Physics of the Earth and Planetary Interiors, 77 (1993) 85–95
Elsevier Science Publishers B.V., Amsterdam

Detection of ultra-low-frequency emissions connected with the Spitak earthquake and its aftershock activity, based on geomagnetic pulsations data at Dusheti and Vardzia observatories

Yu.A. Kopytenko [a], T.G. Matiashvili [b], P.M. Voronov [a], E.A. Kopytenko [a] and O.A. Molchanov [c]

[a] *St. Petersburg Branch, Institute of Terrestrial Magnetism Ionosphere and Radiowaves Propagation, Russian Academy of Science, St. Petersburg, Russia*
[b] *Institute of Geophysics, Georgian Academy of Science, Tbilisi, Georgia*
[c] *Institute of Physics of the Earth, Russian Academy of Science, Moscow, Russia*

(Received 14 November 1991; revision accepted 4 June 1992)

ABSTRACT

Kopytenko, Yu.A., Matiashvili, T.G., Voronov, P.M., Kopytenko, E.A. and Molchanov, O.A., 1993. Detection of ultra-low-frequency emissions connected with the Spitak earthquake and its aftershock activity, based on geomagnetic pulsations data at Dusheti and Vardzia observatories. Phys. Earth Planet. Inter., 77: 85–95.

ULF electromagnetic emissions from the Spitak (Armenia) earthquake site have been detected. Observations were carried out at the Dusheti and Vardzia (Georgia) observatories at distances 120–200 km from the epicentre in a frequency range 0.005–1 Hz. It is shown that the emission appears several hours before the main shock and some of the powerful aftershocks and is not connected with geomagnetic pulsations of magnetospheric sources.

1. Introduction

At present, great importance in the study of the earthquake forecasting problem is attributed to electromagnetic phenomena accompanying tectonic processes at different stages of the earthquake site development.

Lately, the term electromagnetic precursors of earthquake (Sadovsky, 1982) has been established, however, not much evidence of these is available so far. Partly, this is due to a lack of intensive integrated studies in this area.

Below are listed the electromagnetic precursors connected with the processes taking place in the Earth's seismically active area.

(1) Tectonomagnetic effect (Shapiro and Abdullabekov, 1982; Skovorodkin, 1985; Johnston and Muller, 1987).

(2) Change of geoelectric resistance in the earthquake site (Barsukov, 1970; Mazzella and Morrison, 1974).

(3) High-frequency electromagnetic emission (Gokhberg et al., 1980, 1982).

(4) Low-frequency noise emission in the ionosphere, registered by satellite (Larkina et al., 1984, 1988, 1989; Parrot et al., 1985; Parrot and Mogilevsky, 1989; Chmyrev et al., 1989; Molchanov, 1991).

(5) Variations of electrotelluric field (Sobolev and Ponomarev, 1982; Varotsos and Alexopoulus, 1987; Ralchovsky and Komarov, 1988).

Correspondence to: Yu.A. Kopytenko, St. Petersburg Branch, Institute of Terrestrial Magnetism Ionosphere and Radiowaves Propagation, Russian Academy of Science, St. Petersburg, Russia.

0031-9201/93/$06.00

It has been found recently that the upper part of the ULF frequency range (0.01–10 Hz) may contain earthquake precursor signals (Fraser-Smith et al., 1990a,b; Kopytenko et al., 1990; Bernardi et al., 1991; Molchanov et al., 1992).

Since 1986 SPBF IZMIRAN has been carrying out researches into peculiarities in the field of geomagnetic pulsations at a seismically active area in two directions.

(1) Study of relative changes of geoelectric resistance from the analysis of the relations of vertical and two horizontal magnetic components Z/H, Z/D in the narrow range of geomagnetic pulsations frequences ($f \simeq 0.04$ Hz) approximately corresponding to the penetration depth of the plate electromagnetic wave of the natural field to the supposed earthquake site (Kopytenko and Sholpo, 1987; Sholpo et al., 1987).

(2) Detection of direct ULF electromagnetic emission from an earthquake site in a frequency range 10^{-2}–10 Hz (Molchanov, 1991) on the Earth's surface.

This work is devoted to the study of direct electromagnetic emissions in the seismically active area of the Caucasus. The main results were first reported at the October 1989 Conference on Electromagnetic Precursors of Earthquakes in Makhachkala and were published in January 1990 in Russian (Kopytenko et al., 1990).

2. Experimental results

Periodic observations of geomagnetic pulsations in the frequency range 0.005–1 Hz were arranged and conducted by SPBF IZMIRAN and IG Academy of Science of Georgia at the Dusheti Observatory (see Fig. 1; geographic coordinates: $\phi = 42.10°$N, $\lambda = 44.68°$E; geomagnetic coordinates: $\phi_m = 35.7°$, $\lambda_m = 116.1°$, L = 1,5). The ULF magnetic field measurements were made with three-axis high-sensitivity magnetometers of magnetostatic type with photoelectric conversion and a deep negative magnetic field feedback (Kopytenko et al., 1984). A pen recorder and sometimes a digital tape recorder were used for the measurements.

In September 1988 it was noticed that in the field of geomagnetic pulsations in the frequency range 0.1–1 Hz there appeared emission with an amplitude $\simeq 0.03$ nT and duration up to several hours, which was different from the typical pulsations of ionospheric–magnetospheric source. Figure 2 shows a typical example of the emission. The burst is a quasi-noise one and, as a rule, essentially exceeds the background, and is registered during the day-time unlike the geomagnetic Pc1–2 pulsations and, sometimes at least, with vertical (Z) component prevailing over horizontal

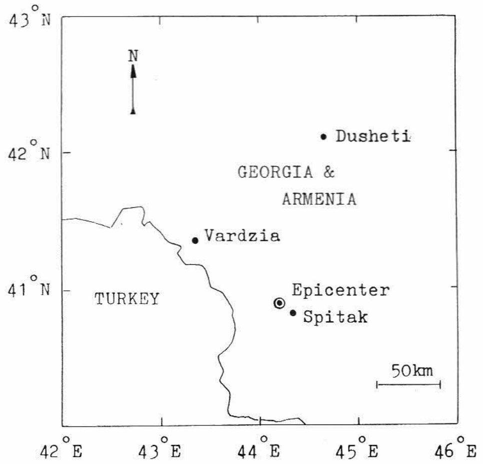

Fig. 1. Map of the region surrounding Spitak, Armenia, showing the relative locations of the Dusheti and Vardzia Observatories, the town of Spitak and the epicenter of the 7 December 1988 earthquake.

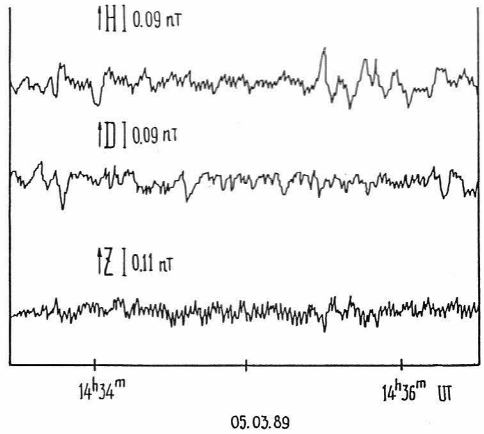

Fig. 2. An example of the exitation of the ULF emissions from the geomagnetic pulsations observations data at the Dusheti Observatory 14:33–14:37 h UT, 5 March 1989.

(*H*, *D*) components (see below). We have analysed such bursts for a period from 14 November 1988 up to 5 March 1989. During this period 59 cases of the generation of ULF signals were registered in a frequency range 0.1–1 Hz with the duration ranging from several minutes to several hours with a mean duration of about 30 min. Any considerable effects in the frequency range 0.005–0.1 Hz were not found, which is why we analysed only 0.1–1 Hz analogue filter data for this paper. The filter rejection index is equal to 40 dB decades. Figure 3 demonstrates some statistical characteristics of the events. The upper part gives the average daily amplitudinal values of the *H* component bursts, averaged by 2 min intervals for each case.

As is known, a strong $M_s = 6.9$ earthquake with epicentre (geographic coordinates: $\phi = 40.90°N$, $\lambda = 44.20°E$) near the town Spitak

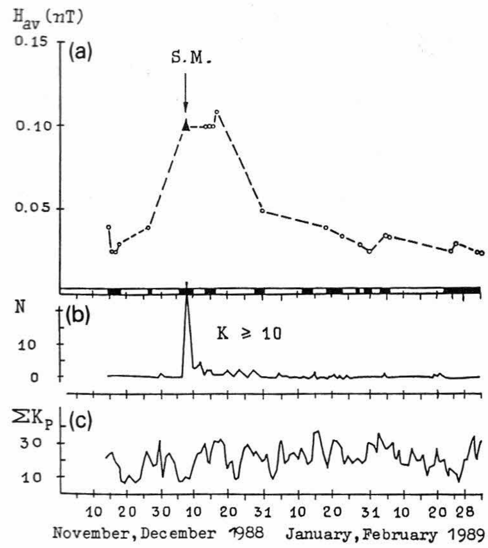

Fig. 3. (a) variations of the averaged mean daily values of *H* component (H_{av}) amplitude of the ULF emissions from the Dusheti Observatory observation data 14 November 1988–5 March 1989. The earthquake shock moment (S.M.) 7 December 1988 is marked by an arrow. Black marked time intervals, show data existence. (b) N, the number of shocks and aftershocks with an energy class $K \geqslant 10$ for every day from 14 November 1988 to 5 March 1989 according to the Caucasus Regional Data Centre. (c) ΣK_p, total value for every day of the geomagnetic activity for the period analysed, 14 November 1988–5 March 1989.

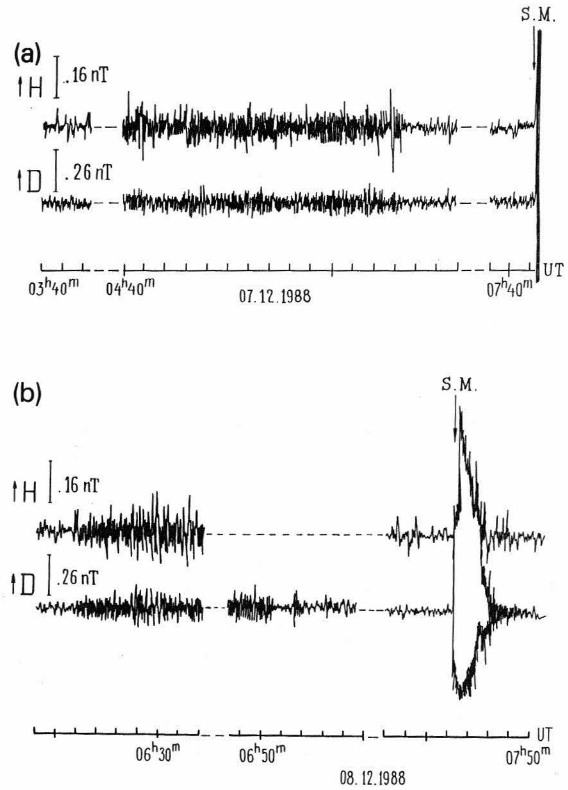

Fig. 4. (a) fragments of records of the exitation of ULF emissions at the Dusheti Observatory from 03:40 h UT to the Spitak earthquake 7 December 1988. The moment of the main shock at 07:41 h UT is shown by an arrow (S.M.). The first fragment represents the background, the second one, the intensive ULF emissions and the abrupt termination of the signal 02 h 48 min in before the main shock, the third fragment, the background. The shock moment (S.M.) is marked by an arrow. (b) An example of the intensive ULF emissions at the Dusheti Observatory. 06:24–06:55 UT which terminated 51 min before the strong aftershock at 07:46 h UT, 8 December 1988 near Spitak.

(Armenia) occurred on 7 December 1988 at 07:41 h UT. The shock moment (S.M.) is shown in Fig. 3 by a triangle. On that day, 4 h before the earthquake, intensive ULF emissions with a great amplitude ($H_{av} \geqslant 0.1$ nT), sometimes reaching a value of 0.2 nT (Fig. 4 (upper part) and Fig. 5) were registered. The emissions stopped abruptly 2 h 48 min before the main shock. The main shock was followed by aftershock activity which continued up to the end of December 1988. The

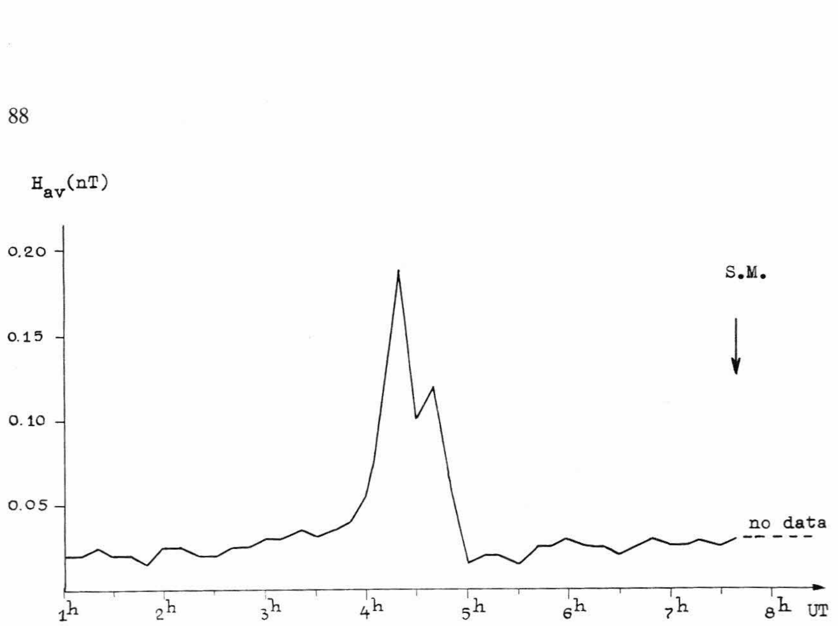

Fig. 5. Variation of the 10 min averaged values of the H-component amplitude of the ULF emissions recorded at Dusheti before the main shock. The shock moment (S.M.) 7:41 h UT 7 December 1988 is marked by an arrow.

middle part of Fig. 3 shows in the Y-coordinate the number of aftershocks class $K \geqslant 10$ for every day during the study period according to the Caucasus Regional Data Centre. On some days after the main shock the large amplitude signals ($H_{av} \geqslant 0.1$ nT) preceding strong aftershocks were repeatedly detected (Fig. 3). Figure 4 (lower part) gives an example of the ULF emissions. The emissions started at 06:25 h UT ($H_{av} \geqslant 0.1$ nT; $H_{max} \simeq 0.2$ nT) and stopped 51 min before the aftershock on 8 December at 07:46 h UT.

The average amplitude of the H-component signal gradually decreases over 2 months down to the background level ($H_{av} \simeq 0.03$ nT) jointly with the decrease in aftershock activity (Fig. 3).

To check the geomagnetic activity during the study period the variations of $\Sigma\ K_p$ for every day are given in the lower part of Fig. 3. It is seen, that the mean value $\Sigma\ K_p = 15$ for the study period, and the K_p curve do not correlate with the curves of seismic activity and the intensity of the ULF noise emission, presented in the upper

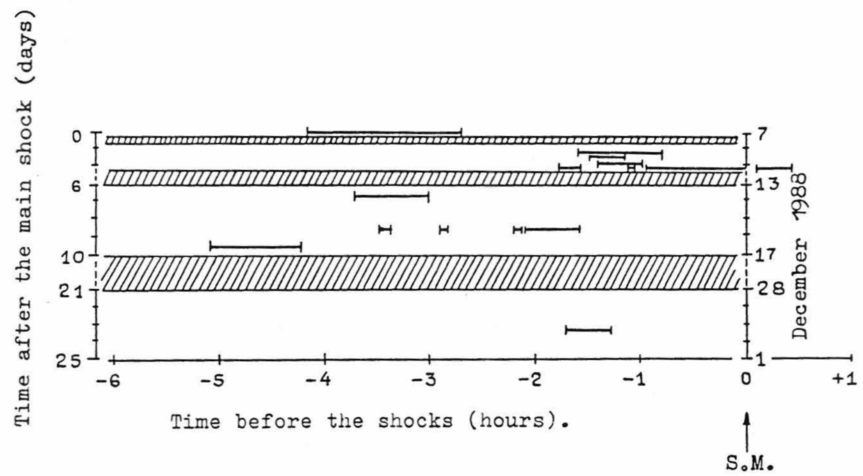

Fig. 6. The excitation of ULF emissions (solid lines) before the beginning of the shocks ($K \geqslant 10$) in the Spitak earthquake area; the horizontal coordinate represents time (h) before the shock moment (S.M.), the vertical coordinate represents time (day) after the main shock (on the left) and real dates (on the right).

part of Fig. 3. It is interesting to make an attempt to find a correlation between ULF emission bursts and aftershocks. The solid lines in Fig. 6 show the times of the appearance of signals with $H_{av} \geqslant 0.05$ nT before the main shock and some of the aftershocks. The moments of the main earthquake and powerful aftershocks are taken equal to "0". The time (h) before the shock moment is shown on the horizontal coordinate. The vertical coordinate represents: on the left, the time in days after the main shock; on the right, the actual dates. It is seen from Fig. 6 that the signals mainly appear 1–4 h before the shock.

In spite of poor statistics we represent below some statistical data. The intensive ULF signals ($H_{av} \geqslant 0.05$ nT) were registered at Dusheti for the interval 7 December 1988 to 31 December 1988 (Fig. 3). There were 24 such ULF signals altogether for this interval; 15 of them appeared 1–4 h before the main shock and before each of the eight powerful ($K \geqslant 10$) aftershocks (Fig. 6). There were 32 powerful aftershocks when the measurements had been carried out. Thus, about 60% of the intensive ULF bursts appeared 1–4 h before the powerful shocks and about 30% of the powerful shocks occurred 1–4 h after the appearance of the intensive ULF signals. In such a way the ULF signals with amplitude higher than 0.05 nT can be regarded as electromagnetic precursors of the strong Spitak earthquake and some of its powerful aftershocks. It is to be noted that any ULF burst will surely have an aftershock folowing after it but there is a possibility that this ULF burst can be connected with another aftershock. To answer this question it is necessery to carry out some more investigations.

Figure 7 demonstrates the daily distribution of the frequency of the appearance of ULF emissions N_s (59 events) and the number of shocks N_{sh} with $K \geqslant 10$ (91 events) during the period studied from 14 November 1988 to 5 March 1989. Both distributions have two maxima of frequency appearance.

It is seen from the N_{sh} distribution that the surrounded epicentre shocks appear more often from 06:00 h until 12:00 h LT and ULF signals (N_s) at Dusheti Observatory have appearance maxima from 03:00 h until 06:00 h LT and from

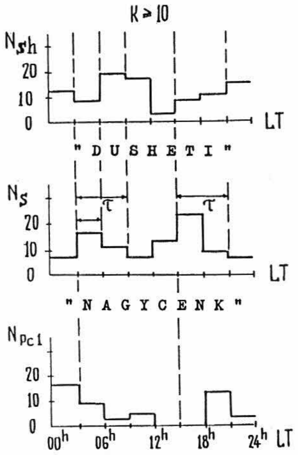

Fig. 7. Daily appearance frequency distributions: N_{sh}, the strong aftershocks ($K \geqslant 10$) 14 November 1988–5 March 1989; N_s, the ultra-low-frequency emissions (signals); N_{Pc1}, the Pc1 type geomagnetic pulsations (τ, the delay time of shocks relative to the appearance of ULF emissions).

15:00 h until 18:00 h LT. Thus, it follows from Fig. 7 that maxima of N_{sh} distribution have a delay time τ ($\tau = 3$–6 h) relative to N_s distribution maxima. For the comparison the lower part of Fig. 7 gives the mean annual daily distribution (N_{Pc1}) of the frequency of appearance of geomagnetic pulsations of Pc1 ($f \simeq 0.2$–1 Hz) type at the low-latitude station of Nagycenk ($\phi_m = 42.4°$; $\lambda_m = 93.8°$, $L = 1.8$) (Geophysical Observatory Report, Observatory Nagycenk 1972, 1973) located at a similar geomagnetic latitude as the Dusheti Observatory. Figure 7 demonstrates that N_{Pc1} distribution is essentially different to the distribution of N_S. Geomagnetic pulsations of the Pc1 type are excited mainly at the recovery phases of negative and positive bay-like disturbances ($\simeq$ 00:00–06:00 h LT and $\simeq$ 18:00–21:00 h LT, respectively), whereas ULF signals at Dusheti were observed more often than not during the periods $\simeq$ 03:00–06:00 h LT and $\simeq$ 15:00–18:00 h LT.

Data on Pc1–Pc2 geomagnetic pulsations (0.1 Hz $\leqslant f \geqslant 1.0$ Hz), registered at middle latitude geomagnetic station Borok ($\phi_m = 53.6°$, $\lambda_m = 115.5°$, $L = 2.9$), have been analysed also. Both Dusheti and Borok are situated on nearly the same geomagnetic meridian. The analyses has detected that while ULF signals were observed at

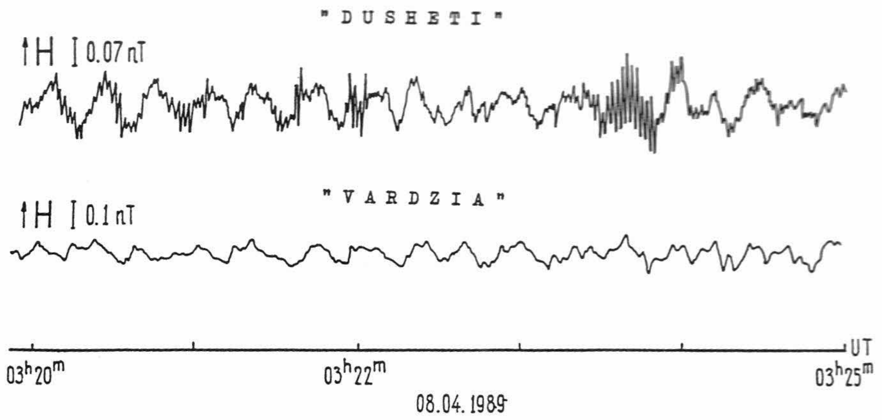

Fig. 8. Local excitation of ULF emission simultaneous with the geomagnetic pulsations of Pc3 type at the separated points (150 km): the Dusheti Observatory and Vardzia station. (Quasi-sinusoidal ULF emission at the Dusheti Observatory; there is none at Vardzia station.)

Dusheti there were no geomagnetic pulsations with amplitude more than 0.01 nT in the Pc1–Pc2 frequency range at the same time ± 2 h at Borok for 95% of events.

From these facts it can be concluded that ULF emissions detected at the Dusheti Observatory were not brought on by the development of magnetospheric storms.

One of the interesting peculiarities of ULF emissions is the fact that in a number of events of ULF emissions amplitude relations are $Z/H \geqslant 1$; $Z/D \geqslant 1$, which is not a property of the geomagnetic pulsations of magnetospheric–ionospheric origin (Fig. 2).

During the decrease of aftershock activity, synchronous H, D, Z component observations of geomagnetic pulsations were carried out at the Dusheti and Vardzia Obsevatories (Fig. 1). The Vardzia station (geographic coordinates: $\phi =$ 41.38°N, $\lambda =$ 43.30°E) was located at a distance of roughly 138 km to the south-west of Dusheti. The distances of the two observatories from the Spitak earthquake epicenter zone are ≈ 130 km north-north-east for Dusheti and ≈ 85 km north-

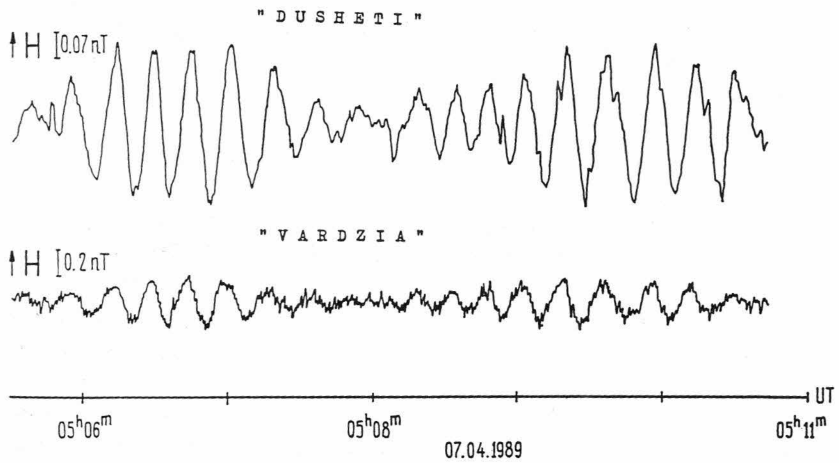

Fig. 9. The local excitation of noise ULF emission at Vardzia station simultaneous with the geomagnetic pulsations of Pc3 type (there is none at the Dusheti Observatory).

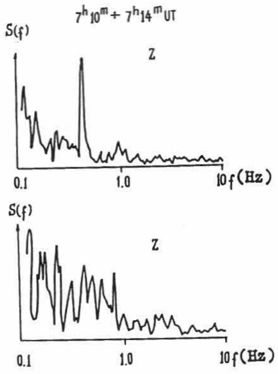

Fig. 10. Two types of ULF emission spectra detected at the Dusheti Observatory 5 March 1989: quasi-sinusoidal (above), noise (below).

west for Vardzia. As a result of the analysis of the simultaneous observations it should be pointed out that regular (Pc3, Pc4) and irregular (Pi2) geomagnetic pulsations of magnetospheric source appeared synchronously at both stations and had the same amplitudes and periods, whereas ULF bursts in the frequency range 0.1–1 Hz, as a rule, were not observed at the two stations simultaneously. They are, therefore, assumed to have been of a local or directional character. Figures 8 and 9 show examples of the appearance of such emissions having quasi-sinusoidal (Fig. 8) character at the Dusheti Observatory and noisy character (Fig. 9) at the Vardzia station with the Pc3-type pulsation modulations.

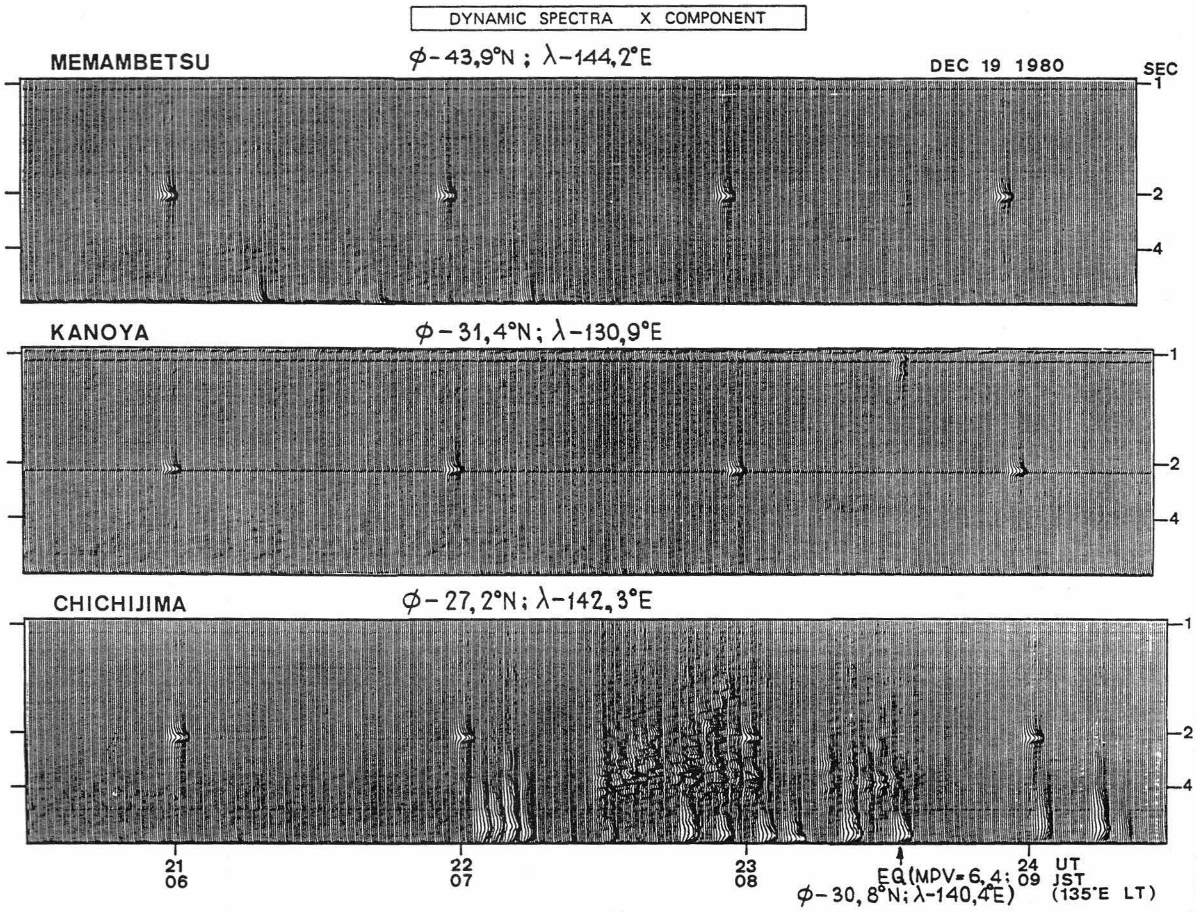

Fig. 11. The excitation of ULF emissions before the $M = 6.4$ earthquake in Japan. (From the Report of Magnetic Pulsations 1980, published in 1981 by the Magnetic Observatory of the Japan Meteorological Agency, Kakioka, Japan, 1981).

It can be concluded from the analysis of the synchronous data of these two stations that ULF signals are not excited by magnetospheric–ionospheric sources. It is also necessary to point out that both stations are located far from industrial noise sources, and microseismic activity has not influenced the appearance of the ULF signals. Therefore, taking into account the differences between the daily pattern of Pc1 and N_s (Fig. 7), the absence of the dependence of the appearance frequency N_s from the magnetic activity and bearing in mind that these emissions are characterized by $Z/H > 1$; $Z/D \geqslant 1$, it is possible to conclude that the local sources of the above-mentioned ULF emissions are situated in the Earth's crust and appear as a result of the development of physical processes in the seismically active area of the Caucasus where tuff-like rocks are found which have a high tensosensitivity coefficient (Kirakosyan, 1989).

It is to be noted that a pen recorder was used usually for the measurements and their time resolution depended on the recorder speed and varied within 0.2 to 2 s. The ULF bursts were only recorded in a few cases with high time resolution by the digital tape recorder and statistically significant conclusions about the character of their spectra cannot be drawn. However, the spectra of ULF signals that were recorded appeared to have quasi-noise-like (Fig. 10, below) and sometimes narrow-band (Fig. 10 above) character in the 0.1–1 Hz frequency range.

In addition, we should point out that the analysis of published geomagnetic pulsation data (Report of Magnetic Pulsations, Kakioka, Japan, 1981, 1984) has detected two similar events of ULF signals occurrence before the earthquakes on 19 December 1980 ($M = 6.4$) and 21 January 1983 ($M = 5.5$) in Japan. Figure 11 represents geomagnetic pulsations H-component dynamical spectra at three magnetic observatories situated at different latitudes: Memambetsu, Kanoya and Chichijima, for the 19 December 1980 event. The earthquake moment is marked by an arrow. Coordinates of earthquake epicentre are given also. One can see that ULF emissions in the range 0.2–1.0 Hz with duration ~ 30 min at the nearest station to the earthquake epicentre are followed by the shock in 1.0–1.5 h. ULF emission appe[illegible] ance at the southern station only indicates th[illegible] non-ionospheric origin. The similarity of the re[illegible] sults probably testifies to the common origin o[illegible] ULF emissions in different seismically active areas.

3. Discussion of results

The experimental results presented give grounds to believe that the bursts of ULF emissions detected are not connected with the sources in the magnetospheric plasma (geomagnetic pulsations), but are a result of the processes in the Earth's lithosphere during the period of earthquake preparation.

Molchanov (1991) examined one of the possible process models with the assumption of the generation of short random current pulses ($\tau \simeq 10^{-6}$–10^{-8} s) in the earthquake site as a result of the organization of the system of the so-called mechano-electric transformers (Gokhberg et al., 1980). Without giving the theoretical calculation details it is necessary to point out that the source size was specified as $d \simeq 10$ km thick and $2L \simeq 20$ km in the horizontal direction with the upper boundary depth $Z_0 = 30$ km, which corresponds to the site of the moderate earthquake. For simplicity, the Earth's medium was considered to be uniform with conductivity $\sigma_g \simeq 10^{-4}$–10^{-3} $(\Omega\ \mathrm{m})^{-1}$ and the atmosphere exponentially conducting with $\sigma_{a0} \simeq 10^{-14}$ $(\Omega\ \mathrm{m})^{-1}$ over the Earth's surface. The work was carried out within the framework of complete electrodynamic equations (without ignoring displacement currents) and taking into account the continuity of the horizontal components of the electric and magnetic field at the boundary of the conducting Earth, and ionosphere. An axial symmetry was assumed and cylindrical coordinates (z, ϕ, r) were used, the projection of the sources centre on the Earth's surface corresponding to the coordinates $r = 0$, $z = 0$.

Sources of two types were considered: (1) With vertical current polarization of the type of electric dipole; (2) With circular polarization of the type of magnetic dipole.

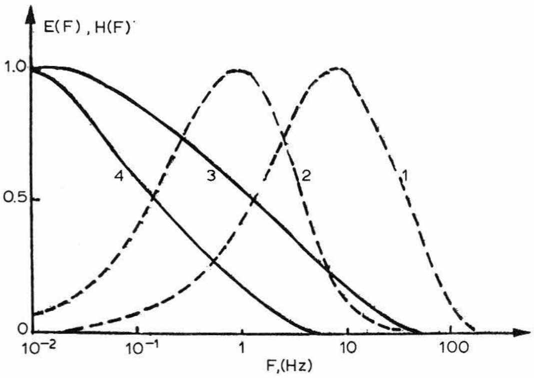

Fig. 12. Emissions spectrum on the Earth's surface. 1,2—electric source; 3,4—magnetic source; 1,3—$\sigma_g = 10^{-4}$ (Ω m)$^{-1}$; 2,4—$\sigma_g = 10^{-3}$ (Ω m)$^{-1}$; $Z_0 = 30$ km.

Now we present only the final expressions for the values of the magnetic field in the zone near the source on the Earth's surface. For the electric source: H_z, $H_r \ll H_\phi$

$$|H_\phi| = \frac{K_0^2 dI_z}{2K_g^2\left[1 + (K_g\ d)^2\right]^{1/2}} \times \frac{S_0^2\ r}{\left(r^2 + S_0^2\right)^{3/2}} \exp(-K_g Z_o)$$

where $K_0 = \omega/C$, $K_g = (\omega\ \mu_0'\ \sigma_g/2)^{1/2}$, $S_0 = L + Z_0$,$I_z = j_{gz} e^2 v\overline{\langle\tau\rangle}$,$j_{gz} = \langle j^2\rangle(t) >^{2/2}_{max}$.

Figure 12 gives the emission spectrum (dashed line) and Fig. 13 gives the radial distribution of the field. It can be seen that, depending on the conductivity, the spectrum has its maximum in a range 0.3–10 Hz and the field radially abates approximately as the square of the distance. As to the specific field values, it follows from elementary evaluations that to achieve values $H_\phi \simeq 0.3$ nT Hz^{-1} at a distance $\tau \simeq 140$ km, it is necessary to have the mean current of the pulse density in the source centre $j_{gz} \simeq 0.1$ A m^{-2} Hz. This evaluation is modest enough from the theoretical point of view (Gokhberg et al., 1980).

For the magnetic source $H_\phi \ll H_r$, H_z:

$$|H_r| = I_\phi T_0 R_1;$$

$$|H_z| = I_\phi T_0 R_z;$$

$$T_0 = \frac{L}{\left[1 + (K_g d)^2\right]^{1/2} S_0^2} \exp(-K_g Z_0);$$

$$I_\phi = j_{g\phi} L dv\overline{\langle\tau\rangle};$$

$$R_\perp = \frac{r S_0^2}{\left(r^2 + S_0^2\right)^{3/2}} - \frac{K_g S_0^2}{\left(r^2 + S_0^2\right)^{1/2}} \times \left\{\frac{r}{\left(r^2 + S_0^2\right)^{1/2}} - \left[1 - \exp(-K_g r/2)\right]\right\};$$

$$R_z = \frac{S_0^3}{\left(r^2 + S_0^2\right)^{3/2}} - \frac{K_g\ S_0^2}{2\left(r^2 + S_0^2\right)^{1/2}}$$

It is easy to see that in this case the emission spectrum drops with frequency (shown in Fig. 12 by a solid line), while the radial distribution is different for the vertical and horizontal components (Fig. 13). As far as the concrete values are concerned, already for $J_{g\phi} \simeq 10^{-2}$ A m^{-2} Hz values $H_z \simeq 3$–5 nT Hz^{-1} in the zone centre and 0.1–0.3 nT Hz^{-1} at a distance of 120–150 km.

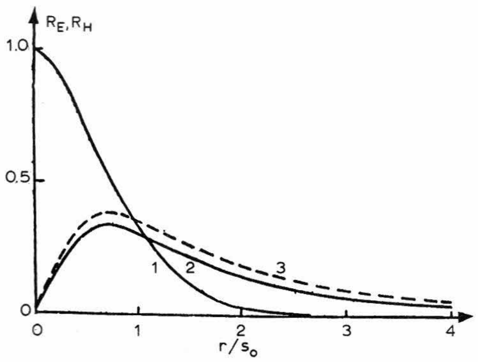

Fig. 13. Radial distribution of the emissions amplitude on the Earth's surface. 1, $H_z(r)$; 2, $H_r(r)$—magnetic source; 3, $H_\phi(r)$—electric source.

Concluding remarks

The following conclusions can be drawn as a result for the research conducted.

(1) At the seismically active area of the Caucasus using a highly sensitive magnetovariational complex created on the basis of the magnetostatic magnetometers, the ULF emissions (signals) in the range of 0.1–1 Hz with an amplitude ranging from 0.03 to 0.2 nT, with a mean duration of

about 30 min were detected in the field of geomagnetic pulsations before the Spitak earthquake and during its aftershock activity. No considerable effects were found in the frequency range 0.005–0.1 Hz.

(2) An ULF signal with an amplitude of more than 0.05 nT was recorded at the Dusheti Observatory 4 h before, and terminated 2 h 48 min before the main shock of the catastrophic Spitak earthquake on 7 December 1988 at 07:41 h UT.

(3) During strong aftershock activity ($K \geqslant 10$) a ULF signal with an amplitude 0.05 nT was observed 1–4 h before the shock for about 30% of events.

(4) The mean daily amplitude of ULF signals dropped from 0.1 to 0.03 nT in the process of the decrease of the aftershock activity over 3 months (from 7 December 1988 to 5 March 1989).

(5) The ULF signals are of local (within the limit of 100 km) or directional character. The ULF emissions sources are located in the Earth's crust and result from of physical processes occurring in the seismically active area of the Caucasus, characterized by tuff-like rocks having a large tensosensivity coefficient.

(6) The ULF signals in a frequency band 0.1–1 Hz detected at the Dusheti Observatory are characterized by two types of spectra: noise-like (0.1–1 Hz) and quasi-sinusoidal (0.5 Hz $\leqslant f_s \leqslant$ 0.8 Hz).

(7) The theoretical calculations are in good agreement with experimental data as to the amplitude order of the magnetic components ($\simeq$ 0.1 nT at a distance of $\sim$140 km from the earthquake site), relations $Z/H \geqslant 1$; $Z/D \geqslant 1$ and explain the noise character of the spectrum.

(8) The signal detected can be referred to the electromagnetic ultra-low-frequency lithospheric emissions (ULE). After a detailed study of the morphology and physics of ULE they might be considered as a possible source of short-term precursors of moderate to large earthquakes and their aftershocks.

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