Reports

Aseismic Uplift in Southern California: An Alternative Interpretation

Abstract. *The previously reported uplift in southern California may have resulted from systematic errors in leveling rather than tectonic activity. Errors are inferred from correlation between changes in elevation and topography at short and long wavelengths. Corrected data show no significant vertical motion except at the time of the San Fernando earthquake. Possible sources of error include inadequate rod calibration and refraction.*

Castle *et al.* (*1*) inferred that between 1959 and 1974 an extensive area of southern California was uplifted as much as 450 mm with respect to a tidal bench mark at San Pedro. The inferred contours of uplift run generally parallel to the San Andreas fault system, but the apparent uplift is not confined to this or any other fault system. Instead, it is spread evenly throughout the Transverse Ranges and the Mojave Desert, with maximum tilting along the southwest face of the Transverse Ranges. The inferred uplift is strongly episodic, with Palmdale rising about 200 mm between 1961 and 1962, remaining relatively stationary between 1962 and 1968, then rising another 150 mm between 1968 and 1974 (*2*). Similarly, Barstow apparently rose more than 170 mm with respect to Mojave between 1973 and 1974. The latest phase of uplift apparently ended in 1974, and Palmdale appeared to sink 170 mm between 1974 and 1977.

If correct, these changes in elevation have surprising and important implications. The inferred rates of uplift are large by geologic standards. Yeats (*3*) estimated an average rate of uplift over the last 600,000 years of 10 ± 0.2 mm/year at the northern margin of the Ventura basin, centered on the Oak Ridge thrust fault system. This is considered a high rate of uplift (if not a world record), and it includes the displacements caused by earthquakes. The inferred rate of uplift between Palmdale and San Pedro is 25 mm/year averaged over the period from 1961 to 1974, and greater than 100 mm/year averaged over the period from 1961 to 1962.

The episodic nature of the inferred uplift and the reversals in its direction are also surprising. The motions between Barstow and Mojave in 1973 to 1974 and between Palmdale and San Pedro in 1961 to 1962 imply tilt rates of at least 10^{-6} per year. In the latter case, much of the apparent action was confined to the profile between Saugus and Palmdale, where the inferred rate of tilt was about 2×10^{-6} per year. These rates are as high as those estimated to occur during postseismic relaxation within a few source dimensions of a moderate to large earthquake (*4*) and are thus remarkably large for aseismic tilts.

Our data analysis consisted of editing, plotting, and modeling. The primary purpose of the editing was to minimize the effects of unstable bench marks. A bench mark was considered unstable if it moved up (or down) with respect to both of its nearest neighbors by more than 10 mm or by more than 5×10^{-5} times the distance between bench marks. Unstable bench marks were treated as temporary bench marks, that is, as stepping-stones between stable bench marks. Only the stable bench marks were used in estimating temporal changes in elevation, and only stable bench marks are plotted in our figures.

Data are plotted in the form of differences in elevation (topography) and apparent temporal changes in elevation differences (change) as a function of distance along the profile. The difference in elevation between bench marks i and $i - 1$ for year t is

$$\Delta h_i(t) = h_i(t) - h_{i-1}(t) \qquad (1)$$

and the temporal change is

$$r_i(t) = \Delta h_i(t) - \Delta h_i(t_0) \qquad (2)$$

where t_0 is some reference time. We departed from the traditional practice of summing differences in elevation to obtain absolute elevation in order to avoid error accumulation and to emphasize short wavelength features of the data. Figure 1 shows plots of $\Delta h_i(t_0)$ and $r_i(t)$

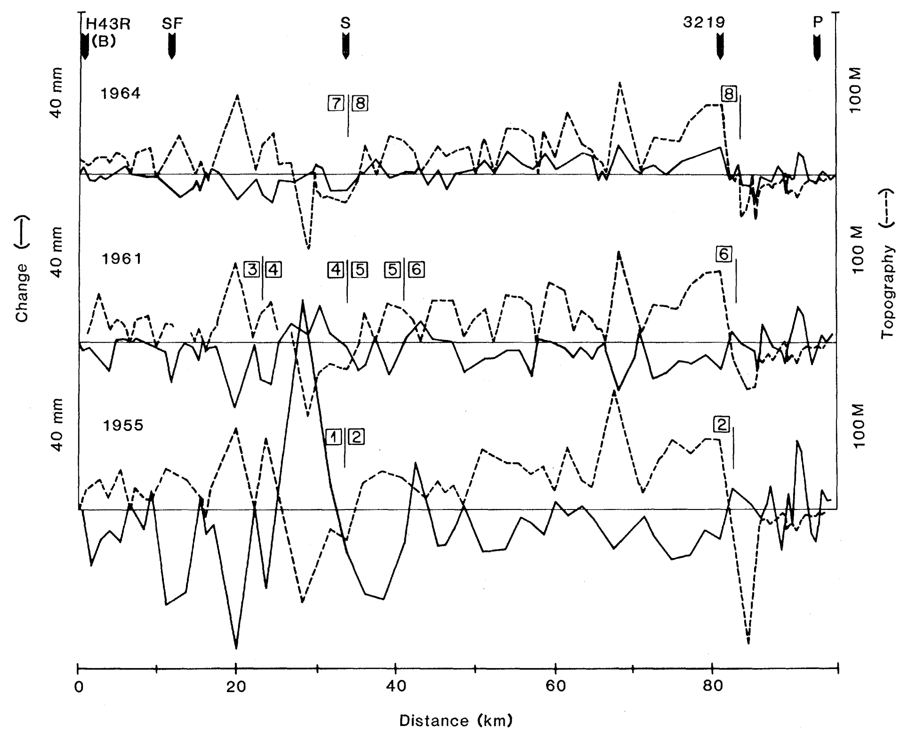

Fig. 1. Topography (dashed lines) and apparent change from 1965 (solid lines) for the profile from Burbank (*B*) to San Fernando (*SF*) to Saugus (*S*) to Palmdale (*P*). Topography and change are defined in Eqs. 1 and 2, respectively. Boxed numerals designate segments referred to in Table 1. Note the reversal of correlation between change and topography at Saugus in 1964. The topography differs slightly from year to year because of differences in bench marks used.

for $t_0 = 1965$ and for $t = 1955$, 1961, and 1964. Striking correlations between change and topography are apparent in every case.

Correlation between topography and apparent change in elevation is a classic symptom of certain types of systematic error, including errors caused by refraction (curvature of the line of sight) and rod miscalibration (5), but it may also arise from tectonic processes. We expect mountains to be uplifted and sedimentary valleys to be compacted such that differences in elevation increase with time. However, there are two reasons for believing that the correlations noted above resulted from systematic errors. First, the correlations persist to very short wavelengths; one would not expect tectonic deformation to affect so many local features in precisely the same way. Second, the correlation changes with position along the profile, often at places where changes were made in the survey. The most dramatic example occurs in the 1964 survey, for which the section from Los Angeles to Saugus was surveyed by a different crew, using different rods, than for the section between Saugus and Palmdale. The former section shows a negative correlation and the latter a positive correlation, although the exact location of the reversal is obscured by local disturbances (possibly of cultural origin) near Saugus.

It may be that there are long wavelength changes related to tectonic activity as well as systemic errors that affect both long and short wavelengths. In an attempt to isolate the effects of systematic errors, we separated the short wavelength variations from the long wavelength variations by fitting low-order polynomials (cubic or quartic) to the data over the intervals between Long Beach and Saugus and Saugus and Palmdale. The profile was broken in this way because the direction of the leveling route changes discontinuously at Saugus. Polynomials of the same order were fitted to the topography and the change data for each year. The polynomial functions were taken as estimates of the long wavelength features of the data, and residuals to these polynomials were taken as the short wavelength features.

We divided each profile into segments, the boundaries of which generally coincide with known changes in crew or equipment, especially rods. After separating out the long wavelength components, we estimated apparent error factors within each segment by using simple linear regression. Our model was

$$\Delta h'_{ik} = (h'_i - h'_{i-1})(1 + \epsilon_k) + e'_{ik} \quad (3)$$

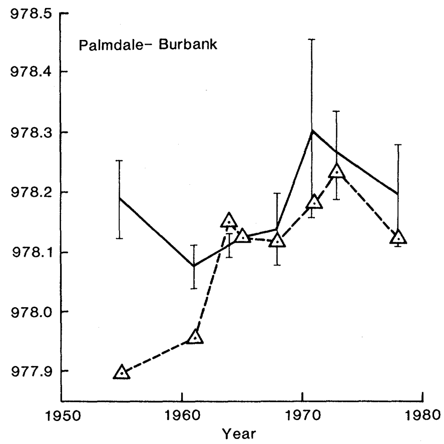

Fig. 2. Elevation difference in meters between bench marks 3219 (Palmdale) and H43R (Burbank) versus time. The dashed line is derived from data supplied by the National Geodetic Survey (12), with standard correlation for rod errors. The solid line shows the result of applying empirical correction based on correlation between apparent change and topography of short wavelength features. The errors bars for the corrected data represent 1 standard deviation, as computed with Eq. 5.

where $\Delta h'_{ik}$ is the apparent difference in elevation between two successive bench marks, k is an index specifying the survey segment, ϵ_k is the average proportional error for the kth segment, and e'_{ik} is a random error of measurement. Primes denote short wavelength components. The apparent change between two levelings becomes

$$r'_{ik} \equiv \Delta h'_{ik} - \Delta h'_{i0} = \Delta h'_{i0}(\epsilon_k - \epsilon_0) + e'_{ik} - e'_{i0} \quad (4)$$

where $k = 0$ refers to the 1965 baseline survey. We have assumed that all time dependence in the true elevations is associated with the long wavelength component and has thus been removed.

We estimated the relative error $\epsilon_k - \epsilon_0$ for each survey segment by a regression of r'_{ik} on $\Delta h'_{i0}$. The results are shown in Table 1. The negative values for 1955 and 1961 are consistent with the fact that Palmdale appeared to be lower in those years than in 1965, the baseline year. We tested the estimated error factors for significance by using the Fisher F test (6), which compares the hypothesis of a true correlation with that of a spurious correlation resulting from random errors. The F value is the ratio of the observed reduction in variance to that expected for purely random data. Table 1 gives the F values and corresponding confidence levels.

After estimating the relative error factors, we corrected the original data to make them consistent with the data obtained in 1965 survey. In Fig. 2, estimated differences in elevation between Palmdale and Burbank, both before and after our correction, are shown as functions of time. The error bars for the corrected data are estimated from the uncertainties in correction factors by the formula

$$\sigma^2 = \sum_k \sigma_k^2 h_k^2 \quad (5)$$

where σ_k^2 is estimate of the variance of error for the kth segment and h_k is the net difference in elevation (in the forward direction) for the kth segment.

The corrected data given in Fig. 2 show no significant change in elevation between Palmdale and Burbank until after the 1971 San Fernando earthquake, which apparently caused a coseismic up-

Table 1. Apparent errors in data for relative change in elevation.

Year	Segment*	$\varepsilon_k - \varepsilon_0$ (ppm)†	σ_k (ppm)	F	Confidence (%)	Net change in elevation
Surveys referenced to 1965 (rod pair 0)						
1955	1	−751	121	148	99	164
	2	−268	102	224	99	624
1961	3	−243	62	107	99	225
	4	−198	94	21	99	−85
	5	−149	91	5.5	95	60
	6	−120	50	2.1	99	547
1964	7	−107	24	204	99	175
	8	99	28	31	99	624
1968	9	−114	34	89	99	175
1971	11	46	723	0.64	55	175
	12	−295	193	1.84	80	452
1973	13	−127	102	55	99	289
1978	15	−412	198	35	99	175
Surveys referenced to 1968 (rod pair 10)						
1973	14	56	35	153	75	521
1978	16	−26	36	75	60	619

*The same rods were used in segments 1 and 2, 4 and 5, and 9 and 13. Many different rods were used in segments 15 and 16. †Parts per million.

lift of 160 mm. After the 1971 earthquake there was a gradual decrease in the elevation of Palmdale. This decrease is not significant at the 95 percent confidence level but, if real, it may have been caused by postseismic stress relaxation.

Our examination of other data for southern California indicates that the correlation between change and topography is widespread, but the similarity between long and short wavelength correlations is not always so close. We suspect that the short wavelength correlation may be easily masked or distorted by local disturbances such as bench mark instability or subsidence caused by fluid extraction.

Karcz and Kafri (*7*) noted a correlation of apparent change with topography in the Negev of southern Israel. They mentioned the possibility of systematic errors, but they preferred tectonic motion since the apparent motions were also strongly correlated with geology and since refraction errors and rod miscalibration were presumed to be too small. Brown and Oliver (*8*) came to similar conclusions about data for the Appalachian highlands and the Atlantic coastal plain in the United States. Citron and Brown (*9*) examined the Appalachian data in more detail, finding correlations between apparent change and topography of about 4×10^{-4}. They concluded that "either refraction or rod errors are larger than expected, or the movement is real and strongly correlates with topography." Chi *et al.* (*10*) noted a large topographic correlation in leveling data for the Sierra Nevada in California. Because one of the surveys was part of a loop around which the elevation change did not sum to zero, they concluded that systematic errors must have occurred. Data for other parts of California also show large correlations between apparent change and topography (*11*). The short wavelength correlations noted in all of these studies strongly suggest the presence of systematic errors.

Curvature of the line of sight (refraction) caused by variations in the refractive index with temperature, pressure, and humidity are a well-known source of errors. These errors are height-dependent because the uphill rod is read at a point closer to the ground, where the temperature variations are more severe, than the downhill rod. Bomford (*5*) cites as extreme a case in which refraction errors were as large as 2×10^{-4} of the difference in elevation. The magnitude of refraction errors is large enough to explain the correlations that we observed, but unfortunately a quantitative evaluation of these errors would require more detailed temperature and humidity data than are available for the earlier surveys.

Inadequate rod calibration is another possible source of height-dependent errors. Calibration errors are generally estimated to be on the order of 10^{-5} (*5, 8*), but we contend that these errors may be as large as 10^{-4} since, in correcting field data, it is generally assumed that rod length errors are distributed evenly along the rod (*12*). Rod calibration data clearly show that this is not the case. Calibration data for the rods used in the southern California surveys (*13*) are generally sufficient for deducing the average distortion in the top, middle, and bottom portions of the 3-m rods. Figure 3 shows the relative distortion (excess length) for a typical rod used in the southern California study. According to the 1966 calibration, the middle section of the rod, where most of the sightings are usually made, is longer than its nominal length by about one part in 10^4. However, the average distortion over the whole rod, which is used in the data reduction, is less than 10^{-5}. The effective errors in any given survey will be a weighted average of the rod distortion. The weighting will depend on the distribution of sightings on the rod and will generally be greatest near its center. If the average rod distortion is 10^{-4} over 1 m of the rod, it must be even greater in other parts of the rod. Thus the calibration corrections may be in error by more than 10^{-4} even if the rod calibrations themselves are accurate to 10^{-5}.

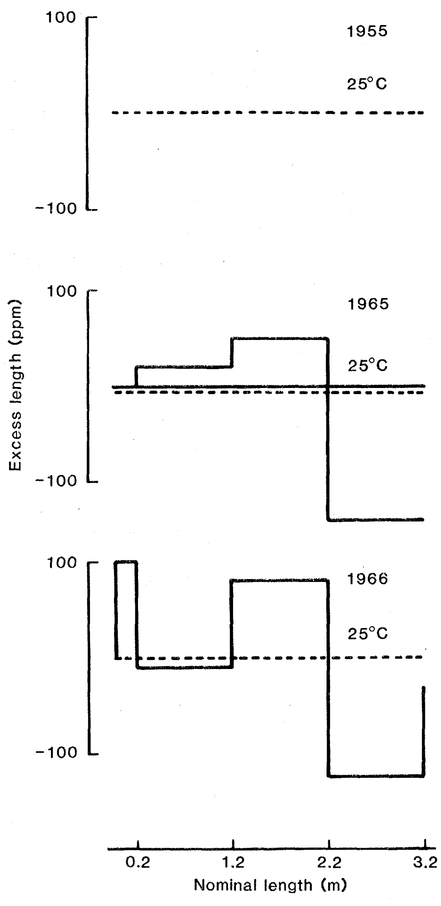

Fig. 3. Excess length averaged over 1-m sections of rod (solid line) and over whole rod (dashed line) for three different calibrations of rod 268 (rod code 312). This rod was used in the 1964 survey. The 1955 calibration showed no difference between nominal length and measured length. The invar strip may have been changed in 1965. Note that the excess length for the whole rod is only a few parts per million, while the rod strain over segments of the rod can exceed 100 ppm.

It is clear that elevation changes are highly correlated with topography for the profiles that we have studied. Because this correlation exists both at short and long wavelengths, it is difficult to explain tectonically and strongly suggests systematic errors in the data. The inferred error has the appropriate sign and order of magnitude to explain the apparent aseismic uplift. Because other leveling for southern California was performed with the same techniques, we presume that the same problem affects the other profiles; further work will be necessary to test this presumption.

We expect that these problems will be resolved and that existing leveling data will yet prove valuable in tectonic studies. However, the inference of widespread aseismic uplift in southern California is not justified.

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12. This is based on information provided by R. Snay, National Geodetic Survey. The rod correction is determined from the slope of a line fit to the calibration data by least squares.
13. These data were obtained from the rod calibration file of the National Geodetic Survey.

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