J. Geomag. Geoelectr., 38, 933–947, 1986

Local Magnetic Fields, Uplift, Gravity, and Dilational Strain Changes in Southern California

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(Received April 1, 1986; Revised June 7, 1986)

Measurements of regional magnetic field during gravity, strain and leveling surveys near the San Andreas fault at Cajon, Palmdale and Tejon are strongly correlated with changes in gravity, areal strain, and uplift in these regions during the period 1977–1984. This correlation principally depends on data taken during 1978–79 and 1981–82 when episodes of the 'Palmdale Uplift' occurred in this general region. Because the inferred relationships between these parameters are in approximate agreement with those obtained from simple deformation models, the preferred explanation appeals to short-term strain episodes independently detected in each data set. Transfer functions from magnetic to strain, gravity, and uplift perturbations, obtained by least-square linear fits to the data, are -0.98 nT/ppm, -0.03 nT/μGal, and 9.1 nT/m respectively. Tectonomagnetic model calculations underestimate the observed changes and those reported previously for dam loading and volcanomagnetic observations. A less likely alternative explanation of the observed data appeals to a common source of meteorologically generated crustal or instrumental noise in the strain, gravity, magnetic, and uplift data.

1. Introduction

Unique opportunities to intercompare various geophysical data during apparent episodes of large scale crustal activity have occurred in western U.S.A. and in Japan during the last eight years as increased monitoring efforts have provided more complete coverage. SAVAGE *et al.*, (1981a), and SAVAGE and GU, (1985) recently reported aseismic strain episodes near the San Andreas fault adjacent to Palmdale. In a more complete study, JACHENS *et al.*, (1983) observed correlated changes in gravity, areal strain, and elevation in the Cajon, Palmdale, and Tejon regions of the fault. Somewhat earlier, JOHNSTON *et al.*, (1979) identified offsets in local magnetic field in the Cajon Pass to Palmdale region during changes in uplift in this region between 1974 and 1976. In Japan, HONKURA and TAIRA (1983), and OHSHIMAN *et al.*, (1983) reported relationships between crustal uplift in the Izu Peninsula, Japan, and both short-period geomagnetic variations and geomagnetic total field intensity.

We report here measurements of continuous magnetic field in the regions investigated by JACHENS *et al.*, (1983). These data, when sampled at the times of the various other surveys, show significant correlation to each of these other data. If the interdependence of these parameters arises from actual changes in the rate of crustal deformation, we obtain an important field calibration of the various measurement systems for one type of deformation and increased confidence that the measurements reflect the state of strain in the earths' crust. On the other hand, if the observed changes result from some common source of noise, meteorological dependence or data aliasing, it is important to identify and remove this contamination. Since the magnetic data are continuous, a more through analysis of these possibilities can be attempted than with other measurement types.

In this era of uncertainty regarding crustal monitoring techniques, the establishment of interrelations between different techniques is of great importance, particularly for assessing the usefulness and potential of young data sets such as local magnetic field monitoring. While changes in magnetic field in response to crustal stress has a strong theoretical basis (STACEY and JOHNSTON, 1972) and support from laboratory observations (OHNAKA and KINOSHITA, 1968), tectonomagnetic models relating magnetic events to fault failure parameters are poorly constrained. During the past ten-year history of moderate seismicity and limited coverage in California, only a few results relating magnetic changes to tectonic and seismic activity have been obtained (JOHNSTON *et al.*, 1975; SMITH and JOHNSTON, 1976; DAVIS *et al.*, 1981; DAVIS and JOHNSTON, 1983).

2. Observations

The data reported by JACHENS *et al.*, (1983) were obtained from the leveling line, trilateration and gravity nets at Tejon, Palmdale, and Cajon shown in Fig. 1. The trilateration nets are subsets of the larger nets reported by SAVAGE *et al.*, (1981b). The leveling lines run from Glendale to Tejon and to Palmdale, and from Riverside through Cajon. All gravity measurements were referenced to Riverside. The measurement uncertainties for these three data types are 0.3 ppm, 15 mm$\pm$1 mm/km$^{1/2}$ and 6 μGals, respectively.

We extend Jachens' study by including the magnetic field measurements from the seven telemetered magnetometer sites shown in Fig. 1. Each of these instruments operates at a 0.25 nT sensitivity. Data are sampled every ten minutes and are transmitted in digital form to Menlo Park, California. Details of the system are described by MUELLER *et al.*, (1981).

For the purposes of this study, the magnetometers were grouped in pairs that correspond roughly to the geodetic nets with AB and CH at Tejon, BU and PL at Palmdale, and LR and SS at Cajon. All data were referenced to GD, a magnetically quiet site far enough to the north to be outside the uplift area. The data from each group were averaged together to obtain a regional mean albeit with only two sample points per region. Since each magnetometer senses the integrated effect of all local magnetic field changes out to a distance of about 5 km depending on the amplitude of these changes, the fact that we have only two sites per region is not as bad as might first appear.

Since all the permanent magnetometer sites are near the San Andreas fault, it was not possible to reference GD to either Riverside or Glendale (the reference points for the gravity and leveling data). Also, the high level of culturally generated magnetic noise in these urban areas precludes using these points as reference sites. Magnetometer sites other than GD were also tested and gave results similar to those reported below. Three-day means of the data from each region were obtained covering the times of the different gravity, strain and leveling surveys. Measurement precision for

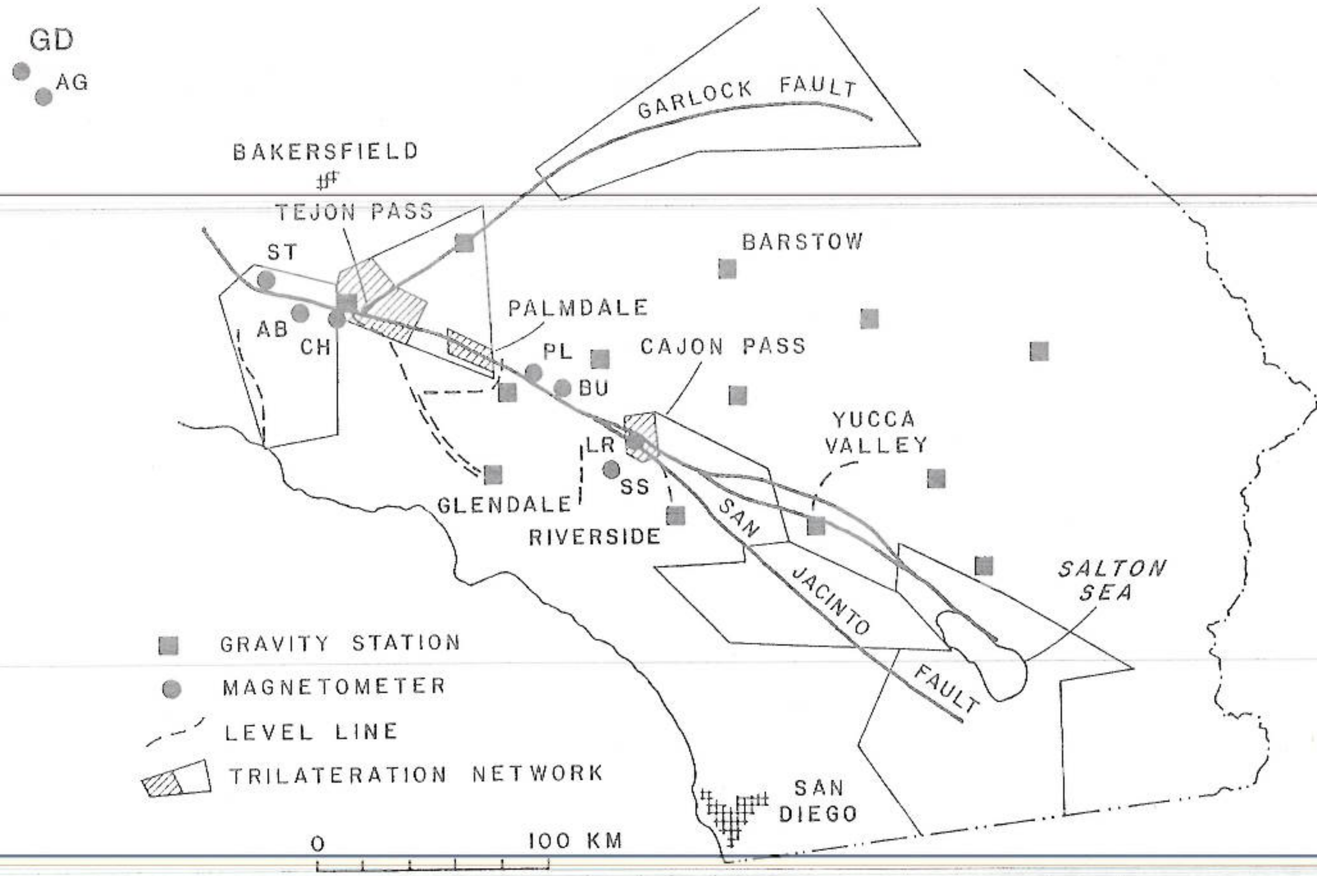

Fig. 1. Level lines, trilateration nets, gravity and magnetic field monitoring sites in southern California that have been surveyed repeatedly during the seven year period 1977–1984. Crosshatching shows the extent of the trilateration nets at Tejon, Palmdale, and Cajon used in this study.

the magnetic data are estimated to be not more than 0.12 nT (JOHNSTON *et al.*, 1984).

Inspection of each time series (Fig. 2) reveals detailed structure at the 0.5 nT level, indications of an annual cycle, but otherwise, not much apparent correspondence between the time series. The annual cycle is seen best in the Palmdale data. Figure 2 also shows the particular set of three-day means (dots) that correspond to the gravity survey data. The values of the magnetic field data in each region as a function of time (survey) and each corresponding survey data is listed in Table 1. A mean value has been subtracted from each data set.

Tests for correlation between the magnetic data and each parallel data set yielded some surprising results. Figure 3(a) shows the composite plot of the magnetic field fluctuations from all three areas against the simultaneously observed gravity variations. When all the data is plotted in this way (i.e. no allowance is made for different behavior in different regions), the correlation coefficient is 0.93 and is

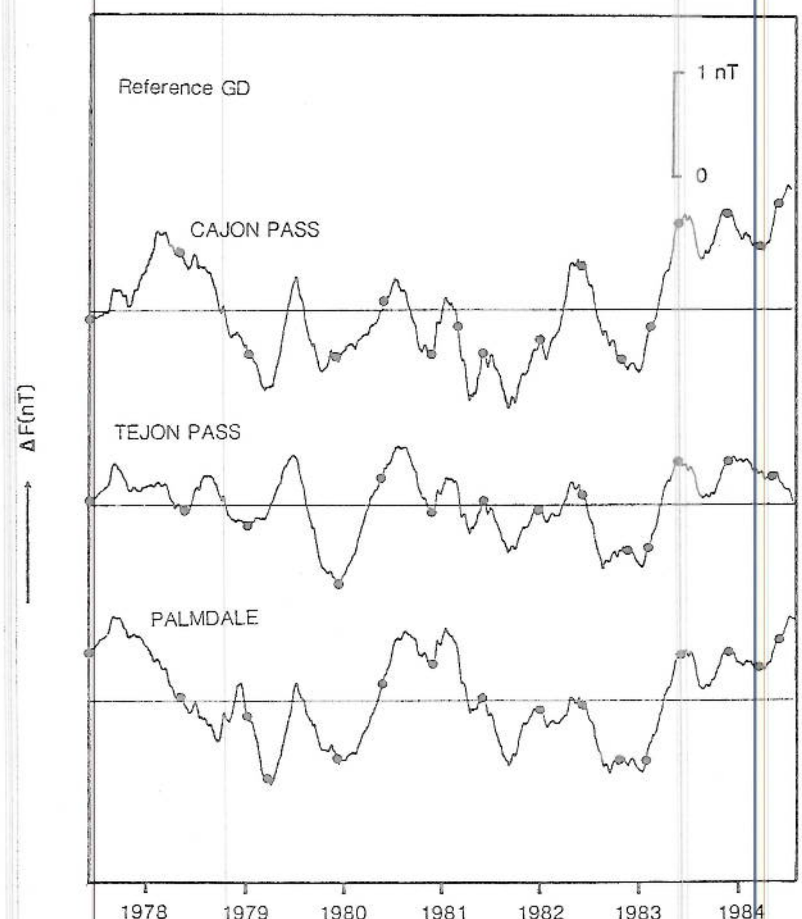

Fig. 2. Continuous record of regional magnetic field at Cajon, Tejon, and Palmdale from mid-1977 to mid-1984. Three day means of the magnetic field during times of gravity surveys are shown as dots superimposed on the record.

Table 1. Three-day means of regional magnetic field and corresponding gravity, trilateration, and uplift data in the three regions studied.

Time	Tejon				Palmdale				Cajon			
	Δg (μGals)	$\Delta Strain$ (ppm)	Δh (cm)	ΔF (nT)	Δg (μGals)	$\Delta Strain$ (ppm)	Δh (cm)	ΔF (nT)	Δg (μGals)	$\Delta Strain$ (ppm)	Δh (cm)	ΔF (nT)
77.37												
77.4	14±7			−0.13	−2±4	−0.35±.35		+0.33	−5±4	0.4±.36		−0.16
77.7		−0.34±.32		+0.34								
78.2			0.0	+0.08		−0.90±.37	−1.5	0.22			1.8	+0.71
78.32	0±5			−0.18	−12±8			0.02	−9±6			+0.49
78.4		−0.53±.32		−0.24								
79.0	7±4			−0.10	2±4			0.08	0±6	−0.80±.32		−0.15
79.2		−0.14±.28		−0.11		−0.91±.36		−0.72				
79.3			−6.8	+0.03								
79.4											0.4	−0.18
79.8						−0.69±.42		−0.47				
79.9	21±6	0.56±.30		−0.53	17±4	0.11±.37		−0.49	−4±4			−0.17
80.3						−0.19±.36		−0.12		−0.63±.36		−0.25
80.37	−7±5			−0.09	5±3			−0.11	+5±4			−0.18
80.45			2.6	+0.21			−1.5	+0.33				
80.6						0.83±.36		0.59				
80.8											−3.8	−0.22
80.9	13±7	0.0±.29		+0.08	7±3	−0.26±.34		+0.37	3±5			−0.25
81.15									10±4			+0.04
81.3										0.49±.30		−0.98
81.39									16±4			−0.68
81.4	13±3		−4.2	−0.13	18±5		−0.8	−0.01				
82.2	27±6			+0.09	−6±6	0.04±.37		−0.02	9±5			−0.20
82.3		−0.35±.24		0.0								
82.4	21±4			0.0	4±5			−0.10	4±5	−0.41±.33		+0.09
82.8	25±5			−0.37	9±4			−0.61	10±4			−0.45
82.9		0.07±.30		−0.28		1.0±.32		−0.57		0.39±.38		−0.43
83.1	5±4			−0.31	−12±4			−0.56	17±4			−0.22
83.4	23±4			+0.25	9±4	−0.02±.33		+0.38	9±4			+0.50
83.9	10±6			+0.53	−1±5			+0.45	2±4			+0.93
84.2					0±5	−0.15±.37		+0.32	−11±3			+0.33
84.4	5±4	0.43±.24		+0.12	4±6			+0.50	21±3	0.63±.35		+0.60

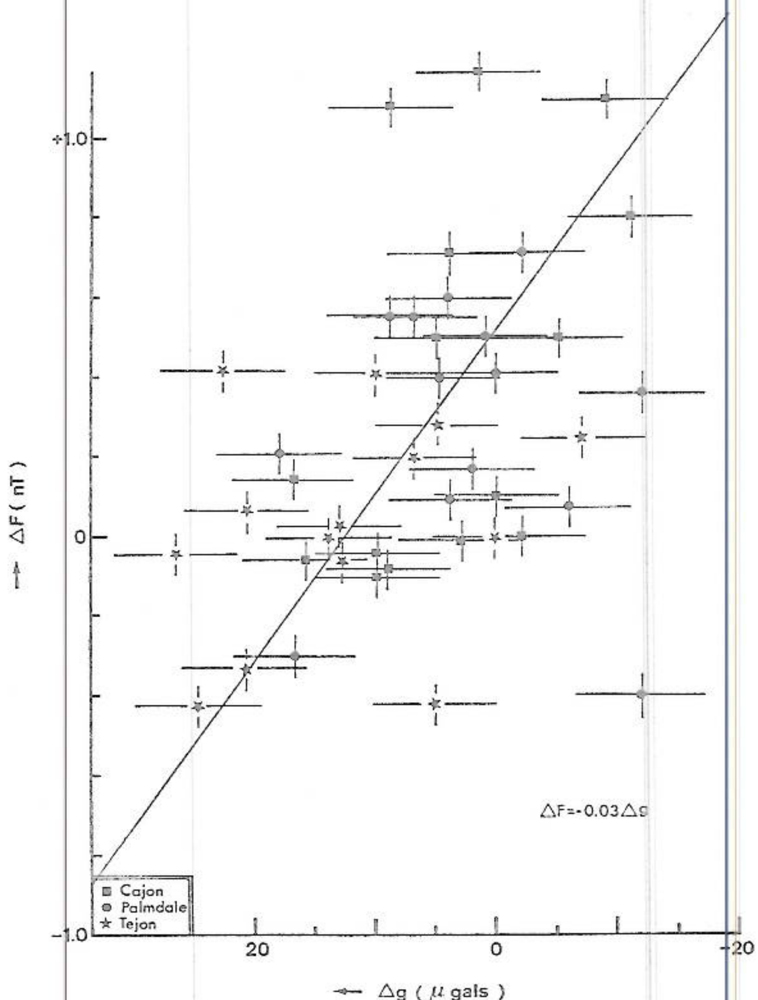

Fig. 3(a). Plot of magnetic field against gravity fluctuations from the three study regions. Shown also is the least-squares linear fit to the data as discussed in the text.

significant at the 1% level. If the data from each region are considered separately, the correlation coefficients are significant at the 1% level for the Cajon and Palmdale data and at the 5% level for the Tejon data. This degraded Tejon correlation is a result of two scattered points for this data set clearly evident in Fig. 3(a). The transfer function relating the magnetic and gravity perturbations was obtained using least-square linear fitting techniques. The function obtained has the form

$$\Delta F = -0.03\Delta g \qquad (1)$$

where ΔF is in nanoTeslas and Δg is in microGals.

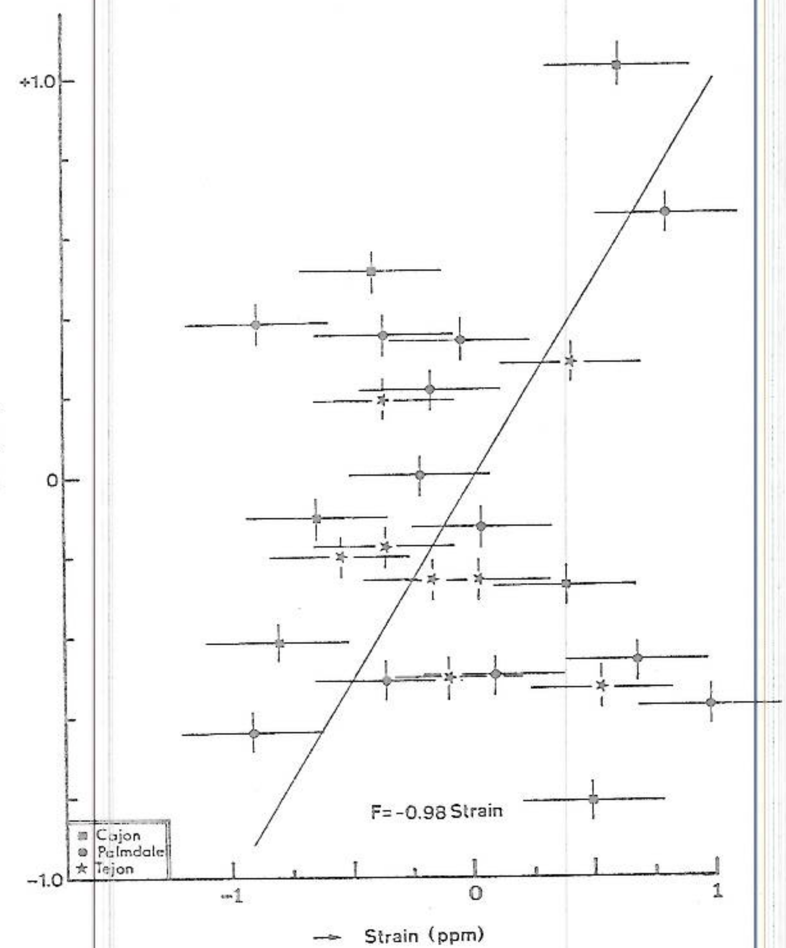

Fig. 3(b). Plot of magnetic field against dilational strain fluctuations from the three study regions. Shown also is the least-squares linear fit to the data as discussed in the text.

Figure 3(b) shows a similar plot of magnetic field fluctuations from all three areas against the simultaneously observed trilateration data. In this case, the correlation coefficient for all data grouped together is 0.89 and is significant at the 5% level. If the data from each region are considered separately, the correlation coefficients are significant at the 1% level for the Cajon data and at the 5% level for the Tejon and Palmdale data. The transfer function obtained by least-squares between the magnetic and the strain data has the form

$$\Delta F = -0.98 \Delta strain \tag{2}$$

where ΔF is in nanoTeslas and $\Delta strain$ is in ppm with the sign convention that compression is negative.

Because the largest magnetic signals are expected from regions where the magnetization is largest (STACEY and JOHNSTON, 1972), the largest strain sensitivity is expected in the Cajon region where the magnetization of the rocks, as inferred from magnetic surveys in these regions (HANNA *et al.*, 1972), is at least several times larger than that at Tejon. If transfer functions are generated for each data subset, a significantly larger strain sensitivity is indeed found for the Cajon data.

Although there are fewer elevation data, similar determinations of correlation coefficients and tests for significance indicate significance at the 10% level. This level of significance is marginal, particularly since only four uplift values were obtained during this period. Within these uncertainties, the transfer function obtained in a similar manner between the elevation data and the magnetic data has the form

$$\Delta F = 9.1 \Delta h \tag{3}$$

where ΔF is again in nanoTeslas and Δh is in meters.

A summary plot showing the superimposed time histories for each data set is shown in Fig. 4 and illustrates the general coherent behavior between the various data sets. The scaling of each data set to the magnetic data is obtained using Eqs. (1), (2), and (3). As a consequence, the relations between Δg, Δh, and $\Delta strain$ obtained by JACHENS *et al.*, (1983) can be easily derived. Wild points are noted in the strain data for Tejon Pass in mid-1984 and the Palmdale data at the end of 1982, and for the leveling data at Palmdale in early 1978.

3. Discussion

While correlated magnetic, strain, gravity, and leveling episodes occurred in these three regions in California during the last seven years, the physical reasons behind these correlations are much less clear. Since each data set was taken by independent observers who did not compare their measurements until 1982, the possibility that these relationships occurred by conscious or unconscious observer bias can generally be discounted. It is also very unlikely that they occurred by chance.

Since the magnetic data can be tested more thoroughly than any of the other data sets, we will first investigate the possibility that all perturbations result from meteorologically generated noise in the crust or the measurement systems. If this noise were common to all or even some of the data, spurious results could be obtained. Also, since survey measurements are made either annually or biannually, aliasing may be occurring. Temperature, pressure, and rainfall records were not routinely collected at any of the sites during the last seven years. However, weather records do exist at Palmdale in the center of the array. These records are ideal for the Palmdale nets but may differ in fine detail from weather records at Tejon to the north and Cajon to the south. For the purposes of this study they provide a useful initial test.

Correlation coefficients were calculated between records of rainfall, temperature, and pressure at Palmdale and the magnetic data from each location. No significant correlation was found with any of these parameters over periods of days to months. This is consistent with results obtained using similar data from other areas where the instruments were subjected the large amplitude thermal cycling (JOHNSTON *et al.*, 1984) and where instruments were operating for almost 10 years in field sites

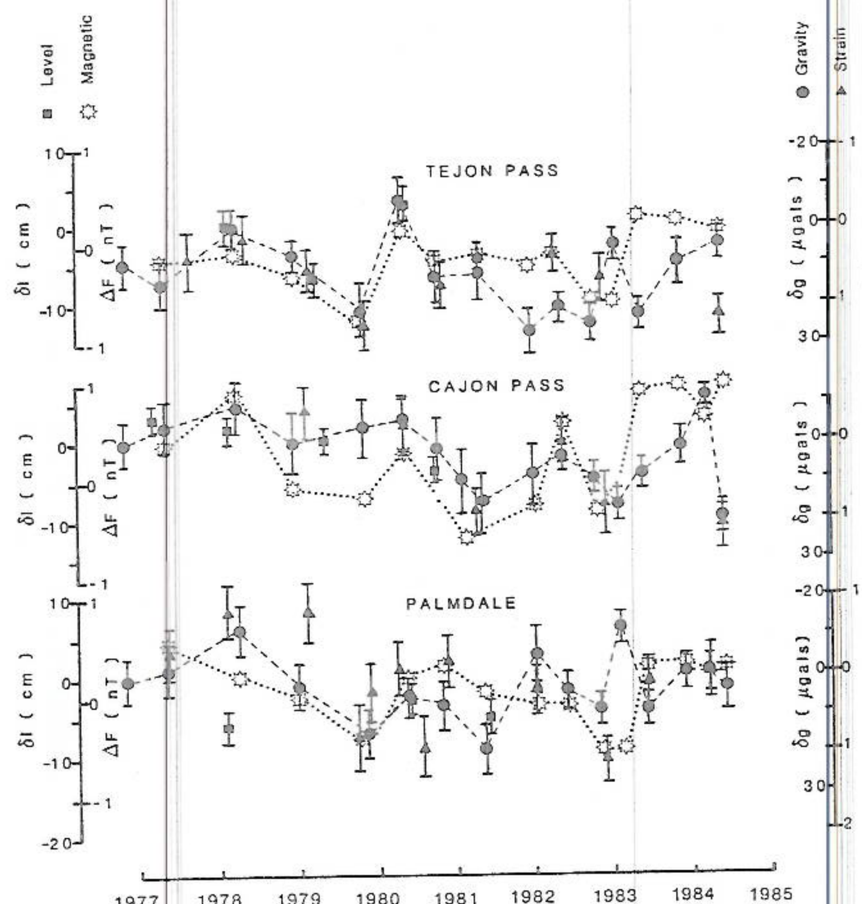

Fig. 4. Superimposed time-histories of magnetic field (stars), gravity (dots), areal strain (triangles), and elevation (squares) data, together with their error bars, from the three study regions in southern California. Single dashed lines connect the gravity data points and dotted lines connect the magnetic data points. Error bars for the magnetic data lie within the star symbol.

through many extremes of rainfall and pressure. The magnetometers are, of course, absolute instruments so tests for such effects have routinely been negative.

An annual periodicity is perhaps indicated in the magnetic difference data shown in Fig. 2, at least in the Tejon data during 1980 and 1981. It is possible that this could have resulted from integrated rainfall, temperature, or pressure effects not seen at shorter periods. However, annual variations do occur in the geomagnetic field with an amplitude of about 10 nT (WITHAM, 1960). The relative reduction of these variations that can be achieved using the simple differencing techniques should be similar to that obtained for diurnal variations.

This can be easily shown by determining a best least-square linear fit of a diurnal harmonic to sets of magnetic difference field data (each set contained 2 months of hour averages) and comparing this to the amplitude obtained from similar fits to total field data during the same time interval. The amplitude of the diurnal contamination in the difference field data obtained this way is typically about 0.5 nT. The least-square fits to the total field data over the same period of time indicates an average diurnal field of 33.7 nT. On this basis an annual term with an amplitude of 10 nT would be expected in difference field data at the 0.16 nT level.

Least-square linear fits of annual and various other harmonics to the magnetic difference field data in Fig. 2 indicate significant fits, as expected, only for the annual harmonic. The amplitudes and phases for the Cajon, Tejon and Palmdale data are 0.15 nT (−68°), 0.2 nT (−39°), and 0.25 nT (−89°), respectively. Zero phase corresponds to the beginning of the records. These amplitudes are close to the measurement error of the magnetic data and are at about the level expected for the geomagnetic annual term. It is most likely therefore that incomplete cancellation of the externally generated fields, due primarily to induction differences between sites (DAVIS and JOHNSTON, 1983), is the source of most of the apparent annual variation in the data in Fig. 2.

To check whether it is this annual term and perhaps aliased annual terms in the other data that is responsible for the correlations between data sets, we attempted to find a correlation between these data sets and the annual term in the magnetic data alone. The largest annual terms in the data are obtained when the data are differenced with site AG (Fig. 1). Figure 5 (upper) shows the Tejon data differenced to AG. The best fit of an annual term to these data obtained by the least-squares technique is shown in Fig. 5 (center). The amplitude (≈1 nT) is the largest obtained between sites along the San Andreas fault and provides the best test of annual term contamination as the reason behind the observed correlations. The lower plot in Fig. 5 shows the residual when the annual term is subtracted from the raw difference field data.

Each of the three data sets in Fig. 5 were sampled at the same time as the gravity surveys and correlation coefficients were calculated to see whether an improved correlation was obtained. To illustrate the results obtained, the annual term magnetic data sampled at the time of the gravity surveys are plotted against the gravity data in Fig. 6. No significant correlation was found. The correlation coefficient found for the residual difference field data (0.89) was similar to that obtained (0.92) for the raw difference data alone. Testing fits of more complex variations to the data without any supporting evidence of the reality of these variations does not seem justified at this point.

Attempts have also been made by PRESCOTT *et al.* (1982) using twelve months of bi-weekly sampled geodolite data to identify weather-related effects in geodetic strain data. While some discussion exists on this point (CHENG *et al.*, 1981) no clear evidence of weather effects have been identified. So, while the hypothesis that some meteorologically generated crustal noise contaminated all of the data and produced the effects reported here cannot be dismissed, it also cannot be readily supported.

The alternative hypothesis that these variations reflect strain episodes in the crust is now considered. JACHENS *et al.*, (1983) have already pointed out that, while the scaling relations between gravity, elevation, and areal strain are in general qualitative agreement with that expected from simple compression of a thick elastic plate, better agreement is obtained with a simple fault model such as proposed by SAVAGE *et al.*, (1981a). What remains is to investigate whether the magnetic changes are consistent

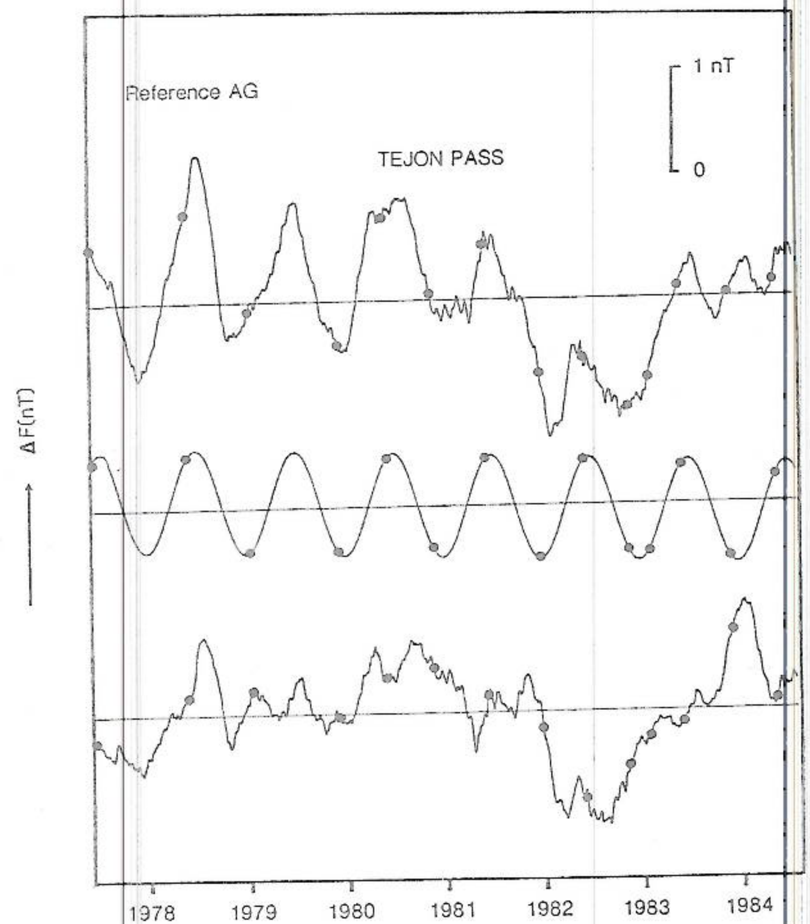

Fig. 5. Time-history plot of the Tejon Pass magnetic data (upper plot) together with the best-fitting sine wave with an annual period and linear fit derived from these data (middle plot). The lower plot shows the residual after the annual and linear terms have been subtracted from the raw magnetic data. On each time-history are the three-day means of the magnetic data (dots) that overlap the times of the gravity survey measurements.

with expectations from tectonomagnetic models and other tectonomagnetic observations.

Apparent tectonomagnetic effects have been obtained as a result of dam loading (DAVIS and STACEY, 1972), volcanic eruptions (JOHNSTON and STACEY, 1969; DAVIS *et al.*, 1979) and crustal uplift (JOHNSTON *et al.*, 1979; OHSHIMAN *et al.*, 1983). Table 2 shows a summary of these various results, including those from this study. While different mechanisms undoubtedly contribute in different ways for these different situations, the results reported here indicate the highest value of apparent strain sensitivity.

A tectonomagnetic model based on the fault model proposed by SAVAGE *et al.*, (1981a) has been developed for the three areas in southern California. If it is assumed

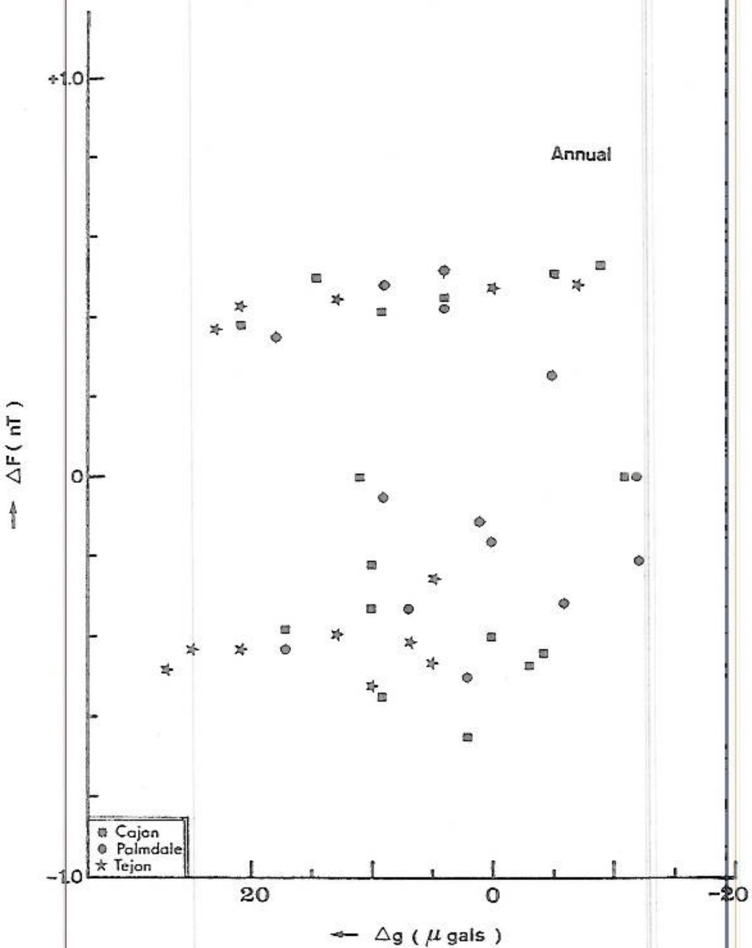

Fig. 6. Plot of field values in an annual magnetic field term during gravity sampling periods against gravity fluctuations from the three study regions.

Table 2. Comparison of tectonomagnetic anomalies, strain anomalies, and apparent strain sensitivities obtained by various tectonomagnetic experiments.

Experiment type	References	ΔF (nT)	Observed field change / Calculated field change
Volcanic eruption	JOHNSTON and STACEY, 1969	~10	~10
Dam loading	DAVIS and STACEY	~1	~5
Uplift	OHSHIMAN *et al.*, 1983	~1/yr	~5
This study		~1	~4–40

that the magnetization, stress sensitivity, and amount of slip are 10 A/m, 10^{-3} MPa^{-1}, and 0.75 m, respectively, then the average magnetic change calculated from this model (JOHNSTON, 1978) in these three areas is 0.24 nT. This a factor four less than that observed but is in general qualitative agreement. However, we note that, while the estimate of magnetization is probably reasonable for the Cajon and some parts of the Palmdale regions, surface samples and inversion of magnetic survey data, imply a lower average magnetization in the Tejon area. If the average magnetization is taken to be 1 A/m, the calculated values are accordingly reduced to 0.024 nT.

Tectonomagnetic calculations therefore appear to underestimate the values observed, although it is not yet clear whether this points to a serious problem with the model because of the uncertainties in the model parameters. The model of HAO *et al.* (1982), in which stress changes related to fault slip are averaged over one third of the total fault length, also underestimates the observed magnetic field changes by at least a factor of ten.

The least constrained parameter in these models is the stress sensitivity of the crustal rocks. If the stress sensitivity is higher than assumed here, it should be possible to identify secular magnetic changes caused by secular stress accumulation in the region. Some secular magnetic field changes are apparent in these data (see data for Cajon Pass in Fig. 2) at about the same level as the anomalies reported here. However, these secular changes are also contaminated by incomplete cancellation of secular variation in the magnetic field. After making the best correction for secular change and other external disturbances with Wiener filtering techniques (DAVIS and JOHNSTON, 1983; JOHNSTON *et al.*, 1985), the averaged data from all three regions do not show any increased field with time (JOHNSTON *et al.*, 1985). This is consistent with the longer term average dilational strain found for the region by SAVAGE and GU (1985).

4. Conclusions

Significant correlation has been observed between magnetic field, gravity, strain and elevation episodes during the past four years along the San Andreas fault in southern California. A common source of meteorological contamination in the strain, gravity, and leveling data with a coincident contamination of the magnetic data seems unlikely, but cannot be ruled out. Attempts to relate frequently sampled (PRESCOTT *et al.*, 1982), infrequently sampled geodetic data (SAVAGE and GU, 1985), and continuous magnetic field measurements (JOHNSTON *et al.*, 1984) to meteorological parameters have been unsuccessful. Indications of an annual cycle can be found in the magnetic data at about the measurement precision. However, this cycle is out of phase with annual temperature variations and tests of the magnetometers indicate temperature insensitivity. The amplitude of the annual cycle is consistent with that expected from incomplete cancellation of the annual geomagnetic field variation and this is the most likely source of the annual variations in the magnetic data. It is, of course, not likely that this effect would occur in the other data sets but aliasing of annual rainfall, temperature, and pressure into the strain, gravity and elevation data can not be excluded.

JACHENS *et al.*, (1983) have pointed out that the gravity, strain and elevation data are in qualitative agreement with simple physical models of deformation. Simple tectonomagnetic models based on the same fault geometry require a higher stress sensitivity for crustal rocks in this region to obtain agreement between observations and calculations than that expected from both theoretical models based on stress effects on single domain assemblages of magnetic grains and laboratory observations of stress effects on rocks with single domain grains. This higher value of stress sensitivity implies that secular strain accumulation should be reflected in the magnetic data. During this period, however, SAVAGE and GU (1985) show that there was no net secular dilational strain change in the region. When the magnetic data is corrected for geomagnetic secular variation and other externally generated disturbances using Wiener filtering techniques (as shown in Fig. 7 of JOHNSTON *et al.*, 1985) there is no net change in magnetic field in the region that could be ascribed to crustal sources during the seven year period from 1977 to 1984.

The weight of evidence seems therefore, to support the occurrence of large-scale episodes of crustal deformation in southern California that are independently reflected in a coherent manner in the different data sets. An alternate explanation of coincidental recordings of simultaneous but not clearly related crustal or instrumental noise is possible but is difficult to justify. The scaling relations developed from these correlations may thus provide an important in-situ calibration and cross-comparison of the various measurement methods.

R. C. Jachens, J. C. Savage, and R. S. Stein provided data used in this study.

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