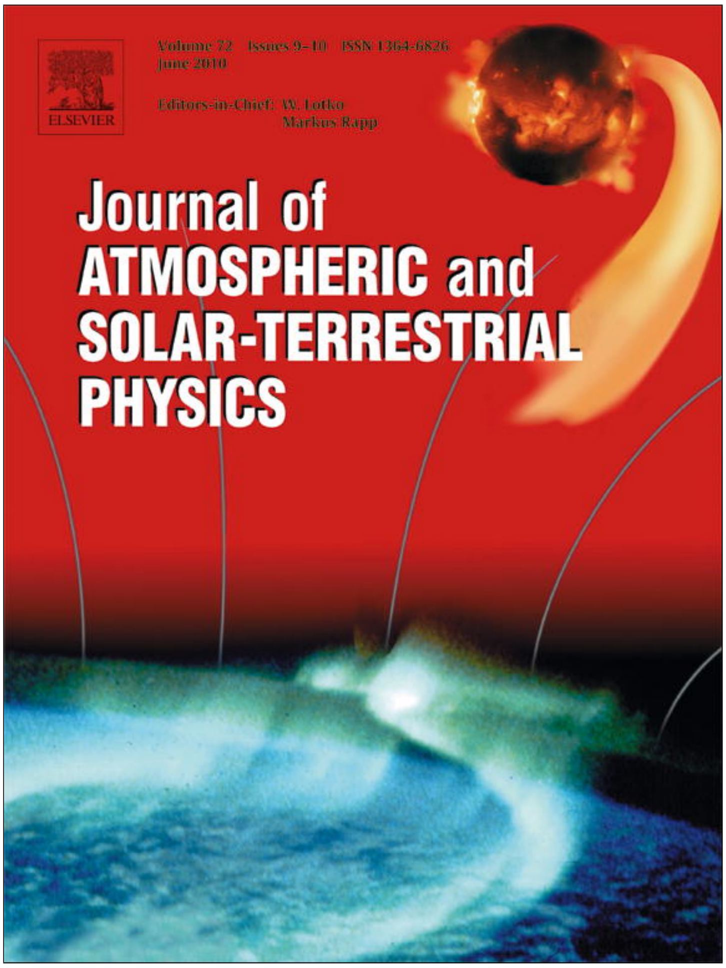
Volume 72 Issues 9–10 ISSN 1364-6826
June 2010
Editors-in-Chief: W. Lotko
Markus Rapp
Journal of
ATMOSPHERIC and
SOLAR-TERRESTRIAL
PHYSICS

Journal of Atmospheric and Solar-Terrestrial Physics 72 (2010) 763–766

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Generation of ULF geomagnetic pulsations during early stage of earthquake preparation

V.M. Sorokin [a,*], O.A. Pokhotelov [b]

[a] Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), Russian Academy of Sciences, 142190 Troitsk, Moscow Region, Russian Federation
[b] Institute of Physics of the Earth (IFZ), Russian Academy of Sciences, 123995 Moscow, 10 B. Gruzinskaya, Russian Federation

ARTICLE INFO

Article history:
Received 26 November 2009
Received in revised form
17 March 2010
Accepted 24 March 2010
Available online 27 March 2010

Keywords:
ULF geomagnetic pulsations
Earthquake preparation
Variation of the conductivity
Telluric currents

ABSTRACT

A new mechanism of generation of ULF geomagnetic pulsations near the Earth's surface near the future earthquake epicenter is proposed. The mechanism is connected with the migration of fluid and gases during the active phase of the earthquake preparation. The motion of fluid and gases is accompanied by the formation of cracks and fast filling of them by fluid and gases. The variation of electrical conductivity in the layer induces the impulsive electric current. The magnetic field due to this current can be registered on the Earth's surface. The corresponding equations for magnetic field perturbations caused by non-stationary conductivity are derived. The amplitude and temporal characteristics of the magnetic impulses are estimated.

1. Introduction

It is of common knowledge that processes arising in the lithosphere as a result of enhancement of seismic activity prior to the earthquakes are accompanied by the ULF magnetic field perturbations near the Earth's surface. The generation of these variations and their use for the short-term warning of the impending earthquakes have been the subject of a great deal of research in recent years and has been reviewed by Varotsos (2001) and Hayakawa and Molchanov (2002). Furthermore, Fitterman (1979) and Surkov and Pilipenko (1999) have discussed the physical mechanisms of generation of ULF magnetic variations in the lithosphere during earthquake preparation. The registration and their propagation from the lithosphere to the ionosphere have been discussed by Molchanov (1999) and Pilipenko et al. (1999). The magnetohydrodynamic effect of the migrating fluid, which can be the cause of the electromagnetic earthquake precursors, has been discussed by Draganov et al. (1999). We assumed that in the course of the earthquake preparation the source of the lithosphere perturbations is due to the migration of gases and fluids. This effect is connected with the heat flux and dynamical motion of fluid. Yamashita (1997) showed that seismic disruptions can arise due to the effect of the fluid super-compression. The gas migration also plays an important role in the earthquake preparation (e.g., Gold and Vogel, 1992). The observed surface atmosphere heating (Tronin et al., 2004) arises due to the heat flux and migration of the fluids and gases. Such a process has been recently considered by Molchanov et al. (2004) as the source of the lithosphere–ionosphere interactions.

The main purpose of the present paper is to develop a theory of ULF magnetic field generation near the Earth's surface arising in the course of rapid expulsion of the background electric field in front of the migrated fluid and gases. The electric field is connected with the magnetotelluric currents that arise in the lithosphere due to the variations of geomagnetic field of the magnetospheric origin.

The present paper is structured as follows. The basic equations necessary for estimation of the amplitudes of electromagnetic fields in the geophysical medium possessing the variable electrical conductivity are derived in Section 2. Section 3 is devoted to the calculation of the magnetic field on the Earth's surface. Our discussions and conclusions are found in Section 4.

2. Basic equations for the electromagnetic fields in the medium with variable electrical conductivity

During the final stage of the earthquake preparation, the fluid, migrating upwards downstream the front, transfers the fluid layer that penetrates the upper ground layers. In front of this layer there is formation of the soil gases the upward motion of which is accompanied by the formation of cracks and fast penetration of the fluid into the newly formed faults. The fluid electrical

* Corresponding author. Tel.: +7 495 330 9902; fax: +7 496 751 0124
E-mail address: sova@izmiran.ru (V.M. Sorokin).

1364-6826/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jastp.2010.03.021

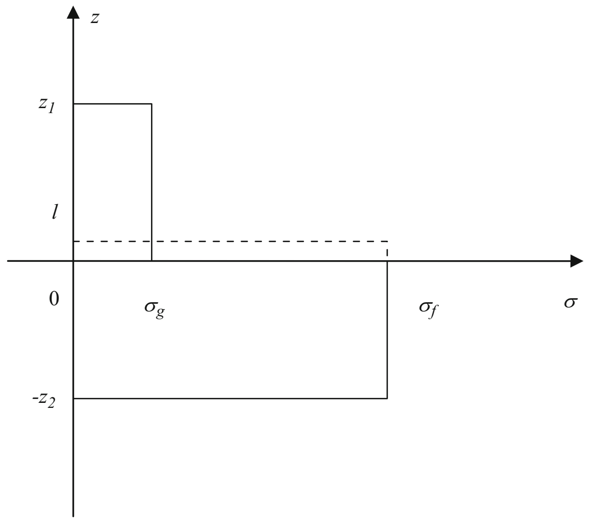

Fig. 1. The vertical distribution of electrical conductivity. The dashed line points out on the location of the conductive layer when fluid is migrated upward.

conductivity substantially exceeds the conductivity of the dry ground. Thus, during jump-like fluid migration the fault possesses the impulsive variation of the conductivity on its upper boundary. Such variation results in the generation of the magnetic field impulses on the Earth's surface arising from the telluric currents.

In order to calculate the magnetic field we introduce the Cartesian system of coordinates with the z-axis directed upward. The plane $z=0$ coincides with the upper boundary of the fluid whereas the Earth's surface coincides with the plane $z=z_1$. Below this there is a layer of dry ground with conductivity σ_g, and the layer $-z_2<z<0$ of the ground with the fluid, the conductivity of which is σ_f, as it is depicted in Fig. 1. Therefore, the unperturbed conductivity of these two layers is

$$\sigma_0(z)=\sigma_g\eta(z)\eta(z_1-z)+\sigma_f\eta(-z)\eta(z+z_2), \tag{1}$$

where $\eta(z)$ is the step function.

The filling of cracks by fluid leads to the change in the electrical conductivity of the thin layer above the plane $z=0$ by a certain value denoted as $\sigma_1(z,t)$. The magnetic and electric fields $\mathbf{B}$ and $\mathbf{E}$ during variation of the medium conductivity can be calculated from the quasi-stationary Ampere and Faraday laws, i.e.

$$\nabla\times\mathbf{H}=(\sigma_0+\sigma_1)\mathbf{E};\quad \nabla\times\mathbf{E}=-\frac{\partial\mathbf{B}}{\partial t};\quad \mathbf{B}=\mu\mu_0\mathbf{H}, \tag{2}$$

where μ_0 is the permeability of free space and μ is the magnetic permeability. We direct the external uniform electric field E_0 along the x-axis. The Ampere's law gives

$$\frac{\partial B_y(z,t)}{\partial z}=-\mu\mu_0[\sigma_0(z)+\sigma_1(z,t)][E_0(t)+E(z,t)], \tag{3}$$

where $E(z,t)$ is the perturbation of the electric field that arises as a result of the variation of the electrical conductivity by the value $\sigma_1(z,t)$.

Let us introduce connected with this electric field perturbation of the magnetic field $B(z,t)=B_y(z,t)-B_0(z,t)$, where unperturbed magnetic field $B_0(z,t)$ is

$$B_0(z,t)=-\frac{1}{2}\mu\mu_0E_0(t)\left[\int\limits_{-z_2}^{z}dz'\sigma_0(z')-\int_z^{z_1}dz'\sigma_0(z')\right].$$

Using this equality from Eq. (3) one finds the relation that defines the magnetic field perturbation in the course of variation of the conductivity

$$B(z,t)=-\frac{1}{2}\mu\mu_0E_0(t)\left[\int\limits_{-z_2}^{z}dz'\sigma_1(z',t)-\int_z^{z_1}dz'\sigma_1(z',t)\right]$$
$$-\frac{1}{2}\mu\mu_0\left\{\int\limits_{-z_2}^{z}dz'[\sigma_0(z')+\sigma_1(z',t)]E(z',t)-\int_z^{z_1}dz'[\sigma_0(z')+\sigma_1(z',t)]E(z',t)\right\}. \tag{4}$$

From Eq. (2) one finds the equation for perturbation of the electric field

$$-z_2<z<z_1;\quad \frac{\partial^2E(z,t)}{\partial z^2}-\mu\mu_0\frac{\partial}{\partial t}\{\sigma_1(z,t)E_0(t)+[\sigma_0(z)+\sigma_1(z,t)]E(z,t)\}=0,$$
$$z>z_1,\ z<-z_2;\frac{\partial^2E(z,t)}{\partial z^2}=0. \tag{5}$$

3. Magnetic field on the earth's surface

We assume that the change in conductivity arises in the thin layer in the vicinity of the plane $z=0$ with the width $l\ll z_1,z_2$

$$\sigma_1(z,t)=l\delta(z)\Delta\sigma(t), \tag{6}$$

where $\delta(z)$ is the Dirac delta function.

Substituting (1) and (6) into (4) one obtains the formula for calculating the time dependence of the magnetic field perturbation on the Earth's surface

$$B(z_1,t)=-\frac{1}{2}\mu\mu_0\left\{\Delta\sigma(t)l[E_0(t)+E(0,t)]+\int_{-z_2}^{z_1}dz'\sigma_0(z')E(z',t)\right\}. \tag{7}$$

Substituting (1) and (6) into (5) and integrating (5) over z in the vicinity of $z=0$ one obtains the equations that satisfy the electric field in the dry ground of the upper layer and wet ground of the lower layer

$$\begin{aligned}&0<z<z_1;\quad \frac{\partial^2E(z,t)}{\partial z^2}-\mu\mu_0\sigma_g\frac{\partial E(z,t)}{\partial t}=0,\\&-z_2<z<0;\quad \frac{\partial^2E(z,t)}{\partial z^2}-\mu\mu_0\sigma_f\frac{\partial E(z,t)}{\partial t}=0,\end{aligned} \tag{8}$$

and the boundary condition on the plane $z=0$

$$E(+0,t)-E(-0,t)=0;\frac{\partial E(+0,t)}{\partial z}-\frac{\partial E(-0,t)}{\partial z}$$
$$=\mu\mu_0l\frac{\partial}{\partial t}\Delta\sigma(t)[E_0(t)+E(0,t)] \tag{9}$$

In order to calculate the perturbation of the magnetic field one has to solve Eq. (8) with boundary conditions (9) and substitute the result into Eq. (7). Let us search for the solution in the form of the power series

$$E(z,t)=\sum_{n=1}^{\infty}E_n(z,t). \tag{10}$$

The perturbation of the magnetic field on the Earth's surface is defined by

$$B(z_1,t)=-\frac{1}{2}\mu\mu_0\left\{\Delta\sigma(t)lE_0(t)\right.$$
$$\left.+\sum_{n=1}^{\infty}\left[\Delta\sigma(t)lE_n(0,t)+\sigma_g\int_0^{z_1}dz'E_n(z',t)+\sigma_f\int\limits_{-z_2}^{0}dz'E_n(z',t)\right]\right\}. \tag{11}$$

Substituting (10) into (9) one finds the recurrent formulae for the boundary conditions of the addends of this series

$$E_n(+0,t)-E_n(-0,t)=0; \quad \frac{\partial E_n(+0,t)}{\partial z}-\frac{\partial E_n(-0,t)}{\partial z}$$
$$=\mu\mu_0 l\frac{\partial}{\partial t}\Delta\sigma(t)E_{n-1}(0,t), \tag{12}$$

where $E_0(0,t)=E_0(t)$.

Furthermore, let us take a Fourier transform of the addends in series (10), i.e.

$$E_n(z,t)=\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}E_n(z,\omega)\exp-(i\omega t);$$
$$E_n(z,\omega)=\int_{-\infty}^{\infty}dtE_n(z,t)\exp(i\omega t). \tag{13}$$

Substituting (10) into (8) and using (13) one finds

$$\begin{aligned} z>0; &\quad \frac{d^2E_n(z,\omega)}{dz^2}+q_g^2(\omega)E_n(z,\omega)=0; \quad q_g=\sqrt{i\mu\mu_0\sigma_g\omega}; \\ z<0; &\quad \frac{d^2E_n(z,\omega)}{dz^2}+q_f^2(\omega)E_n(z,\omega)=0; \quad q_f=\sqrt{i\mu\mu_0\sigma_f\omega}. \end{aligned} \tag{14}$$

Eq. (14) is supplemented by the continuity conditions of the tangential component of the field and its normal derivative at the planes $z=z_1$, $z=-z_2$ and recurrent boundary conditions at the plane $z=0$

$$E_n(+0,\omega)-E_n(-0,\omega)=0; \quad \frac{dE_n(+0,\omega)}{dz}-\frac{dE_n(-0,\omega)}{dz}=\kappa_{n-1}(\omega);$$
$$\kappa_n(\omega)=\mu\mu_0 l\int_{-\infty}^{\infty}dt\left[\frac{d}{dt}\Delta\sigma(t)E_n(0,t)\right]\exp(i\omega t), \tag{15}$$

The solutions of Eq. (14) with boundary conditions (15) take the form

$$0<z<z_1; \quad E_n(z,\omega)=E_n(0,\omega)\frac{\cos[q_g(\omega)(z-z_1)]}{\cos[q_g(\omega)z_1]}; \quad \mathrm{Re}q_g(\omega)>0;$$
$$-z_2<z<0; \quad E_n(z,\omega)=E_n(0,\omega)\frac{\cos[q_f(\omega)(z+z_2)]}{\cos[q_f(\omega)z_2]}; \quad \mathrm{Re}q_f(\omega)>0;.$$
$$E_n(0,\omega)=\frac{\kappa_{n-1}(\omega)}{q_g(\omega)\tan[q_g(\omega)z_1]+q_f(\omega)\tan[q_f(\omega)z_2]} \tag{16}$$

Using the integral transforms (13) and substituting (16) into (11) one obtains

$$B(z_1,t)=-\frac{1}{2}\mu\mu_0\Delta\sigma(t)l\left[E_0(t)+\sum_{n=1}^{\infty}\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}\exp(-i\omega t)E_n(0,\omega)\right]$$
$$-\frac{1}{2}\mu\mu_0\sum_{n=1}^{\infty}\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}\exp(-i\omega t)E_n(0,\omega)\left\{\sigma_g\frac{\tan[q_g(\omega)z_1]}{q_g(\omega)}+\sigma_f\frac{\tan[q_f(\omega)z_1]}{q_f(\omega)}\right\}. \tag{17}$$

Eq. (17) allows us to calculate the amplitude of horizontal component of the magnetic perturbation on the Earth's surface for the arbitrary time dependence of the external electric field and conductivity in the crack filled with the fluid.

For making estimations we reduce Eq. (17) assuming that $E_0(t)$ slowly varies with time and $\sigma_g \ll \sigma_f$. Let us use the first iteration retaining in (17) the first addend in the series

$$B(z_1,t)=-\frac{1}{2}\mu\mu_0 lE_0(t)\left\{\Delta\sigma(t)+\int_0^t dt'\frac{d\Delta\sigma(t')}{dt'}\int_{-\infty}^{\infty}\frac{d\omega}{2\pi i\omega}\exp[-i\omega(t-t')]\right\}$$
$$-\frac{l^2}{2z_2}\mu\mu_0E_0(t)\Delta\sigma(t)\int_0^t dt'\frac{d\Delta\sigma(t')}{dt'}\int_{-\infty}^{\infty}\frac{d\omega}{2\pi i\omega}\exp[-i\omega(t-t')].$$

In the course of derivation we made use of inequality $q_f z_2 \ll 1$ that is satisfied when conductivity is slowly varying function on the time scales $t \gg \mu\mu_0\sigma_f z_2^2$. Moving the integration path into lower complex ω-plane, the integrals over frequency can be

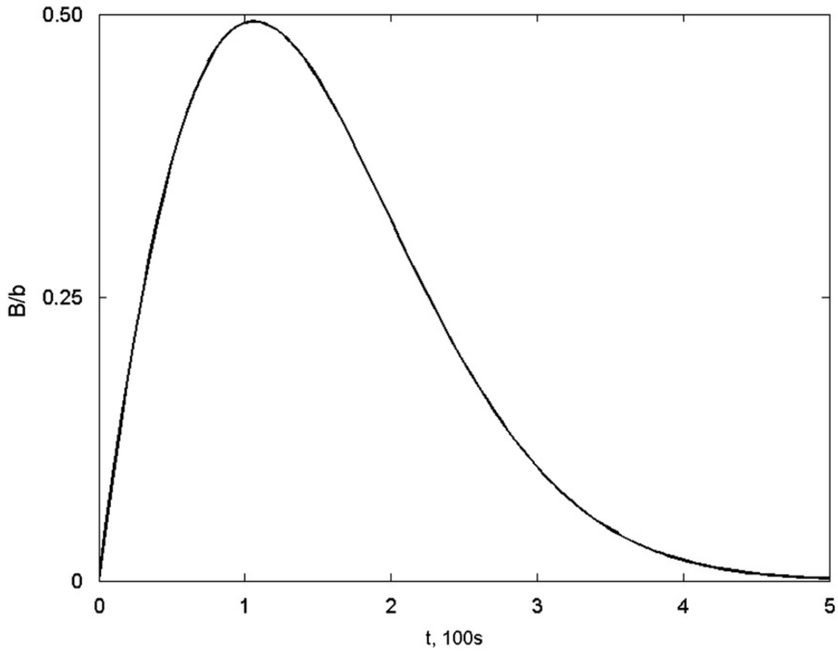

Fig. 2. The temporal variation of the magnetic field perturbation on the Earth's surface arising as a result of the migration of the conductive layer. The following parameters have been selected: $z_2=10^4$ m, $t_0=200$ s and $t_1=100$ s.

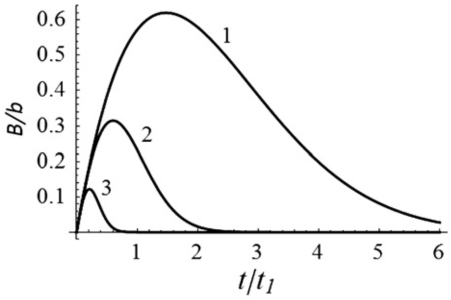

Fig. 3. The temporal variation of the magnetic field perturbation on the Earth's surface arising as a result of the migration of the conductive layer. The following parameters have been selected: (1) $t_1/t_0=0.3$, (2) $t_1/t_0=1.0$ and (1) $t_1/t_0=3.0$.

reduced to residues at the point $\omega=0$. As a result one obtains

$$B(z_1,t) = -\mu\mu_0 l\Delta\sigma(t)E_0(t)\left[1+\frac{l}{2z_2}\frac{\Delta\sigma(t)}{\sigma_f}\right]. \quad (18)$$

In order to estimate the amplitude of the perturbation we choose the functions $\Delta\sigma(t)$ and $E_0(t)$ in the form

$$\Delta\sigma(t) = \sigma_f\left[1-\exp\left(-\frac{t}{t_1}\right)\right]\eta(t); \quad E_0(t) = E_0(0)\exp\left(-\frac{t^2}{t_0^2}\right).$$

Substituting these functions into (18) we find the time dependence of the magnetic field perturbation for $t>0$

$$B(z_1,t) = -b\left[1-\exp\left(-\frac{t}{t_1}\right)\right]\exp\left(-\frac{t^2}{t_0^2}\right)\left\{1+\frac{l}{2z_2}\left[1-\exp\left(-\frac{t}{t_1}\right)\right]\right\};$$
$$b=\mu\mu_0 l\sigma_f E_0(0) \quad (19)$$

Fig. 2 shows the plot of the amplitude of magnetic perturbation as a function of time calculated with the help of Eq. (19). The relevant observations of the background unperturbed electric field $E_0(0)$ give the value of $(10^{-5}$–$10^{-4})$ V/m in the ground (Schekotov, 2010, private communication). Assuming $\mu=1$, $\mu_0=4\pi\times10^{-7}$ H/m, $\sigma_f=0.02$ S/m, $E_0(0)=10^{-4}$ V/m and $l=10^2$ m one finds the characteristic value of the magnetic field perturbation $b=0.2$ nT. The plot of temporal variation of amplitude for the relevant magnetic perturbations at different parameters t_0 and t_1 is depicted in Fig. 3. Calculations show that the upward migration of the ground boundary with the enhanced content of the fluid possessing the high electrical conductivity is accompanied by generation of magnetic impulses on the Earth's surface. Its temporal and amplitude characteristics are defined as temporal scales of the boundary motion and variation of the telluric currents as well as by the values of the fluid conductivity and the electric field of the telluric currents

4. Conclusions

The enhancement of seismic activity is accompanied with fluid upward migration. Various mechanical, chemical and electromagnetic processes display this stage of the lithospheric dynamics. They lead to the appearance of the ULF geomagnetic perturbations on the Earth's surface in the seismo-active zone. For the development of relevant methods of monitoring the seismic activity with the use of these phenomena one requires to study of the mechanisms of generation of geomagnetic variations. One of the possible scenarios of their generation has been presented above. It was found that it is connected with the formation of impulsive perturbations of the telluric current due to sudden perturbation of the electric conductivity in the horizontal layer of the lithosphere. This results in the appearance of the magnetic field from the perturbed electric current on the Earth's surface. The jump of the electric conductivity arises due to cracking of the soil and filling the cracks by gases and fluids that are pushed out by the migrated fluids. The calculations carried out in the present paper showed that the magnetic field perturbations may attain the values comparable to the amplitudes of the ULF pulsations that are observed prior to the earthquake appearance.

Acknowledgement

This research was supported by the Programs of the Presidium of the Russian Academy of Sciences nos 9 and 16.

References

Draganov, A.B., Inan, U.S., Taranenko, Yu.N., 1999. ULF Magnetic signature at the Earth surface due to ground water flow: a possible precursor to earthquakes. Geophys. Res. Lett. 18, 1127–1130.

Fitterman, D.V., 1979. Theory of electrokinetic–magnetic anomalies in a faulted half-space. J. Geophys. Res. 84, 6031–6040.

Gold, T., Vogel, J.E., 1992. Hydraulic–elastomeric mount displacement decoupler. J. Acoust. Soc. Am. 83, 844–851.

Hayakawa, M., Molchanov, O. (Eds.), 2002. Seismo-Electromagnetics (Lithosphere–Atmosphere–Ionosphere Coupling). TERRUPUB, pp. 477.

Molchanov, O.A., 1999. Fracturing as an underlying mechanism of seismo-electric signals. In: Hayakawa, M. (Ed.), Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. Terra Scientific Publishing Company (TERRAPUB), Tokyo, pp. 349–356.

Molchanov, O., Fedorov, E., Schekotov, A., et al., 2004. Lithosphere–atmosphere–ionosphere coupling as governing mechanism for preseismic short-term events in atmosphere and ionosphere. Nat. Hazards Earth Syst. Sci. 4, 757–767.

Pilipenko, V.A., Fedorov, E.N., Yagova, N.V., Yumoto, K., 1999. Attempt to detect ULF electro-magnetic activity preceding earthquake. In: Hayakawa, M. (Ed.), Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. Terra Scientific Publishing Company (TERRAPUB), Tokyo, pp. 203–214.

Surkov, V., Pilipenko, V., 1999. The physics of pre-seismic electromagnetic ULF signals. In: Hayakawa, M. (Ed.), Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. Terra Scientific Publishing Company (TERRAPUB), Tokyo, pp. 357–364.

Tronin, A.A., Biagi, P.F., Molchanov, O.A., Khatkevich, Y.M., Gordeev, E.I., 2004. Temperature variations related to earthquakes from simultaneous observation at the ground stations and by satellites. Phys. Chem. Earth 29, 501–506.

Varotsos, P., 2001. A review and analysis of electromagnetic precursory phenomena. Acta Geophys. Pol. 49, 1–42.

Yamashita, T., 1997. Mechanical effect of fluid migration on the complexity of seismicity. J. Geophys. Res. 102, 797–817.