Reports

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 (δΔ) and elevation (δ*e*) as functions of changes in gravity (δ*g*). The scaling factor between δ*g* and δ*e* 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 δ*g* and δ*e* 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*).

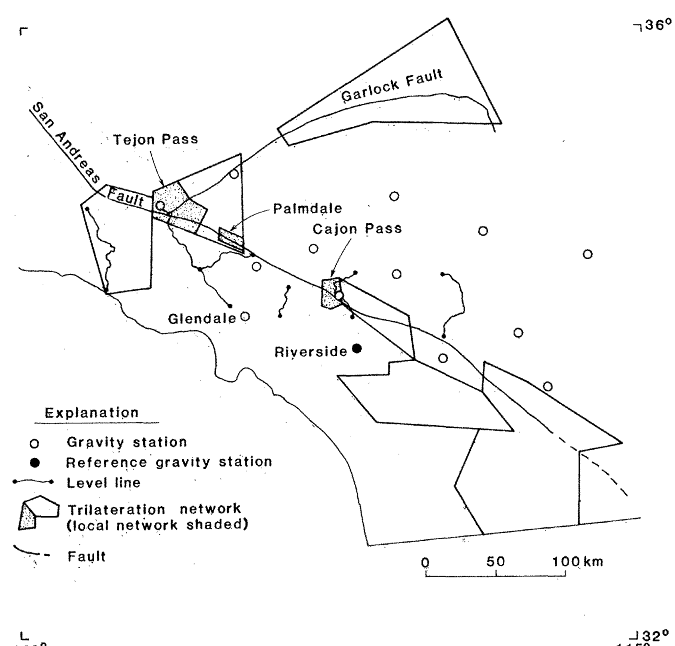
Thus at three sites in southern California, data from three independent measurement systems are correlated for the 4 to 5 years of observation. The correlation between δ*g* and δΔ [$r = .59$, $N = 13$, $P < .05$ (*13*)] is better than that between δ*g* and δ*e* ($r = -.63$, $N = 8$,

$P < .10$). This probably is due to a number of factors, including (i) the number of nearly coincident δ*g* and δΔ observations is larger than that for δ*g* and δ*e* 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 δ*g* and δ*e* is supported by the fact that the value of δ*g*/δ*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 δΔ and δ*e*, 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 δ*g*/δ*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 δ*g* and δ*e* is compatible with dip slip on a low-angle fault. The relation between δΔ and δ*e* 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 δΔ/δ*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 δΔ/δ*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 δ*e* and δΔ 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-



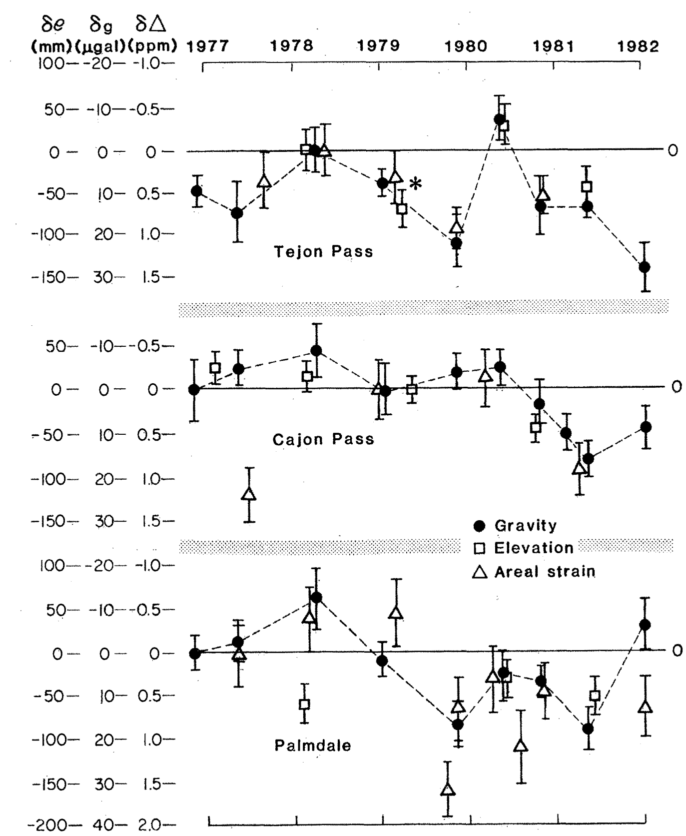


Fig. 1 (left). Index map showing locations of gravity stations, leveling baselines, and trilateration networks in southern California that have been surveyed repeatedly during the past 5 to 10 years. Shaded areas of trilateration networks are local networks used in this study. Fig. 2 (right). Temporal changes in gravity (δ*g*), elevation (δ*e*), and areal strain (δΔ) 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.

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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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18. We thank J. C. Savage for providing us with the strain data as well as performing additional analyses for us.

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Syneresis of Vitreous by Carbon Dioxide Laser Radiation

Abstract. *In carbon dioxide laser surgery of the vitreous a process of vaporization has been advocated. In this report syneresis, a thermal liquefaction of gel, is shown to be over ten times more efficient on an energy basis than vaporization. Syneresis of vitreous is experimentally shown to be a first-order kinetic process with an activation energy of 41 ± 0.5 kilocalories per mole. A theory of laser surgery in which this figure is used agrees closely with results from laser experiments on human eye-bank vitreous. The syneresis of vitreous by carbon dioxide laser radiation could lead to a more delicate form of ocular microsurgery, and application to other biological systems may be possible.*

For applications in ophthalmology, the short penetration depth of CO_2 laser radiation (~ 10 μm at 10.6 μm) is advantageous, since a significant local effect can be achieved in ocular tissues without damaging underlying or neighboring structures. Carbon dioxide lasers have been used for scleral dissection, in filtering procedures for glaucoma (*1*), and as a photocautery to seal fibrovascular fronds and retinal tears at the time of vitrectomy (*2*). It has been suggested that CO_2 laser radiation could be used in a vitrectomy to "vaporize" regions of vitreous (*3–5*) and thus avoid the traction on adjacent structures evident when mechanical instruments are used. In this report we show experimentally and theoretically that there is a more efficient way to remove vitreous. By using thermal syneresis, the same effect can be achieved with over ten times less energy expenditure per unit mass (53 cal/g compared to 576 cal/g for vaporization). This new type of surgery involves local heating of the vitreous gel (with CO_2 laser radiation) from the ambient vitreous temperature of 37°C to a temperature at which the gel is converted to a liquid (*6*), which can be removed by aspiration. The greatly reduced energy requirement for this process may lead to a much more delicate form of ocular microsurgery. The chances of damage to the retina, which can be caused by a temperature elevation of only 10° to 20°C (*7*), are greatly reduced.

The vitreous body is a transparent semisolid gel interposed between the lens and the retina. It is the simplest connective tissue, but knowledge of its structure and function is incomplete. The water content, between 98 and 99.7 percent (*8*), is held in a two-part gel or semigel consisting of a fibrous protein, collagen, and a mucopolysaccharide, hyaluronic acid. Such a two-component structure has greater mechanical stability than the collagen network alone. Because of the large domain of solution occupied by the hyaluronic acid molecules (65 ml/g), such a structure can physically entrain large quantities of water (*6*). Collagen is composed of a triple helical arrangement of three polypeptide chains (*9*). In the native state these are cross-linked, forming fibrils (15 to 25 nm in diameter) randomly distributed in a loose network (less than 1 to 1.5 μm between elements) (*9*). A low concentration of collagen fibrils, as in the owl monkey (25 μg/ml), leads to a liquid vitreous; a greater concentration (for instance, 286 μg/ml in humans), leads to a gel-like vitreous (*10*).

The collagen network and hence the vitreous can be shrunk by processes such as heat, radiation, freezing, and thawing (*10*). When a solution of collagen is heated, the triple helical structure is destroyed and randomly coiled molecules are produced (*9*). This helix-to-coil transition represents the conversion of collagen to gelatin (*9*). In such a thermal denaturation a shortening of the fibrils occurs which results in a volume decrease of the network of collagen fibrils and hence of the gel itself. As an example, after heating, the vitreous gel from human eye-bank eyes is found to consist of both liquid and gel portions. We measured the rate of this process by the following method. With the temperature of the vitreous sample held constant, the liquid portion was drawn off and measurements of the weight of the gel as a function of time were recorded. The data were fit by the equation, $W(t) = W_0 \exp(-kt)$, where W_0 is the initial weight of the vitreous gel, k is the specific rate constant, and t is time. Values of k were determined for a range of temperatures and are plotted in Fig. 1 against inverse temperature. The solid line fit to the experimental points is a plot of the Arrhenius equation $k(T) = A \exp(-E/RT)$, where A is the preexponential factor, E is the activation energy, R is 1.987 cal/