THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989:
EARTHQUAKE OCCURRENCE

PRESEISMIC OBSERVATIONS

SEISMOMAGNETIC EFFECTS

By Robert J. Mueller and Malcolm J.S. Johnston,
U.S. Geological Survey

CONTENTS

ABSTRACT

A differentially connected array of proton magnetometers operated within the epicentral region of the earthquake for 12 years from 1974 to 1986. The closest magnetometer station was located 7.3 km from the epicenter of the earthquake and within 3 km of the site where anomalous ultra-low-frequency (ULF) magnetic-noise measurements were observed. After the earthquake, the magnetometers were reinstalled with sensors replaced in the original undisturbed sensor holders. Comparison of pre-1986 total-intensity magnetic-field data with data obtained during the months after the earthquake indicate that local offsets of about 1 nT may have been generated at stations nearest the epicenter. Tests on other continuous differenced data from 1983 to the present indicate that the offsets determined could be biased by as much as 0.7 nT. These offsets can be approximately fitted with a simple seismomagnetic model of the earthquake for which 1.9 m of right-lateral slip and 1.3 m of dip slip (southwest side up) occurred on a fault patch from 6 to 18 km deep and 45 km long. The total rock magnetization is assumed to be 1.5 A/m. Because the offset has persisted since the earthquake, an alternative explanation in terms of electrokinetic effects is unlikely, even though transient ground-water flow occurred after the earthquake. Comparison of pre-1986 and similar postseismic total-magnetic-field noise indicates no change caused by aliasing of ULF (0.01–10 Hz) magnetic noise in the vicinity of the epicenter.

INTRODUCTION

Stress changes that accompany seismic failure are expected to cause piezomagnetic effects and consequent time-dependent local magnetic anomalies (Stacey, 1964; Nagata, 1970). Local magnetic-field changes accompanying moderate to large earthquakes have been observed and actively sought in regions subject to earthquake hazards (Breiner, 1967; Smith and Johnston, 1976; Rikitake, 1979; Davis and others, 1980; Shapiro and Abdullabekov, 1982; Davis and Johnston, 1983; Honkura and Taira, 1983; Johnston and Mueller, 1987). A coseismic magnetic-field change or seismomagnetic effect should result from piezomagnetic effects generated by earthquake-related changes in the local stress field. This paper reports on possible magnetic-field offsets generated at sites located near the epicenter of the earthquake and the physical implications of these offsets.

INSTALLATION

The U.S. Geological Survey (USGS) operated a network of magnetometer stations in central California near the epicentral region of the Loma Prieta earthquake (fig. 1) from 1974 to 1986 in an effort to detect local magnetic field perturbations. The closest station (EUC) was 7.3 km from the epicenter of the earthquake. All stations use E.G.&G. Geometrics, Inc., model G–856 or G–826 proton-precession magnetometers operated at 0.1- or 0.25-nT resolution. Data collected before 1986 were synchronously sampled (at 10-minute intervals) and transmitted through a 16-bit digital telemetry system to the USGS offices in Menlo Park, Calif. (Mueller and others, 1980). Postseismic data were recorded onsite, using four portable systems that were operated at the stations between October 19 and December 30, 1989, with a synchronous 15-minute sampling interval. Instrument sensors were replaced in their original sensor holders to within 1 cm. Sensors at each stations are in local gradients less than 2 nT/m, and errors resulting from replacement of the sensors are less than 0.02 nT.

DATA

The magnetometer stations were not operational at the time of or during the 3-year period before the earthquake, and so details of preseismic effects, if any, are unavailable. Because these data are obtained by using drift-free magnetometers and are extremely stable over time, comparison of pre-1986 with postseismic data would allow identification of the net magnetic-field offset that occurred with the earthquake. To isolate local magnetic-field changes and reduce the effects of ionospheric and magnetospheric disturbances, synchronously sampled magnetic-field data from pairs of sites are differenced and averaged, and secular variation is removed. For example, 3-day averages of data referenced to station SJN (fig. 1) are plotted in figure 2. Comparison of data collected before 1986 with data obtained during the months after the earthquake indicate offsets of 0.1 to 1.4 nT (table 1). The largest changes were observed at the stations located nearest the epicenter of the earthquake; standard deviations of these data range from 0.2 to 0.6 nT. To test this procedure of extrapolating from 1986 to 1989, continuous differenced data from pairs of stations with similar separations but at large (>100 km) distances from the Loma Prieta region were subjected to identical processing, using data over the same time period (1983–present). Comparison of these data both with and without the 3-year data gap indicate that offsets estimated in this manner could be biased by as much as 0.7 nT.

Table 1.—*Predicted and observed changes in total magnetic field, referenced to station SJN (fig.1), as a function of distance from the epicenter of the Loma Prieta earthquake*

[Errors shown for observed values are standard deviations of pre-1986 data. All observed values are within 0.7 nT of predicted values]

Station	Predicted (nT)	Observed (nT)	Difference observed minus predicted (nT)	Distance (km)
EUC	−1.1	−1.4 ± 0.2	−0.3	7.3
SAR	−1.4	−1.3 ± 0.2	+0.1	28.3
NAN	−0.5	−1.1 ± 0.4	−0.6	3.9
ANZ	−0.5	+0.1 ± 0.6	+0.6	3.9
SNJ	−0.2	−0.3 ± 0.1	−0.1	36.1
SJN		Reference		41.9
HAR	+0.1	−0.6 ± 0.1	−0.7	49.2
LEW	+0.2	+0.1 ± 0.1	−0.1	68.2

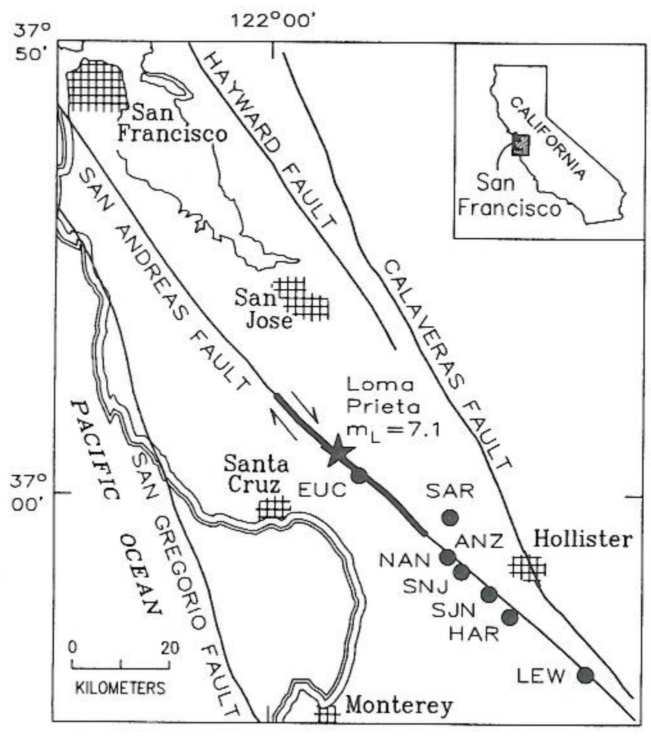

Figure 1.—Loma Prieta region, Calif., showing locations of magnetometer stations (dots) relative to epicenter of earthquake (star). Lines, major faults; heavy line, Loma Prieta rupture zone. Arrows denote direction of fault movement.

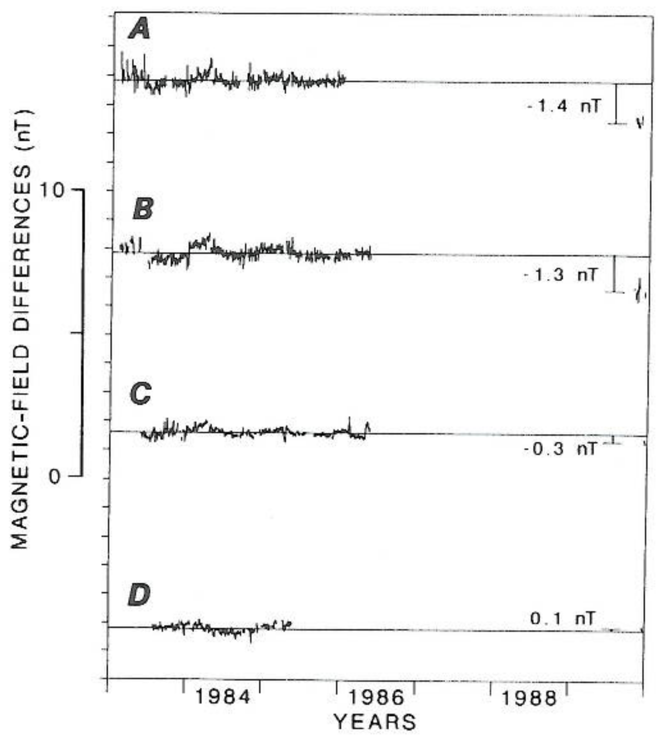

Figure 2.—Processed magnetic-field data from stations EUC (*A*), SAR (*B*), SNJ (*C*), and LEW (*D*), showing offsets between pre-1986 and postseismic data referenced to station SJN (see fig. 1 for locations). All data are displayed with identical vertical scale, and plots from top to bottom represent increasing distance from epicenter of earthquake.

DISCUSSION

Coseismic magnetic-field offsets can result from piezomagnetic effects generated by an earthquake-related change in the local stress field. Estimates of the stress change from dislocation models of the earthquake were combined with a seismomagnetic model to calculate the expected magnetic-field change for the earthquake. This model was constructed for an earthquake in which the strike, dip, depth, fault length, fault width, and style of faulting were chosen to be consistent with the geodetically determined parameters (fig. 3; Plafker and Galloway, 1989). Aeromagnetic data indicate a magnetic high in the epicentral region of the earthquake; this anomaly was inferred to be caused by buried plutonic rocks similar to the gabbro exposed near station ANZ (fig. 1; Hanna and others, 1972). Magnetic measurements on the gabbro exposed near station ANZ indicate magnetizations of 2 to 3 A/m, whereas other rock types in the region ranged in magnetization from 0.01 to 0.7 A/m. For modeling purposes, a value of 1.5 A/m was chosen to represent the average regional magnetization. The contours of calculated magnetic-field change for this model are mapped in figure 3. The observed magnetic-field offsets can be approximately fitted by this seismomagnetic model of the earthquake (table 1). If anything, the model values systematically underestimate the observations but are within the uncertainty of the observed values. Minor modifications of the model parameters could generate a better fit.

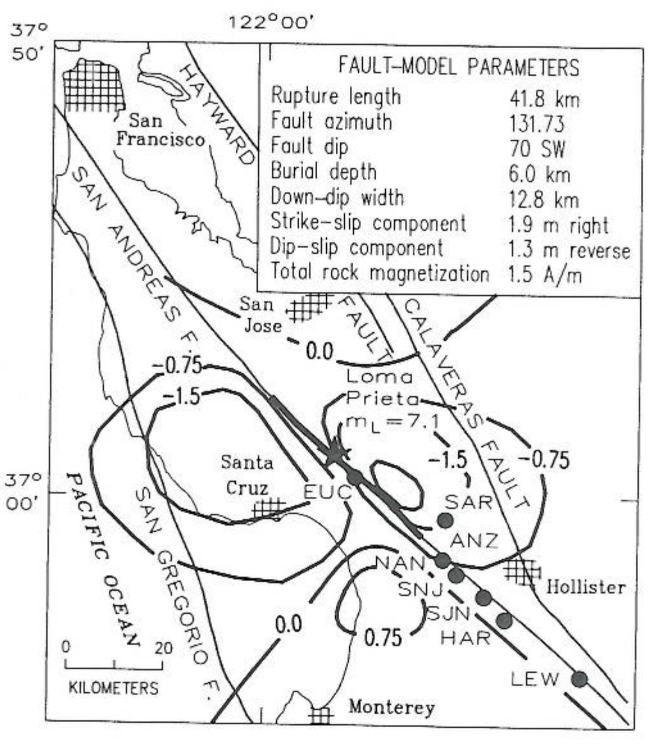

Figure 3.—Loma Prieta region, Calif., showing contours of calculated magnetic-field (in nanoteslas) expected from earthquake. Dots, magnetometer stations; star, epicenter of earthquake; lines, major faults; heavy line, Loma Prieta rupture zone. Fault parameters used to model event are listed in inset.

An alternative explanation in terms of an electrokinetic model is possible (Fitterman, 1979) but unlikely. The magnetic-field offsets have remained invariant for several months, with no indication of decay as the ground-water system stabilized. However, because some ground-water flow did occur immediately after the earthquake, this process cannot be completely ruled out.

Large-amplitude electromagnetic fields in the ultra-low-frequency (ULF) range 0.01–10 Hz were observed near the epicenter of the earthquake (Fraser-Smith and others, 1990). The changes were observed before the earthquake and have continued after it. These ULF magnetic-field measurements were obtained at a site approximately 3 km south of station EUC (fig. 1) and about the same distance from the hypocenter. The proton-precession magnetometers operated in the USGS network have a 10-minute sampling interval, measure total-magnetic-field intensity (least count, 0.1 nT), and are not designed to monitor magnetic-field fluctuations at frequencies of 0.01 to 10 Hz. However, owing to aliasing (Bendat and Piersol, 1966), the effect of 0.5- to 4-nT (A.C. Fraser-Smith, oral commun., 1990) increases in ULF magnetic-field noise could increase the apparent short-period background-noise level recorded by the precession magnetometers.

To search for increases in background noise in the total magnetic-field intensity at station EUC (fig. 1), a 17-day section of data from 1984 was compared with a similar section in 1989 after the earthquake. Both sections contain data with similar levels of solar disturbance activity. The magnetic-field intensity at station EUC referenced to station SJN (fig. 1) is plotted in figure 4*A*, and power spectra obtained from the two sections of data in figure 4*B*. Both the differenced data plots and the power spectra indicate no significant differences between the total magnetic field in 1984 and after the earthquake. Total-magnetic-field data during the time period of the largest observed ULF magnetic-field changes (3-hour period before the earthquake) are unavailable.

CONCLUSIONS

Two physical mechanisms could explain the seismomagnetic effects recorded after the earthquake: (1) The seismic-stress drop caused piezomagnetic effects and consequent local magnetic-field changes, or (2) substantial electrical currents were generated rapidly by either rupture-driven charge-generation mechanisms or earthquake-driven fluid flow (electrokinetic effects). The persistence of these changes for periods of months since the earthquake and the high conductivity of the Earth's crust appear to preclude electrokinetic effects as primary physical mechanisms driving the changes. The observations are generally consistent in amplitude and sense with a reasonable seismomagnetic model of the event. Observed increases in ULF magnetic-field noise near the epicenter of the earthquake were not detected in the total-magnetic-field measurements.

ACKNOWLEDGMENTS

We thank A.C. Fraser-Smith and his colleagues at the STAR Laboratory of Stanford University, Stanford, Calif., for making the ULF magnetic-field records available to us.

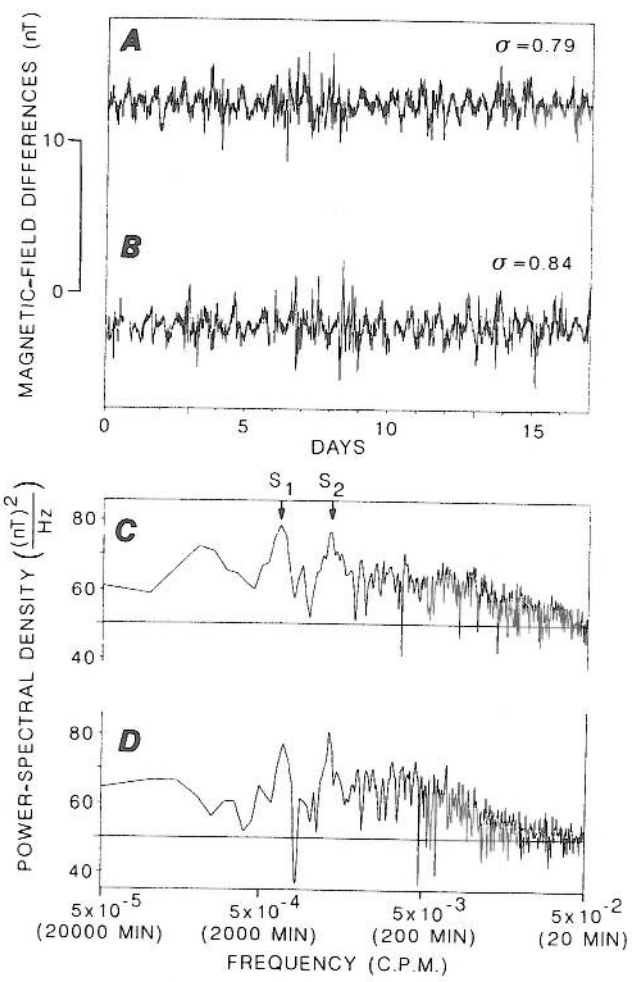

Figure 4.—Comparative 17-day sections of magnetic-field data from station EUC referenced to station SJN (fig. 1) during 1984 (*A*) and 1989 (*B*), with corresponding power spectra (*C* and *D*, respectively). 95-percent-confidence limits in figures 4*A* and 4*B* are 12.1 and –5.1 db, respectively. Dominant power in figures 4*C* and 4*D* is at solar-spectral peaks S_1 and S_2.

REFERENCES CITED

Bendat, J.S., and Piersol, A.G., 1966, Measurements and analysis of random data: New York, John Wiley & Sons, 390 p.

Breiner, Sheldon, and Kovach, R.L., 1967, Local geomagnetic events associated with displacements on the San Andreas fault: Science, v. 158, no. 3797, p. 116–118.

Davis, P.M., Jackson, D.D., and Johnston, M.J.S., 1980, Further evidence of localized geomagnetic field changes before the 1974 Thanksgiving Day earthquake, Hollister, California: Geophysical Research Letters, v. 7, no. 7, p. 513–516.

Fitterman, D.V., 1979, Theory of electrokinetic-magnetic anomalies in a faulted half-space: Journal of Geophysical Research, v. 84, no. B11, p. 6031–6040.

Fraser-Smith, A.C., Bernardi, Arman, McGill, P.R., Ladd, M.E., Helliwell, R.A., and Villard, O.G., Jr., 1990, Low-frequency magnetic field measurements near the epicenter of the M_S 7.1 Loma Prieta earthquake: Geophysical Research Letters, v. 17, no. 9, p. 1465–1468.

Hanna, W.F., Brown, R.D., Jr., Ross, D.C., and Griscom, Andrew, 1972, Aeromagnetic reconnaissance and general geology map of the San Andreas fault between San Francisco and San Bernardino, California: U.S. Geological Survey Geophysical Investigations Map GP–815, scale 1:250,000.

Honkura, Yoshimori, and Taira, S., 1983, Changes in the amplitudes of short-period geomagnetic variations as observed in association with crustal uplift in the Izu Peninsula, Japan: Earthquake Prediction Research, v. 2, no. 2, p. 115–125.

Johnston, M.J.S., 1986, Local magnetic fields, uplift, gravity, and dilational strain changes in southern California: Journal of Geomagnetism and Geoelectricity, v. 38, no. 10, p. 933–947.

Johnston, M.J.S., and Mueller, R.J., 1987, Seismomagnetic observation during the 8 July 1986 magnitude 5.9 North Palm Springs earthquake: Science, v. 237, no. 4819, p. 1201–1203.

Mueller, R.J., Johnston, M.J.S., Smith, B.E., and Keller, V.G., 1981, U.S. Geological Survey magnetometer network and measurement techniques in western U.S.A.: U.S. Geological Survey Open-File Report 81–1346, 44 p.

Nagata, T., 1970, Basic magnetic properties of rocks under the effect of mechanical stresses: Tectonophysics, v. 9, p. 167–195.

Ohshiman, Naoto, Sasai, Yoichi, Ishikawa, Yoshinobu, Honkura, Yoshimori, and Tanaka, H., 1983, Local changes in the geomagnetic total intensity associated with crustal uplift in the Izu Peninsula, Japan: Earthquake Prediction Research, v. 2, no. 3, p. 209–219.

Plafker, George, and Galloway, J.P., eds., 1989, Lessons learned from the Loma Prieta, California, earthquake of October 17, 1989: U.S. Geological Survey Circular 1045, 48 p.

Rikitake, Tsuneji, 1979, Changes in the direction of magnetic vector of short-period geomagnetic variations before the 1972 Sitka, Alaska, earthquake: Journal of Geomagnetism and Geoelectricity, v. 31, no. 4, p. 441–445.

Shapiro, V.A., and Abdullabekov, K.N., 1982, Anomalous variations of the geomagnetic field in East Fergake—magnetic precursor of the Alay earthquake with M=7.0 (1978 November 2): Royal Astronomical Society Geophysical Journal, v. 68, no. 1, p. 1–5.

Smith, B.E., and Johnston, M.J.S., 1976, A tectonomagnetic effect observed before a magnitude 5.2 earthquake near Hollister, California: Journal of Geophysical Research, v. 81, no. 20, p. 3556–3560.

Stacey, F.D., 1964, The seismomagnetic effect: Pure and Applied Geophysics, v. 58, p. 5–22.