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Review of magnetic field monitoring near active faults and volcanic calderas in California: 1974–1995

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Abstract

Differential magnetic fields have been monitored along the San Andreas fault and the Long Valley caldera since 1974. At each monitoring location, proton precession magnetometers sample total magnetic field intensity at a resolution of 0.1 nT or 0.25 nT. Every 10 min, data samples are transmitted via satellite telemetry to Menlo Park, CA for processing and analysis. The number of active magnetometer sites has varied during the past 21 years from 6 to 25, with 12 sites currently operational. We use this network to identify magnetic field changes generated by earthquake and volcanic processes. During the two decades of monitoring, five moderate earthquakes (M5.9 to M7.3) have occurred within 20 km of magnetometer sites located along the San Andreas fault and only one preseismic signal of 1.5 nT has been observed. During moderate earthquakes, coseismic magnetic signals, with amplitudes from 0.7 nT to 1.3 nT, have been identified for 3 of the 5 events. These observations are generally consistent with those calculated from simple seismomagnetic models of these earthquakes and near-fault coseismic magnetic field disturbances rarely exceed one nanotesla. These data are consistent with the concept of low shear stress and relatively uniform displacement of the San Andreas fault system as expected due to high pore fluid pressure on the fault. A systematic decrease of 0.8–1 nT/year in magnetic field has occurred in the Long Valley caldera since 1989. These magnetic field data are similar in form to observed geodetically measured displacements from inflation of the resurgent dome. A simple volcanomagnetic model involving pressure increase of 50 MPa/a at a depth of 7 km under the resurgent dome can replicate these magnetic field observations. This model is derived from the intrusion model that best fits the surface deformation data. © 1998 Elsevier Science B.V.

Keywords: Volcano; Earthquakes; San Andreas Fault; Calderas; California

1. Introduction

Stress changes in the earth's crust that accompany seismic failure and/or volcanic activity are expected to cause time-dependent local magnetic anomalies resulting from stress induced piezomagnetic effects (Stacey, 1964; Nagata, 1969) and perhaps indirect effects resulting from fluid flow, temperature changes, etc. (Fitterman, 1979). Local magnetic field changes which accompany moderate to large earthquakes and volcanic eruptions have been observed and are sought in regions subject to these geologic hazards (Breiner and Kovach, 1967; Johnston and Stacy, 1969; Davis, 1976; Smith and Johnston, 1976;

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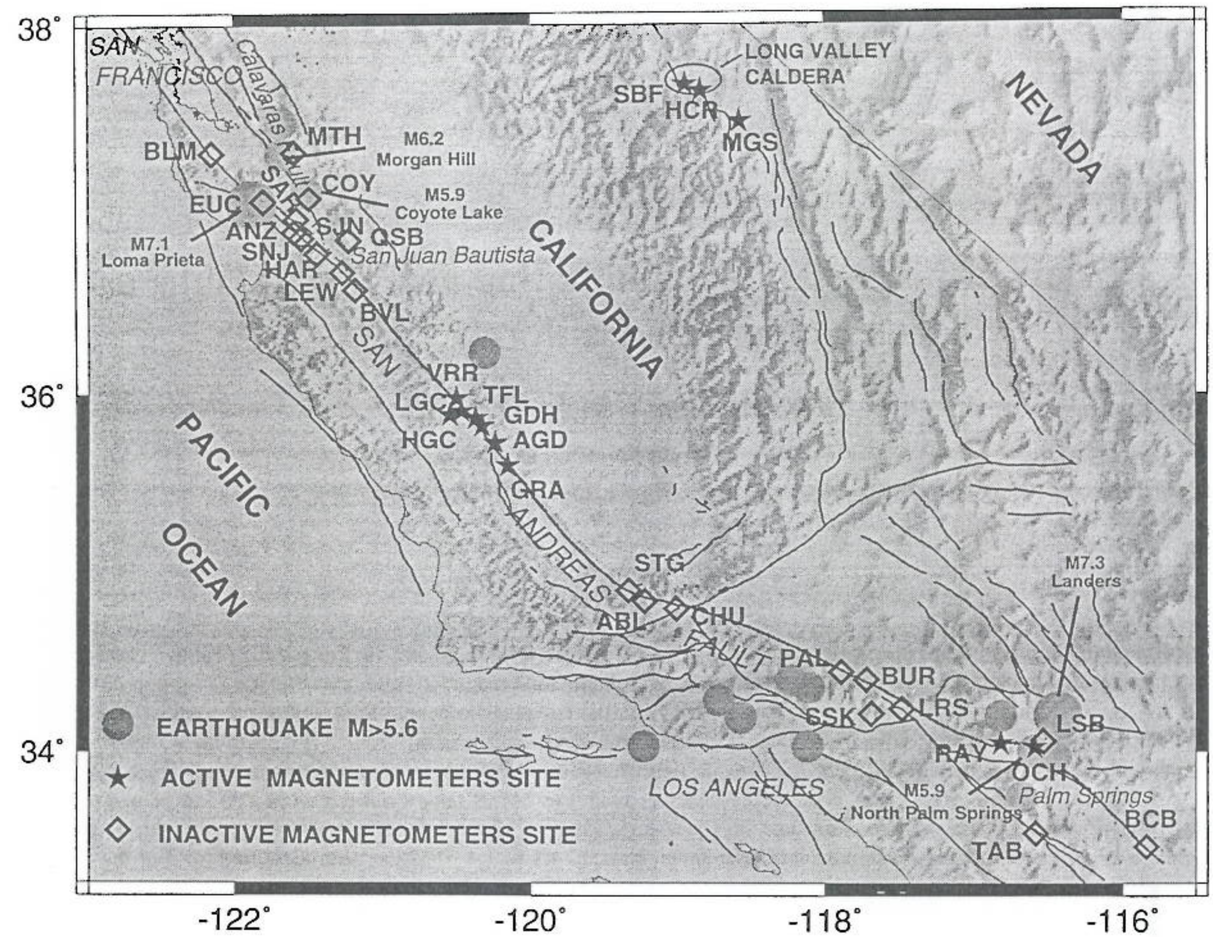


Fig. 1. Map showing magnetometer sites located in California. Solid stars are magnetometers which are presently operational and the open diamonds represent magnetometers previously operated at these locations. Shaded circles represent seismicity along the San Andreas fault system ($M > 5.6$).

Pozzi et al., 1979; Rikitake, 1979; Honkura and Taira, 1982; Shapiro and Abdullabekov, 1982; Davis and Johnston, 1983; Oshiman et al., 1983; and Johnston and Mueller, 1987). This paper reviews our observations after two decades of magnetic field monitoring along the San Andreas fault system and near the Long Valley caldera in California, USA, (Fig. 1).

2. Method

The U.S. Geological Survey has been operating a network of proton precession magnetometers along the San Andreas fault system since 1974 and in the Long Valley caldera since 1983. The initial network consisted of 6 sites located ~ 130 km south of San Francisco, along the San Andreas fault near San Juan Bautista, CA. From 1975 to 1982, the network expanded to 25 telemetered sites located between San Francisco and the Palm Springs region. The present network consists of 12 sites in three regions of California, (Fig. 1). All the magnetometer sites use identical equipment, which are commercially manufactured total field proton precession magnetometers synchronously measuring magnetic field intensity at 0.1 nT or 0.25 nT sensitivity (Mueller et al., 1981). All sites sample synchronously every 10 min and telemeter data via satellite to Menlo Park, CA where these data are processed and analyzed. Although the proton precession magnetometers can only measure total field, this design was chosen for its accuracy and stability.

Magnetic field measurements from adjacent stations within the network are differenced to isolate local magnetic field changes and to cancel common noise from ionospheric and magnetospheric sources. Differencing of these data decreases the standard deviation by a factor of 30 and smoothing (daily averaging) of these differenced data further reduces the standard deviations by a factor of 10. Measurement precision for these data approaches 0.2 nT, dependent on site separation and local magnetic gradients (Johnston et al., 1984). After processing, these total magnetic field data are routinely searched for any local magnetic field changes related to earthquake or volcanic processes.

3. San Andreas fault results

The first magnetic field change observed and the only precursive change identified in over 20 years of monitoring occurred during the first year the network was operating. The magnetic field change preceded a M5.2 earthquake which occurred on 28 November 1974 (Fig. 2). The earthquake was located off the San Andreas fault, but only 15 km from magnetome-

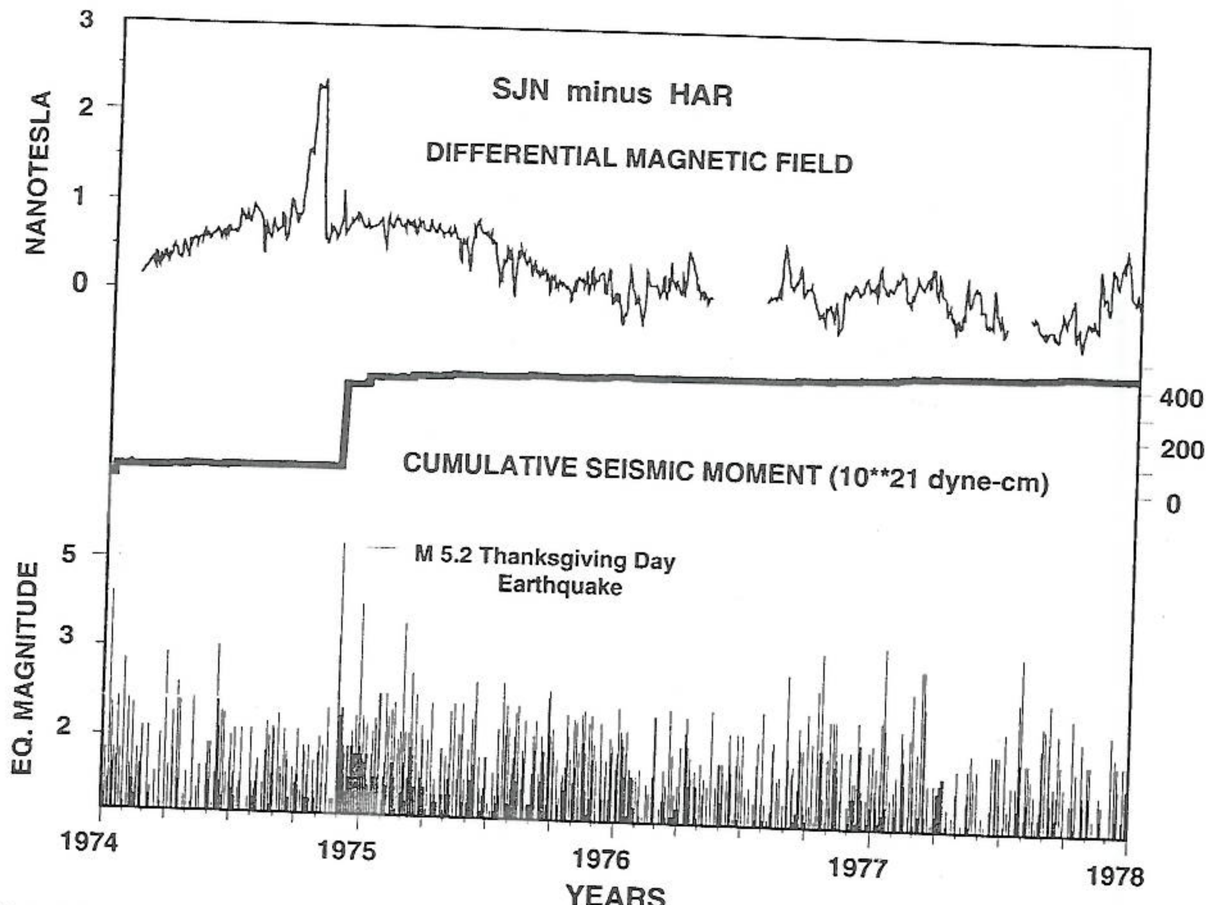


Fig. 2. Differential magnetic field, cumulative seismic moment, and seismicity associated with the $M = 5.2$ event on 28 November 1974. A precursive signal of 1.5 nT is observed during the two-month period before the earthquake (Smith and Johnston, 1976). This signal is the only precursive signal observed in two decades of monitoring magnetic field along the San Andreas fault.

ter site SJN. Seven weeks before the earthquake the magnetic field at site SJN increased by 1.5 nT. The field remained at this level for two weeks, and then decreased by 1.8 nT. Data noise reduction techniques were used to show that this magnetic field signal was observed on data from at least two sites, (Davis et al., 1980). The variation occurred at the two closest sites (SJN and ANZ) and the simultaneity and proximity in space and time argue in favor of a tectonomagnetic effect. Models based only on stress release at the earthquake source do not explain the relationship between the observed anomaly and this earthquake. The change could have resulted from stress redistribution prior to the earthquake in the complex region surrounding the epicenter (Smith and Johnston, 1976; Davis et al., 1980).

During the period from 1974 to 1995, 16 earthquakes greater than M5.6 occurred along the San Andreas fault system between San Francisco and Palm Springs, (Fig. 1). Of these 16 earthquakes, five were located within two earthquake rupture lengths of one or more magnetometer sites within the network and, of these five events, three (60%) have coseismic magnetic field changes associated with them. We will briefly summarize results obtained for these five earthquakes in chronological order.

Piezomagnetic models (Sasai, 1980; Johnston and Mueller, 1987; Sasai, 1991a) were used to calculate

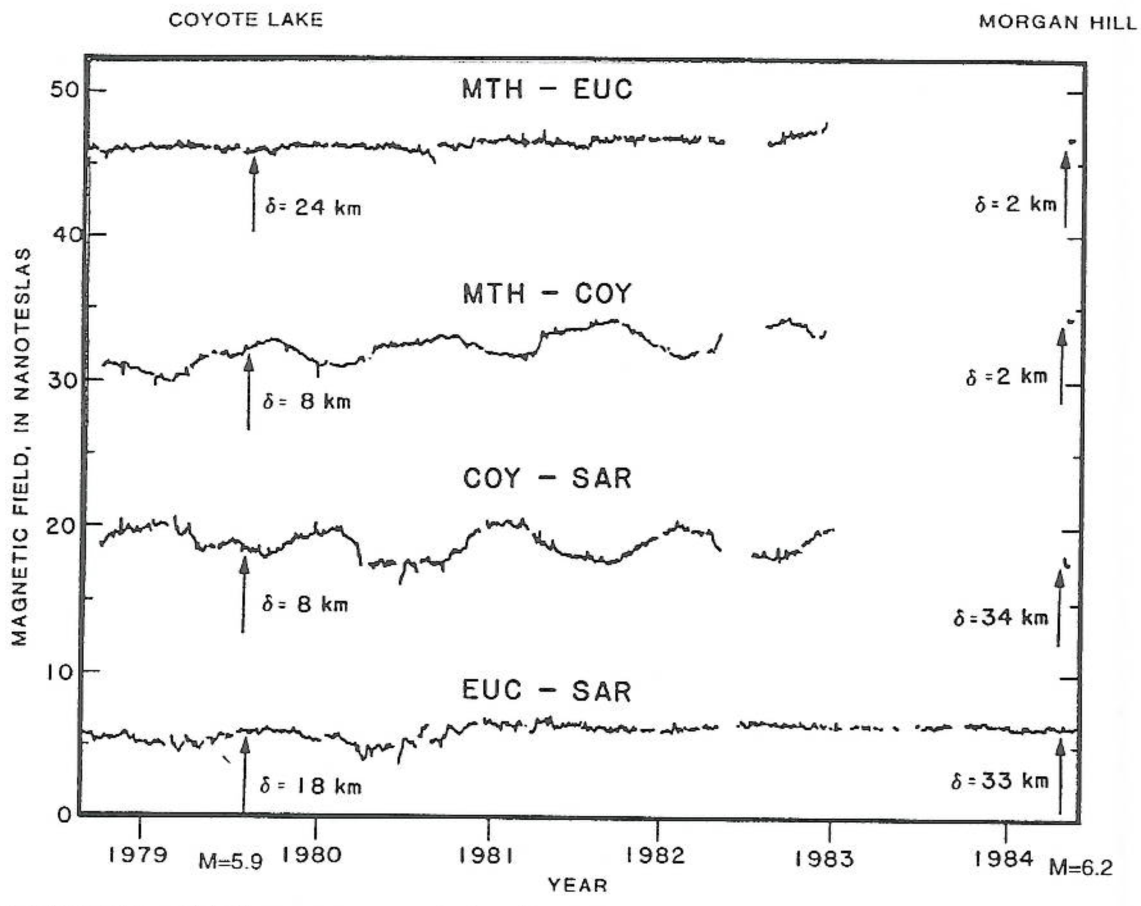


Fig. 3. Differential magnetic field measurements near the time of the M 5.9 Coyote Lake earthquake on 6 August 1979 and the Morgan Hill earthquake on 24 April 1984. Both events occurred on the Calaveras Fault. No piezomagnetic signals were observed during these events (Johnston et al., 1981; Mueller and Johnston, 1987). Distance (*D*) between epicenter and nearest magnetometer. Shows complete time history for sites COY and MTH.

the expected coseismic magnetic field change at the earth's surface for each seismic event. Model parameters were based on estimated fault geometry using seismic and geodetic data from each event. Induced rock magnetization was estimated from surface samples near the various magnetometer sites and $2–3 \times 10^{-3}$ MPa was assumed for stress sensitivity (Table 1).

The first event was the M5.9 Coyote Lake earthquake on 6 August 1979 that occurred on the Calaveras fault 100 km SE of San Francisco, CA. The nearest magnetometer (COY) was located 5 km SE of the epicenter. No magnetic anomalies greater than the noise in these data were observed (Fig. 3, Johnston et al., 1981; Davis et al., 1981). Based on surface slip, geology, and seismic data (Lee et al., 1979), the calculated piezomagnetic surface anomaly (Table 1) for the coseismic stress release (seismomagnetic) indicates that the telemetered magnetometer site was located near a null in the theoretical magnetic field generated by this earthquake (Johnston et al., 1981). Additional magnetometer sites were installed 3–4 days after the main shock near regions of maximum expected magnetic anomaly in an effort to record postseismic magnetic field changes associated with this event (Johnston et al., 1981; Davis et al., 1981). Stress release estimates from aftershocks (Lee et al., 1979) indicate a maximum magnetic field anomaly of 0.2 nT which is below the noise level of the measurements. No magnetic field anomalies were observed before, during, or after the M5.9 Coyote Lake earthquake.

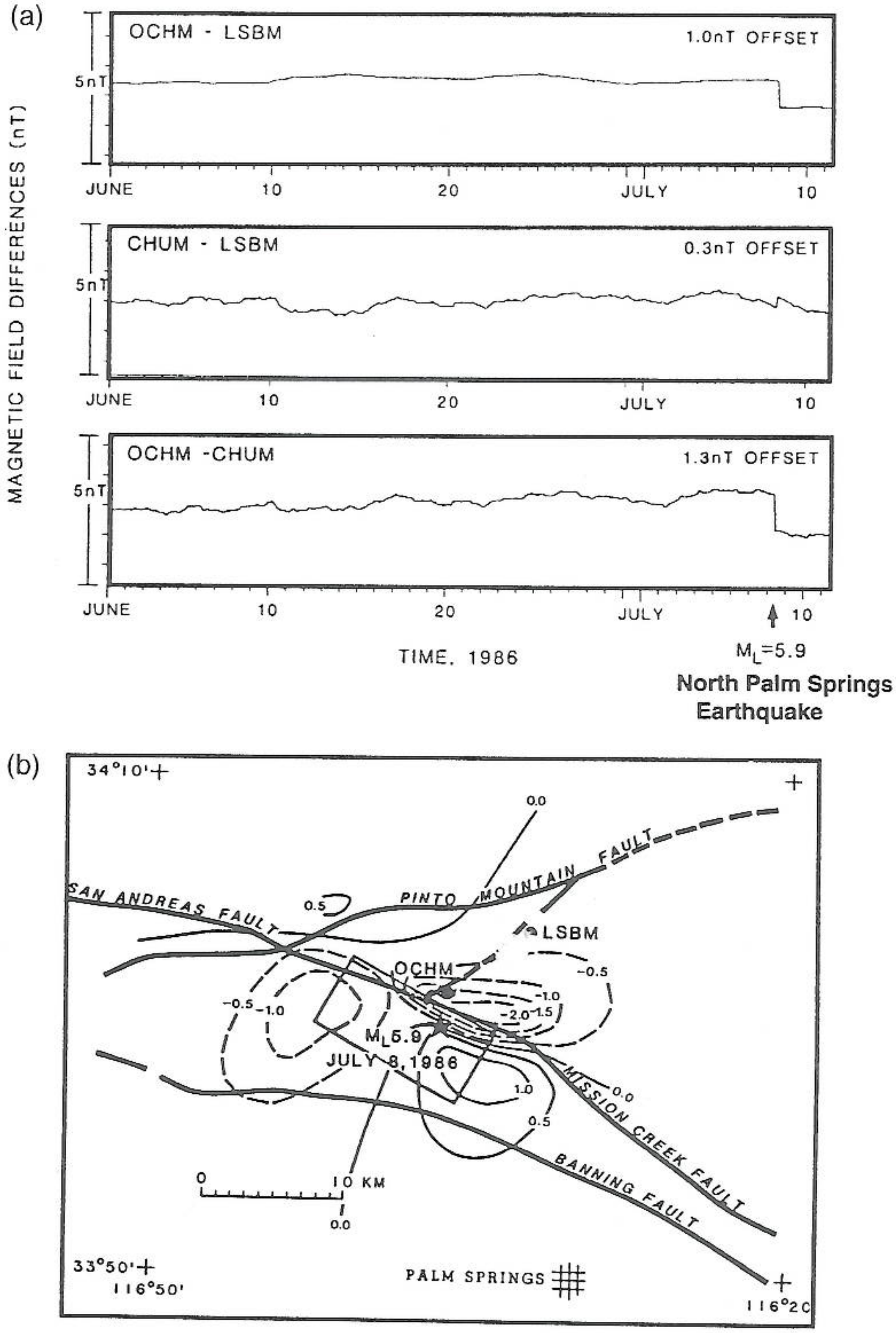
The second event was the M6.2 Morgan Hill earthquake on 24 April 1984 (Eaton, 1987) which also occurred on the Calaveras fault rupturing the segment just north of the Coyote Lake earthquake. The nearest magnetometer (MTH) site was located 2 km east of the epicenter, but neither magnetometer (MTH or COY) were operating at the time of or the 16 month period prior to this event. The sites were reoccupied within 24 h of the earthquake. A least squares fit to the preseismic data was projected to the postseismic data, and no anomalous magnetic field changes were observed in these data (Fig. 3). A seismomagnetic model for this event calculates a field change of −0.6 nT to 1.0 nT at magnetometer MTH (Mueller and Johnston, 1987). Due to the lack of data during the 16 months prior to the event, any preseismic signal can not be detected and the theoretical offset is below the measurement resolution of these data.

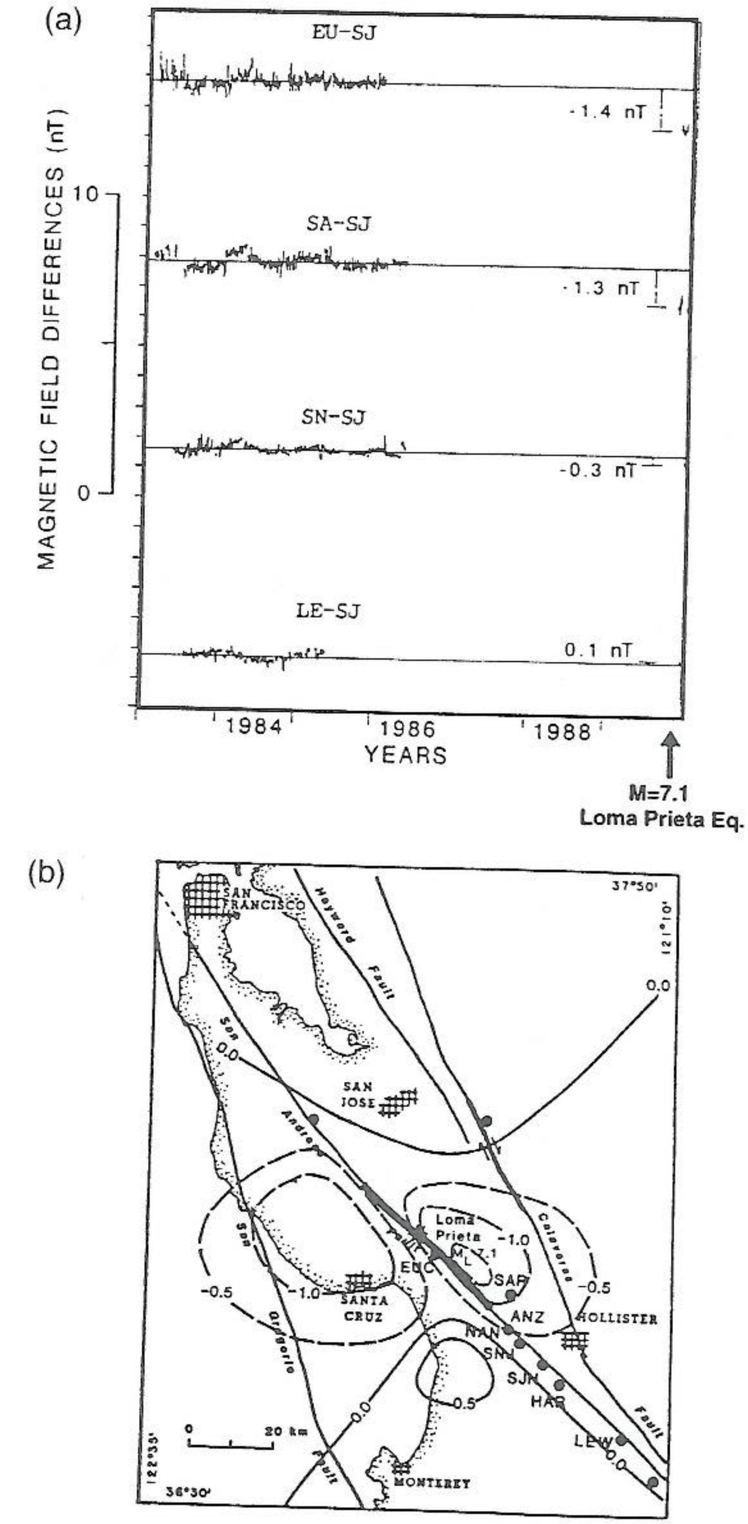
The third event was the M5.9 North Palm Springs earthquake that occurred on 8 July 1986 in Southern California about 28 km north of Palm Springs (Johnston and Mueller, 1987). This earthquake occurred directly beneath magnetometer site OCH and within 10 km of site LSB. The magnetometer sites recorded a 1.3 nT and 0.3 nT coseismic decrease in total

Table 1
Summary of five earthquakes ($M > 5.8$) located within 20 km of a magnetometer site

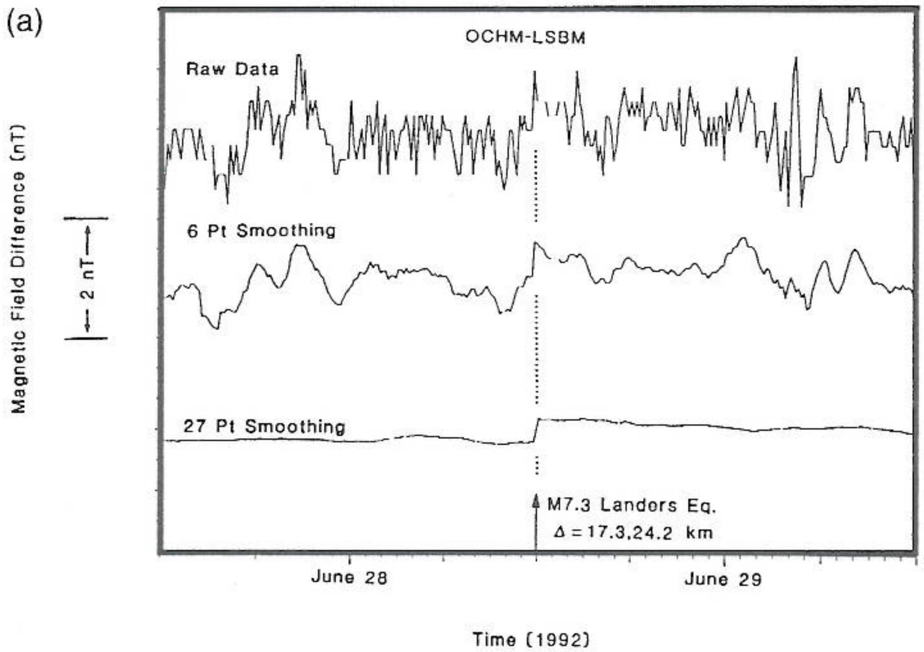
Event	Date	Location		Magnitude	Moment	Calculated	Observed
Model parameters	Year/month/day	Latitude (width)	Longitude (length)	ML or MW[a] (slip)	Nm	nT	nT (rock magnetism)
Coyote Lake	79/08/06	37.10 10 km	−121.51 21 km	5.9 0.1 M	6×10^{17}	−0.3	< 0.8 1 A/M
Morgan Hill	84/04/24	37.31 10 km	−121.68 21 km	6.2 0.1 M	1.9×10^{18}	−0.6 to 1.0	< 0.8 1 A/M
North Palm Springs	86/07/08	34.00 7 km	−116.61 16 km	5.9 0.2 M	7×10^{17}	−1.1	−1.2 1 A/M
Loma Prieta	89/10/18	37.04 13 km	−121.88 42 km	7.1 2.3 M	2.7×10^{19}	−1.0 −1.0	−1.4 1.5 A/M
Landers	92/06/28	34.20 10 km	−116.44 100 km[a]	7.3[a] 1–5 M	1×10^{20}	−1.4	−1.2 2 A/M

[a]Seismomagnetic model for Landers Earthquake used 11 fault segments along 100 km of the fault and summed the results (Johnston et al., 1994).

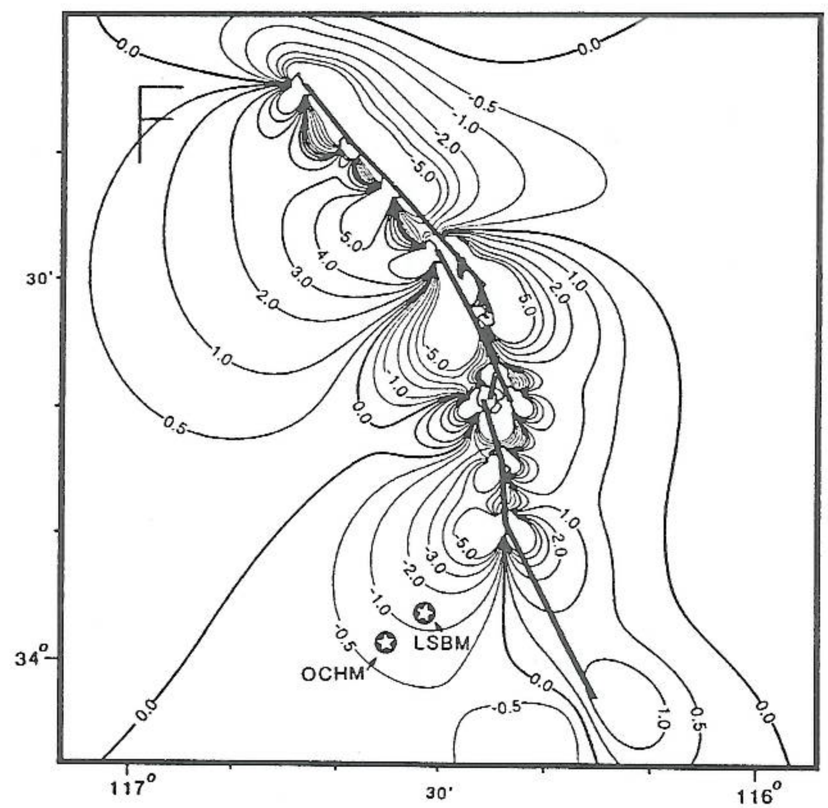

(a)
MAGNETIC FIELD DIFFERENCES (nT)
OCHM - LSBM
1.0nT OFFSET
CHUM - LSBM
0.3nT OFFSET
OCHM -CHUM
1.3nT OFFSET
5nT
JUNE
10
20
JULY
10
TIME, 1986
M$_L$=5.9
North Palm Springs
Earthquake
(b)
34°10'
33°50'
116°50'
116°20
SAN ANDREAS FAULT
PINTO MOUNTAIN FAULT
MISSION CREEK FAULT
BANNING FAULT
LSBM
OCHM
M$_L$5.9
JULY 8,1986
10 KM
PALM SPRINGS


(a)
EU-SJ
-1.4 nT
SA-SJ
-1.3 nT
SN-SJ
-0.3 nT
LE-SJ
0.1 nT
MAGNETIC FIELD DIFFERENCES (nT)
10
0
1984
1986
1988
YEARS
M=7.1
Loma Prieta Eq.
(b)
SAN FRANCISCO
Hayward Fault
San Andreas Fault
SAN JOSE
Loma Prieta M_L 7.1
Calaveras
SANTA CRUZ
San Gregorio Fault
HOLLISTER
MONTEREY
EUC
SAR
ANZ
NAN
SNJ
SJN
HAR
LEW
37°50'
121°10'
122°35'
36°30'
0 20 km
0.0
-0.5
-1.0
0.5

(a)


OCHM-LSBM
Raw Data
6 Pt Smoothing
27 Pt Smoothing
Magnetic Field Difference (nT)
2 nT
M7.3 Landers Eq.
Δ = 17.3, 24.2 km
June 28
June 29
Time (1992)

(b)


LSBM
OCHM
30'
34°
117°
30'
116°

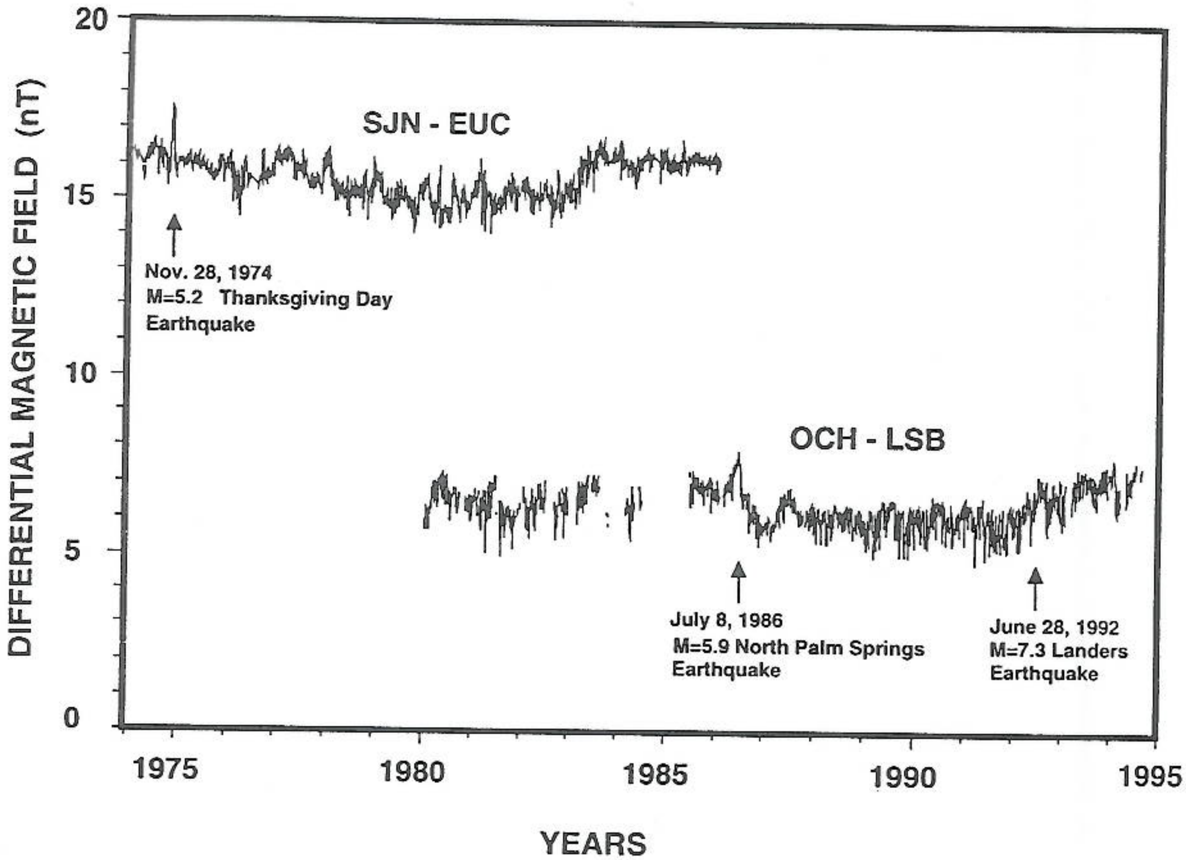


Fig. 7. Total time history of two differenced magnetic field data sets from Northern and Southern California. These daily averaged data illustrate the amplitude of observed changes relative to background noise levels. Data gaps are due to instrument or telemetry failures.

magnetic field related to this event (Fig. 4a). This is the first coseismic or seismomagnetic change observed in this magnetometer network.

Inversion techniques involving both geodetic and seismic data (Jones et al., 1986) were used to determine fault plane geometry and slip for this earthquake. These fault parameters were then used in a seismomagnetic model by Johnston and Mueller, based on the theory of Sasai (1980, 1991a). Fig. 4b shows the calculated anomaly from this model. Predicted values at the magnetometer sites provide a reasonable fit to the observed data (Table 1).

The next earthquake to occur within two rupture lengths of a magnetometer site was significantly larger than the three previous earthquakes. This event was the M7.1 Loma Prieta earthquake on 18 October 1989 (Dietz and Ellsworth, 1990). The earthquake was located 70 km SE of San Francisco, CA on the

Fig. 4. (a) Plot of differential magnetic field at sites OCH and LSB located near the North Palm Springs earthquake on 24 July 1989. (b) Seismomagnetic model for the North Palm Springs earthquake based on geodetic and seismic data using theory from Sasai, 1980.

Fig. 5. Differential magnetic field data at four site pairs (a) and seismomagnetic model (b) for the $M = 7.1$ Loma Prieta earthquake on 18 October 1989 (Mueller and Johnston, 1990).

Fig. 6. Differential magnetic field data (a) and seismomagnetic model (b) for the $M = 7.3$ Landers earthquake on 28 June 1992 (Johnston et al., 1994). Distance (D) between epicenter and magnetometers.

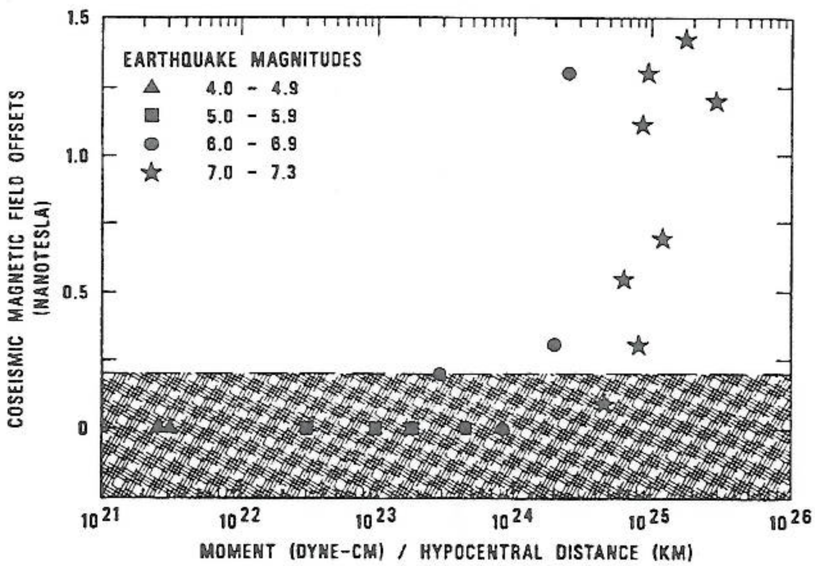


Fig. 8. Plot of coseismic magnetic field offsets vs. moment scaled by distance for seismic events discussed in the text. The shaded region represents measurement resolution of the data. This plot suggest that only earthquakes with magnitudes of about $M = 6$ or greater are capable of generating seismomagnetic signals of a few nanotesla in amplitude.

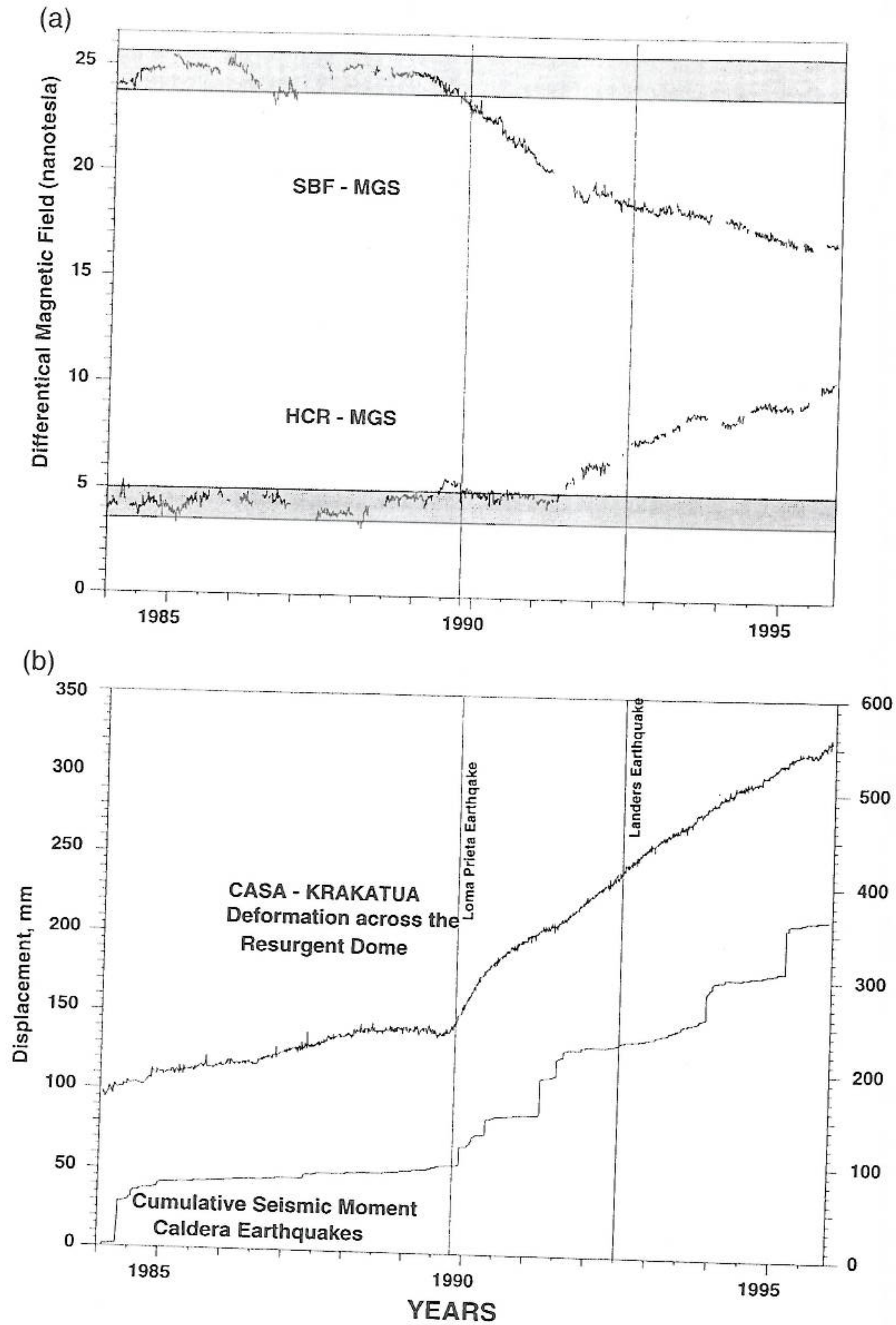
San Andreas fault (Fig. 1). Although, several sites were installed and had operated for many years near the epicenter of the earthquake, these magnetometers were not in operation at the time of or during the 3 year period prior to the earthquake. These sites were reoccupied within 36 h after the earthquake. Extrapolation of least square fits to the data obtained before the earthquake were used to determine coseismic offsets related to the earthquake (Fig. 5a). Sites located nearest the epicenter had the largest offsets and these offsets decreased with increased distance from the epicenter (Mueller and Johnston, 1990). Offsets ranged in amplitude from 1.4 nT to 0.3 nT.

A dislocation model of the earthquake was developed based on geodetic and seismic data (Dietz and Ellsworth, 1990; Lisowski et al., 1990). These same model parameters were used together with estimates of rock magnetization to construct a seismomagnetic model of the earthquake. This model was then used to calculate the expected magnetic field change for this earthquake (Table 1) (Mueller and Johnston, 1990). The calculated values from this model are in good agreement with the offsets observed at the various sites in the region (Fig. 5b).

The latest and largest earthquake to occur near a recording magnetometer site was the M7.3 Landers Earthquake on 28 June 1992 located 40 km north of Palm Springs in Southern CA (Johnston et al., 1994). Magnetometer sites LSB and OCH (Fig. 1) were located 17 km and 25 km from the earthquake epicenter. Data from the two sites indicate coseismic changes of -1.2 and -0.7 nT related to this event (Fig. 6a). A dislocation model developed from geodetic measurements (Murray et al., 1993; Sylvester, 1993) in the Landers region were used in a seismomagnetic model to calculate seismomagnetic changes for this event. The observed data are in general agreement with this model for the earthquake (Fig. 6b, Table 1) (Johnston et al., 1994).

No other clearly observed magnetic field anomalies were detected in the two decades of monitoring along the San Andreas fault. The total time history

Fig. 9. Differential magnetic field (a) from two sites located in the Long Valley caldera. Shaded area represents two standard deviations on pre-1989 differential magnetic field data. Geodetic strain data and seismic moment (b) measured in the Long Valley caldera over the same time period. These data indicate a temporal correlation between magnetic field change and increased deformation and seismic activity.


(a)
Differentical Magnetic Field (nanotesla)
25
20
15
10
5
0
SBF - MGS
HCR - MGS
1985
1990
1995
(b)
Displacement, mm
350
300
250
200
150
100
50
0
600
500
400
300
200
100
0
Loma Prieta Earthquake
Landers Earthquake
CASA - KRAKATUA
Deformation across the
Resurgent Dome
Cumulative Seismic Moment
Caldera Earthquakes
1985
1990
1995
YEARS

for two sets of differential magnetic field data are shown in Fig. 7. These data illustrate the signal amplitude versus background noise level. The observations discussed above are summarized in Table 1. An important feature of these data can be illustrated by plotting the observed coseismic offsets versus the earthquake moments divided by the hypocentral distance (Fig. 8). These data suggest that only earthquakes within one earthquake rupture length and with magnitudes of about $M = 6$ or greater are capable of generating coseismic seismomagnetic signals of a few nanotesla in amplitude on the San Andreas fault.

4. Long Valley caldera results

Two magnetometers were installed inside the Long Valley caldera in 1983 together with a third reference magnetometer installed 26 km southeast of the caldera (Fig. 1). The most significant change in magnetic field to occur here has been a 5 nT decrease at site SBF located closest to the center of the resurgent dome inside the caldera (Fig. 9) from mid-1989 to 1991 (Mueller et al., 1991), followed by a continuous decrease of 3 nT from 1991 to 1996. From 1991 to 1996, the field at the second site in the caldera (HCR) has increased by more than 6 nT.

From October 1989, dramatic inflation of the caldera has been observed with geodetic strain increase of 8.5 ppm/a on the two-color geodimeter network within the caldera which was followed by an increase in seismic activity starting in December 1989 (Langbein et al., 1993). A simple dilatational point-source model at a depth of about 7 km beneath the center of the resurgent dome can be fit to the strain data. If this same model is used to calculate piezomagnetically generated magnetic fields expected in the caldera (Sasai, 1991b), the results obtained agree with the observed local magnetic field data provided the Curie point isotherm is at a depth (≤ 5 km, Fig. 10) (Mueller et al., 1991). Taken together, these magnetic, seismic and geodetic data suggest that an episode of active magmatic intrusion occurred from late 1989 through 1995 at a depth of 7–8 km beneath the resurgent dome within the Long Valley caldera. The magnetic field changes observed in the Long Valley region are the largest

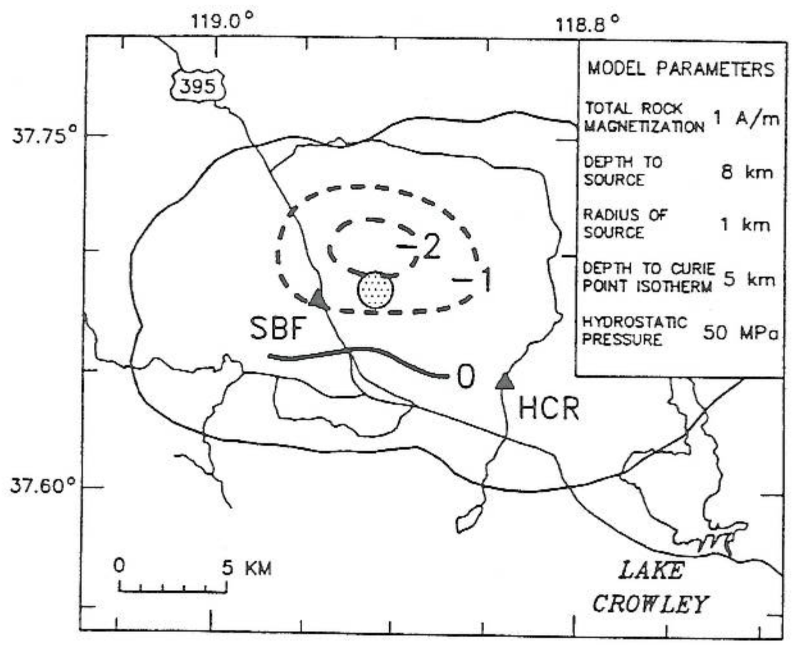


Fig. 10. Piezomagnetic model using a dilational point source at a depth of 7 km beneath the center of deformation in the Long Valley Caldera. Requires curie point isotherm to be less than 5 km in order to fit observed magnetic field data (Mueller et al., 1991).

observed in the network of magnetometer sites during the last two decades.

5. Conclusion

In this paper, we have focused on coseismic piezomagnetic effects since these provide the clearest demonstration of a causal relation between crustal stress changes and local magnetic field changes. Short and intermediate term preseismic and postseismic stress and strain changes are observed to be smaller than those generated coseismically (Johnston et al., 1987). If correspondence between observed field changes and earthquake moment/mechanism can be demonstrated then changes at other times can be reasonably interpreted in term of changes in crustal stress. We have observed such coseismic field changes with a number of earthquakes in California but only when the magnitude is greater than M5.8 and when measurements are within one earthquake rupture length. The observed changes are not more than a few nanotesla. To place these coseismic observations in perspective, we have updated the plot from Rikitake, 1979 (Fig. 11). If the observed coseismic offsets represent the release of accumulated crustal stress acquired during the entire earthquake recurrence period, then detection of precursive signals resulting from the release of a small fraction of the accumulated stress will be difficult with available instruments and background noise limitations. We have observed just one case of a clear preseismic magnetic field anomaly in over two decades of recording (Smith and Johnston, 1976). The amplitudes of inferred stress changes on active faults from the coseismic magnetic field observations and general absence of magnetic field precursors are in agreement with recent fault models that infer low shear strength of the fault on the basis of near-normal principal stress and low heat flow on active faults (Rice, 1992; Byerlee, 1993). The largest magnetic field changes observed in the network are associated with the Long Valley caldera and are believed to be caused by on going magmatic intrusion occurring beneath the caldera between 1989 and the present.

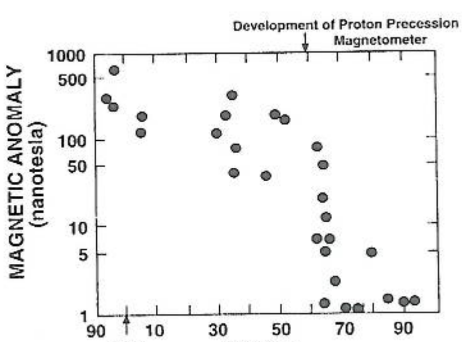


Fig. 11. Plot shows decrease in observed magnetic anomalies with time. A significant decrease is related to the development of more accurate and stable proton precession type instruments (updated from Rikitake, 1979).

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