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Acoustic–electromagnetic effects of tectonic movements of the crust – borehole survey

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Abstract

Borehole radiophysical properties are briefly described. Borehole investigation of lithosphere acoustic-electromagnetic radiation was carried out in a seismically active region. Four main types of anomalies of acoustic-electromagnetic radiation were distinguished. They correspond to shear and bulk relaxations of tectonic stress. Stability of phase relations of acoustic and electromagnetic signals in the region of anomalies was detected that allows us to state their coherence. It was concluded that the reason of mutual coherence of acoustic and electromagnetic signals is the magnetoelastic effect of the casing pipe. A mechanism of generation of rock self-induced vibrations during tectonic stress relaxation causing acoustic-electromagnetic emission was suggested. It was concluded that "sigmoid" anomalies may correlate with excitation of eigen vibrations in a fracture cavity during brittle shear relaxation of rock tectonic stress. An explanation of the change of anomalous "sigmoid" signal frequency was given. It is considered to be the result of growth of rock fracture cavity and the decrease of tectonic stress relaxation. It was concluded that a borehole, cased in a steel pipe, together with a system of inductance coils and a hydrophone is the effective sounding sensor for acoustic fields of interior deep layers. It may be applied to investigate and to monitor the geodynamic activity, in particular, in earthquake forecasts and in monitoring of hydrocarbon deposits during their production.

1 Introduction

Acoustic and electromagnetic signals of lithospheric origin accompanying earthquakes are usually associated with relaxation processes of tectonic stress (Sobolev and Ponomarev, 2003).

We may say that acoustic-electromagnetic emission of the lithosphere is the reflection of its seismo-tectonic state. The deformation-induced acoustic-electromagnetic emission is well known in solid-state physics. It is the effect of stress relaxation processes in acoustic and electromagnetic fields (Hadjicontis et al., 2007). In material sciences, this condition is used in nondestructive testing to get additional information on the medium of propagation and sources (Sikula et al., 2008; Mori et al., 2009). So far, the geophysical aspects of this phenomenon are poorly studied due to the following circumstances.

Electromagnetic radiation of the lithosphere is observed at the background of powerful atmosphere-magnetosphere radiation, investigation of which has long and rich history (Uvarov et al., 2012).

At present, natural atmosphere-ionosphere radiations is used as a source of information in a number of international geophysical projects (WWLLN, AWDANET). Estimations show that atmosphere-magnetosphere radiation is incomparably stronger than that of the lithosphere. Thus, it is necessary to apply special methods to investigate this radiation.

Development of such methods (Uvarov et al., 2010; Uvarov, 2012) allowed us to begin purposeful and correct survey of electromagnetic radiation of lithospheric origin.

An additional and a very important circumstance, which makes the investigation of the crust wave process from surface more complicated, is strong attenuation of both acoustic and electromagnetic radiations in friable near-surface layer of aqueoglacial or eolian origin. In fact, during propagation of waves of any nature in isotropic homogeneous medium, the fraction of the radiation which passed the distance r is determined by exponential Beer–Lambert–Bouguer law $\frac{J(r)}{J_0} = \exp(-\kappa r)$. Here, the transmission coefficient κ is the measure of medium inhomogeneity and does not depend on distance. It has different names in different areas of investigations, they are: extinction coefficient, transmission coefficient and so on. In geology, the measure of medium inhomogeneity, associated with fluid content, is porosity, the parameter depending on depth which, evidently, can characterize propagation of wave fields in some measure. It is clear, that porosity should decrease with depth due to rock pressure.

Nevertheless, due to the great variety of geological conditions, we may state only general dependence of porosity with depth. In the investigations of porosity on large

areas of homogeneous rocks, Athy law was ascertained (Athy, 1930; Engelgard, 1964) which states exponential dependence of porosity with depth

$$p \sim \exp(-\alpha H) \quad (1)$$

If we suggest that transmission coefficient behaves the same way with depth $\kappa \sim \exp(-\alpha H)$, then absorption decreases much faster with depth, than exponentially:

$$\frac{J(r)}{J_0} \sim \exp(-r \times F(\exp(-\alpha H))) \quad (2)$$

In other words, the propagation conditions become significantly worse when approaching the surface. That means that for the effective investigations of lithosphere wave fields, it is necessary to have access to the crust subsurface layers which allow the waves to propagate to great distances. Such access is possible in mines, pits or by the means of boreholes. Application of boreholes is preferable, since they are numerous, cover large areas and different geological conditions.

Borehole surveys of acoustic and electromagnetic radiation has been carried out for quite a long time. Some interesting data have been obtained on the relation of electromagnetic and acoustic radiation with seismic activity, weather and season condition effect and the Earth natural electromagnetic field (Gavrilov et al., 2003, 2013). In these investigations, a borehole is considered as a means for sensor transportation into the interior, and its radiophysical properties are not taken into the account. However, if borehole radiophysical properties are considered, the efficiency of a survey may be considerably improved.

2 Properties of borehole-sensor

A borehole is an opening drilled in a rock to investigate its geological structure or to get fossil fluid. A borehole depth is from several meters to several kilometers. To prevent downfalls, walls are strengthened by cementation or by a casing pipe. We consider only water-filled boreholes formed in the result of drilling for thermal water, one of the main fluid deposits of Kamchatka. Nevertheless, all the facts stated in the paper are true with some corrections for boreholes with other content.

2.1 Acoustic properties of a borehole

The vibration frequency of a borehole water column, just like the frequency of rod natural vibrations f, is determined by the expression:

$$f = \frac{c(2n-1)}{2h} \tag{3}$$

The frequency difference between the adjacent harmonics is given by the relation $\Delta f = c/h$. Here, c is the sound velocity in borehole medium (in water $c = 1500\,\mathrm{m\,s^{-1}}$), n is the integer, the harmonic number, h is the rod length. For example, for a borehole with 1.5 km depth, the frequency of 0.5 Hz corresponds to the first harmonic of water column, and the difference between the harmonics is 1 Hz.

Only longitudinal waves propagate in borehole water, for which it is a waveguide. This circumstance allows us to register waves propagating from the borehole bottom by the sensors at the top.

Since the wall surface of a borehole is the boundary between two mediums, borehole fluid and rock, there are conditions in the borehole for different surface waves (Rayeigh, Stoneley, Love, Lamb waves) to appear (Borehole, 1988). The most significant are Lamb waves. Lamb frequency spectrum of a borehole is determined by the expression:

$$f = \frac{c(2n-1)}{2\mathrm{h}\sqrt{1 + \frac{\delta_l c^2}{\delta_s v_s^2}}} < f_L \tag{4}$$

Here, δ_l, δ_s are fluid densities in a borehole and the surrounding medium, c, v_s are velocities of propagation of fluid elastic vibrations and rock transverse vibrations.

These waves differ from the natural vibrations of a water column by the fact that mechanical interaction of a fluid with the bounding walls is taken into account.

Lamb waves exist in the range less than the critical frequency $f_L > f$ determined by the expression $f_L = \frac{v_s}{\pi D}$, where D is the borehole diameter. For our boreholes, this frequency is within the range from one to several kilohertz.

Due to the difference of sound propagation velocity in rocks of different layers, widening of resonance lines takes place as harmonic numbers increase.

For definite numbers, overlapping of adjacent bands is observed as well as vanishing of their structure.

Longitudinal vibrations in a borehole may be excited by the shear vertical component of both longitudinal and transverse waves. Thus, a sensor, installed at the borehole top allows one to register the vertical component of transverse and longitudinal vibrations of rock different layers. In other words, a borehole is a transducer of rock acoustic vibrations into vertically propagating longitudinal wave. A quite deep borehole crosses several different lithologic layers, each of which is characterized by its elastic constants.

All rock layers, especially near-surface ones, have much higher absorption than borehole water. In the result, a borehole is a collector and a waveguide of acoustic vibrations in all the layers. It collects vibrations of the interior different layers and brings them to the surface. Thus, they bypass the strongly absorbing near-surface layers.

To avoid a downfall, a borehole is usually cased in a steel pipe. Therefore, borehole electromagnetic properties are largely determined by the fact that the borehole casing pipe is a conductor in a weakly conducting medium, and it may be considered as an antenna in a dielectric medium with losses (King and Schmidt, 1984).

a. Registration of the field electric component is realized by measuring the polarization current generating in the conductor under the influence of electromagnetic field.

   Usually a dipole antenna is used. In the simplest case it is a construction of two similar linear conductors symmetrically arranged relatively the measuring instrument.

The peculiarity of the antenna applying a casing pipe is that only one pipe end, projecting over the ground surface, may be connected to the measuring instrument.

If a casing pipe is considered as one of dipole antenna beams, then a conductor-balancer is required to measure voltage on it. The simplest solution is to put the balancer for measurements on the ground surface. However, it will be affected by a strong field of atmospheric-thunderstorm origin. It is very difficult to filter it out of lithospheric signals.

b. There are more opportunities during the registration of the interior field electromagnetic component. The steel casing pipe is a magnetic circuit which pulls the field magnetic component to the surface. Thus, application of a magnetic antenna with a casing pipe as a core is quite an effective solution for registration of the interior field magnetic vertical component.

c. We should, certainly, pay attention to the application of magnetoelastic effect (Villary effect) (Jiles, 1995). The essence of the effect is that the mechanical stress applied to a magnetized ferromagnetic causes the order degree change of a domain structure, formed by external magnetic field effect, the change of ferromagnetic permeability and, correspondingly, of magnetic induction. In an inductor with such a core, the change of the passing magnetic flux induces current under the influence of acoustic vibrations.

Thus, a borehole is:

a. waveguide of longitudinal acoustic and electromagnetic vibrations;

b. transducer of transverse electromagnetic and acoustic vibrations into longitudinal vibrations;

c. collector of acoustic and electromagnetic longitudinal vibrations of the interior depth;

d. resonance structure;

e. transducer of acoustic vibrations into electromagnetic ones;

f. moreover, a steel casing pipe is a magnetic circuit, pulling the depth magnetic fields to the surface.

Due to the large diversity of geological conditions and construction features, each borehole is characterized by a unique amplitude-frequency characteristic.

The paper investigates acoustic-electromagnetic emission of interior subsurface layers in a seismically active region applying a borehole as a radiophysical device.

3 Experiment

For this purpose, a field experiment was carried out at a borehole 74 on Korkina brook of Paratunka river basin (South Kamchatka, 52°58′ N, 158°15′ E). This well was drilled in 1968 to the depth of 649 m during the investigation of Paratunka hydrothermal deposits of Kamchatka.

The casing was made by a steel pipe with 168 mm diameter from the surface to the depth of 195 m. The water maximum temperature of 56,8 °C was registered at the depth of 620 m. At the beginning, the well flow of 0.4 $\mathrm{L\,s^{-1}}$ was observed, whereas the temperature was 31 °C. At present there is no well flow. The borehole is located in the zone of sublatitudinal left-lateral strike-slip fault at the intersection with the North-Western transform zone. There is also a zone of NNE 20° central planetary fault, i.e. the zone of fault junction (NE 50° "opening" zone, subparallel to the Kuril-Kamchatka trench subduction zone). Analysis of the rock bulk allows us to suppose that the main radiation sources may be located at the depth of 120–650 m. The characteristic length of acoustic radiation propagation in the range of 10–100 Hz in rocks at this depth may be within 100–10 000 m.

Registration of acoustic field was carried out by a hydrophone with a pre-amplifier sunk into borehole water at the depth of about 1 m. Magnetic vertical component was

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registered. Weak signals of lithospheric origin were distinguished from the noise powerful background of atmospheric-magnetospheric origin by a compensation method (Uvarov, 2012, 2010). Two magnetic antennas fitted with antenna amplifiers were used for that. One of them was applied for the registration of the mixture of lithosphere electromagnetic signal and noise of atmospheric-magnetospheric and industrial origin.

The other one was used to register only the noise signal. Antennas are two identical coils with the induction of about 4 Hn and 40 sm inner diameter. A part of the casing pipe sticking out of the ground was used in the antenna, registering the mixture, as a magnetic core. The steel casing pipe is a magnetic circuit of the interior electromagnetic field magnetic component.

Averaged spectra of the initial electromagnetic signals (the mixture and noise) are shown in Fig. 1. It is clear from the figure that simple application of the difference of signals does not suppress noise completely, though, it significantly eliminates atmospherics.

Much better results in noise suppression are obtained by the subtraction of average weighted value of noise from the mixture. Weight coefficient is found by minimization of root-mean-square deviation of the mixture from noise value. In the result, significant suppression of noise is achieved. The mode structure of the borehole natural acoustic vibrations, clear spectral bands in the region lower than 50 Hz, is clearly seen in Fig. 1, where it is marked by an ellipse, and in the upper part of Fig. 2.

The basic analysis of signals was carried out applying the Fourier discrete transform with Haar window with 44 100 point length, the number of signal samples per 1 s.

The obtained spectrum has the frequency scale in hertz.

4 Data analysis

Figure 2 shows an example of synchronous fragments of dynamic spectrum variations of electromagnetic and acoustic channels in the rage from 0 to 100 Hz. Application of the differential method for electromagnetic radiation analysis significantly suppressed

the noise of thunderstorm and industrial origin. Thunderstorm radiation (atmospehrics) effect is remained in the form of weak vertical lines. There are weak even lines parallel to the time axis at the frequencies of 50 and 100 Hz in the region of industrial radiation bands. The great part of the objects in this figure is the manifestation of lithospheric processes.

Hereafer, the term "lithospheric" is introduced to denote wave effects of lithospheric processes. The most vividly lithospherics are seen on dynamic spectra in the form of diffuse spots, one or several spectral harmonics evenly or randomly changing with line time (Fig. 2). In the records of initial data, trains with the duration from 1 to 4 min and amplitude, exceeding the background value by 5–20 times, correspond to strong lithospherics. Correspondence between the acoustic and electromagnetic lithospherics is clear.

Two classes were distinguished; they differ by the character of lithospheric spectra, line and diffusive ones. In their turn, lithospherics with a single spectral harmonic (hereafter "monosigmoid") (Fig. 3–1), with several spectral harmonics ("polysigmoid") (Fig. 3–2), and with monochromic randomly changing spectrum ("trill") (Fig. 3–3) may be distinguished among the lithospherics with line spectrum.

Further, the description of lithospheric spectra is presented.

One of the most interesting types of lithosperics is a "monosigmoid" (Fig. 3–1). Their duration is 3–4 min. The frequency range is 70 ÷ 100 Hz. This type of lithospherics has pseudo-monochromatic spectrum. The only spectral line of a lithospheric begins at the frequency of about 100 Hz. Its frequency decreases with time. The lithospheric reaches its maximum intensity a minute after the beginning at about 80 Hz and ends in 2–3 min after the maximum at the frequency of about 70 Hz. The maximum value of the intensity may exceed the background value by 15–20 times. Lithospheric frequency change with time resembles Doppler effect from a source passing by. For the sound velocity of 3000 $\mathrm{m\,s^{-1}}$ in a rock medium, it corresponds to the motion velocity of about 300 $\mathrm{m\,s^{-1}}$. In natural conditions of rock medium, such velocity of a body is impossible. However, such velocities are quite possible for processes, for example, propagation of a fracture front edge. Asymmetry of a "monosigmoid" form relatively the signal maximum value indicates the fact that the duration of process development is two times less than the time of complete attenuation.

"Polysigmoids" are shown in Fig. 3–2. A polysigmoid is a lithospheric with line spectrum. Its duration is 3–4 min. Its spectrum is a set of synchronous harmonic-monosigmoids which frequencies are shifted by 29 Hz. Just like for the monosigmoids, frequency changes to the range of low ones with time. The final change of harmonic frequency is proportional to the spectral component average frequency.

"Trill" lithospheric is illustrated in Fig. 3–3. It has low intensity, line spectrum and is characterized by randomly changing frequency. Its duration is 1–2 min. The frequency range is 50–80 Hz. This type of anomalies does not almost manifest in wave forms.

Figure 3–4 shows a spectrochronogram of a "roar" lithosperic.

This lithospheric is characterized by diffusive spectrum and its wave form amplitude exceeds the background value by 6–10 times. Mainly, it appears at the frequencies in the range of 20–40 HZ, and has the duration of 1–2 min. A series of such anomalies is frequently followed one after the other (Fig. 2).

Anomalies with line spectrum may overlap diffusive anomalies (Fig. 2).

Stability of phase relations of acoustic and electromagnetic vibrations is observed for all types of anomalies. It allows us to state that acoustic and electromagnetic radiations have the same source. On the parametric graph of acoustic and electromagnetic signal wave forms, phase relations (Lissajous figure) of all types of lithospherics form a well-defined ellipsoid, in which electromagnetic signal lags behind the acoustic one.

It may be caused by two alternatives:

1. Acoustic and electromagnetic signals are the effects of the same process.

   During the generation, these signals are synchronous but may differ in phase.

   The difference of the propagation medium effect due to different nature of the signals should lead to the stochastic dependence of the difference of these signal phases on time. In addition, various sources are at different random distances

   from the receiver. It should show up in the different delay times of the acoustic signal relative to the electromagnetic.

   However, it is not observed. Thus, this hypothesis should be rejected.

2. In the case, when one of the signals is generated in the sensor under the effect of the other signal, one should expect a stable phase difference between the signals. The resultant signal is the result of time convolution of transducer transfer function and of initial signal. When the transducer "memory" period is small enough, the insertion phase change is a constant for this mode.

Consequently, the course of electromagnetic signal generation is the acoustic signal.

The most possible reason for this is the magnetoelstic transform of acoustic radiation in the casing pipe (Villary effect).

5 Discussion

The Earth's crust is an inhomogeneous media according to mechanical and physical properties, which is in the state of critically unstable balance between stresses and deformations (elastic and inelastic). Each type of deformation corresponds to a threshold, when it is exceeded the elastic deformation changes to the inelastic one (fracture). Depending on the type of prevailing stresses, a deformation has volumetric, shear or mixed character. Any fracture in the crust takes place in the finite size region. Its creations is an avalanche process accompanied by acoustic and electromagnetic radiation.

Crust inhomogeneity becomes apparent from the fact that every elementary volume of its substance is characterized by a set of fracture process parameters.

Such parameters are the following:

– stress threshold for inelastic initial deformation (shear and volumetric),

– friction coefficient for inelastic deformation, the analog of which in hydrodynamics is viscosity (shear and volumetric),

– stress transfer rate (longitudinal and transverse sound velocity).

It is known that the process of volume element deformation may be presented as a sum of shear and volumetric deformations.

Volumetric deformation occurs under the effect of isotropic (hydrostatic) stress.

The hydrodynamic analog to measure the medium deformation resistance is the second or volume viscosity. During the volumetric deformation, the fracture area is an unloaded structure without well-defined boundaries with multiply connected space topology. Volumetric deformation is accompanied by the change of substance average density. In a sedimentary cover, such a change of a structure causes porosity decrease. In deep layers it may cause phase transfer. For example, it may lead to the transformation of quartz to its more dense modification, coesite and stishovite. The absence of the defined direction and the corresponding resonance structure becomes apparent in the diffusive character of deformation emission spectrum. The volumetric deformation corresponds to a potential component of stress-deformation field.

Shear deformation occurs under the effect of a pair of tangential oppositely directed stresses and is the manifestation of vertex component of stress-deformation field.

The measure of resistance of such a deformation in hydrodynamics is the dynamic viscosity. In contrast to the volumetric deformation, the shear one is characterized by a clear space anisotropy defined mainly by stress field structure. Usually it has a well-defined slip plane coinciding with the plane of the largest tangential stresses. The region of shear deformation has simply connected space topology. From the radio-physical point of view, it is a resonance structure, the eigen frequencies of which are determined by rock properties, dimension and configuration of a fracture region which may be excited during tectonic stress relaxation.

Friction, appearing during mutual displacement of two rock blocks, refers to so called “dry” friction, in which static friction is less than dynamic friction. This property causes

self-induced vibrations. The classical example is the vibration of a violin string under the effect of evenly moving bow (Andronov and Zhurevlev, 2010).

Generation self-induced vibrations to appear requires the following:

– energy source and sink at different energy levels, during the transition between which dissipation work is performed,

– vibrational structure,

– positive feedback.

All these components present during shear rock deformation under the tectonic stress:

– the source is tectonic stress force the most vividly manifesting itself in seismically active regions,

– the result of dissipation is transformed rock,

– shear fracture region is a vibrational structure,

– positive feedback is the result of control of the break-away torque by acoustic disturbance.

The scenario for stress dissipation consists of a series of randomly occurring avalanche processes. It its turn, each avalanche process is a series of discrete acts of relaxation.

Just like in the case with a violin string, rock local stresses have a constant, determined in this case by the force of tectonic origin, and a variable, associated with resonance vibrations of fracture cavity, density-stress waves.

The starting of the initial relaxation act occurs when the damage threshold is exceeded by constant stress.

The initial relaxation act starts when the sum of constant and fluctuating stress exceed the damage threshold. It provides the starting of relaxation acts at the moments of achievement of the damage threshold value by the summary stress, and the beginning of acts with the frequencies of eigen vibrations of the fracture area, generation of relaxation self-induced vibrations. During the starting, accelerated motion of dislocation edges under the effect of accumulated stress in rock and decrease of dry friction coefficient during the increase of deformation rate are observed.

Simultaneously with that, redistribution of stress from the periphery to the fracture area takes place. At the beginning of the process, the density of the accumulated elastic energy in the vicinity of the fracture zone is maximal. Development of the process is accompanied by the transformation of elastic energy to the work on rock fracture and decrease of the accumulated stress potential energy.

It stops when the sum of brake, inertia and stress forces is equal to zero.

During stress dissipation with the increase of the dimension of deformation cavity, the eigen frequencies of fracture cavity and the frequency of repetition of relaxation acts decrease. It completely agrees with the observation results illustrated in Figs. 3–1 and 3–2.

To estimate the parameters of fracture cavity, a simple model, L length string, is used.

Its vibration frequency is determined by the expression $f = \frac{cN}{2\mathrm{L}}$, where c is the sound velocity in a medium, N is the harmonic number. Hence, we obtain that the crack length is determined by the relation $L = \frac{c}{2f}$. Assuming the sound velocity in rock to be $c \approx 3000\,\mathrm{m\,s^{-1}}$, we obtain that during the relaxation process, when the first harmonic frequency changes from 100 to 70 Hz, cavity dimensions increase from 15 to 22 m.

Of course, this simplest estimation is not accurate since it does not take into account a number of important moments, such as fracture cavity form and dimensions, effect of the transformed rock filling this cavity, surface wave features and so on.

It should be noted, that earthquakes accompanied by fracture opening contain all the components of the phenomenon described above.

6 Conclusions

The paper briefly describes borehole radiophysical properties consideration of which improves the efficiency of investigations.

The results of registration of acoustic-electromagnetic radiation, carried out in a borehole in a seismically active region, showed the presence of anomalously high signals exceeding the background value by 10–20 times.

The observed anomalies of both acoustic and electromagnetic radiations have lithospheric origin and are associated with tectonic stress relaxation.

Four main types of acoustic-electromagnetic radiation anomalies were distinguished. They correspond to shear and bulk relaxations of tectonic stresses.

Stability of phase relations of acoustic and electromagnetic signals in anomalies was detected, that indicates their coherence. The acoustic signal advance of electromagnetic signal shows the primary nature of the acoustic signal.

It was concluded that the cause for the mutual coherence of acoustic and electromagnetic signals is the magnetoelastic effect of the casing pipe.

The mechanism for generation of rock self-induced vibrations during tectonic stress relaxation, causing the appearance of acoustic-electromagnetic emission, was suggested.

“Sigmoid” anomalies may be compared with excitation of eigen vibrations of a fracture cavity during brittle shear relaxation of rock tectonic stress.

The frequency change of “sigmoid” anomalous signal is explained as the result of growth of rock fracture cavity and decrease of tectonic stress relaxation.

A borehole cased in a steel pipe together with an induction coil system and a hydrophone is the effective sounding sensor for the acoustic field of interior deep layers. It may be applied to investigate and to monitor the geodynamic activity, in particular, in earthquake forecasts and in monitoring of hydrocarbon deposits during their production.

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References

Andronov, V. V. and Zhuravlev, V. F.: Sukhoe trenie v zadachakh mekhaniki (Dry friction in mechanics problems), Moscow-Izhevsk, NITs "Regulyarnaya i khaoticheskaya dinamika", 2010.

Athy, L. F.: Density, porosity and compactation of sedimentary rocks, A. A. P. G. Bull., 14, 1–24, 1930.

Engelgard, V.: Porovoe prostranstvo osadochnykh porod (Porous space of sedimentaries), Moscow, (Translated from German), 1964.

Gavrilov, V. A. and Morozova Yu. V.: Osnovnye svoistva geoakusticheskoi emissii po rezul'tatam nablyudenii v glubokoi skvazhine G-1 (Main properties of geoacoustic emission according to the observation results in a deep borehole G-1), Sovremennyi vulkanizm i svyazannye s nim protsessy (Modern volcanism and processes associated with it), 44–47, 2003.

Gavrilov, V. A., Panteleev, I. A., Ryabinin, G. V., and Morozova, Yu. V.: Modulating impact of electromagnetic radiation on geoacoustic emission of rocks, russian journal of earth sciences, 13, ES1002, doi:10.2205/2013ES000527, 2013.

Hadjicontis, V., C. Mavromatou, C., Antsygina, T. N., and Chishko, K. A.: Mechanism of electromagnetic emission in plastically deformed ionic crystals, Phys. Rev. B, 76, 024106 doi:10.1103/PhysRevB.76.024106, 2007.

Jiles, D. C.: Theory of the magnetomechanical effect, J. Phys. D. Appl. Phys., 28, 1537–1546, 1995.

King, R. and Schmidt, G.: Antenny v material'nykh sredakh (Antennas in material mediums), V.1, 2, Mir, Moscow, 1984.

Mori, Y., Obata, Y., and Sikula, J.: Acoustic and electromagnetic emission from crack created in rock sample under deformation, J. Acousic Emision, 27, 157–166, 2009.

Sikula, J., Mori, Y., Lokajicek, T., Koktavy, P., Majzner, J., and Sedlak, P.: Crack creation kinetics characterization by electromagnetic and acoustic emission, in: Proc. 28th European Conf. AE Testing, Kracov, Poland, September, 118–123, 2008.

Skvazhinnaya i shakhtnaya geofizika: Spravochnik geofizika (Borehole and shaft Geophysics), V.2, Nedra, Moscow, 1988.

Sobolev, G. A. and Ponomarev, A. V.: Fizika zemletryasenii i predvestniki (Physics of earthquakes and precursors), Nauka, Moscow, 270 pp., 2003.

Uvarov, V. N.: Elektromagnitnoe proyavlenie litosfery v SNCh-ONCh diapazone (Electromagnetic effect of the lithosphere in ELF-VLF range), Geofizicheskii zhurnal, Geophys. J.+, 34, 134–146, 2012.

Uvarov, V. N., Druzhin, G. I., and Sannikov, D. V.: Electromagnetic Radiation of Lithospheric origin, Method for Detection and First Results, Instruments and Axperimental Techniques, Pleiades Publishing Ltd., 53, 895–901, 2010.

Uvarov V. N., Druzhin, G. I., Sannikov, D. V., Pukhov, V. M. et. al.: Sposob passivnoi lokatsii blizko raspolozhennykh istochnikov elektromagnitnogo izlucheniya na fone moshchnykh izluchenii udalennykh istochnikov (The way of passive location of closely located sources of electromagnetic radiation at the background of powerful radiation from remote sources), Patent RF, no. 2473101, 2011.

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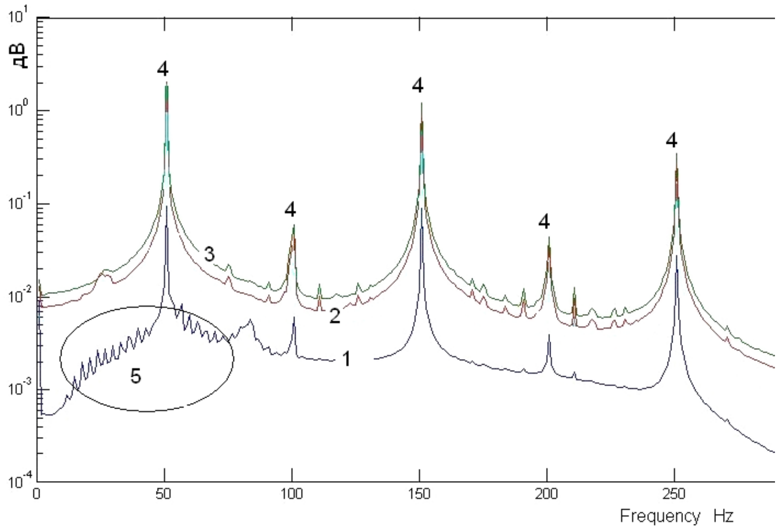

Figure 1. Averaged spectra of initial signals. 1 – acoustic signal spectrum; 2 – noise signal spectrum; 3 – mixture signal spectrum; 4 – industrial noise frequencies; 5 – borehole acoustic resonances.

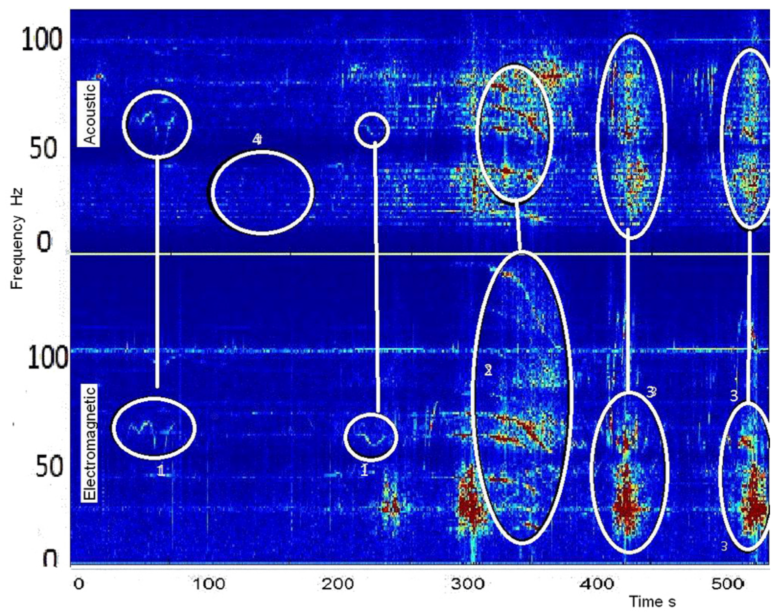

Figure 2. An example of spectrochronogram for lithosphere acoustic (top) and electromagnetic (bottom) signal variations. They are connected by vertical lines on the figure. Indications of the lithospherics correspond to their types.

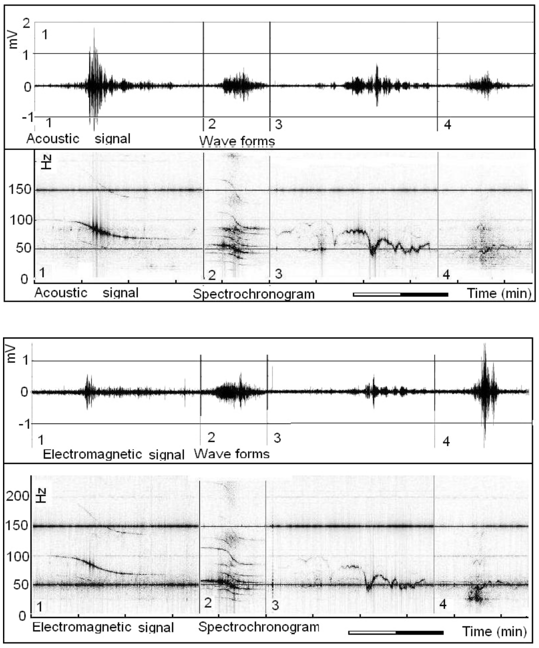

Figure 3. Types of lithospheric signal. 1 – "monosigmoid", 2 – "polysigmoid", 3 – "trill", 4 – "roar".

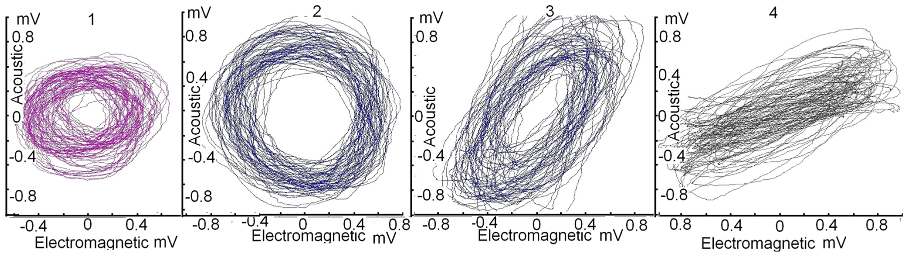

Figure 4. Phase relations of anomalies of different acoustic and electromagnetic signals (Lissajous figures). In horizontal direction is the electromagnetic signal amplitude. In vertical direction is the acoustic signal amplitude. 1 – "monosigmoid", 2 – "polysigmoid", 3 – "trill", 4 – "roar".