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Discussions

The results of experimental studies of VLF–ULF electromagnetic emission by rock samples due to mechanical action

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Study of VLF-ULF EM emission caused by mechanical action on rock samples

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Abstract

The paper presents the results of laboratory experiments on electromagnetic emission excitation (electric component of electromagnetic field) by rock samples due to different forms of mechanical stress applications. It was shown that samples generate electric impulses with different spectra when the impact action, gradual loading or dynamic friction is applied. It was ascertained that level and spectral compositions of signals, generated by rock samples, change with increasing quantity of hits. It was found that strong electromagnetic signals, generated while rock samples were fracturing, were accompanied by repetitive weak, but perceptible variations of the electric field intensity in short frequency range.

1 Introduction

It is know that many earthquakes are accompanied by electromagnetic (EM) anomalies (Molchanov et al., 1992; Hayakawa and Fujinawa, 1994; Hayakawa et al., 2005; Lsaev et al., 2000; Eftaxias, 2003; Ida et al., 2008). Many EM events, registered by different seismo-electromagnetic stations situated in different countries, can be related with the ionospheric perturbations located over seismoactive zones (Hayakawa, 1990; Liu et al., 2004; Rapoport et al., 2004), charged particles coming out the Earth interior (Carpinteri et al., 2012), water solutions flowing in the fracture area (Ishido and Mizutani, 1981), or different mechanoelectrical transformations (Ogawa and Utada, 2000) in hypocenter of the earthquakes. However, the nature of such phenomena is not studied well. So we can not assert with confidence that the observed EM anomalies are of seismic origin (Masci, 2012a, b; Masci and Thomas, 2013).

The difficulty of studying the seismic-electromagnetic (SEM) precursors' nature consists in the absence of precise description of the processes that occur in the zones where the earthquakes are preparing. Also, a big amount of technogeneous EM interferences makes detection of SEM signals complicated. It is obvious that

a process of earthquake initiation accompanies by rocks failure in the hypocenter. Different mechanoelectrical transformations can occur during initiation processes. Laboratory experiments show that rocks, even those that do not contain piezoelectric materials, can generate EM emission in wide frequency range, under mechanical stress (Rabinovitch et al., 1998; Freund, 2007; Yasuhiko et al., 2009). We need to mention that, usually, published papers represent the results of experiments carried out with only one type of mechanical influence like loading with the following fracture of the samples or gradual loading without failure; impact; rubbing samples with, as a rule, smoothed surfaces.

A choice of VLF–ULF range for our researches is associated with the distinctive features of a long EM wave propagation in different mediums. Obviously, some part of the EM radiation, generated in the hypocenter of the earthquake, can reach Earth surface. Also we took in consideration the net of seismic-electromagnetic stations, situated in Magadan region. These stations register EM anomalies, probably of seismic nature, in VLF range.

It is obvious that deformation, fracturing of rocks and formation of EM field proceed during some amount of time. And, within this time, a spectral composition of EM emission can change. To know the characteristics of the signal at different phases of its formation, we can use Short-time Fourier Transform or Wavelet analysis as it was introduced by Kyriazis et al. (2006).

The purpose of our laboratory researches was to determine the characteristic properties of electric emission frequency and amplitude variations in VLF–ULF range during the dynamic action on rock samples.

Electrical component of EM signal generated by rock samples under the impact, gradual loading, and friction is considered in current article. The recorded signals were analyzed by Short-time Fourier Transform.

2 Experimental procedure

Samples of quartz, granite, granodiorite, and shale were selected for our experiments. They had shapes of cubes with 2, 3, and 4 cm edges.

To prevent the influence of various EM interferences and natural noises on the registered signal, the experiment was conducted inside a steel box. To prevent a contact of metallic surface with a rock specimen and undesirable vibrations, due to the impact, a sample was located on the massive plexiglas plate, which was placed on a dense foam-rubber. The receiving antenna was placed 25 mm away from a sample, which had piezo pickup attached to it. Antenna was connected to a signal amplifier with operating frequency band 1–200 kHz; the amplifier was linked to the analog-to-digital converter of a computer. A Power Graph 2.1 software was used for the recording. The monitoring was held in 10–30 kHz range. The diagram of the experimental setup is depicted on Fig. 1a. A 31.4 gm steel ball served as a hummer. The distance of its fall was 243 mm. Since the point of contact of the ball and a rock specimen was slightly varying, the experiment was held 3 times per each sample. Some samples were subjected to a greater quantity of hits (900 impacts) to evaluate the effect of such action on characteristics of the generated EM signal. For the friction and gradual loading experiments, a laboratory press (P-50), with a maximum load of 500kN, was used. 1 cm thick rock samples with square sections (4 cm × 4 cm) were subjected to the friction action. Taking into account that probability of the existence of perfect flat and smooth surfaces in natural conditions is extremely low, the rubbing faces of the samples were not grinded. The rock plates were placed in the clamp which represents vice with the internal 1 cm plywood gaskets for preventing the contact of metal with a sample. Also, thin sheets of fiberboard were attached to the surfaces of the press metallic basses (Fig. 1b). The antenna was situated 1 cm away from a sample's surface. The recording of the signal was carried out via the sound card (frequency bandwidth 10–24 000 Hz) and PowerGraph 2.1 software. Pairs of samples of equal rock types and pair of samples of different rock types were used in the experiments.

The loading was applied till complete fracture of the samples. The diagram of the experimental setup is illustrated in Fig. 1c. Samples of cubic shape, with 3 and 4 cm faces, were placed between two thin fiberboard plates to eclectically insulate them from metallic bases of the press. The antenna was placed 1 cm away from the rock cube. Loading was raised with a constant rate.

A signal, received from the antenna, was amplified by 40 dB in each experiment.

For the spectral-temporal analysis, and for the spectrograms construction, a program was created. It is based on the Short-time Fourier transform which allows us to obtain characteristics of a signal's frequency and amplitude distribution in time. A Hanning window function with optimum width of 32 ms was used for experiments with gradual loading; 5.325 ms – friction test; 1.331 ms – impact action.

3 Results and discussion

3.1 Impact

The EM signals, related with a rock sample and the metal ball, were registered when the sample was hit. Before the experiment was carried out, a registration of EM emission generated by the metal ball hitting a surface of the plate was held. It helped to select a signal, related with the impact action on a test specimen only, when an analysis was implemented. A form and a spectral composition of the EM impulse generated by the ball are depicted in Fig. 2. A level of the emission was 3–5 times lower in the comparison with the impulses excite by the rock samples.

Figure 3 depicts the spectrograms of the EM impulses which were registered during the impact actions (no more than 3 hits) on the granite, granodiorite, quartz, and shale samples. In the tests with granite, granodiorite, and shale specimens, amplitudes of the recorded signals were located in 0–6 kHz frequency range – mainly in the bottom of the given band. During the impacts on the quartz samples, amplitudes of the EM emissions lay in the higher frequency band (6–24 kHz).

At the time of impact on the shale samples, emissions took place in 0–9 kHz frequency range. Maximum amplitudes lay, mostly, below 2 kHz. 5 % of all samples were remarkable for the presence of the high frequency components in 8–21 kHz band. Recordings of EM signals, generated by the specimens that don't contain any piezoelectric materials, are notable for the distinctly lower levels. On average, magnitudes of the EM emissions generated by granite, granodiorite and quartz samples were 50 % higher than ones generated by shale.

All samples, subjected to impact action, produced EM impulses which are notable for the abrupt increase of amplitudes in wide frequency band, and following rapid decay in 6 kHz area and a gradual damping of the signals on the frequencies located below 6 kHz.

Samples, which generated EM signals without pronounced high frequency components, were subjected to a higher quantity of hits. First impacts caused no significant changes in registered EM emissions. Their noticeable decay was observed after 100 hits (Fig. 4). After 300 impacts the experiment was interrupted. Second stage of impact action was carried out in 24 h, and showed that the magnitudes of the signals were relatively close to their levels at the beginning of the experiment. The following decay was less rapid than during the first hundred hits. After 500 impacts high frequency component in 2–3 kHz band appear in the EM emissions, and its maximum magnitude value reaches in the 2–4.5 kHz range at the moment of 700th hit (Fig. 5). Then damping of the signals occurred on the frequencies lying higher than 2 kHz.

Overall, during the experiment, the maximum amplitudes of the signals were located in the 0.25–1.5 kHz range.

3.2 Gradual loading

The strongest signal was observed during the quartz fracturing. Granite and granodiorite specimens are notable for the weaker emission, but some did not generate any EM radiation. Usually, samples failures were accompanied by set of EM impulses. The largest number of ones was observed during fracturing of quartz samples with 4 cm

faces. This factor, for the granite and granodiorite specimens of the same dimensions, was approximately 6 times lower. Samples with 3, and 2 cm faces are notable for less quantity of EM impulses generated during the loading. Granite and granodiorite cubes with 3 cm faces differ from the quartz samples of the same dimensions by a lower quantity of impulses. All specimens with 2 cm faces excite almost the same number of impulses (1 or 2). We found no correlation between quantity of the impulses and type of the rocks or sample dimensions. In a number of cases, EM signals consisted of neighboring pulses groups, among which the main – the strongest impulses, and the series of the numerous weak, but discernible and equispaced peaks. One of the weak spikes is marked by arrow on the Fig. 6. It is obvious that such peaks appear before and after the strongest one. These spikes are located in the 0.5–2 kHz frequency range; the pulse time is 1–2 ms.

In most cases, the formations of cracks in quartz were accompanied by emission of series of EM impulses in a short time interval 10–30 ms. The Fig. 7 depicts two weak signals which forerun the strongest one. And the first impulse is the weakest one. In few cases, low pulses appeared only after the strongest one. Apparently, all of these weak signals are located in wide frequency ranges which can be different for each rock sample.

In 50 % of cases, during the granite samples fracturing, solitary weak pulses arose before or after the main impulses. Time intervals between them are much wider than in case of quartz fracture. These are 400–800 ms. We need to mention that the loading rate was almost the same during the experiment. Also, 50 % of strong impulses were noted for noise-like signals occurred after the ones (Fig. 8). Registered EM signals, which were emitted by 28 % of rock samples, are located in a narrow frequency band; 42 % – wide frequency range (0–6 kHz); 30 % – generated extremely weak emissions.

Granodiorite specimens are notable for appearing weak EM signals before and after some strong impulses during the gradual loading. Three of four samples generated EM impulses in wide frequency band (0–5 kHz) and one did not emit any EM signals.

It was found that emission rate reduced with rock samples dimensions decreasing. The weakest signals were emitted during fracturing the cubes with 2 cm faces. The quantity of impulses: 1 or 2 (in a few cases – 3). In this case, EM fields were usually located in a narrower frequency range than during the gradual loading of big samples. Such situation is characteristic for all types of rocks used in our experiment.

3.3 Friction

For the experiments on rubbing rock samples, 1 cm thick plates with not grinded surfaces were used. Such decision is concerned with extremely low probability of existence of the perfectly flat surfaces in the natural condition. During friction action between not grinded rocks, local hitches take places. In these spots the deformations and the following fractures can occur during stress increasing. Such processes are accompanied by abrupt breaking of the hitches and the following collisions of the asperities of the rock samples surfaces. We assume that low-speed impacts take places there. It is obvious, that such processes can accompany the shifts of rocks in natural conditions. And the characteristics of the EM emission, occurred in the given situation, differ from the ones generated by the rocks with flat and smooth surfaces.

The carried out experiments revealed that, during rubbing the rock samples, low-level EM signals were emitted. During one sample slipping upon the surface of the second one, EM impulses were excited, and also, strong acoustic signals were observed. The generated EM radiation can be represented by one of the three types: a short impulse (Fig. 9a), an impulse which is followed by 10–30 ms emission in narrow frequency range (Fig. 9b), and a noise-like signal (Fig. 8). Weak acoustic radiation is characteristic for a signal of the second type. We need to mention that, in some instances, the amplitudes of the impulses were extremely low. And it was impossible to isolate them among natural noises on amplitude-time diagrams.

It was observed that the EM emission undergoes changes during rubbing rock samples. First impulses were similar to the one depicted on Fig. 9b, and they were located in whole frequency band of interest. Most of the emission energy lay in

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0.75–10 kHz area. The following signals were similar to those that accompanied the fracturing (Fig. 8) and had the noise-like behavior. During the rubbing, the granite and granodiorite specimens, mainly, short impulses, which occupied wide frequency band, were observed. Rubbing of two shale plates was characterized by excitation of less intensive EM emission, and mostly, noise-like signals. That is probably concerned with relatively flat and smooth friction surfaces.

7 out of 9 pairs generated observable EM radiation against natural noises. In general, samples with the largest surfaces irregularities were characterized by strong EM emissions and short impulses. The quantity of ones was higher than in case of rock specimens, which had smooth surfaces.

3.4 Discussion

The results of the laboratory experiments demonstrate that EM emission is generated in wide frequency band during gradual loading with following fracture, impacts, and friction processes. Impulses, accompanied different types of mechanical actions, have particular similarities. As a rule, all signals are characterized by steep increase of intensity at the moment of hit or cracks formation during crushing the samples. Maximum amplitudes were mainly located in 0–9 kHz range. The exception is quartz – in some cases the maximums were in the higher frequency area. The analysis of the findings showed that harmonics of the main signals were distinct on all records. Though, in a few cases, EM impulses, generated by samples, did not contain any observable harmonics. Maximum amplitude of the signals, emitted by almost all rock specimens, fell on the second or the third harmonics.

During the impact and gradual loading actions, before strong impulses, relatively slow growths of EM fields took places. In case of impact action, such behavior can be concerned with approaching the metal ball a sample's surface before the hit. On gradual loading a slow growing pressure leads to the microcracks formation (at that moment we observe weak and quite short EM signal). Then follows avalanche-like

breakdown of samples structures is accompanied by formation of large cracks (sharp increase of EM field intensity).

The appearance of series of repetitive weak peaks (Fig. 6) on certain frequencies, before and after EM impulses emitted, during samples fracturing stays not understood. It could be explained by a process of fracturing that follows large cracks formation. But it is obvious that formation of new cracks with equal periods of time is improbable.

All EM impulses, except the weakest ones, were accompanied by relatively strong acoustic signals during gradual loading.

It was discovered that increasing number of the impacts, results in change of EM emission spectrum and decreasing of impulses intensity during the experiment. We need to mention that after 24 h of standstill, the intensity of signals increases, but it does not exceed 50 % of its value in the beginning of the experiment. Then, with the growing number of hits, the level of signals decreases, but not as rapidly as at the beginning of the experiment.

The EM emission, caused by the fractioning process, was weak, but still, perceptible among the natural noises.

The information about the spectral composition of the EM emission, appeared during different mechanical actions on the rock samples, demonstrates us that the main level of radiation lies in the 0–10 kHz band.

4   Conclusions

According to the findings, during different mechanical actions on rock samples of one type, dissimilar EM signals can be generated. It is shown that EM signals are characterized by different number of impulses and spectral compositions, depending on the specimen dimensions of the same rock species, during the gradual loading.

The experiment on the impact action was held in two stages. It was observed that in the beginning of the second stage, the level of EM emission was 2 times lower than at the start of the experiment, and it was fading slower. As the quantity of hits increased

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on the second stage, high frequency components appeared in spectrum, and theirs magnitudes lowered at the end of the experiment.

We can subdivide EM impulses that were observed during the fractioning process, on two sorts: the first one is typical for hitting action – the impulse, which is followed by 10–30 ms lasting emission in narrow frequency band; and the second one is a noise-like signal, typical for gradual loading action.

Based on the spectral and spectral-temporal analysis, a frequency range, where the most intensive EM emissions were generated by all rock samples during different sorts of mechanical actions, was selected.

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Fig. 1. Diagram of the experimental setup. **(a)** Impact action on samples, **(b)** rubbing of two samples, **(c)** gradual loading.

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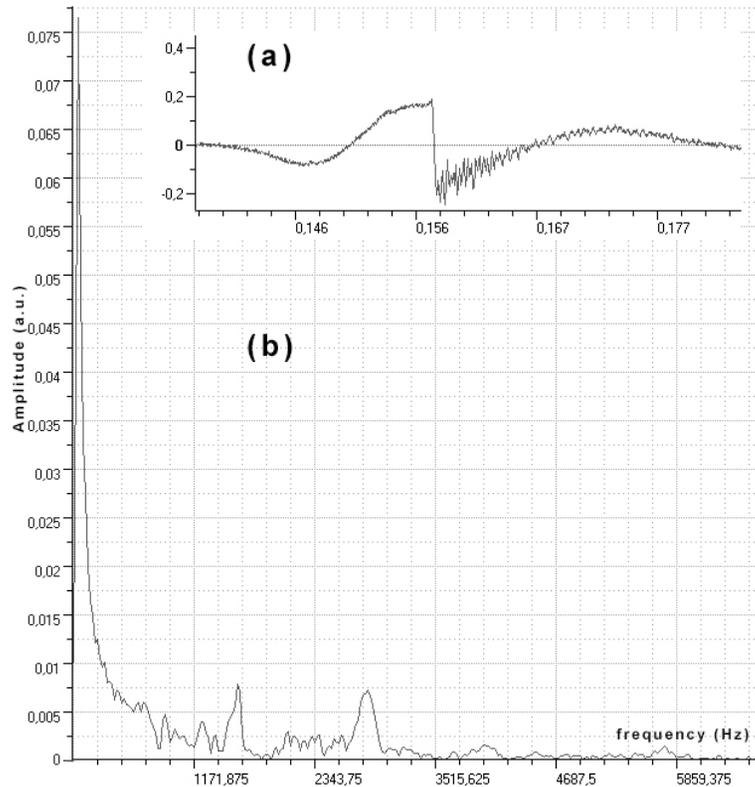
Fig. 2. EM signal registered when the metal ball was hit. **(a)** Amplitude-time representation, **(b)** spectra of the given signal.

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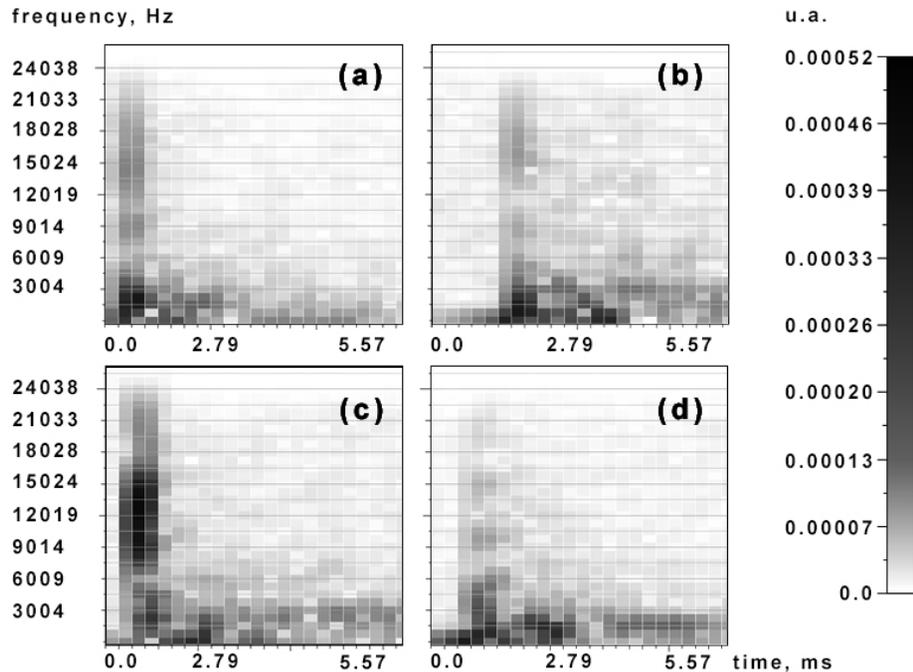
Fig. 3. Spectrograms of the EM impulses generated during impact action on **(a)** granite, **(b)** granodiorite, **(c)** quartz and **(d)** shale samples.

Fig. 4. Decrease of the EM imission magnitude during numiracal impacts on shale (red), granite (green), quartz (blue) samples.
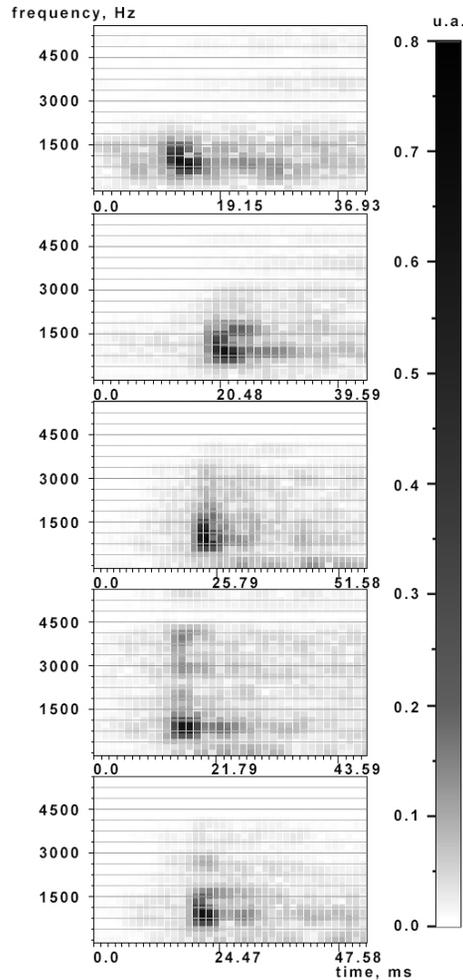
Fig. 5. Spectrograms of the impulses after 100, 300, 500, 900 impacts (from top to bottom).
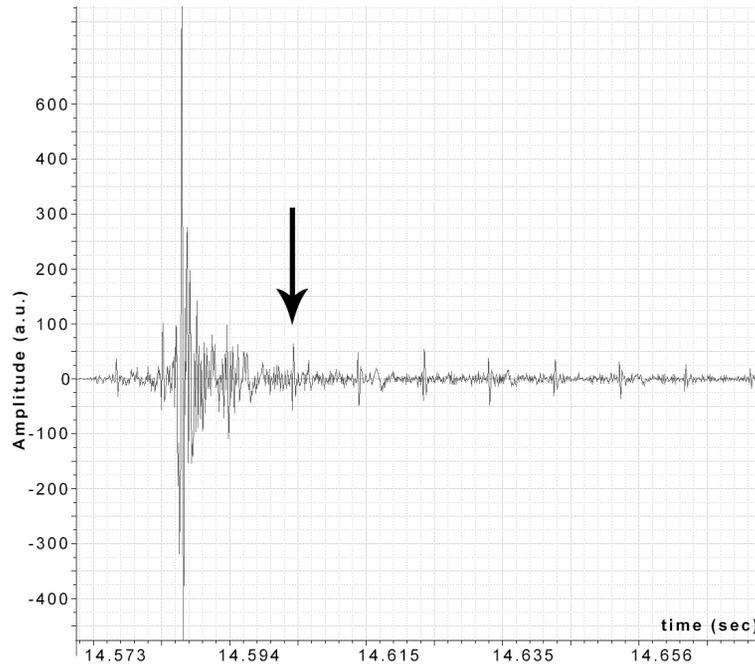
Fig. 6. An EM signal registered during gradual loading a granodiorite sample. The arrow points at one of the weak peaks which accompany the main – the strongest impulse.

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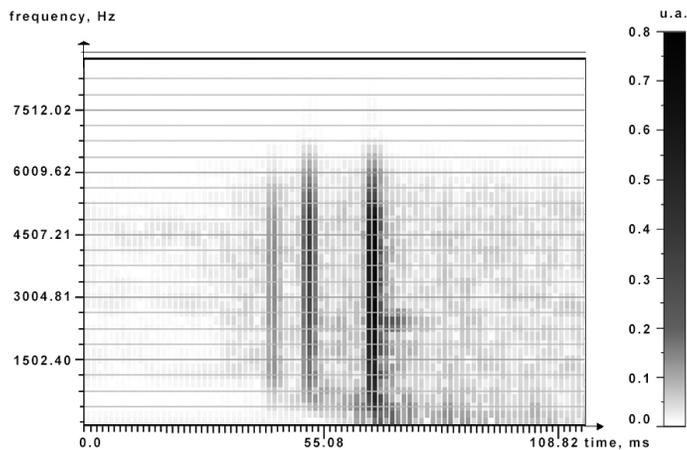
Fig. 7. An EM signal registered during the quartz sample fracturing.
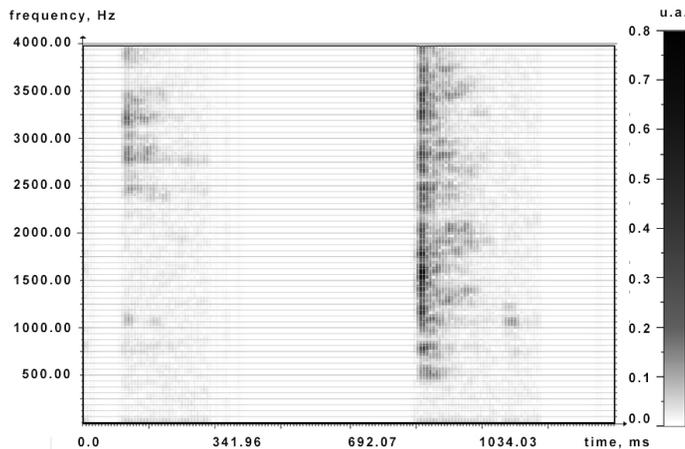
Fig. 8. An EM signal registered during the granite sample fracturing.
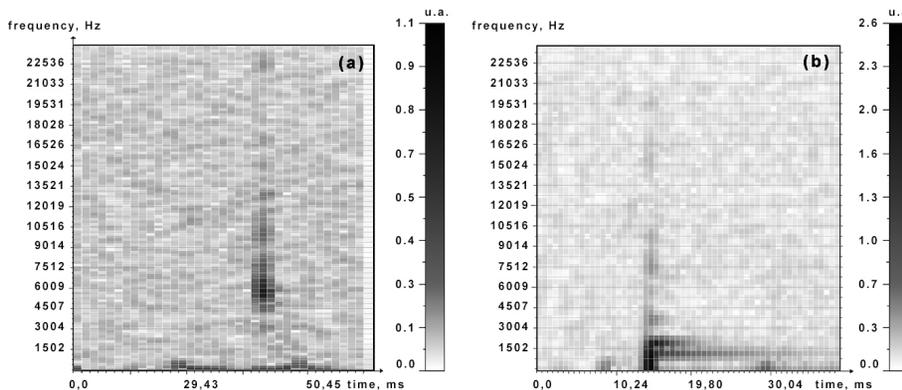
Fig. 9. EM signals registered during rubbing the **(a)** granite, **(b)** granodiorite samples.