Bulletin of the Seismological Society of America, Vol. 83, No. 2, pp. 347–357, April 1993

COMPARISON OF ULTRA-LOW FREQUENCY ELECTROMAGNETIC SIGNALS WITH AFTERSHOCK ACTIVITY DURING THE 1989 LOMA PRIETA EARTHQUAKE SEQUENCE

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ABSTRACT

Ultra-low frequency (0.01 to 10.0 Hz) magnetic field fluctuations near the epicenter of the 1989 Loma Prieta earthquake rose sharply immediately before the earthquake following indications of increased disturbance during the previous 12 days. The magnetic activity remained much higher than the pre-earthquake background level for 6 weeks following the mainshock. These observations suggest a causal relationship between the earthquake failure process and the magnetic signals. A search for similar precursory electromagnetic signals associated with aftershocks of this earthquake yields negative results. Specifically, no correlation appears to exist between the amplitude of the electromagnetic activity and the frequency or magnitude of aftershocks following the mainshock. Either a "threshold" earthquake magnitude larger, in this case, than M_L 5.5, may be necessary to generate precursory electromagnetic signals or the continued generation of magnetic signals related to the mainshock may have masked signals generated by the larger aftershocks.

INTRODUCTION

As reported by Fraser-Smith *et al.* (1990) and Bernardi *et al.* (1991), ultra-low-frequency (ULF) magnetic energy (0.01 to 10.0 Hz) increased almost 12 days before the 17 October 1989, Loma Prieta earthquake. Just 3 hours before the mainshock, the signal strength increased more dramatically. If these signals can be shown to be casually related to the earthquake failure process, then these measurements might provide an important tool for earthquake prediction.

The anomalous magnetic signals persisted for several months following the mainshock (Fig. 1). To understand the cause of these signals, we have attempted to relate the magnetic signal strength following the Loma Prieta earthquake to the aftershocks. Many relevant parameters such as geometry and electrical conductivity should remain similar to their values prior to the mainshock, although large differences are present in the magnitude (size) of the events and the new state of stress in the hypocentral region.

The ULF magnetic data recorded following the Loma Prieta aftershock sequence have a number of problems that impact the most straightforward cross-correlation with aftershock occurrence. Almost 35 hours of data are missing immediately following the earthquake as a result of power loss in the recording instrument at Corralitos, California. Several similar gaps occur in the data in the months that follow. In June 1990, instrument problems render the data unusable. Aside from these glitches, the magnetic time series is fairly complete for nearly 8 months.

During this same time period (19 October 1989 to May 1990), the USGS recorded numerous aftershocks (Fig. 1). In this paper, we search for a correlation between the aftershocks and the magnetic signals, and we look at the implications this might have for physical mechanisms generating the signals.

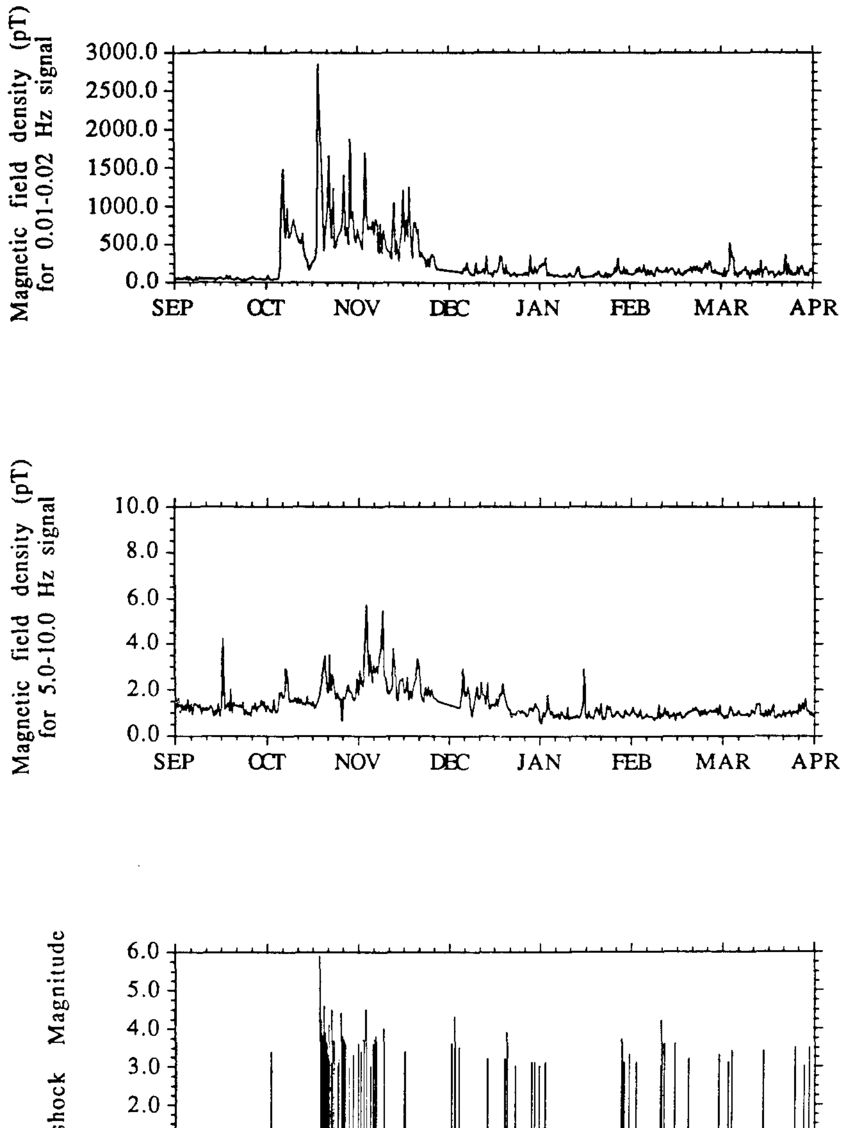

FIG. 1. Seven-month plot of Loma Prieta aftershocks ($M_L > 3.0$) and geomagnetic field values from September 1989 to April 1990.

ULF DATA

A limited passband magnetometer that records geomagnetic activity in the ULF range was deployed in Corralitos, California, in June 1989 to monitor ambient noise levels. The device uses solenoid coils as sensors and outputs a set of magnetic activity (MA) indices that are logarithms to the base two of the half-hourly averages of the power in nine frequency bands. These indices can be simply converted to picoteslas (pT) given the particular frequency bandwidth and a conversion factor (see Fraser-Smith *et al.*, 1990). The close proximity of this instrument to the October 1989 Loma Prieta earthquake at an epicentral distance of only 7 km led to the serendipitous discovery of the ULF signal anomalies associated with that event.

The anomalous ULF magnetic signals were not observed at other magnetometer stations in California (Mueller and Johnston, 1990; Fraser-Smith *et al.*, 1990), or elsewhere. This is attributable in part to their frequency content, which is high compared with those typically measured by geomagnetic observatories. For this reason, few systems in operation could detect them. Another possible reason is the expected distance dependence of the signals and the short range to Corralitos where the anomaly was observed. Assuming that the source of the signals was electric or magnetic dipoles, Fraser-Smith *et al.* (1993) estimate that the range of the ULF signals (for which the signal-to-noise ratio was greater than unity) was at best about 100 km. The dipole sources were assumed to be at the hypocenter of the earthquake, which was relatively deep (17.6 km), and smaller depths would give greater range. In addition, signals in this same frequency band were not detected on high sensitivity strainmeters, 35 km distant (Johnston *et al.*, 1990), or on nearby seismometers (White and Ellsworth, 1993). These data may further constrain the source size, if not the physical mechanisms involved. It is clear that the range of the signals was limited and that they were unlikely to have been detected except at stations within a range of a few hundred km of the epicenter. Another low-frequency noise measurement system was in operation on the Stanford campus during the interval under consideration, but its frequency range is 10 to 32 kHz and its measurements could not be used to confirm those made at Corralitos. As reported by Fraser-Smith *et al.* (1990), there were no detectable changes in the Stanford measurements prior to the earthquake.

Figure 2 (adapted from Fraser-Smith *et al.*, 1990) shows the changes in two of the magnetic frequency bands for October 1989 as recorded at the Corralitos site. As explained in detail elsewhere (Fraser-Smith *et al.*, 1990; Bernardi *et al.*, 1991), neither strong seismic activity nor magnetic storm activity can explain this large increase in the magnetic field amplitude. There were virtually no earthquakes (only one with magnitude > 3.0) in the month before the earthquake, and magnetic storms were neither at the right times nor of the right duration to account for the magnetic anomalies recorded at Corralitos (Fraser-Smith *et al.*, 1990). Further, the magnetospheric activity is recorded over a wide frequency range; therefore, determining the magnitude of these disturbances for a particular band (such as 0.01 to 0.02 Hz) is not possible.

The effects observed before the earthquake range from a marked increase in the 0.01 to 0.02 Hz band to almost no discernible change for the 5.0 to 10.0 Hz range. The 0.01 to 0.02 Hz average magnetic field amplitude exhibits two major increases in activity. On 5 October, the 0.01 to 0.02 Hz signal increases from 50 to 2000 pT. This factor of 24 increase in amplitude occurs nearly 12 days before the earthquake. The larger second jump occurs from 21:30 16 October to the time of the earthquake, at 00:04 minutes UT, 18 October, an increase from 210 to 6700 pT. This is about a factor of 30 increase over this 2-day period and a factor of about 134 increase over the original background level. While there is a change, the effect is far less noticeable for the 5.0 to 10.0 Hz signal; the episode on 5 October changes from only 1 to 4 pT. The 0.01 to 0.02 Hz signal shows the most dramatic increase in amplitude of any of the recorded frequency bands, indicating that the anomaly was only detectable at ultra-low frequencies. The

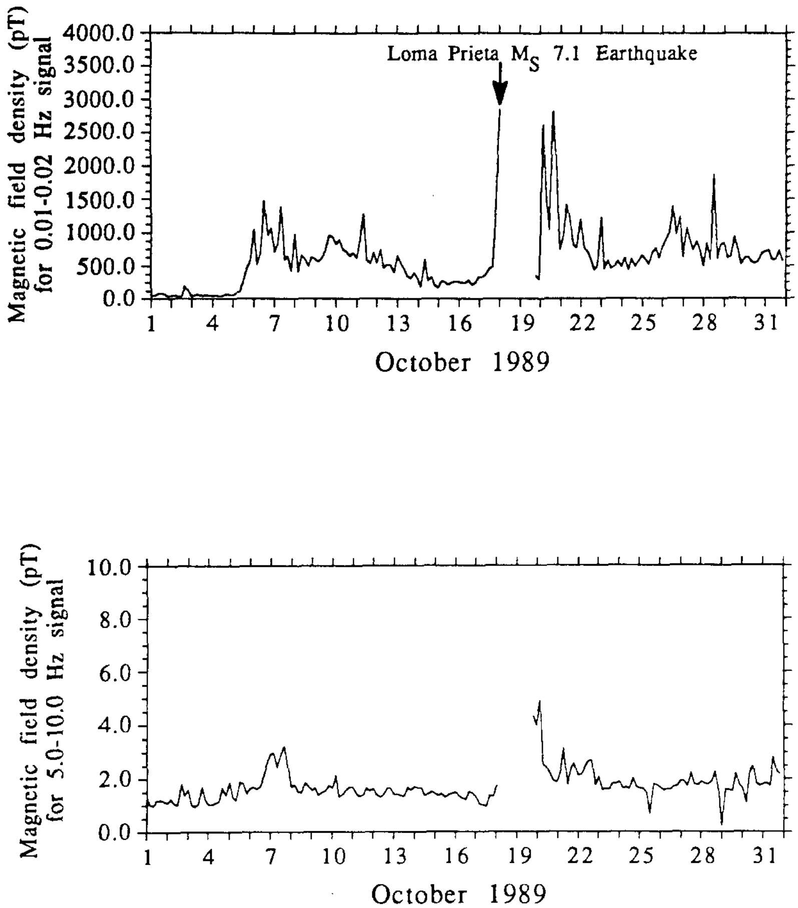

FIG. 2. Comparison of the magnetic precursor signal in 0.01- to 0.02-Hz and 5.0- to 10.0-Hz frequency bands during October 1989. The gap from 18 to 20 October results from power loss following the Loma Prieta Earthquake.

failure of the higher-frequency measurements at Stanford to show any unusual magnetic activity further supports this observation.

Figure 3 shows the 0.01 to 0.02 Hz and 5.0 to 10.0 Hz signal strength for July 1989, when there was virtually no seismic activity in the Corralitos vicinity. During this time, there are indications of a diurnal variation, which has an amplitude (in the 0.01 to 0.02 Hz signal) variation of about 80 pT. The typical diurnal variation virtually disappears during the aftershock sequence of the Loma Prieta earthquake.

LOMA PRIETA AFTERSHOCKS

The available aftershock data (Oppenheimer, USGS, Menlo Park, California) include all earthquakes with magnitudes ≥ 2.5 within the geographical window (36.5° N, 121.0° W) to (37.4° N, 122.2° W) shown in Figure 4. The only earthquake aftershock parameter considered is event magnitude. No attempt was made to account for the hypocentral distance of the events. As expected, the number of aftershocks decreases rapidly with time after the mainshock. While

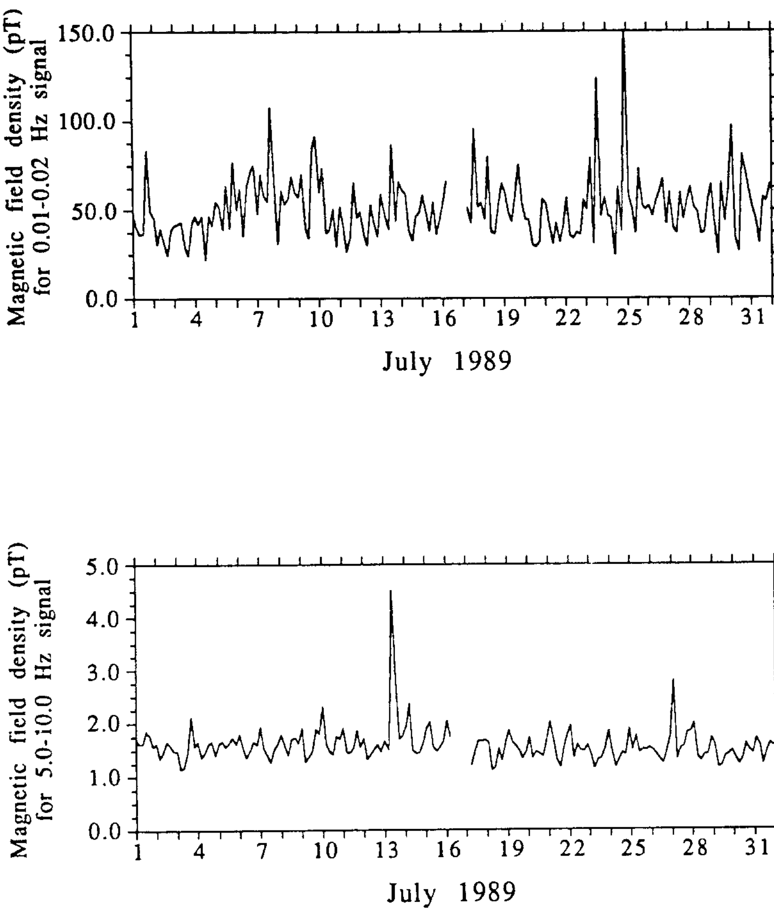

FIG. 3. Comparison of the magnetic signal in 0.01- to 0.02-Hz and 5.0- to 10.0-Hz frequency bands during July 1989. The values in July 1989, when there was no felt earthquake activity, are much lower than their counterparts in October 1989 and display a diurnal variation.

three earthquakes with $M_L > 4.0$ occurred in November, two occurred in December and only one occurred during the first three months of 1990 (7 February). A substantial resurgence of earthquakes in the region occurred in April, including a M_L 5.5 on 18 April 1990.

METHODS OF INVESTIGATION

Simple Cross-Correlation

The aftershock magnitude and magnetic signal strength form two time series. Figure 5 shows the cumulative seismic moment of aftershocks and the complete 0.01 to 0.02 Hz signal from October 1989 to May 1990. The first quantitative attempt to compare the two time signals was by simple cross-correlation of the 0.01 to 0.02 Hz signal with the aftershock magnitude. Initially, monthly data sets were used; i.e., November 1989 aftershocks were correlated with the magnetic data from October to December. This choice is arbitrary; the month merely serves as a convenient time unit.

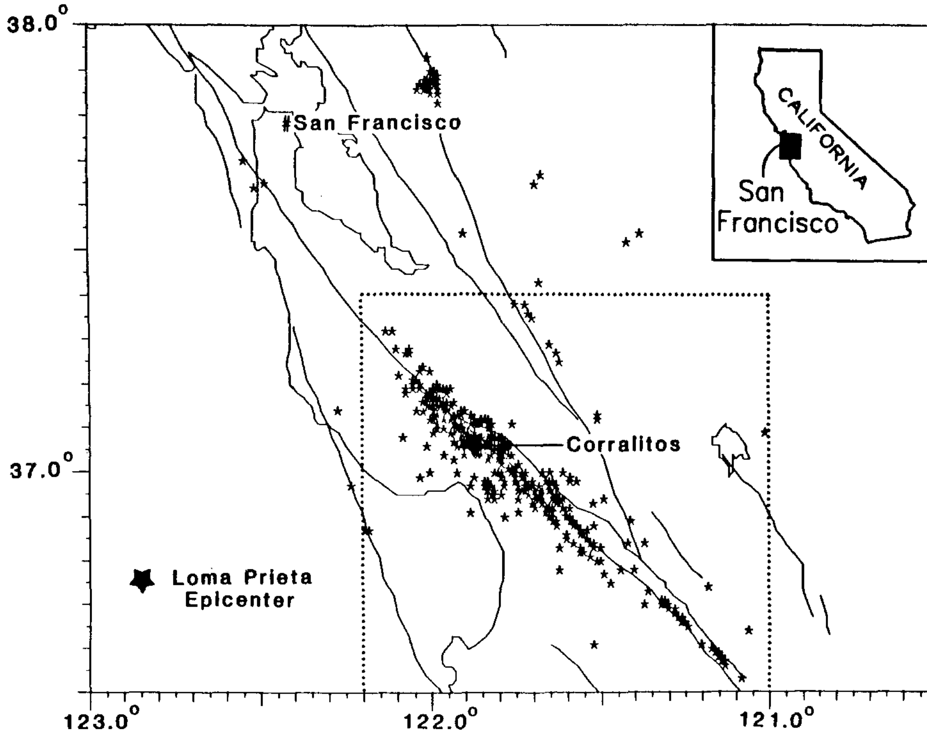

FIG. 4. Map of the geographical region around Loma Prieta showing both the earthquake epicenters and the location of the Corralitos recording instrument. The dotted inset box represents the boundary of the aftershocks used to determine correlation with the recorded magnetic indices.

The cross-correlation of two time series, $g(t)$ and $h(t)$, is defined as

$$\mathrm{Corr}(g, h) = \int_{-\infty}^{\infty} g(t + \tau) h(\tau)\, d\tau,$$

where τ is the temporal offset of $g(t)$ with respect to $h(t)$. However, correlations are simpler to calculate in the Fourier domain, where the cross-correlation can be written

$$\mathrm{Corr}(g, h) = G(f) H^*(f).$$

For this problem, $G(f)$ is the Fourier transform of the magnetic field amplitude time signal and $H^*(f)$ is the complex conjugate of the Fourier transform of the aftershock time series. We use a nearest half-hour sampling rate for the aftershock activity to match that of the Corralitos geomagnetic instrument. Several seismic events may occur in the same time interval. In that case, the events are added logarithmically to determine the moment release (Aki, 1987) using the relation

$$10^{M_T} = 10^{1.5M_1+15.8} + 10^{1.5M_2+15.8} + \cdots 10^{1.5M_n+15.8}.$$

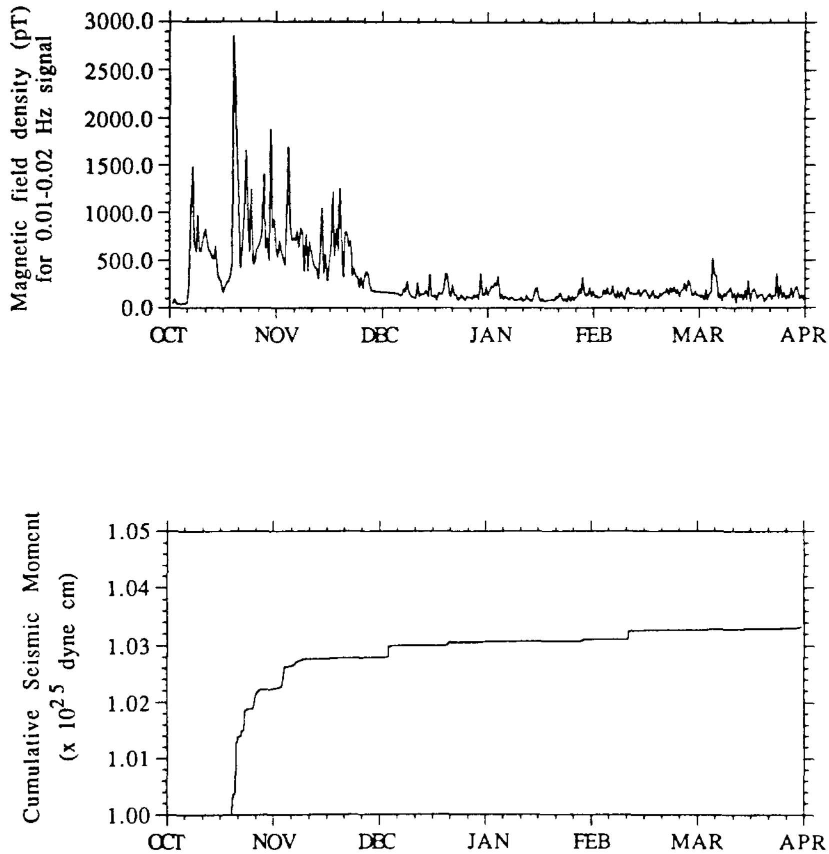

FIG. 5. Seven month comparison of the 0.01- to 0.02-Hz signal and the cumulative seismic moment from October 1989 to May 1990.

After binning the earthquakes, we calculate the correlation coefficient and test its significance level.

The simple cross-correlation failed to yield any strong indication of a correlation between the ULF magnetic field fluctuations and the Loma Prieta aftershocks. This result holds true even when we restrict our study to the aftershocks closest to the Corralitos instrument. Figure 6 shows the correlations for December 1989 to March 1990, which are plotted in terms of the time lag in days. A negative time lag represents the magnetic data preceding (or forecasting) the aftershock data. If the magnetic signals precede seismicity, one might expect a peak in correlation amplitude several hours or even days before the events. Such peaks are not evident in these results. In fact, only the December data shows a generally higher trend for negative time lags; rather, a broad rise exists between -12 and -3 days. Several mechanisms may explain this apparent inconsistency.

For example, a direct correlation of events effectively ignores the variability of aftershock size. The electromagnetic signals might precede a magnitude 3 event by one day, but precede a larger aftershock by several days. Consequently, no peak would exist; rather, there would be a region of high correlation smeared out across negative time lags. Alternately, the huge increase in the magnetic

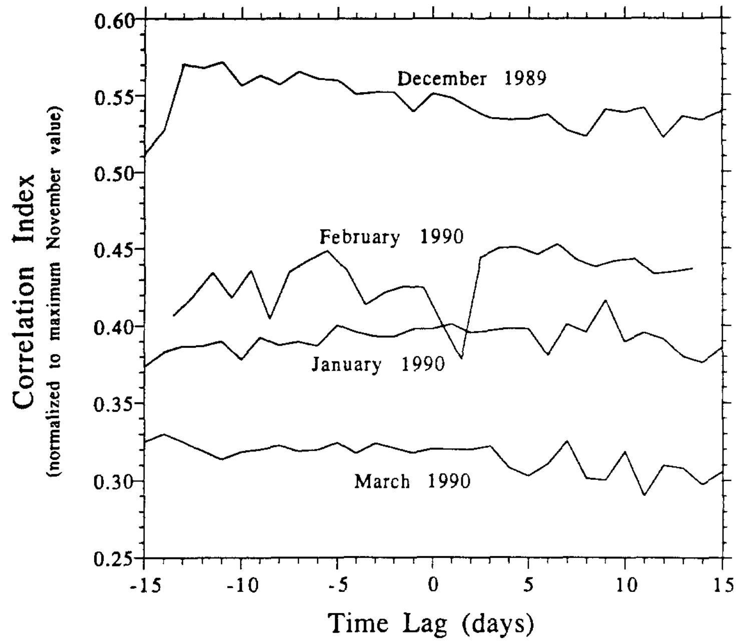

FIG. 6. Comparison of monthly cross-correlations of the 0.01- to 0.02-Hz magnetic signal with the aftershock sequence for December 1989 to March 1990. Negative time lags correspond to precursory magnetic signals. Note that only the results for December 1989 show any generally higher level of correlation in the negative time lags.

signal assumed to be related to the Loma Prieta event may be large enough to overshadow smaller predictive events.

Running Least-Squares Correlation

Another way to search for a possible relationship is through linear correlation of aftershock frequency with magnetic signal strength data. The degree of association is defined through the linear correlation coefficient, r, given by the formula

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_i - \bar{y})^2}},$$

where (x_i, y_i) are the pairs of quantities, $\bar{x}$ is the mean of the x_i's, and $\bar{y}$ is the mean of the y_i's. The linear correlation coefficient measures the strength of a significant correlation and ranges from -1 to 1. The value 1 indicates all the data points lie on a straight line with positive slope (Press *et al.*, 1989).

In our case, the (x_i, y_i) pairs correspond to the seismic and magnetic time series. For the running correlation, the entire seismic sequence initiated by the Loma Prieta earthquake was considered (October 1989 to March 1990) along with the associated magnetic signal data. However, to consolidate the data, the time series were organized into 6-hour intervals, providing a count of aftershocks and average magnetic signal values within the time window.

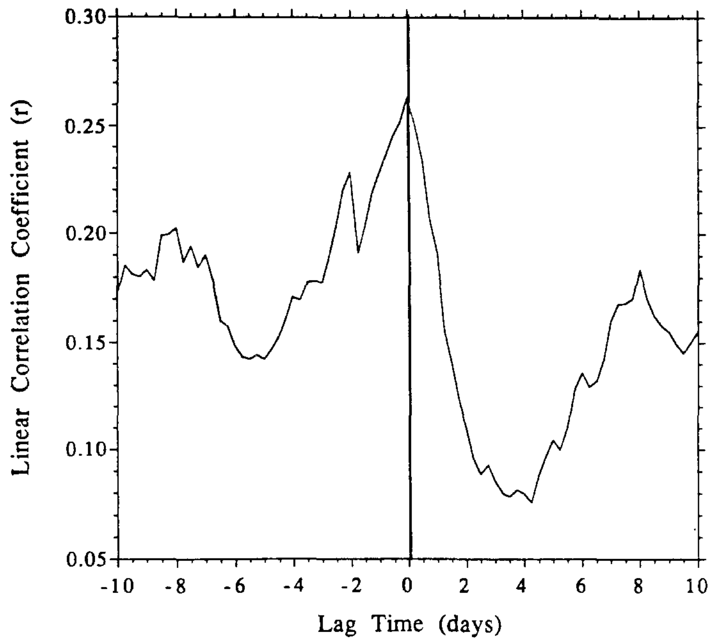

FIG. 7. Plot of the linear correlation coefficient between the entire aftershock sequence ($M_L > 3.0$) and the 0.01- to 0.02-Hz magnetic signal data set (October 1989 to April 1990). Negative time lags correspond to precursory magnetic signals. Though the coefficient is generally higher in the negative time lags, the level of correlation is not significant.

To find the appropriate pairs, the time series are offset with respect to each other. Hence, an offset of the aftershocks two samples forward in time corresponds to pairs of data indicating the magnetic energy preceding the seismic activity by 12 hours. The r value resulting from this pairing yields an approximation of correlation between the data sets. By changing the offset and calculating the r value, a best fit offset (or time lag) was determined. Figure 7 shows the result for the 0.01 to 0.02 Hz signal. Although a peak occurs for a time lag of -2 days (the magnetic signal preceding the aftershock sequence by 2 days), the r values are significantly below 0.5, which indicates no correlation exists.

Electromagnetic Index Stack

Direct correlation failed to show any significant relationship between the magnetic and aftershock sequences. The final attempt at seeking such a relationship involves the stacking technique frequently used in seismology, where stacking has been found to improve the signal-to-noise ratio of data. Here, the stack simply averages the magnetic signal data before and after aftershocks of magnitude 4 or larger.

Figure 8 shows the stack result. Again, no evidence of a predictive nature to the signal exists. However, there is a general decreasing trend from a time lag of -3 days to 1 day that corresponds to a drop of about 75 pT. If this decrease is characteristic for seismic activity, the result is likely drowned out by the overwhelming effect of the mainshock, which resulted in an electromagnetic field increase of nearly 6000 pT.

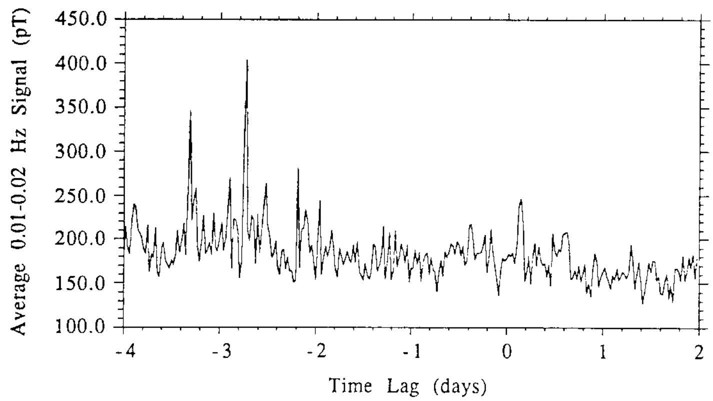

FIG. 8. Averaged stack of the 0.01- to 0.02-Hz magnetic signals in the temporal vicinity (from −4 to +2 days) of the Loma Prieta aftershocks ($M > 4$). Only seismic events separated by a minimum of 3 days are included. Negative time lags correspond to precursory magnetic signals.

CONCLUSIONS

This analysis shows that, in contrast to the results obtained just before the Loma Prieta earthquake (Fraser-Smith *et al.*, 1990), no significant correlation exists between the ULF electromagnetic signals and the aftershock sequence from the Loma Prieta earthquake. There may be obvious reasons for this.

The rise in the 0.01 to 0.02 Hz signal prior to the Loma Prieta earthquake is extremely large: the amplitude of the field fluctuations increases to 6000 pT in the hours before the event. While the magnetic field data then clearly show a gradual decrease in ULF magnetic signal amplitude from 18 October 1989 until mid-February 1990, magnetic signals associated with particular aftershocks may be too small to be detected. This would imply that a certain "threshold" magnitude (or seismic moment release) of earthquake may be necessary before the precursor magnetic signal reaches detectable levels. In the case of the Loma Prieta aftershock sequence, we would conclude that the minimum threshold value is about $M_L \geq 5.5$. This conclusion supports the observations by Fraser-Smith *et al.* (1990) for several other isolated $M_L > 5.0$ earthquakes prior to the Loma Prieta earthquake. Alternatively, changes in the state of the Earth's crust following rupture during the mainshock may disrupt the mechanism responsible for generating the mainshock magnetic effects from operating on the same scale for individual aftershocks.

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Manuscript received 17 February 1992