STUDY OF THE EM RESPONSES UNDER SHOCK IMPACTS ON ROCK SAMPLES. I. LABORATORY EXPERIMENTS

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The problem of the electromagnetic responses at mechanical shock impacts on rock samples of various structure and composition is studied experimentally. This part presents the results of laboratory investigations in the ULF and VLF frequency ranges with use of the experimental complex specially developed. The possibility of the occurrence of pulsed electrical signals excited by mechanical impacts is shown. It was found that, at least for rocks containing crystalline quartz, such impacts excite low-frequency signals caused by the piezoelectric effect. It was also shown that upon sample destruction, radio-pulse signals are generated. It was noted that when impacted on samples of other quartz-containing rocks (granite, mudstone, siltstone), similar responses are also observed, but their level is 3-10 times lower. The results obtained can be considered as some ideological premise for explaining the nature of some radiophysical precursors that are observed both directly in the earthquake preparation zone and are manifested in ionospheric processes.

A description of the experiments and obtained results on studying the structure of EM emissions generated by shock and explosive impacts on large monolithic blocks of rocks of complex structure, and also at power industrial explosions will be presented in the next parts of the work.

1. Introduction

To understand the physics of seismic events, an important field of research is the study of seismo-electromagnetic effects associated with the generation of electromagnetic (EM) signals at the destruction of samples of various rocks. Such studies are important, first of all, from the point of view of modeling processes occurring at the stage of earthquake preparation and at its initial stage (when the foreshocks are observed), and can contribute to a better understanding of the physics of the earthquake's process. The latter, in particular, is necessary for constructing an adequate model of a seismic event, that should be the basic element of any possible forecast system.

One of the main approaches in the implementation of such studies is the study of EM responses on mechanical impacts and the destruction of rock samples in laboratory experiments. Unfortunately, well-known studies conducted earlier in this field (see, for example, [1]) were being limited only to a statement of the occurrence of EM emission at shock impact on a quartz-containing sample and did not include any comparison of the EM oscillations with the seismic ones as of the processes having a special time-frequency structure.

The second approach, which is a natural development of the mentioned above direction of research, is the initiated and fulfilled by us in [2, 3] study the structure of EM emission arising as a result of shock and explosive impacts on large monolithic stone blocks of the rocks of complex structure. For this, special nature experiments were conducted in the field away from sources of industrial interference, preliminary results of which were presented in [2, 3].

In [4-6] only preliminary results of a common analytical interpretation of experimental data obtained by us in laboratory and field experiments, that do not satisfy the criteria of statistical significance were published. Nevertheless, these results can be the basis for establishing the relationship between the nature of such oscillations, and this, in its turn, can become the key to understanding the physical processes caused by seismic events and be useful for formation of the methodics of their forecasting.

Part I of the work presented here is devoted to the description of the results of our laboratory experiments on study of EM responses under shock impacts to rock samples and physical interpretation of the results obtained. A detailed description of the experiments on the study of the structure of EM emission generated by both shock and explosive impacts on large monolithic blocks of rock of complex structure, and interpretation of the results obtained in these experiments will be presented in Parts II and III of the work.

Note that the bulk of the experiments were carried out in the Magadan region, Russia, and data processing and interpretation was carried out both in Russia and in Georgia.

2. Measuring Complex

In our laboratory investigations of the EM responses at shock impacts on rock samples, the experimental complex "IMPULSE-ND1" [2, 4] specially developed in the Laboratory of Seismology and Petrophysics of the North-Eastern Complex Research Institute of FEB RAS was used.

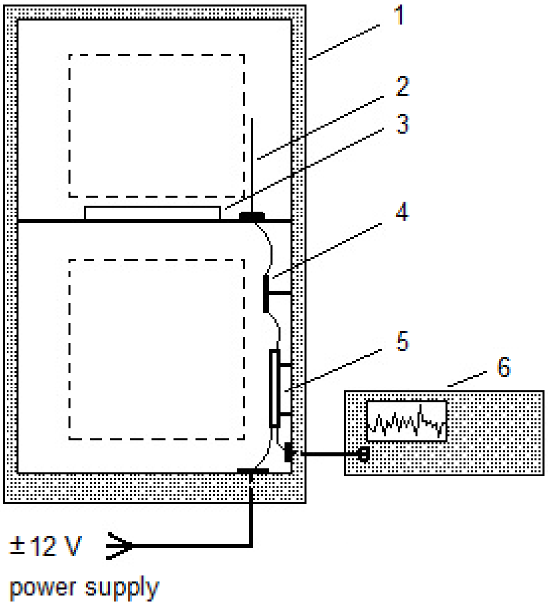

Fig. 1. Scheme of the two-chamber measuring complex "IMPULSE – ND1": 1 – shielding metal camera, 2 – antenna, 3 - place for the test rock sample, 4 - antenna amplifier, 5 – main amplifier, 6 - recording oscilloscope.

The receiving part of the complex is structurally located in the two-chamber shielding metal camera (see Fig. 1). In the upper chamber there is a damping (foam) lining for the test sample, a device for dumping a weight (steel ball) on it, and a receiving electric antenna (EM field sensor). In the lower chamber there is a receiving-amplifying apparatus (the boards of the antenna amplifier and the main amplifier of the recorded signals, to which the constant ± 12 V power supply is connected) and the piezoelectric sensor, which uses to record the moment of impact with appearance of the vibrations arising in the camera partition.

The signal from the receiving part of the complex is fed to the central computer controlling the experiment, the analog information is digitized using a 16-bit computer sound card, and the maximum information input frequency is 44.1 kHz. The control of the received information is carried out using an oscilloscope (see Fig. 1).

In the experiment, the steel ball was released by turning off the electromagnet and at the same time, the input of the investigated signals into the recording device was started. The oscillogram was used to determine the moment of occurrence of seismic oscillations and to analyze the electrical signal before the appearance of seismic one. We were also analyzing the frequency-time spectra of realizations and determining the energy characteristics of the response (see [2]).

3. Laboratory Experiments

The structure of the response of the electromagnetic field under the mechanical (shock) action of the dumped spherical steel balls on rock samples of various compositions was studied in two frequency ranges: 4–1000 Hz and 0.2–10 kHz (ULF and VLF frequency ranges), where, in principle, any significant effect can be expected. The time moment of impact was being recorded using a seismic sensor (Sect. 3.1) and a piezoelectric one (Sect. 3.2).

3.1.The results with using the seismic sensor

Figure 2 shows a characteristic example of recording of the EM response in the ULF frequency range with use of the seismic sensor. Curves 1 and 2 correspond to the electric and seismic signal, respectively. The signal amplitude is indicated in units of the least significant bit of the ADC. It can be seen that, as a result of hitting the sample, the electrical response is a bipolar surge at the beginning of the recorded temporal realization, and subsequent oscillations are associated with the arrival of the seismic wave to the receiving antenna and amplifier board.

We have noted that with a decrease of the impact energy, for example, due to a decrease of the height of the suspension of the ball, the amplitude of the electric response decreased [2]. However, this decrease was only statistical in nature. Individual realizations could have a large spread of response value under equal initial conditions. The most likely cause of such scatter is the random nature of the occurrence of micro-fractures. Besides, it is possible that in reality the conditions were not completely equal, since the location of the point of impact also had small random deviations. Depending on the location of the point of impact, a slightly different on amplitude and phase seismic oscillations in the sample could be excited and their superposition on the random domain structure of quartz inclusions in the sample increased the discrepancy between the results. Figure 3 shows the scatter of responses at the same weight (80 g) and the height of the ball suspension (50 cm) due to the above reasons, and illustrates the spectral-temporal characteristics (instantaneous spectrum versus time) for several responses at measures in the wide ULF-VLF frequency range.

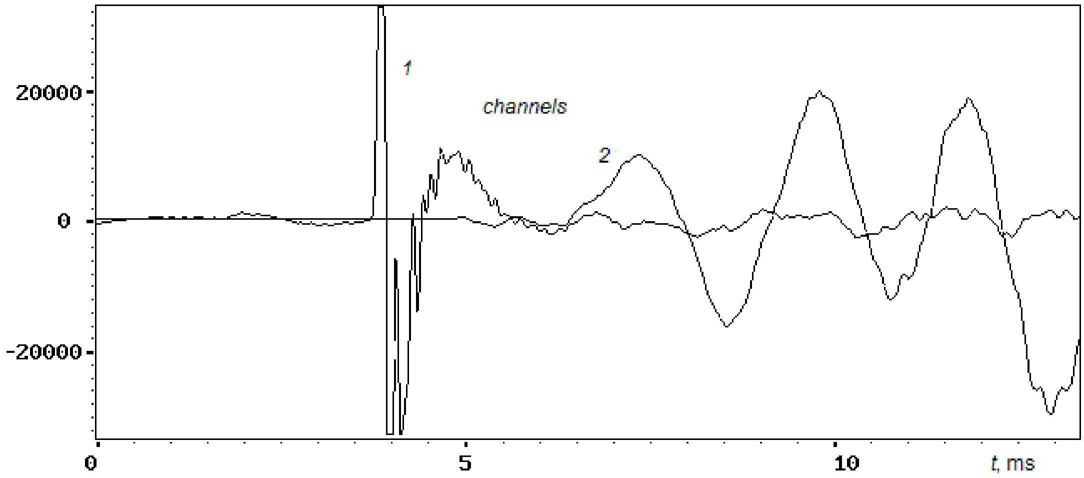

Fig. 2. An example of the temporal realization for the granite sample in the ULF frequency range with using the seismic sensor. Drop height of a steel ball weighing 80 g to sample is 50 cm.

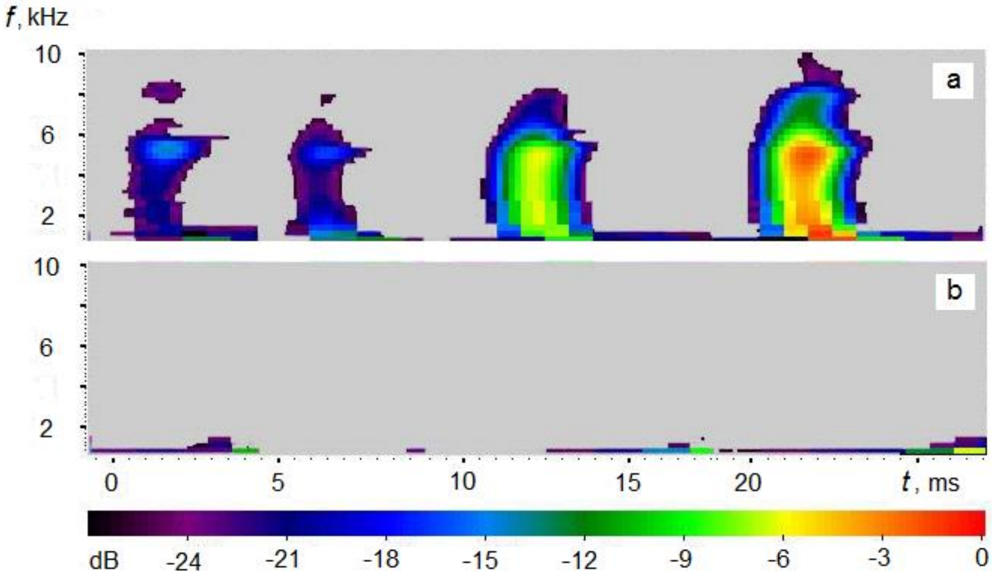

Fig. 3. The spectral-temporal characteristics for four responses:
a – electrical signal, b – seismic signal.

The intensity of responses is reflected in the color scheme in accordance with the lower scale, gray color corresponds to the lack of response in the analyzed amplitude range. In electrical responses one can observe high-frequency and low-frequency parts, it is possible that this corresponds to elastic and inelastic (micro-fractures) deformations of the sample. If we look at the spectrograms of the impacts on the quartz-free samples [2], then one can also notice a presence of some low-frequency component there. It is ahead of the appearance of the seismic response by 0.5-0.7 ms against 2-3 ms in Fig. 3 and, apparently, is associated with another effect.

The experiments carried out allow us to conclude that the electrical impulses observed upon impact on rock samples are associated with the presence of crystalline quartz in their composition and the piezoelectric effect caused by it. If there are other sources of emission, for example, associated with appearance of the microfractures in quartz-free rock, then they have a much lower level and are not identified in the laboratory experiments performed. So, the conclusion that the piezoelectric effect is the source of pulses was made on the basis of the absence of signals identifiable as a response when striking to samples without quartz (see [2]) in our experiments.

It should be noted that in some experiments in the ULF frequency range the EM response did not appear so distinctly as in Fig. 2. Since one of the possible reasons for this could be the localization of most of the pulse energy at higher frequencies (as an example, see Fig. 3), the studies were transferred to the VLF frequency range. In these experiments we have obtained that the impulse has shortened and sharpened [2], that confirmed the assumptions made. But, in these cases the moment of impact was completely indistinguishable in the seismic record and further we used a piezoelectric sensor instead of a seismic one.

3.2.The results with using the piezoelectric sensor

For the experiments, the same methods were used as in previous experiments (see the previous section). Pieces of granite and quartz with dimensions of 10-15 cm and real samples from the "Natalka" deposit (Magadan region) in the form of 2×2×2 cm cubes were studied as samples. The shielded piezoelectric sensors were attached to the samples. The purpose of the experiments was to clarify the mechanisms of the occurrence of piezoelectric responses and to determine the relationship between the low-frequency ULF responses and VLF radio-pulse emission.

In the study of piezoelectric responses, their strict repeatability with identical impact was established. Figure 4 shows three realizations of responses from impacts on a small quartz cube.

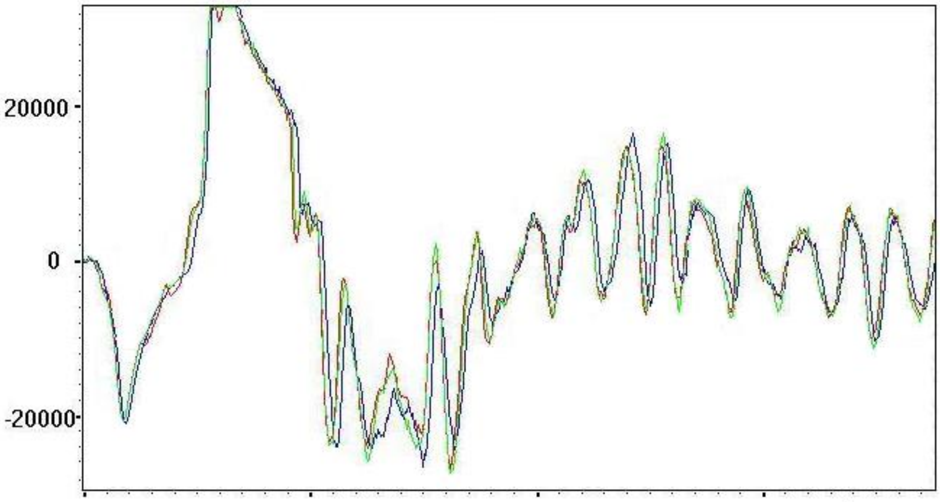

Fig. 4. Electrical responses from three impacts on a quartz cube sample.

Figure 5 shows the time spectrogram of two responses from one sample. In addition to the initial response with a maximum at lower frequencies, there is a long “tail” with a maximum in the region of 80–120 kHz. These frequencies correspond to the mechanical resonance of the sample.

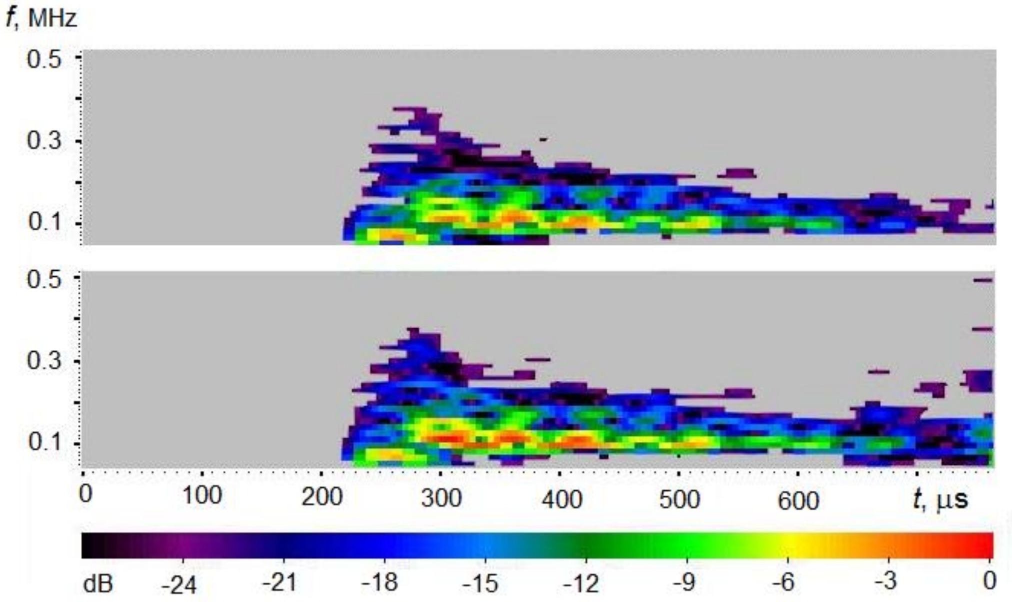

Fig. 5. Spectrograms of two responses from a quartz sample.

Figure 6 shows the temporary realizations of the electric and two seismic components (from two perpendicular faces) at the impact on quartz cube. There is a long “tail” of mechanical and electrical oscillations caused by them.

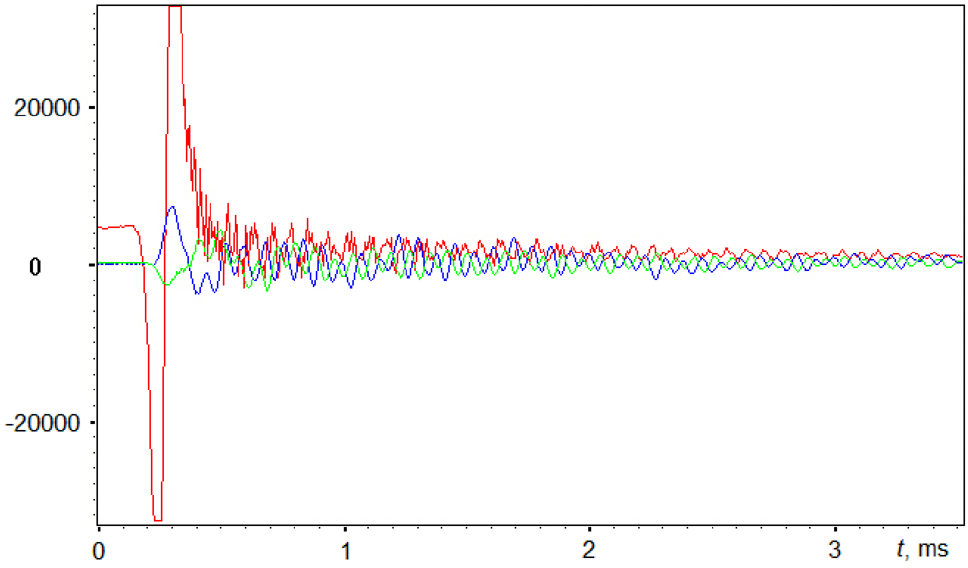

Fig. 6. Oscillograms of the electrical (red line) and two seismic (blue and green lines) components.

Figure 7 shows spectrograms of three impacts on quartz sample. In the upper half of the figure the spectrum of the electrical signal is displayed, and in the lower half –

one of the seismic ones. One can see the coincidence of the frequencies of the tails of the seismic and electrical narrow-band responses. The quartz sample had a complex shape with a chipped edge and the spectrum of its mechanical resonant frequencies is very wide, but the coincidence of the two lower frequencies is clearly visible. Note that the occurrence of a "tail" of electrical oscillations caused by mechanical ones was also found for a granite sample.

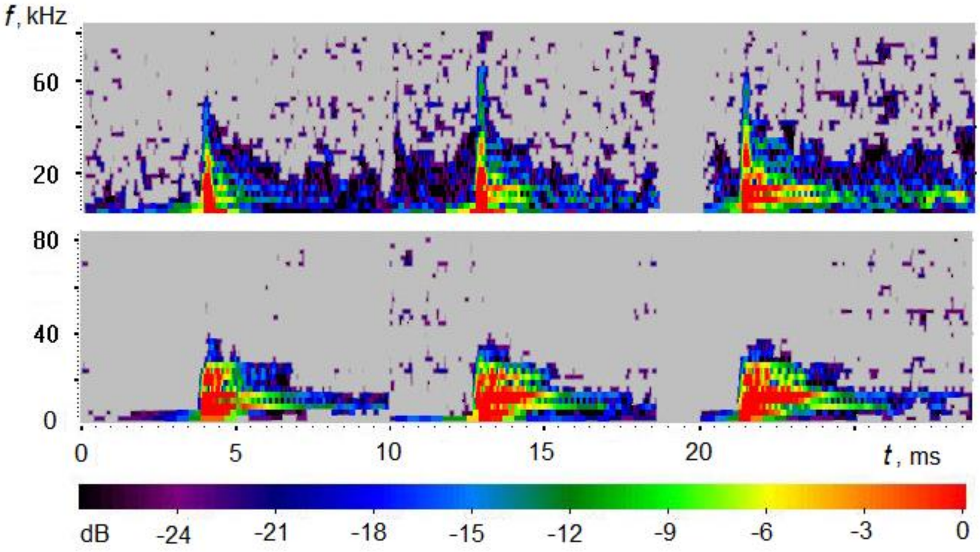

Fig. 7. Spectrograms of three impacts on a quartz sample.

Figures 8 and 9 show the oscillograms and the corresponding spectrograms of two impacts. At this, the spectrograms of the electrical signal are arranged in pairs with each of the seismic channels, first for the first realization, and then for the second. Here, the sample has one frequency of mechanical resonance in the region of 20 kHz and the electric response is also observed at this frequency. Note that the initial pulses of two impacts in Fig. 8 are a little different. Accordingly, in Fig. 9 in the spectrogram of the first impact, the high-frequency component associated with the effect of sample destruction (radio pulse signal) is more pronounced.

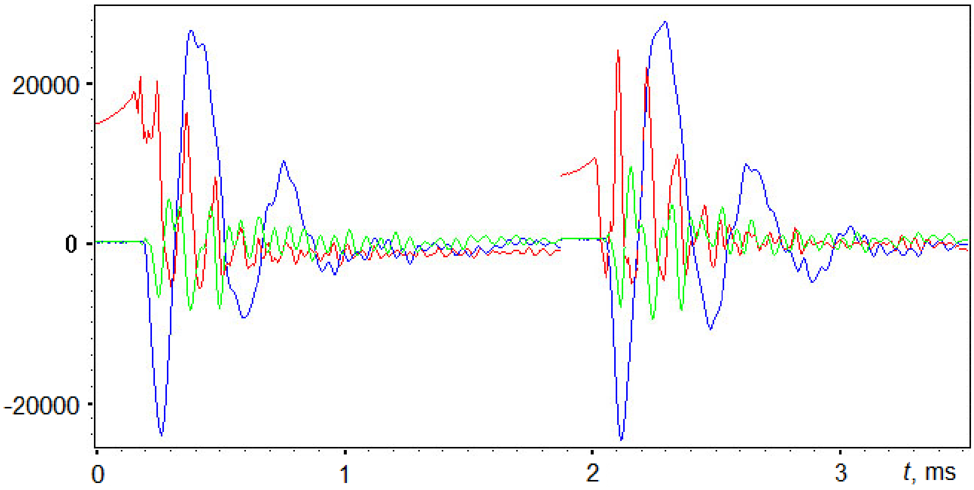

Fig. 8. Oscillograms of two impacts on a granite sample: red line – the electrical signal, blue and green lines – two seismic components.

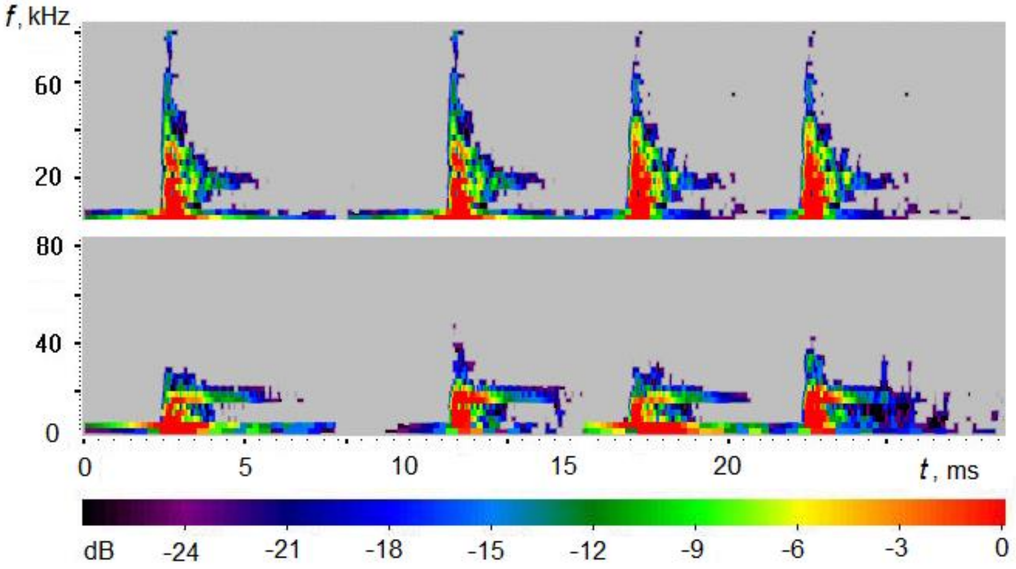

Fig. 9. Spectrograms of the impacts on a granite sample corresponding to the oscillograms shown in Fig. 8.

The effect of the appearance of a radio pulse signal was being studied in detail in [3] and some of the results obtained there will be discussed later. Here we stay on some points of the observed piezoelectric effect.

In our experiments, it was found that although the response is unchanged when the impact conditions are completely identical (see Fig. 4), the waveform at the excitation of seismic oscillations in the sample is not a fixed function of the sample and depends on direction of the applied force and boundary conditions. If the boundary conditions remain unchanged for the elements of a real geological object (absence of damage due to the action of a seismic wave), we should expect the piezoelectric response from a geological object with a high quartz content to remain unchanged at remote seismic effect. Somewhat different (from the cases of quartz-containing samples) results occurred when the impact on the samples of other rocks was impacted. Figure 10 shows the oscillograms for four impacts on a mudstone cube. One can see that although the temporal realizations have common features, the response varies in amplitude and shape.

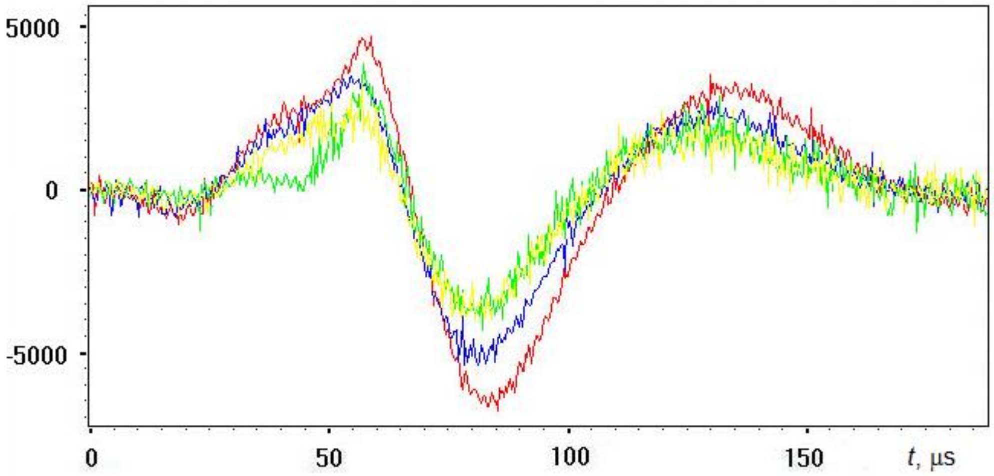

Fig. 10. Electrical signal at the four impacts on the mudstone sample.

Note that the response amplitude in this case is 3–10 times lower than that of quartz samples (in Fig. 10 the scale along the ordinate axis is increased 4 times comparatively to one in Figs. 2, 4, 6 and 8). We also note that the noise observed in the signal records is associated not with the response, but with the interferences from the high-speed ADC which used in this experiment.

A response similar in its properties was also observed when striking a cube of mudstone with a quartz core. Fig. 11 shows the realization for two impacts. For these realizations the amplification of the electric channel was increased by a factor of 2.5 and, therefore, it is clear that the response is lower than for pure quartz, although higher than for pure mudstone. There are also no responses from subsequent natural oscillations of the sample, which are characteristic for quartz, and a variability of the response parameters which is characteristic for non-quartz samples takes place. In addition, for the second realization, the response is inverted at the first 100 μs, that was also observed earlier [6] and in our experiments for quartz at a change in the angle of impact (Fig. 12). It can be assumed that in the case of heterogeneous samples, a significantly greater sensitivity to random small changes in the conditions of shock excitation is observed, or the nature of mechanical oscillations excited by shock has its own instability at the interfaces of media. The observed variability of the response for this sample was confirmed in several more experiments.

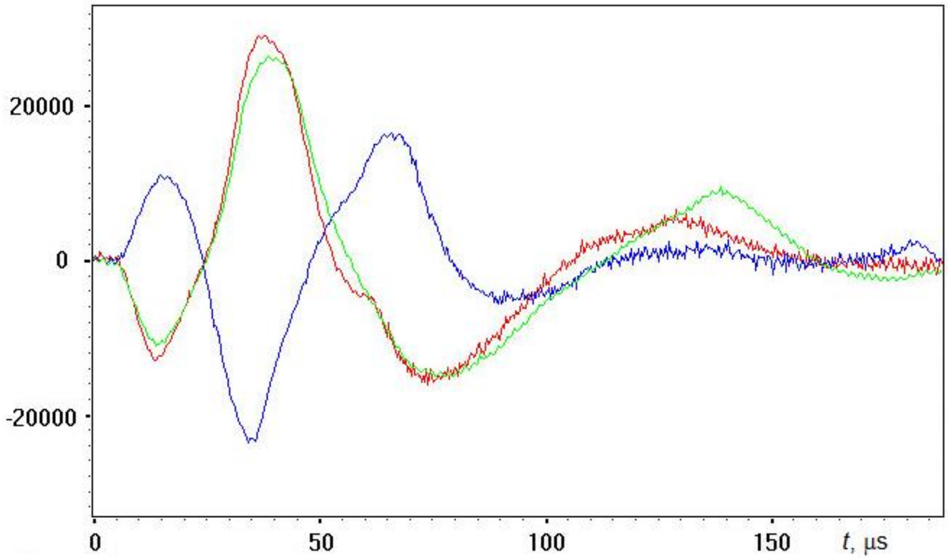

Fig. 11. Electrical signal at the three impacts on the sample of mudstone with a quartz core.

Note that in experiments with samples of another rock, siltstone, fulfilled by us earlier a response amplitude and its instability are also small compared to quartz.

To confirm our assumption that a sample destruction at impact is a source of radio-pulse signals, the experiment with a mudstone sample under enhanced mechanical stresses was carried out. A ball with a diameter of 19 mm was used, instead of 12.5 mm, which was used in previous experiments with small samples. Figure 13 shows the waveforms of electrical signals from five impacts, and Fig. 14 shows their spectrograms. As one can see in Figs. 13 and 14, in the first and fourth realizations there are single radio-pulse signals, in the second realization there are no radio-pulse signals, and in the third and fifth realizations series of radio-pulse signals are observed.

During the third impact, a piece of the sample broke off, and during the fifth impact the sample cracked. If the spectrum has no obvious maxima for a solitary radio pulse (since its upper frequency is determined only by the steepness of the front), that when a wave pulse packet arises at significant destruction of a sample, an obvious spectral structure is present.

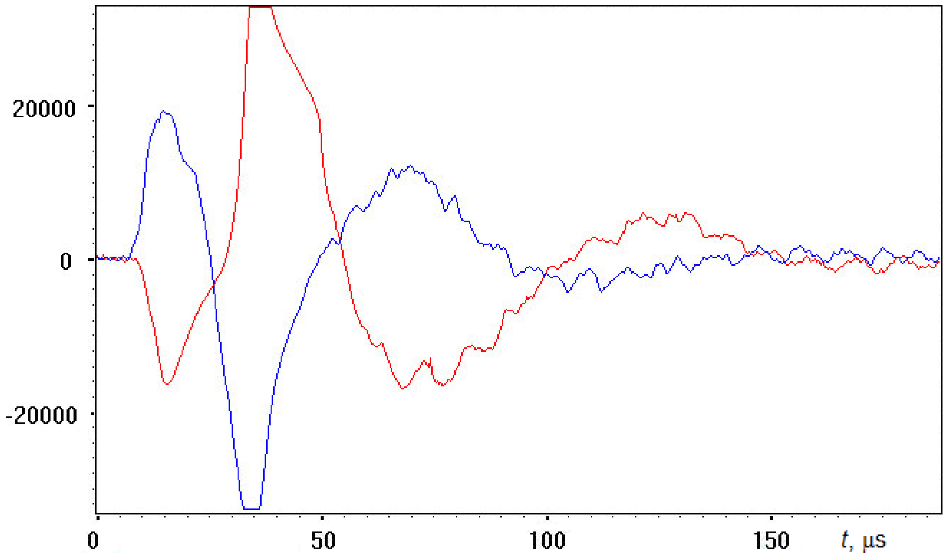

Fig. 12. Oscillograms of two impacts on quartz sample at different angles: red line corresponds to the inclination of the sample plane at an angle of about 20 degrees to the horizontal one, blue line – the impact is strictly perpendicular.

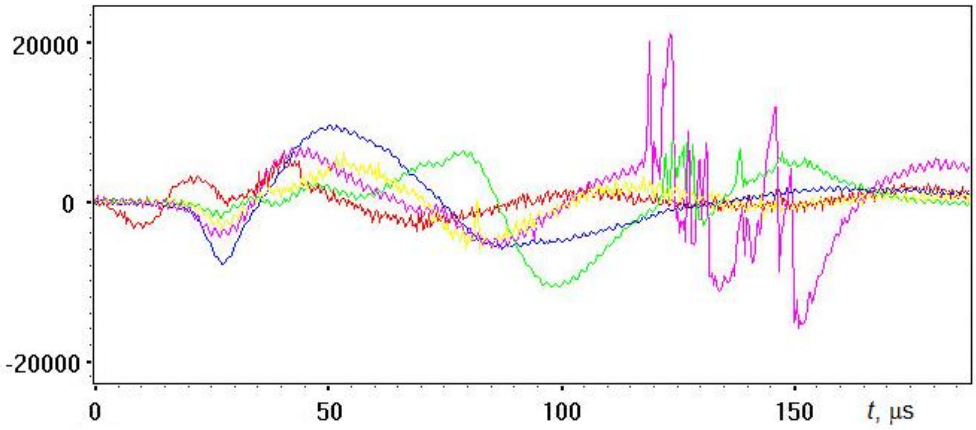

Fig. 13. Oscillograms of five enhanced impacts on mudstone sample.

Based on the performed experiment, we can conclude that radio-pulse signals are generated when the sample is destroyed. With a narrowing of the recording band, as digital filtering has shown, the response in form of radio-pulse signals in the time region decreases sequentially and in the band of 10 kHz they become indistinguishable from other oscillations. Consequently, at receiving in the VLF range the radio pulse signals themselves will not display in a records as a response to impact. But they always arise against on a background of more low-frequency oscillations. Therefore, the latter will be present in the recorded signal and at receiving in the VLF range as a condition of the appearance of radio-pulse signals. Thus, although there is no direct relationship between radio-pulse oscillations and more low-frequency ones, there is an indirect relationship between them.

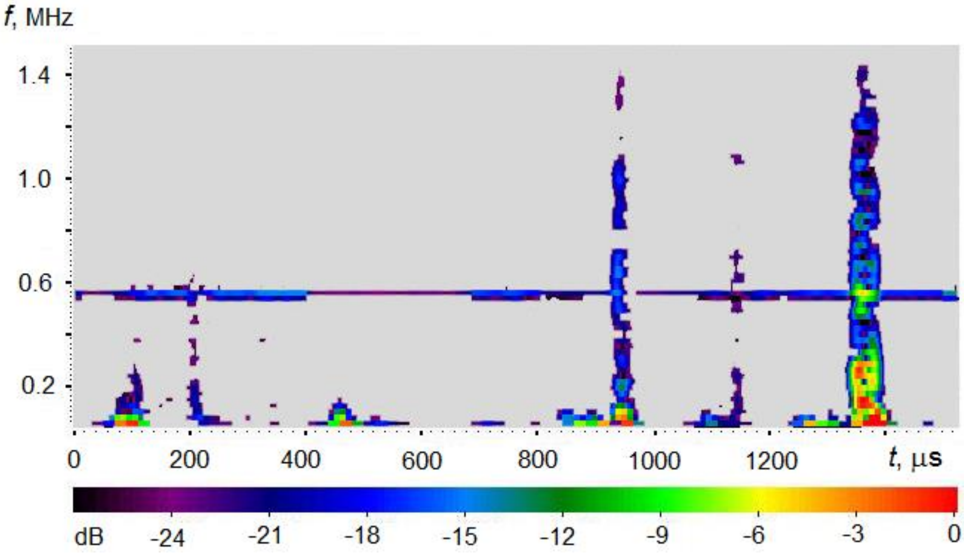

Fig. 14. Spectrograms of the impacts shown in Fig. 13. The correspondence of the spectra to the realizations shown in Fig. 13: 0–300 µs – red, 400–700 µs – blue, 800–1000 µs – green, 1000–1200 µs – yellow, and 1200–1500 µs – pink, respectively.

4. Discussion and Conclusion

Summarizing the results of laboratory experiments and their interpretation presented above, we can conclude the following:

a) the impact on the test sample is indeed accompanied by the appearance of electrical impulses excited in it;

b) emission is observed only upon impact on samples containing crystalline quartz, i.e. it is associated exclusively with the manifestation of the piezoelectric effect. If there are other sources of emission, for example, associated with microdestructions of non-quartz rock, then they have a much lower level and are not identified in the performed laboratory experiments;

c) with increasing the mass of the balls falling on the sample, as well as the height of their suspension, the intensity of the emitted pulses of the electric field increases, but this growth has probabilistic (weakly deterministic) nature. This is manifested primarily in the fact that the value of the amplitude of the pulses under the same conditions has a fairly large scatter. According to the results of measurements in two frequency ranges, this effect can be explained by the fact that the observed pulse is a superposition of responses from the totality of seismic oscillations in the sample with the frequencies which exceed the corresponding range of measurement frequencies;

d) an effect is observed that is not directly related to the field of our investigations being carried out, but it is of fundamental importance in the framework of the general problem of seismo-electromagnetic relationships. It consists in the following. A few milliseconds after the appearance of an EM pulse, a sufficiently strong surge of the electric field oscillations is always observed, which arises as a result reaching by the seismic wave from the sample the receiving electric antenna. At the same time, a signal burst is observed at a nearby piezoelectric sensor;

e) the piezoelectric response is a function of the exciting seismic action vector and its spectrum will extend from units of kilohertz for the shock wave and up to several tens of kilohertz for excited seismic waves;

f) high-frequency radio-pulse signals appear at frequencies up to 1.5 MHz (and possibly higher) and they are associated with a violation of the bulk integrity of the sample.

In conclusion, as a general result, we note the following. When conducting laboratory experiments on the registration of electrical signals arising at mechanical impact on rock samples, we have confirmed the results [1] regarding the possibility of the occurrence of pulsed electrical signals excited by impacts. In particular, we have found that, at least for the rocks containing crystalline quartz, mechanical forces excite the signals presumably associated with the piezoelectric effect. This can be considered as an ideological prerequisite for explaining the nature of some radiophysical precursors, which are observed both directly in the zone of preparation of earthquake and manifested in ionospheric processes [4–9].

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