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GEOPHYSICS

Geoacoustic Location of Earthquake Preparation Areas

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High-frequency geoacoustic emission during the preparation of strong earthquakes in Kamchatka is characterized by an intensification of radiation for a few hours before the seismic event and coincidence of the signal bearing with the direction to the stress source, which is sometimes located at a distance of several hundred kilometers from the observation point [1]. Taking into account strong attenuation of high-frequency acoustic oscillations in the hypocenter and the impossibility of their registration at great distances, it is possible to explain the nature of the forerunners by the propagation of strains from the earthquake source as short-period shocks before the beginning of the earthquake. Owing to the high sensitivity of geoacoustic emission toward the state of rocks [2], its responses are noticeable even at small variations in the level of strains best manifested in the kilohertz range, where the noise level is relatively lower [1]. However, similar phenomena termed as microearthquakes can also appear at lower frequencies [3].

It is known that any arbitrary strain can be decomposed into all-around compression and shear. The strength of rocks relative to compression is greater than the shear strain. Therefore, the formation of fissures is accompanied first by the appearance of a strike-slip component, which determines the orientation of both shears (or displacements) along the existing fractures [2] and sound excited by this process [4–6]. This explains the anisotropy of sound that appears during the preparation of earthquakes [1]. During four years, seismometers installed in Kamchatka recorded approximately 100 acoustic responses to the major part of the seismic events with energy class $K_S \geq 11$ located usually within the radius up to 200 km (sometimes up to 400 km). The efficiency of the response depended not only on the energy and distance of the event, but also on the angle of the place with respect to the subduction zone. We note that the possibility of the propagation of notable strains over distances of hundreds of kilometers from the earthquake is confirmed by GPS observations [7].

The distribution of geoacoustic radiation by angles was measured on the basis of the intensity of signals in directional receivers oriented along the azimuths and downward [1]. The width of the directional diagram of the receivers was 60°. The root-mean-square deviation of the bearing of the signals from the direction to the earthquake epicenter did not exceed this value. Vector-phase methods of observations [9] were used for more detailed investigations of the anisotropy of geoacoustic radiation in the periods of earthquake preparation [8, 9]. Recently, these methods were successfully developed in hydroacoustics. They make it possible to increase the noise immunity and accuracy of determining the direction to the source of the signal at limited possibilities of receiving the spatiotemporal sampling of the signal.

A receiving system for observations at the bottom of Lake Mikizha (depth ~5 m, size 200 × 700 m) was deployed at a point with coordinates 52.995° N, 158.23° E. The system included a spherical receiver (diameter 8 cm) developed at the Geoakustika Closed Joint-Stock Co. in the VNIIFTRI State Unitary Enterprise [10]. The receiver made it possible to simultaneously register sound pressure and three orthogonal components of the sound pressure gradient in the frequency range of 0–10 kHz, without amplitude-phase distortions. As is known, these components are used for the determination of acceleration, oscillatory velocity,

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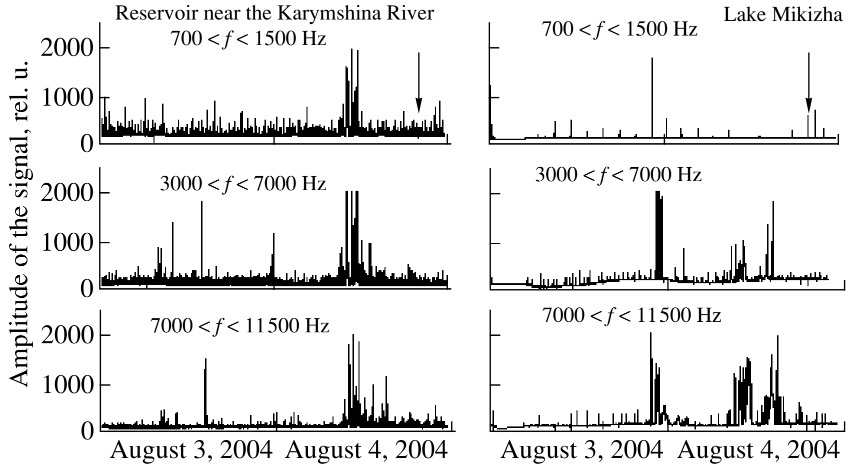

Fig. 1. An example of variations in the geoacoustic signal during two days in three spectral ranges (*f* is frequency) at two observation points before earthquake no. 1 (August 4, 2004; 21:15:11.2 UT; 159.88° E, 52.14° N; H = 8 km, K_S = 13, distance from Lake Mikizha 147 km, azimuth 130°) shown by the arrow (seismic data of KOMSP GS RAN).

and displacement of particles in the medium. The stationary system of five directional hydrophones [1] and the Pacific Institute of Oceanology's acoustic complex of three spherical hydrophones installed in various areas of the lake were used to control the measurements. Therefore, we could apply the triangulation method for the investigation of the spatiotemporal distribution of sound sources. Signals from the three observation systems were identical.

The wideband signal from the hydrophone was a series of shock pulses with amplitude of ~0.1–1 Pa [1]. The frequency of pulse appearance depends on the relative strains and varies from solitary clicks over a time interval of a few seconds during calm periods to rumble and thunder before the earthquakes. The shape of pulses indicates their origin in a solid medium, because one can clearly see *P*- and *S*-phases of the wave. The ratio of their amplitudes varies strongly, while the time lag between them corresponds to the distance from the source that does not exceed 100 m. This is confirmed by calculations based on the triangulation method and agrees well with the attenuation of high-frequency acoustic oscillations in bottom sediments.

The dependence of the appearance frequency of pulses on their amplitude in double logarithmic scale is similar to the Guttenberg–Richter ratio, which indicates that the generation of signals is related to fracturing, which occurs in this case at stresses much smaller that the strength limit of the medium. Increase in strains during the periods of earthquake preparation provokes anomalies in the intensity of geoacoustic emission and the appearance of anisotropy of signals (Fig. 1).

Figure 2 shows an example of time dependence of the horizontal components of the signal, while phase relations between pressure and pressure gradient components are shown in Fig. 3. The *X* axis is directed to the north, *Y* axis is directed to the east, and *Z* axis is directed downward. Bearings of the signals are demonstrated in the insets and their coincidences with the direction to the events are shown in Fig. 4. According to Fig. 2, the geoacoustic signal consists of a series of pulses, each of which corresponds to the cluster of sources. This follows from approximate equality of bearings in the series.

As was shown above, anomalous intensity of signals and anisotropy in their distribution by directions appear during the period of earthquake preparation. Series of pulses with heightened frequency of appearance repeat during a day and last for tens of minutes or a few hours (Fig. 1). Bearings of pulses in a series vary within small limits (Fig. 2), while a large scatter can be observed in different series. For example, on November 16, 2004, the bearing was much stronger than on August 4, 2004, and was equal to tens of degrees, which can be explained by significant difference in spatial distribution of foreshocks and aftershocks of these events. However, the mean bearing of the anomalous signal coincides with an accuracy of ~10° with the direction to the earthquake epicenter. During the preparation of several events in different directions, a multitude of maxima appear in the distribution of bearings.

The application of vector receivers along with other observation methods made it possible to investigate the characteristics of the signals, peculiarities in the spatial distribution of the sources, and efficiency of the generation of geoacoustic emission. During the periods of intensification of strains, anomalies appear in intensity and anisotropy of signals, while the bearings of individual high-frequency pulses generally coincide with the direction to the epicenter of the event. We believe that the application of this effect based on the vector-phase measurements can foster the development of geoacoustic systems for the location of earthquake preparation areas.

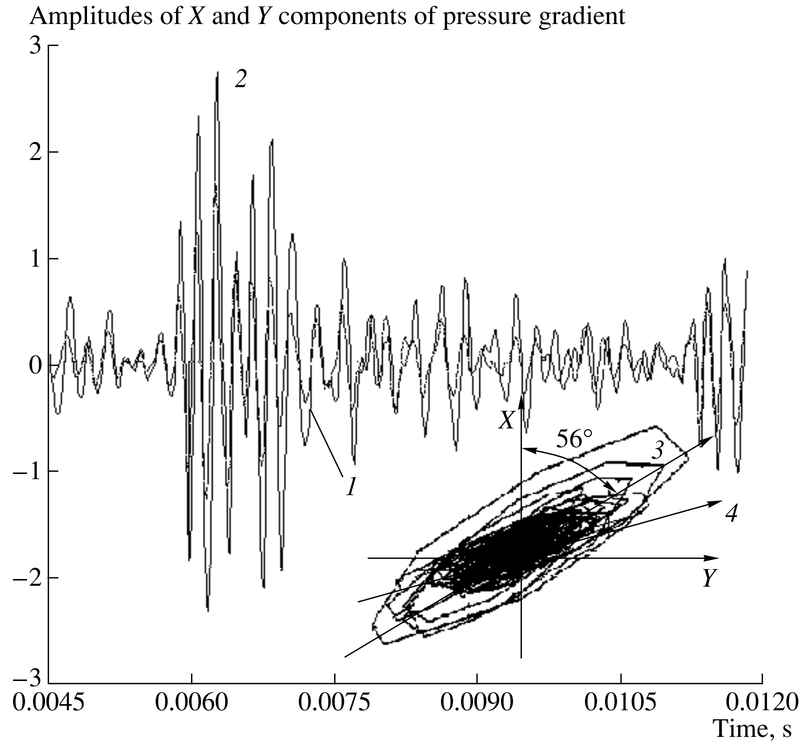

Fig. 2. An example of fluctuations of horizontal components of pressure gradient (*X* (*1*), *Y* (*2*)) and determination of the signal bearing from the principal axes of the phase portrait (*3, 4*) before event no. 2 (November 16, 2004; 11:57:25.5 UT; 160.48° E, 52.97° N; H = 37 km, K_S = 12.8, distance from Lake Mikizha 151 km, azimuth 90°).

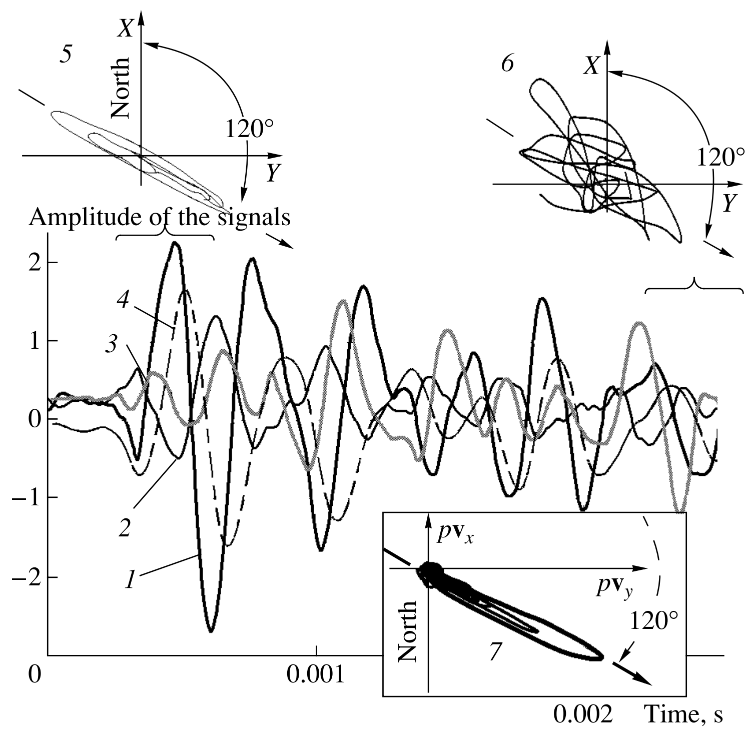

Fig. 3. An example of geoacoustic signal recorded by the pressure gradient channels (*X* (*1*), *Y* (*2*), and *Z* (*3*)) and (*4*) by hydrophone of the combined receiving system on Lake Mikizha before event no. 1. Phase portraits at different segments of the pulse: (*5*) no reverberation noise, (*6*) with the reverberation noise. (*7*) Diagram of the density vector of acoustic power (Umov vector) $p\mathbf{v}$, where p is pressure and $\mathbf{v}$ is oscillation velocity.

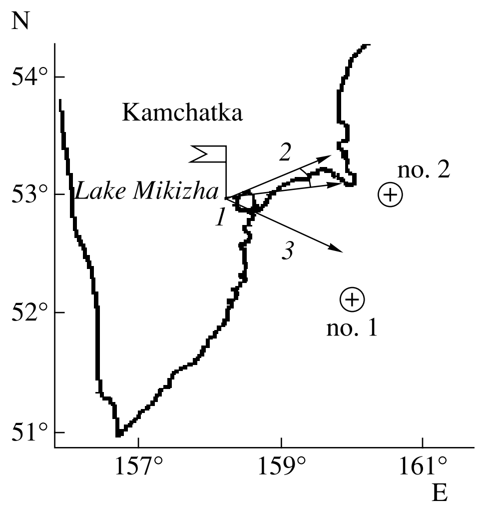

Fig. 4. Positions of event nos. 1 and 2, point of observations (*1*), and directions of signal arrival (*2, 3*) corresponding to Fig. 2, 3.

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