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GEOPHYSICS

Electromagnetic Effects during Relaxation Processes in the Earth's Inhomogeneous Crust

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This paper reports data on the joint recording of microseismic oscillations and the electric field in near-surface sectors of the Earth's crust. Based on the results of their analysis, we propose a model for the source of low-frequency electromagnetic signals as an electric dipole generated by the constrained rotation of structural blocks during the relaxation of a medium with a low moisture content. According to this model, separation of electric charges and generation of currents are related to the breakdown of mechanical bonds between the neighboring blocks during differential motions or to the electric polarization of rock during a dramatic variation in the stressed state. The results show that the value of the electric dipole moment appearing in the active (relaxing) block segment with a linear dimension of ~10 m is as much as 10^{-7}–10^{-6} C · m during the formation of a system of subparallel fractures in the interblock space and as much as 10^{-9}–10^{-7} during the electric polarization of rock. In both scenarios, the dipole moment can provide an amplitude of electric pulses equal to 0.01–1 mV/m in the surface layer of the Earth's crust over distances exceeding the block dimension by two to three orders of magnitude. The parameters of electric pulses obtained in the model and recorded under natural conditions are in good agreement.

Specific features of the manifestation of electromagnetic effects in the near-surface sectors of the Earth's crust with a low moisture content are related to the low-frequency pulsed electric signals, the number and parameters of which are defined by the tectonic activity of the study region and its structure and stressed-strained state [1, 2].

Electromagnetic effects related to seismic and deformation processes in rock massifs are very diverse, and their physical nature is different [1, 3–7]. Among the mechanisms of electromagnetic signal generation in the Earth's crust, the electric polarization of rocks deserves special attention [8]. This mechanism is realized, for example, in the course of explosive loading of the rock massif or relaxation processes in a hierarchic-block geophysical medium [10].

It was shown in [11] that, in contrast to the shock polarization of crystals and some other natural materials characterized by the threshold character of electric polarization, the electric polarization of rocks is observed at sufficiently low amplitudes of the dynamic impact and is distinguished by the continuous dependence of polarization from the load value.

Data reported in [8, 9] indicate that the presence of structural inhomogeneities in the rock massif has a marked influence on the generation of the low-frequency electromagnetic field. Variations in the electric and magnetic fields under an external impact upon a geological medium serve as an indicator of the present-day activity of tectonic structures and the intensity of interactions between geospheres at the Earth's crust–atmosphere boundary [1]. Therefore, it is essential to investigate electromagnetic effects appearing in the geological medium and the atmosphere in the course of natural and anthropogenic geodynamic processes.

We carried out instrumental observations of successions of electric pulses in the near-surface sectors of the Earth's crust and microseismic pulses accompanying relaxation processes in rock blocks in crustal sectors marked by the present-day seismic activity. Measurements were carried out in the Nelidovo–Ryazan tectonic structure (NRTS) confined to the Moscow syneclise, which is characterized by low tectonic activity, and in the domain of the Kurai tectonic structure (Gornyi Altai), which is marked by high present-day activity (source zone of the Gornyi Altai earthquake on September 27, 2003, with a magnitude of 7.5 on the Richter scale) [1].

We analyzed relaxational seismic pulses and electric pulses in the soil, which differed (in shape and spectral composition) from the atmospheric pulses and known anthropogenic interferences [1, 10].

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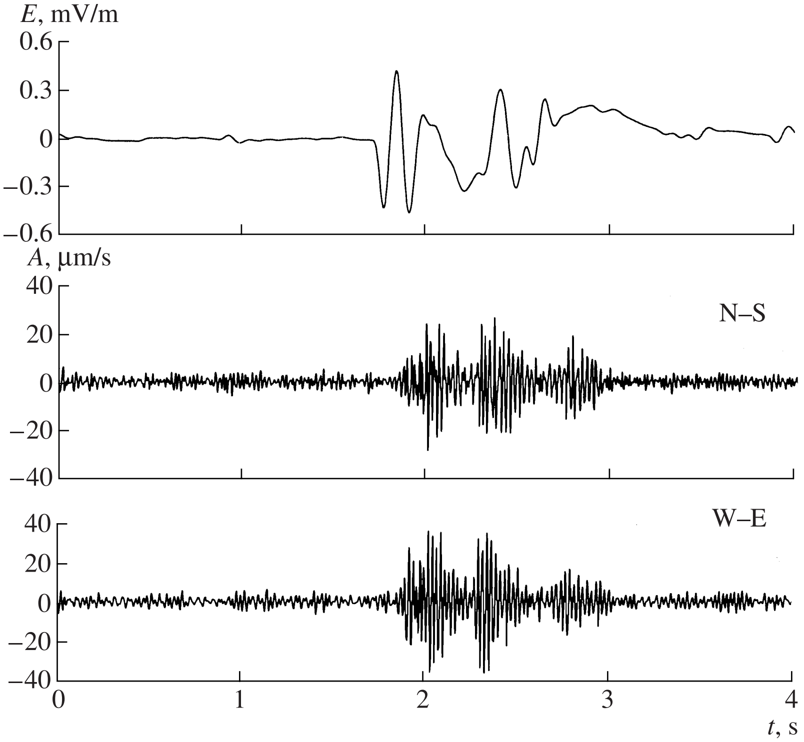

Fig. 1. Example of the joint record of electric field E in soil (N–S component) and microseismic oscillations A (N–S and W–E components) at observation point Aktash (Gornyi Altai).

Figure 1 presents an example of the joint recording of the electric field in the near-surface soil layer and the microseismic background. The figure clearly shows that the microseismic pulse of low-amplitude electric field provokes an anomalous variation in the electric field as an electric pulse.

The results of instrumental observations suggest the following facts:

(i) Relaxation processes are universal in the Earth's crust. Relaxation sources are confined to tectonic fracture zones. The intensity of relaxation processes (the number of relaxations combined with the value of the released energy) is defined by the present-day tectonic activity in a specified sector of the Earth's crust. For example, based on the number of accompanying microseismic pulses, the number of relaxations N_R is as much as 550 events per 1 h in the Kurai tectonic structure and varies from 5 to 40 events per 1 h in different sectors of the NRTS zone.

(ii) Relaxation processes are accompanied by the generation of electric pulses, the probability of their origination being 0.05–0.4 (in sectors with a low tectonic activity, the relative number of recorded electric pulses and, correspondingly, the probability of their origination are significantly lower relative to sectors characterized by a high tectonic activity).

(iii) The statistical characteristics of successions of electric and microseismic pulses coincide. Statistics of the recurrence of recorded pulses with an amplitude 2.5 times higher than that of the background amplitude are presented in Fig. 2. The figure shows the number of seismic ($N_s = N_R$) and electric (N_e) pulse events with amplitude exceeding A_s and A_e, respectively.

Taking into consideration statistics of successions of seismic and electric pulses, along with the corresponding choice of the ratio between amplitudes A_s and A_e, we can assume that both phenomena have a common source. Such a source could be represented, for example, by a local oscillatory system related to the constrained deformation of an active block of the Earth's crust in the course of stress relaxation [10]. In this case, the velocity of differential dislocation $v(t)$ on the active plane of the block is described well by the following dependence (Berlage pulse):

$$v(t) = \alpha v_0 t e^{-\beta\omega t}\sin\omega t, \qquad (1)$$

where α is the normalization coefficient and v_0 is the maximal velocity of displacement in the case of intermittent sliding of the active plane

$$v_0 = \frac{\omega}{2N}\sqrt{\frac{2E}{GL}}.$$

Here, ω is the cyclic frequency of the process; N is the number of displacements during the intermittent sliding; G is the effective elastic modulus of block material; and E is the elastic energy released by the relaxation of a block with the linear dimension L.

The value of the active plane displacement $u(t)$ is determined by integrating (1) and is approximated with a sufficient accuracy for practical estimates:

$$u(t) = u_0\{1 - e^{t/T} + \beta t e^{-\omega t/2} \sin \omega t\}, \qquad (2)$$

where $u_0 = \frac{2v_0 N}{\omega}$ is the maximum displacement of the active plane [12].

Assuming that the process is defined by ratios of linear elasticity, we obtain the following dependence for the stress released during the block relaxation:

$$\Delta\sigma(t) = \left\{\frac{2EG}{L}\right\}^{1/2} \{1 - e^{-t/T} + \beta t e^{-\omega t/2} \sin \omega t\}. \qquad (3)$$

Let us examine the mechanism of electric signal generation as newly formed or revived fractures. If rotation of the structural block is constrained, the activated interblock space in the form of a structural distortion of the respective rank can be considered as the major fracture of a certain thickness associated with the system of subparallel surfaces characterized by a lower strength [12]. Thus, the differential motion developed on the active side of a relaxing block generates systems of subparallel fractures. In this case, the predominant orientation is similar for dipole moment vectors of fractures and, correspondingly, microfields of fractures are coherent.

Let us estimate, for example, the interblock space adjacent to the active plane of a relaxing block. If the block dimension L = 10–100 m, the interblock space has a width of $m \sim L \cdot 10^{-3} = 10^{-2}$–$10^{-1}$ m. Opening of the interblock space is estimated as Δl = 0.1 m, which yields in our case $\Delta l = 10^{-3}$–10^{-2} m. We assume that opening of the interblock space generates electric charges on the walls of the fracture system located parallel to the interblock boundary over an area S equal to ~0.1 part of the surface of the active block plane. The average surface density of electric charges $\Sigma = 10^{-5}$–10^{-4} C/m^2. At S = 10 m^2 (we assume that the active plane of the relaxing block is 10 × 10 m), the dipole moment of the newly formed charge system is estimated as $p \approx S\Sigma L = 10^{-7}$–$10^{-6}$ C · m.

In the case of electromagnetic signal generation by the electric polarization of rocks during dynamic impacts [8, 9], the stick-slip unloading of the stressed structural element of a medium in the form of an asymmetric constrained rotation of block leads to drastic variation in the stressed–strained state of the active block and the adjacent medium volume [10]. Consequently, the rock is subjected to electric polarization (let us note that if the stress field is symmetric, the electric dipole moment developed in the rock volume due to its electric polarization will be equal to zero).

Laboratory experiments [11] with the dynamic loading of granite in a wide pressure range (from a few MPa to tens of GPa) demonstrated that the electric polarization of granite is a continuous process correlated with the growth of load. Discernible electric signals are already recorded at small values of the stress jump (~10^5–10^6 Pa). Using relations (1)–(3), data reported in [11], and electric polarization models [8, 9], let us estimate the dipole moment developed in the rock volume of an active block due to sharp variation in its stressed–strained state.

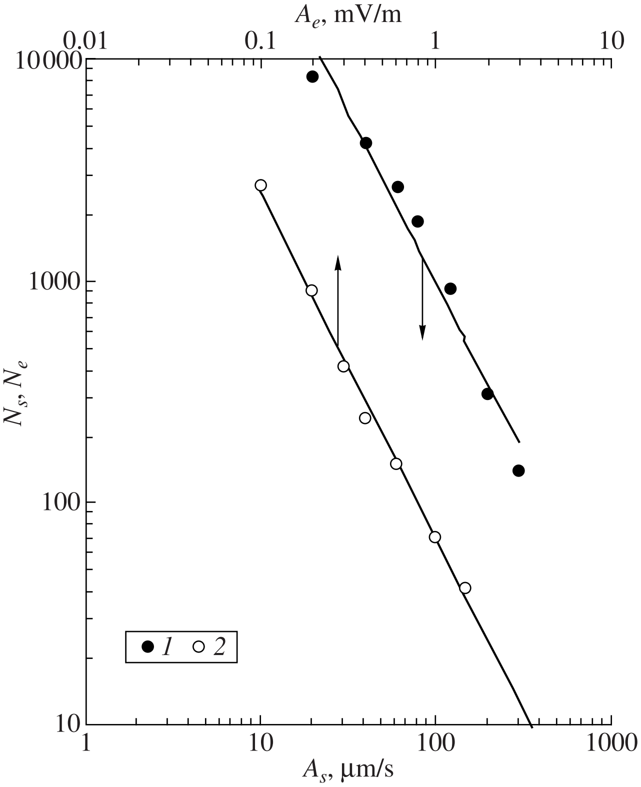

Fig. 2. Number of seismic (*1*) N_s and (*2*) electric N_e pulses with amplitude exceeding the specified value.

The amplitude of seismic pulses recorded in the highly active sectors of the Earth's crust is as much as 30–300 μm/s. Hence, the maximum displacement velocity of the active block plane is 50–500 μm/s and the released stress $\Delta\sigma \approx 10^4$–$10^6$ Pa. The dependence of the electric polarization P_0 on the acting stress σ is nonlinear [11]. In the region of small σ values, we can use the following approximation for calculations:

$$P_0 \approx A \cdot \sigma,$$

where $A = 4 \cdot 10^{-7}$; P_0 is given in C/m^2; and σ, in GPa.

Thus, for an active block with the linear dimension of L = 10 m, we obtain $p \approx 10^{-9}$–10^{-7} C/m^2.

The estimates of the dipole moment obtained for the two mechanisms of electromagnetic signal generation described above allow us to determine the amplitude of the low-frequency electric and magnetic field during the constrained rotation of a relaxing block. Let us use the scheme presented in Fig. 3. The dipole with the ver-

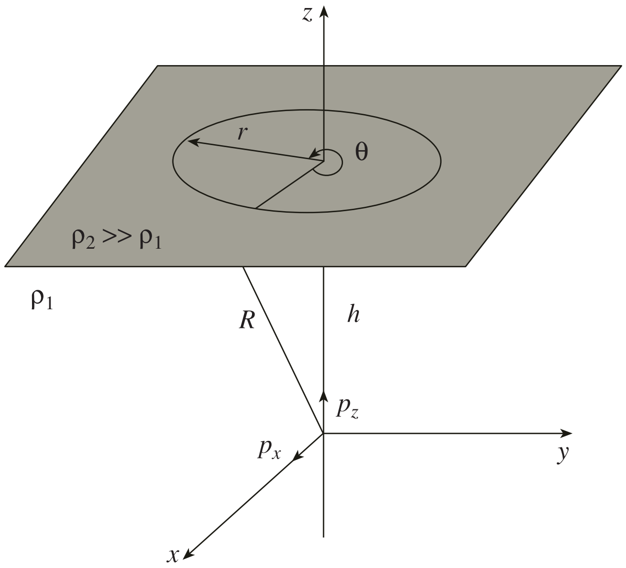

Fig. 3. System of coordinates and scheme of the electric dipole location in the conductive medium.

tical p_z and horizontal p_x components is located at a depth of h from the horizontal interface between two media with finite electroconductivity values.

Components of the electric and magnetic fields at the soil–air interface have the following shape [2]:

$$E_{2z} = \frac{p_z(2h^2 - r^2) + 3p_x hr\cos\theta}{2\pi\varepsilon_0 R^5},$$

$$E_{2r} = \frac{3p_z hr + p_x(2r^2 - h^2)\cos\theta}{2\pi\varepsilon_0 R^5}, \quad E_{2\theta} = \frac{p_x \sin\theta}{2\pi\varepsilon_0 R^3},$$

$$B_{2z} = \frac{\mu_0 p_x}{4\pi\varepsilon_0\rho_1}\frac{r\sin\theta}{R^3}, \tag{4}$$

$$B_{2r} = \frac{\mu_0 p_x}{4\pi\varepsilon_0\rho_1}\sin\theta\left(\frac{1}{r^2} - \frac{h}{r^2R} - \frac{h}{R^3}\right),$$

$$B_{2\theta} = -\frac{\mu_0 p_x}{4\pi\varepsilon_0\rho_1}\cos\theta\left(\frac{1}{r^2} - \frac{h}{r^2R}\right),$$

where p_z and p_x are the vertical and horizontal components, respectively, of the dipole moment; $R = \sqrt{r^2 + h^2}$, ε_0 is the dielectric permittivity of free space; μ_0 is the magnetic permittivity of free space; ρ_1 is the resistivity of the soil; and indices 1 and 2 belong to the soil and air, respectively. Components of the electric and magnetic fields E_r, E_θ, B_z, B_r, and B_θ at the interface are continuous, and component E_z has a step change: $E_{1z} = E_{2z}\frac{\rho_1}{\rho_2} = E_{2z}\frac{\sigma_2}{\sigma_1}$.

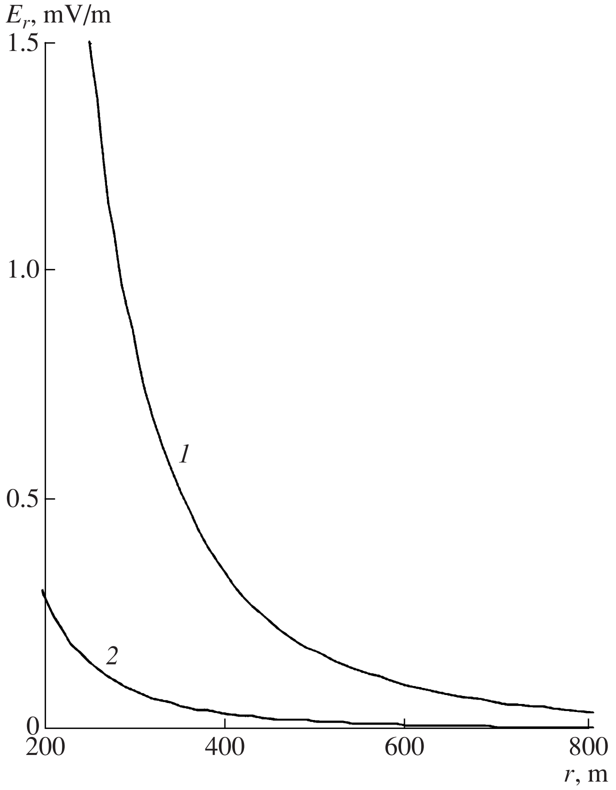

Fig. 4. Variation in the amplitude of the electric field in soil with distance p, C · m. (*1*) 10^{-6}; (*2*) 10^{-7}.

Calculations with the involvement of relations (4) suggest that the constrained rotation of the block generates significant values of perturbation of the electric field along its horizontal components in the soil. Figure 4 presents an example of variation in the radial component of the electric field E_r in the soil as a function of the distance from the source. One can see that the amplitude of the electric signal generated by the relaxational motion of the block over a distance of (10–100) L exceeds 0.01 mV/m. The experience of recording pulsations of the horizontal components of the electric field in soil shows that perturbations of such amplitude can easily be distinguished against the background of natural pulsations of the electric field.

The signal amplitude of the electric field component E_z in air is about 1 mV/m at the distance of 100 m from the source. This component cannot be distinguished reliably in experiments against the background of natural pulsations of the atmospheric electric field in the frequency range up to 10 Hz.

The values of components of the magnetic field at a distance of r = 100 m from the source are ~4–40 pT. In some cases, a perturbation of such amplitude can be distinguished from background pulsations of the magnetic field.

Values of perturbations of the electric and magnetic fields obtained in the calculations are consistent with the data based on the recording of microseismic and electric pulses [1].

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