SEISMOACOUSTIC AND SEISMOELECTRIC RESPONSES OF NEAR-SURFACE SEDIMENTARY ROCKS IN KAMCHATKA

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Relevance of research

In the Earth near-surface layer rocks are constantly deformed here under the effect of different causes (moon-solar tides, weather parameter variations, Earth eigen movements etc.). Rock deformation in seismically active regions also occurs under the impact of seismic waves from earthquakes of different energy.

Sedimentary rocks are widely spread among the near-surface rocks. They cover about 80% of the continents surface [Garrels, Mackenzie, 1971]. Sedimentary rocks are a complicated polydisperse water- and gas-saturated porous medium of low rigidity and, thus, are easily deformed. Of great interest is the transformation of energy of these rocks deformations by seismic waves from earthquakes into acoustic signal energy and electric field variations. Investigation of near-surface sedimentary rock seismoacoustic and seismoelectric responses, different in genesis but having common deformation nature, characterizes the deformation process better and is topical for investigation of mechanic and electric properties of these rocks. Moreover, seismic waves affect sedimentary rocks, which are in stress state. That is why the intensity of transformation of elastic impact energy of seismic waves into acoustic and electric fields energy will be mainly determined not only by rocks structure and texture but their stress-strain state as well [Migunov, 1984; Marapulets et al, 2012]. Thus, when we record a response of near-surface sedimentary rocks on seismic wave impact in the form of generation of acoustic and electric signals, we can indicate the changes of properties, stress state and the deformation pattern of these rocks at the observation site.

During sedimentary rock deformations by seismic waves from earthquakes, relative micro displacements of fragments and interactions of their surfaces occur. That is accompanied by acoustic signal generation in the frequency range from seismic waves up to the first tens of kHz [Marapulets, Shevtsov, 2012]. Seismoelectric effect of the second kind, also known in Geophysics and detected on sedimentary complex rocks [Ivanov, 1940], appears under the impact of elastic oscillations of these waves. Thus, sedimentary rocks can be considered as acoustic and electric seismographs simultaneously appearing during seismic wave passage. They are formed in the result of collective reaction of rocks fragments on their elastic deformation.

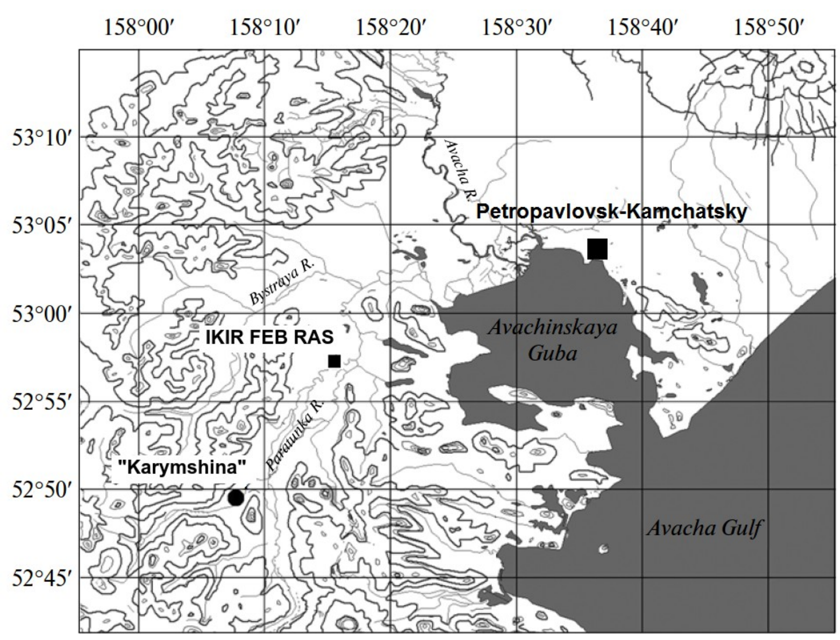
Simultaneous investigations of seismoacoustic and seismoelectric responses of near-surface sedimentary rocks were first begun in Kamchatka in 2012 and are still carried out at Karymshina site (52.83º N, 158.13º E) of IKIR FEB RAS [Muratov et al, 2018; Muratov, Rulenko, Marapulets, 2019; Mishchenko, Rulenko, Marapulets, 2020; Mishchenko, Rulenko, Marapulets, 2021]. This site is located in the region of Verkhne-Paratunskaya hydrothermal system of the Southern Kamchatka, in the zone of intersection of different-rank tectonic faults [Serezhnikov, Zimin, 1976].

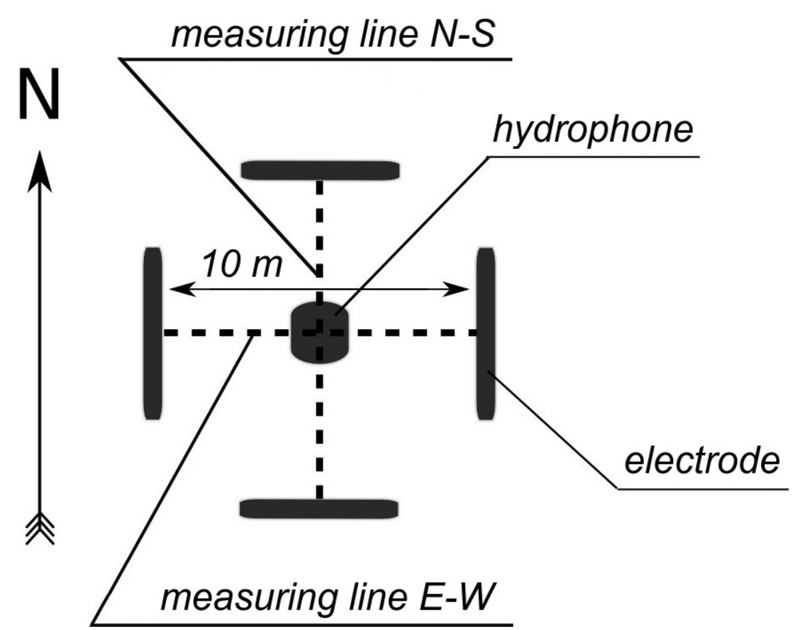
In the present paper, we added 20 cases of joint responses of near-surface sedimentary rocks recorded in 2012-2023 to the 18 cases described in [Mishchenko, Rulenko, Marapulets, 2021]. Results of records of acoustic signals at the frequencies higher than seismic waves at Krutoberegovo site, located 480 km to the south-east of Karymshina site, are presented.

Observation method and data analysis

A wide-band piezoceramic hydrophone, having the sensitivity together with a pre-amplifier of about 1 V/Pa, was used as an acoustic signals receiver. It was hung in an artificial water reservoir of the size 1×1×1 m^3 at the depth of 0.5 m. The hydrophone had a directivity pattern diagram of 60º, was oriented vertically downwards and was arranged at the point of intersection of measuring lines for recording the electric field in rocks. Electric field horizontal components were recorded by two orthogonal measuring 10-meter lines oriented along the magnetic meridian (N-S) and perpendicularly to it (E-W). Lead plates with the size of 0.25 × 1.0 m^2 were used as electrodes. They were dug into the ground at the depth of 1.0 m. The resistance between N-S line electrodes was 10.5 kOhm and that of the E-W line was 8.7 kOhm. The potential difference between the electrodes was applied to the pre-amplifier with input impedance of 1 MOhm. The pre-amplifier was near the measuring lines. Acoustic and electric signals were simultaneously digitized by a general 8-cannel 16-bit professional sound card M-Audio Fast Track Ultra 8R with the sampling frequency of 48 kHz. The frequency range of the recorded signals was 0.1 Hz – 11 kHz.

According to the drilling results, the near-surface rocks at Karymshina site are sedimentary with the layer thickness of about 50 m [Kuptsov et al, 2005]. There is a well No. 99-8 with the depth of 19 m, located 170 m from the hydrophone. Its geological column is represented by boulder-cobble deposits with sand-clay filler (0-5 m), block-rubble deposits with clay filler (5-14 m) and boulder-cobble deposits with sand filler (14-19 m). Based on the estimates from the paper [Marapulets, Shevtsov, 2012], sources of the acoustic signals, occurring at the frequencies from the first hundreds of Hz to the first tens of kHz, are located at the distances up to the first tens of meters from the hydrophone. Taking all that into the consideration and the distance between the electrode and their position in the ground, we think that seismoacoustic and seismoelectric signals were generated in the near-surface sedimentary rocks.





Observation method and data analysis

Seismoacoustic and seismoelectric responses of sedimentary rocks are formed as follows. In case of the applied installation of the hydrophone, the compressional *P*-waves are recorded without significant distortions since seismic wave refraction can be neglected when the water reservoir is small. Water does not have form elasticity that is why shear *S*-waves do not propagate in water reservoirs. However, when initiating horizontal and vertical motions of soil, they cause rock acoustic emission and affect, together with the emission, the hydrophone though the hanger, manifesting in the obtained data [Marapulets, Shevtsov, 2012]. Taking that into consideration, we considered acoustic signals occurring only during *P*-wave passage. These signal frequencies are determined by the sizes of rock fractions interacting at the given time. Electric field variations in rocks occur only at the frequencies of seismic wave mechanic impact.

Table. Parameters of earthquakes during which seismoacoustic and seismoelectric signals were analyzed. *R*, *D* are epicentral and hypocentral distances.

No.	Earthquake		Epicenter coordinates		Depth, km	Magnitude (mww)	*R*, km	*D*, km
	Date, UTC	Time, UTC	Lat.° N	Long.° E				
1	2016-01-30	03:25:12	53.978	158.546	177	7.2	131.1	220.2
2	2018-12-20	17:01:55	55.100	164.699	16.6	7.3	497.5	497.8
3	2020-03-25	02:49:21	48.964	157.696	57.8	7.5	430.2	434.0

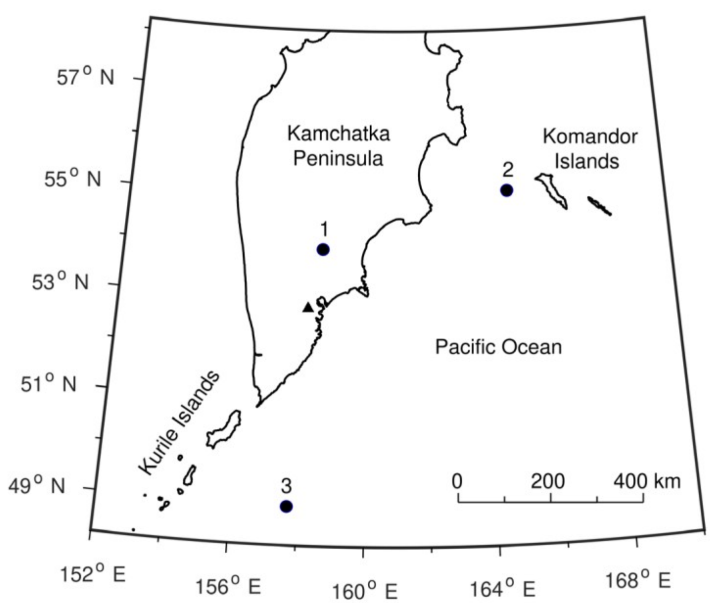
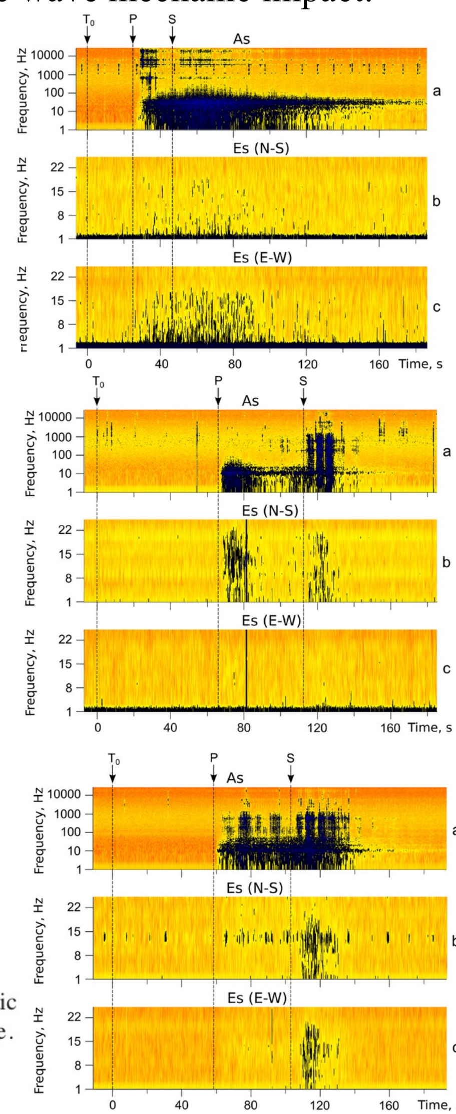


Figure. Location of “Karymshina” site (▲) and of earthquake epicenters (●), for which seismoacoustic and seismoelectric signals were analyzed. Earthquake parameters and their numbers are in the table.



Spectrograms of acoustic (As) and electric Es (N-S), Es (E-W) signals recorded during seismic wave propagation from earthquake No. 1,2,3 (table 1). Arrows indicate the times of earthquake T0 and longitudinal (P) and transversal (S) wave arrival to the seismic “Karymshina” station.

Seismoacoustic and seismoelectric responses of rocks at Karymshina site

The paper investigates the correlation relations between earthquake energy and the distance to a hypocenter for a seismoacoustic response only, as well as for both seismoacoustic and seismoelecreic responses of near-surface sedimentary rocks. We considered the cases of response records for the period from November 2012 to May 2023. The energy class K_s was considered as the earthquake energy characteristics. It is the decimal logarithm of the energy emitted from a source in the form of seismic waves [Fedotov, 1969; Федотов, 1972]. Earthquake parameters were taken from the catalogue of Kamchatka Branch of the Federal Research Center "Geophysical Survey, Russian Academy of Sciences" (KB GS RAS) (http://sdis.emsd.ru/info/earthquakes/catalogue.php). Earthquakes with K_s>11 and the epicentral distances up to 600 km were under consideration from this catalogue.

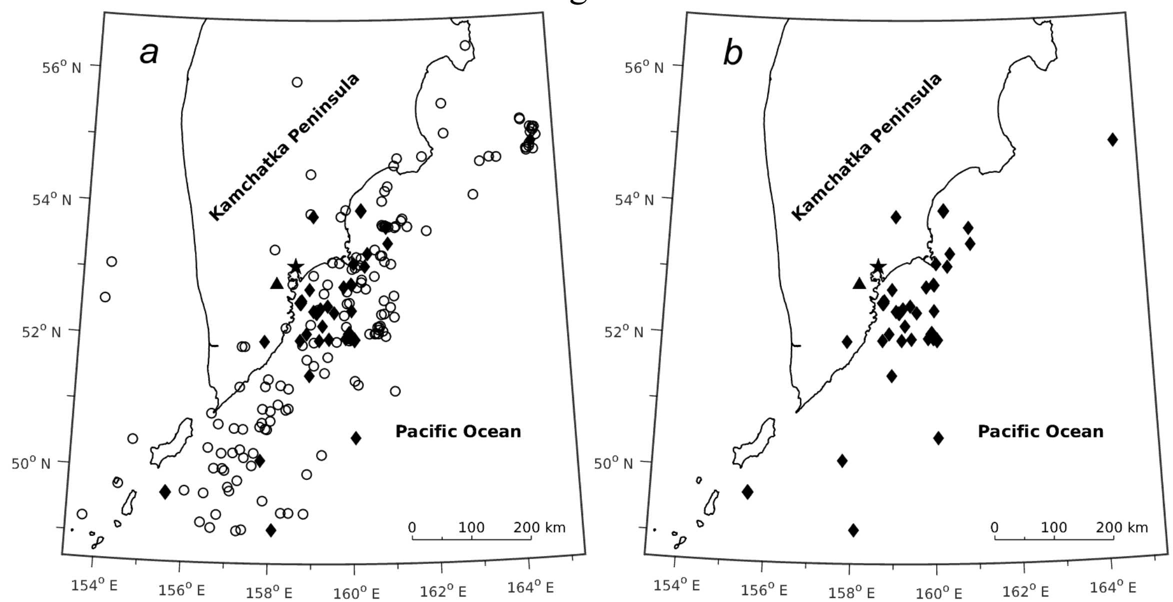


Fig. 1 Earthquake epicenter maps during which only acoustic response (*a*, ○) or both acoustic and electric responses of near-surface sedimentary rocks (*a*,*b*, ◆) were observed; ▲ – Karymshina site location, ★ - Petropavlovsk-Kamchatskiy

We detected 196 earthquakes, during which rock acoustic responses were observed. Rock electric responses, that is both acoustic and electric responses occurred together, were detected during 38 earthquakes from them. Earthquake epicenter maps for the both cases are represented in Fig. 1*a*,*b*, respectively.

The earthquakes, during the passage of seismic waves from which only acoustic or both acoustic and electric responses were observed, are denoted differently in Fig. 1. Using the same symbols for all 196 earthquakes as in Fig. 1, Fig. 2 compares their energy classes K_s with the distances from hypocenters to Karymshina site *D*.

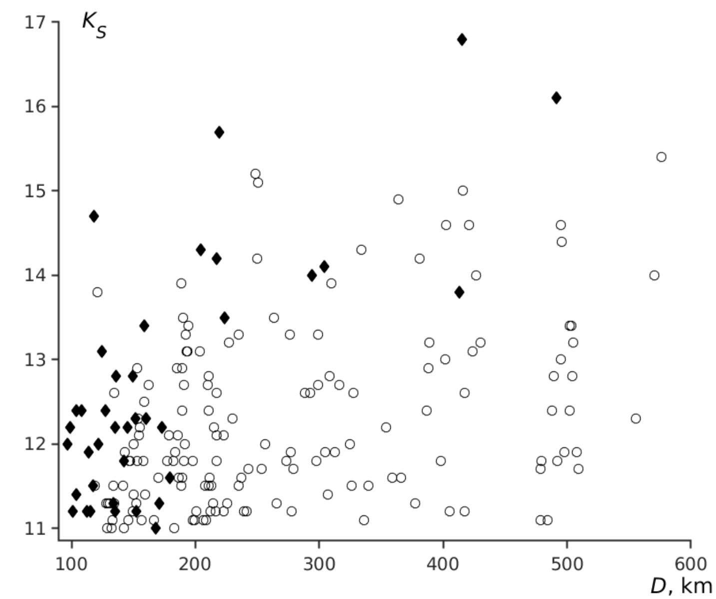


Fig. 2. Comparison of the considered earthquake energy classes K_s with distances from hypocenters to Karymshina site *D*. Rock response symbols (○, ◆) are the same as in Fig. 1.

Seismoacoustic and seismoelectric responses of rocks at Karymshina site

The correlation relation between K_s and D was considered for the two earthquake groups. As it was mentioned above, the first group (No. 1) includes 38 earthquakes, during which both seismoacoustic and seismoelectric responses of rocks were observed. The second group (No. 2, 158 earthquakes) contains the earthquakes during which only seismoacoustic responses of rocks without seismoelectric responses were observed. Nonparametric correlation analysis was applied in the both cases. Spearman's rank correlation coefficient r_s was considered. It is less sensitive to spikes and errors in observation results. Moreover, it also allows us to estimate monotonous nonlinear relations between variables and, that is important in our case, can be used for sample small sizes [Borovikov, 2003].

Table represents the estimates of Spearman's correlation coefficient r_s and its significance level p between K_s and D values for the two specified groups of earthquakes. According to Table, there is a highly significant correlation relation (r_s = 0.53, p < 0.001) between the energy classes of earthquakes, during which both seismoacoustic and seismoelecreic responses of rocks were observed, and the distances from hypocenters. In spite of the larger sample size, there is the same highly significant but weaker relation (r_s = 0.37) for the earthquakes, during which only seismoacoustic response of rocks was observed. The highly significant correlation relations indicate the fact that manifestation of seismoacoustic and seismoelectric responses of near-surface sedimentary rocks is determined by energy, emitted from an earthquake source in the form of seismic waves and delivered to the observation site by these waves.

Table Estimates of Spearman's correlation coefficient rs and its significance level p between earthquake energy classes and hypocentral distances to Karymshina site for the first (No. 1) and the second (No. 2) groups of earthquakes

Group / Earthquake number	r_S	p
No.1 / 38	0.53	< 0.001
No.2 / 158	0.37	< 0.001

High-frequency seismoacoustic response of rocks at"Krutoberegovo" site

As it was mentioned above, during the passages of seismic waves from some earthquakes at Karymshina site, acoustic signals appear not only at seismic wave frequencies but also at higher kilohertz frequencies. They indicate the transformation of low-frequency energy of seismic waves to significantly higher energy of acoustic radiation of sedimentary rocks close to the hydrophone. We think that such signals are generated during rock intensive deformations when relative micro displacements and interactions of smallest fragment surfaces occur.

Detection of seismoacoustic signals, including kilohertz ones, at other site in Kamchatka is of interest. To do that, we organized and began geoacoustic observations at Krutoberegovo site (56.26 N, 162.71 E), located 480 km to the north-east from Karymshina site. An artificial water reservoir of the size 1×1×1 м^3 was set to install a piezoceramic hydrophone. When digging a hole for the water reservoir, it was discovered that the rocks under the soil layer are sedimentary (large and fine send, clay band). The measuring-recording complex, observation and data analysis methods were the same as at Karymshina site.

Three close earthquakes occurred from January 2022 to July 2023. Their hypocenters were located close to each other. During the passage of seismic waves from these earthquakes, acoustic signals were recorded in high-frequency kilohertz frequency range besides the low-frequency one. Earthquake parameters, taken from the catalogue of KB GS RAS (http://sdis.emsd.ru/info/earthquakes/catalogue.php), and the distances from hypocenters to Krutoberegovo site are shown in Table.

Table Parameters of the earthquakes, during which high-frequency acoustic signals were recorded besides the low-frequency ones at Krutoberegovo site. D is the distance from a hypocenter.

No.	Date, UTC	Time, UTC	Lat.° N	Long.° E	H, km	K_s	D, km
1	2022.01.18	22:54:59.2	56.26	163.00	11.3	10.0	21.1
2	2023.06.29	02:24:17.6	56.24	162.97	6.3	10.5	17.3
3	2023.07.04	02:48:19.8	56.25	162.96	7.9	10.6	17.3

As an example, Figure shows a record and a spectrogram of the acoustic signal which was observed during the passage of waves from the earthquake No. 1 (Table 2). It is clearly seen on the spectrogram of this signal that acoustic energy was emitted in different frequency clusters during the passage of seismic waves just like during some earthquakes recorded at Karymshina site [Muratov et al, 2018; Muratov, Rulenko, Marapulets, 2019; Mishchenko, Rulenko, Marapulets, 2020]. The first cluster manifested at the frequencies up to about 100 Hz, the second one manifested at the frequencies from 100 Hz to about 10 kHz. The same clusters are observed on the spectrograms of acoustic signals recorded during the earthquakes No. 2, 3 (Table 2). That all indicates the fact that generation of high-frequency seismoacoustic signals manifests in sedimentary rocks in different near-surface zones of the earth crust in Kamchatka.

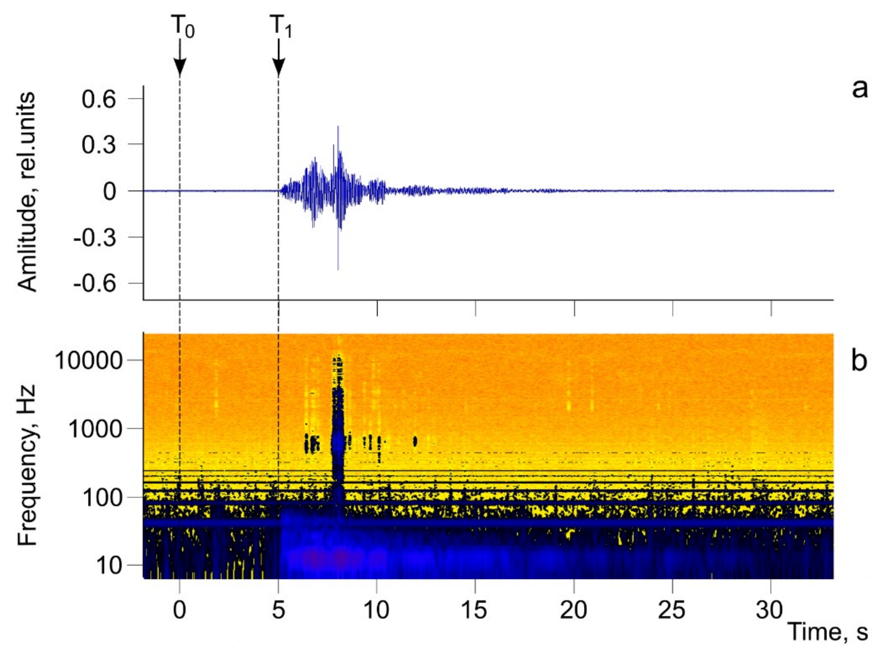


Figure. Record (a) and spectrogram (b) of acoustic signal at Krutoberegovo site during the passage of seismic waves from earthquake No. 1 (Table). Arrows indicate the times of earthquake occurrence T_0 and P-wave onset.

Conslusion

We considered the cases of records of seismoacoustic and seismoelectric responses of near-surface sedimentary rocks at Karymshina site in Kamchatka from November 2012 to May 2023. The relation between the energy classes of earthquakes K_s, during which there was only seismoacoutic or both seismoacoustic and seismoelectric responses, and the distances from earthquake hypocenters D to this site were under investigation. In both cases, highly significant correlation between K_s and D was discovered. It indicates that manifestation of seismoacoustic and seismoelectric responses on near-surface sedimentary rocks is determined by the energy emitted from an earthquake source in the form of seismic waves and delivered to an observation site by these waves.

The high-frequency seismoacoustic signals were also detected at Krutoberegovo site located 480 km to the north-east from Karymshina site. They were observed during three close earthquakes, the hypocenters of which were located close to each other. Observation of high-frequency signals at two sites shows that their generation manifests in sedimentary rocks in different near-surface zones of the earth crust in Kamchatka.

Observation of the high-frequency seismoacoustic responses of rocks at Karymshina and Krutoberegovo sites confirms the fact that these responses occur during strong and moderate in energy remote earthquakes and during weak in energy close earthquakes.

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References

Slater L. Near-Surface geophysics. A new focus group // EOS. 2006. V. 87. No. 25. P. 248–249.

Adushkin V.V., Spivak A.A. Problems Related to the Interaction of Geospheres and Physical Fields in Near-Surface Geophysics // Izvestiya, Physics of the Solid Earth. 2019. V. 55. No. 1. P.1–11. - https://doi.org/10.1134/S1069351319010014

Garrels R.M., Mackenzie F.T. Evolution of sedimentary rocks. Norton and Company: NewYork, NY, USA, 1971. P. 397.

Migunov N.I. On the use of seismoelectric phenomena to study the stress state of saturated rocks // Izvestiya AN SSSR, Physics of the Solid. 1984. No. 9. P. 20–28. (in Russian).

Marapulets, Y.V.; Shevtsov, B.M.; Larionov, I.A.; Mishchenko, M.A.; Shcherbina, A.O.; Solodchuk, A.A. Geoacoustic emission response to deformation processes activation during earthquake preparation. Russ. J. Pac. Geol. 2012. No. 6. P. 457–464.

Yu.V. Marapulets, B.M. Shevtsov. Mesoscale acoustic emission. Vladivostok: Dal'nauka, 2012. P. 126. (in Russian).

Ivanov A.G. Seismic and electrical effect of the second kind // Proceedings of the Academy of Sciences of the USSR, a series of geographical and geophysical. 1940. № 5. P. 18–21 (in Russian).

P.V. Muratov, O.P. Rulenko, Yu.V. Marapulets, A.A. Solodchuk. Electrical and acoustic response of the near-surface sedimentary rocks to seismic earthquake waves passing // Bulletin KRASEC. Physical & Mathematical Sciences. 2018. No. 5(25). P. 62–73. (in Russian).

P. Muratov, O. Rulenko, Yu. Marapulets. Manifestation features of near-surface sedimentary rock electric and acoustic responses on seismic waves from earthquakes // E3S Web of Conferences **127,** 02015 (2019). - https://doi.org/10.1051/e3sconf/201912702015

M. Mishchenko, O. Rulenko, Yu. Marapulets. Some features of acoustic and electric responses of near-surface sedimentary rocks during deformations by seismic waves from strong earthquakes (M_w > 6.5) // E3S Web of Conferences **196,** 02028 (2020). - https://doi.org/10.1051/e3sconf/202019602028

M. Mishchenko, O. Rulenko, Yu. Marapulets. Analysis of manifestation of joint acoustic and electric responses of near-surface sedimentary rocks on the deformation by earthquake seismic waves in the South of Kamchatka // EPJ Web of Conferences **254**, 02002 (2021) - https://doi.org/10.1051/epjconf/202125402002

Serezhnikov, A.I. and Zimin, V.M. Geological structure of the Paratunka geothermal region; the influence of some geological factors on the current hydrothermal activity, in Gidrotermal'nye sistemy i termal'nye polya Kamchatki (Hydrothermal Systems and Thernal Fields of Kamchatka).

Vladivostok: DVNTs AN SSSR, 1976, P. 115–142. (in Russian).

Kuptsov, A.V., Larionov, I.A., and Shevtsov, B.M. Geoacoustic emission during the precursory periods of Kamchatka earthquakes // Vulkanol. Seismol., 2005, No. 5, *P. 45–59.* (in Russian).

Fedotov S.A. On energetic classification of Kuril-Kamchatka Earthquakes, Q-frequency dependence and magnitude problem // Program and Abstracts, General Scientific Assembly JASPEI-IAGA. Madrid: 1969. V. 1.

Fedotov S.A. On energetic classification of Kuril-Kamchatka Earthquakes and magnitude problem Moscow: Nauka, 1972. P. 114. (in Russian).

V. Borovikov. STATISTICA. The Art of Computerized Data Analysis: For Professionals. St. Petersburg: Piter, 2003 P. 688. (in Russian).