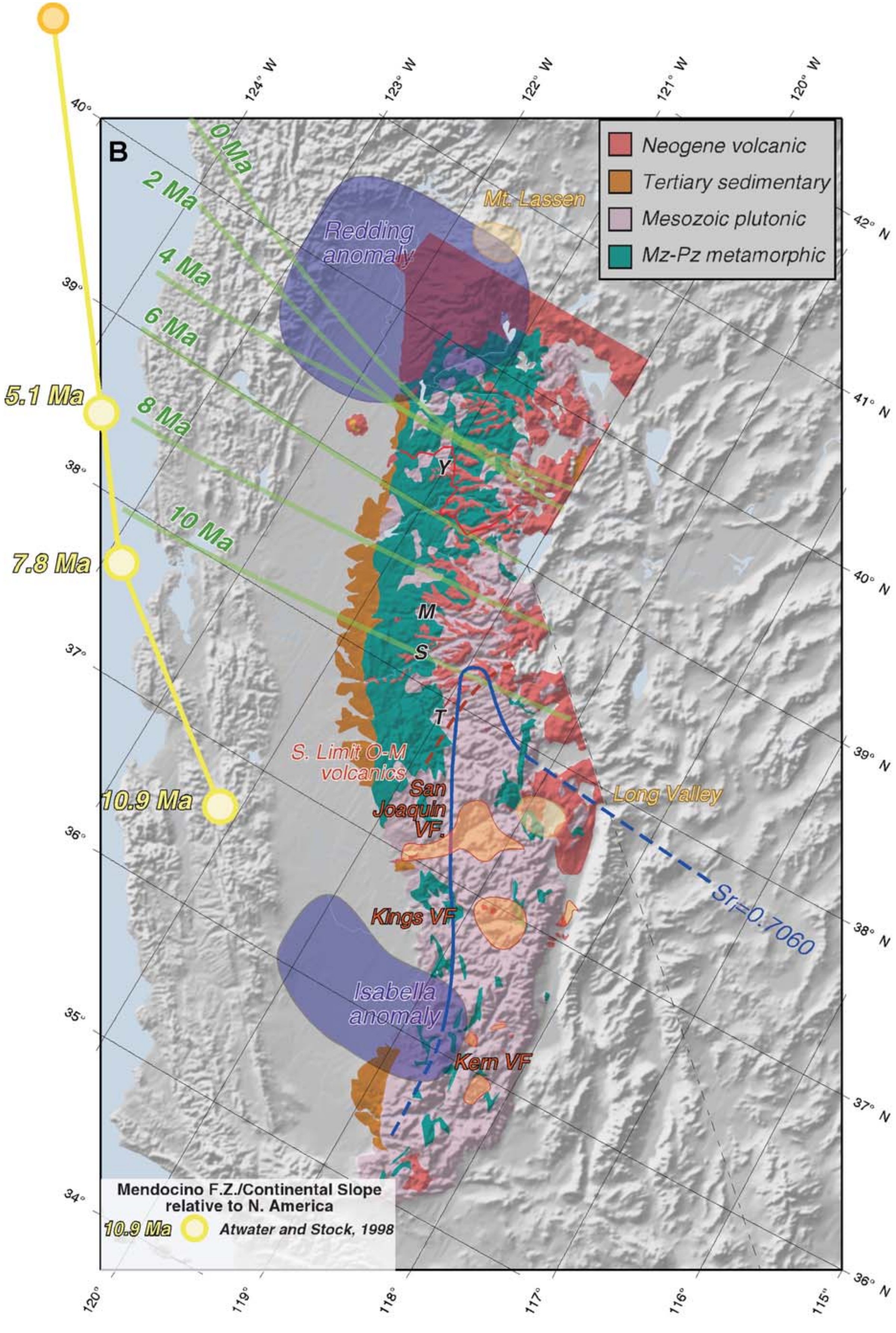


Figure 1 (*continued*)

at ca. 10–8 Ma (Atwater and Stock, 1998), although hotspot-based calculations still suggest a change at 3.5 Ma (Wessel and Kroenke, 2000). Therefore, a third prediction is that an increase in extensional displacement rates must be accommodated by a decrease in rates of extension or an increase in rates of shortening somewhere in the vicinity of the Sierra Nevada.

EXTENT OF LITHOSPHERIC FOUNDERING AND ANOMALIES IN THE UPPER MANTLE

As is discussed more below, geomorphic evidence for late Cenozoic tilting is present along most of the western flank of the Sierra Nevada (Unruh, 1991; Stock et al., 2004), implying that the physical process or processes driving uplift affect both the northern and southern parts of the range. The part of the southern Sierra Nevada where xenolith and volcanic rock data provide direct evidence for removal of lithosphere, however, is limited to the Kings and San Joaquin volcanic fields (Fig. 1; Ducea and Saleeby, 1996; Manley et al., 2000). In fact, no evidence exists that a discrete pulse of potassic, low-ε_{Nd} (<–5), magmatism even occurred at ca. 3.5 Ma in the Sierra Nevada north of ~38°N (Yosemite Valley). This observation may indicate that the potassic volcanic rocks were generated only in Precambrian North American lithosphere, which originally underlay the southern, but not the northern, Sierra Nevada (note Sr_i line in Fig. 1B). Or the distribution of the potassic volcanic rocks might demarcate the whole area beneath which mantle lithosphere was removed (Zandt, 2003). However, little published age or chemical information exists for the abundant Miocene and younger volcanic rocks present in the northern half of the Sierra Nevada (Slemmons, 1966). As a result, there simply may not be sufficient data from which to discern a discrete pulse of Pliocene volcanism in this region, a distinct possibility given that mafic volcanic rocks present just west of Lake Tahoe yield Pliocene (2–4 Ma) whole-rock K-Ar ages (age determinations by D.S. Harwood reported in Saucedo and Wagner, 1992).

If a large volume of dense eclogitic material was removed from the Sierran lithosphere in the past 4 m.y., it is reasonable to expect it to still be distinguishable in the mantle. Two prominent seismological anomalies are likely candidates, given the inferred extent of lithospheric foundering: the "Isabella anomaly" under the southern Great Valley (e.g., Benz and Zandt, 1993; Jones et al., 1994) and the Redding anomaly (Benz and Zandt, 1993). These anomalies are at the southern and northern edges, respectively, of the region that we suggest has lost its lower lithosphere (Fig. 1B). Zandt and Carrigan (1993) previously associated the Isabella anomaly with small-scale convection associated with passage of the Mendocino triple junction but were unaware of the eclogites to the east. The Isabella anomaly has long been enigmatic, occurring under a region with no obvious associated tectonism. Seismological examination of this area suggests that the Isabella anomaly is probably seismically isotropic (Jones and Phinney, 1999), which is characteristic of eclogites (Fountain and Christensen, 1989). Zandt (2003) associated the Isabella anomaly with eclogite removed from the area around Long Valley and also suggested that the absence of Tertiary outcrop from the San Joaquin River to Kings River is due to subsidence from downwelling of the eclogite.

Previous workers associated the northern anomaly with the subducting Juan de Fuca/Gorda plate (e.g., Benz and Zandt, 1993; Zandt and Carrigan, 1993), but this anomaly also appears to be seismically isotropic (station ORV of Özalaybey and Savage, 1995; Hartog and Schwartz, 2000) and thus could be eclogite up to the base of the crust. Additionally, regional images of the upper mantle do not contain an equally significant anomaly farther north along the slab, as might be expected of a slab-generated anomaly (Dueker et al., 2001).

DEFINING UPLIFT

We argue below that the Cenozoic uplift of the Sierra Nevada is linked to the removal of deeper parts of the Sierran lithosphere. Unfortunately the term "uplift" has come to mean different things in different contexts (e.g., England and Molnar, 1990, 1991a, 1991b; Hatfield, 1991; Pinter and Keller, 1991). Following England and Molnar (1990), we define "uplift" as a net increase in mean elevation over time. Usually in this paper we refer to changes in elevations near the crest of the Sierra; the flanks generally rise or fall proportionately less. Increase in the mean elevation can only occur as mass is removed at depth or forces are applied to the lithosphere (e.g., basal normal forces or bending moments within the lithosphere); when isolated from other effects, this type of uplift is termed tectonic uplift. In the course of these events, rocks within the lithosphere may move upward; their approach toward (or away from) the surface is termed exhumation (or burial). At the same time, rocks may be rising (or falling) in elevation relative to sea level, which can be quantified as the rock uplift (or rock subsidence). One potential source of confusion is that rock uplift usually accompanies subsidence due to erosion, a point key to Small and Anderson's (1995) discussion of Sierran uplift.

Some of these relationships can be clarified through equations. The net uplift rate U is the tectonic uplift rate U_T minus the passive subsidence rate due to erosion S_P. When we can assume local isostasy, this last term is directly related to the mean erosion rate E of material of mean density ρ_s in an area by

$$S_P = E\,(\rho_a - \rho_s)/\rho_a\,, \tag{1}$$

where the density of the asthenosphere is ρ_a. So then the net uplift rate is

$$U = U_T - E\,(\rho_a - \rho_s)/\rho_a\,. \tag{2}$$

The mean rock exhumation rate is exactly the amount of the mean erosion rate, but because the surface is changing elevation, the rock uplift rate U_R is the net uplift rate plus the erosion rate, or

$$U_R = U_T + E\,\rho_s/\rho_a\,. \tag{3}$$

From this last equation we can see that rock uplift is possible when there is no tectonic uplift but there is erosion.

When considering uplift of geologic markers such as old river deposits, it is helpful to consider the effect of nonuniform erosion. Most simply, consider a region where a fractional area f comprises uplands of elevation ε_u eroding at a rate e_u and the remaining fraction $(1 - f)$ is in the valleys at elevation ε_v eroding at a rate of e_v. Then the mean erosion rate E is

$$E = e_u f + e_v(1-f) + \frac{\partial f}{\partial t}(\varepsilon_u - \varepsilon_v), \tag{4}$$

which can be recast in terms of the change in relief, $\partial r/\partial t = e_v - e_u$, as

$$E = e_v - f\frac{\partial r}{\partial t} + \frac{\partial f}{\partial t}r\,. \tag{5}$$

Equation 5 in turn can be used to reconsider the net uplift and the rock uplift when the upland erosion rate is much lower than the valley erosion rate, i.e., when $\partial r/\partial t \cong e_v$ and

$$U \cong U_T - \left((1-f)\frac{\partial r}{\partial t} + \frac{\partial f}{\partial t}r\right)\frac{\rho_a - \rho_s}{\rho_a} \tag{6}$$

$$U_R \cong U_T - \left((1-f)\frac{\partial r}{\partial t} + \frac{\partial f}{\partial t}r\right)\frac{\rho_s}{\rho_a}. \tag{7}$$

These relationships illustrate that when downcutting of canyons is the principal erosional process and there is no tectonic uplift, rock uplift can only approach the incision rate if there is substantial widening of the valleys. Note that the assumption of local isostasy means that rock uplifts will be smaller in the presence of flexurally strong lithosphere (Montgomery, 1994).

TIMING OF THE UPLIFT OF THE SIERRA

A late Miocene to early Pleistocene age for creation of the modern elevation of the Sierra has long been advocated (e.g., Christensen, 1966; Huber, 1981; Unruh, 1991; Wakabayashi and Sawyer, 2001). Two principal sets of observations support this timing: tilting of paleovalleys within the Sierra and westward tilting of deposits and late Cenozoic geomorphic surfaces along the western margin of the range. More recently, Wakabayashi and Sawyer (2000, 2001) argued that the change from accumulation of volcanic flows to incision through those volcanic rocks and underlying sedimentary rocks is a consequence of uplift of the Sierra starting at ca. 5 Ma.

The interpretation of these phenomena as a consequence of late Cenozoic increase in mean elevation has been challenged (Fig. 2). Small and Anderson (1995) argued that much of the post–3.8 Ma tilting of sedimentary rocks at the eastern edge of the Central Valley was an isostatic response to both increased incision of the Sierra due to late Cenozoic climate change and loading by sedimentary rocks in the Central Valley. Thus, in their view, the mean elevation along the crest has decreased as rocks along the crest have undergone rock uplift through creation of relief (see equation 7). On the basis of variations in U-He geothermometers along the Sierra, House et al. (1998, 2001) inferred that the Sierra was much higher with greater relief in early Cenozoic time. They postulated that Sierran elevations have been declining steadily since the early Cenozoic. This model requires a decrease in relief with time, contrary to Small and Anderson's inference, but as the time scales are somewhat different (post-Miocene vs. post-Paleocene), these two hypotheses need not be incompatible.

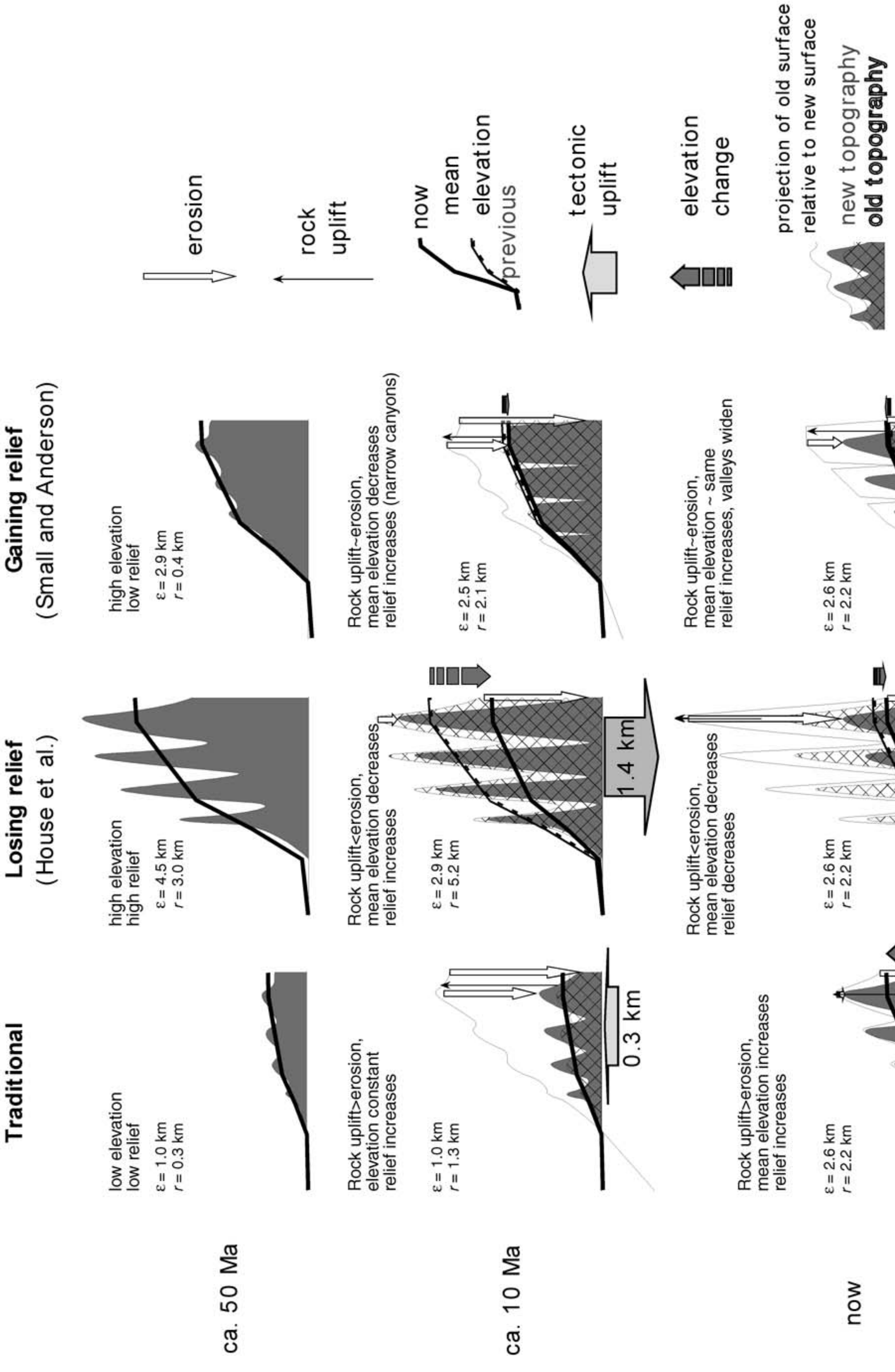
Evidence for Late Cenozoic Uplift

In the northern Sierra, true surface uplift must have occurred in the late Cenozoic. Eocene fluvial gravels of the ancestral Yuba River channel today can be traced from the western foothills eastward to elevations of >2000 m (Hudson, 1955; Lindgren, 1911). The ancestral Yuba channel is quite sinuous; individual reaches of the river flowed toward directions between north-northeast to nearly due south (Fig. 1B). The modern slope of the paleochannel systematically varies with orientation (Fig. 3). This variation can be removed best by subtracting a tilt of 12 m/km (65 ft/mi or 0.7°) to 17 m/km (90 ft/mi or 1.0°) to the southwest or west-southwest, leaving the ancestral Yuba flowing at a mean grade of 1.7–3.3 m/km (~0.1°–0.2°) when the gravels were deposited in the Eocene. The gravels near the modern crest of the range now at 2200 m (7200 ft) originally were at 700–1000 m. Our estimate of the paleogradient is in agreement with Christensen's (1966) estimate that was based on analogies to gradients of modern streams. We think this simple analysis reinforces Lindgren's (1911) original supposition that the range was tilted; Hudson (1955) proposed a more complex deformation producing only 500 m (1700 ft) of rock uplift at the crest that seems inconsistent with relationships discussed by Wakabayashi and Sawyer (2000, 2001). The presence along ridge crests in the northern Sierra of Miocene volcanic rocks overlying the Eocene channel deposits indicates that any erosion-induced rock uplift must be from canyon incision; this contribution to rock uplift has been calculated to be no more than ~180 m (Montgomery, 1994). Thus, tectonic uplift of the crest of the northern Sierra must exceed 1000 m (equation 2).

Eocene channels are found as far south as the Tuolumne River (Fig. 3), but they are preserved progressively farther west of the crest. Tilts might increase somewhat to the south (Fig. 3), so greater late Cenozoic rock uplift southward along the crest is possible but ill constrained. South from the Tuolumne, Eocene channel deposits have been completely eroded away. Instead, inferences of Sierran uplift depend upon Miocene channels preserved under lava flows south to the San Joaquin drainage (e.g., Huber, 1981, 1990). No main channel deposits are found between the Middle Fork of San Joaquin River and the Kern River, where some 3.5 Ma andesites flowed down the middle reaches of the Kern and were subsequently incised, consistent with post–3.5 Ma southward tilt of the upper Kern (Jones, 1987).

The Eocene channels only constrain post-Eocene uplift, but Wakabayashi and Sawyer (2001) pointed out that the Miocene volcanic and volcaniclastic section overlies the Eocene units near the crest of the northern Sierra, indicating little change in elevation from Eocene to Miocene. These Miocene units are continuous with the pre–10 Ma strata such as the Mehrten Formation and geomorphic surfaces at the eastern edge of the Central Valley (Unruh, 1991). In the northern Sierra, where the paleochannel evidence is most complete, the tilt of middle Neogene strata in the eastern Central Valley is compatible with the uplift of the crest of the range by tilt of a rigid Sierra (Wakabayashi and Sawyer, 2000). The gradients of coeval units and surfaces south to the Kings River are similar to those in the northern Sierra, indicating that the tilting was relatively uniform in timing and magnitude along the length of the range (Unruh, 1991). This tilting and unconformity might extend south of the mouth of the Kern River: the 8.2–6.1 Ma Kern River Formation (Negrini et al., 2000) is partially correlative with the Mehrten and has been similarly tilted and truncated (Bartow, 1984). Continuity of tilt north to south along the range is compatible with the available information from the paleochannels (Fig. 3). For uplift in the south to be due to erosion, the time history of erosional denudation in the south must nearly match the tectonic uplift to the north, an unlikely coincidence of tectonism and climate. If the tilted Central Valley section

Figure 2. Cartoons drawn to reflect changes in mean elevation and relief near the San Joaquin River at 50 Ma, 10 Ma, and today for three models: a traditional late Cenozoic tectonic uplift, a decrease in relief and elevation over the past 50 m.y. (House et al., 1998, 2001), and a decrease in mean elevation and increase in relief over the late Cenozoic (Small and Anderson, 1995). Arrows show changes from 50 to 10 Ma (in the 10 Ma panel) and from 10 to 0 Ma (in the "today" panel). Erosion of 1 km assumed to produce rock uplift of 875 m. In all cases the 10 Ma diagram seeks to honor Huber's (1981) 2150 m rock uplift at the Sierran crest and Wakabayashi and Sawyer's (2000) 1000 m of incision of the San Joaquin River since 10 Ma. When possible, Small et al.'s (1997) low erosion rates on upland surfaces are presumed for the past 10 m.y. The 50 Ma diagram honors total erosion from the uplands of 2.5–4.5 km (House et al., 1998, 2001). For the traditional model, tectonic uplift is allowed, the relative proportion of upland and valley elevations is fixed, and at 50 Ma, relief was reduced with no change in mean elevation, and the river valley was placed at 850 m as suggested by our analysis of the Yuba River. For the decreasing-relief model, tectonic uplift is forbidden, the relative proportion of upland and valley elevations is arbitrarily held at 1, and the 50 Ma relief and mean elevation are as specified by House et al. (House et al., 1998). For the increasing-relief model, a small (400 m) "tectonic" uplift is allowed to simulate a flexural bulge from sediment loading in the Central Valley, and relief must uniformly decrease. In this last case, to honor all the constraints, the 10 Ma ratio of uplands to valleys would be ~9. Mean elevation of the crest (ε) and the greatest relief in the range (r) are listed for each panel.


Traditional
Losing relief
(House et al.)
Gaining relief
(Small and Anderson)
ca. 50 Ma
low elevation
low relief
ε = 1.0 km
r = 0.3 km
high elevation
high relief
ε = 4.5 km
r = 3.0 km
high elevation
low relief
ε = 2.9 km
r = 0.4 km
ca. 10 Ma
Rock uplift>erosion,
elevation constant
relief increases
ε = 1.0 km
r = 1.3 km
0.3 km
Rock uplift<erosion,
mean elevation decreases
relief increases
ε = 2.9 km
r = 5.2 km
1.4 km
Rock uplift~erosion,
mean elevation decreases
relief increases (narrow canyons)
ε = 2.5 km
r = 2.1 km
now
Rock uplift>erosion,
mean elevation increases
relief increases
ε = 2.6 km
r = 2.2 km
1.7 km
Rock uplift<erosion,
mean elevation decreases
relief decreases
ε = 2.6 km
r = 2.2 km
Rock uplift~erosion,
mean elevation ~ same
relief increases, valleys widen
ε = 2.6 km
r = 2.2 km
0.4 km
erosion
rock
uplift
now
mean
elevation
previous
tectonic
uplift
elevation
change
projection of old surface
relative to new surface
new topography
old topography

of Mehrten is as young as 5 Ma (Wakabayashi and Sawyer, 2001), then the tectonic uplift dates from 5 to 3.5 Ma.

Another constraint on the timing of uplift is provided by the erosional history of the range. Incision of the volcanic section in the northern Sierra began at 5–3.5 Ma, possibly in response to uplift at that time (Wakabayashi and Sawyer, 2001). A major incision event is also seen along several rivers in the southern Sierra, where rates measured from sedimentary deposits in caves show canyons incising 0.2 mm/yr from at or before 3.1 Ma until dropping by a factor of 10 after 1.5 Ma (Stock et al., 2004). This enhanced erosion rate is consistent with tilting of the west slope of the Sierra between ca. 10 and 3.5 Ma. Numerical simulation of the erosional history preserved in the caves indicates that the erosion is largely driven by a tilting of the range and is not predominantly due to climatic factors (Stock et al., 2004). This result suggests that the erosional history is indeed a good guide to the timing of uplift, and so a date of 5–3.5 Ma for the initiation of tectonic uplift seems warranted.

The very southern Sierra contains evidence suggesting that an older Tertiary uplift event may have preceded Pliocene uplift. An influx of coarse clastic debris to basins on both sides of the range indicates the presence of significant topography by ca. 8 Ma (Bartow, 1984; Bartow and McDougall, 1984; Bartow and Pittman, 1983; Loomis and Burbank, 1988), but the general conformity of the resulting beds on the west flank of the Sierra with underlying sedimentary rocks might reflect a structural history similar to that of the tilted Mehrten Formation to the north. It is possible that the 8–5 Ma sedimentary rocks are a product of a changing climate, whereas the subsequent tilt and erosion are effects of tectonism.

Other evidence bears on the uplift history, but yields little additional clarity. Axelrod (1962, 1980, 1998; Axelrod and Ting, 1960) used flora found in Cenozoic sedimentary rocks to suggest substantial Pleistocene uplift of the Sierra, but more recent paleofloral analysis has been more equivocal. Over much of the western United States, analysis of paleofloral samples using a multivariate regression for climatic factors that then are interpreted for paleoelevation has led to the suggestion that much of the western United States was higher in middle Tertiary time than at present (Wolfe et al., 1997, 1998). One exception to that finding is the set of collections from the Sierra, where Wolfe et al. (1997) reported post–18–10 Ma uplift of ~0.3 km ± 1 km (blue dots, Fig. 1) and Wolfe et al. (1998) suggested that the 33 Ma LaPorte flora currently at an elevation of 1.5 km was originally deposited below 100 m.

Another approach has been to look at the climatological impact of the Sierra, mainly the rain shadow over the western Great Basin. Axelrod (1962) suggested that Miocene floras were inconsistent with a rain shadow and therefore the range must be young. Such interpretations are suggestive but not conclusive owing to the complex interaction of late Tertiary climate change and ongoing floral evolution. Winograd et al. (1985) first suggested that isotopic changes in precipitation could be isolated from low-temperature secondary mineral phases that had equilibrated with meteoric water; they interpreted a 40‰ decrease in the δD values of Pliocene–Pleistocene calcitic veins in the Death Valley region as the result of uplift of the Sierra since 2 Ma. In contrast, the O and H isotopic compositions of secondary clay minerals present in ash-flow tuffs east of the Sierra suggest that no resolvable change in the Sierran elevation has occurred since 15 Ma (Chamberlain and Poage, 2000; Poage and Chamberlain, 2002). However, "resolvable" appears to be ~1–2 km in mean elevation, which is larger than the elevation gains most workers have suggested for the Sierra over the late Cenozoic. Additionally, uncertainty on the relative importance of snow vs. rain in the Sierra and the summer monsoon vs. winter westerly storms in the Great Basin over the past 10 m.y. suggests that a robust geochemical test of Sierran elevations remains to be completed (Poage and Chamberlain, 2002; Winograd et al., 1985).

Rock Uplift Through Erosion?

Small and Anderson (1995) pointed out that tilted Miocene volcanic and sedimentary rocks reflect rock uplift that need not indicate an increase in mean elevation. For erosion-driven isostatic uplift (or "passive rock uplift") alone to elevate deposits of the ancestral Yuba River by >1200 m, a mean erosion of more than about ~1400 m over the region must have occurred (equation 3). However, the maximum incision of the Yuba River below the Eocene gravels is only 640 m (Wakabayashi and Sawyer, 2000). Erosion alone could only have elevated the gravels if the mean elevation around the ancestral Yuba was >400 m (and probably >800 m) above the ancient channel and the surrounding elevations were reduced to channel level since the Eocene. Widespread deposition and preservation of volcanic and volcaniclastic rocks across this region over the Eocene sedimentary rocks (e.g., Wakabayashi and Sawyer, 2000) and preservation of low-relief Miocene surfaces preclude such large relief existing at this time in the northern Sierra.

The situation farther south is more complicated because the ancient channels and surrounding uplands are less extensively and completely preserved, and paleorelief was clearly greater in the middle Tertiary. For instance, in the San Joaquin drainage (the southernmost river with preserved remnants of the main channel), Huber's (1981) estimate of 2150 m of rock uplift of the crest could be produced isostatically by removing an average of >2.3 km of rock since 10 Ma with a slight decrease in mean elevation (equations 2 and 3). The San Joaquin channel thalweg is, at its deepest, now almost 1 km below the 10 Ma channel (Wakabayashi and Sawyer, 2001), so removal of somewhere between 1 and 2 km of rock, on average, from the area above the paleochannel is required. Such rock removal would demand that relief in the area was certainly no less than today's and probably greater in the past, which is in fact inferred by House et al. (1998) from U-He geothermometry in this area. This hypothesis appears unlikely, however, because the required massive erosion of the uplands since 10 Ma conflicts with measured Sierran upland erosion rates of <7.6 ± 3.9 m/m.y. (Small et al., 1997). Preservation of 12–3.5 Ma flows in the San Joaquin/Kings River volcanic fields in the broad Kings–San Joaquin interfluve argues for limited erosion outside of the inner river canyons and high cirques over most of the Sierra. Finally, Riebe et al. (2000) suggested from analysis of cosmogenic isotopes in Sierran drainages that most areas are eroding rather slowly (well below the mean 0.14 mm/yr required by Small and Anderson [1995]) and the most rapid erosion is near the river channels. These results taken together suggest that the maximum averaged post–10 Ma erosion over the whole of the upper San Joaquin drainage is less than the 1 km maximum incision of the main river channel. The only possible reconciliation of hypothesis and data are that the canyons at ca. 10 Ma were exceptionally narrow and deep and that the main erosional signature comes from widening of the canyons.

Attempts to both honor the relationships in the previous paragraph and minimize tectonic uplift at the latitude of the San Joaquin River while late Cenozoic relief increased prove problematic (Fig. 2). Around the headwaters of the San Joaquin River, the mean elevation is 2600 m, upland elevations e_u are ~3700 m, valley elevations e_v are 1500 m, and the modern relief R_{end} is ~2200 m. Thus, the fraction of the Sierra in uplands today (f_{end}) is close to 0.5. To achieve the necessary rock uplift of 2150 m with no local tectonic uplift, we need no less than 2000 m of mean denudation since 10 Ma, allowing for ~400 m of uplift driven flexurally by subsidence in the Great Valley to the west. If we integrate equation 4, assuming a linear change in f and elevations over time, then we find that the mean denudation D is

$$D = \int E dt = D_u \bar{f} + D_v \left(1 - \bar{f}\right) + \bar{R}\left(f_{end} - f_{start}\right), \quad (8)$$

where D_u and D_v are the mean incision of upland and valley, respectively, and bars denote the average over the past 10 m.y. Equation 8 can be rearranged to

$$D = -f_{end} \Delta R + D_v + R_{end}(f_{end} - f_{start}), \quad (9)$$

which is in terms of known quantities. For ΔR to be positive, f_{start} (the fraction of the Sierra in uplands at 10 Ma) must be between 0.95 and 1. The 10 Ma Sierra would have had uplands over >95% of its area with limited deep canyons punctuating the fairly uniform surface. These canyons then would have widened out considerably since 10 Ma, as most of the erosion is from canyon widening rather than deepening. This latter requirement is at odds with modern measures of erosion, which are greatest in the trunk-stream beds (Riebe et al., 2000; Stock et al., 2004). Additionally, the uplands would have to lose nearly 1 km of elevation, which would indicate a higher Miocene to Pliocene erosion rate than occurs today (Small et al., 1997). Integration of equation 7, which has very small upland erosion rates, cannot satisfy the observations in the San Joaquin drainage: the hypothesis of rock uplift through increasing relief is really rock uplift through canyon broadening (Fig. 2, right column).

Slowly Eroding Sierra?

House et al. (1998) first proposed the idea of the Sierra being an ancient high mountain range that has been slowly reduced in both relief and elevation over the Cenozoic. The support for this idea came from He diffusion ages along a transect paralleling the crest of the southern Sierra: old ages of nearly 80 Ma were interpreted as recording cooling under paleovalleys, and young ages of ca. 60–55 Ma were interpreted as being under interfluves that were several kilometers above the paleovalleys. Although there are no constraints on middle Cenozoic topography from this approach, a sudden removal of elevation followed by its reappearance a few million years later is unappealing. A second paper presented nearly constant ages along a higher transect just to the east, which was interpreted as indicating that the western edge of a high, low-relief plateau existed above the area between the two transects (House et al., 2001). To honor both the maximum 1 km incision below the 10 Ma volcanic flows in the San Joaquin River drainage and the 2 km rock uplift near the Sierran crest, relief at 10 Ma

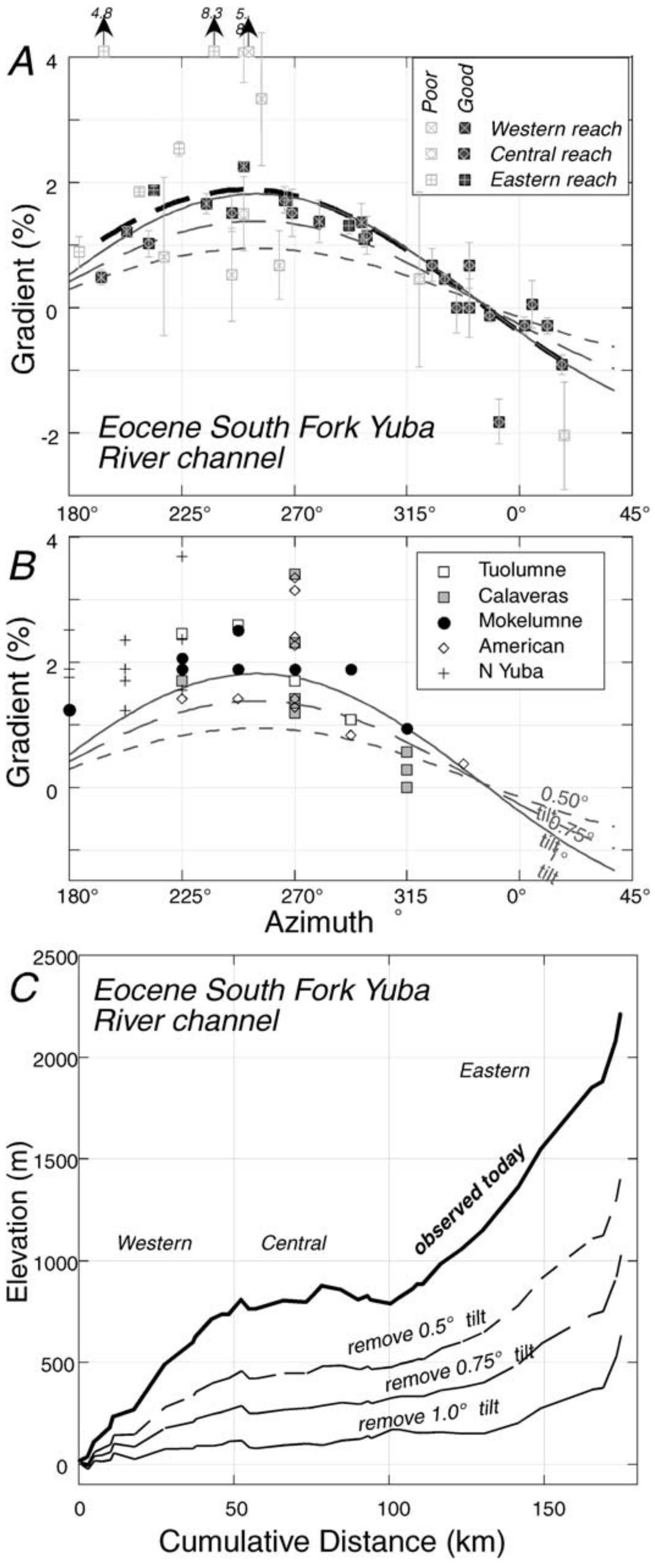
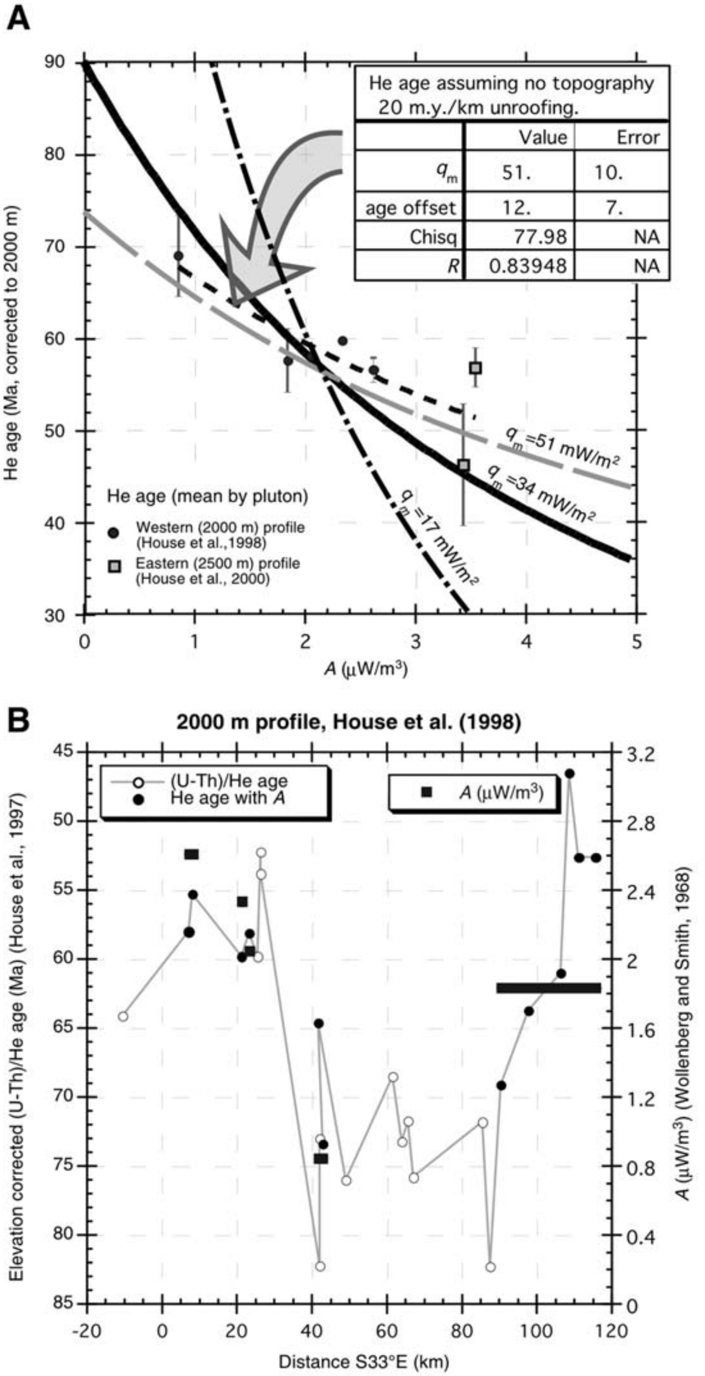


Figure 3. Plot of modern slope of Eocene river channels, from Hudson (1955) and Lindgren (1911), vs. azimuth. Heavy dashed line in (A) shows the best fit to the good data, a tilt of 0.98° to 251° with a mean original gradient of 0.17% (9.2 ft/mi), R = 0.94. Thinner curves in (A) and (B) are for tilt to 255° (S75°W) of an original grade of 0.076% (4 ft/mi).

would have had to be greater than today's, if an equal percentage of highlands and valleys is assumed. In fact, equation 9 requires the relief at 10 Ma to be exceptional, >4 km (Fig. 2, middle center panel). Removal of this relief over the past 10 m.y. requires much higher erosion rates along interfluves than in the canyons, a problem mentioned above in association with the increasing-relief hypothesis.

Unfortunately, at least one key assumption of the geothermometric analysis is flawed: the assumption that lateral variation in heat production is unimportant. In the Sierra today, shallow geotherms are largely dictated by the variation in plutonic heat production (Saltus and Lachenbruch, 1991). Observed variations in heat production today place the 65 °C isotherm at depths as shallow as 3 km and as deep as 8 km. Even if heat influx from the mantle were double in the past, the isotherm still moves between 2 and 4 km, depending on the heat production. House et al. did not measure heat production at their sites, but such data do exist for some of the plutonic rocks they sampled (Wollenberg and Smith, 1968). Plotting available heat productions vs. elevation-corrected He diffusion ages clearly shows a correlation between the two, and a shape very similar to that expected from variations in heat production under a flat surface (Fig. 4). Furthermore, heat production varies considerably on the 2000 m western transect (~0.8–2.6 μW/m^3), where substantial topography was inferred, but available measures of heat production are more uniform along the "low-paleorelief" eastern transect (3.5 ± 0.1 μW/m^3). This correlation between heat production and the variability in He diffusion ages could explain much of the longer-wavelength age variations in the House et al. (1998) data set. We also note that most of the older He diffusion ages inferred by House et al. to be caused by an ancestral San Joaquin canyon are from a thin strip of granites and granodiorites present between the low-heat-producing Bass Lake Diorite to the west and the high-heat–producing Mount Givens granodiorite to the east. To our knowledge, heat-production measurements from this strip of rocks are unavailable but will be required if the He diffusion ages determined for these rocks are to be fully evaluated.

Until further analysis shows that variations in heat production are not dominating the He diffusion ages, we tend to think that the extremely low relief in the Eocene in the northern Sierra indicated by the Ione Formation and the auriferous gravels is most consistent with subdued relief and low mean elevations in the south, probably not more than 2 km of relief and 1–1.5 km of mean elevation near the modern crest (e.g., Wakabayashi and Sawyer, 2001).



He age assuming no topography
20 m.y./km unroofing.

	Value	Error
q_m	51.	10.
age offset	12.	7.
Chisq	77.98	NA
R	0.83948	NA

Figure 4. (A) Heat production *A* (Wollenberg and Smith, 1968) vs. elevation-corrected He-diffusion ages of Sierran plutonic rocks (House et al., 1998, 2001). All ages are corrected to 2000 m here, and ages have been averaged by pluton for comparison with the heat-production measurements, which are only available by pluton. Error bars are the standard deviation of multiple ages within a single pluton. Curves show the expected relationship for an equilibrium 65° C + surface geotherm with no surface topography for three different reduced heat flows. Dashed line shows the best fit to these points with a 65° C + surface geotherm. (B) Part of the He ages from the 2000 m profile of House et al. (1998) (red circles) overlain with available heat-production measurements (A, squares and bars). Single pluton's heat-production data connected by horizontal lines. Filled circles—ages measured in a pluton with a heat-production measurement; open circles—ages measured in a pluton without heat-production estimates. The old ages in the center are the points interpreted by House et al. (1998) as the effect of a deep canyon roughly along the modern San Joaquin River.

TABLE 1. TIMING OF INITIATION OF SUBSTANTIAL EXTENSION ALONG EASTERN SIERRA

Timing	Fig. 1A location	Location	Citation
After 6.8 Ma, possibly after 5–3.8 Ma	A	Mehrten mudflows originating east of Sierra	Summarized in Wakabayashi and Sawyer (2000)
3.1–2.61 Ma	B	Disruption of Boca Basin (angular unconformity) (basin itself from earlier, less intense extensional faulting at ca. 12 Ma)	Henry and Perkins (2001)
10–3 Ma	C	Modeling of track lengths, apatite fission tracks, Carson and Pine Nut Mountains	Surpless et al. (2002)
After 3.6–2.2 Ma	D	San Joaquin River volcanic flow from east of crest	Bailey (1989) cited by Wakabayashi and Sawyer (2000)
After 3.7 Ma	E	Owens Valley (deposition of scoria in Sierra at 4 km)	Phillips et al. (2000)
1.7 Ma	F	Deep Springs Valley (extrapolation of slip rate)	Lee et al. (2001)
Ca. 3–2 Ma	G	Panamint/Saline Valleys (Hunter Mountain Fault if constant rate)	Oswald and Wesnousky (2002)
After 3.3 Ma	H	Northern Panamint Valley (dismemberment of Nova Basin)	Snyder and Hodges (2000)
4.3–4.0 Ma	H	Northern Panamint Valley	Larson (1979) cited by Oswald and Wesnousky (2002)
Before 5.7 Ma	I	Darwin Plateau high-angle faulting	Schweig (1989)
3.18 Ma	J	Initiation of lacustrine sedimentation, Searles Valley (deformation occurred after a volcanic flow in north Searles Valley considered Pliocene or post–middle Miocene)	Smith et al. (1983)

This interpretation also avoids the difficulties encountered in attempting to reconcile high early Cenozoic relief with late Pleistocene erosion rates, measured incision of the San Joaquin River, and estimated rock uplift in the upper San Joaquin drainage (Fig. 2).

We conclude that considerable evidence exists supporting tectonic uplift of the Sierran crest by 1 km or more near or slightly before 3.5 Ma. Removal of ~15 km of eclogitic rock 200 kg/m^3 denser than asthenosphere (Ducea and Saleeby, 1998) would produce 1 km of tectonic uplift; 30 km of such material is estimated to have underlain the southern Sierra prior to 8 Ma (Ducea and Saleeby, 1998). The removal of such an eclogitic layer would also increase the gravitational potential energy by ~1.2×10^{12} N/m, a value comparable to that driving extension in the Great Basin today (Jones et al., 1996). Even if a considerable volume of crust has been transported eastward by mid-crustal flow in the late Cenozoic (Wernicke, 1992; Wernicke et al., 1996), removing 30 km of eclogite and 5 km of low-density crust still produces 1 km of surface uplift and an even greater increase in the gravitational potential energy. Additional buoyancy that could offset crustal thinning was likely produced by removing the cold, garnet-rich mantle lithosphere present at 10 Ma below 60 km depth (Ducea and Saleeby, 1998).

INITIATION OF LATE NEOGENE LITHOSPHERIC THINNING WITHIN AND ADJACENT TO THE SIERRA

Prior to ca. 5 Ma, the eastern edge of the relatively undeformed Sierra Nevada was located tens of kilometers east of the present range front (Fig. 1). This region, now in the western Great Basin, was probably affected by extensional tectonism, but the product was largely broad basins without pronounced changes to stream drainages (e.g., Henry and Perkins, 2001; Wakabayashi and Sawyer, 2000, 2001). The drainage divide between the Pacific and Great Basin remained east of the present Sierra, as demonstrated by volcanic flows that crossed the modern Sierra crest (e.g., Wakabayashi and Sawyer, 2000). A westward shift of the edge of significant normal faulting during the Pliocene has been documented along the entire eastern edge of the Sierra (Fig. 1, Table 1). The uniformity of timing of this event is somewhat startling as, prior to this event, extensional histories along this margin of the Basin and Range varied from north to south. For instance, extension began in the Wassuk Range at ca. 25 Ma, shifted westward into the Yerington District at 15 Ma (Dilles and Gans, 1995) and didn't shift much to the west until the past few million years (Henry and Perkins, 2001; Surpless et al., 2002). Farther south, extension at the latitude of Death Valley was minor until ca. 15–12 Ma (Snow and Wernicke [2000] and references therein). Thus, this latest extensional event seems unusual in its continuity from south to north.

This expansion of extensional tectonism is fairly well dated in many areas and agrees well with the postulate that extension and crustal thinning should have been initiated at ca. 3.5 Ma with the onset of foundering of the eclogitic material. We note that extension should also have begun farther west, within the modern Sierra where removal of eclogite has been documented. Such extension might be evident in minor faulting within the range (Unruh et al., 1998a; Wakabayashi and Sawyer, 2000) and modern extensional seismicity (Jones and Dollar, 1986; Unruh et al., 1998b). It is possible that onset of significant large-scale extensional strain has been delayed by uncommonly cold crust (Saltus and Lachenbruch, 1991) and consequently strong lithosphere in much of the modern Sierra (Unruh et al., 1998a). The westward expansion of extension seems compatible with removal of the lower lithosphere, especially if such removal is found to have occurred east of the modern range crest.

Alternatives to Removing Dense Lithosphere

Other explanations for the westward jump of extension include evolution of an existing extensional system and a response to a thermal pulse. Wernicke's (1985) conception of the evolution of a low-angle normal-fault system such as the west-dipping Death Valley system includes progressive breakup of the distal part of the system. In the southern Sierra, Owens Valley, Panamint Valley, Saline Valley, and Eureka Valley might all lie in such a position. However, if continued slip on an underlying master fault is the explanation in the south, it produces problems in the north. In the general vicinity of Walker Lake, the underlying faults active prior to ca. 10 Ma dip east (Dilles and Gans, 1995; Proffett, 1977). Continued slip on this system should produce deformation farther east, not in the footwall of the fault system.

Lateral migration of a thermal pulse has long been an explanation for migration of extensional faulting (e.g., Best and Hamblin, 1978; Lachenbruch et al., 1976; Saltus and Lachenbruch, 1991; Surpless et al., 2002). The principal effect of such a pulse is to weaken the lithosphere; a change in the forces on the lithosphere is generally secondary. The cause of such a pulse is

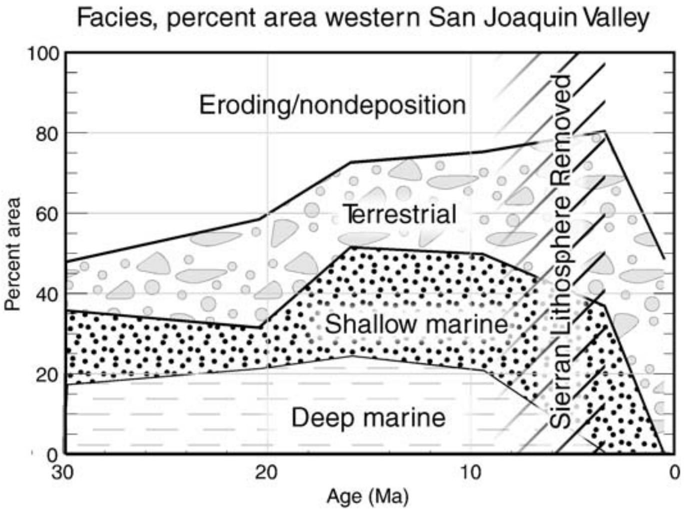


Figure 5. Distribution of sedimentary facies, as percentage of total area, in the vicinity of the San Joaquin Valley east from the San Andreas Fault to the middle of the Central Valley (an axis running through modern Bakersfield and Stockton), derived from paleogeographic maps of Bartow (1991). Note the abrupt change from pre–3.5 Ma to post–3.5 Ma patterns, including the end of all marine deposition and the great increase in the area being eroded.

unclear. Lateral conduction of heat from the hot Great Basin is a possibility, but such conduction should be gradual. Simultaneous extension across an ~50-km-wide area at ca. 3.5 Ma is not consistent with conduction. Removal of the cold Farallon/Juan de Fuca slab through northward migration of the Mendocino triple junction has been put forward as a means of heating the lithosphere (e.g., Atwater, 1970; Best and Hamblin, 1978), but this pattern should be a northward, not a westward, migration of extension.

THRUSTING WEST OF THE SIERRA NEVADA AS A RESPONSE TO EXTENSION EAST OF THE SIERRA NEVADA

If extension is initiated within a region with constant-velocity boundary conditions and is not parallel to the bounding velocities, then the extension must be offset by shortening elsewhere. Since 8 Ma, Pacific–North American plate motion has probably been unchanged in rate or direction (Atwater and Stock, 1998). During this time, coastal mountains formed in western California in response to shortening across the boundary between the Pacific plate and the Sierran microplate. Stratigraphic relationships bracket the timing of Coast Range uplift (e.g., Page et al., 1998) as well as record eastward propagation of shortening into the western Great Valley.

Because of earlier tectonism along the plate boundary, the exact time of emergence of the Coast Ranges as a continuous fold-and-thrust belt is difficult to pinpoint. Within a transform regime characterized by regional horizontal plane strain, we would expect that geometric irregularities would produce pull-apart basins roughly equal in volume to push-up ranges. As these processes occur, the net area receiving sediments would tend to stay about the same. A change from transcurrent to transpressional deformation, however, will drive uplift throughout the region and increase the area being eroded. When we examine the percentage of the eastern Coast Ranges and adjacent San Joaquin Valley that was accumulating sediments of different types, we find that from 30 to 3.5 Ma there was a slow increase in the area receiving sediments, whereas the percentage of area below sea level remained roughly constant at 30%–50% (Fig. 5). This finding is consistent with a transform environment; the slowly increasing sedimentation could reflect climatic changes occurring through the Neogene. After 3.5 Ma there were dramatic changes; the area receiving sediments dropped from 80% to below 50% of the total area, and marine conditions ended throughout the area. Climate could have contributed to this pattern, but could not have produced the whole picture, as some of the stratigraphic details from this time illustrate.

During the middle to late Miocene the San Joaquin Valley was a forearc basin open to the sea (Bartow, 1991, 1992; Lettis and Unruh, 1991; see these references for a complete description of the late Cenozoic stratigraphic framework and correlations among units in the western Central Valley). The major provenance region for this basin was the Neogene Sierran arc. Coarse-textured volcaniclastic rocks and debris flows of the late Miocene–Pliocene Mehrten Formation can be traced westward from the Sierra slope in the subsurface of the Central Valley and correlated with the compositionally and temporally equivalent Neroly Formation (Bartow, 1987), which currently crops out in the Diablo Range. Some exposures of the Neroly Formation contain shallow-marine fossils, demonstrating that the late Neogene shoreline was located within the area now occupied by the eastern foothills of the Diablo Range (Bartow, 1987; Graham et al., 1984). The Neroly Formation is mapped on both the east and west sides of the Diablo Range, indicating that the mountain range did not exist in Neroly time, or at least was not as laterally continuous and extensive as it is now.

The emergence of a subaerial source region in the vicinity of the modern Diablo Range is recorded by deposition of coarse-grained continental fanglomerates conformably over the Neroly Formation in the vicinity of what is now the western San Joaquin Valley. These sedimentary rocks are variously mapped as unnamed Tertiary continental deposits (Dibblee, 1980), the Carbona unit (Raymond, 1969), and the Oro Loma Formation (Bartow, 1992). Clast lithologies in the fanglomerates clearly indicate a provenance in the Diablo Range rather than in the Sierra Nevada. The lower part of the Carbona unit contains late Clarendonian vertebrate fossils (late middle to late Miocene) and late Miocene–early Pliocene diatoms in the upper part (Bartow, 1992). Deposition of the fanglomerates thus marked a regional reversal in sediment-transport direction in the ancestral western San Joaquin Valley and emergence of the Diablo Range as a sediment source area in late Miocene time (ca. 5 Ma or somewhat earlier).

Similar stratigraphic relationships are present in the western Sacramento Valley (the northern arm of the Central Valley) bordering the northern Coast Ranges. Late Cenozoic emergence of a highland west of the modern Sacramento Valley is indicated by deposition of coarse fluvial deposits of the Tehama Formation, derived from the Coast Ranges, over older Neogene deposits primarily derived from the Sierra Nevada to the east. The Tehama Formation contains the 3.3 Ma Putah Tuff at or near its base, indicating a Pliocene age for uplift of the northern Coast Ranges (Unruh and Moores, 1992). Although the available stratigraphic data suggest that growth of the western California mountains began earlier to the south than the north, the locus and timing of uplift are not correlated with position or passage of the Mendocino triple junction (Fig. 1, Atwater and Stock, 1998).

To summarize, stratigraphic, structural, and geomorphic relationships in the western Central Valley provide evidence for regional reversal of sediment-transport direction, emergence of the coastal mountains as a sediment source, and eastward propagation of uplift and shortening since 5.0–3.5 Ma. These phenomena are documented for a minimum distance of ~300 km along the western margin of the Central Valley and are correlated in time with the regional disappearance of marine conditions and reduction in the area receiving sediments in west-central California. These observations are compatible with the hypothesis that extension associated with removal of eclogite should trigger transpression along the western margin of the Sierran microplate.

Alternative Explanations

Because of its proximity to the plate boundary, shortening along coastal California has been tied in one way or another to Pacific–North American plate interactions, and a link to any extensional tectonism in the Basin and Range has been discounted owing to the much longer history of extension there (Page et al., 1998). The plate-boundary effect has generally taken the form of shortening as the motion of the Pacific plate becomes somewhat more to the east of north relative to North America (Page et al., 1998). It is clear, however, that the modern transpressional deformation is a consequence of Sierran motion being more to the west than that of the Pacific plate relative to North America (Argus and Gordon, 2001). Older reconstructions of Pacific–North American plate motion were consistent with some change in Pacific–North American plate direction in the appropriate time interval, but the most recent plate-circuit analysis of Atwater and Stock (1998) explicitly rules out any significant change in either speed or direction of relative motion in the past 8 m.y. and possibly in the past 12 m.y. (Fig. 1B). For the Coast Ranges to be a product of plate motions, either the analysis of Atwater and Stock (1998) is in error, or the age of the Coast Ranges is greater than usually inferred (e.g., Argus and Gordon, 2001).

Analysis of hotspots in the Pacific plate has led Wessel and Kroenke (2000) to continue to suggest a major change in Pacific motion at 3.5 Ma. Because there is not as good a record of hotspot tracks on the North American plate, these motions still need to be carried to North America from another plate. Thus, this suggestion seems weak at present when compared with the full global plate reconstruction. As for the age of the Coast Ranges, Argus and Gordon (2001) have suggested that geodetically observed shortening rates would require at least 4 m.y. to create most modern ranges and the Diablo Range would require more like 8 m.y. They proposed that the ranges really date to 10–8 Ma and suggest that some geologic observations in the vicinity of the Diablo Range support this age. As we noted above, tectonism associated with the plate boundary's evolution is to be expected; the regional changes such as those shown in Figure 5 occurred later than the 10–8 Ma date, and so we prefer the more recent age for transpressional growth of the coastal mountains.

RATES OF EXTENSION AND SHORTENING

The temporal components of the story presented above are in good agreement with lithosphere being removed shortly before 3.5 Ma: uplift of the Sierra occurred largely after 10–3.5 Ma and likely after 6.1–3.5 Ma; extensional faulting in the Great Basin within 50 km of the Sierra began at ca. 3.5 Ma; and shortening across the bulk of the Coast Ranges appears to date to ca. 5.0–3.5 Ma. Our proposal also requires the horizontal velocities across the Sierra before and after foundering of the eclogite to add up to the boundary condition of Pacific–North American motion. Extension across the newly extending region adjoining the Sierra should match any decrease in rates of extension to the east plus any increase in rates of shortening to the west, if Atwater and Stock's (1998) constant velocity of the Pacific plate relative to the North American plate is assumed.

Although the timing of changes in the region being extended is well established, the magnitude of extensional strain is not. The only quantitative analysis of incremental strain across this region at this time is adjacent to the southern Sierra (Snow and Wernicke, 2000). Snow and Wernicke (2000) estimated that Sierra Nevada–Colorado Plateau motion slowed from 2.0 to 1.5 cm/yr across the central Basin and Range at ca. 5 Ma, and the 1.5 cm/yr rate is slightly higher than modern geodetic estimates of crustal velocities in this region (e.g., Dixon et al., 2000; McClusky et al., 2001; Miller et al., 2001). When cast as extension normal to the edge of the Pacific plate (S60°W), the rate slows from 7.5 mm/yr (10–4 Ma) to 5 mm/yr (4–0 Ma). However, consistent with our hypothesis, rates east of the newly extending area (west of the purple line in Fig. 1) are much smaller than pre–4 Ma rates, whereas rates in the newly extending area are of course much higher. One possible explanation for the lower extension rate after removal of the eclogite is that the removal occurred as overall Basin and Range extension was slowing for unrelated reasons.

The likely emergence or acceleration of shortening across the Coast Ranges in the past few million years poses an interesting quandary: If the Pacific plate moves with a constant velocity relative to North America, how can margin-normal extension wane and shortening wax? One (or more) of the three inferences must be in error: either the Pacific did not move with constant velocity (e.g., Wessel and Kroenke, 1997, 2000), Coast Range shortening rates slowed, or Basin and Range extension rates increased. Of the three there is only support in the literature for the first and last. The most current plate circuit calculations show that the last change in Pacific–North American plate motions was at ca. 10–8 Ma (Atwater and Stock, 1998) although hotspot-based calculations still suggest a change in Pacific motion at 3.5 Ma (Wessel and Kroenke, 2000). A late, rapid phase of Basin and Range extension was proposed by Topping (1993) on the basis of rock-avalanche deposits inferred to connect the Panamint and Kingston Ranges; such rapid extension was discounted with cause by Snow and Wernicke (2000) but remains a possible reconciliation. Neither of these alternatives is, at present, compelling.

Until the problems of margin-normal rates since 8 Ma are solved, the ability of such observations to test the implications of Pliocene removal of eclogitic lithosphere are limited. We suggest that a plausible scenario is that the extension rates in the westernmost Great Basin (between red and purple lines, Fig 1A) increased at ca. 3.5 Ma and were kinematically tied to increased rates of shortening across the Coast Ranges.

IMPLICATIONS FOR THE EASTERN CALIFORNIA SHEAR ZONE AND SAN ANDREAS

Somewhat more indirect effects could be produced by removing dense lower lithosphere. As extension shifted to the west, it broke apart a previously rigid piece of lithosphere. As the lithosphere fragmented, the east-west extent of the rigid Sierran block became narrower. Sonder and Jones (1999) showed that a rigid block at a transform plate boundary will tend to localize shear strain along its edges. As the block narrows, its rate of motion will increase and thus increase the shear on the east side of the block and decrease the slip rate on the west side. Thus, at ca. 3.5 Ma, we might expect slip along the Eastern California shear zone to have increased and slip on the San Andreas system to have slowed.

Dokka and Travis (1990) first suggested a total offset on the Eastern California shear zone of ~65 km and limited this slip to have accumulated in no less than 6 m.y. and probably longer. The modern rate of motion of ~11 mm/yr would generate this slip in ~6 m.y., so a constant rate from inception is possible. It is also possible that the slip rate on the Eastern California shear zone is somewhat higher: Gan et al. (2003) inferred a 5.0 ± 0.4 Ma age for the eastern part of the Eastern California shear zone along the Garlock fault and a 3.4 Ma age for the western part by assuming a constant 12.5 mm/yr slip rate and then fitting the observed bends of the trace of the Garlock fault. However, they presented no evidence requiring a constant rate, so the 6 Ma minimum age for the Eastern California shear zone could be honored with an increasing rate of slip. Paleomagnetic and structural work within the Walker Lane tends to show initiation of oblique-slip deformation consistent with initiation of the Eastern California shear zone at ca. 10–7 Ma (e.g., Dilles and Gans, 1995; Cashman and Fontaine, 2000). The shift in style from oblique-slip extensional structures such as the Death Valley Fault system to nearly pure strike-slip faults such as the Owens Valley Fault would seem to suggest a growing importance of strike-slip motion in the region. This possibility would seem to support our expectation from the changing dimensions of the Sierra–Great Valley microplate.

However, Snow and Wernicke (2000) have inferred a decreasing rate of north-northwest motion of the Sierra from 8 Ma to the present, with rates slowing by almost a factor of 2. If true, this scenario contradicts our inference (and probably the estimated slip history on the Eastern California shear zone in the Mojave). Although the most thorough reconstruction of a part of the Basin and Range to date, Snow and Wernicke's (2000) inferences on strike-slip motion produce a number of problems that suggest that additional work is needed. One is that they require a much larger amount of strike-slip motion across the Mojave (~150 km) since 10 Ma than has been documented (e.g., Dokka et al., 1998). Large amounts of extension across the Owlshead Mountains inferred by Snow and Wernicke have been disputed by Guest et al. (2003). Snow and Wernicke also required 20° of clockwise rotation of the Sierra since 10 Ma, contrary to paleomagnetic observations in the region (Bogen and Schweickert, 1985; Burbank and Whistler, 1987; Coles et al., 1997; Frei, 1986; Kanter and McWilliams, 1982; McWilliams and Li, 1985; Wilson and Prothero, 1997) and causing difficulties with plate reconstructions (discussions in Atwater and Stock, 1998). Finally, timing of strike-slip motion is poorly constrained, as might be total Cenozoic displacement of features like the Owens Valley fault that lack a clear piercing point. Clearly, additional work is needed, but we proceed here with the assumption that the slip rate on the Eastern California shear zone has increased in the past few million years.

Recalling that the Pacific–North American plate boundary shows no significant change in rates since 8 Ma (Atwater and Stock, 1998), any increase in the slip rate on the Eastern California shear zone should produce an equal decrease in motion along the San Andreas system (broadly defined as all the faulting west of the Great Valley). Despite intensive study, detailed variations with time in the total slip rate across this system are poorly constrained since 8 Ma. The most tightly defined synthesis, that of Dickinson (1996), shows a decrease in rate across the whole San Andreas system of ~12 mm/yr at 4 Ma—from 58 mm/yr from 8 to 4 Ma to 46 mm/yr from 4 to 0 Ma—an amount nearly identical to present estimates of the slip rate along the Eastern California shear zone. However, even this synthesis is forced to assume uniform rates of deformation over the period of interest, including a constant rate of motion on the San Andreas Fault itself since 7 Ma, so the apparent reduction in San Andreas slip rate at the time of lithospheric foundering might be a coincidence. The bulk of the change in rate of slip on the San Andreas system comes from the cessation of vertical-axis rotations found in the western Transverse Ranges (Dickinson, 1996).

CONCLUSIONS

Removing an eclogitic root from under the Sierra Nevada at ca. 3.5 Ma should initiate uplift at that time and increase extensional strain rates in eastern California and western Nevada. Within the accuracy of available information, these predicted events did occur: the Sierra gained ≥1 km of mean elevation, and extensional deformation began within 50 km of the eastern margin of the modern range. Another predictable result is that strain rates elsewhere would have to adjust to accommodate the extension. The timing of a slowing of extension rate in the eastern Death Valley area and of an increase in rate of shortening in the California Coast Ranges is consistent with this prediction, but existing observations of a slowing extensional rate across the whole Central Basin and Range, an increasing rate of shortening across the California Coast Ranges, and an unchanging Pacific–North American plate motion vector are inconsistent and so limit our ability to evaluate this prediction at this time. The facts that these four events are logical consequences of removing dense lithosphere, are temporally indistinguishable, and have spatial extents similar to bodies in the upper mantle possibly removed from the Sierra strongly support the idea that the events are consequences of the foundering of sub-Sierran lithosphere.

Alternative explanations lack internal consistency. Increasing plate convergence across the plate margin at 3.5 Ma might cause the Coast Ranges, but a coeval renewal of extension on the eastern margin of the Sierra is puzzling and certainly does not share the same cause. If extension is tied to the kinematic development of master fault systems east of the Sierra, then why would the footwall begin extending in the north as the distal hanging wall was extending in the south, and why would both adjoin an uplifting block of Mesozoic crust? It seems that the alternative to foundering of an eclogitic lithosphere is a patchwork of separate events that, coincidentally, cannot be separated in time with available data.

More speculatively, we expect the strike-slip rate across the Eastern California shear zone to increase as the width of the rigid Sierra Nevada–Central Valley block decreases, a prediction that is in gross agreement with the history inferred from the Mojave Desert but quite different from the reconstruction in the Death Valley area. An increase in rate east of the Sierra must necessarily cause a decrease to the west of the Central Valley in the San Andreas system, a decrease that has been proposed. This suggestion awaits development of more detailed reconstructions along both the San Andreas and Eastern California shear zones, but the potential for locally-derived buoyancy forces generated by changes in the density structure of the lithosphere to influence the strike-slip kinematics of a transform plate boundary is intriguing.

These varied effects suggest that the interaction between plate-boundary kinematics and locally derived forces may be more pervasive than commonly perceived. Furthermore, this example shows that basic physical understanding of the locally derived forces can lead to an integrated understanding of regional events that might appear at first to be unrelated. Application of this approach to other complex boundaries might account for kinematic complexities that plate-boundary forces alone do not explain.

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