Reprint Series
11 March 1983, Volume 219, pp. 1215–1217

SCIENCE

Correlation of Changes in Gravity, Elevation, and Strain in Southern California

Robert C. Jachens, Wayne Thatcher, Carter W. Roberts, and Ross S. Stein

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Correlation of Changes in Gravity, Elevation, and Strain in Southern California

Abstract. *Measurements made once or twice a year from 1977 through 1982 show large correlated changes in gravity, elevation, and strain in several southern California networks. Precise gravity surveys indicate changes of as much as 25 microgals between surveys 6 months apart. Repeated surveys show that annual elevation changes as large as 100 millimeters occur along baselines 40 to 100 kilometers long. Laser-ranging surveys reveal coherent changes in areal strain of 1 to 2 parts per million occurred over much of southern California during 1978 and 1979. Although the precision of these measuring systems has been questioned, the rather good agreement among them suggests that the observed changes reflect true crustal deformation.*

The U.S. Geological Survey's Earthquake Hazards Reduction Program has supported period surveys during the past 5 to 10 years to detect changes in elevation, horizontal strain, tilt, in situ stress, local values of the earth's gravity and magnetic fields, radon emission, and many other quantities (*1*). Although temporal anomalies in many of these quantities have been reported (*2–4*), the relations between the various anomalies are not well understood because, in general, the measurements that define them lack spatial or temporal coincidence. We present the results from gravity, elevation, and areal-strain surveys near Tejon Pass, California (Fig. 1). All the data display temporal fluctuations in excess of their estimated uncertainties, and they are remarkably well correlated for the 4 years that measurements overlap. In addition, we show that there are similar correlations at other localities in southern California.

Gravity measurements have been made near Tejon Pass and at 12 other sites in southern California (Fig. 1) during surveys made at 6-month or annual intervals since late 1976. During each survey, relative gravity with respect to a base station at Riverside was measured at each site along two closed circuits with sets of three to five gravimeters (*5*). These procedures typically yielded relative gravity values with uncertainties of 4 to 6 μgal (one computed standard error) and revealed temporal fluctuations as large as 25 μgal.

The 100-km leveling route between Glendale and Tejon Pass is one of a set of baselines (Fig. 1) that has been resurveyed yearly during the past 4 to 5 years. The surveys were conducted with first-order instrumentation and procedures and were either single run or run both in a forward and backward direction (*6*). Uncertainties in observed elevation differences resulting from the accumulation of random errors are given by $aL^{1/2}$ mm (1 standard deviation), where L is the traverse distance and a is approximately 1 mm/km$^{1/2}$. Because of the relatively short sighting distances (15 to 40 m), we estimate possible errors due to unequal atmospheric refraction (*7*) to be less than 15 mm.

Strain accumulation in southern California has been monitored at approximately yearly intervals since 1974 by electro-optical surveys of seven trilateration networks (Fig. 1), and the results of surveys through 1980 have been reported by Savage *et al.* (*2*). The strain data that we report derived from the surveys of Savage *et al.* (*2*) but differ slightly because we analyzed only localized subsets of the lines that make up the Tehachapi and Cajon networks (*8*). Uncertainties associated with the areal-strain data are approximately 0.3 part per million (ppm) (1 standard deviation), in comparison with observed changes as large as 2 ppm.

Superposed time histories of relative gravity (Tejon Pass–Riverside), relative elevation (Tejon Pass–Glendale), and areal strain (Tejon Pass local network) are shown in Fig. 2. In constructing this plot, four independent parameters were determined from the data—datum levels for two of the time histories relative to the third and two scale factors relating two of the time histories to the third. For the three time histories, zero was arbitrarily set at the 1978 survey values, and the histories were scaled to each other by factors (−0.01 ppm/mm and −0.2 μgal/mm) based on plots of changes in strain ($\delta\Delta$) and elevation (δe) as functions of changes in gravity (δg). The scaling factor between δg and δe not only applies to these data, but also represents the ratio of gravity change to elevation change that characterized coseismic deformation associated with the 1964 Alaska (*9*) and 1971 San Fernando, California (*10*), earthquakes. Dislocation model studies predict a similar relation between δg and δe for deformation associated with dip slip on buried faults (*11*). With these scale factors, Fig. 2 shows that the changes in gravity, elevation, and areal strain near Tejon Pass have been coherent during the entire period for which the data overlap.

The three-way correlation is particularly striking near Tejon Pass but is also apparent in data from the other two locations where coincident gravity, strain, and elevation observations were made. Figure 2 shows similar time histories (plotted with the same scale factors) near Cajon Pass and near Palmdale (Fig. 1). As with the Tejon Pass data, datum levels of two time histories from each location were arbitrarily adjusted to that of the third. Near Cajon Pass, the data are well correlated for the entire interval of data overlap, with the exception of one strain measurement in mid-1977. Although the Palmdale gravity station lies outside the trilateration network, gravity and areal strain data significantly disagree at only one point, in early 1982. Note that the strain measurements at 1979.8 and 1980.6 also depart from the line connecting the gravity data but that no gravity measurements were made at these times. Between 1978.1 and 1980.3 the gravity and areal strain changed by approximately 15 μgal and 0.7 ppm, respectively—changes that are not reflected in the data on elevation.

It should be emphasized that all the gravity changes reported are relative to Riverside, whereas the areal strain represents a change that is local to each geodetic network; the elevation data are measured over distances of 40 to 100 km. The good agreement among the various measurements is somewhat surprising. A consistent interpretation of these observations is that Riverside and Glendale were relatively stable and that the observed changes were localized closer to Tejon Pass, Palmdale, and Cajon Pass (*12*).

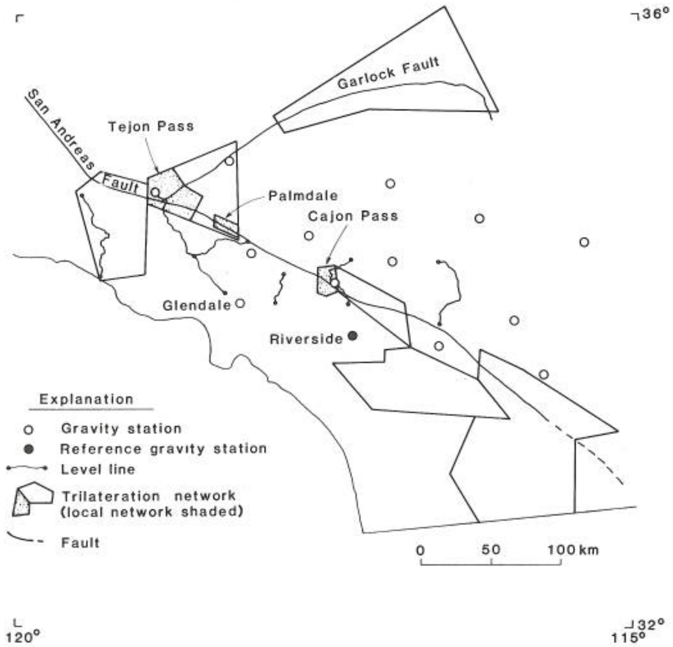
Thus at three sites in southern California, data from three independent measurement systems are correlated for the 4 to 5 years of observation. The correlation between δg and $\delta\Delta$ [$r = .59$, $N = 13$, $P < .05$ (*13*)] is better than that between δg and δe ($r = -.63$, $N = 8$,

$P < .10$). This probably is due to a number of factors, including (i) the number of nearly coincident δg and $\delta\Delta$ observations is larger than that for δg and δe observations (16 versus 11), (ii) only one large excursion in the elevation data (at Tejon Pass) was detected during the observation period, (iii) the elevation data from Palmdale do not reflect the changes in the gravity and strain data between 1978.1 and 1980.3, and (iv) possible errors in some leveling data acquired with compensation-leveling instruments (*14*). The correlation of δg and δe is supported by the fact that the value of $\delta g/\delta e$ in this study is the same as that in studies of coseismic deformation. Therefore, we argue that the good agreement among these three independent data sets indicates that the observed changes reflect crustal deformation in southern California rather than some undiscovered error sources in each of the measuring systems or some phenomenon unrelated to deformation, such as ground water fluctuation.

The style of deformation suggested by the data in Fig. 2 is that of aseismic cyclic fluctuations during which uplift is accompanied by gravity decrease and areal compression, whereas subsidence is associated with gravity increase and areal dilatation. Some of the fluctuations occurred during short intervals. The observed relations between changes in gravity, elevation, and areal strain are qualitatively consistent with deformation resulting from lateral compression or extension of a thick elastic plate. To satisfy the quantitative relation between $\delta\Delta$ and δe, however, a plate 200 to 300 km thick is required for an assumed Poisson's ratio of 0.25 to 0.30. Also, the effective width of the deformation can be no more than 30 to 40 km because gravity changes resulting from density changes in a zone wider than about 40 km would cause the $\delta g/\delta e$ ratio to be smaller than that observed. Although a zone of deformation 30 to 40 km wide is not unreasonable, a plate thickness of 200 to 300 km is unlikely. Continental lithospheric plates are generally thought to be only about 100 km thick or less, and some evidence suggests that in southern California the plates may be only a few tens of kilometers thick (*15*).

An alternative explanation of the data is that they reflect aseismic slip on a buried horizontal or low-angle fault, a model proposed by Savage *et al.* (*3*) to explain the Palmdale strain data. The observed relation between δg and δe is compatible with dip slip on a low-angle fault. The relation between $\delta\Delta$ and δe for this type of model is complex. Analytical results shown in figure 3 of Savage *et al.* (*3*) of vertical displacement and horizontal strain caused by slip on a buried horizontal plane indicate that the $\delta\Delta/\delta e$ ratio is a function of position on the deformation curve. Thus, a migrating slip event would appear at a fixed observation point as a time-varying $\delta\Delta/\delta e$ ratio. Similar features are characteristic of more complex slip models. Therefore, to satisfy the data in Fig. 2 with this type of model, the generally constant relation observed between δe and $\delta\Delta$ requires that the slip be fixed in space but vary in amplitude over time. The two times (Fig. 2) at which the constant strain-elevation correlation appears to break down could indicate slip migration.

Additional gravity, elevation, and strain observations should help us further test and refine the observed correlations. The speed with which some changes occurred suggests that measurements of various parameters must nearly coincide in time if their interrelations are to be accurately portrayed. In some cases, measurements separated by only a few months may not correlate. The potential influence of short-period fluctuations must also be considered when in-



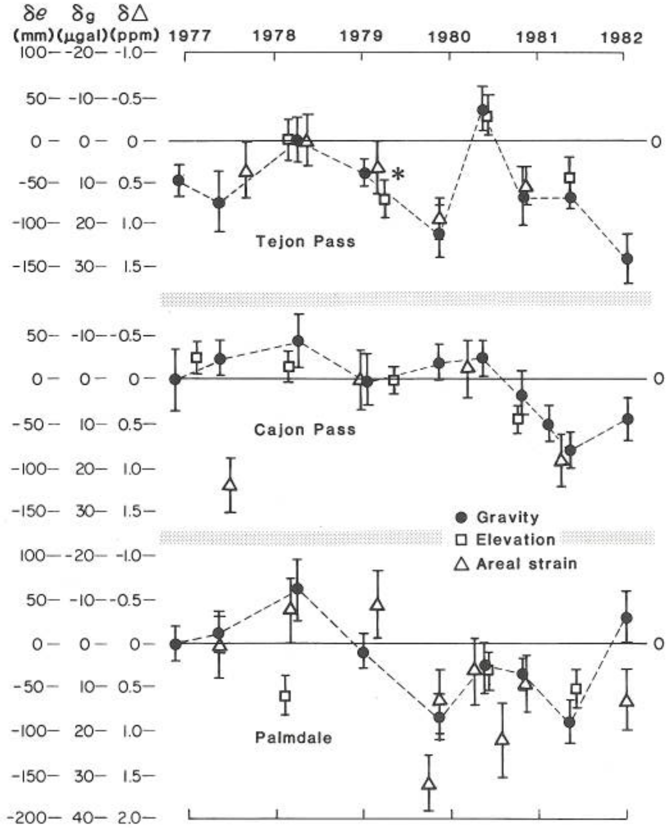


Fig. 1 (left). Index map showing locations of gravity stations, leveling baselines, and trilateration networks in southern California that have been surveyed repeatedly during the past 5 to 10 years. Shaded areas of trilateration networks are local networks used in this study. Fig. 2 (right). Temporal changes in gravity (δg), elevation (δe), and areal strain ($\delta\Delta$) measurements from three areas in southern California. Gravity data represent changes in relative gravity with respect to assumed invariance at Riverside. Elevation data represent changes in relative elevation at benchmarks MP2N (Tejon Pass) and U899 (Palmdale) with respect to benchmark 09-01710 (Glendale) and at benchmark L 1290 (near Cajon Pass) with respect to RIALTO D (south of Cajon Pass). Error bars on the gravity data represent 1 standard error and those on the elevation and strain data represent 1 standard deviation. Dashed lines connect the gravity data. See (*14*) for an explanation of the asterisk.

terpreting the results of measurements that require extended periods to perform. For example, changes in relative elevation determined by repeated leveling surveys between widely separated points could reflect both intersurvey and intrasurvey deformation. Castle *et al.* (*16*) suggest that in some cases movements are the reason that elevation differences measured around closed circuits do not always sum to zero. Finally, the possibility that episodic aseismic deformation is common and widespread in southern California suggests that a monitoring strategy focused on episodic deformation (*17*) would permit an assessment of the likelihood of a specific deformation event triggering an earthquake.

ROBERT C. JACHENS
WAYNE THATCHER
CARTER W. ROBERTS
ROSS S. STEIN

U.S. Geological Survey,
Menlo Park, California 94025

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12. One line of evidence supports this conclusion: gravity changes in the Glendale area (the south terminus of the leveling routes to Tejon Pass and Palmdale) relative to Riverside were stable within 5 μgal from 1977 to 1981. A single 16-μgal excursion in 1979.1 was localized at the Glendale base station and absent at stations 10 to 20 km away.
13. In order to avoid the uncertainties in choosing datum levels for each of the time histories, the correlation coefficients were determined from the population of changes between adjacent pairs of nearly coincident δg and $\delta\Delta$ or δg and δe observations.
14. It recently has come to light that some leveling data may contain errors resulting from interaction between magnetic fields and automatic compensators in leveling instruments. At this time the error is poorly understood but appears to vary with the make and model of the instrument, would be different for individual instruments, and would be subject to changes with time in any particular instrument. We have identified one point in the leveling data reported here, the 1979 elevation at Tejon Pass, that might be contaminated by a magnetically induced error. If a 1982 laboratory calibration of the instrument used in this survey is applicable to the 1979 results, then the 1979 relative elevation at Tejon Pass would be approximately 200 mm higher than that shown in Fig. 2. At present we do not know whether, in general, laboratory calibrations are strictly applicable to field survey results nor whether it is valid to apply a calibration of this particular instrument obtained in 1982 to data acquired with it in 1979 [National Geodetic Survey, *Prof. Surv.* **2–5**, 38 (1982)].
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25 May 1982; revised 10 September 1982

11 March 1983, Volume 219, Number 4589 **SCIENCE**

Does California Bulge or Does It Jiggle?

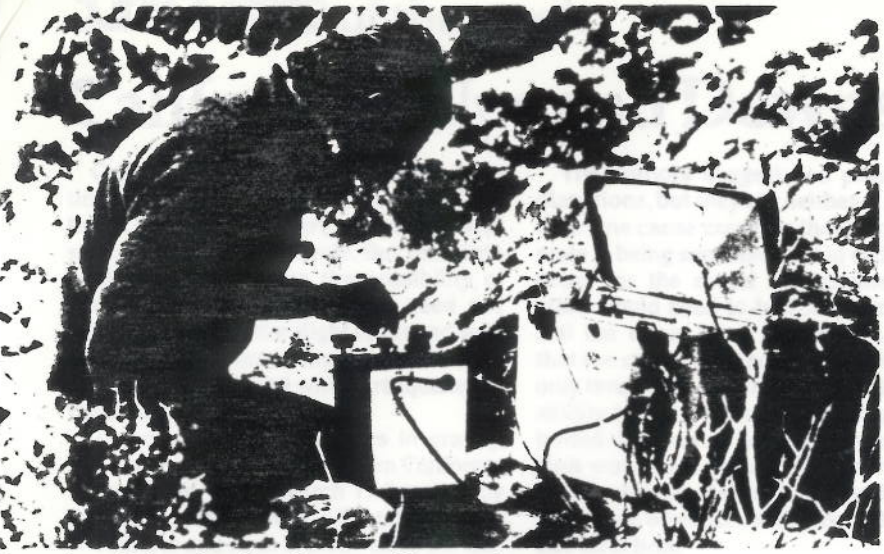
Southern California may be bouncing up and down every few years; could this have been mistaken for the ominous bulge?

First, it was the Palmdale bulge, a 35-centimeter-high, 200-kilometer-long swelling of the ground that reportedly developed during the 1960's. Now, a group of geophysicists is suggesting that some of the same area of southern California may be bouncing up and down every few years, although these apparent oscillations in elevation have never lifted the ground to the extreme height claimed for the bulge. In fact, such rapid but modest oscillations, together with recently discovered measurement errors, may account for most of the reported towering bulge.

In this issue of *Science* (p. 1215), Robert Jachens, Wayne Thatcher, Carter Roberts, and Ross Stein of the U.S. Geological Survey (USGS) in Menlo Park, California, present a 5-year record of three different geophysical measurements, each of which bears on changes in elevation. All three seem to trace the same pattern of uplift and subsidence at Tejon Pass on the San Andreas fault about 100 kilometers northwest of Los Angeles. The ground there seems to have risen and fallen 5 to 15 centimeters twice during the past 5 years. The USGS group reports similar but less striking movement at two other San Andreas sites: Palmdale, which is at the center of the purported bulge, and Cajon Pass, 70 kilometers northeast of Los Angeles.

Researchers keeping an eye on southern California have seen plenty of variations in the crustal properties they have been monitoring (*Science*, 15 February 1980, p. 748), but all too often the anomalous readings have been at different places, at different times, or on instruments whose measurements could not be checked against related observations. Three measurements, gravity, strain, and elevation, were made at each of several sites by the USGS group, and the possible errors in each type of measurement are thought to be unrelated. All three measurements at a particular site tend to record the same episodes of uplift and subsidence. When the ground rises, strain (the distortion of the rock) increases and gravity decreases. That is just what theory would predict if the crust were being squeezed like a sponge. Squeezing the crust would distort the rock, push the ground up, and carry any gravimeter farther from the center of the earth's mass, which decreases the observed gravity.

The concerted behavior of the three measurements impresses many researchers, more so than a glance at the plotted values might seem to warrant. The apparent changes are only a few times larger than the calculated errors, and the statistical correlations among the three are only significant at the 90 to 95 percent confidence levels. Still, the changes appear surprisingly well behaved when compared to the assortment of microearthquakes, bubbling springs, and barking dogs that have often created excitement in California. In addition, the observed elevation changes, which have



Robert Jachens

Measuring relative elevation changes with a gravimeter

This gravimeter, which is temperature-controlled and weighs about half a kilogram, can measure differences in the force of gravity at different locations that are as small as one hundred millionth of Earth's gravity. That is sensitive enough to detect its being lifted 5 centimeters farther from the center of mass of Earth. It contains a weight suspended from a sensitive spring-lever system, the change in the stretching of the spring being a measure of the change in gravity.

the poorest correlations of the three, and the gravity changes have the same relation as that determined from measurements in the aftermaths of the 1964 Alaska and 1971 San Fernando earthquakes. "That seems to me to be a very strong argument that [the changes] are real," says James Savage of the USGS in Menlo Park. "The correlations look too strong to be a coincidence. It's very impressive."

Although not reported in this paper, the earth's magnetic field seems to be varying in step with the changes in elevation, strain, and gravity, according to Malcolm Johnston of the USGS in Menlo Park. The magnetic field, which is continuously recorded at the same sites at which the other properties were measured, could be responding to changes in the magnetic materials of the crust induced by changes in strain, Johnston says. He has so far been unable to identify any extraneous causes, such as variations in rainfall or temperature.

If the jiggling is real, what could be causing it? The squeezed-sponge analogy holds well for the relation between gravity and elevation but not for the elevation-strain relation. That has prompted the USGS group to suggest that the ground may be bouncing up and down because southern California is occasionally slipping sideways. It will not slip into the sea, as fantasized by some, but a number of investigators have speculated that a nearly flat-lying fault has detached the upper 10 kilometers of southern California from the rock below. Such a detachment fault underlies at least part of the Appalachian Mountains and piedmont region of the eastern United States. Uneven slipping on this fault might produce the observed rapid heaving without generating any earthquakes, the group says. Savage cautions, however, that although the required calculations can be made to be consistent, they remain somewhat strained and unsatisfying.

Whatever the cause, these apparent oscillations in elevation could have contributed to the current confusion over the true size of the uplift centered on Palmdale. The leveling surveys used to measure those elevation changes were separated by several years, and each took as long as a year or more to complete. Rapid oscillations between and even during surveys could have created inconsistencies that later were taken as evidence of large elevation changes by some. Others saw them as systematic leveling errors.

Any real, enduring increase in elevation, however modest, may have been inflated into an intimidating bulge by leveling errors that have only recently been fully appreciated (*Science*, 14 December 1981, p. 1331). Some researchers had expected that correction for errors due to atmospheric refraction would reduce the reported 30- to 45-centimeter height of the bulge, as William Strange of the National Geodetic Survey (NGS) in Rockville, Maryland, had claimed. Sandford R. Holdahl of the NGS has now made a more sophisticated calculation of the refraction errors. He also has evaluated 14 years of corrected leveling surveys by a mathematical method that fits all survey results to a single, steady uplift. Holdahl's final bulge is 7.5 ± 4.0 centimeters high at Palmdale, a far cry from 35 centimeters. Even that uplift might be due to other errors, he says.

Although other investigators have praised Holdahl's approach, they caution that his assumption that a bulge's motion would be steady and uniformly distributed must be suspect, if the oscillations reported by Jachens and his colleagues have any validity. In part because of these reservations, many observers still do not believe that all of the uplift attributed to the bulge has been explained away as erroneous. Stein, for one, thinks that the fit of the observations to Holdahl's mathematical model is poor enough that the model could contain significant but irregular uplifts. In a survey-by-survey analysis, Stein notes, corrections can reduce the uplift but not eliminate it. The refraction correction to the 1964 leveling survey between Saugus and Palmdale, a line crucial to the construction of a large bulge, would drop the apparent uplift from about 20 centimeters to about 13, he says. An additional correction of about 7 centimeters for a rare error related to the surveying rod used would lower that uplift to about 6 centimeters.

Surveys of areas including Tejon Pass, which shows the greatest changes of the past 5 years, fare better, Stein says. The leveling route up to Tejon Pass is too steep to accumulate significant refraction error, and surveying rod errors were negligible there. Thus, the refraction-corrected, 15-centimeter uplift across this route that persisted from 1965 to 1971 and then partially collapsed seems to be real, he says. No one has applied corrections to all of the individual leveling routes around the periphery of the bulge, but some researchers expect that, were this done, the shoulders of the reported bulge would be much reduced or would disappear, leaving the bulge not only lower but also narrower than originally reported.

If there is a middle ground in this debate, it is the view that the surveying errors are larger and the bulge smaller than had been thought. The reasonably good correlation of several kinds of observations, suggesting rapid elevation changes over the past 5 years, supports the reality of some kind of uplift in southern California. What it all may mean for the next large earthquake there no one is quite sure.—**RICHARD A. KERR**

Additional Reading

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