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Seismoacoustic and Electromagnetic Emission of Rocks in Boreholes

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Abstract

One of the few opportunities to receive information on a stress field and deformation processes within geomedium volume is connected with the investigation of spatial-temporal distribution of seismoacoustic (SAE) and electromagnetic (EME) emission according to sections of deep boreholes. SAE and EME were observed at low and high pressure, exceeding 100 MPa. Anomalously high SAE and EME levels are often connected with blocks' boundaries, zones of crushing and increased rocks' jointing. In this case, SAE and EME are sufficiently sensitive indicators of stressed state in the Earth's crust, reflecting even so weak actions, as Earth's tides at depths of at least 5 km. Corresponding data were received with instruments, including acoustic channel in 20-2500 Hz frequency band with three orthogonal sensors and electromagnetic channel in 46-120 kHz frequency band with vertical magnetic aerial. Simultaneous use of acoustic and electromagnetic channels raised the authenticity of measured signals, caused by deformation processes and not other factors.

INTRODUCTION

When arranging investigation, we had in mind the following consideration. The Earth's crust is an open thermodynamic system with hierarchical block structure and is in a stressed state under the action of outer and inner forces: stress distribution depends not only on acting loads but also on the degree of heterogeneity, rocks jointing and saturation with fluids; the change of the rocks stressed state causes their deformation, leads to rearrangement of contact surfaces and crack system, to emergence of new defects, which is accompanied by SAE and EME. Such is the general picture. Essentially, this is the mechanism of scattered faults, peculiar nanoearthquakes, which has been functioning during a long geological time even in tectonically stable areas. But what actuates such a mechanism, why efficiency is higher in the zones of increased rock jointing? To have these problems classified there have been worked out instruments and carried out investigations with measurements of SAE and electromagnetic emission in deep boreholes. It should be noted that such measurements of a section, opened by a borehole, give information, that is next to impossible to receive in mines, adits and caves. Measurements were conducted in magmatic, metamorphic and sediment rock strata with the use of deep and superdeep boreholes (Dyakonov B.P., Troyanov A.K., etc., 1985). The dynamic model of discrete medium with the use of kinetic theory of solid bodies strength has been developed for interpretation of the data received. It creates preconditions for solving an inverse problem, i.e. for evaluation of the rocks stressed state changes according to SAE and EME parameters data.

INSTRUMENTATION AND MEASUREMENT PROCEDURES

The measurements were carried out by a complex of instruments, including: borehole probe with sensors – accelerometers to measure three components of elastic vibrations (one along the plane and two – in the plane normal to its axis), magnetic aerial outside the probe case to measure the vertical (along borehole's shaft) component of electromagnetic field, preamplifiers, a commutator and calibration device; a pressure transducer outside the probe case was used for some other measurements surface unit with an amplifier, control device and recording instruments (a tape-recorder, a recorder). The signal transmission with consecutive interrogation of sensors, as well as instruments supply is realized along a three-core cable. The cooperating frequency band of acoustic path is 20-2500 Hz, that of electromagnetic – 46-120 kHz, with consecutive interrogation of frequency channels 51, 60, 70, 80, 88, 100 and 110 kHz, into which the whole band is divided. It also must be noted, that the difference in also two orders of operating frequency band of acoustic and electromagnetic paths is caused by necessity to coordinate to some degree the radius of corresponding signals reception, taking into account their attenuation during propagation in the medium. Measurements in cased, as well as in open boreholes were carried out according to discrete logging method with observation time of 2-4 min in one point. During this time the control of inner noises level of amplifying path, recording of calibration signal and sensors interrogation were also carried out. The distance between observation points was chosen in accordance with a problem stated and differentiation of a geological section and it was changed from 1 to 50 m. During repeated measurements, conducted in 4-12 h, the shift of the whole level of seismoacoustic noises distribution curve with insignificant changes of its form and preservation of anomalies at former depth intervals were registered. The data given here were received under conditions, when there were no intensive technogeneous and other noise sources at a considerable distance from measurement points on the surface and in the neighboring boreholes.

THE ANALYSIS OF THE EXPERIMENTAL DATA ON BOREHOLES

a) Distribution of signals intensity.

Investigations of acoustic and electromagnetic fields along sections of deep boreholes showed that the maximum signal levels of one, as well of the other nature are often linked with the intervals of increased jointing and disturbance of rocks. The graphs of borehole 319 on Figure 1, where big signal levels correspond to increased jointing of rocks, that was determined according to a core, are a good illustration of this. It testifies to a single initial mechanism of SAE and EME formation. First of all, SAE and EME are connected with dynamics of faults, formation of new interface surfaces in the medium, which leads to excitation of elastic vibrations' appearance, displacement and relaxation of electric discharges. It should be noted, that zones of increased jointing, on the one hand, are reduced in the structure of rock mass, and, on the other hand, maximum stresses are realized in them virtually, these zones fulfil the function of amplifiers of compressive, as well as of shear stresses through the mechanism of contact surfaces (bonds) with an average notch-sensitivity index $K=S/S_1$, where S – surface area of complete blocks contact, divided with a jointed zone, S_1 – contact sectional area. Heterogeneity of surfaces leads to irregular distribution of stresses and deformations at contacts and, therefore, to considerable variations of K. As a result, contact bonds between blocks of different scale level under the action of gravitational, tectonic and other forces are distributed along starting rupture stresses. Thus, there are conditions for trigger mechanism of SAE and EME initiation with comparatively weak actions. It is for example observed in correlation of SAE and EME variations with earth tides and other pulse and periodic actions, but the deformations created by them in the Earth's crust are far from destructive and do not exceed several units in 10^{-8}. It should be noted that in sedimentary rock complexes the intensity of SAE and EME is three times lower than in crystalline ones.

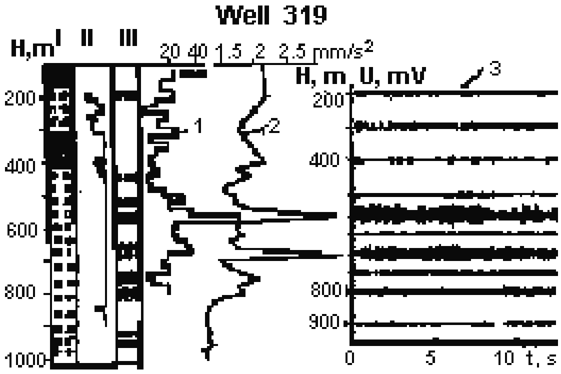

Figure 1 – SAE and EME distribution in borehole 319 (Lomonosovskoye iron-ore deposit, Northern Kazakhstan). 1 – jointing over a core, 2 – SAE level, 3 – recording fragments of EME signal envelope at frequency of 88 kHz.

b) Frequency spectra.

If we apply to spectra of electromagnetic signals in a borehole, whose distribution of signals is shown on Fig. 1, we should note, that more high-frequency spectra in the main correspond to fine-grained rocks, and low-frequency – to coarse – grained ones. It also agrees with the results of laboratory experiments on samples (Nitsan U., 1977), that show that spectra of EM pulses of more coarse crystals displace towards low frequencies. Simultaneous examination of EME and SAE spectra, received at different frequency ranges, gives additional information about the mechanism of signals formation. Figure 2 presents spectra of simultaneously registered EM and acoustic signals at the depths from 960 m. The graphs of EME spectra are given in relative units to the level at a frequency of 51 kHz. In the depth interval of 1260-1620 m with disseminated magnetite ores the spectra of EME, as well as of SAE are considerably changed in comparison to embedding rocks. In this case, the amplitudes at frequencies hear 100 kHz are sharply increased in EME, and in SAE – higher than 500 Hz with maximum approximately at a frequency of 1 kHz. Proceeding from laboratory data, received on samples (Yamada I, etc., 1989; Ivanov V.V. and Pimonov A.G., 1990), we may assume that in this case spectrum reflects elementary initial acts of microjoints formation and along with this the composition, structure of rocks and, certainly, acting stresses. Close connection between EME and SAE spectra puts a question of how the sources of more low-frequency SAE signals, are formed from elementary acts of fracture. Series of elementary acts of rupture, which form corresponding clusters and which are the source of elastic vibrations appear in the medium with discrete structure. Their dimensional characteristic reflects SAE spectra. If it is so, then the envelopes of EME signals must fluctuate with frequencies close to ones separated in SAE. Spectral analysis of EME signal envelope at a frequency of 100 kHz confirmed this conclusion. And this, in its turn, indicates that frequencies, coinciding with the observed ones in acoustic paths, are present in EME spectrum in many cases.

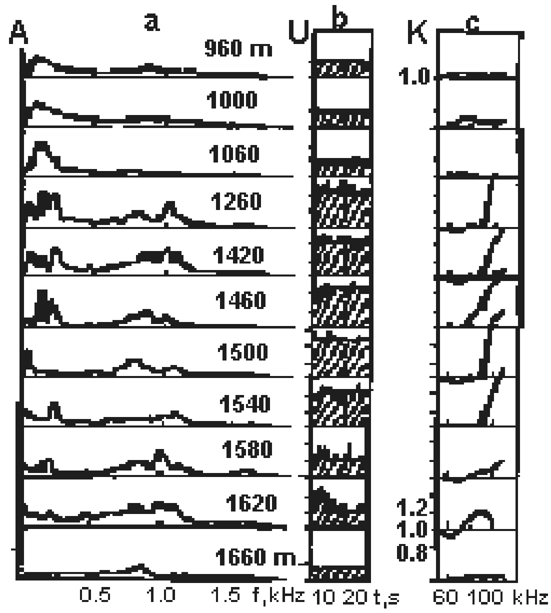

Figure 2 – SAE and EME distribution in borehole 1573 (Kacharskoye iron-ore deposit, Northern Kazakhstan).
a – averaged pulse-frequency SAE spectra; b – fragments of EME signal envelope at the frequency 100 kHz; c – frequency distribution of EME intensity relative to EME level at the frequency of 51 kHz.

DYNAMIC MODEL OF THE MEDIUM WITH ACOUSTIC AND ELECTROMAGNETIC ACTIVITY

It is known from laboratory and natural observations and also from practice of non-destructive testing that each brittle rupture is accompanied by an elastic pulse emission, i.e. the flux of acoustic pulses in a second will correspond to the number of ruptures in a unit of time. General kinetic equation in an ensemble of $n(\sigma,t)$ stressed bonds may be written in the following way:

$$n'(\sigma_r,t) = -\nu_r n(\sigma_r,t) + m(t) \qquad (1)$$

where $n(\sigma_r,t)$ - the number of bounds with the strength σ_r in a moment of time *t*, ν_r - the frequency of bonds disintegration, that depends on their strength and acting rupture stresses; $m(t)$ - the function of frequency of bonds restoration, that depends on flaws structure and compressive stress. The equation (1) describes two opposite processes: bonds rupture and their restoration.

A number of newly emerged defects is determined by the difference between initial n_0 and remaining by the time *t* number of bonds:

$$n_r(t) = n_0 - n(t) \qquad (2)$$

From this we may evaluate the number of cracks, emerged during the unit of time:

$$n'(t) = \int_{\sigma_1}^{\sigma_2} \frac{P(\sigma_r)}{n'(\sigma_r,t)} d\sigma_r \qquad (3)$$

It is not difficult to note that, it is lesser than the number of emerged ruptures as per the share of bonds, restored during this time. It is an important difference, as it grounds physical preconditions for prognosis SAE and EME properties, when controlling deformation processes in rock masses.
To evaluate the intensity of SAE and EME, depending on structure, rock properties and acting stresses, it is necessary to determine the type of function ν_r, that includes corresponding parameters. Let us use for this an expression from kinetic theory of solid bodies strength (Zhurkov S.N., 1968) and write it in the following form:

$$\nu_r = \nu_0 \exp\left[-\frac{U}{kT}\left(1-\frac{\sigma_t}{\sigma_r}\right)\right] \qquad (4)$$

Here: $U = U_0 - \gamma\sigma_0$ - energy of ruptures activation, taking into account the action of constant bonds, γ – structural parameter, taking into account overstresses at heterogeneities, ν_0 – frequency of heat oscillations of atomic lattice, *k* – Boltzmann's constant, *T* – absolute temperature. In this case, the significance of rupture stresses is determined by relationship between the energy of rupture activation and the structural parameter $\sigma_r = \frac{U}{\gamma}$. In addition to acoustic and electromagnetic activity of the medium, evaluation of expected amplitudes and emerging SAE and EME pulses of great interest, as it is equivalent to a great degree to evaluation of sources according to seismic and electric moments. For this, let us substitute the relation of stresses for relation of seismic moments $\frac{M}{M_r}$, where $M_r = \mu s d$ by definition, μ - shear modulus, $s = \alpha i^2$ - rupture area, *d* – dislocation displacement.
Now, we may write the other expression, suitable for evaluation, of number of pulses in a unit of time with a seismic moment not less than M_1:

$$n'_r(M \geq M_p, t) = \frac{1}{\alpha l^3} \int_{M_1}^{M_2} P(M_r) n'(M_r,t) dM_r \qquad (5)$$

We may receive density of $P(M_r)$ distribution from density of rupture distribution, using the equation $M_r = \sigma_r l^3$, where l - coefficient, that takes into account the form and dislocation displacement of a rupture. Accumulated elastic energy is proportional to a volume, i.e. l^3. On the other hand, electric moment of a source $I = \beta l^2 \frac{dq}{dt}$, where β - coefficient, that takes into account the form and type of a source, $\frac{dq}{dt}$ - the velocity of movement of electric charge density, similar dependence, only with different coefficient β, is true for sources with linear charges at the top of cracks, as well as for sources with mosaic distribution of charges on the surface, taking into account that opening of cracks is proportional to their length. From relation $\frac{I}{M}$ we see that with increase of rupture length and time of its distribution the amplitude of electromagnetic signal with other equal conditions increases in lesser degree than acoustic. Physically it means proportionality of seismic moment of accumulated elastic energy in a volume, and of electric – only in rupture plane. For EME intensity we may receive similar relation (5), using the relation of *I* and *M* moments, corresponding to different rock types. Putting the medium parameters and values of acting stresses into the previous integral, we'll receive pulse flux intensity with amplitudes, increasing the predetermined one. It should be noted that separate SAE and EME pulses may change into intensive flux of signal pulses. Not dwelling on concrete examples now, let us separate several general regularities of distribution of geoacoustic and geoelectromagnetic background intensity in time. First, if density of bonds distribution along rupture stresses and emerging charges at this is uniform, and discreteness of the medium is notably lower than the radius of EME and SAE reception, then we observe regular character of variations of electric and acoustic signal corresponding to deformation processes, though this regularity may depend on the mechanism of SAE and EME forming and elastic-viscous properties of the medium. Second, if discreteness of the medium is comparable or larger than reception radius and the function of distribution of rupture stresses $P(M_r)$ in the medium is not uniform, there may be observed sharp signal changes that may testify to appearance of slow stress waves in block structure of the medium, where the phase of accumulation is replaced by the phase of stress release. The examined model may take into account not only heterogeneous distribution of stresses, but also the effect of fluids that very often decrease surface energy of emerging defects and with this decrease the strength of bonds σ_r .

CONCLUSIONS

The conducted investigations have shown, that SAE and EME characteristics on cross-sections of deep boreholes contain a great volume of information to solve many geologogeophysical problems, including:

- separation of dynamically active fractures and other structures;
- evaluation of rocks stressed state at great depths that is essential for optimization of exploitation mineral deposits and for prediction of technogeneous earthquakes and rock bumps;
- conducting the monitoring at great areas with use of structures of the maximum strain-sensitivity to control accumulation of elastic energy and predict dangerous geodynamic phenomena.

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