Reports

Aseismic Uplift in Southern California

Abstract. *Preliminary examination of the historic geodetic record has disclosed crustal uplift of 0.15 to 0.25 meter that apparently began around 1960 and has since grown to include at least 12,000 square kilometers of southern California. This uplift extends at least 150 kilometers west-northwestward along the San Andreas Fault from Cajon to Maricopa, southward from the San Andreas into the northern Transverse Ranges, and eastward from Lebec into and including much of the western Mojave block. It seems to have grown spasmodically eastward from a center near the junction of the San Andreas and Garlock faults and has occurred largely within an area that has remained virtually aseismic since at least 1932. Although much of this area has been characterized by crustal mobility since at least the turn of the century, the described uplift seems to be an unusually large and probably unique event superimposed on the existing pattern of continuing deformation.*

An exceptionally large number of high-precision, repeated level surveys has permitted the detection of a broadly defined and apparently recently developed zone of uplift that probably extends over more than 12,000 km^2 of southern California. This interpretation of recent uplift in the southern California area is confined to the region between and adjacent to the San Andreas and Garlock faults eastward from Maricopa to Barstow (Fig. 1) and is based on our current assessment of the recent vertical control record. A more detailed investigation and more rigorous analysis of the existing data will probably permit a much more explicit description of the vertical movement in this area and may reduce the assumptions and generalizations required of the interpretation shown here. Nevertheless, even the most rigorous study will probably not significantly alter the gross pattern of vertical movement shown in Fig. 1.

The described crustal movements (Fig. 1) are based on observed (unadjusted) elevations derived from the results of repeated level surveys along the routes shown in Fig. 2. Nearly all of this leveling meets first-order standards, and while the results of 1973 second-order surveys have also been utilized locally, a variety of considerations indicate that these data are very nearly as accurate as the first-order work to which they have been tied. All of the elevations (and hence all of the elevation changes) are referred to bench mark Tidal 8, San Pedro (Fig. 1), as invariant in elevation. Because this control point is adjacent to a continually recording tide gauge identified with a history of relative uplift with

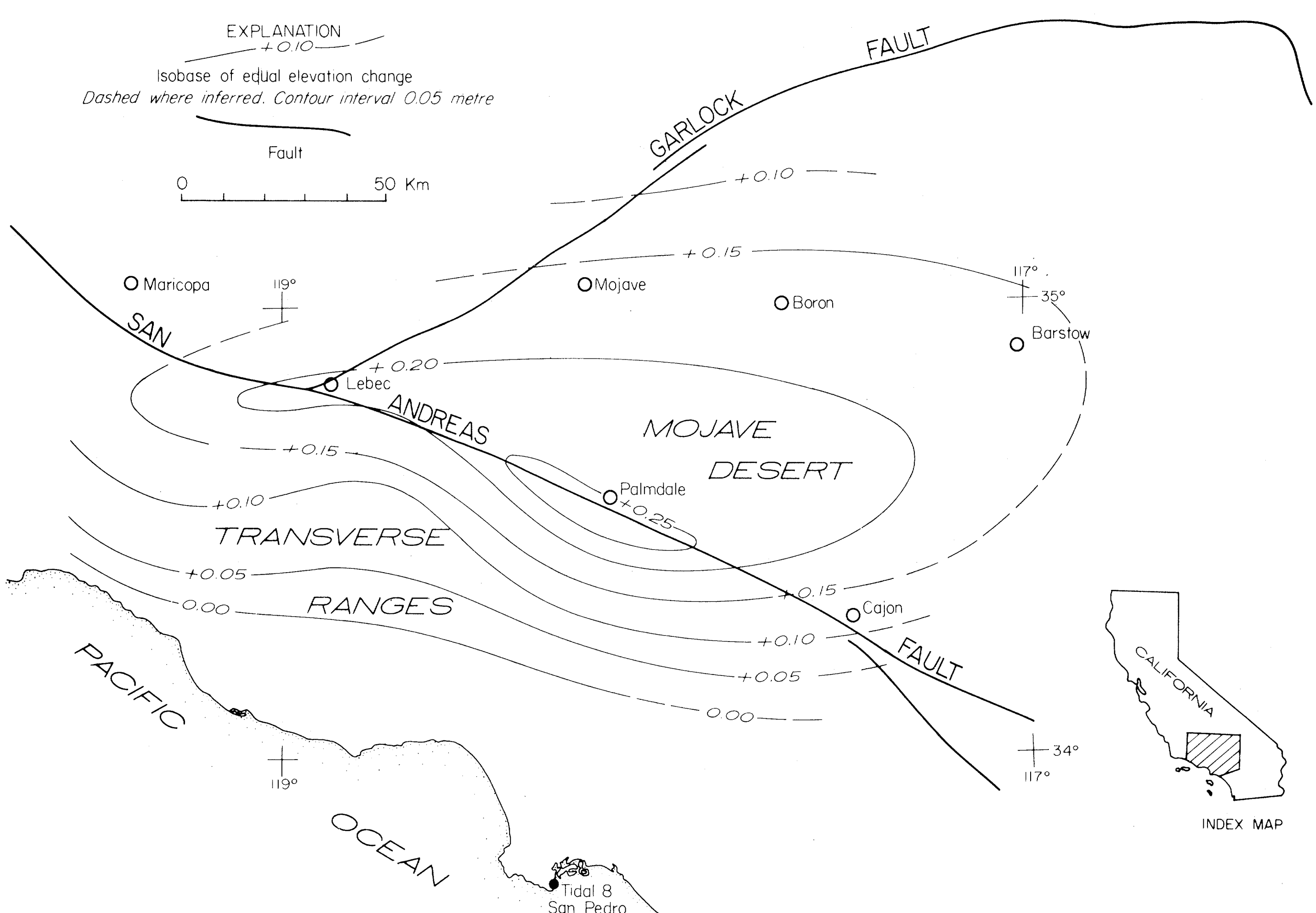

Fig. 1. Minimum uplift in the Transverse Ranges and adjacent parts of the Mojave Desert, California, during the period 1959–74.

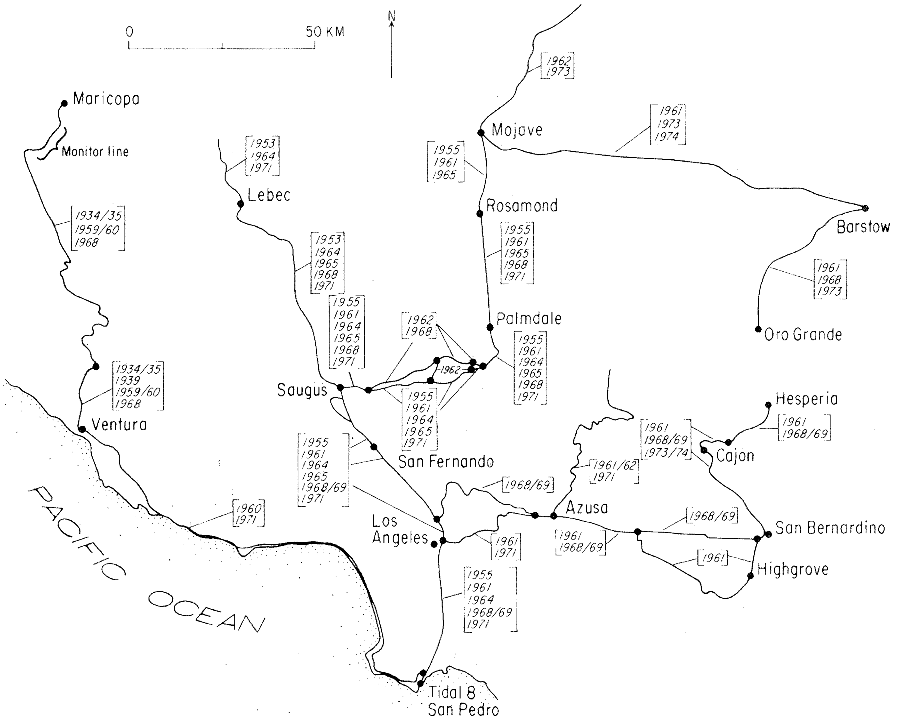

Fig. 2. Routes and dates of level surveys used in the construction of Fig. 1.

respect to most other California tide stations (*1*), elevation changes referred to it are biased against the recognition of uplift; had these changes been referred to either San Francisco or San Diego, for example, this uplift (Fig. 1) would have been increased by 25 to 30 mm. The uplift shown in Fig. 1 is, both of necessity and for purposes of clarity, interpretive and generalized. We have, for example, removed what we interpret as coseismic effects associated with both the 1971 San Fernando (*2*) and the 1973 Point Mugu earthquakes, which would have locally overwhelmed the movements shown here. Similarly, we have subtracted the differential subsidence known to have developed as a result of either artificially or naturally induced compaction of the poorly indurated sedimentary rocks that veneer many of the basinal areas. Moreover, because the most recent releveling used here (Fig. 1) locally is as old as 1965, the indicated magnitude and extent of the 1959–74 uplift may be even larger than shown in Fig. 1, provided only that the sense of movement has remained unchanged since 1965.

The uplift shown here (Fig. 1) is thought to have begun around 1959 or 1960 and certainly no later than 1961. This point is clearly demonstrated near Palmdale (Fig. 1), whereas westward toward Lebec and Maricopa it is less easily established. Nonetheless, the short monitor line across the San Andreas Fault near Maricopa (Fig. 2) remained relatively free of differential warping along its full length from the initiation of the monitoring program in 1935 until sometime after the completion of the January–April 1959 leveling. Moreover, although the represented uplift south of Maricopa is based on a 1968 comparison with a 1934 datum, in which it has been assumed that Ventura has continued to subside at about 2.5 mm/year (the average rate of subsidence between Tidal 8 and Ventura during the interval 1920–68) over the full period 1934–68, utilization of a 1959/60 datum would reduce the maximum uplift between Ventura and Maricopa by no more than 0.05 m (*3*). Accordingly, we infer that significant uplift did not begin south of Maricopa before 1959, yet could have commenced no later than the up-to-the-north tilting north of Ventura that must have begun no later than 1960 (*4*). Similarly, although no control surveys were run between Lebec and Tidal 8 between 1953 and 1964, at least 0.08 m of uplift occurred south of Lebec between 1953/55 and 1964. Because the sharply episodic uplift near Palmdale could not have begun before March–May 1961, and because the uplift at Maricopa probably did not begin until about 1959, it is not unlikely that relatively episodic uplift near Lebec began at about the same time or shortly thereafter.

The earliest surge of crustal uplift apparently began near or conceivably northwest of Maricopa. It must have expanded rapidly east-southeastward, for Palmdale rose about 0.20 m between 1961 and 1962 (*5*). Furthermore, elevation changes of up to about +0.18 m that could have begun no earlier than 1961 had spread northward to Mojave and perhaps eastward to Boron by 1965. The movements disclosed by the 1965 leveling seem to define the end of the first phase of crustal uplift in this area. Whether continued expansion proceeded episodically is uncertain, but at least part of the growth after 1965 was as abrupt as the elevation changes that occurred near Palmdale between 1961 and 1962. Between 1961 and 1971 uplift of about 0.15 m had spread east-southeastward to a point midway between Palmdale and Cajon. Similarly, it is estimated that between 1968 and 1973 the elevation of Cajon increased by about 0.12 m and certainly no less than 0.06 m. What clearly identifies this second growth phase as partly episodic is the 0.17 to 0.18 m of uplift at Barstow that must have occurred between 1973 and 1974. We emphasize, however, that while we interpret the 1973–74 elevation change between the Mojave-Boron area and Barstow as uplift at Barstow rather than subsidence at Mojave and Boron, in the absence of 1974 or later leveling between either Mojave or Barstow and Tidal 8, this interpretation remains conjectural; nonetheless, in support of this interpretation, the geodetic history suggests little subsidence of Mojave during any of the leveling intervals since at least 1926.

Although the uplift shown here (Fig. 1) is clearly anomalous within the period 1926–74, similarly anomalous movement probably occurred in the southern part of this area between 1897 and 1914. However, the data recovered and analyzed to date do not permit a unique determination of the vertical movement history during this earlier period and are virtually limited to the line between San Pedro and Mojave (Fig. 2). The critical data derive from 1897 (primary, double-rodded) leveling between San Pedro and the San Andreas Fault, 1902 (precise) leveling between San Fernando and Mojave, and 1914 (precise) leveling between San Pedro and Mojave. Comparisons between the results of the 1897 and 1914 surveys suggest uplift increasing gradually northward from San Pedro to Los Angeles, steepening abruptly to 0.51 m along the south margin of the Transverse Ranges province, declining gradually to about 0.05 m at Saugus, increasing relatively sharply to 0.57 m about 16 to 18 km south-southwest of the San Andreas Fault, and finally decreasing to less than

0.33 m at the fault. Continuation of the 1897 datum by means of the 1902 survey data indicates that uplift between 1897 and 1914, averaging about 0.3 m, may have persisted northward as far as Mojave. Comparisons between the results of the 1914 and 1926 San Pedro to Mojave surveys suggest that the 1897/1902–1914 uplift had partially collapsed by 1926 by amounts that increased more or less uniformly northward to a maximum of 0.38 m immediately south of the San Andreas and averaged about 0.3 m northward across the western Mojave block. The interval between the apparently aseismic 1897/1902–1914 uplift and this seeming collapse is not known to have been associated with any significant seismic event other than the 1916 "Tejon Pass" earthquake, which was characterized by a relatively small seismic moment (*6*). Nevertheless, the 1897/1902–1914 uplift differed significantly from that developed during the 1959–74 interval in that it was much more clearly associated with the Transverse Ranges, and specifically the frontal fault system, than it was with the San Andreas. Moreover, although we may never be able to demonstrate the point conclusively, circumstantial evidence argues that the 1897/1902–1914 uplift was confined largely and perhaps exclusively to the Transverse Ranges, and that as much as 0.3 m of the uplift that occurred within the northern Transverse Ranges and the western Mojave block is probably specious and attributable simply to systematic error in the 1914 leveling.

Whether or not the described upift (Fig. 1) will continue to enlarge both laterally and vertically is problematic. A comparison with the seismicity of this region since 1932, and especially since 1960 (*7*), shows that the area elevated above 0.15 m has remained virtually free of seismic activity west of the 117th meridian (except for the area north of Lebec, which has continued to experience aftershock activity associated with the 1952 Kern County earthquakes); this correlation between uplift and seismic quiescence is particularly striking if the comparison is restricted to earthquakes of magnitude 4 or larger. Hence, if it is assumed (i) that this uplift (Fig. 1) is either a direct or an indirect effect of elastic strain accumulation; (ii) that any future seismic activity will coincide roughly with the pattern of activity after 1932; and (iii) that the presumably continuing seismic activity east, south, and north of the uplifted area is a significant index of elastic strain release, any future lateral growth may be restricted to the northwest, an area in which we lack appropriate geodetic control. Parenthetically, the southeast end of the uplifted area, near Cajon, coincides closely with the southeastern extent of reported surface rupturing associated with the great 1857 earthquake on the San Andreas; the uplifted zone extends northwestward along the San Andreas at least two-thirds the length of the 1857 zone of surface breakage, which was traced as far as Cholame (*8*).

Continued monitoring of the uplifted area is desirable not only to assess further growth of this feature, but to detect any reversals in movement as well. For example, comparisons between geodetic data developed within the epicentral region both before and immediately after the 1971 San Fernando earthquake suggest a tilt reversal north of the epicenter that may have preceded the main shock (*2*). However, regardless of its desirability, detailed monitoring of this vast area by means of frequently repeated level surveys seems prohibitively costly. Alternatively, precise gravity surveys with a resolution of $\pm$ 6 to 9 μgal (equivalent to a free-air difference of 2 to 3 cm) are now considered feasible (*9*); combining these surveys with perhaps biannual releveling across the short axis of the uplifted area, so that each could be continually checked against the other, might provide a relatively inexpensive yet highly reliable monitoring system.

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26 January 1976

Diamonds in an Upper Mantle Peridotite Nodule from Kimberlite in Southern Wyoming

Abstract. *Diamonds in a serpentinized garnet peridotite nodule from a diatreme in southern Wyoming are the first known occurrence in an upper mantle peridotite xenolith from a kimberlite intrusion in North America as well as the second authenticated occurrence of diamonds from kimberlite pipes in North America. The nodule is believed to have come from a section of depleted (partially melted) lherzolite at a depth of 130 to 180 kilometers.*

Small diamond crystals have been recognized in an altered garnet peridotite nodule from a kimberlite diatreme in southern Wyoming. This is one of a very few reported occurrences of diamond in a peridotite xenolith from a kimberlite intrusion. Dawson and Smith (*1*) have identified diamond in a mica-garnet lherzolite from the Mothae kimberlite in northern Lesotho. Sobolev *et al.* (*2*) have found diamonds in five nodules of garnet serpentinite (altered garnet peridotite) from the Aykhal kimberlite diatreme in Siberia. The Wyoming discovery is only the second authenticated occurrence of diamonds from a kimberlite locality in North America; the other occurrence was in the Murfreesboro district of Pike County, Arkansas, where diamonds were first found in 1906 and were recovered commercially until 1919 (*3*).

The presence of diamond in the Wyoming nodule was first suspected when F. J. Nowacki and R. Jensen encountered difficulties in preparing thin sections at the U.S. Geological Survey in Denver, Colorado. They noticed deep scratches on a grinding plate and isolated a small white crystal (approximately 1 mm in diameter) as the source of the problem. X-ray diffraction analysis by T. Botinelly and B. F. Leonard (U.S. Geological Survey), using a Gandolfi camera, confirmed the diamond identification. Subsequent examination of the nodule revealed that three small diamonds were