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Magnetic Field Observations in the Near-Field the 28 June 1992 M_w 7.3 Landers, California, Earthquake

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Abstract Recent reports suggest that large magnetic field changes occur prior to, and during, large earthquakes. Two continuously operating proton magnetometers, LSBM and OCHM, at distances of 17.3 and 24.2 km, respectively, from the epicenter of the 28 June 1992 M_w 7.3 Landers earthquake, recorded data through the earthquake and its aftershocks. These two stations are part of a differentially connected array of proton magnetometers that has been operated along the San Andreas fault since 1976. The instruments have a sensitivity of 0.25 nT or better and transmit data every 10 min through the GOES satellite to the USGS headquarters in Menlo Park, California. Seismomagnetic offsets of -1.2 ± 0.6 and -0.7 ± 0.7 nT were observed at these sites. In comparison, offsets of -0.3 ± 0.2 and -1.3 ± 0.2 nT were observed during the 8 July 1986 M_L 5.9 North Palm Springs earthquake, which occurred directly beneath the OCHM magnetometer site. The observations are generally consistent with seismomagnetic models of the earthquake, in which fault geometry and slip have the same form as that determined by either inversion of the seismic data or inversion of geodetically determined ground displacements produced by the earthquake. In these models, right-lateral rupture occurs on connected fault segments in a homogeneous medium with average magnetization of 2 A/m. The fault-slip distribution has roughly the same form as the observed surface rupture, and the total moment release is 1.1×10^{20} Nm. There is no indication of diffusion-like character to the magnetic field offsets that might indicate these effects result from fluid flow phenomena. It thus seems unlikely that these earthquake-generated offsets and those produced by the North Palm Springs earthquake were generated by electrokinetic effects. Also, there are no indications of enhanced low-frequency magnetic noise before the earthquake at frequencies below 0.001 Hz.

Introduction

Time-dependent local magnetic anomalies have long been expected to result from stress changes that accompany seismic failure, either as a result of piezomagnetic effects (Stacey, 1964; Nagata, 1969; Stacey and Johnston, 1972; Sasai, 1980) or from electrokinetic effects (Mizutani *et al.*, 1976; Fitterman, 1979; Ishido and Mizutani, 1981; Dobrovolsky *et al.*, 1989). Local magnetic field changes accompanying moderate to large earthquakes have been actively sought in regions subject to earthquake hazards (Breiner and Kovach, 1967; Smith and Johnston, 1976; Rikitake, 1979; Honkura and Taira, 1982; Shapiro and Abdullabekov, 1982; Davis and Johnston, 1983; Johnston, 1989) and were clearly observed at the time of the 8 July 1986 M_L 5.9, North Palm Springs earthquake (Johnston and Mueller, 1987) and the 18 October 1989 M_L 7.1 Loma Prieta earthquake (Mueller and Johnston, 1990). Low-frequency magnetic noise, primarily in the band 0.01 to 0.05 Hz (20 to 100 sec), was observed before and after the Loma Prieta earthquake (Fraser-Smith *et al.*, 1990). This noise was not apparent at periods greater than 600 sec (Mueller and Johnston, 1990). The 28 June 1992 M_w 7.3 Landers earthquake provided a new opportunity to quantify these effects during a large damaging earthquake.

The U.S. Geological Survey has been operating a time-synchronized network of absolute proton precession magnetometers along the San Andreas fault in the southern California region since 1976. The purpose of this network is to quantify the form and character of local magnetic fields along active faults preceding and during fault rupture. However, owing to budget cutbacks, network maintenance in southern California was discontinued in 1985. Only the two sites, Little San Bernardino (LSBM) and Old Canyon House (OCHM), shown in Figure 1, were in operation at the time of the Landers earthquake. The closest operating sites to these instruments are located in the Parkfield region, about 400 km northwest along the San Andreas fault. Both the LSBM and the OCHM proton magnetometers operate at 0.25 nT sensitivity. The data are synchronously sampled every 10 min and telemetered with GOES digital satellite telemetry (Mueller *et al.*, 1981) to Menlo Park, California, for processing. The sensors are mounted within wooden posts that are cemented deeply into the ground in regions where the spatial magnetic gradient is low (<1 nT/m). Sensor displacement of more than several tens of centimeters during earthquakes should not generate apparent seismomagnetic effects of displacement origin.

The location of the mainshock, surface rupture, and aftershocks in relation to the major faults in the region are also shown in Figure 1. Moment tensor inversion (Kanamori *et al.*, 1992) indicated a moment for the earthquake of about 10^{20} Nm. The strike varied systematically from 351° in the south to 318° in the north. Slip at depth, and at the surface, along the rupture was approximately bimodal, reaching a peak of just over 4 m about 10 km north of the epicenter, a minimum 20 km north of the epicenter, and up to 7 m about 40 km NNW of the epicenter (Kanamori *et al.*, 1992). Inversion of geodetic data taken before and after the earthquake (Murray *et al.*, 1993) indicated a more irregular slip profile. The style of faulting was primarily right-lateral rupture on a series of connected near-vertical faults. The epicenter was located 17.3 and 24.2 km from the magnetometers LSBM and OCHM, respectively. This article reports co-seismic magnetic field offsets (i.e., seismomagnetic effects) observed at these sites. These changes were apparently generated by earthquake-related stress release and have implications for the relative importance of the two most likely physical mechanisms that could have generated these offsets.

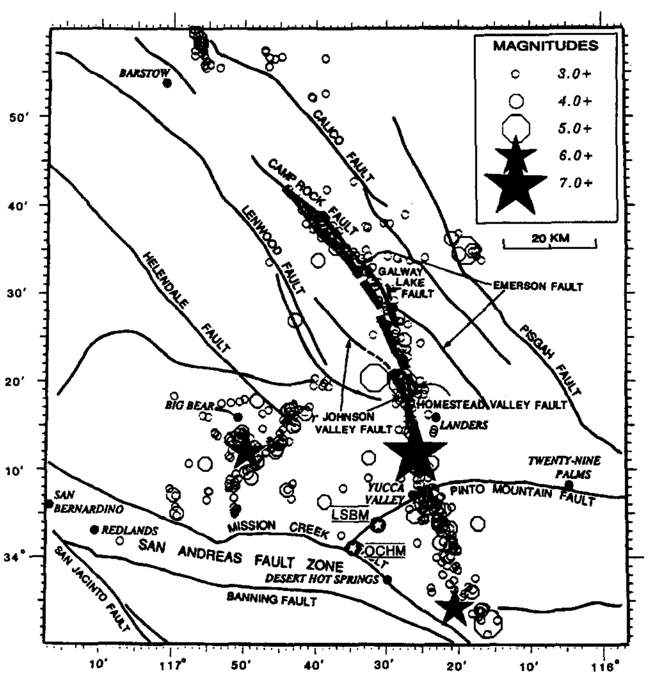

Figure 1. Location of magnetometer sites (star inside circle) relative to the epicenter (largest star) of the Landers earthquake and its subsequent aftershocks. Smaller stars show the locations of the 23 April 1992 M_w 6.1 Joshua Tree preshock and the 28 June 1992 M_w 6.2 Big Bear aftershock. The thickened lines indicate the rupture zone of the earthquake.

Data

To isolate magnetic field changes of local origin and to reduce common noise from ionospheric and magnetospheric sources, we difference data from adjacent sites. The standard deviation σ of hourly means of the resulting difference field data increases with site separation as

$$\sigma = a + bd, \qquad (1)$$

where $a = 0.07 \pm 0.08$ nT, $b = 0.01 \pm 0.003$ nT/km, and d is the site separation in kilometers (Johnston *et al.*, 1984). Figure 2 shows the differenced data for station OCHM minus LSBM for 1 day before and after the Landers earthquake. The upper plot shows the 10-min (raw) data values. The same data with 6-point and 27-point smoothing applied before and after the earthquake are shown in the middle and lower plots, respectively. The difference in absolute field offsets at the two mag-

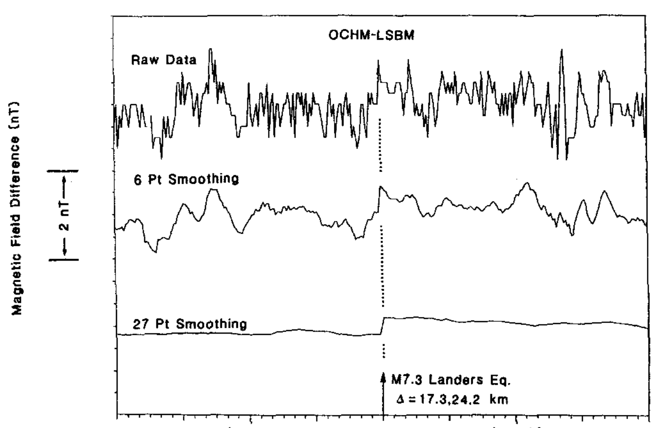

Figure 2. Magnetic field differences between OCHM and LSBM on the day before and after the M_w 7.3 28 June 1992 Landers earthquake showing 10-min samples (*upper plot*), the same data with 6-point smoothing (*middle plot*), and the same data with 27-point smoothing before and after the earthquake (*lower plot*). All data are displayed with identical vertical scale.

netometer sites is 0.4 ± 0.1 in the 27-point smoothed data. This offset represents the second seismomagnetic change we have observed on this station pair. The first had an amplitude of about 1 nT and occurred during the 1986 North Palm Springs earthquake (Johnston and Mueller, 1987). The epicenter of this earthquake was within a few kilometers of OCHM. In Figure 2, it is also apparent that no unusual magnetic field changes above the noise levels occurred in the 10-min sampled data during the hours to minutes before the earthquake.

Short-term magnetic field differences of 0.4 nT are not uncommon in magnetic difference field data taken with a 7-km site separation. Changes of this amplitude occur frequently during magnetic disturbances, solar flares, and solar storms and arise largely from differences in magnetic induction at the two sites. Adaptive filtering techniques can reduce these signals (Davis *et al.*, 1980). Fortunately, the solar activity during the 24 hr before and after the Landers earthquake was quiet, and the change coincident with the earthquake at 11:58 a.m. on 28 June cannot easily be ascribed to magnetic disturbance effects since differences between other sites with similar site separations but further to the north along the San Andreas fault show no similar offsets at this time.

A longer-term plot of smoothed difference data from OCHM and LSBM during the previous 7 yr (Fig. 3—*upper*) shows the occurrence times of the M_L 5.9 North Palm Springs and M_w 7.3 Landers earthquakes, magnetic storm effects (negative pulses), and an obvious 1.5-nT field offset during the North Palm Springs earthquake. The offset coincident with the Landers earthquake is not apparent in these long-term data. If known storms and diurnal magnetic variations are largely removed by using only nighttime values (9 p.m. to 6 a.m. local time) as shown in Figure 3 (*lower*), the record is much cleaner. The short-term offset at the time of the Landers earthquake can be seen in the data, but this change is not significantly above the long-term noise. There are also some hints of a longer-term transient of about 1 nT in the data during the 6 months before the Landers earthquake, but this also could not be called significant. Future use of adaptive filtering on these data may clarify these issues.

Determination of the absolute magnetic field changes at the two magnetometer sites is more difficult, because we currently do not have other operating magnetometers in southern California against which we can reference these data. The nearest magnetometers of similar design and synchronized sampling times are located near Parkfield, California, some 375 to 450 km to the northwest (Fig. 4). The 95% confidence limits ($\pm 2\sigma$) of continuous hour averages of difference field data between either OCHM or LSBM and GRAM (375 km distant) are expected from equation (1) to be 3.75 ± 1.1 nT. To obtain finer resolution of the offsets, we have further processed the two difference data sets LSBM–GRAM and OCHM–GRAM during the month before and after the earthquake. We have rejected all data for days in which magnetic disturbances occurred and all data during daytime hours when S_q disturbances are evident. Linear regression fits were then made to the remaining nighttime values during the month before and the month after the earthquake, as shown in Figure 5. Offsets in the regression lines at the

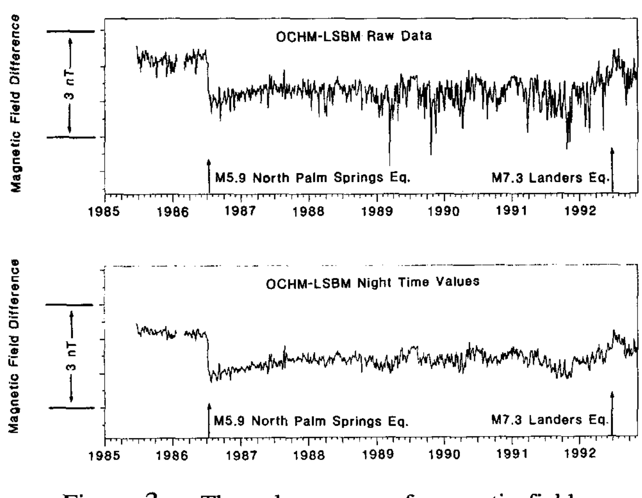

Figure 3. Three-day means of magnetic field differences between OCHM and LSBM from 1985 through 1992 showing the occurrence times of the July 1986 M_L 5.9 North Palm Springs and the June 1992 Landers earthquake (*upper plot*). The same data with all daytime (6 a.m. to 9 p.m. local time) values removed is shown in the lower plot.

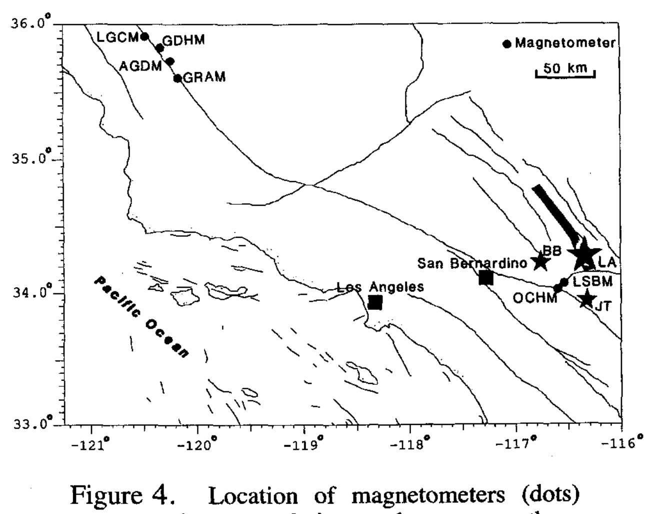

Figure 4. Location of magnetometers (dots) OCHM and LSBM relative to the most southern magnetometers in central California (GRAM, AGDM, GDHM, and LGCM, respectively). The large star shows the location of the Landers earthquake (LA) with its associated rupture. Shown as small stars are the locations of the 23 April 1992 M_w 6.1 Joshua Tree (JT) and the 28 June 1992 Big Bear earthquake (BB). The locations of the towns of San Bernardino and Los Angeles are shown as squares.

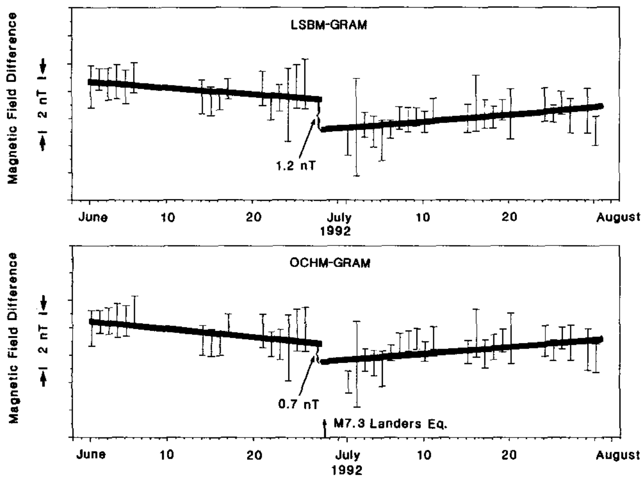

Figure 5. Linear regression fits to difference field data between LSBM and GRAM (*upper plot*) and OCHM and GRAM (*lower plot*) during the 1-month period before and after the 1992 Landers earthquake (*lower plot*). Only nighttime and magnetic disturbance free data are used. Error bars show the 95% confidence limits on each data point.

time of the earthquake are -1.2 ± 0.6 and -0.7 ± 0.7 nT for the differences LSBM–GRAM and OCHM–GRAM, respectively. The errors are the sum of the standard errors of variation about each regression line and are approximately equal to the 95% confidence limits. The difference in these offsets is consistent with the 0.4 ± 0.1 nT offset reported in Figure 2. The data indicate that the largest observed seismomagnetic change occurred at site LSBM, located nearest the earthquake, and that the seismomagnetic change corresponded to a decrease in the local field at both sites.

Increased ULF magnetic field noise was reported prior to the 1989 M_L 7.1 Loma Prieta earthquake (Fraser-Smith *et al.*, 1990), and this result has been suggested to be a useful earthquake prediction tool. While our data do not cover the exact frequency band (10^{-2} to 10 Hz) monitored by Fraser-Smith *et al.* (1990), we would expect that, if this noise occurs generally with major earthquakes, it would not be purely monochromatic and some indication should be apparent in the frequency bands near those monitored by Fraser-Smith before and after the earthquake. Furthermore, even if the source were monochromatic with large amplitudes in the 10^{-2} to 10^{-1} band, some aliasing of these effects should be apparent in the frequency band 10^{-4} to 10^{-3} Hz (Bendat and Piersol, 1966). With this in mind, we searched the data from both LSBM and OCHM before and after the Landers earthquake and at other times of similar solar activity for indications of increased noise. For this analysis, noise power spectra were computed from 20-day sections of data during the pre-earthquake and postearthquake periods and also during similar consecutive 20-day periods at other times. No significant differences in noise power were observed in the data before and after the earthquake (Fig. 6—*upper left* and *upper right*) compared with noise power at other times. An example is shown in Figure 6 (*lower left* and *lower right*) for the period June to July, 1991.

Discussion

The observed magnetic field perturbations could result from seismomagnetic effects since both the induced and remanent magnetization of rocks are sensitive to changes in crustal stress (Stacey, 1964; Nagata, 1969; Stacey and Johnston, 1972; Sasai, 1980), and crustal stress certainly changed during this earthquake. The magnetic field changes might also be expected to accompany earthquakes as a result of electrokinetic effects generated by fluid flow (Mizutani *et al.*, 1976; Fitterman, 1979; Ishido and Mizutani, 1981; Dobrovolsky *et al.*, 1989). However, to explain the observed rapid and irreversible offsets in terms of electrokinetics, particularly in the case of the North Palm Springs but less so for the more distant Landers earthquake, would require rapid and implausibly continuous fluid flow. There was no indication of fluid flow from the ground at any point along the surface rupture (Rymer, 1993, personal comm.). The most likely scenario for fluid flow would be rapid diffusion of fluids through cracks and fractures, and this could give rise to short-term transient and temporally decaying magnetic signals. Such signals might explain the increased noise observed prior to the Loma Prieta earthquake that was discussed above. Thus, while the electrokinetic mechanism cannot be discounted, we favor a more straightforward explanation in terms of the piezomagnetic effect.

Using the techniques described in Sasai (1980), Johnston and Mueller (1987), Mueller and Johnston (1990), and Sasai (1991), seismomagnetic models for the Landers earthquake were constructed from fault rupture models obtained by least-square inversion of the seismic data (Kanamori *et al.*, 1992) and inversion of geodetic data in the area before and after the earthquake (Murray *et al.*, 1993). Fault displacements from the fault rupture models were first used to calculate changes in stress in the surrounding region. Magnetic field perturbations resulting from stress-induced changes in magnetization were then determined for observed values of inclination, declination, and reasonable values of rock magnetization and stress sensitivity (Table 1). In these seisomagnetic models, we also included some buried slip (2 m between 5- and 15-km depth) on the Eureka Peak fault, as indicated in the postseismic displacement measurements by Sylvester (1993) and the aftershock distribution (Kanamori *et al.*, 1992). All models gave similar results. Inclusion of slip on the Eureka Peak fault reduces the amplitude of signals expected at both LSBM (0.7 nT) and OCHM (0.4 nT) over those expected from the geodetic inversion or the

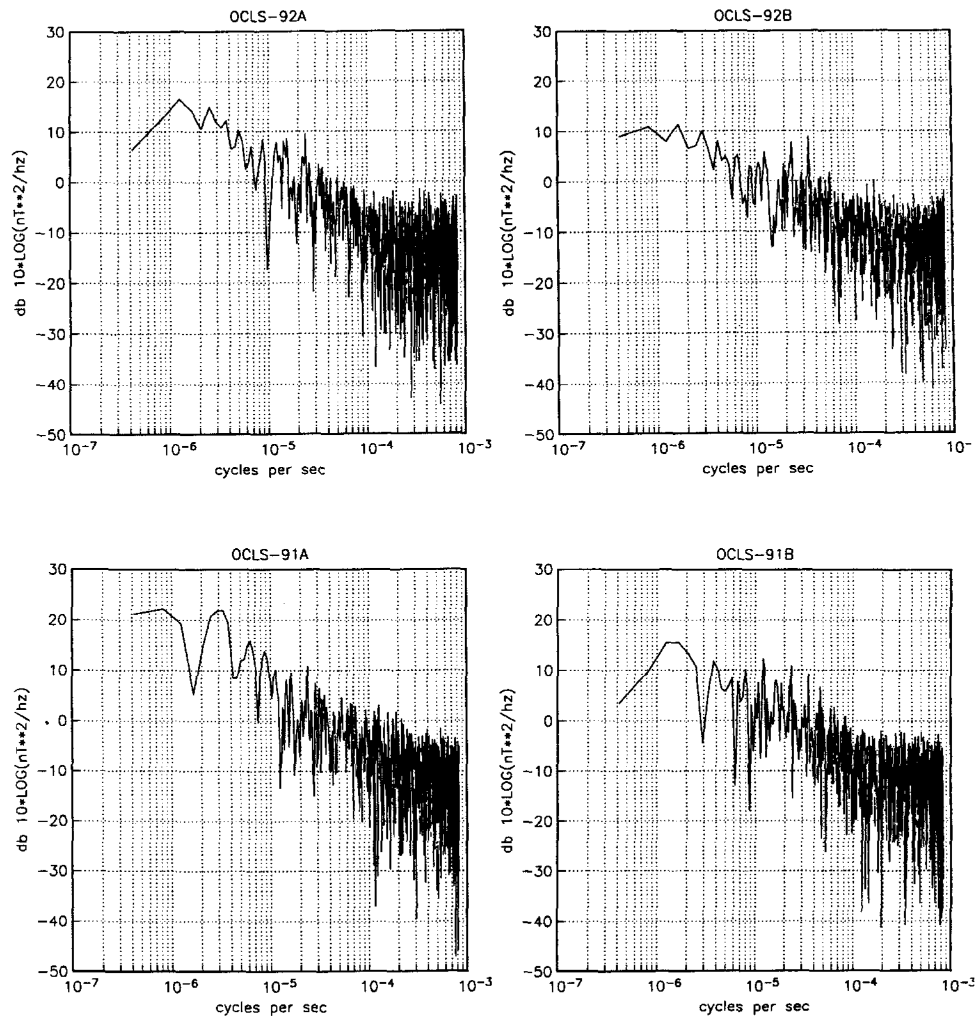

Figure 6. Comparative power spectra from 20-day sections of magnetic field data from station LSBM referenced to station OCHM for the months of June and July 1992, before and after the Landers earthquake (*upper plots*) and during June and July 1991, when no earthquakes occurred (*lower plots*). The 95% confidence limits are 12.1 and −5.1 db. The dominant power in these data is at the S_1 and S_2 solar spectral peaks.

seismic inversion models alone. Details of the Kanamori *et al.* (1992) seismic inversion model, including slip on the Eureka Peak fault, are listed in Table 2. The total moment is 1.1×10^{20} Nm. The fault strike varies along rupture from a direction N9°W at the southern end to N42°W at the north. The geometry and slip in different segments of the fault are listed in Table 2. Integration of the fields as a result of the distributed change in magnetization imposed by the earthquake allows the surface anomaly to be calculated at points 2 m above the earth's surface at the magnetic sensors. The most uncertain parameters are the average rock magnetization and the stress sensitivity. Since observations of surface magnetization at the two sites ranged between 2 and 0.1 A/m, and since magnetization usually increases below the weathered near-surface rocks, an average magnetization of 2 A/m was assumed. A stress sensitivity of 2×10^{-4} bar^{-1}, consistent with theoretical calculations (Stacey and Johnston, 1972) and conservative values of laboratory measurements (Revol *et al.*, 1977; Martin, 1980), was chosen.

With this model, the expected seismomagnetic anomaly at the LSBM and OCHM sites are −1.3 and −0.7 nT, respectively, in general agreement with the amplitudes and sign of the observed signals. The spatial variation of the calculated change in near-surface magnetic

Table 1
Parameters Used in Piezomagnetic Model

Sensitivity (bars^{-1})	Magnetization (A/m)	Inclination	Declination	Curie Depth (km)
0.0002	2	60°	16°E	25

Table 2
Geometry and Slip Used in Fault Model

Fault	Latitude	Longitude	Dip	Rupture Depth (km)	Slip (m)	Rupture Top (km)
Camp Rock	34.6918	−116.7230	90°	15	−2.0	0
	34.6187	−116.6530	90°	15	−3.0	0
Emerson	34.5708	−116.5940	90°	15	−5.0	0
Emerson	34.4977	−116.5130	90°	15	−3.0	0
Emerson	34.4612	−116.4730	90°	15	−1.0	0
Homestead	34.4954	−116.5300	90°	15	−3.0	0
Homestead	34.4121	−116.4760	90°	15	−2.0	0
Kickapoo	34.3436	−116.4460	90°	15	−1.0	0
Johnson	34.3155	−116.4620	90°	15	−3.0	0
Johnson	34.2420	−116.4350	90°	15	−2.0	0
Eureka Pk.	34.1667	−116.4290	90°	15	−2.0	5

field for this model is shown in Figure 7. If slip on the Eureka Peak fault is not included, the model overestimates the observations by about 50%. However, uncertainty in model parameters such as magnetization and stress sensitivity is at least 50%.

Conclusions

Static magnetic field decreases of −1.2 and −0.7 nT occurred at distances of 17 and 24 km from the epicenter of the 28 June 1992 M_w 7.3 Landers earthquake. These were similar in amplitude to those recorded during the smaller, but closer, 8 July 1986 M_L 5.9 North Palm Springs earthquake. Some longer-term changes in magnetic field may also have occurred during the 6-month period prior to the earthquake, but, while these changes may be precursive to the earthquake, they cannot be uniquely attributed to it. We have no evidence for rapid large-scale, large-amplitude magnetic field transients prior to or following this earthquake. Higher-frequency electromagnetic fields may have occurred, but our sample rate (1 sample/10 min) may have been too slow to detect them.

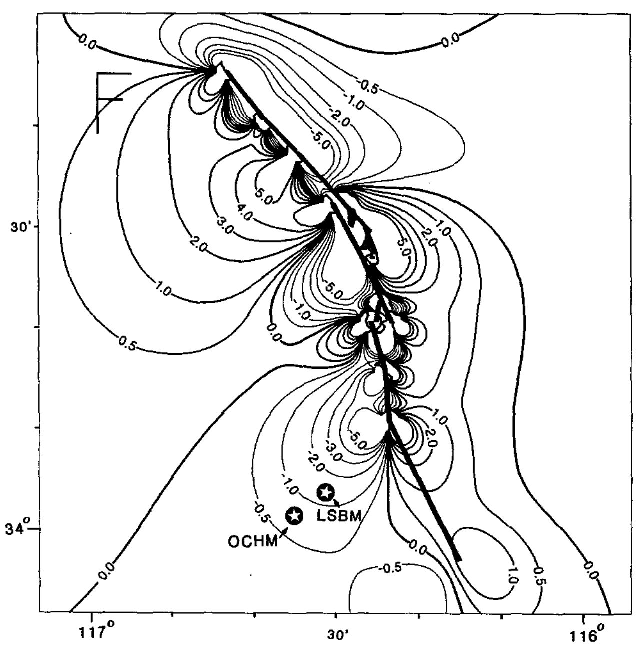

Figure 7. Contours of calculated magnetic field (nT) expected from the Landers earthquake. Fault parameters used to model the event are listed in Tables 1 and 2.

The co-seismic seismomagnetic effects recorded during the earthquake could be explained by two primary physical mechanisms: either the seismic stress drops caused reversible changes in magnetization (piezomagnetic effects) which resulted in changes in local magnetic field, or substantial electric currents were generated rapidly by rupture-driven charge-generation mechanisms or by earthquake-driven fluid flow (electrokinetic effects).

These observations are most consistent (in both amplitude and sense) with a piezomagnetic model of the earthquake. This model has as its essence the same general fault-slip geometry, slip amplitudes, and earthquake moment that can be used to explain the seismic and geodetic ground-displacement data generated by the earthquake. Long-term continuous fluid flow would be required to explain the magnetic field offsets in terms of electrokinetic effects resulting from fluid flow at seismogenic depths. The absence of surface indications of major subcrustal fluid flow argues against the likelihood of such a physical mechanism at Landers.

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