STUDY OF EM RESPONSES UNDER SHOCK IMPACT ON ROCK SAMPLES. III. POWER INDUSTRIAL EXPLOSIONS

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Abstract

The problem of the electromagnetic (EM) responses at mechanical shock impacts on rocks of various structure and composition caused by the powerful industrial explosions is studied experimentally. This part of the paper is a logical prolongation of previous laboratory and field experimental investigations described in Parts I and II, and presents the results of field investigations obtained on real geological objects on studying the structure and intensity of the EM responses generated in the ELF-VLF frequency range in dependence on a character and power (energetic characteristics) of seismic impact. In the investigations both the seismo-electromagnetic and the radio-impulse methods realized in the field experimental complex were used. At the explosive impacts on rocks and ore bodies at distances of 100-200 m from the point of explosion, the intense signals in the ELF (1-30 Hz) and VLF (1-20 kHz) frequency ranges were registered in the experiments, and the cause of this was the piezoelectric effect, arising as a result of the impact of a shock wave to quartz inclusions in rocks. Studies have shown that similar responses in the ELF and VLF ranges can be observed (in the presence of quartz-containing ore bodies) at natural seismic events – the earthquakes of the 9-13 energetic class.

The results obtained are in good agreement with our previous ones obtained in laboratory and field experiments and presented in the Parts I and II of the work. Besides of registration of the seismic responses in the EM field, the results obtained can also be useful when performing direction finding works to ore deposits using spatially diversited ELF-VLF receiving stations.

1. Introduction

Studies of electromagnetic (EM) responses at impacts to rocks and ore objects were carried out in the North-East of Russia (the Magadan city and the Magadan Region) in order to determine the spectral-temporal characteristics and intensity of these responses in dependence on the nature and power (i.e. energetic characteristics) of seismic impact, and also for study the possibility of identifying responses from ore bodies at various seismic effects. In Parts I and II, the results of studies obtained in laboratory and field experiments were considered (see [1] and [2], respectively).

In this part of the work, we consider the results of experiments on real geological objects[1] conducted with the aim of recording the responses from powerful industrial explosions in the ranges of VLF, 0.4-9.5 kHz, and ELF, 1-30 Hz. The registration was performed using an experimental complex that implements the seismo electromagnet-

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[1] Tenkinsky area of the Magadan region.

ic method (the SEM method, see [3]) described in Part II of the work, at a distance of about 1 km from the point of explosion, at this the signal from the piezoelectric seismic sensor was being recorded per 1st channel, and the electric component of the EM field was being registered per the other (in some experiments, per the other two channels). The response spectrum was formed due to the interference of signals from objects that was excited by a passing explosive wave.

Besides, a mobile experimental complex was used that carried out measurements by the radio-impulse method (the RIM complex) in the range from tens of kHz to units of MHz [4]. At this, the recorded RIM realizations represented the registration of the group of pulses, the positions of which depended on the presence of ore objects on the propagation path of the explosive wave, the amplitudes were determined by the concentration of minerals giving responses, and the pulse spectrum depended on the composition of the ore objects.

Note that the spectra of signals recorded by RIM and SEM complexes have different formation mechanisms, and the integrated response energy is determined: for RIM signals – by the total concentration of ore objects in the vicinity of the explosion; and for the frequency range of the SEM complex – by signals from individual ore objects. Both methods, therefore, complement each other, and a joint analysis of the data obtained in the experiments allows us to give a more reliable interpretation of the results. Besides, we used the fact that the coordinated change in the integral energies of the responses registered by the RIM and SEM complexes at changing geological and seismic conditions indicates that both methods reflect the real picture, and not, for example, record the response from the occurrence of an ionized gas cloud at an explosion [4].

2. Work Area and Explosive Characteristics

To conduct research, we have selected the region for experimental works on registration of the EM responses from quartz veins and sulfidization zones at the passage of a seismic wave arising from powerful industrial explosions. The choice was determined by a set of features: the presence of ore objects that generate EM emission at shock impacts, the convenience of access and placement of SEM and RIM receiving systems, and the relative simplicity and low cost of a series of explosive works. The works were carried out in the quarry site "North-West" of the Natalka gold-ore deposit (Magadan region). The ore zones here are a series of subparallel linearly elongated bodies composed by the various on morphology quartz veins, lenses, streaks and hydrothermally altered rocks. In their core part the lens-like and vein-like quartz bodies of a thickness from 2-4 m to 10 m and a length of 80-100 m located rocker-similar both in plan and in section lie. Thus, this experimental site has a large set of “active” objects that, when a seismic wave propagates, emit a wide spectrum of EM waves, starting from low frequencies (up to 1000 Hz - the piezoelectric signals being registered by SEM) to high frequencies, 10-15 MHz (the signals that are being registered by RIM).

Excitation of seismic waves generating EM signals in rocks was carried out using the explosions of ammonite charges of different masses. The mass of explosives varied from 1 to 8 kg depending on the distance of the explosion points to the recording complexes. A total of 10 explosions were made. We studied the EM reaction of ore objects in the area of work to seismic signals of different intensities.

2. Results of Experiments During Power Industrial Explosions

In the experiments the field complexes SEM and RIM, and also the mobile complex for registration of the VLF emissions [3, 4] were used (see Introduction). The registration band of the VLF complex was selected from two conditions: the lower frequency of 1 kHz – from the condition of reducing interference from nearby industrial objects, and the upper frequency 15 kHz – from the condition of approaching on frequency to the RIM range.

From a series of 10 explosions, it was possible to qualitatively register 8 events in the ELF and VLF frequency ranges and 6 events in the range used by RIM. Figure 1 shows the oscillograms of impulses from explosions for the ELF range recorded on two space diversited antennas. The time in seconds is indicated on the abscissa axis, and the signal level in units of the least significant digit of the ADC is indicated on the ordinate axis. The numbers on the oscillograms correspond to the number of the explosion. The impulses corresponding to the moments of the explosions are clearly visible on both recording channels.

Figure 2 shows the segments of the signals recorded by the RIM complex. If in the ELF range only one pulse is observed, then using the RIM complex a whole series of the pulses with different amplitudes and spectral characteristics is registered.

Figure 3 shows the oscillograms of the response in the VLF range from the explosion number 1 and of the signal of mark of the explosion moment. One can see that the response signal is powerful and very clearly distinguished against the general background. Figure 4 shows the spectrograms of responses.

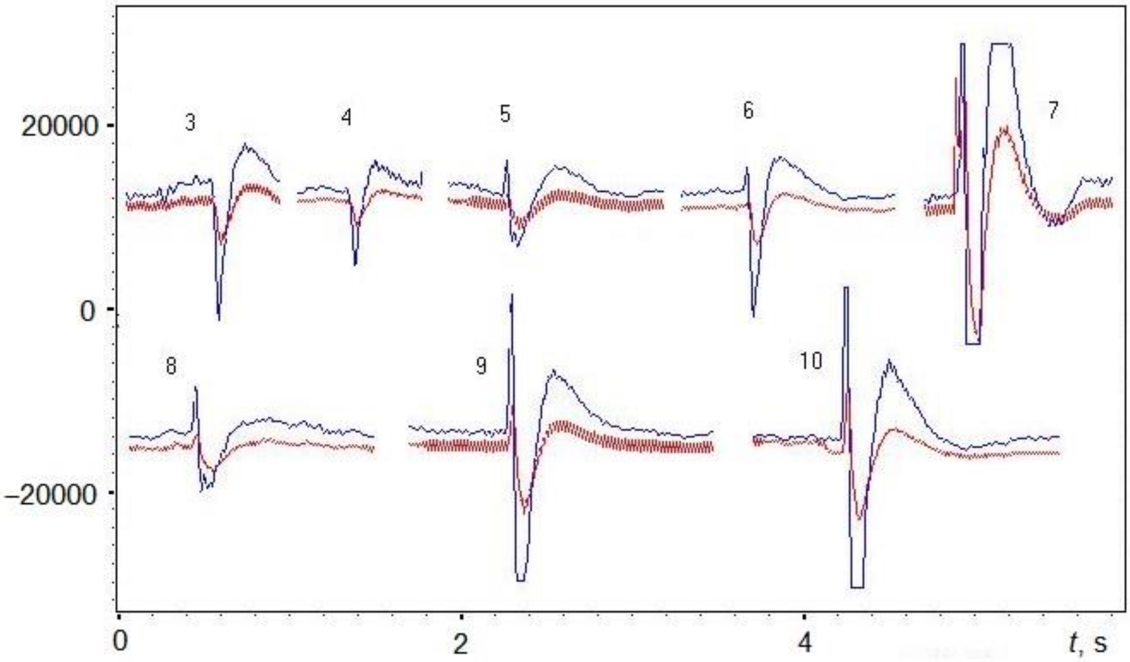

Fig. 1. Oscillograms of the responses from the explosions in the ELF frequency range received using two antennas.

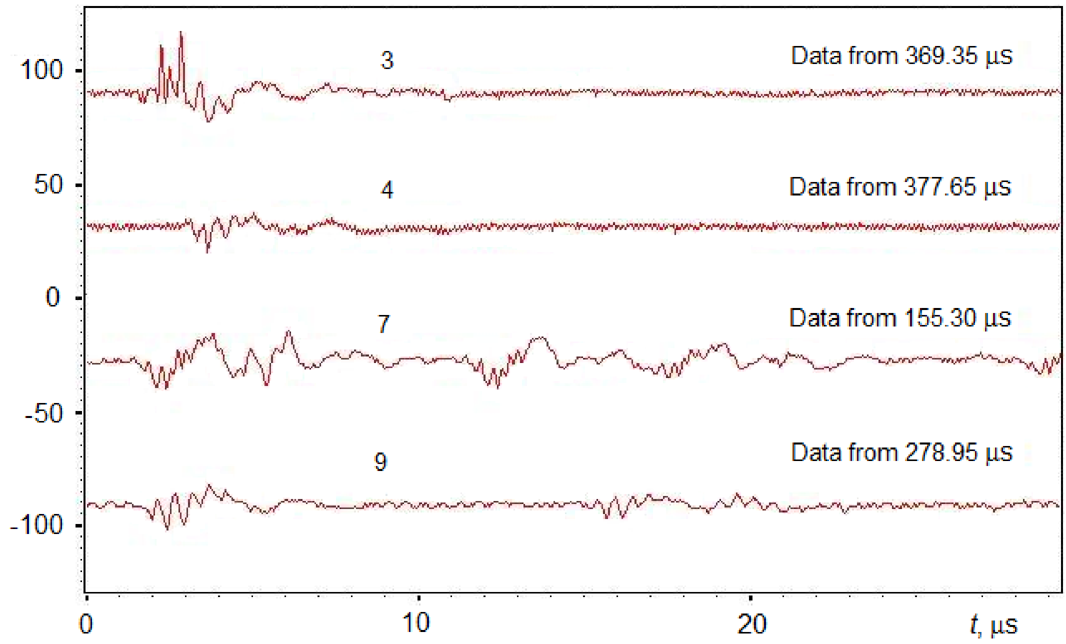

Fig. 2. Oscillograms of segments of RIM complex records.

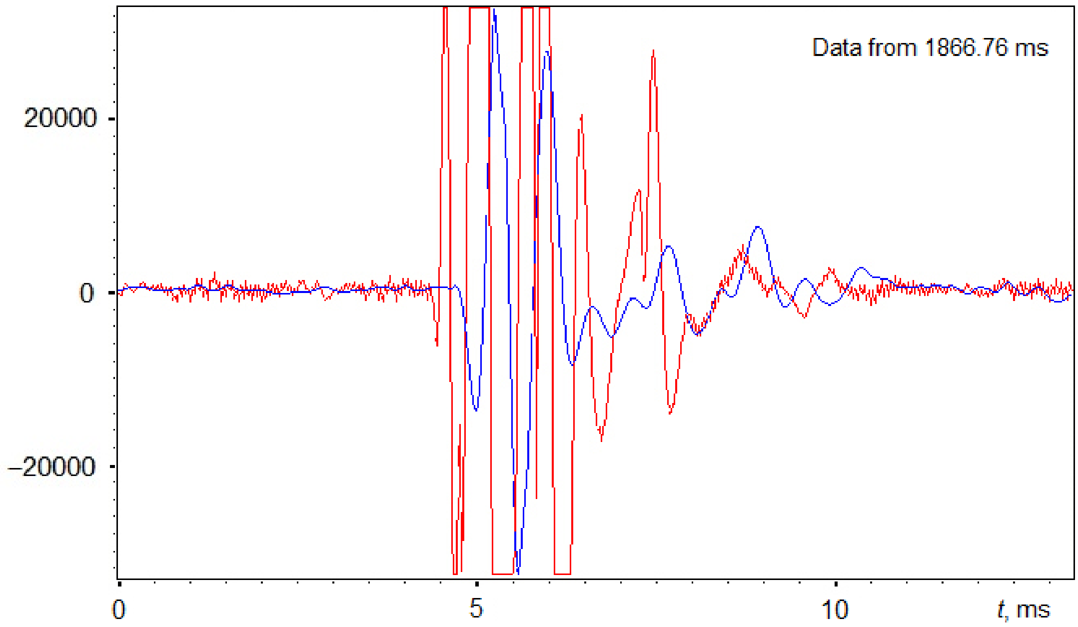

Fig. 3. Oscillograms of the electrical response from the explosion N 1 in the VLF range (red) and the signal of mark of the moment of explosion (blue).

In Fig. 5 the oscillogram of the VLF response from the explosion number 9 is shown. The main part of the response lasts more than 30 ms and, in comparison with the field in the absence of a explosive wave (before the response) and with field after its main part, we can assume a presence of a longer response in the high-frequency range.
We also recorded the EM field during mass explosions. Figure 6 shows the examples of these oscillograms. The second and third channels correspond to electrical signals from two ELF antennas, which were located on different sides from the ledge of the

hill at the top of the mountain. The first channel shows the signal from the seismic sensor. Figure 7 shows the spectrograms of these signals. The records are very noisy, however, during their processing, it was possible to detect the presence of a response approximately 0.6 s before the appearance of the seismic signal.

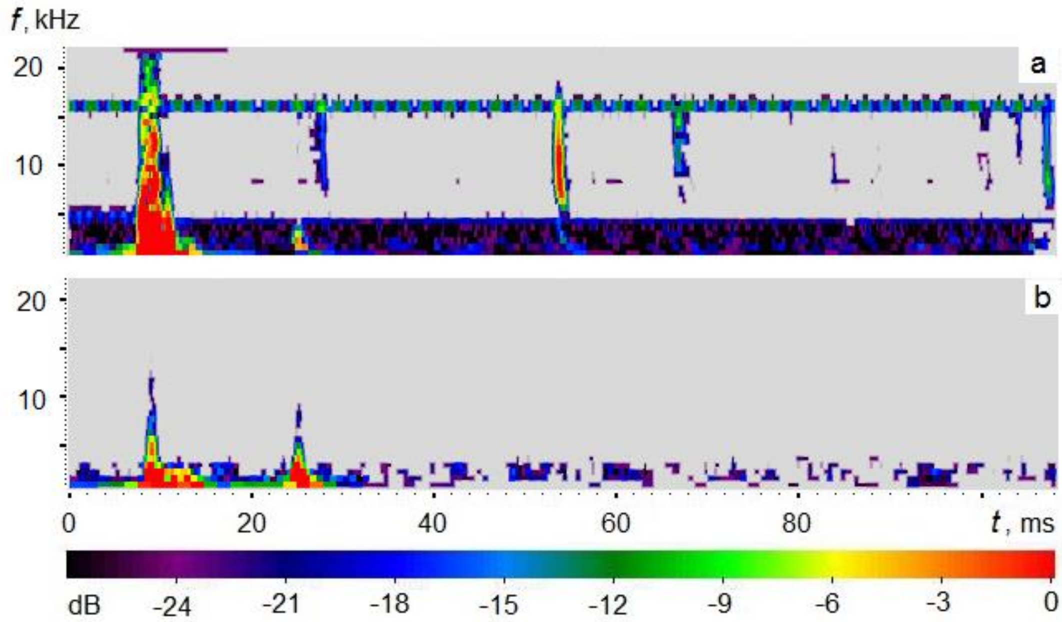

Fig. 4. Spectrograms of the electrical response from the explosion N 1 in the VLF range (a) and the signal of mark of the moment of explosion (b).

Another mass explosion took place on the same day as a series of explosions. The response signal is very clear (Fig. 8) and is clearly visible against a background of weak atmospheric interferences.

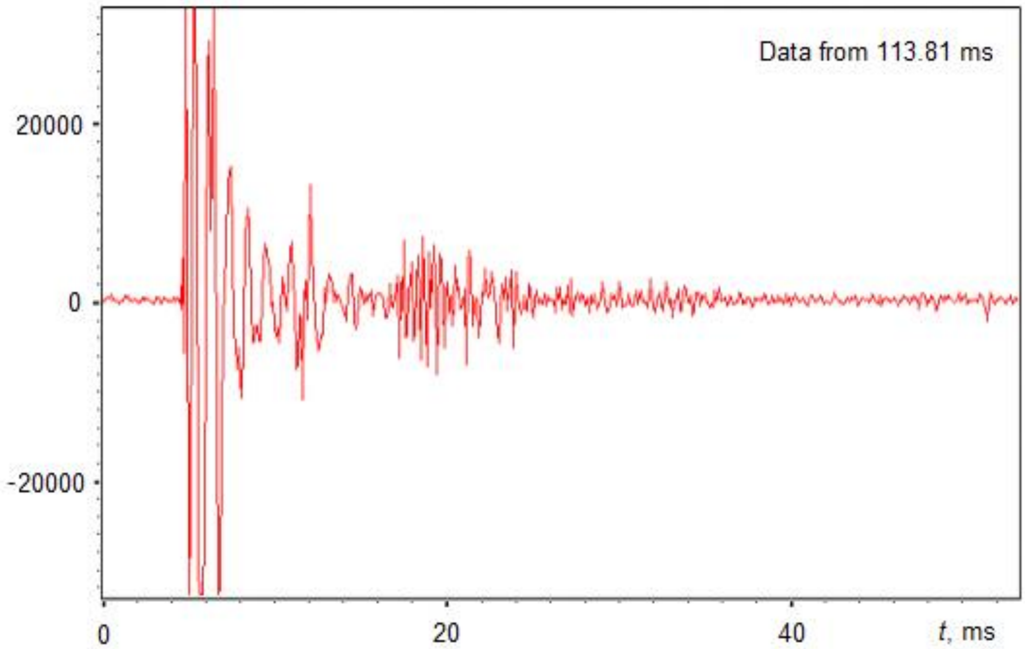

Fig. 5. Oscillogram of the VLF response from the 9th explosion.

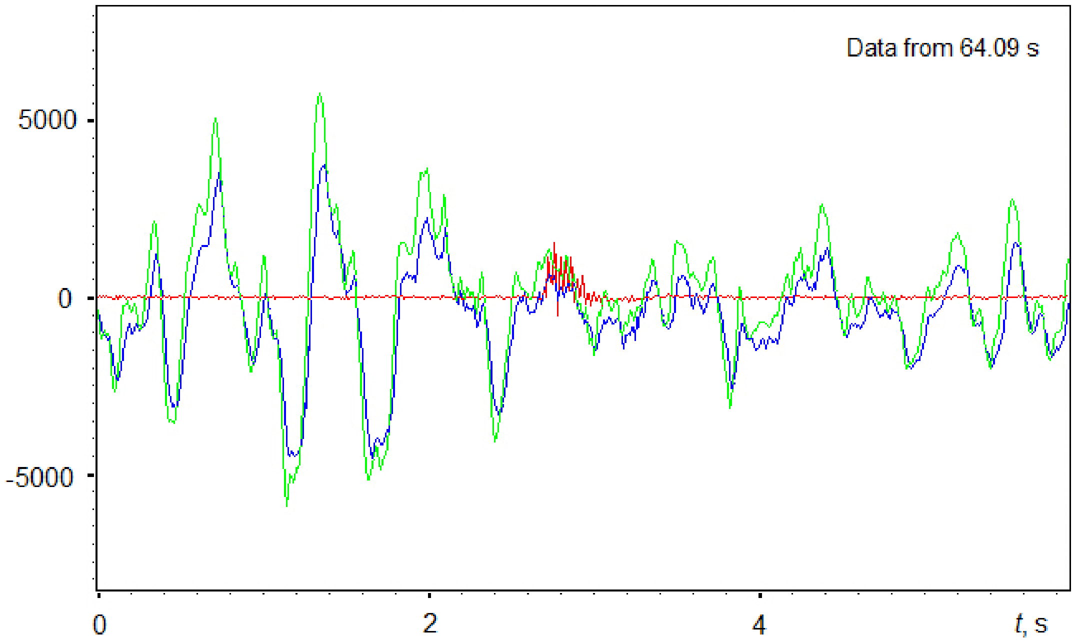

Fig. 6. Oscillograms of the signals of the seismic sensor (red), 1st ELF antenna (blue) and 2nd ELF antenna (green) during the time of the mass explosion of Sept. 14.

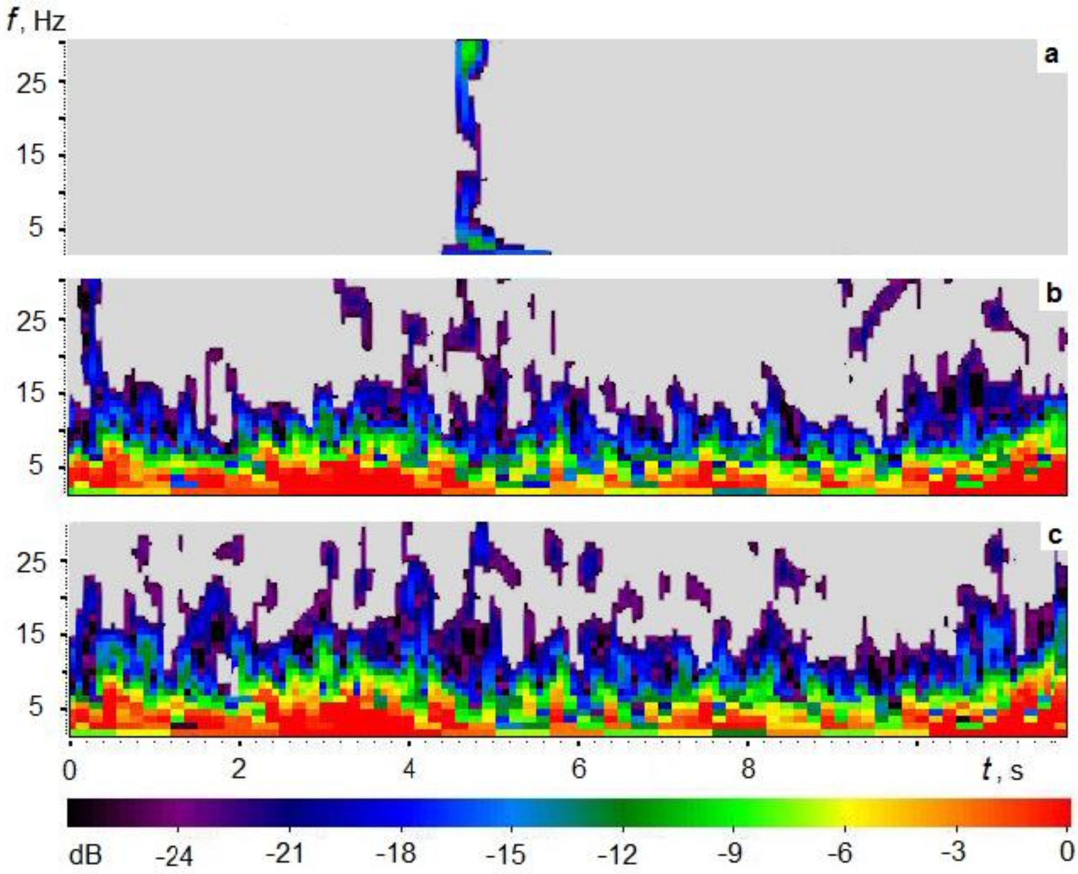

Fig. 7. Spectrograms of the signals of the seismic sensor (a), 1st ELF antenna (b) and 2nd ELF antenna (c) during the time of the mass explosion of Sept. 14 (spectrum from 62 s).

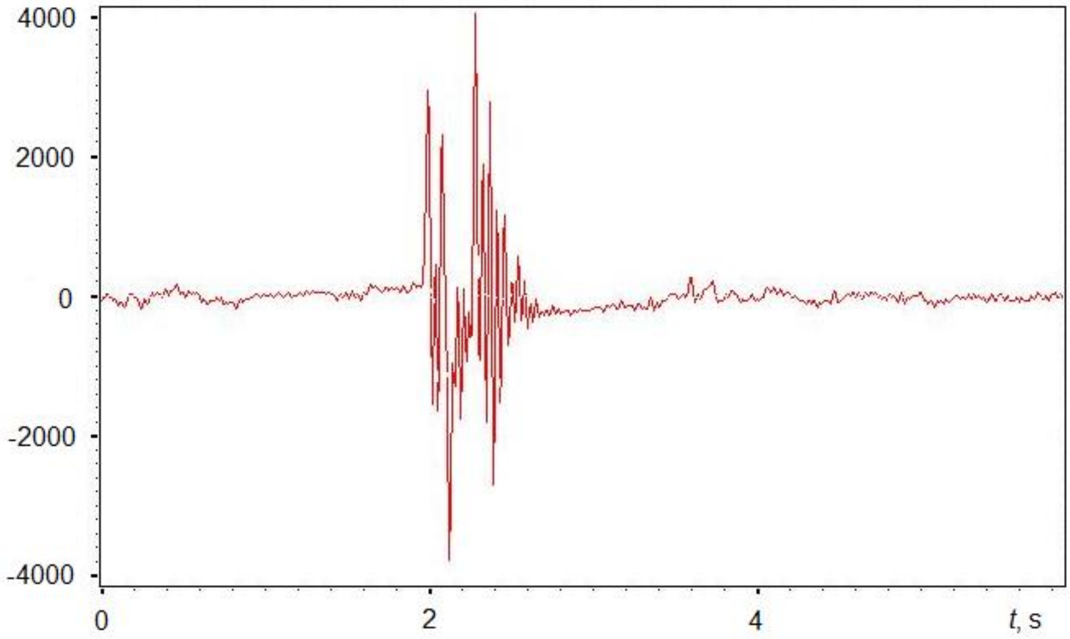

Fig. 8. Response in the ELF range from the mass explosion of Sept. 21.

We also give recordings of signals from a piezoelectric seismic sensor, which are necessary for evaluating the parameters of seismic impact. Figure 9 shows the oscillograms (a) and spectrograms (b) for explosions 7 and 8, corresponding to the distances to the sensor 55 and 110 m, respectively. The first pulse corresponds to the moment of the explosion. For the 7th explosion, there is also the impulse at the 65th ms, corresponding to the moment the seismic wave arrives at the receiver. In the spectrograms (Fig. 9b) one can see also the presence of the fastest wave (longitudinal [5]) with a response frequency of 200 Hz and slower, but somewhat more intensive (transverse) with frequency of 300 Hz. For the first wave, the propagation velocity is 2.5 km·s^{-1}, and for the second it is 1.5 km·s^{-1}. There is also a third, even more intensive wave (surface Rayleigh wave) with the upper frequency of about 100 Hz. Its velocity is 0.75-1 km·s^{-1}.

For a more detailed analysis of VLF responses, we will need their spectrograms shown in Fig. 10 (explosions 1-4) and 11 (explosions 7 and 8), and in Fig. 12 and 13 (explosions 9 and 10). In Fig. 11 and 12 for explosions 7, 8 and 9, the arrows indicate the moments when the explosive wave reaches the ore object. These time moments were calculated taking into account the distance to the object and the average propagation velocity of the fastest mode of the seismic wave, 2.5 km·s^{-1}. Explosion moments correspond to the beginning of responses. Note that the mode of the seismic wave of the largest amplitude propagated at velocity that was approximately 1.7 times lower.

In the spectrograms one can see the powerful responses in the low-frequency range and their continuation to the frequency range 10–16 kHz and higher, beyond the receiver passband. If for the initial part of the response this can be due to signal limitation, for explosions of 8 and 10, the response in the frequency range of more than 16 kHz is also observed at the 6th and 5th ms. This indicates a significant level of signals also for frequencies in the region of 20 kHz.

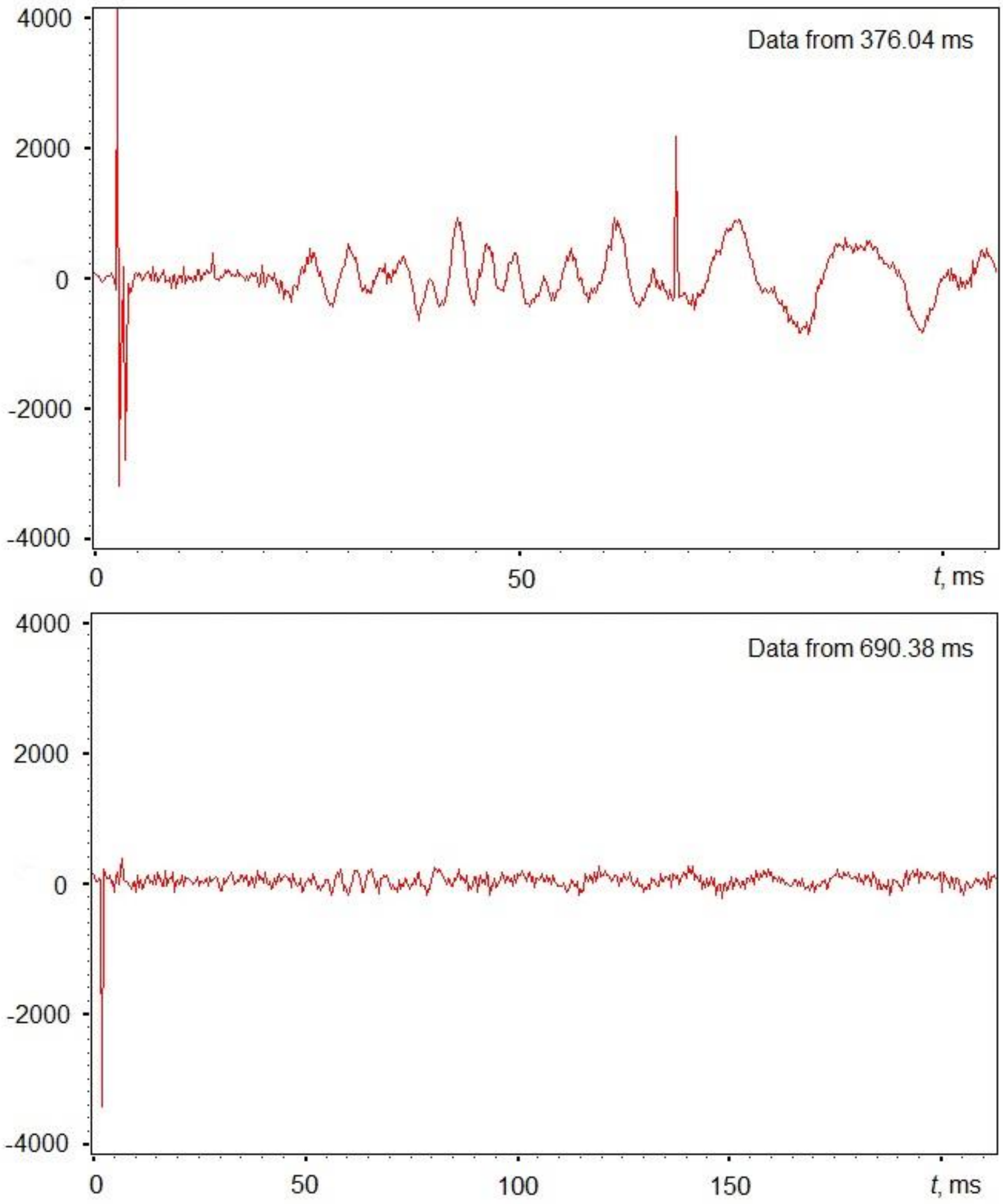

Fig. 9a. Oscillograms of the seismic signals for the explosions 7 and 8.

For explosions 1–4 the responses are short, and for explosions 7–9 the responses are long with a line structure. At the explosion 10 clearly shows two separate responses. Since the observation of signals in the region of the first kHz is the realization of the piezoelectric method, we can talk about the presence of significant domains of quartz-containing objects in the vicinity of points of the explosions 7–10.

We also present spectrograms of several explosions with a higher time resolution and lower amplifying so that the spectral-temporal structure in the low-frequency region would be visible. Figure 14 shows spectrograms for explosions 1-4, and in Figs. 15, 16 and 17 – for explosions 7, 8 and 9. As can be seen from these figures, the strongest responses are oscillations of decreasing frequency. The maximum signal amplitude in Fig. 14 is first observed at frequencies of 3-5 kHz and within a few ms is shifted to the region of lower frequencies. This is characteristic of piezoelectric responses (see [1, 2]). This effect is also visible in Figs. 15-17. First, the excitation arises in the boundary region of the massive domain (with quartz inclusions) with transverse dimensions of 0.3–1 m, and then, as the shock wave propagates deeper, the oscillation frequency decreases with an increase of transverse dimensions. Along with this effect, a faster decay of high-frequency seismic waves compared to low-frequency ones can also lead to decrease of the frequency of observed oscillations. The electric field generated due to the piezoelectric effect has the same spectral composition as the seismic oscillations, as shown in our laboratory experiments (see Part I of the paper [1]).

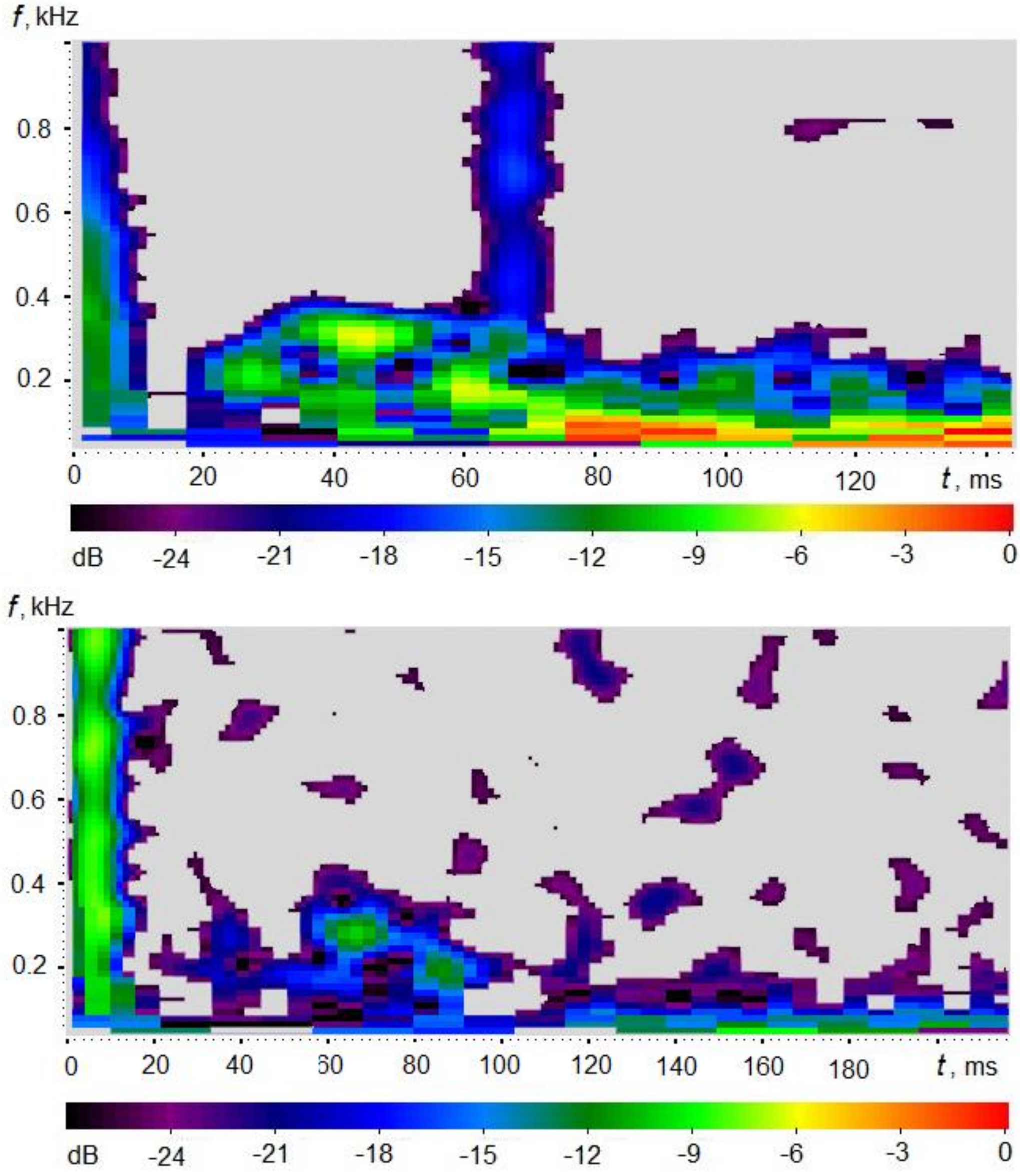

Fig. 9b. Spectrograms of the seismic signals for the explosions 7 and 8 corresponding to oscillograms shown in Fig. 9a.

The ELF receiver responds to the low-frequency "tail" of the observed piezoelectric oscillations. In the case of several "emissing" domains, the excitation of which occurs with an interval of several ms (that we see in Figs. 15-16), in the low-frequency region the interference of the oscillations will occur. As a result, amplification of oscillations in some frequency range or their weakening can occur, which we observe for explosions 7 and 8 in Fig. 1. The response from the explosion 7 (in the first channel, where there is no restriction) has, at first, an oscillating part, and the response from the explosion 8 has a reduced amplitude and small oscillations. This can be seen more clearly in the spectrograms (Fig. 18). The response from explosion 7 has a clearly impressed spectral maximum observed in the region of 18 Hz. The response from the explosion 8 also has a spectrum rise in the region of 15 Hz. The response from the explosion 9 has a spectrum decreasing with a frequency. In fig. 17 there is only one strong burst of low-frequency oscillations in the first 3 ms from the moment of explosion.

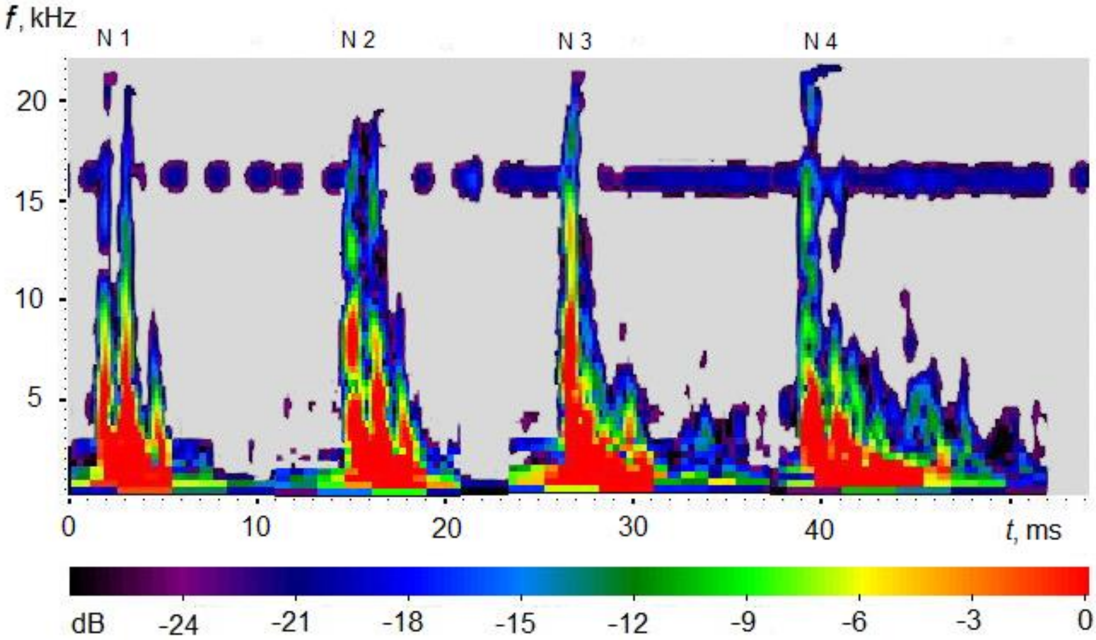

Fig. 10. Spectrograms of the responses in the VLF range from the explosions 1-4.

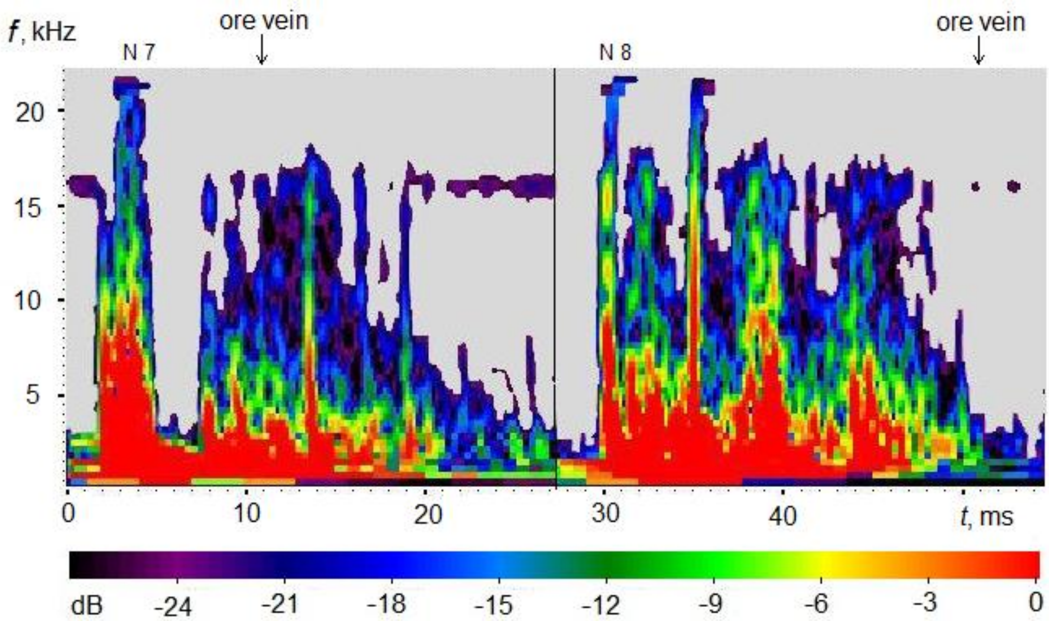

Fig. 11. Spectrograms of the responses in the VLF range from the explosions 7 and 8.

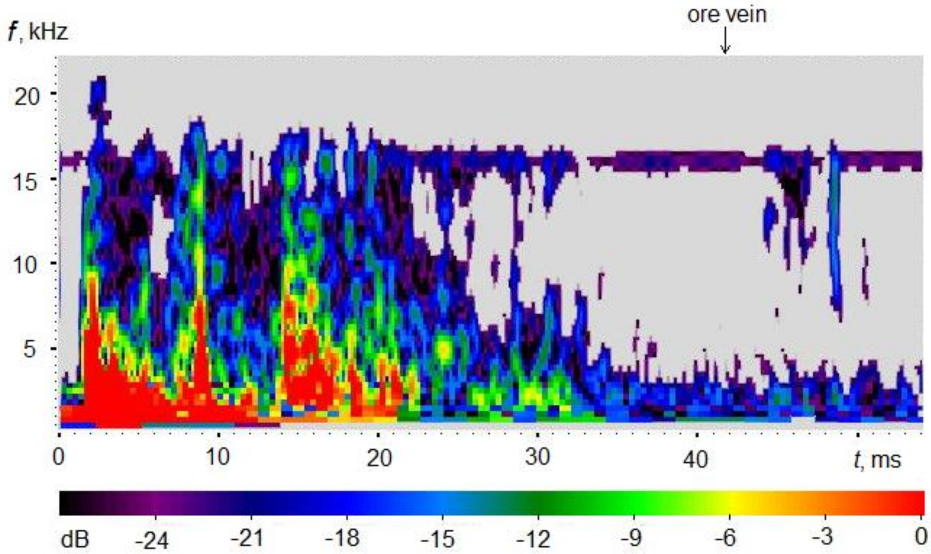

Fig. 12. Spectrogram of the response in the VLF range from the explosion 9.

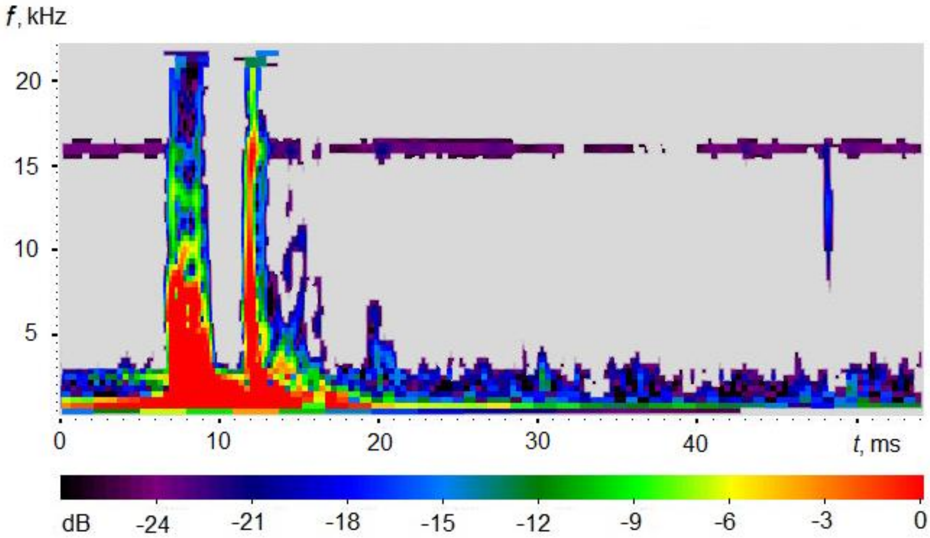

Fig. 13. Spectrogram of the response in the VLF range from the explosion 10.

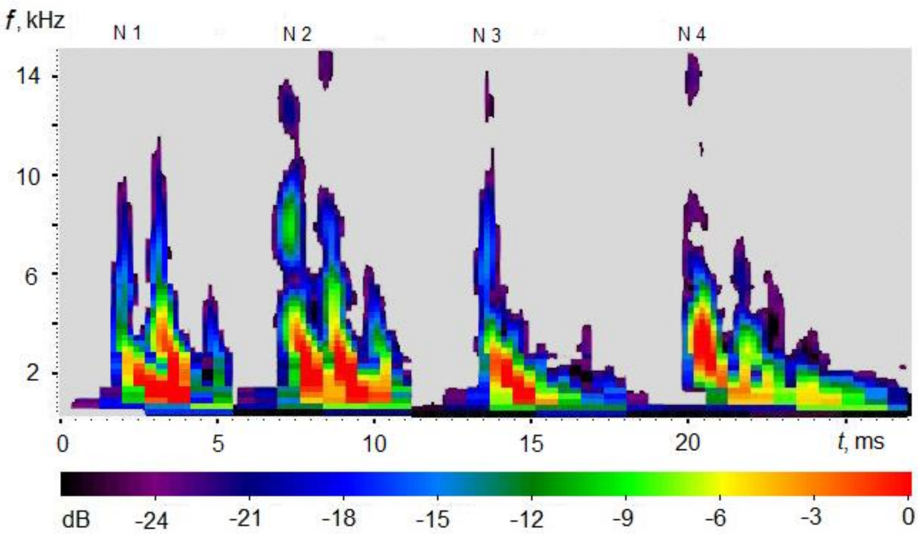

Fig. 14. Spectrograms of the low-frequency part of the responses
in the VLF range from the explosions 1-4.

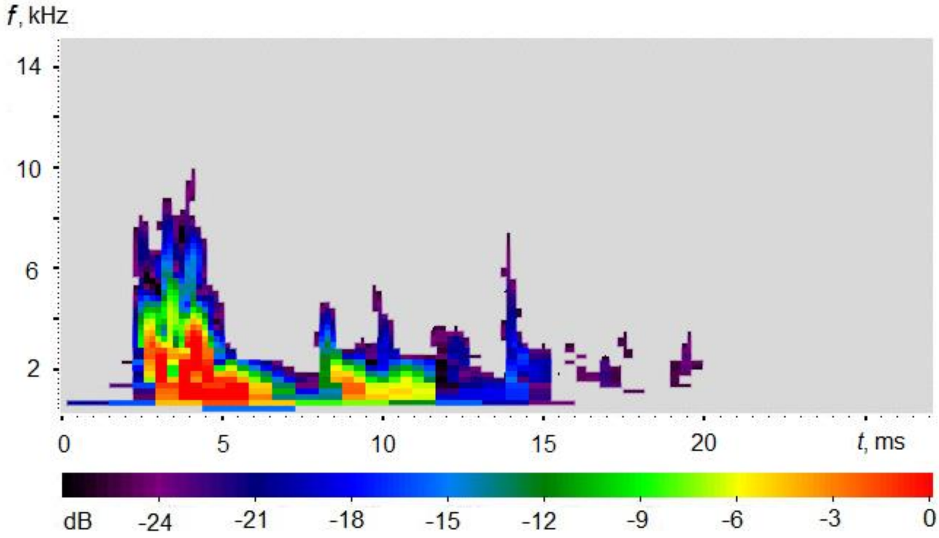

Рис. 15. Spectrogram of the low-frequency part of the responses in the VLF range from the explosion 7.

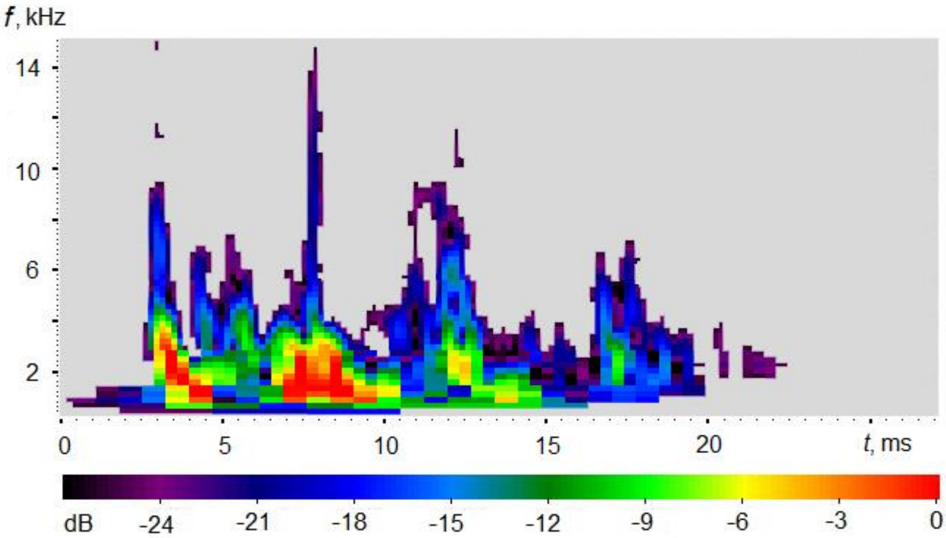

Fig. 16. Spectrogram of the low-frequency part of the response in the VLF range from the explosion 8.

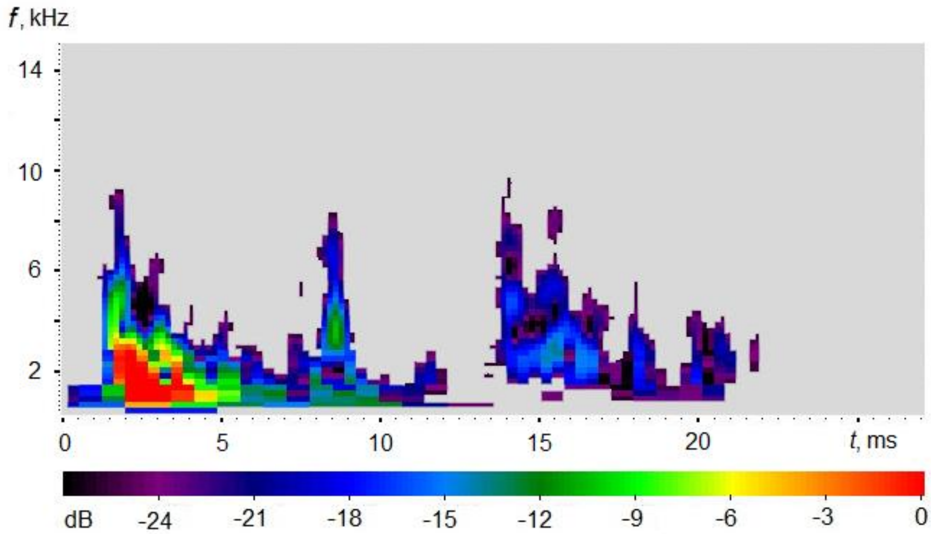

Fig. 17. Spectrogram of the low-frequency part of the response in the VLF range from explosion 9.

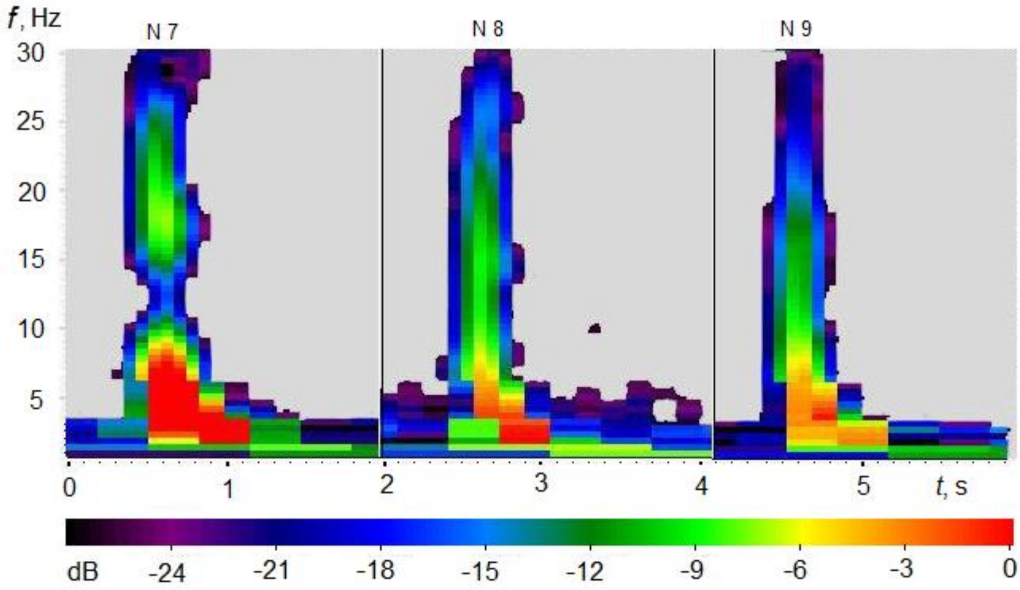

Fig. 18. Spectrograms of the responses in the ELF range from the explosions 7-9.

Thus, there is the same piezoelectric nature of the observed responses in the ELF range and in the VLF range at frequencies up to 5-6 kHz.

As for the pulsed emissions observed on the spectrograms of responses in the VLF range, the most likely cause of their occurrence is the reaction of cracks to a seismic wave. There is a reaction both to existing ones and to cracks that arise or evolve during the first explosion – at the next explosion (explosions 3 and 4 were carried out at one point). In Fig. 14 during the third explosion, a continuous signal with decreasing frequency is observed, and at the fourth explosion, three impulse signals are superimposed on it.

It is necessary to note that based on the experiments performed, it cannot be argued that significant responses can be observed in the VLF range at impacts to quartz-free rocks. The responses, although observed in laboratory experiments (see [1]), in real conditions may have insufficient excess over the background. But for the considering case of quartz-containing rocks, there is a strong reaction to seismic impact at least up to frequencies of the order of 20 kHz, and responses in the low-frequency RIM range are confidently recorded.

Consider the spectrogram of the longest high-frequency RIM response for explosion number 7 (Fig. 19). Noticeable impulses are usually observed only during the first millisecond, although in Fig. 15 during the first 5 ms, three surges are visible, and with an increase of their order number, the signal in the high-frequency region also increases.

There are two reasons for the absence of signals recorded by the VLF complex on the RIM complex records, and both of them are associated with the use of a magnetic antenna (frame). The first one is that the sensitivity of magnetic antennas decreases proportionally to decreasing the registration frequency, and the second is that the signal itself from an electric type source for distances much shorter than the wavelength has an electric component that depends on the distance as r^{-3}, and the magnetic as r^{-2} [6]. If in the RIM complex an electric antenna were used, the signals observed by the VLF complex would be visible on it too. The second important point is the absence of RIM signals after the first millisecond, which is observed for all explosions. It can be assumed that, either for existing quartz-containing ore bodies, the impact resulting from the explosions is simply not enough outside the first few meters of the explosion to generate high-frequency RIM signals, or these signals simply did not enter the set duration of the RIM station registration band. Taking into account the technology for the production of explosions (consignment notes), the first variant is more likely. Therefore, the registration of responses in the VLF range is possible with a significantly lower level of seismic impacts than in the RIM range. This conclusion agrees well with the results of laboratory experiments (see [1, 3]), in which high-frequency radio-pulse signals were observed on the background of low-frequency ones only at significant violations of the bulk integrity of the samples. Here, the result is further enhanced by the presence of quartz, that was also observed in laboratory experiments.

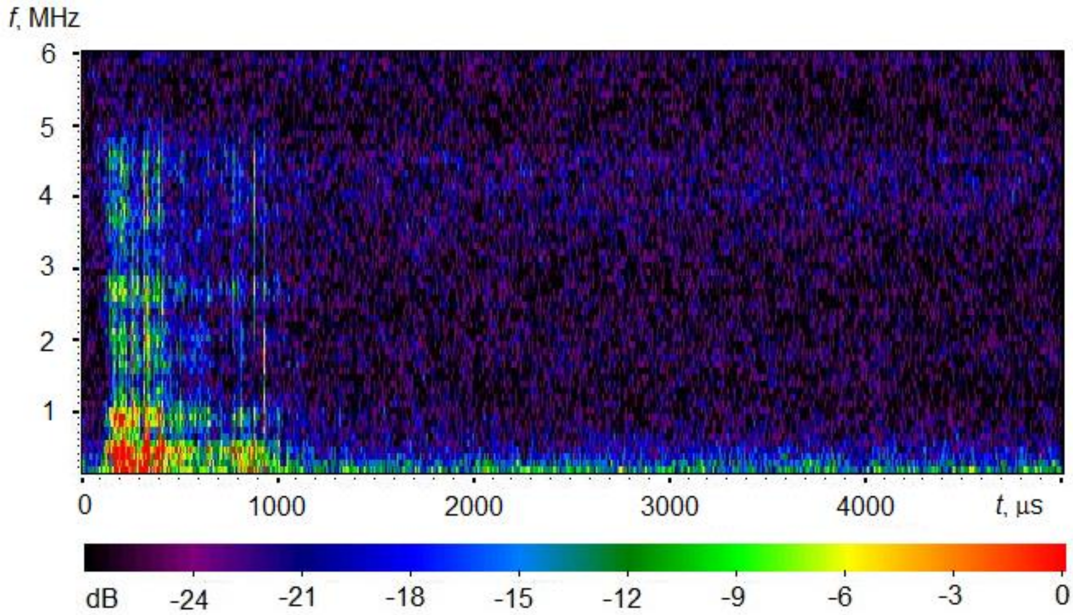

Fig. 19. Spectrogram of the RIM response from explosion 7.

3. Interpretation of the Experimental Data and Discussion

In [4], it was shown that the ELF responses (1–30 Hz) from explosions correlate in energy characteristics with high-frequency RIM signals. It was also found that for all types of ore objects present in the region of explosions, the RIM signals, are generated at small distances from the point of the explosion. For the RIM signals, this distance is up to 3–4 m (basing on the velocity of propagation of the shock up to 4 $km \cdot s^{-1}$ near the point of explosion). ELF signals are generated as low-frequency tails of piezoelectric responses arising in the first 10–12 ms after an explosion moment (the distance is up to 30 m at the seismic wave velocity 2.5 $km \cdot s^{-1}$). Of course, one can expect ELF responses at lower levels of seismic impact, but the EM signals from such responses will be essentially lower.

At the same time, in the VLF range, we observed responses within 22 ms from the moment of the explosion (explosions of 7 and 8 – 2 kg of ammonite) and 26–32 ms (for the explosion of 9 – 4 kg of ammonite). Based on the velocity of the fastest mode of the seismic wave (2.5 km·s^{-1}), the distances to the point of explosion correspond to 55 m and 65–80 m. It can also be assumed that in Fig. 12 a weak response observed at time 57 ms ahead of the atmospherics signal registered at time 60 ms belongs to the vein located at a distance of about 100 m. But, since it is impossible to confidently state that all responses are caused by the leading front of the shock wave (because the latters from them can be associated with a slightly stronger, up to 3 dB, seismic wave mode with a propagation velocity of the order of 1.5 km·s^{-1}), the corresponding distances may decrease up to 33 m and 39–48 m. The third, surface Rayleigh wave, has an even lower velocity and 7 dB greater amplitude, but at the same time and 3–4 times lower prevailing frequencies, and the pressure created by it is less than from faster waves. Nor can it be argued that all registered responses are associated only with the waves propagating along the surface. One can also observe them when the wave propagates deep into the bedrock, and the velocity of such a wave can be 1.5–2 times higher (about 4–5 km·s^{-1}). For such a wave, the damping can also be smaller [7] and, therefore, there is a high probability of receiving the responses. This will result in a corresponding increase of distances.

Let us use the results of [4]. The maximum response duration from the explosion 7 corresponds (for different variants, in decreasing magnitude order) to pressures 350, 125 and 30–50 Nm. For the explosion 9, we have 320–485, 115–175 and 30–70 Nm. Then, for minimal estimates of pressure, we can expect responses similar to observed from the earthquakes of classes 9, 10, and 13, respectively, at distances up to 10, 25–30, and 600–1200 km. For average earthquake classes we obtain: 5–8, 10–15 and 300–750 km. In the worst case scenario, we obtain: 2.5–5, 8–10 and 170–470 km.

Thus, although the most frequent weak earthquakes can generate responses only in their vicinity up to 30 km, rarer significant earthquakes (for example, such as the one that occurred 200 km from Magadan on January 7, 2001) can cause the VLF responses at distances of hundreds of kilometers and possibly throughout the large region.

Therefore, we can talk about the possibility of generating the responses obtained in the VLF range and under natural seismic events. However, for a clear identification of responses, it is necessary to have a noticeable excess of the signal level over background noise. To estimate this ratio, two parameters must be estimated, namely: attenuation of the signal during its propagation and the initial signal/noise ratio. Based on the recorded realizations, the last parameter was estimated as 19–33, 26–39, and 20–33 dB for the ELF bands of 1–5, 5–10, and 10–30 Hz, respectively. For the VLF range, we have obtained 38–52, 40–50 and 33–48 dB in the bands 1–5, 5–10 and 10–15 kHz.

To estimate the attenuation of radio waves, one can use the expression for the field E of an electric dipole (with the dimensions much smaller than the wavelength) [6]:

$$E = I_e l \ (4\pi\omega\varepsilon\, i)^{-1} \left\lfloor r^{-3} + ikr^{-2} - k^2 r^{-1} \right\rfloor \exp(-ikr) \qquad (1)$$

where $I_e l$ is the dipole current moment, ω is the circular frequency, ε is the dielectric constant, $i = \sqrt{-1}$, r is the distance, $k = 2\pi/\lambda$, λ is the wavelength.
At distances essentially shorter than λ (a near zone), the main contribution is defined by term r^{-3}, and at distances essentially greater than λ (a radiation zone) by term r^{-1}. In the radiation zone, the field E is proportional to the frequency. At $r = \lambda / 2\pi$ all three terms in Eq. (1) give the same contribution.
Take, for example, frequency 15 kHz, then the boundary between the near zone and the radiation zone will be located approximately 3 km (λ = 20 km) from the source. If now to take the average distance from the source in our experiments as 150 m, then at a distance of 3 km all signals will be weaker by 8000 times (by 78 dB), and if to take into account the existing signal/noise ratio, no more than by 40-50 dB, i.e. the signals could be not distinguished at the background level. If we take the distance of 150 km to the receiving point, the signal of frequency 15 kHz will weaken additionally 50 times and the possibility of registering such a signal will practically disappear.
However, it should be noted that in the experiments we observed responses from individual ore bodies, and during an earthquake, seismic impact will affect the entire deposit simultaneously, and we will deal with superposition of the responses. In addition, the waves damping in the VLF range is much lower than in the ELF range due to the exit of the wave from the near zone. One can also get an additional gain due to the increase in antenna sizes and optimal signal processing, since in the VLF range, unlike the ELF one, no own fluctuation component is formed [8], and the potential efficiency of the suppression of pulsed noises is defined precisely by the level of the fluctuation component [9]. Moreover, the method of broadband receiving in the VLF range used in our experiments refers to the cases of possible substantial gain from multidimensional processing of the recorded signal [9]. Therefore, in order to obtain the highest quality results, it is recommended to carry out observations in the VLF range, using not a single receiving point, but a network of stations.
As for the observations in the ELF range, according to the estimates made in [4], as a result of such observations, one cannot expect the detection of responses from remote deposits, that is explained by the attenuation of radio waves according to the law r^{-3} in the whole zone (up to 1500 km for the upper frequency of the range f = 30 Hz). A response distinguished against the background of noise can be obtained only in the case of a spatial coincidence of the earthquake epicenter with the deposit. However, when registering the EM field in the ELF range, one can expect responses from extended objects at the distances up to 10-15 km. The premises for this are two factors. The first is the correspondence of the frequencies of the propagating seismic wave to the reception band. As a result, one can expect inphase summation of responses from individual objects and their correlation with the shape of the seismic wave. The second factor is the high spatial correlation of the atmospheric interferences field in the ELF range. According to [10], at distance of 1000 km, this correlation reaches 0.95. Therefore, in the case of absence of meteorological interferences, the use of a “pure” reference signal from a station where there are no deposits nearby can significantly improve the signal/noise ratio at station where responses from ore bodies are present. The loca-

tion of the bodies themselves can be estimated by comparing the seismic and the EM records.
We also note that the organization of parallel registration of high-frequency RIM signals is very useful, since they almost immediately exit into the radiation zone. However, here it should be take into account that, besides the lowest frequencies of their range, one cannot expect from these signals will bend around the bumps of a relief. Besides, according to the results obtained in [4], they require essentially more powerful seismic effects for their generation, therefore their emission can be expected only from the zone of the earthquake source itself.

3. Conclusion

In conclusion, we carried out the experimental works on the registration of the EM radiation generated by quartz-containing ore objects when shock (seismic) waves passed through them, using the SEM and RIM methods.
In the experiments on investigation of the EM responses at explosive impacts on rocks and ore bodies the intensive signals in the ELF (1–30 Hz) and VLF (1–20 kHz) ranges were registered at distances of 100–200 m from the point of explosion. These signals were caused due to the piezoelectric effect arising from the action of an explosive wave on quartz inclusions in rocks. The measurements were carried out using a stationary computer powered by a gasoline generator (ELF range) and a mobile notebook computer (VLF range) using appropriate receivers and analog-to-digital conversion tools built into computers. Simultaneously, we registered the pulse signals using the radio impulse method (RIM). The energy characteristics of the responses in the ELF and VLF ranges were correlated with the energy of the observed RIM signals, that indicates the real presence of the same geological bodies generating EM emission simultaneously in these frequency ranges.
Estimates made showed that similar responses in the ELF and VLF ranges can be observed (at presence of quartz-containing ore bodies) also at natural seismic events – the 9–13 energy-class earthquakes.
In addition to registration of the responses from seismic events in the EM field, this gives a possibility to define directions to ore deposits using a network of spatially diversited ELF-VLF receiving stations. The only difficulty to the realization of this possibility is the fast attenuation of radio waves within the near zone of the source until the wave exits the radiation zone to zone where the low-frequency waves can propagate over long distances bending around the bumps of a relief. This difficulty is naturally overcome in the case of natural seismic events, when instead of emission from a single event (explosion), at the network stations, a superposition of signals from the spatially diversited ore bodies will be recorded.

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