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HIGH-FREQUENCY ACOUSTIC EMISSION EFFECT

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Complex monitoring of acoustic emission (AE) in the sound frequency range has been carried out in the Kamchatka peninsular since 1999. In the course of the investigation, the existence of acoustic emission effect in sedimentary rocks was detected. It consists in the increase of geoacoustic radiation intensity in the frequency range from hundreds of hertz to the first tens of kilohertz during the growth of rock mass deformation rate. This effect was stably observed at several spaced stations and appears the most vividly at the final stage of earthquake preparation.

During the acoustic emission effect, clear anisotropy of geoacoustic radiation directivity occurs which is determined by the source orientation of acoustic oscillations in the stress field of near surface sedimentary rocks.

Key words: acoustic emission, acoustic activity, acoustic emission directivity, deformation rate, high-frequency acoustic emission effect

Inroduction

Acoustic emission (AE) is elastic wave emission occurring during local dynamic restructuring of solid body inner structures. The main sources of AE are plastic deformation processes associated with formation, movement and disappearance of crystal lattice defects, formation and development of micro and macro cracks as well as friction, in particular, of crack edges against each other. Acoustic emission phenomenon is observed in a wide scale range and the corresponding wave lengths of emitted oscillations. We may distinguish three frequency ranges of the emission, investigations of which differ both by tasks and by observation means. The infrasound frequency range (fractions – units of hertz), the seismic one, is used to register earthquakes and to estimate their characteristics, to monitor nuclear tests, in seismic exploration. The ultrasound frequency range from 20–30 kHz to the first MHz is used in industry for early crack recognition, detection of hidden defects in constructions of different types, as well as in geophysics during laboratory deformation of rock samples to investigate crack formation

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mechanisms. The sound range takes the intermediate position and plays an important role in the interaction of micro and macro dislocations, thus, acoustic emission at these frequencies is of special interest during the investigation of plastic processes in natural environments. Stability of landscapes, mountain slopes, glaciers, snow mantles and large technical constructions is associated with them. They also play an important role in the formation of earthquake precursors of different nature. The peculiarities of generation and propagation of sound range signals in complicated natural conditions retarded the development of acoustic methods for diagnostics until recently.

To register acoustic emission signals in the sound frequency range (geophysicists often use the term seismoacoustic emission), high-frequency seismic stations with magnetoelastic [1] or piezoceramic [2] seismoacoustic receivers (hydrophones) are applied. The upper limit of the operational rang of such devices does not usually exceed a hundred of hertz and only in some models reaches 1 kHz. Up to the present time, the sound range of more than 1 kHz has been considered to be ineffective due to the strong attenuation of elastic oscillations at such frequencies in heterogeneous rocks [3]. The results of AE investigations carried out at the beginning of the 21st century in seismically active regions of our country, in Sakhalin [4] and Kamchatka [5], and abroad in Italy [6] showed that in the frequency range of more than 1 kHz, quite strong geoacoustic signals, including those associated with earthquake preparation, are registered. It is appropriate to call this range a high-frequency one relatively the standard range for registration in seismoacoustics. Hence, we shall hereafter use the term high-frequency acoustic emission to describe the geosignals registered in the frequency range from hundreds of hertz to the first tens of kilohertz.

Method for registration of acoustic emission in the sound frequency range

During the investigations in Kamchatka [5] it was shown that a typical signal of acoustic emission is composed of a sequence of relaxation pulses of different amplitude and duration with shock excitation and filling frequency from hundreds of hertz to the tens of kilohertz [7]. To study such signals, it was necessary to develop a hardware-software complex allowing us to register and to make analysis of acoustic emission in a wide range of sound frequencies from units of hertz to the first tens of kilohertz. Besides data registration, it was necessary to provide the possibility for data storage, analysis in different frequency ranges, ideal time synchronization as well as registration and consideration of meteorological values. Owing to the perspective of allocation of the registration system in remote hard-to-reach regions, to decrease the industrial noise effect, we had to realize remote control of the equipment organizing computer radio connection channel via a retransmitter. Fig. 1 illustrates the structure of hardware-software complex for registration and analysis of acoustic emission signals.

Owing to the absence of hydrophones capable to register geosignals within the whole range of sound frequencies and considering the results obtained during registration of seismoacoustic signals by hydroacoustic stations installed on an ocean shelve [4], piezoceramic hydrophones placed by the bottom of natural and artificial reservoirs were used as acoustic emission sensors. Results of experimental studies of signal propagation in closed inner reservoirs [5] and on an ocean shelve [8] show that at small distances, pulse-shape distortion is not significant during the propagation in a waveguide composed of a water layer and a near-surface soil layer.

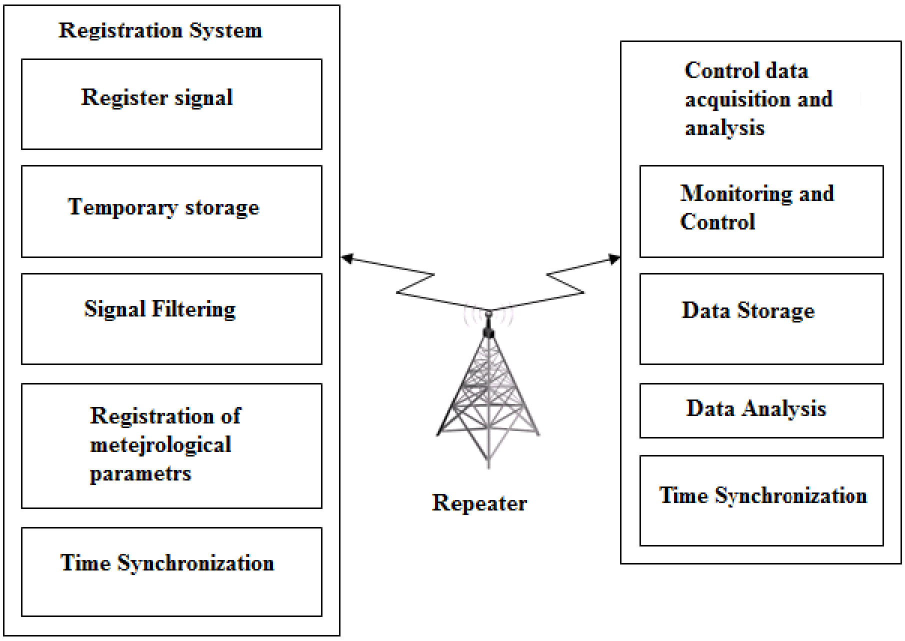

Fig. 1. Structure of hardware-software complex for registration and analysis of acoustic emission signals in the sound frequency range

Thus, investigation of gydroacoustic signals by hydrophones installed in water by the bottom of reservoirs is quite acceptable. We should note that there are no transverse oscillations in fluids. This may be applied for selection of sound waves propagating in solid mediums.

Fig. 2 shows an exemplary scheme of an acoustic experiment. Emission generation takes place in near-surface sedimentary rocks and signal registration is carried out in a fluid medium by the bottom of a reservoir. At the boundary of two mediums, refraction occurs. During the transition of longitudinal oscillations from sedimentary rocks into water, the refraction index is about 1.2 – 1.7. Taking into the account small distances of signal propagation, we may neglect the refraction effects.

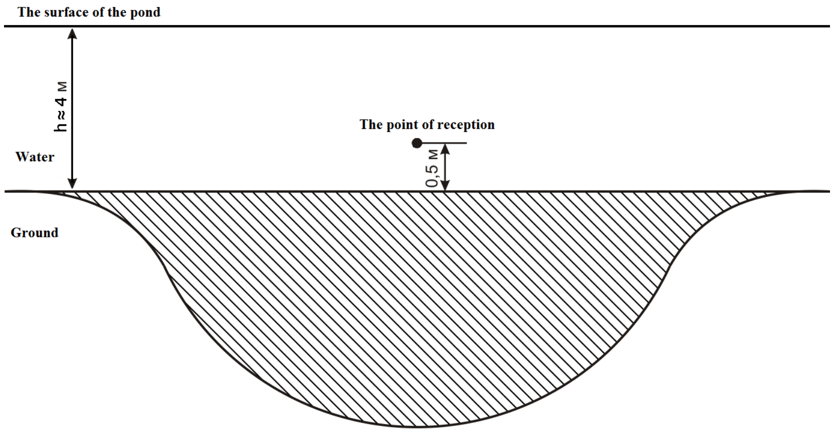

Fig. 2. Scheme for acoustic emission observation. Vertical section at the point of receiver location is presented. Shaded is the area from which a signal may be registered

In the experiments for registration of acoustic emission signals in the sound frequency range, we used a system of four piezoceramic hydrophones directed according to the cardinal points with direction diagram of 60° developed at IKIR FEB RAS.

The problem of detection of wave arrival direction was solved by vector-phase methods [9, 10]. A combined receiver (CR), constructed by ZAO «Geoakustika» at FGUP VNIIFTRI, was applied. It measures acoustic pressure and three mutually orthogonal components of pressure gradient. During the processing of these four signals, vectors of oscillating speed, shift and power density of acoustic emission are found. To detect and to determine the direction to the radiation source and to analyze geoacoustic pulse flux, an automation method was developed [7]. The method considers signal envelope form and determines its beginning. The amplitude is found from the maximum values of the envelope, then pulses and their directivity are determined. We exclude signals with increased noises from the analysis. They are revealed by the estimation of the relation of circumellipse minor and major semiaxes.

In the investigations of acoustic radiation directionality, the notions of integral $\Omega(t)$ and differential $D(\alpha,t)$ acoustic activities were used [7, 11]. The first one from these values is the pulse repetition frequency dependent on time, and the second one is the direction distribution of these pulse repetition frequencies.

A hardware-software complex was developed. It allows us to register and to determine the direction of arrival of original signal in the sound frequency range. “Wave” format of sound data was used for data storage [12]. Simultaneously with that, digital filtration in seven frequency subranges was carried out: less than 10, 30 – 60, 70 – 200, 200 – 600, 600 – 2000, 2000 – 6500, more than 6500 Hz, followed by detecting and signal collection on a 4-second interval for each subrange. To reveal the reason of anomalies in acoustic signals, their correlations with deformation and meteorological parameter measurements as well as with seismic data are under analysis.

Registration systems for acoustic emission were installed in reservoirs at three sites of complex geophysical observations of IKIR FEB RAS in Kamchatka: at “Paratunka” basic observatory (since 2008) and at remote “Karymshina” (since 1999) and “Mikizha” (since 2001) stations located at the distances of 20 km and 4 km respectively [12].

Features of high-frequency acoustic emission effect

In the course of the study it was ascertained that acoustic signals of deformation nature may be divided into pulses during background period and during the increase of rock deformation rate. Intensification of plastic process may be associated with rock loosening at the observation point or with the formation of a stress remote source [13]. During the background period, insignificant in amplitude acoustic pulses with the repetition frequency within 0.1 – 0.5 pulses per second are observed. As an example, Fig. 3a shows a 10-minute fragment of the record of such a signal. Fig. 3b illustrates an example of its energy spectrum obtained by averaging of 16 realizations of fast Fourier transform (FFT) estimated by 2048 signal samples. Thus, to construct the energy spectrum, realization of a signal 0.76 s long was used for the sampling frequency of 44100 Hz. As it is clear from Fig. 3b, the signal spectrum is smoothed and has gradual decrease with frequency increase. Such signals are called pink or gray noises. In the spectrum in Fig. 3b, there is a local maximum in the region of 18-21 kHz determined by receiver resonance. At low frequencies, there is an increase at the supply network frequency of 50 Hz.

During the growth of rock stress and deformation rate, increases of both pulse amplitude and of their number per time unit are observed. As an example, consider acoustic signal recorded on November 16, 2007. Fig. 3c illustrates a 10-minute fragment of signal record, and its energy spectrum is shown in Fig. 3d.

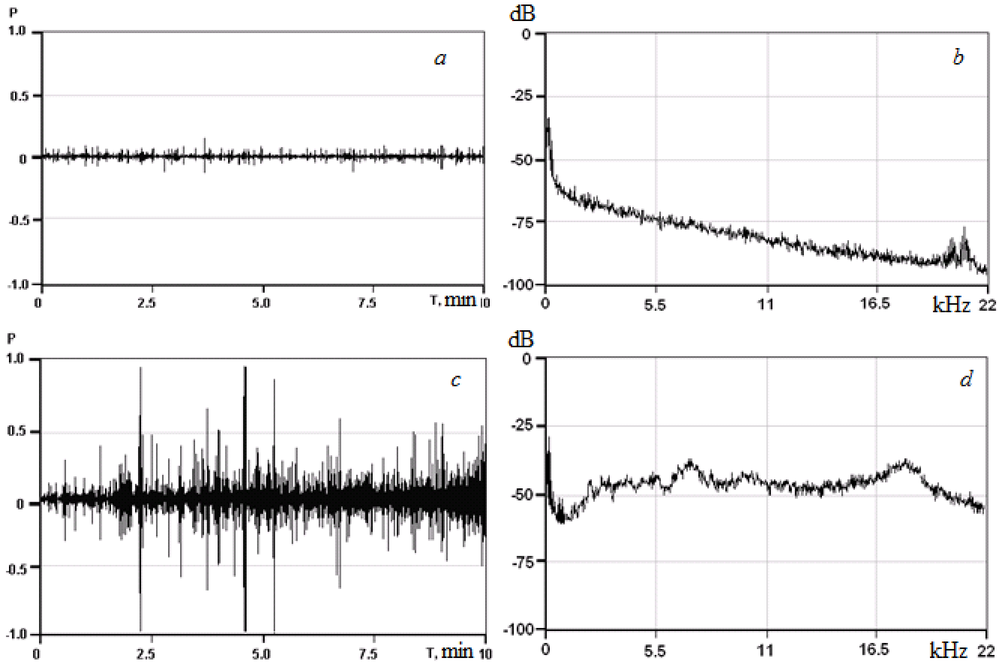

Fig. 3. Examples of acoustic signals during background period (*a*) and during deformation rate increase (*c*), and their energy spectra (*b*, *d*) respectively

Comparison of the signal spectrum during disturbances (Fig. 3d) with the spectrum during the calm period (Fig. 3b) shows that significant increase of the signal level in the range of 1-18 kHz is observed. “Gray” or “pink” noise of the background period was changed by almost “white” noise of deformation disturbances. The signals (Fig. 3a) were observed on November 16 from 02:30 UT within 11.5 hours. In 1.5 of a day on November 17, 2007 at 17:16 UT an earthquake with the energy class of K = 12.8 occurred at the epicentral distance of 104 km. Hypocentre coordinates are 52.8°N, 159.63°E, the depth is 17 km (hereafter the data of Kamchatka Branch of GS RAS were used in the text; for energy classification of earthquakes, K classes according to S.A. Fedorov scale were used; the relation of K with magnitude M_{LH} is determined by the formula $M_{LH}=(-4.6)/1.5$). The effect of weather conditions and industrial noises on the formation of acoustic emission signals was considered. We should note that it is not difficult to recognize additional disturbances of the emission under the influence of bad weather conditions according to meteorological observations, and industrial noises are classified easily [13].

Evaluation of acoustic emission directivity was carried out during background periods when there were no strong and long acoustic anomalies and during disturbances [11, 13]. Fig. 4 shows examples of diagrams of acoustic activity azimuthal distribution during intensive disturbances determined by deformation changes in sedimentary rocks at the site at the background of their averaged values on calm days.

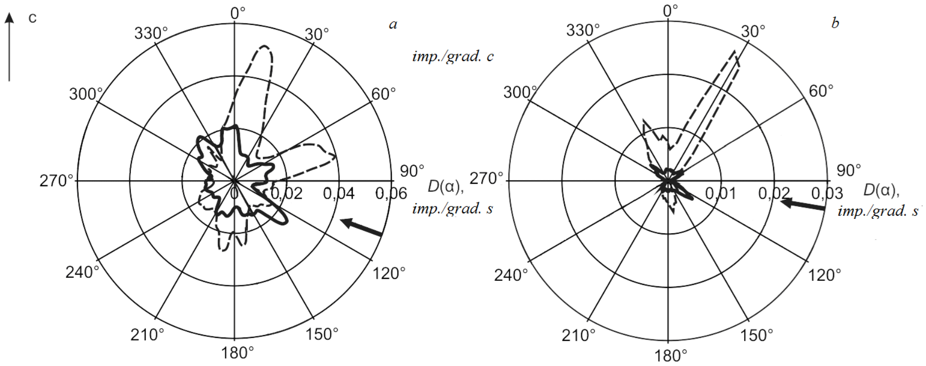

Fig. 4. Diagram of acoustic activity azimuthal distribution (dashed line) on December 14, 2007 (*a*) and on May 14, 2008 (*b*). Solid line is the background acoustic activity in November 2007 – Febryary 2008(*a*), in May – June 2008 (*b*). Arrows indicate the directions from earthquake epicenters

Usually, space distribution of acoustic activity is quite isotropic in the absence of disturbances. In the both cases shown in Fig. 4, increased activity is registered from the South-East and the North-West (solid line). The structure of other lobes is repeated to a large extent. Differences in emission activity have seasonal character. According to the large number of irregularly arranged lobes of the emission directivity diagram in Fig. 4, we may judge on the complicated character of stresses, and according to the asymmetry of arrangement of radiation maxima, we may conclude on the inhomogeneity of medium properties around the observation point. At the background of smooth seasonal variations of acoustic emission, short-time (within a day) intensive disturbances occur. In Fig. 4, acoustic activity $D(\alpha,t)$ during these periods is shown by a dashed line. An example of anisotropy of acoustic emission directivity registered on December 14, 2007, a day before the earthquake with the energy class of K=11.6 which occurred on December 15, 2007 at 9:00 UT at the epicentral distance of 175 km in the azimuth of 114°, hypocentre coordinates are 52.34°N, 160.61°E, is shown in Fig. 4a. Emission anomaly lasted for seven hours, from 3:00 to 10:00, on December 14, 2007. In this case the highest activity of pulses was observed from the directions of 10 – 20 degrees. Moreover, somewhat smaller increase of activity was also registered from the direction range of 60 – 80 degrees. For comparison, the solid line shows the averaged background activity for the period from November 2007 to February 2008. Fig. 4b shows an example of anisotropy of acoustic emission directivity registered on May 14, 2008, a day before the earthquake with K=11.1 which occurred on May 15, 2008 at 5:49 at the epicentral distance of 127 km in the azimuth of 104°, hypocentre coordinates are 52.7°N, 160.06°E. The emission anomaly lasted of eight hours, from 0:00 to 8:00, on May 14, 2008. The highest activity of pulses was observed in the direction of 30°. Moreover, somewhat smaller activity increase was also registered from the direction range of 330 – 340 degrees. For comparison, the solid line shows the averaged background activity for the period from May to June 2008.

In spite of the fact that both earthquakes occurred in the azimuth of 100 – 115 degrees relatively the site, anomalous increases in pulse activity in the directions close to 15 – 30 degrees were registered before the events, though the graphs slightly differ on the whole. We should note that none of the active regions corresponds to the direction of earthquake epicenter.

To confirm the deformation nature of the detected high-frequency anomalies of acoustic emission, simultaneous observations of rock emission and deformation were carried out. A laser unequal-arm strainmeter-interferometer constructed at TOI FEB RAS was used to measure relative deformations. It was installed at the distance of 50 m from the acoustic system on casing pipes of two 5-meter dry wells located at the distance of 18 m from each other.

On one of the wells we put an interference unit with a frequency-stabilized helium-neon laser covered by a box. On the other is an angle reflector protected by a container. Instability of laser frequency for a day is not more than 2×10^{-9}, radiation wavelength is 0.63 µm, measurement frequency is 860 Hz. When a 14-bit AD converter is used, strainmeter sensitivity is about 4×10^{-11} m, and the measurement accuracy for relative deformations is about 2×10^{-12}. Of course, when a strainmeter is installed on the ground surface, such accuracy of measurements may not be realized without a special cover. Taking into account the vibration and weather condition effect at the point of observations, the measurement accuracy for relative deformations was about 10^{-8}. The acoustic observation data were compared with rock relative deformations ε and estimates of deformation rate $\dot{\varepsilon}$ calculated as the first differences of ε measurements averaged on 1-second interval [14].

The results of joint investigations of acoustic emission and deformations showed that high-frequency anomalies of the emission were observed both during near surface rock tension (Fig. 5a) and compression (Fib. 5b) with relative deformation for a day of 10^{-7}, and in an number of cases 10^{-6} (Fig. 5) during significant increase of deformation rate. When comparing the graphs of the emission and deformations, it is clear that acoustic disturbances occur during multiple shifts of near surface rocks of different amplitude. Deformations of some shifts are small, even for comparatively large amplitude they are not more than 10^{-8} (Fig. 5). The data illustrated in Fig. 5 were obtained during seismically calm periods when no earthquakes with $K>10$ were registered at the distance up to 250 km.

During the final stage of earthquake preparation, the effect of deformations on acoustic emission behavior is the most vivid [14]. Fig. 6 illustrates an example of simultaneous acoustic emission anomaly and rock deformation registered on May 1, 2007, 25 hours before the earthquake with the energy class of 12.1 which occurred on May 2, 2007 at 12:00 UT at the epicentral distance of 154 km. Hypocentre coordinates are 52.44°N, 160.33°E, the depth is 12 km. It is clear from the figure that from 1:00 to 9:00 quite a sharp compression of rocks was observed. It was followed by relieves from 1 to 5 minutes long accompanied by deformation rate increase and simultaneous rise of emission level in kilohertz frequency range. Compression amplitude reached 0.025 µm, and deformation rate increased up to 10^{-9} s^{-1}.

To estimate the relation between acoustic emission and rock deformations, we calculated cross-correlation functions (CCF) between acoustic pressure P series in the range of 2.5 – 6.5 kHz and relative deformation , as well as the deformation rate ε from 0:00 till 12:00 on May 1. The sampling frequency of all the series was reduced to 0.25 Hz. In both cases the CCF maximum was observed at zero shift and it was –0.53 and 0.42 respectively for the significance level of no less than 0.001 [14].

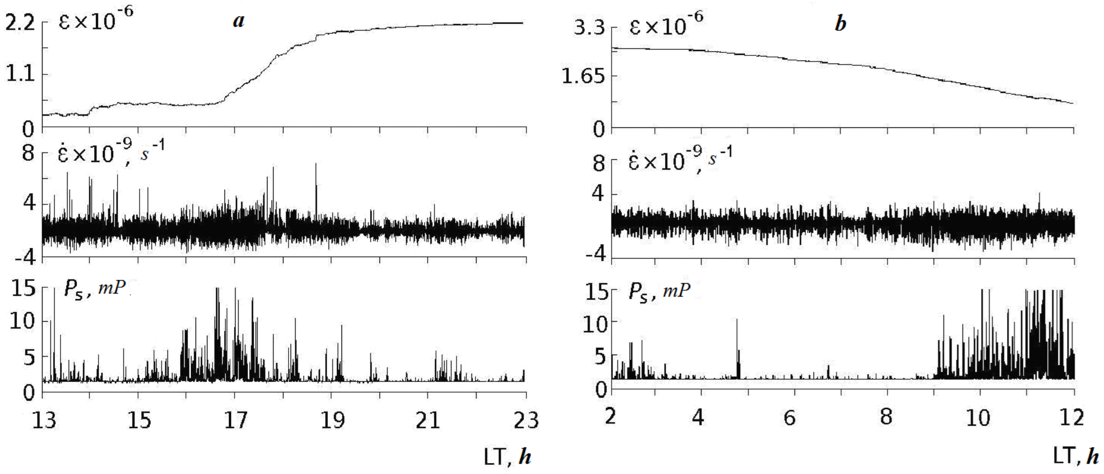

Fig. 5. Examples of acoustic emission anomalies and deformations during near surface rock tension on October 14, 2009 (*a*), and near surface rock compression on October 18, 2009 (*b*). ε is rock relative deformation, $\dot{\varepsilon}$ is deformation rate, P is acoustic pressure accumulated over the 4-second period in the frequency range of 0.6 – 2.0 kHz

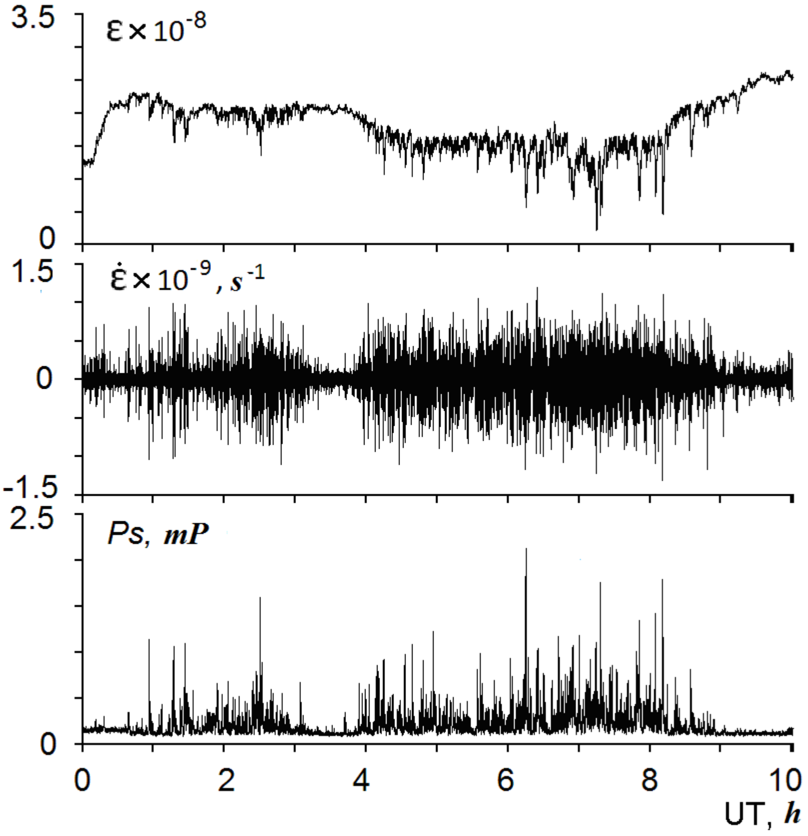

Fig. 6. Example of acoustic emission anomaly and rock deformations before the earthquake on May 2, 2007 at 12:00 UT. P is acoustic pressure accumulated over the 4-second period in the frequency range of 2.0 – 6.5 kHz. Other symbols are the same as in Fig. 5

Conclusion

We ascertained the existence of acoustic emission effect in sedimentary rocks which consists in the increase of geoacoustic radiation intensity in the frequency range from hundreds of hertz to the first tens of kilohertz during rock mass deformation rate increase. The effect has been stably observed during more than 10-year natural experiment at several spaced sites in Kamchatka, and it occurs the most intensively during the final stage of earthquake preparation.

During the acoustic emission effect, a clearly defined anisotropy of geoacoustic radiation directivity occurs. It is determined by the source orientation of acoustic oscillations in the stress field of near surface sedimentary rocks.

References

1. Belyakov A.S., Nikolaev A.V. Seismoakusticheskie priemniki s magnitouprugim preobrazovatelem [Seismoacoustic receivers with magnetoelastic converter]. Fizika Zemli – Izvestiya. Physics of the Solid Earth, 1993, No. 7, pp. 74-80.

2. Rykunov L.N., Khavroshin O.B., Tsyplakov V.V. Apparatura i metody issledovaniya slabykh seismicheskikh effektov [Instumentation and methods for investigation of weak seismic effects]. Dep. V VINITI, No. 2919-78, 1978.

3. Belyakov A.S. Zemletryaseniya i podzemnyi zvuk [Earthquakes and underground sound]. Zemlya i Vselennaya - Earth and Universe, 1996, No. 2, pp. 23-29.

4. Levin B.V., Sasorova E.V., Borisov S.A. et.al. Otsenka parametrov slabykh zemletryasenii i ikh signalov [Estimation of parameters of weak earthquakes and their signals]. Vulkanologiya i seismologiya – Volcanology and Seismology, 2010, No. 3, pp. 60–70.

5. Kuptsov A.V., Marapulets Yu.V., Shevtsov B.M. Analiz izmenenii geoakusticheskoi emissii v protsesse podgotovki sil'nykh zemletryasenii na Kamchatke [Analysis of changes of geoacoustic emission during the preparation of strong earthquakes in Kamchatka]. Issledovano v Rossii – Investigated in Russia. 2004, V. 7, pp. 2809-2818, Available at: http://www.sci-journal.ru/articles/2004/262.pdf.

6. Paparo G., Gregori G.P., Coppa U., De Ritis R., Taloni A. Acoustic Emission (AE) as a diagnostic tool in geophysics. Annals of Geophysics. 2002. Vol.45. N. 2. P. 401-416.

7. Marapulets Yu.V., Shcherbina A.O. Metody issledovaniya prostranstvennoi anizotropii geoakusticheskoi emissii [The methods for study of spatial anisotropy of geoacoustical emission]. Tekhnicheskaya Akustika – Technical Acoustics, 2008, 14, 17 pp. Available at: http://ejta.org/archive/articles2008-marapuletz1.zip.

8. Voitenko E.A., Morgunov Yu.N. Eksperimental'nye issledovaniya rasprostraneniya impul'snykh akustichesskikh signalov v grunte [Experimental studies of the propagation of buried pulse acoustic signals in the ground]. Akusticheskiy Zhurnal – Acoustical Physics, 2011, V. 57, No. 1, pp. 73-74.

9. Gordienko V.A., Gordienko T.V., Kuptsov A.V., Larionov I.A., Marapulets Yu.V., Rutenko A.N., Shevtsov B.M. Geoakusticheskaya lokatsiya oblastei podgotovki zemletryasenii [Geoacoustic location of earthquake preparation regions]. Doklady Akademii Nauk, 2006, V. 407, No 5, pp. 669-672.

10. Gordienko V.A. Vektorno-fazovye metody v akustike [Vector-phase methods in acoustics]. Moscow, Fizmatlit, 2007, 480 p.

11. Shevtsov B.M., Marapulets Yu.V., Shcherbina A.O. O napravlennosti pripoverkhnostnoi vysokochastotnoi geoakusticheskoi emissii v periody deformatsionnykh vozmushchenii [The direction of near surface high-frequency geoacoustic emission during deformation disturbances]. Doklady Akademii Nauk, 2010, V. 430, No. 1, pp. 119-122.

12. Marapulets Yu.V., Shevtsov B.M., Larionov I.A., Mishchenko M.A., Shcherbina A.O., Solodchuk A.A. Otklik geoakusticheskoi emissii na aktivizatsiyu deformatsionnykh protsessov pri podgotovke zemletryasenii [Geoacoustic emission response on activation of deformation processes during earthquake preparation]. Tikhookeanskaya geologiya – Russian Journal of Pacific Geology, 2012, V. 31, No. 6, pp. 59-67.

13. Marapulets Yu.V., Shevtsov B.M. Mezomasshtabnaya akusticheskaya emissiya [Mesoscale acoustic emission]. Vladivostok, Dal'nauka, 2012, pp. 126.

14. Larionov I.A., Marapulets Y.V., Shevtsov B.M. Features of the Earth surface deformations in the Kamchatka peninsula and their relation to geoacoustic emission. Solid Earth. 2014. N. 5. P. 1293-1300.

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