VOL. 84, NO. B11 JOURNAL OF GEOPHYSICAL RESEARCH OCTOBER 10, 1979

Tectonomagnetic Anomaly During the Southern California Downwarp

M. J. S. JOHNSTON

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

F. J. WILLIAMS, J. MCWHIRTER, AND B. E. WILLIAMS

Geology Department, San Bernardino Valley College, San Bernardino, California 92403

Resurveys of the local geomagnetic field in southern California, using magnetometers in a differential mode, indicate the development of an anomalous field of more than 10 γ that appears to correspond to the partial collapse of the southern California uplift. The 10-γ field increase occurred within a 30-km fault segment near the junction of the San Andreas and San Jacinto faults. It took place episodically in time, 80% accumulated between late 1973 and the end of 1974 and the remaining 20% between 1974 and 1976. Changes of smaller maximum amplitude and opposite sense occurred to the southeast along the San Jacinto fault. Swarm seismicity started at the northwest end of the zone of maximum anomaly in late 1976 but ceased in late 1977. The anomaly amplitude has slowly decreased with time since its peak in 1976. Tectonomagnetic models imply localized stress changes at depth of at least 10 bars in the vicinity of the magnetometer sites near the various faults, although details concerning the geometry and dimensions of the region responsible for the magnetic field changes are poorly resolved.

INTRODUCTION

Magnetic field perturbations should be expected to accompany crustal stress changes along active faults where rock magnetizations exceed 10^{-4} emu and where stress variations from 1 to 100 bars occur. These expectations derive from both laboratory experiments [*Wilson*, 1922; *Kapitsa*, 1955; *Ohnaka and Kinoshita*, 1968; *Kean et al.*, 1976; *Martin and Wyss*, 1975; *Revol et al.*, 1978] and theoretical calculations [*Nagata*, 1970; *Stacey and Johnston*, 1972].

Continuously recording proton magnetometers have been installed at more than 20 locations within the San Andreas fault system, and encouraging preliminary results have been obtained [*Smith and Johnston*, 1976; *Johnston et al.*, 1976]. However, in order to obtain coverage over more of the thousands of kilometers of major faults in California, a resurveying technique has also been used [*Johnston et al.*, 1976]. This technique involves recording data simultaneously at adjacent sites, 10–15 km apart, once or twice a year. During these visits, about 76 synchronized data are recorded on proton magnetometers with a 0.25-γ sensitivity between each pair of sites.

The most significant changes detected anywhere in California since 1973 have occurred along the San Andreas and San Jacinto faults in southern California. The array on which these data were measured was originally installed in 1973 and has subsequently turned out to be fortuitously located with respect to the large-scale crustal uplift in southern California and its partial collapse recently discovered in geodetic leveling lines by *Castle et al.* [1976, 1977].

The main features of the crustal elevation data appear quite clear, even though in some locations, details of the space-time history are complicated by lack of data at critical times [*Castle et al.*, 1977]. These features are the following: (1) a first stage of uplift during 1959 and the early 1960's of as much as 20 cm, which apparently was initially localized near the Garlock/San Andreas fault intersection but subsequently spread rapidly eastward, (2) a second stage of uplift during about 1973 that extended the area uplifted by more than 30 cm to over about 80,000 km^2, the point of maximum uplift by now being about 100 km north of the Salton Sea, and (3) a partial collapse or downwarp between 1974 and 1976 of the central and northern part of the uplift. It is only for this last episode that regional magnetic data are available, and it is these observations that we report on here.

OBSERVATIONS

The sites for the original array in southern California are shown as triangles numbered 1–12 in Figure 1. Triangles without numbers have been installed since 1973. The general 30-cm uplift contour at the end of 1974 from *Castle* [1978] is shown as a shaded line. This contour probably enclosed only a very localized region near Palmdale in the early 1970's.

Also plotted are earthquakes in southern California ($M > 3$) during the period July 1974 through September 1976 from *Fuis et al.* [1977] and, anticipating the results discussed below, the general location and maximum significant changes in local magnetic field that have occurred since 1973. (These changes in gammas are shown within open circles referenced to the site at which they were observed. They are all calculated with respect to San Bernardino (site 5).)

Before a set of measurements is taken, the sensors are relocated to less than a centimeter at each pair of adjacent instrument sites. The sites were initially chosen such that the local horizontal and vertical field gradients were less than 0.2 γ/cm, and for many sites these gradients are less than 0.05 γ/cm. The sites are also routinely checked for indications of possible cultural contamination (tin cans, site disturbance, etc.).

At each pair of adjacent sites the simultaneous data are then recorded over a 10-min period. Differences between the data for these site separations reduce effects of large-scale ionospheric and magnetospheric disturbances to less than a gamma during period of low geomagnetic activity and to a gamma or so during active times [*Johnston et al.*, 1976]. The measurement precision for long-term local magnetic field changes with this sampling period is less than 2 γ. The reproducibility of data taken for 6 years along 70 km of a seismically quiet section of the Owens Valley with this technique and for shorter periods in other seismically quiet areas indicates this to be a conservative estimate of the standard deviation [*Johnston et al.*, 1976]. In contrast, the standard deviations of individual

Paper number 9B0524.
0148-0227/79/009B-0524$01.00

sets of data are typically less than 0.75 γ. Various loops that contain up to 26 sites over a 240-km distance have been repeatedly closed in both northern and southern California. The best closure for these large loops is 0.5 γ. More typical closure errors are from 1 to 3 γ depending on the level of geomagnetic activity. Repeated measurements 1 week apart at pairs of sites agree to within 0.75 γ. These repeat measurements have, however, only been made a few times.

The data recorded at each site with respect to site 5 (in the middle of the array) for each of the different observational periods, are listed in Table 1. Site 5 was chosen as a reference, since the magnetic field data from this site apparently have not changed by any significant amount with respect to other array data in 5 years. The data in Table 1 indicate that substantial systematic changes have occurred with time at some sites.

In order to identify and compare the relative changes at different locations, each data set has also been arbitrarily referenced in time to run 1. Since no data were obtained at sites 11 and 12 during run 1, changes with time at these two sites are with respect to their values for run 2 in September 1973.

Local magnetic changes that have occurred subsequent to run 1 in July 1973 for sites 1–10 and subsequent to September 1973 for sites 11 and 12 are shown as a function of site location along the San Andreas and San Jacinto faults in Figure 2. Time history plots at each site can easily be derived from the figure.

The most significant features of these data are the following:

1. There is an increase in local magnetic field at sites 1 and 2 to the northeast of San Bernardino of up to 10 γ (site 2) that started during 1974 and reached a peak amplitude in May 1976. It is during this period that the cumulative uplift in southern California identified by *Castle et al.* [1976] was reduced by about 50% by a partial collapse or downwarp [*Castle et al.*, 1977].

2. There is a decrease during the same period of 5–6 γ primarily at sites 6–9 to the southeast of San Bernardino.

The data also indicate that subsequent to the peak field changes recorded in May 1976 the amplitudes of these changes to the north of San Bernardino have reversed trends and have decreased by about 4 γ in 2 years. This decreasing trend is only marginally significant. Data from recording differential magnetometers recently installed 4 km south of site 2 and a few kilometers north of site 4 indicate, however, that this trend is real. Since mid-1977, daily means of difference measurements taken every minute between these sites and a remote reference site show that the field at both has decreased linearly by at least a gamma. The standard deviation of the continuously recorded data is less than 0.5 γ. We note that from late 1976 to late 1977, increased swarmlike seismicity has been observed [*McNally et al.*, 1978] in the region around site 1.

There are few other data that might help in interpreting these magnetic measurements. The level survey lines which cross the fault near site 1 and site 4 were remeasured in 1968/1969, 1971, and 1973/1974 for the lines Cajon to Hesperia, Azusa to Llano, and San Bernardino to Cajon, respectively [*Castle et al.*, 1976]. The recently completed releveling of southern California will allow 1974–1978 comparisons in some locations and on shorter segments 1974, 1976, and 1978 comparisons.

Savage and Prescott [1979] have reported geodimeter measurements from nets to the northwest of site 1 (Palmdale net) and around site 4 (Cajon net). These data place important constraints at geodetic scales on physical mechanisms re-

TABLE 1. Summary of Observed Changes in Local Magnetic Field as a Function of Site for Each Data Set (Run)

	Site Number														
	15	14	13	1	2	3	4	5	6	7	8	9	10	11	12
Run 1 (July 1973)	...	...	...	+101.8	+478.9	+224.3	−216.6	0	−102.3	−207.5	−203.4	−281.8	−331.3	...	...
Run 2 (Sept. 1973)	...	...	...	+102.6	+477.7	+227.6	−217.3	0	−98.9	−208.8	−203.5	−284.2	−334.1	−342.5	−377.3
Run 3 (Dec. 1974)	...	...	...	+106.9	+486.9	+228.3	−217.2	0	−102.3	−211.8	−206.3	−285.2	−334.4	−339.9	−388.0
Run 4 (Dec. 1975)	...	...	...	+105.1	+487.0	+226.3	−217.4	0	−105.7	−214.3	−206.4	−285.6	−337.9	−327.8	−376.1
Run 5 (May 1976)	+767.3	+497.1	+346.5	+107.0	+489.4	+227.1	−217.7	0	−107.6	−213.2	−208.6	−287.4	−335.9	−339.9	−380.4
Run 6 (Sept. 1976)	+766.1	+494.4	+342.5	+103.1	+486.1	+224.5	−218.6	0	−107.2	...	...	...	...	...	...
Run 7 (April 1977)	...	...	...	+104.7	+486.3	+225.3	−218.5	0	−108.0	−212.6	−208.2	−287.9	−337.0		
Run 8 (July 1977)	...	...	...	+104.7	+485.6	+226.2	−219.1	0	−108.4	...	...	...	...	...	...
Run 9 (April 1978)	...	...	...	+102.9	+485.3	+225.6	−218.7	0	...	...	...	...	...	...	...
Run 10 (July 1978)	...	...	...	+104.9	+485.6	+225.7	−218.3	0	...	...	...	...	...	...	...

Site 5 in the middle of the array has arbitrarily been held invariant, and each set represents the change with respect to this site since the first data were recorded in June 1973 (run 1).

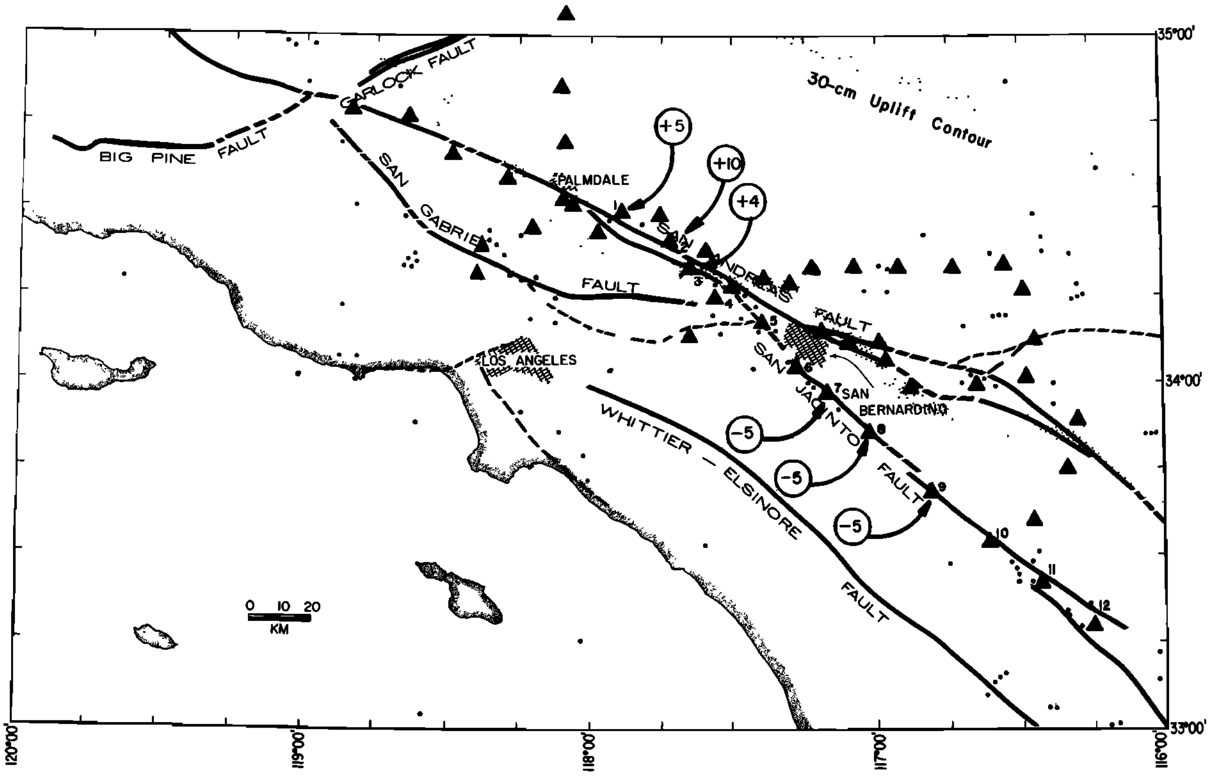

Fig. 1. Map of southern California showing numbered magnetometer survey sites (triangles), earthquakes with $M > 3$ (dots) from *Fuis et al.* [1977], the 1974 position of 30-cm uplift contour (dashed) from *Castle* [1978], and maximum changes in gammas in local magnetic field (circles) observed during the period 1973–1978 with respect to a reference site near San Bernardino.

sponsible for the magnetic data. For the period 1971.6–1977.4 through the last uplift stage and collapse, Savage et al. observe a typical shear strain of 0.2 strain/yr. From late 1973, increased compression has occurred normal to the fault. Compressional strain of about 0.2 strain/yr is evident also in the Cajon data during this period. *Savage et al.* [1978] have subsequently identified a net north-south compression during the period 1973–1977 in almost all the geodetic nets (Salton, Cajon, Palmdale, Tehachapi, Garlock, and Los Padres) along the San Andreas fault system in southern California.

DISCUSSION

The observed magnetic changes can be interpreted in terms of several of the various physical explanations that have been suggested to occur near major fault systems. Alternative explanations might arise from (1) changes in crustal stress that result in corresponding changes in induced and remanent magnetization [*Stacey and Johnston,* 1972], (2) small-scale sources related to changes in electrical induction or secular variation, (3) telluric currents generated by electrokinetic effects (streaming potentials, magnetohydrodynamic effects), a phenomenon suggested by *Mizutani et al.* [1976] to result from fluid redistribution around the fault as proposed for the dilatancy fluid-diffusion failure model [*Nur,* 1972], (4) change in the thermal regime at shallow depths, and (5) largely irreversible mechanisms such as squeezing serpentinite up in the fault zone, destroying or changing magnetization by changing the density of microcracks.

These last two suggestions are probably the least physically plausible. The irreversible mechanisms can probably be disregarded, since first, these effects have not been observed close to the San Andreas fault at times when the faulting is creeping episodically [*Johnston et al.,* 1979] and second, rocks along the fault with magnetic properties have been stress-cycled many times during recent geologic history and should be in a cyclic state.

For changes in the thermal regime to be effective, rapid temperature changes in excess of several hundred degrees Celsius would be required at depths of less than 10 km. While these temperatures may occur in a very localized region from frictional heating due to fault slip, their general occurrence is unlikely and the surface heat flow data [*Lachenbruch and Sass,* 1973] preclude their past occurrence over a wide region in this tectonic environment.

Telluric current from electrokinetic effects appears to be too small to generate observable magnetic changes if plausible potential sources and conductivities (~0.01 Ω/m) are assumed. Temporal changes in potential gradients in this area and other areas along the fault are less than 10 mV/km (T. Madden, personal communication, 1978). No unusual or unexpected changes in well water level have been reported at the time that might indicate unusual fluid pressure gradients. Furthermore, this effect arises by virtue of heterogeneity, since for an *n*-layered half-space the surface magnetic field will be identically zero no matter what the fluid pressure gradient is taken to be [*Fitterman,* 1978]. We are left then with the two remaining possibilities.

The difficulty with an explanation based on induction or secular variation is that these effects should have been observed at other locations in California where continuous magnetic recordings are being made (we note that the skin depth for electrical induction at periods of greater than a day in crustal/mantle material with a conductivity of 0.01 Ω/m is more than 1000 km). Furthermore, similar effects should have

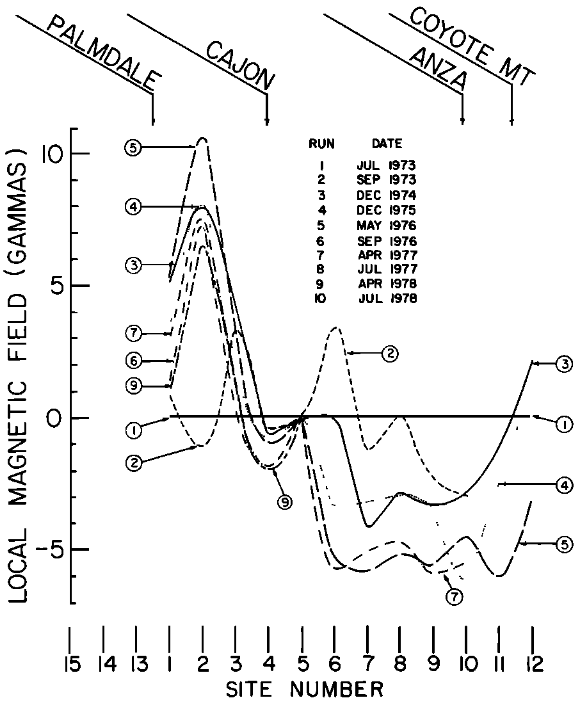

Fig. 2. Changes in local magnetic field (gammas) as a function of site locations along the San Andreas/San Jacinto faults for each run since the first data were taken in July 1973. Site 5 is held invariant. Run 8 and run 10 data are superimposed on run 9 data and to avoid confusion are not plotted.

been observed at other times in similar experiments such as in Colorado [*Beahn*, 1976] and in eastern Australia [*Johnston*, 1970].

The stress-magnetic explanation seems therefore the most plausible at this point. We note that if this interpretation is correct, the amplitude of the surface anomalies generated at each observation point should be dependent on both the stress state and the magnetization of the rocks within about 5–10 km of the measurement points. This does seem to be the case, since on one hand, the largest changes have been observed in the regions where the magnetization is highest [*Hanna et al.*, 1972]. On the other hand, the indications of a common sense in the changes to the north (positive) and to the south (mostly negative) of San Bernardino could support expectation of a common but different deviatoric stress state on either side of this intersection of major active faults.

No generally accepted physical model exists at present that explains the available deformation data. From such a model the general magnetic changes expected and their change with time might be calculated for the regions monitored and tested against the observations. Reversing the problem, there are unfortunately too few total field data and no reliable magnetic component data recorded during this time to attempt any rigorous inversion toward a viable mechanical model of southern California deformation. Simple models, however, can be fit to these data in this region and can provide constraints on the geometry and amplitudes of crustal stress in future models and testable predictions in other data.

The simplest tectonomagnetic models in which a step increase (or decrease) in shear stress occurs on an infinitely long fault in material with a magnetization of 10^{-3} emu [*Shamsi and Stacey*, 1969] can hardly be applied to the present situation of obvious heterogeneity in observations, fault geometry, and seismicity. Tectonomagnetic models for which a finite section of fault is locked and slip occurs around and beneath this section, thereby increasing the loading on the section, are perhaps more relevant. This type of model has been applied to the southern end of the 1906 fault break near San Juan Bautista by *Johnston* [1978].

The principal difference between this and the infinite model is the generation of anomalous changes of much larger amplitudes around the ends of the locked fault.

Assuming slip is occurring on the San Jacinto fault but not on the San Andreas to the north of their intersection, then the solution obtained by *Johnston* [1978] for the San Juan Bautista area is directly applicable. The sense of the changes expected from this solution is the same as that observed. There are, however, several important apparent difficulties. First, the change in stress necessary to produce a 10-γ field change is in excess of 100 bars if the magnetization is 10^{-3} emu or in excess of 10 bars if the magnetization is 10^{-2} emu. This latter magnetization is an upper limit of the values measured at the surface in the Wrightwood region, although magnetization probably increases with depth. Second, it is unlikely that stress changes of this amplitude could occur essentially aseismically over a broad region. According to *Chinnery* [1964] the slip required to produce these stresses would be in excess of 5 m if the slip depth is 5 km. This could hardly go unnoticed, and the corresponding strains certainly violate the strain measured geodetically by *Savage et al.* [1978].

As mentioned previously, the general change in strain state along the San Andreas fault, measured during the period of downwarping by *Savage et al.* [1978], has been a pure north-south compression at an average rate of 0.2 strain/yr. No significant east-west extension was observed. This is indeed a remarkable result, and non-Poissonion behavior is clearly indicated if net subsidence and negative areal strain occur during increased compression. The region of largest anomalous change in magnetic field lies between two of the geodetic strain networks, and if the total change in strain averaged over 20-km lines in this region also does not exceed a few tenths microstrain per year, the corresponding average stress changes within these crustal rocks will generally not be more than a 0.1 bar/yr.

There appears to be no easy way to retain the simplest large scale tectonomagnetic model discussed above and also satisfy the probable geodetic constraint. Although less satisfying, we are forced, if this is correct, to a more complex model invoking inhomogeneous stress or stress concentrations of smaller scale at up to a few kilometers of surface along and near the fault in order to explain these data.

We note that for linear increases in deviatoric stress and magnetization with depth, almost all of a surface anomaly is generated within about 5 km of the observation point. Large signals, such as observed, can be easily generated by a localized and changing stress concentration at shallow depths near the faults. It is more difficult, however, to test and independently support a more complex model with available data. One testable generalization of these tectonomagnetic models can be made. This concerns the amplitude of the changes in mean stress, if only in localized regions, needed to replicate the observed data with this mechanism. It is unlikely that these can be much less than about 10 bars, although, of course, an appeal might be made to some particular geometry or even to some yet unknown amplifying effect in this region.

Some support for the concept of a localized change in stress at depth near the fault does derive from the occurrence of a swarm of earthquakes in a region near the fault extending from just north of site 1 to site 2 [*McNally et al.*, 1978]. These earthquakes started at the time of the peak magnetic anomaly (peak stress change?) at site 2 and finally ceased in September 1977. During this time the magnetic anomaly decreased by about 3 or 4 γ. *Mogi* [1962] observes that acoustic emission occurs in stressed rock samples with a probability distribution $P(t, t + \Delta t/\sigma)$ which changes with stress σ in bars as

$$P(t, t + \Delta t/\sigma) \propto e^{\beta\sigma}$$

where β is an empirical constant with a value of about 0.3. For a 10-bar stress increase the probability distribution increases tenfold, as was in fact observed by *McNally et al.* [1978].

Thus despite the uncertainty in mechanism details, it does appear that localized stress/magnetism effects generated substantial magnetic anomalies during the partial downwarping in southern California between 1974 and 1976. Other physical processes are not obviated. Significant improvement in the interpretation of similar anomalies in the future will be difficult without other independent data that reflect near-fault crustal phenomena on similar scales.

Acknowledgments. We thank K. Aki for bringing to our attention the paper by K. Mogi, and Renata Dmowska and Gary Fuis for useful comments.

REFERENCES

Beahn, T. J., Geomagnetic field gradient measurements and noise reduction techniques in Colorado, *J. Geophys. Res., 81,* 6276–6280, 1976.

Castle, R. O., Level surveys and the Southern California Uplift, *Earthquake Info. Bull., 10,* 88–92, 1978.

Castle, R. O., J. P. Church, and M. R. Elliott, Aseismic uplift in southern California, *Science, 192,* 251–253, 1976.

Castle, R. O., M. R. Elliott, and S. H. Wood, The southern California uplift (abstract), *EOS Trans. AGU, 85,* 495, 1977.

Chinnery, M. A., The strength of the earth's crust under horizontal shear stress, *J. Geophys. Res., 69,* 2085–2098, 1964.

Fitterman, D. V., Electrokinetic and magnetic anomalies associated with dilatant regions in a layered earth, *J. Geophys. Res., 83,* 5923–5928, 1978.

Fuis, G., M. E. Friedman, and J. H. Hileman, Preliminary catalog of earthquakes in southern California July 1974–September 1976, *Open File Rep. 77-181,* p. 107, U.S. Geol. Surv., Menlo Park, Calif., 1977.

Hanna, W. F., R. D. Brown, D. C. Ross, and A. Griscom, Aeromagnetic reconnaissance and generalized geologic map of the San Andreas fault between San Francisco and San Bernardino, California, *Geophys. Invest. Map GP 815,* U.S. Geol. Surv., Menlo Park, Calif., 1972.

Johnston, M. J. S., The volcanomagnetic effect, Ph.D. thesis, p. 210, Univ. of Queensland, Australia, 1970.

Johnston, M. J. S., Local magnetic field variations and stress changes near a slip discontinuity on the San Andreas fault, *J. Geomagn. Geoelec., 30,* 511–522, 1978.

Johnston, M. J. S., B. E. Smith, and R. Mueller, Tectonomagnetic experiments and observations in western U.S.A., *J. Geomagn. Geoelec., 28,* 85–97, 1976.

Johnston, M. J. S., B. E. Smith, and R. O. Burford, Local magnetic field measurements and fault creep observations on the San Andreas fault, *Tectonophysics,* in press, 1979.

Kapitsa, S. P., Magnetic properties of eruptive rocks exposed to mechanical stress, *Izv. Akad. Nauk SSSR, Ser. Geofiz., 6,* 489–504, 1955.

Kean, W. F., R. Day, M. Fuller, and V. A. Schmidt, The effect of uniaxial compression on the initial susceptibility of rocks as a function of grain size and composition of their constituents titanomagnetites, *J. Geophys. Res., 81,* 861–872, 1976.

Lachenbruch, A., and J. S. Sass, Thermomechanical aspects of the San Andreas Fault, in *Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System,* edited by R. L. Kovach and A. Nur, pp. 192–205, Stanford University, Stanford, Calif., 1973.

Martin, R. J., and M. Wyss, Magnetism of rocks and volumetric strains in uniaxial failure tests, *Pure Appl. Geophys., 113,* 52–61, 1975.

McNally, K. C., H. Kanamori, J. Pechmann, and G. Fuis, Seismicity increase along the San Andreas fault, southern California, *Science, 201,* 814–817, 1978.

Mizutani, H., T. Ishido, Y. Yokokura, and S. Ohnishi, Electrokinetic phenomena associated with earthquakes, *Geophys. Res. Lett., 3,* 365–369, 1976.

Mogi, K., Study of elastic shocks caused by the fracture of heterogeneous material and its relation to earthquake phenomena, *Bull. Earthquake Res. Inst. Tokyo Univ., 40,* 125–173, 1962.

Nagata, T., Basic magnetic properties of rocks under the effects of mechanical stress, *Tectonophysics, 9,* 167–195, 1970.

Nur, A., Diatancy, pore fluids and premonitory variations of $t_s t_p$ travel times, *Bull. Seismol. Soc. Amer., 62,* 1217–1222, 1972.

Ohnaka, M., and H. Kinoshita, Effects of uniaxial compression on remanent magnetization, *J. Geomagn. Geoelec., 20,* 93–99, 1968.

Revol, J., R. Day, and M. Fuller, Magnetic effect of stress cycling of magnetite and magnetite bearing andesite and relevance to seismomagnetic effect, *J. Geomagn. Geoelec., 30,* 593–606, 1978.

Savage, J. C., and W. H. Prescott, Geodimeter measurements of strain during the southern California uplift, *J. Geophys. Res, 84,* 171–177, 1979.

Savage, J. C., W. H. Prescott, M. Lisowski, and N. King, Measured uniaxial north-south regional contraction in southern California, *Science, 202,* 833–855, 1978.

Shamsi, S., and F. D. Stacey, Dislocation models and seismomagnetic calculations for California 1906 and Alaska 1964 earthquakes, *Bull. Seismol. Soc. Amer., 59,* 1435–1448, 1969.

Smith, B. E., and M. J. S. Johnston, A tectonomagnetic effect observed before a magnitude 5.2 earthquake near Hollister, California, *J. Geophys. Res., 81,* 3556–3560, 1976.

Stacey, F. D., and M. J. S. Johnston, Theory of the piezo-magnetic effects in titanomagnetite-bearing rocks, *Pure Appl. Geophys., 97,* 146–155, 1972.

Wilson, E., On the susceptibility of feebly magnetic bodies as affected by compression, *Proc. Roy. Soc., Ser. A, 101,* 445–452, 1922.

(Received October 6, 1978;
revised March 26, 1979;
accepted March 28, 1979.)