Acoustic-electromagnetic effects of tectonic movements of the crust. Borehole survey

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Abstract

Acoustic and electromagnetic investigations in VLF range in a borehole were carried out in a seismically active region. An inoperative cased well with the depth of 649 m was used for the extraction of thermal water. A hydrophone was installed 1 m below the water level. Two magnetic antennas for compensation technique to eliminate the influence from distant thunderstorms, technical and household interference were used. Four main types of anomalies of acoustic-electromagnetic radiation were distinguished. 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. "Sigmoid" type anomalies may correlate with excitation of eigen vibrations in a fracture cavity during brittle shear relaxation of rock tectonic stress, 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 the interior deep layers and the distribution function of anomaly types can indicate the phase of earthquake preparation.

Introduction

1. Extensive knowledge on electromagnetic effects of seismic events has been collected by the present [see Hayakawa 1994; Hayakawa 1999; Hayakawa 2002; Molchanov 2008; Hayakawa 2009]. In the basis of interpretation of these phenomena is the idea on mechanic-electromagnetic transformation of energy of crust tectonic stress during its deformation. These ideas were confirmed by numerous laboratory researches on rock deformations [for example, Ogawa 1985; Freund 2002; Fried 2003].
A number of models and mechanisms of charge separation was suggested: dislocation flows in rockforming mineral crystals, activation of mobile charge carriers, piezoelectric, piezomagnetic, electrokinetic, triboelectric, inductive, seismo-magnetic and other effects [Molchanov 2001; Freund 2002; Guglielmi 1996; Hadjicontis 2011].
Though the definite mechanisms of mechano-electromagnetic transformation during seismic events are still unknown, there is no doubt that acoustic-electromagnetic emission of the lithosphere is the reflection of its seismo-tectonic state. These circumstances allow us to hope for the significant increase of the role of remote electromagnetic diagnostics of the crust state which is necessary for geophysical survey and monitoring of its geodynamic state.

2. 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) [Sornette 2006]. 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 and 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. 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 an evenly moving bow [Tworzydlo, 1997; Alexander Fidlin 2005; Johnson 2008; Vladimir Sergienko 2014].

Generation of self-induced vibrations 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 characteristic frequency of the emerging oscillations is determined by the parameters of the resonant structure, in this case the length of the crack. To estimate the parameters of fracture cavity, a simplest model, L length string, is used. Its vibration frequency is determined by the expression $f = \frac{cN}{2L}$, 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 $L = \frac{c}{2f}$. It should be noted, that earthquakes accompanied by fracture opening contain all the components of the phenomenon described above. 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.

3. As long as the main information on the crust deformation processes is carried by low-frequency radiation in VLF-ELF range, we should note some peculiarities of the geophysical survey of electromagnetic radiation in this range from the Earth surface.

A. Due to the unpredictability of the place and time of seismic events, the great majority of electromagnetic effects of this phenomenon were carried out not in the intermediate vicinity of the radiation source, but at the places convenient for the measurements. These are usually geophysical observatories or observation sites. In this case, direct investigations of the radiation associated with stress relaxations are impossible. Available is the radiation emitted from the lithosphere into the atmosphere and propagated through the atmosphere to a detector. The radiation changes during the process of propagation across the border, averaging over the emission surface and propagation over the unknown way. All these cause the ambiguity of the results on the properties and parameters of lithospheric seismo-electromagnetic radiation sources.
B. The character of propagation of electromagnetic radiation is determined by the propagation conditions, in particular, the conducting Earth surface and ionosphere form a cavity having waveguide conditions for the horizontally propagating radiation with the wavelength not exceeding the doubled ionosphere height. The same conditions form a flat open resonator for vertically propagating waves of the same length. The horizontal radius of radiation coherence in this resonator is of wavelength order. Electromagnetic radiation of the lithosphere during the transition into the atmosphere is in the waveguide where it propagates at large distances and in regional resonator. The thunderstorm radiation from lightning near the equator acting as noise is the prevailing radiation in the horizontal waveguide. This radiation significantly exceeds the lithospheric radiation in strength making it more difficult to investigate the radiation of lithospheric origin applying the horizontally propagating waves. In the regional resonator, the conditions for investigation of lithospheric radiation are more favorable since the radiation of lightning origin is strongly weakened.
C. There are several ways to determine the signal under investigation from the noise background.
    a. Physical limits (shielding) of the space occupied by a radiation source and a detector. It is realized during the measurements in lithospheric cavities, for example, in mines and wells.
    b. Application of a sensor with controllable sensitivity area size.
    c. Detection of a useful signal by the following parameters: frequency, amplitude or polarization.

We should note that signals of lithospheric origin do not differ from other signals in frequency, amplitude and polarization. Thus, the detection methods applied in this study are based on shielding and usage of a sensor with controllable sensitivity area size.
Development of such methods [Uvarov et al, 2010; Uvarov, 2012] allowed us to begin purposeful and correct survey of electromagnetic radiation of lithospheric origin.

4. 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 the 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 is determined by exponential Beer-Lambert-Bouguer law

$$\frac{J(r)}{J_0} = \exp(-\kappa r) \qquad (1)$$

Here, the transmission coefficient 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] which states exponential dependence of porosity with depth

$$p \sim \exp(-\alpha H) \qquad (2)$$

If we suggest that transmission coefficient behaves the same way with depth, then absorption decreases much faster with depth, than exponentially:

$$\frac{J(r)}{J_0} \sim \exp(-r * F(\exp(-\alpha H))) \qquad (3)$$

In other words, 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; Gavrilov et al, 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.

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.

1. Acoustic properties of a borehole [Frederick, 1991; Peterson 1974]

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

$$f = \frac{c(2n-1)}{2h} \qquad (4)$$

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 m/s), 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 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. The most significant are Lamb waves. These waves differ from 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 hertz 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 a 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 (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.

Data Investigation

A) The experimental conditions

A field experiment was carried out at a borehole 74 on Korkin brook of Paratunka river basin (South Kamchatka) in a forest far from industrial and domestic noises. 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 l/s 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 registered. Weak signals of lithospheric origin were distinguished from the noise powerful background of atmospheric-magnetospheric origin by a compensation method [Uvarov 2010; Uvarov 2012]. 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 cm 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. The measurements were carried out for 49 hours straight. The sampling frequency is 44100 Hz. The total data for three channels is about 560*10^10 measurements.

B) **Processing**

The signal antenna has a magnetic core changing its transfer function f in comparison to the compensating antenna. To simplify the calculation, we neglect the instrumental noise. The signal at the signal antenna output I_0 is a mixture of signals of lithospheric I_l and ionospheric-lightning origin I_n, which in this case are the noises:

$$I_0 = f \otimes (I_n + I_l). \qquad (5)$$

Here $\otimes$ means the convolution operation. The signal at the compensating antenna output is I_k.

Pass to the frequency plane ω and consider the spectral power of signal mixture and the compensating: $\hat{I}_0(\omega),\ \hat{I}_k(\omega)$. Since the power of signals of lithospheric origin is significantly less than that of noise signals, we shall consider that the average signals from compensating and signal antennas are equal with the accuracy up to an unknown transition function determined by the core effect and the difference of receiving unit gain coefficients

$$\left(\overline{\hat{I}_0(\omega)}\right) \approx a(\omega) \cdot \left(\overline{\hat{I}_k(\omega)}\right) \qquad (6)$$

To find the unknown function $a(\omega)$ we apply the least square technique. Choose the objective function in the form

$$F(\omega) = \overline{\left(\hat{I}_0(\omega) - a_1(\omega)\cdot \hat{I}_k(\omega)\right)^2} \quad (7)$$

The vertical bar above the expression is the notation of averaging. Solving the problem

$$\frac{\partial F(\omega)}{\partial a_1(\omega)} = 0, \quad (8)$$

we obtain an approximate value of spectral transition function

$$a_1(\omega) = \frac{\overline{\left(\hat{I}_0(\omega)\cdot \hat{I}_k(\omega)\right)^2}}{\overline{\left(\hat{I}_k(\omega)\right)^2}} \quad (9)$$

Detection of lithospheric signal power spectrum is now carried out by subtraction of compensating signal power spectrum multiplied by the determined transition function from mixture power spectrum

$$\hat{I}_l = \left(\hat{I}_0(\omega) - a_1(\omega)\cdot \hat{I}_k(\omega)\right). \quad (10)$$

We should note that the obtained lithospheric power spectrum is inconvenient for visual presentation since it has amplitude drops of several orders. That is why for the final analysis of the results, power spectrum logarithm normalized by its power spectrum average value

$$I_r = \log\left(\frac{\hat{I}_l}{\overline{\hat{I}_l}}\right) \quad (11)$$

was used. It is shown in the following figures. Registration of signals by two antennas (main and compensating) with the following processing by the described method allow us not only to detect signals from closely located sources but to eliminate the effect of constant signals of anthropogenic origin as well.

C) Analysis

Initial average spectra

During the analysis of registration results, similarity of acoustic and electromagnetic component average spectra draws the attention (Fig.1). There are many lines of acoustic resonator in the acoustic component spectrum, the region is marked by ellipse 5. The presence of radiation of unknown origin is clearly seen at the frequencies of 25-27 Hz. It is well defined both in acoustic and magnetic components.

The peaks marked by 4 correspond to industrial radiation of 50 Hz and its harmonics. The upper curve is the average radiation spectrum of a compensating antenna on which an antenna amplifier with somewhat larger gain coefficient was used. The middle curve is the spectrum of a signal from the antenna, the core of which is a casing pipe. Ellipse 6 in Fig. 1 indicates the spectrum region with increased radiation in the range of 25-27 Hz. It is clearly defined both in acoustic and magnetic components. Looking ahead, we should note that this part of the spectrum is associated with diffuse radiation, the so called “roar”. Appearance of radiation in this frequency range at the averaged spectrum indicates quite frequent occurrence of radiation bursts at this frequency.

It is clear from the figure that simple application of the difference of signals does not suppress noise completely, though, it significantly eliminates atmospherics.

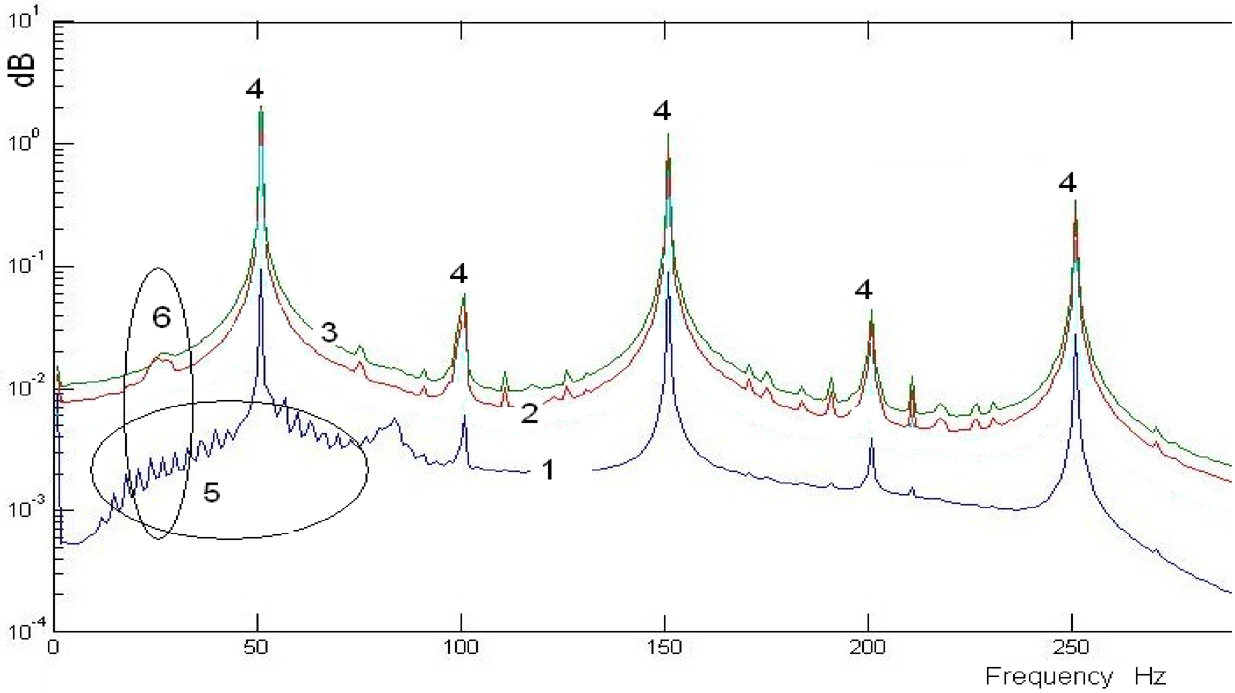

Figure. 1. Averaged spectra of initial signals.

Dynamic spectra of the lithospheric signals

Much better results in noise suppression are obtained by the subtraction of average weighted value of noise from the mixture (Fig 2, 3). 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.

Fig.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 effect of lithospheric processes, as long as the measurements were carried out in unfrequented spot far from the sources of industrial and domestic noises, power lines, traffic and other sources of noise.

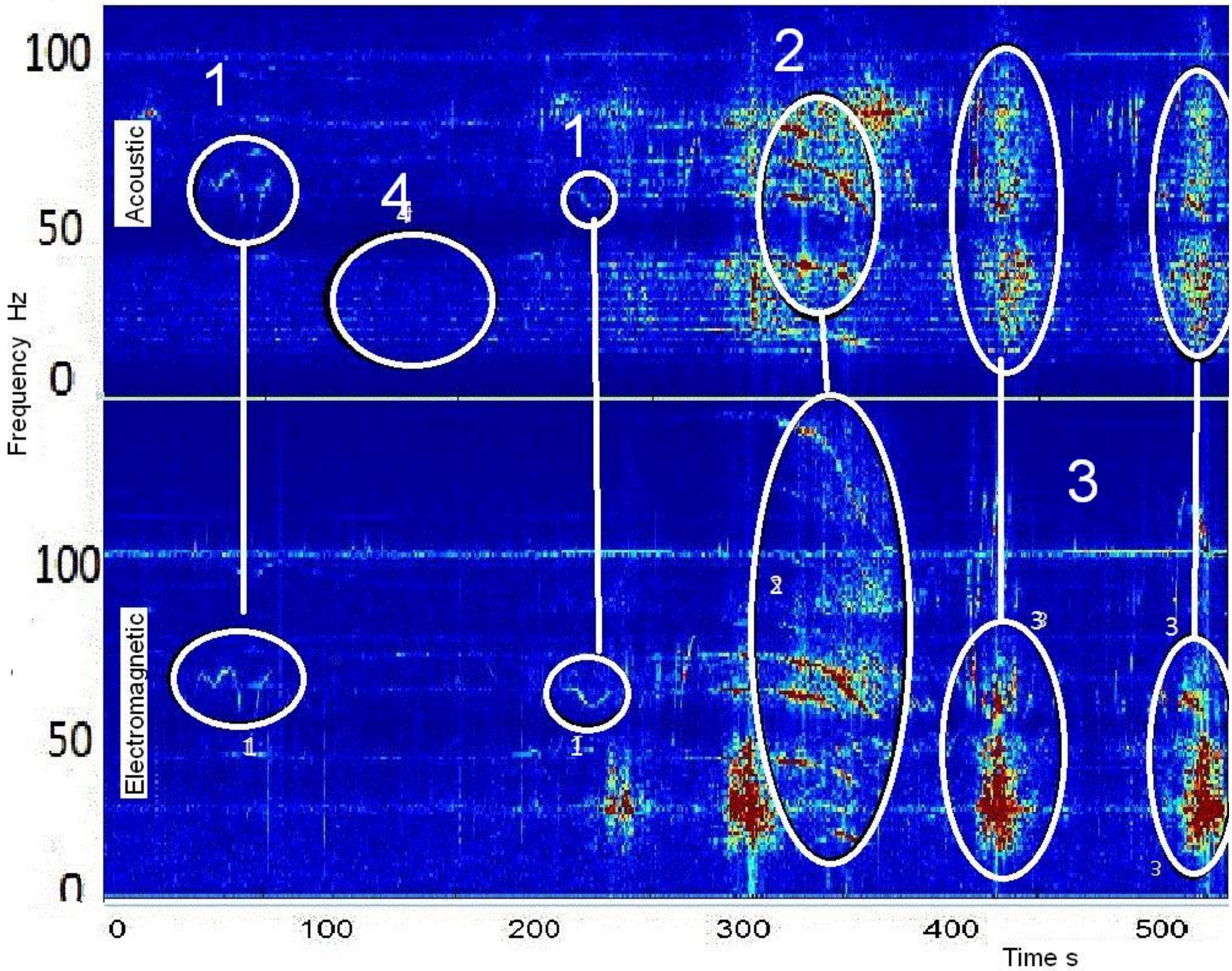

Figure 2. An example of spectrochronogram for lithosphere acoustic (top) and electromagnetic (bottom) signal variations. They are connected by vertical lines on the figure. Indications of the lithospherics correspond to their types.

Hereafter, 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 (in figure 2 are marked with circles with the number 3), one or several spectral harmonics evenly (in figure 2 are marked with circles with the number 2) or randomly (in figure 2 are marked with ellipses with the number 1) changing with line time (Fig.2). In the records of initial data, trains with the duration from 1 to 4 minutes and amplitude, exceeding the background value by 5-20 times, correspond to strong lithospherics. Correspondence between the acoustic and electromagnetic lithospherics is clear.

Classification of anomalies

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 minutes. The frequency range is 70 ч 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 minutes 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 m/s in a rock medium, it corresponds to the motion velocity of about 300 m/s. 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.

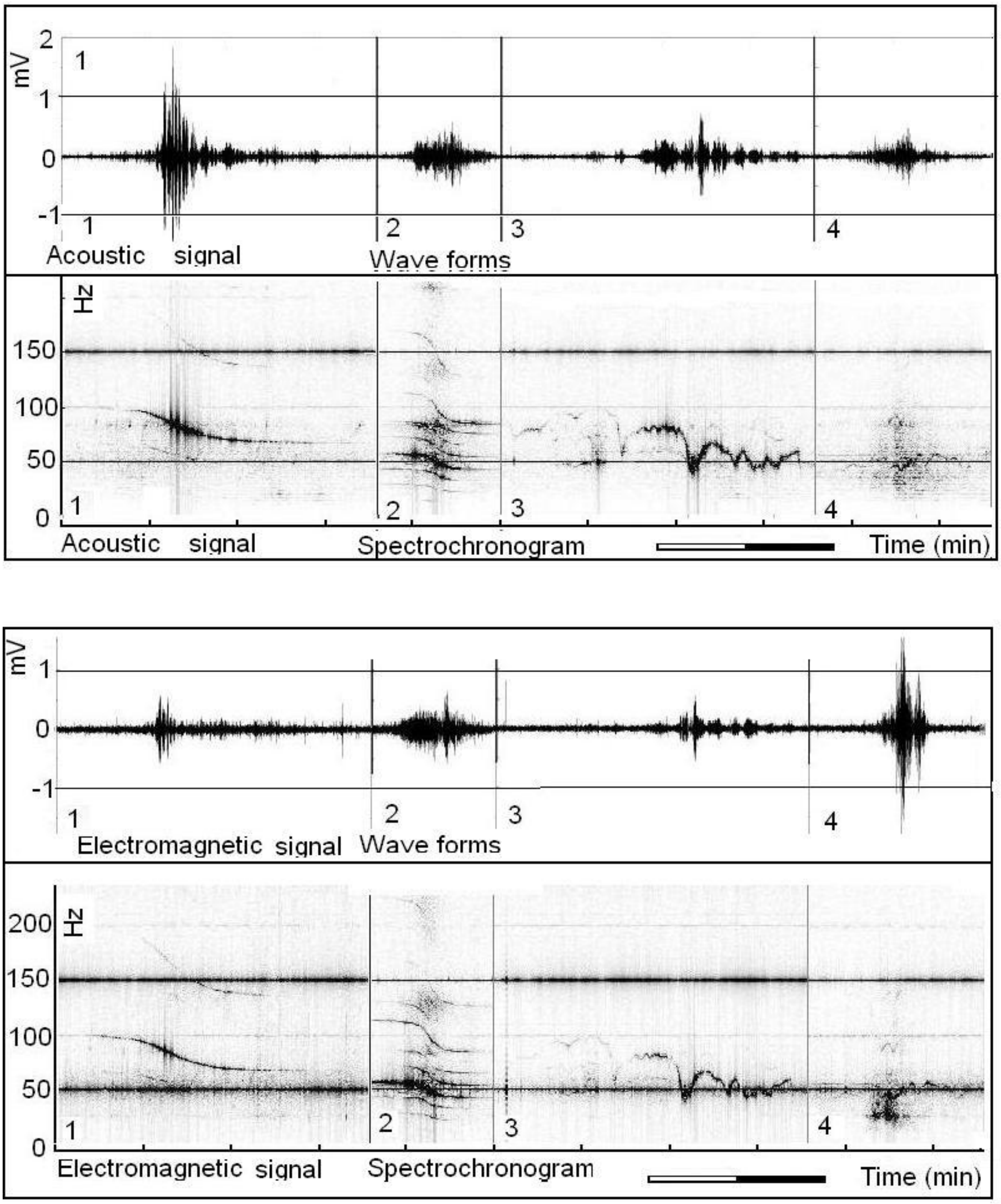

Figure 3. Types of lithospheric signal.
1 – "monosigmoid", 2 – "polysigmoid", 3 – "trill", 4 – "roar".

More plausible interpretation of this phenomenon is self-excited oscillations of the cavity of the cracks in the process of stick-slip motion in the tension relaxation of the rocks. To estimate the parameters of fracture cavity, a simple model, L length string, is used. Its vibration frequency is determined by the expression $f = \frac{cN}{2L}$, 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 $c \approx 3000 м/с$, we obtain that during the relaxation process, when the first harmonic frequency changes from 100 to 70 Hz, cavity dimensions increase from 15 m to 22 m. Again, that is the simplest assessment does not take into account a number of important points.

"Polysigmoids" are shown in Fig. 3-2. A polysigmoid is a lithospheric with line spectrum. Its duration is 3-4 minutes. 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 minutes. The frequency range is 50-80 Hz. This type of anomalies does not almost manifest in wave forms.

Fig. 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 minutes. A series of such anomalies is frequently followed one after the other (Fig. 2). Anomalies with line spectrum may overlap diffusive anomalies (Fig.2).

Phase relation analysis

Phase relations were investigated to determine the detailed relation between the acoustic and electromagnetic components. 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 (Fig.4). Stability of phase relations of acoustic and electromagnetic vibrations is observed for all types of anomalies.

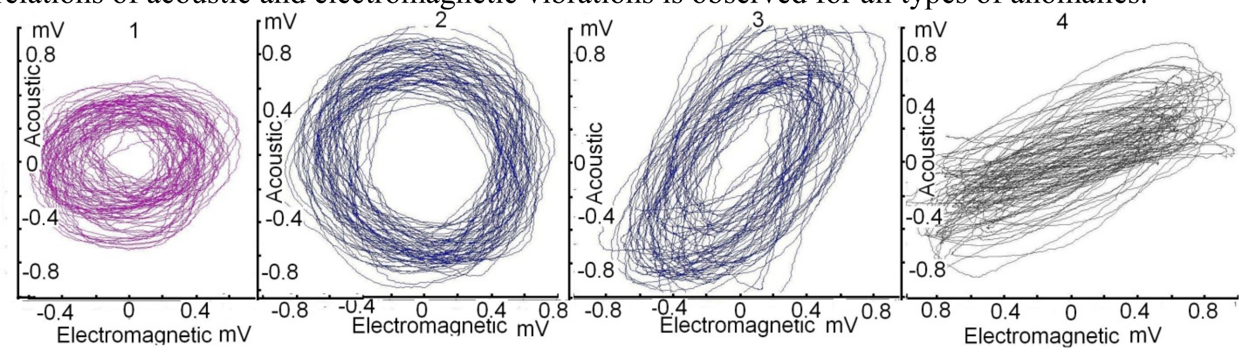

Figure 4. Phase relations of anomalies of different acoustic and electromagnetic signals (Lissajous figures). In horizontal direction is the electromagnetic signal amplitude.
In vertical direction is the acoustic signal amplitude.
1 – "monosigmoid", 2 – "polysigmoid", 3 – "trill", 4 – "roar".

Figures 2 and 3 demonstrated a good agreement of spectra of acoustic and magnetic component. It allows us to state that acoustic and electromagnetic radiations have the same source.

Discussion

A) Study of acoustic-electromagnetic radiation with use of drilling wells in a seismically active region have shown the existence of coherent bursts of acoustic - electromagnetic radiation lasting 1 – 4 minutes, the amplitude of which exceeds the background by 5 - 20 times . Especially the measures taken for the registration and processing of signals suggest that these signals are of lithosphere origin.

The synchronization of acoustic and electromagnetic perturbations in seismic processes are known well enough. Synchronism of these phenomena indicates the commonality of causes for the formation of sources of acoustic and electromagnetic disturbances occurring during earthquakes [Hayakawa 1994; Hayakawa 1999; Hayakawa 2002; Molchanov 2008; Hayakawa 2009]. Nevertheless, the synchronism is not the indication of cause singleness. Indication of the singleness may only be the coherence response which is observed in our investigations.

This singleness was shown in the laboratory experiments during rock deformations [Ogawa 1985; Hadjicontis 2011]. In the figure (Fig. 5) taken from the paper [Ogawa 1985] coherence of acoustic and electromagnetic oscillations occurring during an impact on a sample containing rock quartz is clearly seen.

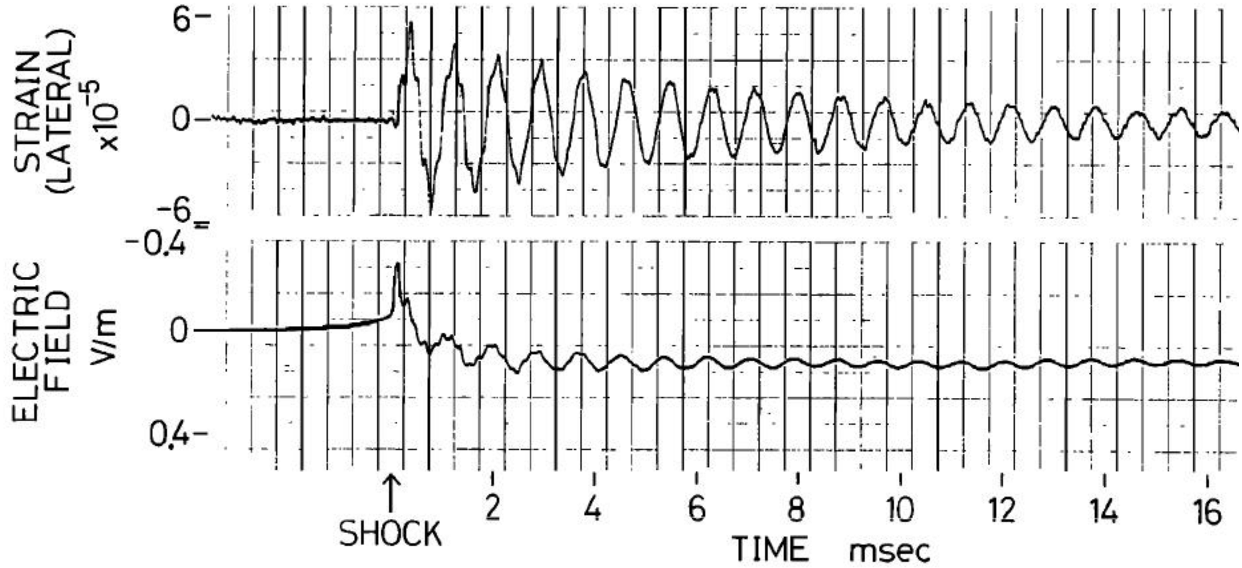

Figure 5. Simultaneous record of the electric field and strain in granite plate [Ogawa 1985]

The coherence of acoustic and electromagnetic signals (Fig. 4) is the effect of the same process. It may be caused by two alternatives:

1. Magnetoelastic waves are observed which propagate with the velocity close to the sound velocity and having acoustic and magnetic components. Such waves are characteristic for a magnetized ferromagnetic environment. The Earth crust is such an environment since it contains 5,1 % of iron magnetized by the constant magnetic field of the Earth.
2. A steel casing pipe is a good converter of acoustic radiation into magnetoelastic waves, since steel is a good ferromagnetic which is magnetized by the Earth constant field. In this case, the acoustic oscillations incoming from the rock of annular space will be transformed into magnetic permeability oscillations and registered as magnetic waves.

Both in the first and in the second cases, constant phase difference between the acoustic and the magnetic components should be observed just like in our investigations.

B) 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. It can be assumed that they correspond to the shear and bulk relaxation of tectonic stresses.

We can assume that rock motions during tectonic stress relaxations of shear type are self-induced vibrations of dry friction [Tworzydlo 1997]. "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.

C) Fig. 2 shows that the frequency of occurrence of anomalous signals of different types (probability distribution function of anomalies of different type) is different. It is clear that the resulting averaged spectrum will be determined by this distribution function. That means that the fractal dimension of the resulting signal which is determined by the resulting spectrum pattern will also be determined by this distribution function. Nevertheless, as it was shown in [Hayakawa 2011], the fractal dimension of lithospheric signals is associated with earthquake preparation phase. Thus, the distribution function of anomalies is also determined by the earthquake preparation phase.

Conclusions

A) A borehole cased in a steel pipe together with an induction coil system and a hydrophone is the effective sounding sensor for the acoustic end electromagnetic field of the 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.

B) This shows the existence of several types of acousto-electromagnetic manifestations that may be associated with different types of relaxation processes of tectonic stresses in the crust. Clarifying the nature of relaxation movements corresponding to different types of spectra is one of the most important unsolved issues that will allow us to answer the questions about the dynamics of relaxation of a stressed rock. It follows from the foresaid that its own anomaly distribution function corresponds to each earthquake preparation phase.

C) The difference of occurrence probability of acoustic – electromagnetic anomalies at different stages of earthquake preparation may be one of the possible precursors. Comparison of anomaly types with mechanical motion types will help us to understand the character of mechanic transformation processes in the crust. However, additional investigations are necessary.

D) Coherence of acoustic and magnetic oscillations has been determined that may indicate the presence of mangetoelastic oscillations in the crust or the transformation of elastic oscillations into electromagnetic in the casing pipe of the well. Additional studies are required to make more definite conclusions. Such investigations allow us to study the totality of local processes in the lithosphere at different stages of earthquake preparation.

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