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RESULTS OF ULF MAGNETIC FIELD MEASUREMENTS NEAR THE EPICENTERS OF THE SPITAK (M_s = 6.9) AND LOMA PRIETA (M_s = 7.1) EARTHQUAKES: COMPARATIVE ANALYSIS

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Abstract. The characteristics of the ULF magnetic field emissions measured at two magnetic observatories in the Republic of Georgia prior to and after the M_s = 6.9 earthquake that occurred near Spitak, Armenia, on December 7, 1988, are compared with the apparently similar emissions associated with the M_s = 7.1 earthquake that occurred near Loma Prieta, California, on October 17, 1989. The main features of the Spitak measurements, according to observations made at the Dusheti station (128 km to the Spitak epicenter), as compared with the Loma Prieta measurements, which were made at Corralitos, California (7 km to the Loma Prieta epicenter), are the following: (1) The intensity of ULF background activity started growing 3 to 5 days before the Spitak earthquake, whereas the corresponding increase in activity began 12 days before the Loma Prieta earthquake; (2) a substantial ULF emission burst was recorded at Dusheti starting 4 hours prior to the main shock; a similar large burst of ULF activity commenced 3 hours before the Loma Prieta event, and continued until the occurrence of the main shock; (3) ULF activity remained high for about two weeks after the Spitak earthquake, and for several months after the Loma Prieta earthquake; (4) ULF noise bursts were observed 1 to 6 hours before powerful aftershocks at Spitak during the period of enhanced activity, but there was no conclusive link between the ULF noise at Corralitos and the aftershocks. A major difference in the ULF activity preceding the two earthquakes is a difference in amplitude (0.2 nT at Spitak and 5 nT at Loma Prieta), but this is easily explained as being caused by the different distances of the observation stations from the epicenters.

Introduction

The nature of short-term precursors of earthquakes and their possible use in earthquake prediction have been widely discussed in recent years. A variety of short-term precursors have been proposed, including water level variations in wells, radon content variations in underground water and gases, the anomalous behavior of animals, atmospheric lights, and variations in atmospheric electric fields and electrotelluric fields [*Rikitake*, 1976; *Varotsos and Alexopoulos*, 1987; *Ralchovsky and Komarov*, 1988].

Electromagnetic precursors to earthquakes form a special class. Historically they had been studied in the comparatively high-frequency ELF/VLF range (100 Hz to 32 kHz), using both ground-based [*Gokhberg et al.*, 1982] and spaceborne observations [*Larkina et al.*, 1989; *Parrot and Mogilevski*, 1989], as well as in the lower-frequency range ($f < 10^{-3}$ Hz) of long-term geomagnetic field variations [*Johnston and Mueller*, 1987].

It has recently been found that the upper part of the ULF frequency range (0.01–10 Hz), in which Pc 1–4 geomagnetic pulsations characteristically occur, may contain earthquake precursor signals [*Fraser-Smith et al.*, 1990a, b; *Bernardi et al.*, 1991; *Kopytenko et al.*, 1990]. Recognizing that a common drawback of the various proposed short-term precursors of earthquakes is their lack of reliability, and that the characteristics the same type of precursor often differ in descriptions given by different authors, we here compare the ULF signals recorded independently at Corralitos, California, in association with the M_s = 7.1 Loma Prieta earthquake [*Fraser-Smith et al.*, 1990a, b; *Bernardi et al.*, 1991], and at two observation sites in the Republic of Georgia in association with the similarly-sized (M_s = 6.9) earthquake near Spitak, Armenia [*Kopytenko et al.*, 1990].

Experimental Results

On December 7, 1988, at 0741 UT a strong earthquake (M_s = 6.9) occurred near the town of Spitak in Armenia; its epicenter was located at 41.00° N, 44.20° E, or roughly 19 km to the NW of Spitak. At the time of this earthquake, ULF magnetic field measurements were being made at the Dusheti observatory in the Republic of Georgia (geographic coordinates: 42.10° N, 44.68° E; geomagnetic coordinates: $\phi = 35.7°$, $\lambda = 116.1°$, $L = 1.5$) and the measurements analyzed for this communication are primarily those from Dusheti for the interval November 14, 1988 to March 5, 1989. Also included are some supplemental measurements taken at the Vardziya observatory (41.38° N, 43.32° E) during the February–April, 1989, decrease of aftershock activity. The Vardziya station was also located in the Republic of Georgia, at a distance of roughly 138 km southwest of Dusheti. The distances of the two observatories from the Spitak earthquake epicenter zone are $\sim$ 129 km NNE for Dusheti and $\sim$ 85 km NW for Vardziya. A map showing the relative locations of the observation sites, the town of Spitak, and the epicentral region is given in Figure 1.

The ULF magnetic field measurements were made with three-axis high-sensitivity magnetometers of magnetostatic type with photoelectric conversion and deep negative magnetic field feedback. The main performance characteristics of these magnetometers, including the frequency ranges of their HF and LF filters, are listed in Table 1. A pen recorder was used for the measurements and their time resolution depended on the recorder speed and varied within $\sim$ 0.2 to 2 s.

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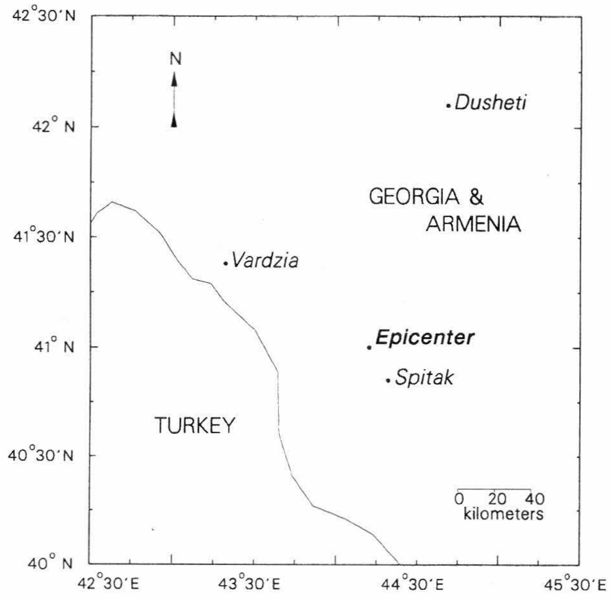

Fig. 1. Map of the region surrounding Spitak, Armenia, showing the relative locations of the Vardzia and Dusheti observatories, the town of Spitak, and the epicenter of the December 7, 1988, earthquake.

Table 1. Some characteristics of the magnetometers used in Georgia.

Sensitivity	3 pT/$\sqrt{\text{Hz}}$
Dynamic Range	120 dB
Frequency Range:	
LF Filter	0.005–1 Hz
HF Filter	0.1–1 Hz
Filter Rejection Index	40 dB/decade

The following are the main results derived from the analysis of the Dusheti measurements:

Starting about four hours before the main shock (M_s = 6.9) of the Spitak earthquake, and also several hours before some of its powerful aftershocks, the Dusheti station recorded ULF quasi-noise bursts with durations varying from several minutes to 1.5 hour and with amplitudes varying in the range 0.05 to 0.2 nT amplitude. The form of these data is illustrated in Figure 2, where segments of the HF filter recordings of H and D components prior to the main shock (top panel) and prior to one of the powerful aftershocks (bottom panel) are plotted. Shown to the left in the figure is the sensitivity of the recording, some parts of which have been omitted to make the picture more compact. Time marks in minutes are shown along the horizontal axis. The times of occurrence of the shocks are shown by arrows. The results of the mechanical effects on the magnetometer during the shock are well seen. Unfortunately, the Z–component recording is absent for technical reasons.

Bursts of ULF activity, preliminary to the main shock and to 8 powerful aftershocks, started to occur on average about 3 hours before the following shock. The occurrence times and durations of these various ULF bursts relative to the following shocks are illustrated in Figure 3. The zero of time on the horizontal axis is assumed to be the moment of occurrence of each shock, and solid line horizontal lines show the time intervals of the ULF bursts, including the one preceding the main shock. The vertical axis on the left gives the time in days after the main shock; the real

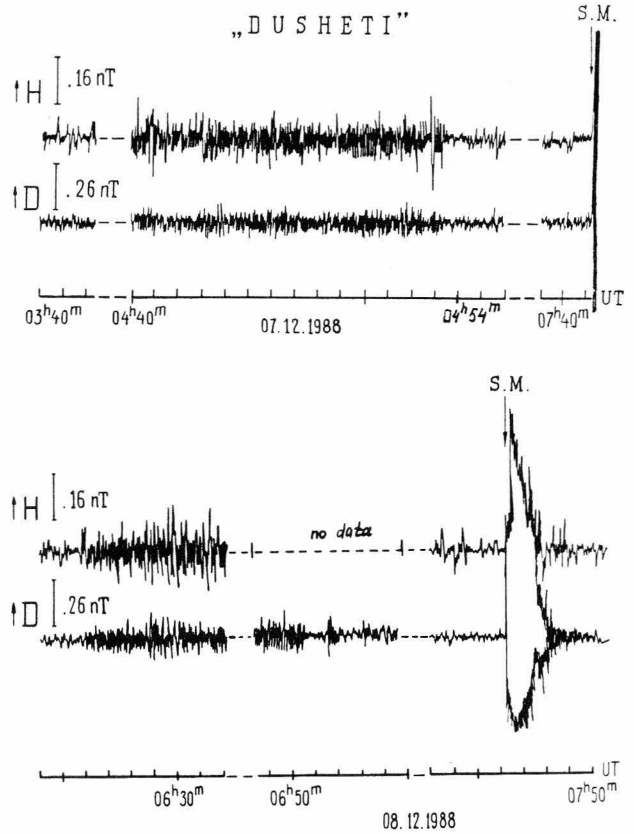

Fig. 2. (Upper Panel) Sections of chart recordings showing the ULF emissions recorded at Dusheti on 7 December 1988 during the time interval 0340 – 0741 UT, the latter time corresponding to the onset (arrow) of the Spitak earthquake. Time marks in minutes are given on the horizontal axis. The first section of recording shows the background noise level, the second section shows some of the intensive ULF emissions preceding their abrupt termination at 0454 UT, i.e., 02 hr 47 min before the main shock, and the third section shows the background level just prior to the main shock. (Lower Panel) An example of the intensive ULF emissions recorded at Dusheti prior to the strong aftershock (arrow) that occurred near Spitak at 0746 UT on 8 December 1988.

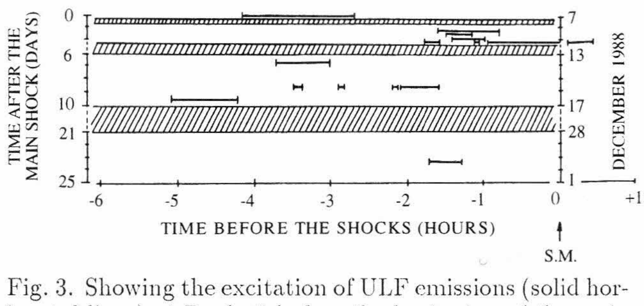

Fig. 3. Showing the excitation of ULF emissions (solid horizontal lines) at Dusheti before the beginning of the main shock in the Spitak earthquake area and eight powerful aftershocks. The horizontal coordinate represents time in hours before the shock; the vertical coordinate shows the time in days after the main shock (left) and the actual dates (right). The frequency range for the ULF emissions was 0.1–1 Hz (HF filter) and the hatched areas indicate intervals where data are lacking.

dates are given on the right. Hatched areas in the figure denote intervals when, for various technical reasons, data were not acquired by the measurement system.

According to the Dusheti observatory data, the bursts were excited over the entire period under analysis. As the top panel in Figure 4 shows, the mean amplitude of the ULF signals began increasing several days before the main shock, remained at a comparatively high level for about 2 weeks, and then decreased for about 1.5 months down to the background level of ~ 0.02 nT. The midpanel in the figure characterizes the seismic activity of the Caucasian seismic zone by plotting the number of shocks with the energy class K ≥ 10 (magnitudes ≥ 3.4) for every day. For comparison with these data, the bottom panel in the figure shows the simultaneous variation of natural geomagnetic activity, as represented by the daily sum of the Kp index. Statistically, the increase in amplitude of the ULF signals shown in Figure 4 is quite exceptional. In the two years preceding the earthquake, similar increases in the mean amplitude of the ULF signals were only observed during the reconstruction phases of large magnetic storms (Kp > 7) and they typically lasted for less than 30 minutes. We note that there were no magnetic storms just before the Spitak earthquake or during its aftershock activity (bottom panel). Futhermore, no significant pulsation activity was observed during the times of interest at auroral and subauroral geomagnetic obervatories in Russia (Lovozero

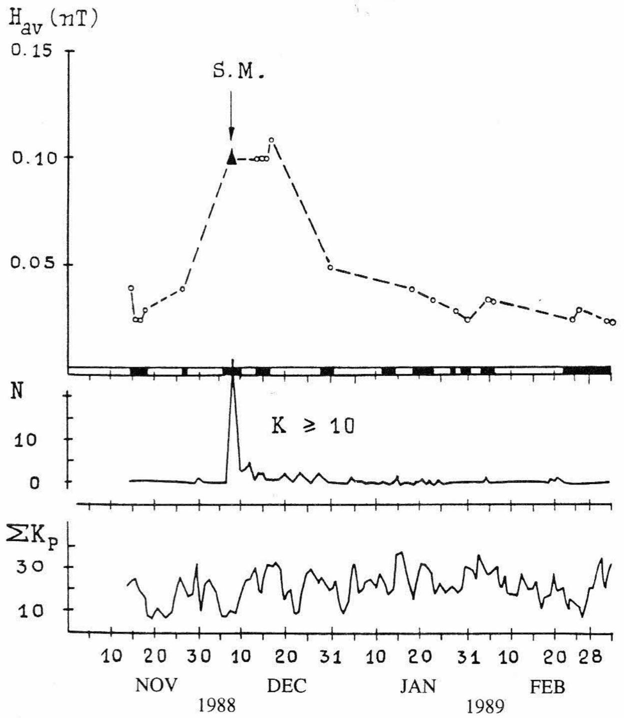

Fig. 4. (Upper Panel) Variation of the mean daily values of the amplitude of the H component of the ULF emissions recorded at Dusheti in the range 0.1–1 Hz (HF filter) during the interval 14 November 1988 through 5 March 1989. The time of the Spitak main shock on 7 December 1988 is marked by an arrow. The time intervals marked in black denote intervals with data. (Middle Panel) A plot of the number, N, of shocks and aftershocks with an energy of $K \geq 10$ for every day in the above time interval. The data are those held by the Caucasus Regional Data Center. (Lower Panel) A plot of ΣK_p for each day of the period analyzed.

and Borok) and in Finland (Oulu, Sodankyla, and Nurmijarvi).

Comparison of observations made simultaneously at Dusheti and Vardzia during the decrease in aftershock activity shows that, as a rule, ULF bursts were not observed at the two stations simultaneously; they are therefore assumed to have been of a local or directional character. In addition, the component ratios Z/H, Z/D were usually greater than unity, which is not typical of pulsations of ionospheric/magnetospheric origin.

Discussion of Results

The Corralitos measurements were made with a one-component induction coil magnetometer operating in the frequency range 0.01 to 10 Hz with a sensitivity of $\sim$1–2 pT/$\sqrt{\text{Hz}}$ at 1 Hz. These parameters are quite similar to the corresponding parameters for the instrumentation at the Dusheti and Vardzia stations. The principal difference between the measurements involved the signal recording and processing (*Bernardi et al.*, 1989, 1991).

The magnitudes of the Spitak and Loma Prieta earthquakes were very nearly the same (6.9 and 7.1, respectively), whereas their hypocentral depths (6 km and 15 km, respectively [*Pacheco et al.*, 1989; *Houston*, 1990]) differed roughly by a factor of two. Thus the main characteristics of the two earthquakes were similar but not identical. Under the circumstances, we would expect any ULF bursts that were generated as a result of the earthquake preparation process to show some similarities. Let us now briefly list the major characteristics of the Loma Prieta signals and compare them with the corresponding characteristics of those at Spitak.

The characteristics of the Corralitos ULF magnetic signals [*Fraser-Smith et al.*, 1990a, b; *Bernardi et al.*, 1991] can be summarized as follows: (1) There was a broadband increase in the amplitude of the ULF magnetic fluctuations beginning just over 12 days before the main shock; (2) Starting three hours before the main shock there was a further considerable increase in the amplitude of the ULF magnetic fluctuations. The largest amplitudes were measured at the lowest frequencies, reaching values in the range 4–5 nT at 0.01 Hz. (3) The amplitude levels at the lowest frequencies remained very high for several days after the main shock, and then gradually decreased back to their previous background levels over a time interval of several months. A recent study of the ULF magnetic field fluctuations after the main shock has concluded that there was no obvious correlation between their amplitudes and either the number of occurrences or the magnitudes of the aftershocks [*Fenoglio et al.*, 1991].

There are several important similarities between the characteristics of the Loma Prieta ULF magnetic signals, as summarized above, and those associated with the Spitak earthquake, which we have described in this paper. Probably the most significant of these similarities is the occurrence of ULF magnetic field activity in the same limited frequency range of 0.01–1 Hz before the two earthquakes. However, there are also several differences in the characteristics of the signals that are also likely to be important, particularly in view of the possible generation mechanisms for the signals. We will now briefly discuss these differences.

One of the most noticable differences between the Loma Prieta and Spitak ULF magnetic field fluctuations is the abrupt termination over two hours before the main shock occurred of the strong ULF burst measured at Dusheti, whereas the Corralitos burst continued until the time of the main shock. There is also a difference in frequencies, with the ULF activity measured at Corralitos before the Loma Prieta main shock reaching its greatest amplitudes at 0.01 Hz, the lowest frequency at which measurements were possible, whereas the ULF bursts measured at Dusheti and Vardzia before the Spitak main shock and its aftershocks appear to have reached their highest amplitudes in the range 0.1–1 Hz. It is possible, however, that this difference is at least partly caused by the different depths of the hypocenters. Assuming that the ULF bursts originated in the vicinity of the hypocenters, the greater depth of the Loma Prieta hypocenter would make it more difficult for the higher frequency magnetic field fluctuations to reach the surface. Another difference involves the observation of ULF bursts preceding the Spitak aftershocks. However, here it must be recognized that the Corralitos data, consisting of half-hour indices, are not ideal for aftershock correlation studies, particularly when the aftershocks occur in large numbers as they did immediately following the Loma Prieta earthquake. The final difference, smaller magnetic field amplitudes measured at Dusheti, is easily explained by the different distances of the measurement instruments from the epicenters: 7 km (Corralitos) and 129 km (Dusheti).

Clearly more measurements must be made of ULF magnetic field fluctuations preceding moderate to large earthquakes before it can be asserted that ULF magnetic precursors certainly exist. However, the results reported here of similarities between the possible ULF precursor signals observed independently before the Loma Prieta and Spitak earthquakes are encouraging and they suggest that further studies of magnetic and electric field fluctuations in the frequency range 0.01–1 Hz preceding earthquakes are desirable as part of the continuing search for a technique to provide warning of moderate to large earthquakes.

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