Compressional uplift in the central California Coast Ranges

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ABSTRACT

Controversy over the relative importance of transverse and compressional deformation surrounds continuing debate over uplift in the California Coast Ranges. A simple model for compressional deformation in the central California Coast Ranges predicts a significant part of reconstructed post–3 Ma surface uplift. This result suggests that, in addition to passage of the Mendocino triple junction and fault interactions in a dominantly strike-slip setting, late Cenozoic surface uplift in the California Coast Ranges reflects a small compressive component of deformation across the Pacific–North American plate boundary.

INTRODUCTION

Geologic evidence requires significant late Cenozoic surface uplift in the California Coast Ranges. Pliocene-Pleistocene uplift in the Coast Ranges has been recognized since the late 19th century on the basis of uplifted and deformed marine strata, elevated marine terraces, and the elevation of inferred Tertiary erosion surfaces (Lawson, 1893, 1894). More recent studies of marine deposits currently in upland environments, sediment provenance, and Quaternary faults and folds corroborated evidence for significant local and regional Pliocene-Pleistocene compression and uplift throughout the Coast Ranges (e.g., Taliaferro, 1943; Christensen, 1965; Page, 1981; Aydin and Page, 1984). Christensen (1965) used such evidence together with physiographic inferences to estimate post–3 Ma surface uplift in the central Coast Ranges (Fig. 1). Although this reconstructed surface-uplift pattern is crude, it provides an opportunity to examine relations between tectonic forcing and geomorphic response. Three general hypotheses have been offered to explain uplift of the Coast Ranges: passage of the Mendocino triple junction, local fault interactions, and increased compression across the plate margin. Any general explanation for Coast Range orogeny must account for both regional uplift and differential uplift between large structural blocks. In this paper, a simple model for compression of a tectonic wedge is combined with estimates of plate convergence and erosion rates to examine whether compression across the Pacific–North American plate boundary could account for significant late Cenozoic surface uplift.

DEFORMATION OF THE PACIFIC–NORTH AMERICAN PLATE MARGIN

Strike-slip offset dominates deformation of the Pacific–North American plate margin, but displacement parallel to the San Andreas fault does not account for a small, but significant, component of relative plate motion. Negligible shear strength on major transverse faults may resolve regional strain into components parallel and orthogonal to the plate margin (Zoback et al., 1987), and there is abundant geomorphic evidence for Pliocene-Quaternary strike-slip and compressional deformation in the central Coast Ranges (Aydin and Page, 1984). Strike-slip offset across the San Andreas fault system is ~45 mm/yr (DeMets et al., 1990), roughly an order of magnitude greater than estimates of convergence rates across the plate margin (Table 1). Although the dramatic geomorphic expression of lateral offset along the San Andreas fault is well known, the geomorphic effect of compressional deformation in the Coast Ranges has received relatively little attention. This smaller compressional component may be geomorphically significant, as transverse deformation can contribute to uplift only locally where fault patterns create compressive geometries (e.g., Anderson, 1990). Cox and Engebretson (1985) hypothesized that an increase in compression associated with a Pliocene change in Pacific–North American plate motion initiated regional Coast Range uplift. Harbert and Cox (1989) argued that his change in plate motion occurred between 3.40 and 3.86 Ma. While an increase in compressional strain is consistent with the numerous Pleistocene folds and reverse faults that roughly parallel the major transverse faults (Aydin and Page, 1984), the relation to uplift remains speculative.

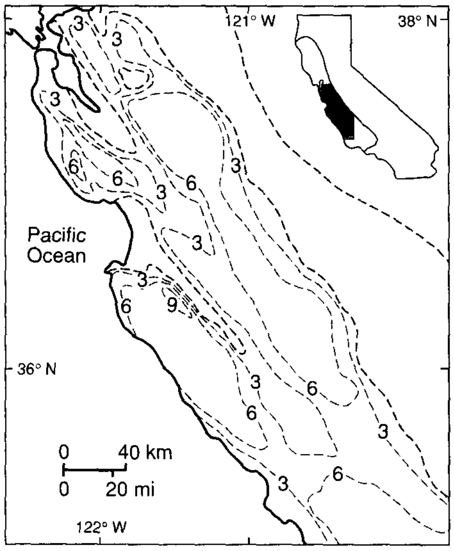

Figure 1. Simplified rendering of Christensen's (1965) map of reconstructed surface uplift in coastal central California since 3 Ma. Contours are in hundreds of metres; shading indicates areas of subsidence. Inset shows extent of Coast Ranges and area covered in Figure 1 (dark shading).

Seismic refraction surveys reveal a complex picture of deformation in the central Coast Ranges and suggest that compression across the Pacific–North American plate boundary is thrusting a tectonic wedge up a low-angle mid-crustal detachment (Fig. 2). Although this interpretation is controversial, hypocenter locations (Hill et al., 1990) indicate both that the zone of brittle deformation in the central Coast Ranges is at least ~10–15 km thick and that major transverse faults divide the Coast Ranges into a series of discrete structural blocks. Compressional deformation in the Coast Ranges may be accommodated by distributed faulting and folding and differential uplift between these structural blocks. Increased loading from wedge thickening may also explain subsidence along the eastern front of the Coast Ranges (Fig. 1). It remains to be shown, however, that crustal thickening associated with a compressing tectonic wedge could account for reconstructed regional surface uplift.

TABLE 1. PACIFIC-NORTH AMERICAN PLATE-CONVERGENCE RATES

Study	Convergence rate (mm/yr)
Argus and Gordon (1991)	2 ±2
Ward (1990)	3 ±1
Crouch et al. (1984)	5 - 13
Feigl et al. (1990)	6 ±2
Harris and Segall (1987)	6 ±2
Pollitz (1988)	6 - 8
DeMets et al. (1990)	7
Kroeger et al. (1987)	8
Minster and Jordan (1987)	9 ±3
Namson and Davis (1988)	11

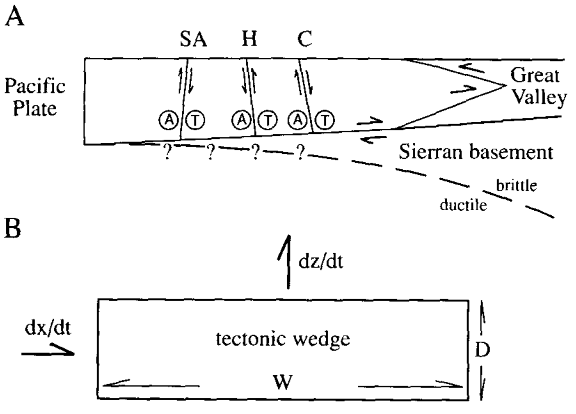

Figure 2. A: Hypothetical cross section across California Coast Ranges (top part of Fig. 1) after Wentworth et al. (1984), Namson and Davis (1988), Fuis and Mooney (1990), and Jones et al. (1992). Structure below hypothesized mid-crustal detachment is speculative. Arrows indicate relative motion across major faults: SA = San Andreas; H = Hayward; C = Calaveras (A = away and T = toward viewer). B: Schematic illustration of a tectonic wedge illustrating relation between tectonic convergence rate (dx/dt) and rock uplift rate (dz/dt).

MODEL FOR COMPRESSIONAL SURFACE UPLIFT

A simple model for surface uplift is obtained by combining models for isostatically compensated rock uplift and erosion. Rock uplift in response to compression of a tectonic wedge can be derived from continuity of mass within the deforming wedge. For a three-dimensional wedge of incompressible material, continuity requires that

$$du/dx + dv/dy + dw/dz = 0, \qquad (1)$$

where u is the normal strain in the direction of plate convergence, x; v is the component parallel to the plate boundary, y; and w is the component in the vertical, z. Assuming that changes in wedge thickness result solely from compressional shortening requires that

$$-du/dx = dw/dz. \qquad (2)$$

This formulation ignores vertical deformation resulting from transverse displacement (i.e., $dv/dy = 0$). If it is further assumed that the leading edge of the wedge is fixed and that the trailing edge is advancing at a constant velocity equal to the rate of plate convergence, dx/dt, then the spatially averaged rate of wedge thickening, dz/dt, is given by

$$dz/dt = (dx/dt)\,(D/W), \qquad (3)$$

where D and W are the wedge thickness and width, respectively. If wedge thickening is isostatically compensated, then the rock uplift rate (dr/dt) at the surface of the wedge due to compression is given by

$$dr/dt = [1 - (\rho_c/\rho_m)]\,(dx/dt)\,(D/W), \qquad (4)$$

where ρ_c and ρ_m are the density of the crust and mantle. Because surface uplift is the difference between rock uplift and erosion (England and Molnar, 1990), the isostatically compensated surface uplift (ds/dt) is given by

$$ds/dt = [1 - (\rho_c/\rho_m)]\,[(dx/dt)\,(D/W) - E], \qquad (5)$$

where E is the erosion rate. Thus, the spatially averaged surface uplift rate can be calculated from crust and mantle densities, the plate-convergence rate, geometry of the zone of deformation, and the erosion rate.

Previous work allows estimates of reasonable ranges for these factors. Estimates of the plate-margin-normal convergence rates for the Pacific and North American plates vary from 2 to 11 mm/yr (Table 1). Spatial variability in plate convergence rates is unlikely, and this range in published values reflects various assumptions, methods, and sources of data. The best constrained estimates of plate convergence are on the lower end of this range, and it is likely that the underlying convergence rate is between 2 and 6 mm/yr. This range should also provide a conservative estimate of surface uplift.

Erosion rates, on the other hand, reflect spatial and temporal variability in erosional processes and the resistance of different lithologies and soils to these processes. Significant variation is expected in the average erosion rate over a large area, especially one with the variety of lithologies present in the California Coast Ranges. Estimated erosion rates for drainage basins in the central Coast Ranges vary from 0.02 to 0.20 mm/yr (Table 2). The combined drainage area of the basins compiled in Table 2 covers ~45% of the area of the Coast Ranges depicted in Figure 1. The weighted average of the contemporary erosion rates in Table 2 yields an estimate of the spatially averaged erosion rate of 0.08 mm/yr.

There are a number of reasons to suspect that contemporary erosion rates are not representative of longer term erosion rates: the short period of record, widespread agricultural, grazing, and forestry practices, and the influence of glacial-pluvial periods on erosion rates. Although the short period of record may not include the geomorphic effect of large infrequent events, much of the sediment transport by a channel occurs during discharges with roughly annual recurrence intervals (Wolman and Miller, 1960); multiple-year records should improve estimates of contemporary erosion rates. Accelerated erosion from land disturbance undoubtedly increased contemporary erosion rates above average Holocene rates. This inference is supported by turn-of-the-century erosion rates (Dole and Stabler, 1909) that were two to three times smaller than subsequent calculations for the same rivers (Table 2). I am unaware of data on Pleistocene erosion rates in central coastal California south of San Francisco Bay, but several lines of evidence are available. First, sedimentation rates at Clear Lake in the northern Coast Ranges were only 112% and 75% of the average Holocene rate, respectively, during the last glacial and interglacial periods (Robinson et al., 1988). Second, although rainfall during the last glacial maximum was greater than during the Holocene in the central Coast Ranges (COHMAP, 1988), greater vegetation density and ground cover may have actually reduced erosion. At present, most of the central Coast Ranges

TABLE 2. EROSION RATES IN THE CENTRAL CALIFORNIA COAST RANGES

Basin	Study	Period	Drainage area (km^2)	Erosion rate (mm/yr)
Alameda Creek	Judson and Ritter (1964)	1956-60	1639	0.05
Big Sur	Griggs and Hein (1980)	1973-77	119	0.18
Carmel	Griggs and Hein (1980)	1973-77	637	0.02
Pajaro	Griggs and Hein (1980)	1956-69	3144	0.04
Salinas	Griggs and Hein (1980)	1967-77	10764	0.07
San Antonio	Griggs and Hein (1980)	1973-77	350	0.09
San Lorenzo	Griggs and Hein (1980)	1973-77	355	0.20
Santa Maria	Griggs and Hein (1980)	1969	1507	0.13
	Dole and Stabler (1909)			0.04
Santa Ynez	Griggs and Hein (1980)	1956-69	1106	0.09
	Dole and Stabler (1909)			0.05
Hollows	Reneau (1988)	0 - 29 ka	<<1	~0.05

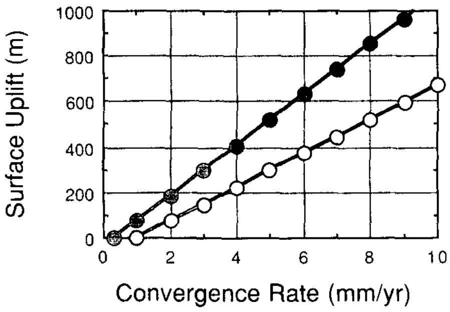

Figure 3. Predicted surface uplift over 3.5 m.y. as function of plate convergence rate for maximum (solid circles; $E = 0.05$ mm/yr, $D = 15$ km) and minimum (open circles; $E = 0.10$ mm/yr, $D = 10$ km) surface-uplift scenarios.

are covered by oak forests and grassland, whereas coniferous forests were more widespread during the Pleistocene. Langbein and Schumm (1958) showed that contemporary erosion rates in areas of the United States covered by forests are roughly half those in drier grasslands. Finally, Reneau (1988) reported data that imply hillslope erosion rates were not appreciably greater during the latest Pleistocene than they were during the Holocene. Considered together, these studies suggest that contemporary erosion rates in the central Coast Ranges provide a conservative estimate of long-term erosion rates. At present, it is difficult to constrain estimates of long-term erosion rates more accurately, and I estimate that the average Quaternary erosion rate for the central Coast Ranges was between 0.05 and 0.10 mm/yr.

Predicted surface uplift also is sensitive to the assumed wedge geometry. The Coast Ranges are ~100 km across in central California, and hypocenter locations in the central Coast Ranges indicate that major faults extend to depths of 10–15 km (Hill et al., 1990), implying that these depths provide an estimate of the minimum depth to any midcrustal detachment. Thicker wedge geometries also are compatible with the available data and would provide even greater estimates of surface uplift.

These ranges in wedge thickness (10–15 km) and erosion rates (0.05–0.1 mm/yr) were used together with crust and mantle densities of 2.6 and 3.3 g/cm^3 to predict surface uplift in response to the 3.5 Ma change in plate motion as a function of the plate convergence rate (Fig. 3). For the most likely range of convergence rates (2–6 mm/yr), the maximum uplift scenario ($E = 0.05$ mm/yr; $D = 15$ km) predicts surface uplift of 200–600 m. The minimum uplift scenario ($E = 0.10$ mm/yr; $D = 10$ km) predicts surface uplift of 100–400 m. This range covers a significant proportion of the total surface uplift reconstructed by Christensen (1965), and I consider it reasonable to infer that post-3.5 Ma surface uplift of 200–400 m is potentially attributable to regional compression.

DISCUSSION

Although these results indicate that compressional deformation could be responsible for significant post-3.5 Ma surface uplift in the central California Coast Ranges, several other factors require consideration. They include the accuracy of the reconstructed uplift pattern, various styles of deformation in the central Coast Ranges, and other hypothesized mechanisms for Coast Range uplift. Considered together, these factors provide a coherent framework for analyzing late Cenozoic deformation and uplift throughout the California Coast Ranges.

Evaluation of surface uplift often is limited by poorly constrained initial conditions. Little of the stratigraphic information used to constrain Christensen's (1965) pattern of reconstructed surface uplift came from the core of elevated areas. Thus, it is possible that some of the areas of greatest reconstructed uplift were emergent prior to 3 Ma and that the reconstructed uplift is exaggerated. This would bring the magnitude of regional post-3.5 Ma surface uplift in the central Coast Ranges closer to that potentially attributable to regional compression.

There is little reason to expect strain to be uniform across the Coast Ranges, as the Coast Ranges are composed of many different lithologies bounded by complex fault geometries. The geometry of major structural blocks may control the internal distribution of strain within the Coast Ranges, and the style in which compression is accommodated differs significantly in the northern and southern parts of the central Coast Ranges (Fig. 1). In the San Francisco Bay area (northern part of Fig. 1) there are several major strike-slip faults with orientations different from that of the plate margin, suggesting that a significant part of far-field convergence may be accommodated by transverse and oblique slip along these faults, or on subparallel bands of thrust faults (Aydin and Page, 1984). In the southern part of Figure 1, the San Andreas fault is the only major active strike-slip fault. Compressional deformation in this area is accommodated by a parallel array of thrust faults and folds (e.g., Crouch et al., 1984). Perhaps the geometry of preexisting faults controlled whether block uplift or distributed folding and faulting dominated response to increased compressional deformation. In any case, simple models, such as the one presented above, only provide an assessment of average surface uplift. They do not provide significant insight into how this strain is accommodated.

Several other hypotheses have been proposed to explain uplift in the California Coast Ranges. These hypotheses involve uplift in response either to passage of the Mendocino triple junction or to fault geometries in a transverse fault system. Although both mechanisms are consistent with evidence for uplift in the California Coast Ranges, neither can account for significant regional post-3.5 Ma surface uplift throughout the Coast Ranges.

Zandt and Furlong (1982) proposed that asthenospheric upwelling in the wake of the northward-migrating Mendocino triple junction resulted in a pulse of uplift that progressed from southern to northern California over the past 20–30 m.y. Their model predicts rapid uplift within ~1 m.y. of triple-junction passage, which suggests that the associated uplift in the central Coast Ranges occurred during the Miocene and Pliocene. Although passage of the triple junction is unlikely to have contributed significantly to post-3.5 Ma uplift south of San Francisco, high Pleistocene and Holocene uplift rates in an area extending ~50–100 km south of the present triple junction (Merritts and Bull, 1989), and the general northward elevation increase in the northern Coast Ranges are best explained by a triple-junction–related mechanism.

Fault geometries, such as laterally-stepping faults or fault bends, also may generate pronounced local uplift in a transverse deformation regime. Anderson (1990), for example, showed that translation of crust through a restraining bend along the San Andreas fault may account for a significant part of the topography of the Santa Cruz Mountains. The pattern of uplift associated with triple-junction passage also may reflect local space problems between discrete structural blocks (Dumitru, 1991). Local fault geometries, however, cannot explain contemporaneous regional uplift throughout the Coast Ranges, even though they may dominate local topographic development.

CONCLUSIONS

Comparison of previously reconstructed surface uplift and model predictions based on reasonable plate-convergence and erosion rates supports the hypothesis that compressional deformation is responsible for significant regional uplift in the central California Coast Ranges. Better information on long-term uplift rates and patterns, as well as erosion rates, is needed to evaluate the relative influence of hypothesized mechanisms for Coast Range uplift, because even small differences between rock uplift and erosion rates may become significant topographic differences over geologic time. At present, it appears that all three hypotheses provide a unified explanation of the present topography of the Coast Ranges. Passage of the Mendocino triple junction is responsible for the generally greater elevations in the northern Coast Ranges, fault geometries influence local topographic development, and regional compression contributes to uplift throughout the Coast Ranges. These results illustrate how a small convergent component of relative plate motion is sufficient to generate significant post-3.5 Ma surface uplift in the central California Coast Ranges. The potential importance of compressional uplift in this area illustrates how a minor component of the tectonic regime may play a major role in the development of topography, the primary geomorphic attribute of a landscape.

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