Tectonomagnetism and Intermediate-Term Stress Monitoring

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Two extensive arrays of proton precession magnetometers deployed in different tectonic settings have been investigated for the significance of piezomagnetic stress monitoring in earthquake studies. The first of these has operated since 1973 in California, involving up to 34 continuously monitored sites. The second operated in a region of very high seismicity in the southern Pacific ocean since 1980 and comprised 25 sites. The arrays have provided considerable insight into the capabilities and limitations of piezomagnetic monitoring which on well documented physical principles and extensive laboratory studies was expected to provide a reasonable basis for large scale intermediate term stress monitoring.

It is now clear that these experiments have provided continuous high resolution data at the sensitivities originally proposed, that co-seismic signals have been observed and that regional strain anomalies of tectonic causes can be effectively mapped using piezomagnetic anomalies. However, few examples of intermediate or short term precursors to earthquakes have been obtained. The primary reasons for this appear to derive from accumulating evidence that the ambient shear stress near active faults and the mean deviatoric stress release prior to and during earthquakes is lower than than had been assumed when the studies were initiated and that the observational limits of magnetometers separated by about 10 km, after application of a variety of noise reduction techniques, appear to be no better than about 0.2 nT. Lower estimates of the average change in deviatoric stress associated with earthquake rupture correspondingly reduce the fields calculated from tectonomagnetic models.

Some unexpected and exciting results have been obtained which indicate many potentially useful aspects of magnetic field changes near active faults are still not completely understood. The more important of these results are: 1) the observation of correlated magnetic, strain, uplift, and gravity changes during the latter stages of a remarkable deformation episode near the San Andreas fault in southern California, 2) indications of anomalous change in magnetic fields along the San Andreas fault to the southeast of Palm Springs, 3) the first observations of coseismic seismomagnetic effects on two independent magnetometers during the July 8, 1986, M_L 5.9 North Palm Springs earthquake.

BACKGROUND

Tectonomagnetism - the study of magnetic fields that result from earthquake or volcano related crustal deformation - has long shown promise as a simple and inexpensive method for monitoring deviatoric crustal stress and perhaps providing a tool for predicting crustal failure (*Wilson*, 1922; *Kalashnikov*, 1954; *Stacey*, 1964; *Stacey et al.*, 1965), but few unambiguous results have been obtained. Subfields of tectonomagnetism are volcanomagnetism and seismomagnetism which describe the magnetic field perturbations related to the actual volcanic eruption process and the earthquake rupture process, respectively.

The stress dependence of rock magnetization has been demonstrated under laboratory conditions (*Kalashnikov and Kapitsa*, 1952; *Katipsa*, 1955; *Ohnaka and Kinoshita*, 1968; *Kean et al.*, 1976; *Revol et al.*, 1977; *Martin*, 1980; *Pike et al.*, 1981) and theoretical models have been developed in terms of single domain and pseudo-single domain rotation (*Kern*, 1961; *Stacey*, 1962; *Nagata*, 1969; *Stacey and Johnston*, 1972) and multi-domain wall translation (*Kern*, 1961; *Kean et al.*, 1976; *Revol et al.*, 1977).

The stress sensitivity of induced and remanent magnetization from theoretical and experimental studies have been combined with stress estimates from dislocation theory of fault rupture and elastic pressure loading in active volcanoes to calculate field changes expected to accompany earthquakes and volcanoes (*Stacey*, 1964; *Stacey et al.*, 1965; *Johnston*, 1978; *Davis et al.*, 1979; *Sasai*, 1980; *Hao et al.*, 1982; *Davis et al.*, 1984). These models show that moderate scale magnetic anomalies of a few nanoTeslas (nT) should be expected to accompany earthquakes and volcanic eruptions for rock magnetizations and stress sensitivities of 1 Ampere/meter (A/m) and 10^{-4} bar^{-1}, respectively. Unambiguous observation of local magnetic signals of this amplitude require dedicated efforts to understand and reduce noise in magnetic field measurements. An intrinsic appeal of the technique is that piezomagnetic anomalies are stress induced, and hence in principle allow monitoring networks to isolate stress accumulations from simple strain changes accompanying creep processes in the earth.

TECTONOMAGNETISM

a) Crustal Deformation

A very notable result for intermediate term monitoring studies obtained during the past four years has been the identification of temporal magnetic fields that correspond to local gravity, strain, and uplift changes during part of a remarkable episode of crustal deformation in southern California. This deformational episode, known generally as the "Palmdale Uplift", was first identified in leveling data (*Castle et al.*, 1976). During the period between 1974 and 1976 changes in the uplift in the region between Cajon Pass and Palmdale occurred at the same time as offsets in local magnetic field (*Johnston et al.*, 1979). Aseismic strain changes were also identified in geodetic data taken near the San Andreas fault between 1979 and 1982 (*Savage et al.*, 1981a, 1981b; *Savage and Gu*, 1985) and, in an attempt to intergrate these and other data, *Jachens et al.*, (1983) reported that, during the 1979 to 1982 period, changes in level lines, changes in strain, and changes in gravity, all occurred in a correlated manner.

When continuous measurements of magnetic field in each of the regions investigated by Jachens were sampled at the same time as the gravity strain, and level data, and then tested for correlation, the results showed correlation significant at the 95% level or better (*Johnston*, 1986). Figure 1 shows the regression plot between gravity data and magnetic data from the Tejon, Palmdale and Cajon regions. When the data are plotted all together in this way (i.e. with no allowance for different response in different regions) the correlation coefficient is 0.93 and is significant at the 1% level. Figure 2 is a composite plot showing superimposed time-histories of magnetic field (stars), gravity (dots), areal strain (triangles), and elevation (squares) data, together with their error bars, from the three regions in southern California.

Least-square fits between the magnetic data and each of the various parameters give transfer functions of the form;

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

where ΔF is in nanoTeslas and Δg is in microGals,

$$\Delta F = -0.98 \Delta strain \qquad (2)$$

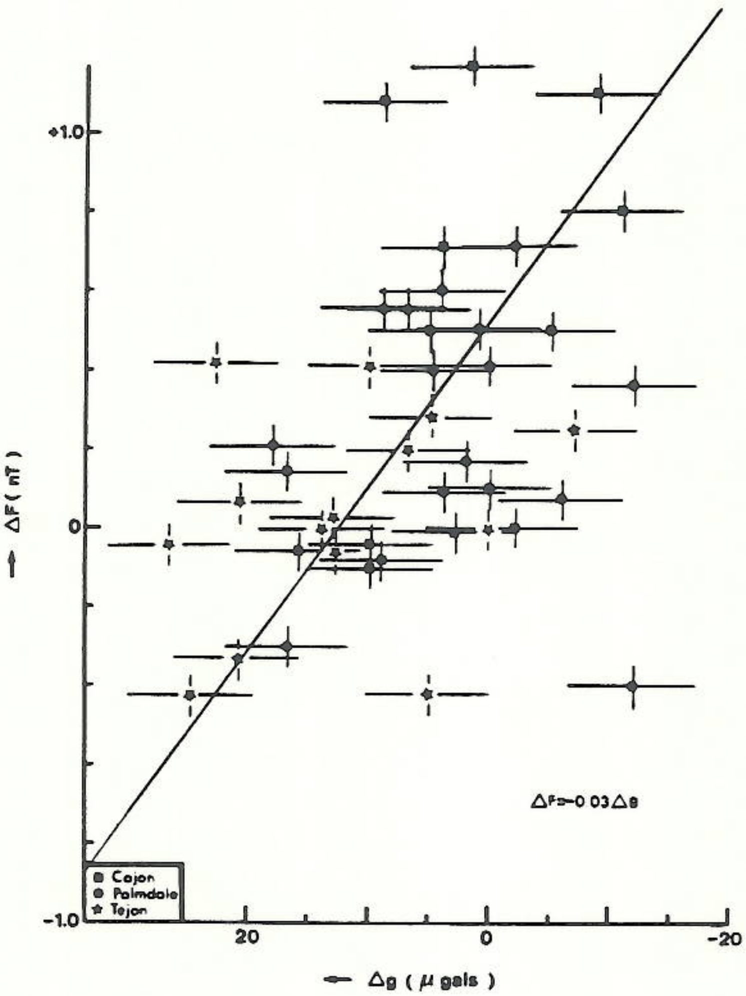

Fig. 1. Plot of magnetic field against gravity fluctuations from the Tejon, Palmdale, and Cajon regions in southern California. Shown also is the least-squares fit to the data (from *Johnston et al.*, 1986).

where $\Delta strain$ is areal strain in ppm (compression negative), and

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

where Δh is in meters.

Two possible explanations for these relationships exist. Either a short term deformational episode has been independently recorded in each data set or all data sets have been contaminated by a common source of meteorologically generated crustal or instrumental noise. Because the inferred relationships between these parameters is in approximate agreement with those expected from simple deformational models (*Jachens et al.*, 1983) and tectonomagnetic models (*Johnston*, 1986), and since no relation was found between the continuous magnetic field data and either rainfall, pressure, or temperature, the deformational explanation is preferred (*Johnston*, 1986). Correspondence between leveling data and magnetic field changes have been also observed in Japan associated with an episode of uplift on the Izu Peninsula (*Ohshiman et al.*, 1983; *Honkura and Taira*, 1983).

b) The Hollister 1974 Earthquake

For the two data arrays, the only possible precursor identified related to the Hollister, November 28, magnitude 5.2 earthquake of 1974. A systematic increase in magnetic field of 0.9 nTesla occurred at a magnetometer site 11 km from the epicentre during the early part of 1974. A more dramatic increase on 1.5 nTeslas occurred about seven weeks before the earthquake and lasted for about two weeks. Four weeks prior to the earthquake, the magnetic field returned to approximately its initial value, and remained at this value through to April 1975. These data cannot be explained by ionospheric disturbances or telluric currents. The anomaly was demonstrated to be present at a much reduced level at another site 15 km from the epicentre (Davis *et al.*, 1980). The most probable cause for the anomaly is the piezomagnetic effect, but since it is not possible to easily relate the time history of the anomaly to known fault motions in this time interval, the anomaly's only value is as a precursor to this particular event. The stress sensitivity of the technique is supported by the event, but implications regarding stress redistribution with time and fault interactions are poorly understood.

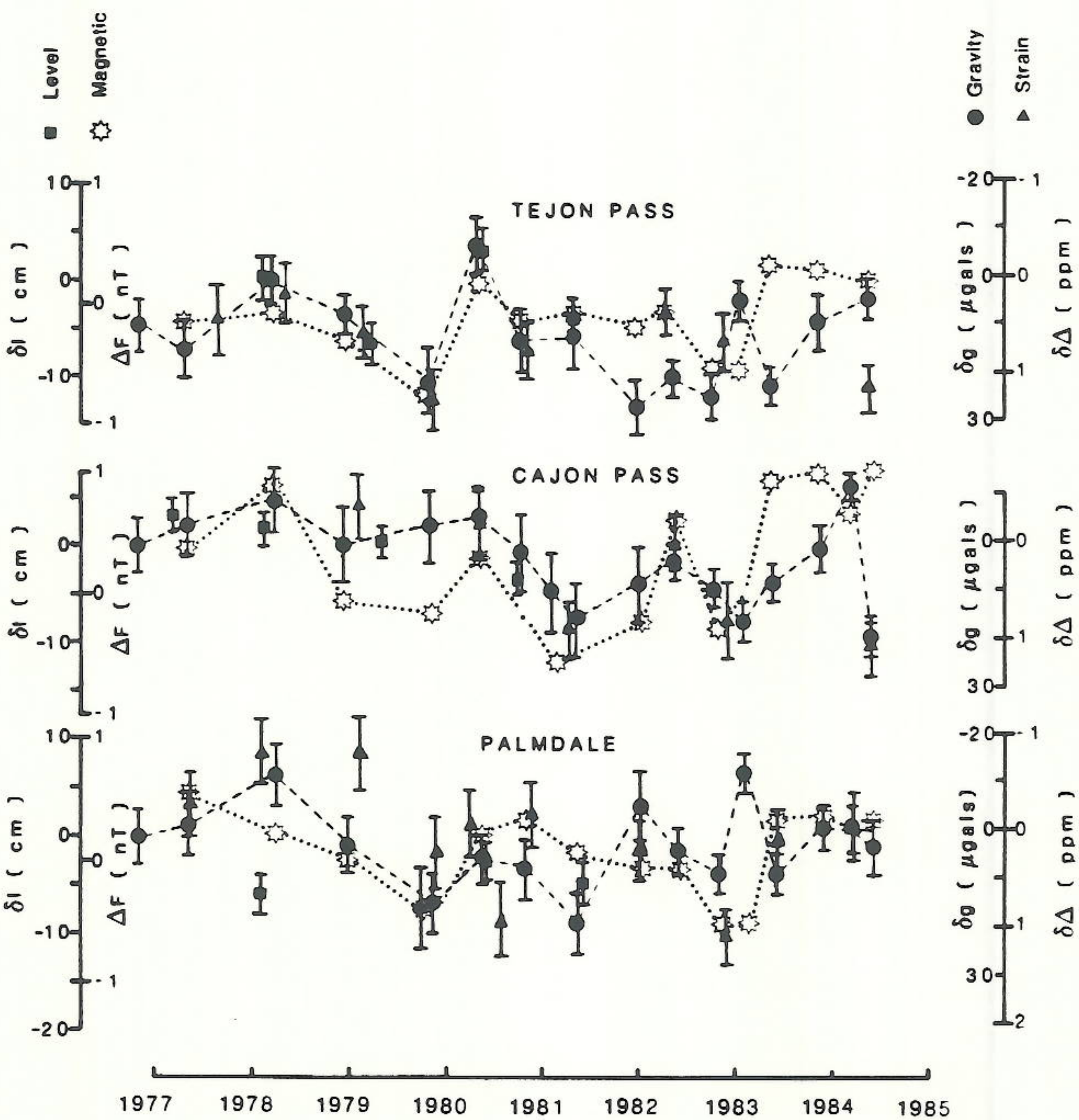

Fig. 2. Superimposed time-histories of magnetic field (stars), gravity (dots), areal strain (triangles), and elevation (squares) data, together with their error bars, from Tejon, Palmdale, and Cajon. Shown also is the least-square linear fit to the data (from *Johnston*, 1986).

c) South Pacific Array

Two major earthquakes occurred within 50 km of at least two monitoring sites. Neither event produced co-seismic offsets at any station at the 0.5 nTesla level, though anomalies could reasonably have been expected from both events. In the twelve months prior to the two earthquakes, however, all stations within 200 km of the epicentres had experienced anomalies which were well above the noise, and could be interpreted as a slow propagation stress episode moving north to south across the array. The offsets did not coincide with significant ionospheric disturbances, and all sites showed maximum calibration errors of less than 0.5 nTesla at subsequent maintenance visits. These offsets are probably of piezomagnetic origin, but again bear no simple relationship to present understandings of fault dynamics and interactions.

d) Instrument Development and Measurement Precision

Determination of the precision of local magnetic field measurements with arrays of magnetometers as a function of instrument, spatial scale, sampling frequency, and site location has attracted continued attention since 1982. Simple differences from 5 km to 10 km station separations are quite effective at reducing disturbance fields from external geomagnetic field variations common to all sites. However, the ability to resolve temporal magnetic fields of crustal origin becomes progressively worse with increasing site separation, increasing time duration, and with differences in magnetization between sites. The decreased resolution with increasing site separation measured on the 27 recording magnetometers installed along 800 km of the San Andreas fault has the form;

$$\sigma(nT) = 0.01(\pm 0.003)D\,(km) + 0.07(\pm 0.08) \tag{4}$$

over the spatial scale of most interest for tectonic processes of 0 to 50 km. σ is the standard deviation of hour averages of magnetic field differences (*Johnston et al.*, 1984). This linear increase in

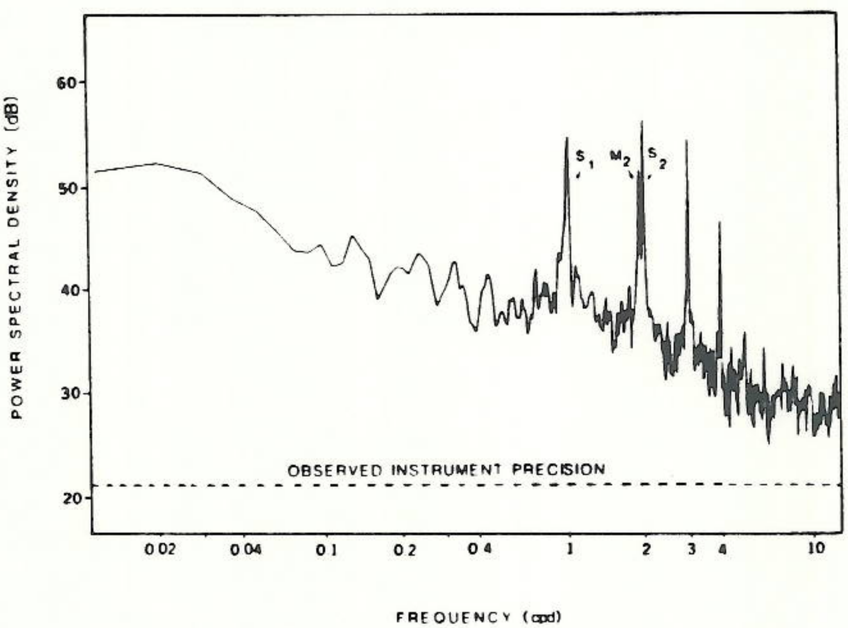

Fig. 3. Geomagnetic difference-field noise spectra obtained from multiple magnetometer pairs with site separations between 10 and 15 km. Shown also is the observed instrument precision limit obtained from magnetometers with a o.25 nT sensitivity (from *Johnston et al.*, 1984). Piezomagnetic monitoring is not limited by instrument precision.

standard deviation with station separation was not observed in the south Pacific array, where the noise limitation expressed in equivalent form was

$$\sigma(nT)=0.0004(+-0.0007)D\,(km)+0.34(\pm0.12). \qquad (5)$$

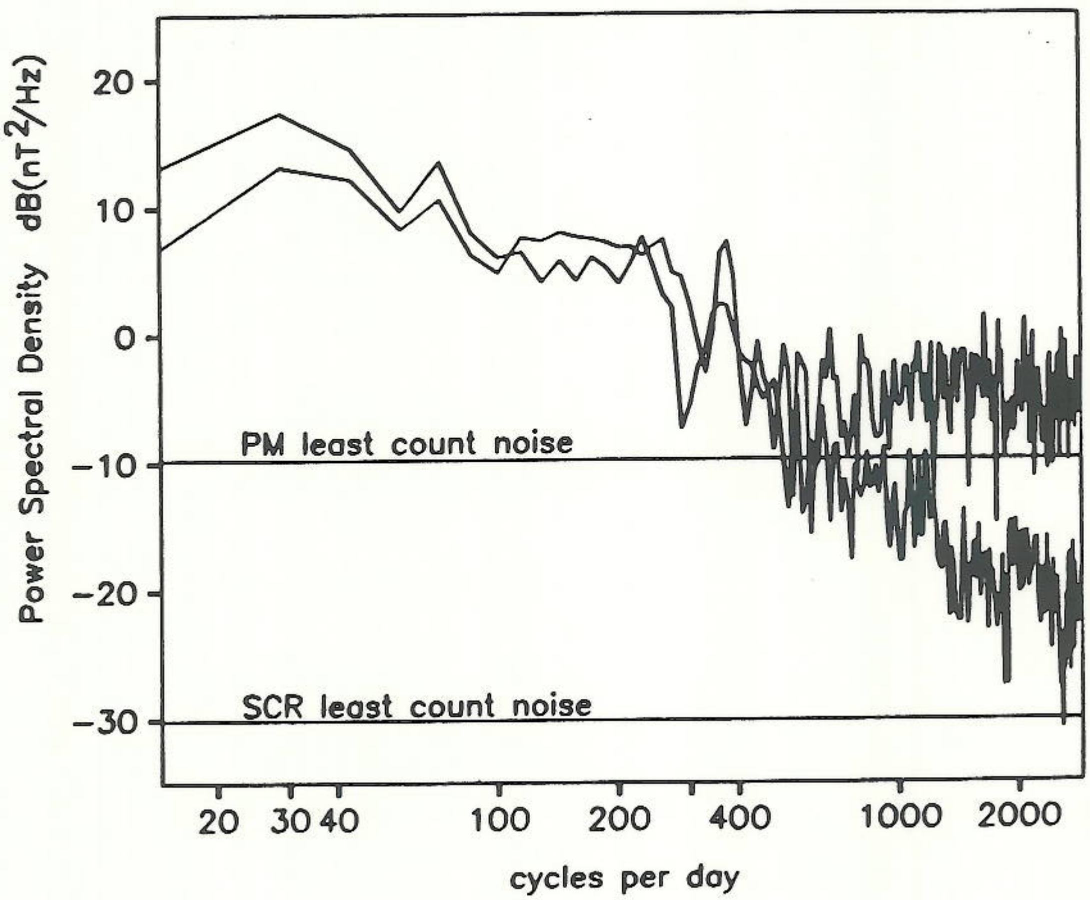

Fig. 4. Comparative power spectral density of simultaneous differences from proton magnetometers with a 0.12 nT sensitivity and self-calibrating rubidium magnetometers with a 0.014 nT sensitivity. Both sets of magnetometers were installed in a tectonically active region near the San Andreas fault with a site separation of 13 km (from *Ware et al.*, 1985).

Power spectra obtained in California from pairs of typical magnetometers with site separations between 8 and 15 km show noise power decreases with increasing frequency by about 8 dB per decade of frequency, as shown in Figure 3. It is only at high frequencies (more than 10 cpd in this case) that the noise power approaches the least count noise limit of the magnetometers (0.25 nT). At lower frequencies these spectra have dominant noise peaks that result from diurnal variations and tidal effects from ocean tide induction (*Johnston et al.*, 1983).

A comparison of proton and self-calibrating rubidium magnetometers with 0.01 nT sensitivity and proton magnetometers with 0.12 nT sensitivity over a range of baselines in seismically inactive and seismically active regions has been made to determine whether and under what conditions improved sensitivity might be useful in tectonomagnetic measurements (*Ware et al.*, 1985). The most relevant experiment using a 13 km baseline in a seismically active and geologically complex region of the San Andreas fault showed that external noise which decreases at about 10 dB per decade of frequency, dominates the observations at periods longer than about 10 minutes and both systems make equivalent measurements. This is shown in the comparative plots of power spectral density in Figure 4. For periods less than 3.5 minutes (420 cycles/day), the proton magnetometers become limited by least-count noise (0.12 nT) and the improved sensitivity of the rubidium magnetometer becomes apparent. If noise power continues to decrease with frequency magnetic field measurements at about the 0.001 nT level should be possible at frequencies greater than 1 Hz. This raises the intriguing possibility that magnetic variation corresponding to the propagation of dynamic seismic waves might be detectable on ultrasensitive magnetometers.

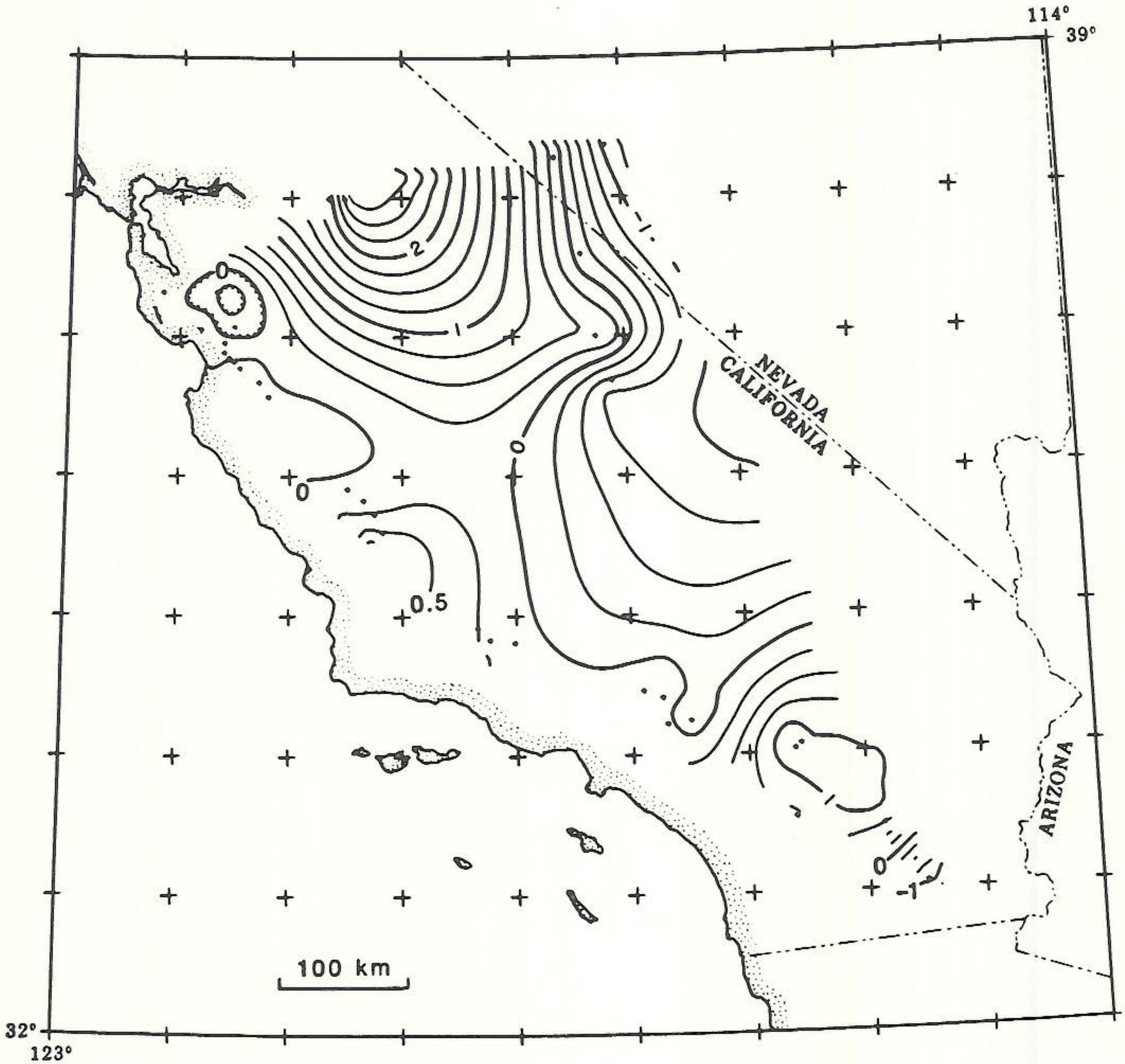

Fig. 5. Residual total secular magnetic field changes along the San Andreas fault in central and southern California not apparently related to sources in the core or the ionosphere/magnetosphere (from *Johnston et al.*, 1985). This figure (prepared December,1984) shows a clear anomaly in the vicinity of the Palm Springs July 8 Palm Springs Earthquake, and regionally identifies the Coyote Lake, Morgan Hill, Quiensabe and Mt. Lewis earthquakes.

With regard to the detection threshold for tectonomagentic effects, the most important development concerned the realization that most of the noise (long period and short period) can be removed if corrections are made for local site response to external field variations. Since different sites will respond differently because disturbance fields are in different directions and since disturbance fields in the same direction may generate different responses at different sites because the site magnetization vectors are different, these response effects limit the detection threshold. These effects can be identified and removed by defining multichannel Wiener filters which predict the total magnetic field at a site from component magnetic data during periods of disturbed geomagnetic field (*Davis et al*, 1979; *Davis et al*, 1980; *Davis et al.*, 1981; *Davis and Johnston*, 1983). This technique reduced the noise in hour averages from 0.7 nT to 0.3 nT for baselines from 8 km to 100 km (*Davis and Johnston*, 1983).

c) Short Wavelength Secular Variation

Further application of this technique was made to correct for site response and identify the secular variation in data from the array of 34 total field magnetometers throughout central and southern California during the period 1976 to 1984 (*Johnston et al.*, 1985). The secular variation obtained has the form;

$$\dot{F} = k_1 * \theta + k_2 * \phi + K \tag{6}$$

where $\dot{F}$ is in nT/a, θ and ϕ are the geographic latitude and longitude, and k_1, k_2 and K are 1.50±0.08 nT/a.degree, -0.23±0.06 nT/a.degree, and -129.2±0.1 nT/a, respectively.

Surprisingly, the observed secular variation obtained did not agree with that predicted from global secular variation models. The secular variation was removed from the data to attempt to identify crustal fields of tectonic origin. The residual fields obtained are shown in Figure 5 first prepared in September, 1984, and are most apparent on the San Andreas fault in southern California where subsequently a M_L 5.9 occurred (see below). This regional stress anomaly mapping provides a new dimension in intermediate term prediction studies by identification of areas of stress accumulation. The technique is insensitive to strain, and could be performed on a routine basis to identify changes to the large scale stress regime in a regional sense. The areas identified in figure 5 account for most of the major events in the San Andreas system since 1984.

SEISMOMAGNETISM

a) North Palm Springs Earthquake

A most important result in the field of seismomagnetism was the first recording of co-seismic seismomagnetic effects during the July 8, 1986, North Palm Springs earthquake. This earthquake had a moment of $2*10^{25}$ dyne-cm and a magnitude of 5.9. Two total field proton magnetometers were installed at distances of 3 km and 8 km from the subsequent earthquake and had been sampling once every 10 minutes since early 1979. The data are transmitted with digital telemetry to Menlo Park, California (*Mueller et al*, 1981).

The local magnetic field at the magnetometer closest to the earthquake decreased by 1.2 nT while that at the second, eight kilometers from the epicenter, increased by 0.33 nT. Both instruments were on the same side of the fault. Figure 6 shows the records from the two sites OCHM and LSBM referenced to another site in the area CHUM during the period June 1 to July 12, 1986, and also the difference between the two local sites OCHM and LSBM.

A tectonomagnetic model of the earthquake has been constructed using seismically determined parameters for the rupture length, width, and the depth. To satisfy the moment a slip of 20 cm was assumed and the magnetization in the region was estimated from surface samples and regional magnetic anomalies to be 2 A/m. Within the uncertainties this model predicts the changes observed (*Johnston and Mueller*, 1986). The observation confirms the stress sensitivity of the tectoniomagnetic effect in large scale phenomena, at the sensitivity expected from theory and laboratory values.

TECTONOMAGNETIC MODELS

No new work has been reported on tectonomagnetic models but results from related fields may have a serious impact on interpretation of these calculations. New work of the state of stress in seismically active areas (*McGarr et al.*, 1982) and observations of measured stress drops for earthquakes (*Hanks*, 1980) suggests the average deviatoric stress change during earthquakes may be about 10 or 20 bars rather than 100 bars as had been previously assumed (*Stacey*, 1964; *Sasai*, 1980; *Hao et al.*, 1982). If stress changes are at this level, then the fields expected from them as a consequence of the piezomagnetic properties of rocks are correspondingly reduced. This, plus the fact that the present tectonomagnetic models already underestimate observations of tectonomagnetic effects generated by dam loading (*Davis and Stacey*, 1972) and uplift (*Ohshiman et al.*, 1983; *Johnston*, 1986) by at least a factor of five, indicates possible inadequacies in the current theory and modeling techniques.

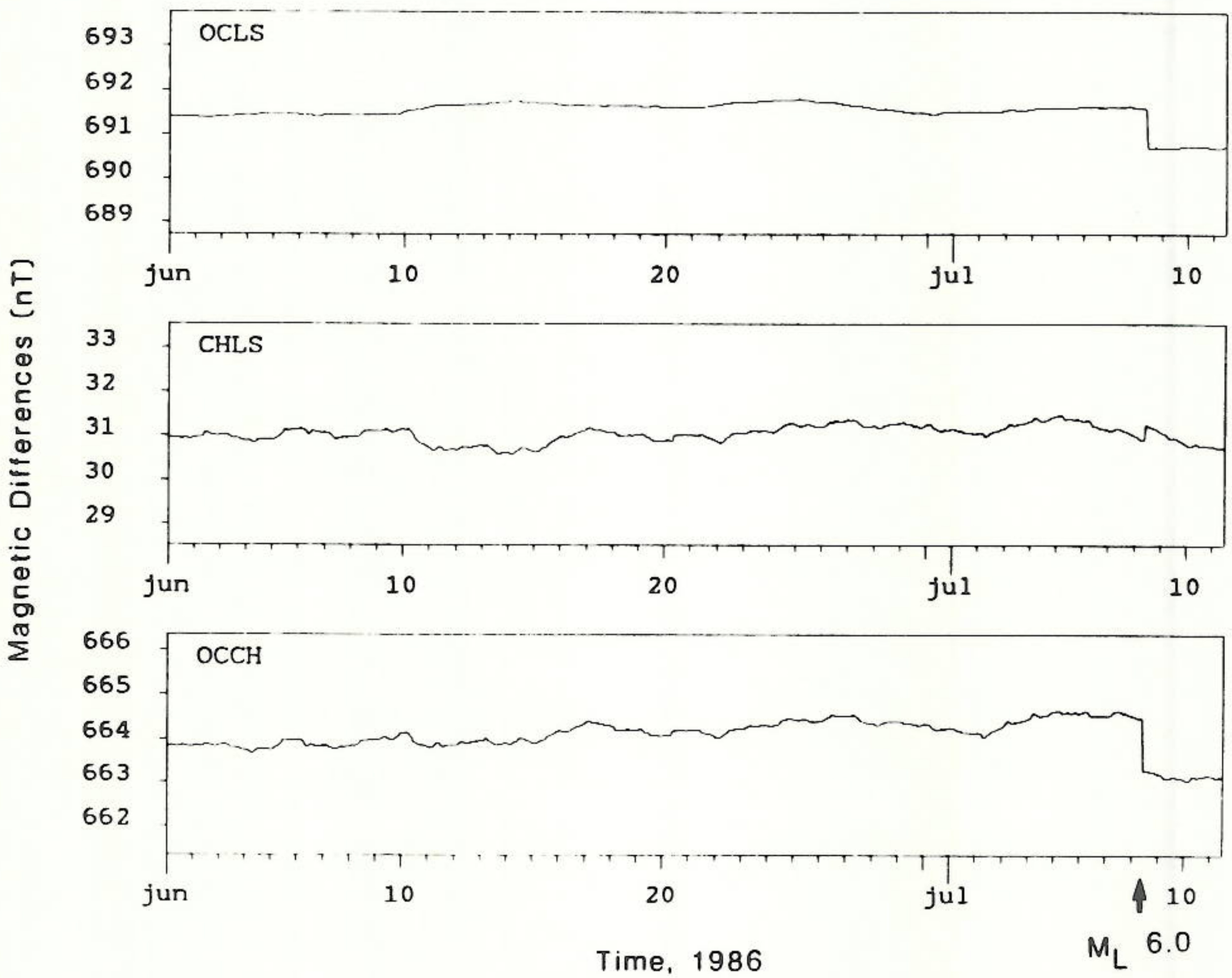

Fig. 6. Magnetic field at sites LSBM and OCHM with respect to a common site CHUM (OCCH - bottom, and CHLS - middle) as a function of time from June 1 to July, 12, 1986, and also the difference between the two local sites (OCLS, top). The M_L 5.9 North Palm Springs earthquake (occurrence time shown with arrow) occurred on July 8, 1986, at an epicentral distance of 3 km from OCHM and 8 km from LSBM (from *Johnston and Mueller*, 1986).

Conclusions

Extensive array studies using proton precession magnetometers have shown that though the physical basis of piezomagnetic stress monitoring has been verified in field experiments, the value of the technique to intermediate earthquake prediction studies is limited for small stress changes by extraneous electromagnetic noise sources. Recent studies on estimates of the stress drop in earthquakes have lowered reasonable expectations on the stress accumulation which may be expected in months to weeks before an earthquake. Piezomagnetic monitoring remains the only stress monitoring technique which has been successfully implemented and has demonstrated considerable potential in identification of regional stress anomalies associated with earthquake genesis. Our decision to close operation of the arrays is based on the limited resources available to the subject and on an emerging appreciation of the efficacy of continuous borehole strain array studies for improved insight into the earthquake process. Piezomagnetic monitoring in volcanic studies where it has demonstrated success in distinguishing strain cycles which are accompanied by stress accumulation from those which are not should be continued.

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