ANNALI DI GEOFISICA, VOL. XL, N. 2, March 1997

Magnetic effects due to earthquakes and underground explosions: a review

Vadim V. Surkov (1) **and Viatcheslav A. Pilipenko** (2)
(1) *Moscow Engineering Physics Institute, Moscow, Russia*
(2) *Institute of the Physics of the Earth, Moscow, Russia*

Abstract
The physical nature of quasi-static and transient anomalies in the geomagnetic field induced by underground explosions or earthquakes is reviewed. New theoretical results obtained recently and so far little known to general circles of geophysicists are presented. The physical nature of residual magnetic and electrotelluric fields at the explosion point are considered. The seismic waves from explosions or distant earthquakes are suggested to be used as a tool for the preliminary probing of the Earth's crust sensitivity to various seismo-electromagnetic effects. The use of magnetic induction effects for tsunami detection and for crust sounding is outlined. The nature of ULF magnetic impulses related with earthquakes is discussed.

Key words *earthquake – explosion – seismo-electromagnetic phenomena – ULF waves*

1. Introduction

This paper gives a concise treatment of the physics of the electromagnetic response of the geophysical medium to impact by explosion or earthquake. Two classes of physical phenomena are related to such impact. The first is associated with the emergence of quasi-static anomalies of the magnetic and telluric fields near the explosion site and quake epicenter. The other is related to propagating seismic waves. The specific radiative and plasma effects which accompany the nuclear explosions (Longmire, 1978; Price, 1974) are not considered.

The considered effects might be effectively incorporated into research on seismo-electromagnetic phenomena. The effectiveness of the monitoring of earthquake electromagnetic precursors greatly depends on the choice of most «sensitive» observation points. On the other hand, the electromagnetic response of the crust to seismic waves is determined by local mechano-electrical properties of the crust. So, the preliminary probing of a seismo-active region with seismic waves from an explosion, using simultaneous seismic and electromagnetic observations, could indicate the most promising observation sites for monitoring electromagnetic precursors. However, reliable extraction of necessary information requires the clear physical understanding of various mechanisms of magnetic response on acoustic impact on the geophysical media. Some of these mechanisms are outlined in this review.

2. Local anomalies of the Earth's electromagnetic field after an explosion

A feature of an underground explosion is a generation of long-lasting perturbations in the Earth's electromagnetic field. In performing these experiments, the anomalous magnetic field was revealed through difference in

Mailing address: Dr. Viatcheslav A. Pilipenko, Institute of the Physics of the Earth, B. Gruzinskaya 10, Moscow 123810, Russia; e-mail: pilip@iephys.msk.su

records obtained at remote stations and at observation points nearby. The perturbations were observed at distances up to 10 km from the epicenter for a few days after underground and surface nuclear explosions (Undzenkov and Shapiro, 1967; Barsukov and Skovorodkin, 1969; Hasbrouk and Allen, 1972), and conventional chemical explosions (Akopyan *et al.*, 1973; Kozlov *et al.*, 1974; Yerzhanov *et al.*, 1985). Some offset of the magnetic field has been observed after strong earthquakes.

2.1. *Seismo-magnetic effects*

The residual magnetic field which was observed near the explosion point can be attributed to the seismo-magnetic effect (Stacey, 1964) – magnetization or demagnetization of rocks containing ferromagnetic inclusions. Such rocks can be found, for example, at the deposits of magnetite and other natural ferromagnetic materials. The substance is magnetized when the medium is shaken up by the shock wave generated by an explosion. The vector of the substance magnetization is directed along the geomagnetic field. The physical mechanism of this phenomenon consists in a partial orientation of domains along the external magnetic field due to the effect of elastic stress in the substance (Kondorsky, 1959).

The crashed zone created near the explosion chamber contributes insignificantly to the seismo-magnetic effect. The reason is that the magnetic moments of individual fractions of the fractured rock are chaotically oriented and their vector sum is close to zero. In the elastic zone, there exists an empirical relationship $\Delta \boldsymbol{J} = \boldsymbol{J}\delta_r/A$ between the magnetization increment $\Delta \boldsymbol{J}$ and the amplitude of radial stresses δ_r (here $\boldsymbol{J}$ is the initial magnetization of medium, A is an empirical parameter) (Stacey, 1964). The value of δ_r diminishes with the distance r from the explosion point following the relationship $\delta_r = \delta_*(a_0/r)$ (here δ_* is the rock rupture strength, a_0 is an inelastic zone radius). By integrating the magnetic fields of elementary magnetic moments $\Delta \boldsymbol{J}$ and taking into consideration the dependence $\delta_r(r)$, one can obtain the following equation for the anomalous magnetic field (Surkov, 1989a):

$$\boldsymbol{B} = \frac{\mu_0 \delta_* a_0}{2Ar}\left(1 - \frac{a_0^2}{r^2}\right)\left(\frac{3(\boldsymbol{J}\cdot\boldsymbol{r})\boldsymbol{r}}{r^2} - \boldsymbol{J}\right), \quad (a_0 \le r \le a) \tag{2.1}$$

$$\boldsymbol{B} = \frac{\mu_0 \delta_* a_0 (a^2 - a_0^2)}{2Ar^3} - \left(\frac{3(\boldsymbol{J}\cdot\boldsymbol{r})\boldsymbol{r}}{r^2} - \boldsymbol{J}\right), \quad (r > a) \tag{2.2}$$

where μ_0 is a magnetic constant, a is the radius of the elastic wave front. It was expected that the decrease of the field with distance should obey the law $B \sim r^{-3}$, typical for the stationary magnetic dipole (Barsukov and Skovorodkin, 1969). However, the experimental results turned out to be closer to the dependence $B \sim r^{-1}$ (Yerzhanov *et al.*, 1985). This discrepancy can be removed with the use of the formulas (2.1) and (2.2) if one takes into consideration that the observations are normally carried out in the region of $a_0 \ll r < a$. At such distances the magnetic dipole generated by the shock-magnetized rocks cannot be considered a point one, hence the law (2.2) is not valid and (2.1) should be applied. Figure 1 shows the good correspondence between the experimental dependence $B(r)$ obtained during the MASSA experiment with the ground chemical explosion of 251 t TNT (Yerzhanov *et al.*, 1985) and the calculation results according to (2.1) with the following parameters: $\delta_* = 0.1$ GPa, $A = 1$ GPa, $a_0 = 100$ m, $J = 0.12$ A/m. The difference between curves at $r < 0.5$ km may be caused by the influence of other mechanisms which will be considered later on.

It should be remembered, that in experiments with underground explosions the effect similar to a seismo-magnetic one can also be due to the shock magnetization of metallic casing string. Magnetization of metal with a shock is much stronger than that of the rock surrounding the string and this can cause an appreciable effect. The estimates show that at distance from the casing string ~ 500 m with 10% of shock magnetization of metal saturation the magnetic effect may be about 20 nT.

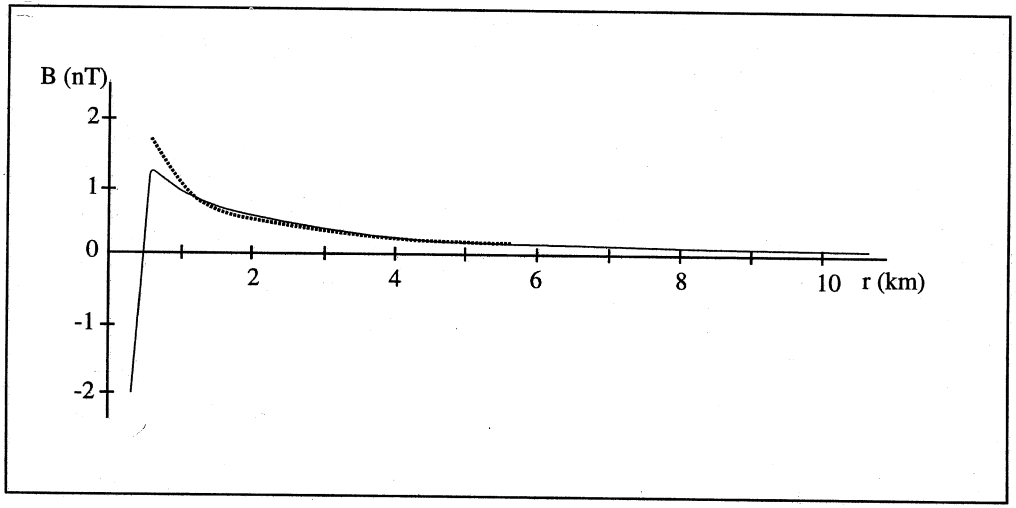

Fig. 1. Decrease of the residual magnetic field at the explosion point. Solid line is an experimental dependence measured after the MASSA explosion; dotted line shows the results of the theoretical calculations.

2.2. *Anomalies of geoelectrical conductivity and redistribution of telluric currents*

The distortion of the Earth's local electromagnetic field by an underground explosion can also be caused by the variation in the Earth's electrical conductivity and redistribution of the Earth's currents of artificial (due to currents in the casing string) and natural origin. Generation of currents near the casing string is determined by the contact potential difference because of different conductivities: the ionic conductivity in a medium and the electron one – in a metal. The similar effect exists near the ore deposits, so, local anomalies of terrestrial telluric field are used for the detection of deposits. The contact potential difference is strongly depth-dependent due to different mineral composition of salts in the pore water at different depths. The electrochemical processes ensuring in the surface layer generate currents in the medium. The current lines are of a typical toroidal pattern with the symmetry axis of the tore coinciding with the string axis. The arising magnetic field contains only the azimuthal component. According to the theory, in the homogeneous crust this component tends to zero near the Earth's surface.

The current system near the casing string causes a perturbation not only of the magnetic field but also of the Earth's electric field. The explosive processes result in a destruction zone with a changed electrical conductivity. This in turn leads to a redistribution of currents in the medium and a change in the electromagnetic field. The theoretical analysis of this problem is reduced to the solution of Poisson's equation for the conductive semi-space of the electric conductivity σ_0, which contains a ball-shaped intrusion with a radius a_0 and electric conductivity σ_1. The top of the string casing acts as a negative electrode while its bottom section is a positive electrode (this kind of polarization can be found in ore bodies) (fig. 2). In this case, the electrical field potential on the Earth's surface can be written as (Surkov, 1989a):

$$\varphi = \varphi_0 + \varphi_1,$$

$$\varphi_0 = -\frac{Ih(h+1)}{4\pi\sigma_0\rho^3}, \quad \varphi_1 = \frac{3I(\sigma_0 - \sigma_1)ha_0^2}{4\pi(h-1)\sigma_0(\sigma_1 + 2\sigma_0)\rho^3}, \tag{2.3}$$

where I is the total current on the casing string

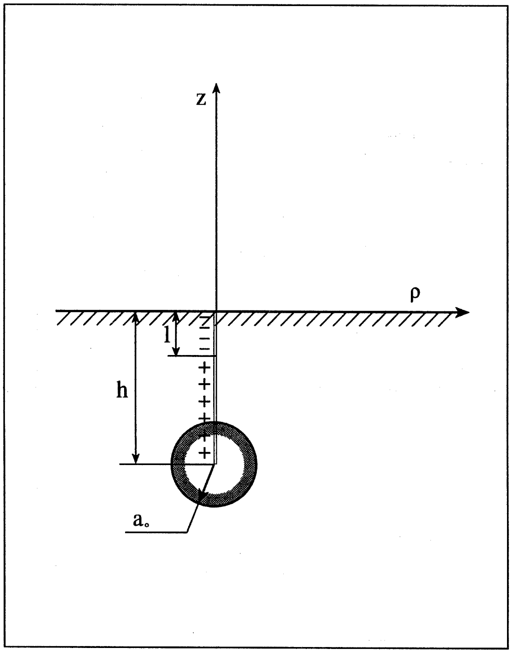

Fig. 2. The model presentation of the destruction zone at the end of the casing string, used in calculations of an anomalous electrotelluric field at the explosion point.

surface; h – its length, ρ is the distance from the string. The formula (2.3) holds true provided $a_0 \ll h$, $h-1 \ll \rho$. The term φ_0, describes the undisturbed field potential before an underground explosion, and φ_1 refers to the potential disturbance related with the formation of a crashed zone. In the same approximation the azimuthal component of a magnetic field B_φ can be presented as

$$B_\varphi = B_0 + B_1,$$

$$B_0 = \frac{\mu_0 I h (h+1) z}{4\pi\rho^4}, \quad B_1 = \frac{9\mu_0 I (\sigma_0 - \sigma_1) a_0^2 h z}{4\pi (h-1)(\sigma_1 + 2\sigma_0)\rho^4}, \tag{2.4}$$

where $z < 0$ is a vertical coordinate. The eqs. (2.3) and (2.4) prove useful for practical assessment of the consequences due to an underground explosion. The parameters I, l and h can be determined before the explosion by comparing experimental and theoretical dependencies $\varphi_0(\rho)$ and $B_0(\rho)$. Then the measurement of the disturbances of potential $\varphi_1(\rho)$ and magnetic field $B_1(\rho)$ after the explosion and the comparison of these values with the theoretical predictions (2.3) and (2.4) enable the size of a crashed zone a_0 and the electrical conductivity σ_1 to be determined within it. As follows from (2.3) and (2.4), the perturbations φ_1 and B_1 are connected by a simple relationship $\varphi_1 = \rho B_1/(3\mu_0\sigma_0 z)$. According to measurements the magnetic field perturbation at a few kilometers from the explosion $B_1 \sim 10$ nT (Hasbrouk and Allen, 1972). Assuming that $\rho/z = 10$ and $\sigma = 10^{-2}$ S/m one obtains that this magnetic disturbance should be accompanied by the disturbance of the potential $\varphi_1 \sim 3$ V.

Telluric electric field anomalies can also be caused by the redistribution of telluric currents due to the creation of crashed rock zone. We assume the field of telluric currents to be uniform at infinity. The solution of this problem for a uniform medium with conductivity σ_0, which contains a ball-shaped intrusion (crashed zone) with different conductivity σ_1, is known

$$\varphi = -\frac{(\boldsymbol{jr})}{\sigma_0} + \frac{(\boldsymbol{jr})\, a_0^3 (\sigma_1 - \sigma_0)}{\sigma_0 r^3 (\sigma_1 + 2\sigma_0)}, \quad (r \geq a_0). \tag{2.5}$$

Here $\boldsymbol{j}$ denotes the current density at infinity, a_0 is the ball radius and r is a distance from the ball center. From (2.5) one can find the potential disturbance. The similar formalism can also be applied to estimate the probable magnetic and telluric effects caused by the formation of the consolidation zone with different geoelectrical properties at the final stage of the earthquake preparation process (Gokhberg *et al.*, 1985).

The long-lasting electrical anomalies can also arise as a result of electrokinetic effects under the influence of residual stress in the medium. The quantitative assessment of these effects is difficult because of unreliable determination of the medium parameters: the permeability of natural rocks, the sizes of a water-permeable filtering bed, the rate of solution filtration, etc.

2.3. *Relaxation of anomalous magnetic fields*

Up till now, practically no investigations have been conducted on the relaxation processes resulting in a decline of quasi-static anomalous fields. The electromagnetic effect caused by the fracture of medium is irreversible. At the same time, one cannot rule out the relaxation processes which can, for example, occur due to collapsing of underground cavities or structural changes in the porous space filled with fluid. In relaxation of medium magnetization, the key part seems to be played by the processes wherein the rock massive compressed by explosion is unloaded and by the processes of heat disorientation of domains which are contained in the composition of ferromagnetic inclusions (Barsukov and Skovorodkin, 1969). It is interesting to observe the relationship of these processes and the changes in the stressed state of the medium due to its mechanical unloading (Belokopytov *et al.*, 1985). Such investigation would be very useful in analyzing the phenomenon of the impending earthquake and should be treated as a promising trend in future research. The analysis presented above does not cover all the possible physical mechanisms involved in generation of magneto- and electrostatic fields after an explosion. Further research in this domain is underway.

3. Induction effects due to seismic waves

The seismic waves emitted by explosion or earthquake can also generate geomagnetic disturbances. In contrast with the effects considered above, these disturbances can travel together with the seismic waves over long distances. The disturbance of the external magnetic field by elastic waves, propagating through the conductive medium, is caused by generation of the induction currents (Knopoff, 1955; Kalisky, 1960; Kalisky and Rogula, 1960; Viktorov, 1975; Guglielmi, 1986a,b). The interest in studying this phenomenon in geophysical research has emerged due to investigations of electromagnetic effects related with earthquakes, as well as to tackle the problem of excitation of magnetoelastic waves near the boundary of the Earth core (Keilis-Borok and Monin, 1959).

Maxwell's quasi-stationary equations describing the induction effect of the seismic waves are as follows

$$\frac{\partial \boldsymbol{H}}{\partial t} - D\nabla^2 \boldsymbol{H} = \mathrm{rot}\,[\boldsymbol{v}\times\boldsymbol{H}_0] \qquad (3.1)$$

$$\nabla^2 \boldsymbol{H} = 0 \qquad (3.2)$$

$$\mathrm{rot}\,\boldsymbol{E} = -\mu_0 \frac{\partial \boldsymbol{H}}{\partial t}. \qquad (3.3)$$

Equation (3.1) is valid for the Earth, and eq. (3.2) for the atmosphere. Here $\boldsymbol{H}$ is the perturbation of geomagnetic field $\boldsymbol{H}_0$, $\boldsymbol{v}$ is the medium velocity in seismic wave; σ is the Earth's electrical conductivity, $D = (\mu_0\sigma)^{-1}$ is a diffusion coefficient of the magnetic field disturbances. In the vicinity of the front of the elastic seismic wave the right-hand term in (3.1) acts as an external perturbation.

Far from the seismic source the geomagnetic perturbations will spread along with seismic waves. The magnitude of the magnetic field induced by the conductor oscillations is determined by Reynold's magnetic number $\mathrm{Re}_m = \mu_0\sigma C_s\lambda$, where C_s is the velocity of the seismic wave, λ is the wavelength. The induced electric field E in the inertial reference system can be estimated from the eq. (3.3). Usually, sensors oscillate with the Earth's surface, so transformation of the electric field into a laboratory system should be taken into account.

The case $\mathrm{Re}_m \gg 1$ (or $\lambda \gg (\mu_0\sigma C_s)^{-1}$) means the «freezing» of the geomagnetic field lines into a medium. This inequality holds, for example, in wet grounds with the electric conductivity σ = 1 S/m for seismic waves with $\lambda >> 1$ km. In this limiting case the diffusion term can be neglected which leads to the following estimate of the induced magnetic field

$$H/H_0 \simeq v/C_s \simeq \xi/\lambda. \qquad (3.4)$$

The magnitude of the disturbance is determined by the medium displacement ξ only and does not depend on the crust parameters. Assuming that $v = 1$ cm/s and $H_0 = 40$ A/m we obtain from (3.4) $H \sim 0.08$ mA/m. The electric fields in the inertial and the laboratory systems are of the same order, *i.e.* $E \simeq \mu_0 C_s H \simeq \mu_0 v H_0$, and for the above parameters $E \simeq 0.5$ μV/m.

The reverse extreme case $\mathrm{Re}_m \ll 1$ (or $\lambda \ll (\mu_0 \sigma C_s)^{-1}$) corresponds to the «diffusion» limit. This case is more typical for geological media and ocean waves. For example, in a sedimentary layer with $\sigma = 10^{-2}$ S/m this restriction holds for seismic waves with $\lambda \ll 100$ km or $\omega \gg 0.3$ Hz. The induced magnetic field in the diffusion limit can be estimated as

$$H/H_0 \simeq (\xi/\lambda)\,\mathrm{Re}_m. \qquad (3.5)$$

By substituting $\lambda = 1$ km and $v = 0.1$ m/s in (3.5) we obtain the estimate $H \simeq 50$ mA/m. The electric field in the laboratory system is determined by a transformation factor, *i.e.* $E \simeq \mu_0 v H_0$.

The relationships (3.4) and (3.5) enable one to estimate the magnetic and electric effects of seismic waves by the order of magnitude. More detailed calculations indicate some additional peculiarities of the seismo-magnetic signals. For a longitudinal seismic wave propagating through a uniform conducting medium there exist two essentially different phases of induction currents spreading (Surkov, 1989b). At first the geomagnetic perturbation front spreads according to the diffusion law: $r \simeq 2\sqrt{Dt}$, faster than seismic front. At the time $t_* \simeq 4D/C_s^2$ the longitudinal wave outruns the diffusion front and moves ahead. With $t > t_*$ the second stage of the process begins when the geomagnetic perturbations become localized in the vicinity of the elastic wave front and propagate together with the velocity C_s. For a crust with $\sigma = 10^{-2}$ S/m and $C_s = 5$ km/s the critical time $t_* \simeq 12$ s and the distance at which the propagation regime of geomagnetic perturbations changes $r_* \simeq 60$ km. At larger distances from a source of seismic wave the geomagnetic perturbations and seismic signal will travel together.

The geomagnetic perturbations propagate somewhat ahead of the seismic wave front and can be treated as its forerunner (Surkov, 1989b,c; Guglielmi, 1991; Gershenzon *et al.*, 1993). To illustrate this effect, fig. 3 shows the dependence of the vertical component of the magnetic perturbations $H_z(t)$ calculated for $\sigma = 0.1$ S/m at $R = 5$ km from a source. The source for this example was the seismic longitudinal wave emitted by the underground explosion from the boundary of the destruction zone. The arrow indicates the arrival of the elastic seismic wave. To the left from the arrow a magnetic forerunner can be seen, which emerges due to the diffusion of induction currents excited at the front of the elastic wave. The amplitude of the forerunner decreases away from the seismic front, which acts as a moving source of magnetic disturbances. Within the region of magnetic forerunner (*i.e.* $r-R > C_s t$) magnetic disturbance decreases with distance r as

$$H(r) \simeq H_0 v(r) C_s^{-1} (\lambda/r_*)^2 \exp\left[-(r-R-C_s t) r_*^{-1}\right] \qquad (3.6)$$

where $r_* = D/C_s \simeq C_s t_*$ denotes a typical spatial scale of magnetic forerunner, oscillatory velocity of a medium varies with distance as $v(r) \simeq v_0 R/r$. So, the magnetic forerunner is confined in the region about several r_* near the front of the seismic wave. The ratio between the magnitudes of the magnetic forerunner and the main signal is about $(\lambda/r_*)^2$ in the «frozen-in» limit and is about (λ/r_*) in the «diffusion» limit. In the latter case the magnitude of the magnetic forerunner is smaller, but its spatial scale is larger. Another interpretation of magnetic forerunner was given by Guglielmi (1991) who explained its appearance as a result of the effect similar to Cherenkov emission. This analogy seems incorrect, because in a conductive homogeneous media, described by non-wave equations, emission does not appear.

At large distances from the source, where the seismic Raleigh surface wave dominates,

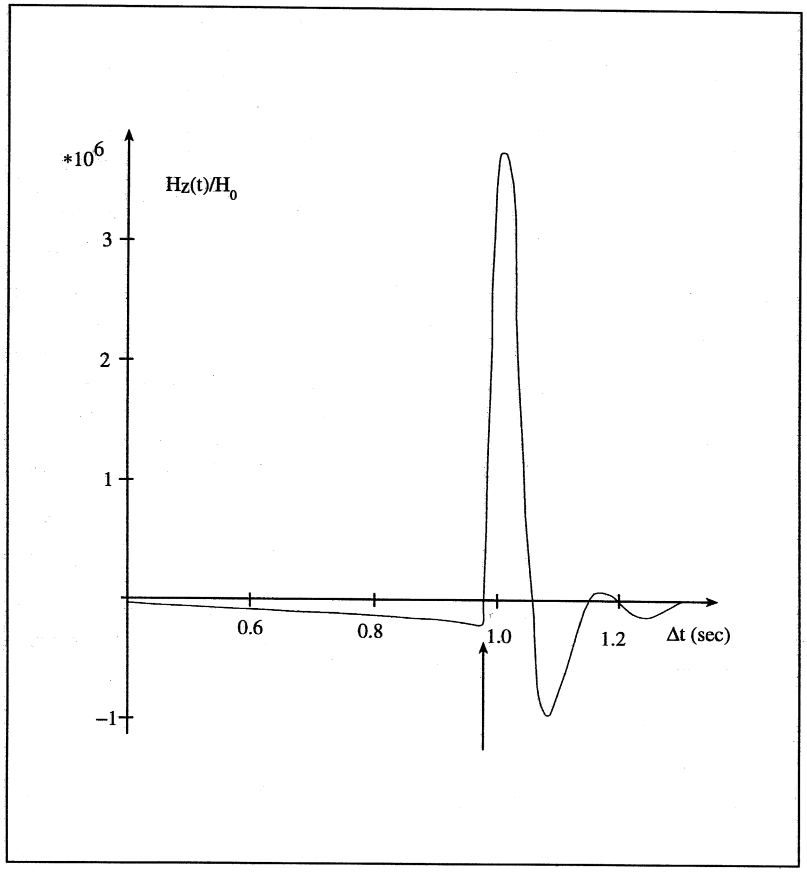

Fig. 3. Perturbation of the vertical component of the geomagnetic field H_z caused by longitudinal seismic wave.

the dependence of the induced electromagnetic signal amplitude on the distance r is $\sim r^{-1/2}$ (Gorbachev and Surkov, 1987). The dependence of amplitude on the depth l of the seismic source is $\sim l^{-5/2}$. At small distances the amplitude of magnetic perturbations diminishes with distance obeying the same law as the amplitude of the longitudinal seismic waves: $\sim r^{-1}$. Recently the reports on non-linear dissipative effects in the seismic waves which are associated with dispersive and dissipative properties of geological media have appeared. According to phenomenological theories, the amplitude of the Raleigh wave turns out to diminish as $\sim r^{-7/4}$, while its scale grows as $\sim r^{1/2}$. Then in the low-conductive media the damping rate of both acoustic and magnetic signals increases as compared with the ideally elastic media: $\sim r^{-5/4}$ (Dunin and Surkov, 1992). The lesser decrease of magnetic perturbation as compared with the seismic one is physically connected with the fact that the magnetic perturbations are an integral effect of all currents induced in the region with a scale $\sim \lambda \sim r^{1/2}$.

However, experimental detection of seismomagnetic events is not a simple task, because the induction signal would essentially be masked by the seismographic effect, *i.e.* vibrations of magnetic sensors under the action of the seismic wave. So, one has to isolate the induction seismo-magnetic signal from external noises and perturbations. This problem can be solved based on the specific features of seismo-magnetic signals as compared with typical ionosphere-magnetosphere disturbances. The ratio of the electric component of the seismo-magnetic signal to the magnetic one is nearly equal to the speed of the seismic wave: $Z_s = E/H \simeq \mu_0 C_s$ (Guglielmi, 1986a,b). Contrary to this, the above ratio for ionospheric signals equals the Tikhonov-Cagniard impedance Z_0, determined by the crust geoelectrical structure. The polarization of the inductive seismo-magnetic signal in the vertical plane in the atmosphere is strictly circular. From Maxwell's equations (div $\boldsymbol{H} = 0$ and rot $\boldsymbol{H} = 0$) it follows that, irrespective of the polarization of the seismic wave, the magnetic field induced by the wave is polarized in the (X, Z) plane, where the X axis is oriented along the propagation direction. Furthermore, this leads to $H_x/H_z = -i$, which means that the oscillations are polarized in a circular pattern. The component H_y is negligible compared with H_x and H_z as (ω/σ).

4. Probing the mechano-electrical sensitivity of the crust with seismic waves

The manifestation of electromagnetic precursors of earthquakes has a «mosaic» character, even in tectonically homogeneous blocks. Hence, the application of electromagnetic methods of seismic warning requires a selection of most «sensitive» points where such effects would be most pronounced. Preliminary probing of mechano-electrical properties of the region under study can be done with seismic waves from explosions or distant earthquakes.

4.1. *Seismo-magnetic probing*

Electromagnetic signals induced by seismic waves can be used for the induction seismo-magnetic probing (Guglielmi *et al.*, 1987). This method may be used in geological exploration and is implemented by recording of seismic ξ_z and associated magnetic B_z oscillations. Then the interpretation parameter $\zeta(\omega) = B_z(\omega)/\xi_z(\omega)$, *i.e.* the ratio of the vertical components of magnetic and deformation fields, which might be called the seismo-magnetic impedance, is analyzed. The frequency dependence $\zeta(\omega)$ enables the parameters of the geoelectrical structure to be restored. The induction seismo-magnetic probing differs from the known method of magnetotelluric sounding in that the source of the electromagnetic oscillations is under the Earth and not above it. The inverse problem to restore the vertical crust geoelectrical structure from seismo-magnetic impedance $\zeta(\omega)$ can be handled by the numerical model of the Earth core in the form of N layers with the conductivities σ_i and thicknesses h_i ($i = 1, ..., n$). The solution of the inverse problem considering the experimentally measured frequency dependence $\zeta(\omega)$ provides information on the values of σ_i, h_i. Thus seismo-magnetic probing allows us to acquire information on geoelectrical properties of the region at the explosion point (a testing ground, a mine, etc.) as a by-product obviating extra expenditures on electro- and magneto-exploration.

4.2. *Electromagnetic method for detection of tsunami wave*

Large scale movements of ocean water in the geomagnetic field due to earthquakes generate electric and magnetic fields. The theoretical models of the induction electromagnetic fields caused by ocean waves are well elaborated (Larsen, 1971). The estimates show that the magnetic effect of the tsunami wave does not exceed several nT, which is much less than typical magnetic disturbances of magnetospheric-ionospheric origin. Nonetheless the tsunami generated electromagnetic field has a number of specific peculiarities which may enable the expected signal to be retrieved from an intensive background noise (Gershenzon and Gokhberg, 1992a). These features are the following:

– the velocities of long wavelength tsunami waves $V \simeq (0.4\text{-}2) \cdot 10^2$ m/s are much lower than propagation velocities of magnetospheric-ionospheric disturbances, which are about 1-10^2 km/s. The magnetic disturbance a quarter of period runs ahead of the tsunami wave, *i.e.* about 10 min;

– the tsunami-generated magnetic signal has a peculiar vertical structure of polarization. Near the ocean surface the signal has a right-hand circular polarization ($B_z/B_x = i$), while at the bottom the signal is left-hand circular polarized ($B_z/B_x = -i$). Because the skin-depth of external disturbance is larger than the ocean depth, these disturbances should have the same polarization throughout the ocean;

– the impedance of the tsunami signal does not depend on water resistivity, but on wave propagation velocity only, *i.e.*, $Z_t = E/H = -i\mu_0 V$. Thus, Z_t of the tsunami-generated signal and Z_0 of external disturbances are essentially different.

Based on the above properties of the tsunami signal a system may be constructed to detect weak tsunami signals and to determine the magnitude and propagation direction of the tsunami wave. This system should consist of several bottom and surface magnetometers with sensitivity ~ $10^{-1} - 10^{-2}$ nT and electric field sensors with sensitivity ~ 0.1 mV/m.

4.3. *Probing of local mechano-electrical parameters*

The electric effects connected with the propagation of seismic waves were first pointed out by Ivanov (1939, 1940). At a distance of up to 120 m from a weak explosion a potential difference between grounded electrodes was recorded. This phenomenon was referred to as a seismoelectric effect of the type II, or E-effect (in contrast with the effect type I, or J-effect, which consists in a changed current between the grounded electrodes in the travel of elastic waves). Its explanation proposed by Frenkel (1944) proceeds from the electrokinetic effects in the fluid filling the capillaries and cracks in the Earth's surface layer. The variation in the electrical potentials of fluid and capillary walls is due to changes in the capillary pressure during deformation of the ground in the wave. The electrokinetic effect can be accounted for with the additional term in Ohm's law, which is proportional to pressure gradient

$$j = \sigma(E - C\nabla P). \tag{4.1}$$

In wet ground the empirical electrokinetic coefficient C is about $10^{-6} - 10^{-8}$ V/Pa (Strelkov, 1990). The pressure gradient produced by a seismic wave with $\lambda \simeq 10^3$ m, will generate a telluric electric field $E \simeq C|\nabla P| \simeq 10^{-3} - 10^{-5}$ V/m.

However, the quantitative assessment of the magnitude of the electrokinetic effect is difficult because of the uncertainty of many parameters: electrical potential, specific resistance of pore liquid, viscosity, rock porosity, etc. The ground magnetic signal produced by electrokinetic currents can be observed only above some crust inhomogeneity. Gathering of preliminary information on these parameters, which could be performed with seismic probing, is especially important for earthquake prediction research. Many geophysicists believe that electrokinetic effects might be responsible for emergence of magnetic anomalies prior to earthquakes (Mizutani *et al.*, 1976; Mizutani and Ishido, 1976; Strelkov, 1990). In that case the convective electric fields and currents may be produced by pressure gradient caused by a tectonic stress. However, the estimates of the role of this mechanism are still controversial because of great uncertainty in the medium parameters (Barsukov, 1990; Gershenzon and Gokhberg, 1992b). The same uncertainty persists concerning the effectiveness of the piezomagnetic effect. The seismo-electric probing of seismically active zone may help to solve these problems.

5. Seismogenic ULF noises and impulses

Studies of ULF (Ultra Low Frequency) magnetic disturbances in seismically active regions have revealed three classes of electromagnetic phenomena related with earthquakes:

– Seismo-magnetic signals synchronous with the passage of seismic waves through the observation point after strong distant earthquakes (Eleman, 1965; Gogatishvili, 1984). Also, correlated seismic and electromagnetic fluctuations were recorded at distances of 2.5-5.5 km after industrial explosions (Anisimov *et al.*, 1985).

– Sporadic magnetic impulses, slightly preceding seismic fronts. Two events with amplitudes ~ 0.5 nT were recorded at Kamchatka after earthquakes with $M = 6$ and $M = 7$ (Belov *et al.*, 1974). At distances $R \simeq 60$ km from epicenters magnetic impulses run ~ 10 s ahead of seismic fronts. A special technique of gradient measurements with small baselines to suppress the influence of ionospheric magnetic variations has been developed for detection of weak seismo-magnetic signals (Gokhberg *et al.*, 1989). With the use of this technique weak impulses with amplitudes $B \simeq$ 3-30 pT and $E \simeq 0.07$ μV/m were detected 10-30 s before seismic waves from local earthquakes with $M = 1.3\text{-}4.6$ at Caucuses (Guglielmi and Levshenko, 1994). The apparent propagation velocity of magnetic impulses from the quake focus was estimated to be about 14 km/s.

– Irregular magnetic pulsations (Gogatishvili, 1984; Fraser-Smith *et al.*, 1990; Molchanov *et al.*, 1992; Park *et al.*, 1993) or sporadic impulses (Moore, 1964), observed tens of minutes – hours before strong earthquakes.

The physics of the first class of events has been discussed above. The third class of events is poorly studied and has no clear physical explanation. These anomalous ULF pulsations might be related with pre-shock seismic activity, electromagnetic radiation emitted by large-scale cracks during the final stage of the crust destruction, or with global coordinated systems of mechano-electrical transformers in the forthcoming fault (Gokhberg *et al.*, 1985).

The second class of events does not have an obvious explanation either. These signals cannot be interpreted as magnetic forerunners of a seismic wave. The above consideration showed that the amplitude of the magnetic forerunner should gradually increase till the onset of the seismic wave front. Meanwhile, a clear gap between the arrival moments of magnetic impulse and seismic wave front has been observed. Probably, these magnetic impulses are related with transient magnetic fields excited by rapid movement of large-scale crust blocks during a quake. Some indirect indications on the emergence of short-lived intense electromagnetic fields during a quake were obtained in (Lockner *et al.*, 1983; Goshdzanov *et al.*, 1991). Though no theory of this process has been developed so far, some rough estimates of the effect can be made.

The induction field generated during the shift of two blocks along a fault during a quake can be estimated in the same way as in the theory of seismo-magnetic signals. Let us denote a fault scale as L, displacement of tectonic block during quake as ξ, typical time of displacement as τ, and skin-depth as $\delta_s \simeq (\tau/\mu_0\sigma)^{1/2}$. The similar to (3.4) and (3.5) analysis of the system (3.1) and (3.3) shows that: a) when $L < \delta_s$ the magnetic disturbance is $H/H_0 \simeq \xi L/\delta^2$; b) while in opposite case $L > \delta_s$: $H/H_0 \simeq \xi/L$.

For the parameters, corresponding to published events (Gokhberg *et al.*, 1989): magnitude $M = 6$, $L = 10^4$ m, $\xi = 0.4$ m and $\delta_s = 10^5$ m it follows from first estimate that $B = \mu_0 H \simeq 0.02$ nT. For another event with $M = 7$ and $L = 4.10^4$ m, $\xi = 1.3$ m, $\delta_s = 10^4$ m, from the second estimate one get $B \simeq 1.5$ nT. However, at the Earth's surface the magnetic field of the quake focus will be strongly attenuated. Even the geometrical damping factor $(l/r)^3$ will result in amplitudes at the observation point at $r \simeq 200$ km from the epicenter by at least 4 orders of magnitude less that in the quake focus. So, the possibility to interpret observations at Kamchatka, where magnetic impulses with magnitudes ~ $(2\text{-}10) \cdot 10^{-3}$ nT had been detected, seems questionable.

Another mechanism of quake-generated magnetic signals – an inertial (or electrokinetic) one, has been suggested by Guglielmi and Levshenko (1993). The current generation due to this mechanism takes place because of the difference between the vorticities of pore liquid flow and of rock skeleton movement. Similar to the well-known Tolman-Stuart effect, the inertial mechanism of magnetic field generation can be theoretically described by the additional term in the right-hand side of the magnetohydrodynamic equation

$$\frac{\partial \boldsymbol{H}}{\partial t} - \kappa\Delta \boldsymbol{H} = \mathrm{rot}\ [\boldsymbol{v}\boldsymbol{H}_0] - (m_{\mathrm{eff}}/e)\ \mathrm{rot}\ \dot{\boldsymbol{v}}, \tag{5.1}$$

$$m_{\mathrm{eff}} = e\varepsilon\zeta/4\pi\mu_0\, \nu\sigma_w .$$

The effective mass m_{eff} was derived via macroscopic parameters: dielectric permeability ε, conductivity σ_w ($\sigma = m\sigma_w$, where m is porosity), viscosity ν of pore liquid, the electrokinetic potential ζ and the charge e of the conductivity ion (Guglielmi, 1992). A magnetic disturbance generated by accelerated movement of two blocks along a fault during a quake can be roughly estimated with eq. (5.1). Assuming that the typical time of seismic shock is τ, acceleration along the fault is w and the typical scale of current system is a skin-depth δ_s, the magnetic field in the hypocenter is given by $H \simeq (m_{\mathrm{eff}}/e)w\tau\delta_s^{-1}$. According to this estimate the magnetic disturbance within the quake focus can reach $B \simeq 50$ nT, which shows that the inertial mechanism is more effective that the induction one. Comparative analysis (Guglielmi, 1995) testifies that the induction mechanism prevails at relatively low frequencies compared with the electrokinetic mechanism.

So far, only quasi-stationary and ULF electromagnetic response on seismic impact has been considered. The physics of the electromagnetic response of rocks on seismic waves is much wider than in the consideration above. Beyond the scope of the present review are such phenomena as the generation of impulsive electromagnetic radio emission (Gokhberg *et al.*, 1987; Hayakawa and Fujinawa, 1994).

6. Conclusions

The estimated magnetic effects of the underground explosion show that the anomalous fields are of an appreciable magnitude within the radius of a few kilometers from the explosion epicenter. The long duration of the anomalous field is an essential factor. It can be used to set up measurement complexes whose information on the electromagnetic field within the near zone of an explosion, along with the seismic data, will make it more reliable to control the conditions and parameters of underground nuclear explosions. The geomagnetic perturbations prove to be considerable not only at near distances from an explosion, but at far distances also, where these perturbations propagate together with seismic waves.

The theoretical models and experimental data acquired during experiments with underground and surface explosions will be useful for investigations on earthquake dynamics. It is widely believed that electromagnetic methods will play a key role in the operative forecasting of earthquake risk (Hayakawa and Fujinawa, 1994). The experimental studies would be more effective if some criteria for the separation of signals of different nature were used. Even the current rough knowledge of the physics of seismo-electromagnetic phenomena allows us to suggest some of them, based on the polarization and impedance properties of these signals. For that purpose the special methods of the polarization filtering could be used.

The described methods for seismo-magnetic probing allows us to use the data obtained from the synchronous recording of the explosion seismic wave and its magnetic response to receive additional information on the structure of the Earth's crust at the recording point. Despite their small amplitudes, the seismo-magnetic signals can be used in tsunami warning systems. The magnetic impulse of a quake could be used to elaborate the systems for urgent switch-off of dangerous industry plants prior to the arrival of destructive seismic waves.

Acknowledgements

This research was supported by INTAS (grant # 93-3412) and partly by grant 96-05-64838 from the Russian Fund for Fundamental Research.

REFERENCES

AKOPYAN, TZ.G., V.V. NAGAPETYAN, A.N. PUSHKOV, G.V. RASANOVA and YU.P. SKOVORODKIN (1973): Magnetic investigation during the explosions at the region of the Kadzharinky quarry, *Izv. Akad. Nauk Arm. SSR (Earth Sciences)*, **26** (6), 90-92.

ANISIMOV, S. V., M.B. GOKHBERG, E.A. IVANOV, M.N. PEDANOV, N.N. RUSAKOV, V.A. TROITSKAYA and V.I. GONCHAROV (1985): Short-period oscillations of the Earth's magnetic field during an industrial explosion, *Dokl. Akad. Nauk SSSR*, **281** (3), 556-559.

BARSUKOV, O.M. (1990): The assessment of magnetic perturbations of an electrokinetic nature, *Izv. Akad. Nauk SSSR, Fizika Zemli*, **1**, 125-128.

BARSUKOV, O.M. and YU.P. SKOVORODKIN (1969): Magnetic observations in the region of the Medeo explosion, *Izv. Akad. Nauk SSSR, Fizika Zemli*, **5**, 68-69.

BELOKOPYTOV, V.A., M.B. GOKHBERG, T. V. GUSEVA, YU.P. SKOVORODKIN and YU.A. TRAPEZNIKOV (1985): Influence of an impulsive impact on deformation processes, *Dokl. Akad. Nauk SSSR*, **280** (3), 575-578.

BELOV, S. V., N.I. MIGUNOV and G.A. SOBOLEV (1974): Magnetic effects accompaining strong earthquakes in Kamchatka, *Geomagn. Aeron.*, **14** (2), 380-382.

DUNIN, S.Z. and V. V. SURKOV (1992): Excitation of the external magnetic field by the Rayleigh wave propagating over the elastic dissipative semispace, *Magnetic Hydrodynamics*, **1**, 3-10.

ELEMAN, F. (1965): The response of magnetic instruments to earthquake waves, *J. Geomagn. Geoelectr.*, **18** (1), 43-72.

FRASER-SMITH, A.C., A. BERNARDI, P.R. MCGILL, T.E. LADD, R.A. HELLIWELL and O.G. VILLARD (1990): Low frequency magnetic field measurements near the epicenter of the $M_s = 7.1$ Loma Prieta earthquake, *Geophys. Res. Lett.*, **17**, 1465-1468.

FRENKEL, YA.I. (1944): On the theory of seismic and seismoelectric phenomena in wet grounds, *Izv. Akad. Nauk SSSR (Geography and Geophysics)*, **8** (4), 133-150.

GERSHENZON, N.I. and M.B. GOKHBERG (1992a): Electromagnetic forcasting of tsunami, *Izv. Akad. Nauk SSSR, Fizika Zemli*, **2**, 38-42.

GERSHENZON, N.I. and M.B. GOKHBERG (1992b): About earthquake precursors in variations of geomagnetic field of electrokinetic nature, *Izv. Akad. Nauk SSSR, Fizika Zemli*, **9**, 100-105.

GERSHENZON, N.I., M.B. GOKHBERG and A.V. GUGLIELMI (1993): Electromagnetic field of seismic impulse, *Izv. Akad. Nauk SSSR, Fizika Zemli*, **9**, 48-52.

GOGATISHVILI, YU.M. (1984): Geomagnetic precursors of intensive earthquakes in the spectrum of geomagnetic pulsations with frequencies 1-0.02 Hz, *Geomagn. Aeron.*, **24** (4), 697-700.

GOKHBERG, M.B., I.L. GUFELD, N.I. GERSHENZON and V.A. PILIPENKO (1985): Electromagnetic effects during the distruction of the Earth's crust, *Izv. Akad. Nauk SSSR, Fizika Zemli*, **1**, 72-87.

GOKHBERG, M.B., I.L. GUFELD, O.V. KOZYREVA, N.N. NIKIFOROVA, A.A. ROZNOY, M.S. SOLOV'EVA and A.YA. FEDOTOV (1987): Electromagnetic emission of rocks under explosive impact, *Dokl. Akad. Nauk SSSR*, **295** (2), 321-325.

GOKHBERG, M.B., S.M. KRYLOV and V.T. LEVSHENKO (1989): Electromagnetic field of the earthquake focus, *Dokl. Akad. Nauk SSSR*, **308** (1), 62-65.

GORBACHEV, L.P. and V. V. SURKOV (1987): Perturbations in the external magnetic field caused by the Rayleigh surface wave, *Magnetic Hydrodynamics*, **2**, 3-12.

GOSHDZANOV, M.B., M.B. MUKHANOV and V.A. PILIPENKO (1991): Impulsive disturbances of the ionosphere caused by thunderstorm and seismic activity, *Geomagn. Aeron.*, **31** (6), 1064-1069.

GUGLIELMI, A. V. (1986a): Magnetoelastic waves, *Izv. Akad. Nauk SSSR, Fizika Zemli*, **7**, 112.

GUGLIELMI, A.V. (1986b): Excitation of oscillations of the electromagnetic field by elastic waves in the conducting body, *Geomagn. Aeron.*, **27** (3), 467-470.

GUGLIELMI, A.V. (1991): Magnetic structure of the elastic wave front in conductive media, *Izv. Akad. Nauk SSSR, Fizika Zemli*, **4**, 753-758.

GUGLIELMI, A.V. (1992): The Tolman-Stuart effect in the Earth's crust, *Izv. Akad. Nauk SSSR, Fizika Zemli*, (10), 109-112.

GUGLIELMI, A.V. (1995): The equation for generation of seismomagnetic signals, *Dokl. Akad. Nauk SSSR*, **342** (3), 390-392.

GUGLIELMI, A.V. and V.T. LEVSHENKO (1993): Inertial mechanism of the seismo-magnetic signal generation, *Dokl. Akad. Nauk SSSR*, **329** (4), 432-434.

GUGLIELMI, A.V. and V.T. LEVSHENKO (1994): Electromagnetic signals from earthquakes, *Izv. Akad. Nauk SSSR, Fizika Zemli*, **5**, 65-70.

GUGLIELMI, A.V., M.B. GOKHBERG, B.I. KLAIN and N.N. RUSAKOV (1987): Induction seismomagnetic probing of the Earth crust, *Dokl. Akad. Nauk SSSR*, **293** (4), 828-830.

HASBROUK, W.P. and J.H. ALLEN (1972): Quasi-static magnetic field changes associated with Cannikin nuclear explosions, *Bull. Seism. Soc. Am.*, **62** (6), 1479-1480.

HAYAKAWA, H. and Y. FUJINAWA (Editors) (1994): *Electromagnetic Phenomena Related to Earthquake Prediction*, Tokyo, pp. 677.

IVANOV, A.G. (1939): The effect of electrolization in the Earth's beds during the travelling of elastic waves, *Dokl. Akad. Nauk SSSR*, **24** (1), 41-43.

IVANOV, A.G. (1940): The seismo-electric effect of the second type, *Izv. Akad. Nauk SSSR (Geography and Geophysics)*, **5**, 699-726.

KALISKY, S. (1960): Solution of the equations of motion in a magnetic field for an isotropic body in an infinite space assuming perfect electric conductivity, *Proc. Vibr. Probl.*, **1** (3), 53-67.

KALISKY, S. and D. ROGULA (1960): Rayleigh waves in a magnetic field in the case of a perfect conductor, *Proc. Vibr. Probl.*, **1** (5), 63-80.

KEILIS-BOROK, V.I. and A.S. MONIN. (1959): Magnetoelastic waves and the boundary of the Earth core, *Izv. Akad. Nauk SSSR (Geophysics)*, **11**, 1529-1541.

KNOPOFF, E.L. (1955): The interaction between elastic waves motions and a magnetic field in electrical conductors, *J. Geophys. Res.*, **60** (4), 617-629.

KONDORSKY, E.I. (1959): On the theory of persistent magnetic states of ferromagnetic substances in magnetization, *ZETF (J. Exp. Theor. Phys.)*, **37** (4), 1110-1115.
KOZLOV, A.N., A.N. PUSHKOV, R.SH. RAKHMATULIN and YU.P. SKOVORODKIN (1974): Magnetic effects during explosions in rocks, *Izv. Akad. Nauk SSSR, Fizika Zemli*, **3**, 66-71.
LARSEN, J.C. (1971): The electromagnetic field of long and intermediate water waves, *J. Mar. Res.*, **29** (1), 28-45.
LOCKNER, D.A., M.J.S. JOHNSTON and J. BYERLEE (1983): A mechanism to explain the generation of earthquake lights, *Nature*, **302** (59), 3-9.
LONGMIRE, C.L. (1978): On the EMP produced by nuclear explosions, *IEEE Trans. Electromagn. Compat.*, **20**, 3-13.
MIZUTANI, H. and T. ISHIDO (1976): New interpretation of magnetic field variation associated with the Matsushiro earthquakes, *J. Geomagn. Geoelectr.*, **28** (2), 179-188.
MIZUTANI H., T. ISHIDO, T. YOKOKURA and S. OHNISHI (1976): Electrokinetic phenomena associated with earthquakes, *Geophys. Res. Lett.*, **3** (7), 365-368.
MOLCHANOV, O.A., YU.A. KOPYTENKO, P.M. VORONOV, E.A. KOPYTENKO, T.G. MATIASHVILI, A.C. FRASER-SMITH and A. BERNARDI (1992): Results of magnetic field measurements near the epicenters of the Spitak (M_s = 6.9) and Loma Prieta (M_s = 7.1) earthquakes: comparative analysis, *Geophys. Res. Lett.*, **19** (14), 1495-1498.
MOORE, G.W. (1964): Magnetic disturbances preceding the 1964 Alaska earthquake, *Nature*, **203** (4944), 508-509.
PARK, S.K., M.J.S. JOHNSTON, T.R. MADDEN, F.D. MORGAN and H.F. MORRISON (1993): Electromagnetic precursors to earthquakes in the ULF band: a review of observations and mechanism, *Rev. Geophys.*, **31** (2), 117-132.
PRICE, G.H. (1974): The electromagnetic pulse from nuclear detonations, *Rev. Geophys. Space Phys.*, **12** (3), 389-400.
STACEY, F.D. (1964): The seismo-magnetic effect, *Pure Appl. Geophys.*, **58** (11), 5-23.
STRELKOV, E.M. (1990): The estimation of the effect of magnetic field generation by seismoelectric currents, *Izv. Akad. Nauk SSSR, Fizika Zemli*, **10**, 17-23.
SURKOV, V.V. (1989a): Local changes in geomagnetic and geoelectric fields under rock deformation near the Earth surface, *Izv. Akad. Nauk SSSR, Fizika Zemli*, **5**, 91-96.
SURKOV, V.V. (1989b): Distortion of external magnetic field by a longitudinal acoustic wave, *Magnetic Hydrodynamics*, **2**, 9-12.
SURKOV, V.V. (1989c): Geomagnetic disturbances in a layered medium caused by propagation of a longitudinal spherical wave, *ZPMTP (J. Appl. Math. Theor. Phys.)*, **5**, 20-30.
VIKTOROV, I.A. (1975): Elastic waves in a solid semispace with a magnetic field, *Dokl. Akad. Nauk SSSR*, **221** (5), 1069-1072.
UNDZENKOV, B.A. and V.A. SHAPIRO (1967): Seismomagnetic effect exerted upon the magnetite deposit, *Izv. Akad. Nauk SSSR, Fizika Zemli*, **1**, 121-126.
YERZHANOV L.S., A.K. KURSKEEV, T.E. NASYNBAEV and A. V. BUSHUEV (1985): Geomagnetic observations during the MASSA experiments, *Izv. Akad. Nauk SSSR, Fizika Zemli*, **11**, 80-82.