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One mechanism for generation of the co-seismic electromagnetic oscillations

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Abstract

The paper deals with the problem of electromagnetic pulses, which are generated in the earthquake centre at the very moment of main shock, and the co-seismic magnetic oscillations accompanying the propagation of the Love waves far away from the epicentre. The generation of electromagnetic signals under the action of acceleration of the rocks is inertial mechanism in the Earth's crust, which is also known as the Tolman–Stewart effect. Theoretical investigations for excitation of magnetic oscillations by mechanical motion in the earthquake centre are considered, and we have analysed the 1D and 2D models. Using those models we interpret the magnetic signal associated with the $M = 7.2$ earthquake on January 17, 1995. The detection of magnetic oscillations accompanying the propagation of surface Love wave after the strong earthquake far away from the epicentre gives one further argument in support of the hypothesis on the inertial mechanism operating in the Earth's crust. We examine the data of seismic station Talaya and magnetic observatory Mondy located in East Siberia.

Keywords: Earth crust; Tolman–Stewart effect; Electromagnetic pulses

1. Introduction

A strong electromagnetic pulse is generated in the earthquake centre at the very moment of main shock. Leaving the region of generation, the pulse arrives at the Earth's surface and propagates along it ahead of the front of elastic wave. It can be observed under favourable conditions in the epicentral zone prior to the seismographic noise (Belov et al., 1974; Iyemori et al., 1996). The analysis of such signals can provide useful information on the physical processes in an earthquake centre.

Far away from the epicentre the seismic waves excite the rather weak electromagnetic oscillations. Observation of these oscillations is also interesting, but it is a difficult problem due to the seismographic, microphone and magnetospheric interferences (Eleman, 1965; Guglielmi, 1986; Tsegmed et al., 2000).

The present work is devoted to both of these cases. We have paid our main attention to the inertial effect in the Earth's crust, which is the generation of electromagnetic signals under the action of acceleration of the rocks (Guglielmi, 1992; Guglielmi et al., 2002).

2. Inertial mechanism

The equation

$$\frac{\partial}{\partial t}(\mathbf{B} + \beta\boldsymbol{\Omega}) = \alpha\nabla^2\mathbf{B}, \qquad (1)$$

describes the generation of quasi-stationary magnetic field $\mathbf{B}(\mathbf{x}, t)$ due to the acceleration of the conductive body. Here $\boldsymbol{\Omega} = \nabla \times \mathbf{v}$ is the vorticity, $\mathbf{v} = \partial\mathbf{u}/\partial t$ is the velocity, $\mathbf{u}(\mathbf{x}, t)$ is the vector field of displacements, $\alpha = c^2/4\pi\sigma$ is the diffusion coefficient for the magnetic field, c is the velocity of light, σ is the electroconductivity, and β is the coefficient of mechano-magnetic transformation.

The inertial mechanism is also known as the Tolman–Stewart effect. This is a simple and universal mechanism.

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It operates in the terrestrial and celestial bodies, which are in motion with time-dependent vorticity.

Let us estimate the coefficient of mechanomagnetic transformation. In the metal conductor (Landau and Lifshitz, 1984)

$$\beta = -m_e c/e, \tag{2}$$

where m_e is the electron mass, and e is the elementary charge. Numerical value is $\beta = -5.7 \cdot 10^{-12}$ T s. In the neutron star (Sedrakian, 1974)

$$\beta = m^*_{\mathrm{ef}} c/e, \tag{3}$$

where the effective mass m^*_{ef} of the charge carrier is of the order of $m_p + m_n(N_n/N_p)$, so that $\beta = 10^{-4}$ T s. Here m_p and m_n are the proton and neutron masses, and N_p and N_n are the corresponding number densities. In the Earth's crust (Guglielmi, 1992)

$$\beta = m_{\mathrm{ef}} c/e. \tag{4}$$

Here $m_{\mathrm{ef}} = m_i + m_{\mathrm{virt}}$ is the effective mass, m_i is the mass of carrier ion, m_{virt} is some virtual mass which is expressible in terms of the electrokinetic coefficient K and the density ρ of porous fluid: $m_{\mathrm{virt}} = \rho e K$. With $\rho = 10^3$ kg/m^3 and $K = 10^{-7}$–10^{-5} V/Pa we have $\beta = 10^{-4}$–10^{-2} T s.

A note of historical interest is appropriate here. Electron inertia in metals was discovered by Tolman and Stewart in 1916. Against the background of the remarkable discoveries in the physics, which were made in 1916, the discovery of electron inertia in metals slipped by almost unnoticed. Only in 1936 Ch. Darwin presented an interpretation of the Tolman–Stewart effect. According to his theory, the greater the ratio of electron mass to its charge, the higher an amount of effect. Among other things, the effective electric field equals

$$\mathbf{E}_{\mathrm{ef}} = \mathbf{E} + \frac{m_e}{e}\dot{\mathbf{v}}, \tag{5}$$

where $\dot{\mathbf{v}}$ is the acceleration of metal body. In 1965 Eleman (1965) noted that the effect of acceleration is negligible in the Earth's crust. However, his opinion is open to argument. There are grounds to assume that it was just a fallacy.

Although the Tolman–Stewart effect itself is negligibly small, there exist something similar to such an effect in the Earth's crust, and formally an effective electric field is defined by the Eq. (5) if we substitute e for $-e$ and m_e for $m_{\mathrm{ef}} = m_i + m_{\mathrm{virt}}$. In other words, weighting of charge carrier occurs in the Earth's crust as a result of adding the virtual mass m_{virt}. It is likely that F. Eleman expected just the case of electronic mechanism of conductivity, which operates in the Earth's core and lower mantle. Here an inertial effect is truly negligible. In the upper mantle the ionic mechanism operates, but the inertial effect is also negligibly small. In ocean which is a weak water solution of strong electrolyte, the effect is much more than that in the Earth's core, but less than in upper mantle. (It is easy to check that m_{ef} is of the order of the difference of anion and cation masses in sea water.) And only in the Earth's crust of primary interest in seismoelectrodynamics, the inertial mechanism operates no less efficiently than alternative mechanisms of the electromagnetic field generation. Here as though "aggravation" of the conduction ion is the case. This results in high magnification of inertial effect in the Earth's crust as compared with the classical Tolman–Stewart effect. As far as we know, something similar occurs in the neutron stars (Sedrakian, 1974).

3. Magnetic pulse from earthquake centre

Having known the equation of generation (1), we may search for the answer to the question: what is the spatial-temporal structure of electromagnetic field generated by the earthquake?

Let us consider the plane conformal fault, which is the simplest 1D model of mechanical motion in the earthquake centre: $\mathbf{u} = (0, u, 0)$, $u(x,t) = -u_0(t) f(x)$. The solution of Cauchy problem for the parabolic Eq. (1) with $f(x) = \operatorname{sign} x$ is

$$B(x,t) = \frac{\beta}{\sqrt{\alpha\pi}} \int_0^t \mathrm{d}\tau \frac{u_0(\tau)}{\sqrt{t-\tau}} \exp\left\{-\frac{|x|^2}{4\pi(t-\tau)}\right\}, \tag{6}$$

for $t \geqslant 0$. To specify the time function of a source, the Brune model (Brune, 1970) is chosen: $u_0(t) = u_m[1-\exp(-t/T)]\theta(t)$. Here $\theta(t)$ is the Heaviside function. Then

$$B(x,t) = \frac{\beta u_m}{\sqrt{\pi T D}} \Phi\left(\frac{x}{D}, \frac{t}{T}\right), \tag{7}$$

where the space–time structure of the field is described by the following function

$$\Phi(\xi,\tau) = \frac{1}{\sqrt{\tau}} \exp\left(-\frac{|\xi|^2}{4\tau}\right) - \mathrm{e}^{-\tau} \int_0^\tau \frac{\mathrm{d}\eta}{\sqrt{\eta}} \exp\left(\eta - \frac{|\xi|^2}{4\eta}\right). \tag{8}$$

At the initial moment the magnetic field seems to be buried in the source, because the currents flowing along the fault form a kind of infinite plane solenoid. In the course of time the field leaves the source and diffuses into the surrounding space.

Our estimates have merely an illustrative character. Nevertheless, let us calculate the magnetic moment μ of unit area of the fault surface. Expressing Φ through the incomplete gamma function at $\xi = 0$, we find $\mu = \beta u_m / 2\pi T$. Now, let us estimate the magnetic moment of the source M. For this purpose μ is multiplied by the fault area. As a result

$$\mathsf{M} = \beta \cdot 10^{1.385M + 5.65}. \tag{9}$$

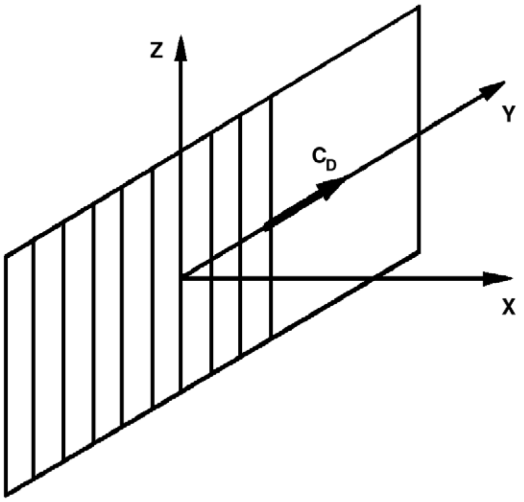

Fig. 1. The model of propagating fracture.

Here M is the magnitude of earthquake, $M \geqslant 5$. The values M and β are both measured in the absolute units. When evaluating formula (9), we have used the known empirical relations between M, $u_{\rm m}$, T, and the fault area obtained by Steinberg, Kasahara, and Shebalin (e.g., (Kasahara, 1981)).

Now let us consider the magnetic field of propagating rupture. In the frame of 2D Knopoff–Gilbert model (e.g., (Kasahara, 1981)) we have $\Omega = -u_{\rm m}\delta(x)\delta(t - y/c_{\rm D})$, that is a vortex line with a constant vorticity moving at the constant velocity $c_{\rm D}$ on the fault plane in the direction normal to the line itself (see Fig. 1). The corresponding solution of the basic Eq. (1) decreasing at infinity has the following form

$$B(x,y,t) = \frac{\beta u_{\rm m} c_{\rm D}^3}{2\pi\alpha^2}\left\{K_0\left(\frac{rc_{\rm D}}{2\alpha}\right) + \left(\frac{y - tc_{\rm D}}{r}\right)K_1\left(\frac{rc_{\rm D}}{2\alpha}\right)\right\} \times \exp\left[-\frac{c_{\rm D}}{2\alpha}(y - tc_{\rm D})\right]. \tag{10}$$

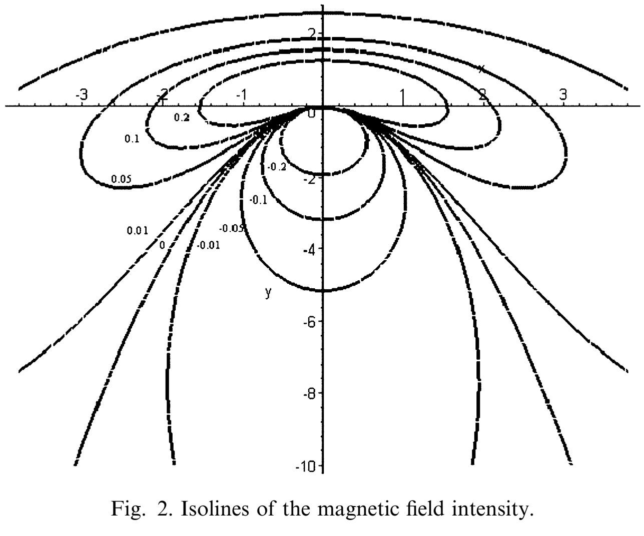

Fig. 2. Isolines of the magnetic field intensity.

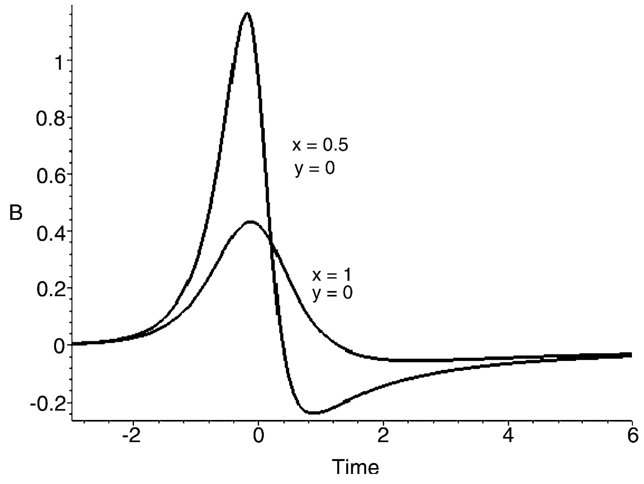

Fig. 3. Magnetic field of the propagating fault.

Here $r = [x^2 + (y - c_{\rm D}t)^2]^{1/2}$. We see that the field is transferred as a whole together with the moving front of the fracture. Fig. 2 shows the isolines of the magnetic field at the moment $t = 0$. Here we use the dimensionless units for the spatial coordinates and for the magnetic field intensity. The character of magnetic signals at various distances from the fault is evident from Fig. 3.

4. Interpretation of the event on 17.01.1995

Iyemori et al. (1996) observed the magnetic signal from the $M = 7.2$ earthquake of January 17, 1995. The coordinates of epicentre were 34.6° N, 135.0° S; the depth of hypocentre was 17.2 km. The unipolar magnetic pulse 20–30 s duration with amplitude of 0.6 nT appeared at the station Mineyama without any visible delay at the starting moment of the earthquake. The station was located at a distance of 100 km north–northeast of the epicentre. The front of seismic wave reached Mineyama 17 s after the beginning of the earthquake, so that we can only make guesses on the trailing part of the pulse.

Iyemori et al. (1996) discuss whether the observed signal may be interpreted as the effect of Faraday's induction. Using the seismological data, they specify the geometry and kinematics of the earthquake source and find that the electromagnetic induction generates a signal with amplitude of about 0.03 nT, which is significantly deviated from the experimental data.

As an alternative, we suggest to consider the observed signal as a manifestation of the inertial effect. We would like to use the equation for the magnetic moment (9) with $M = 7.2$. Let us assume that $\beta = 2 \cdot 10^{-4}$ T s. (This is a rather moderate value of the coefficient of mechanomagnetic transformation in the Earth's crust.) Then, in the quasi-static approximation $B \sim 0.8$ nT at the distance of 100 km from the earthquake centre. Hence, our hypothesis on the action of inertial mechanism in the earthquake centre provides an amplitude estimate of seismomagnetic signal, which is reasonably in good agreement with the observations.

5. Electromagnetic field of the Love wave

The detection of the magnetic oscillations accompanying the propagation of surface Love wave after the strong earthquake far away from the epicentre gives one further argument in support of our hypothesis on the inertial mechanism operating in the Earth's crust. A specific property of these waves is that, theoretically, they are represented by at least three physically different mechanisms of their excitation (inertial, inductive, and piezomagnetic), but the inertial mechanism alone is responsible for the magnetic field that penetrates to the surface of the Earth.

The observations of seismomagnetic signals are impeded by the noise of magnetospheric origin. To suppress the magnetospheric interference, we have elaborated a special method (Tsegmed et al., 2000). The idea resides in the tapping of a priori information on the polarization state of seismomagnetic field. On the Earth's surface and above it, the signal has the circular polarization with counterclockwise rotation, and the magnetic field rotates in the vertical plane parallel to the direction of seismic wave propagation. These polarization properties are quite general and so specific, that one can try to use them for detection of seismomagnetic signals.

An earthquake with magnitude $M = 7.7$ occurred on November 29, 1998 with epicentre in the Ceram Sea. Fig. 4 shows the oscillograms of mechanical and magnetic oscillations after broadband filtration. The coordinate system is oriented in such a way that the axis x coincides with the tangent to the arc of great circle passing through the epicentre. The magnetometer and seismograph were located in East Siberia at about 6400 km from the epicentre.

Fig. 4 shows oscillograms of mechanical and magnetic oscillations after the rotation of the coordinate axes and broadband filtering. Here, V_y is the transverse component of the velocity, and $\dot{B}_x$ and $\dot{B}_z$ are time derivatives of the horizontal and vertical components of the magnetic field, respectively. The seismogram displays some quasi-harmonic oscillations of Love wave. The record of magnetic field is highly complicated by magnetospheric noises. Against the background of this noise, the seismomagnetic signal cannot be detected by a simple comparison of the oscillograms. The mechanical spectrum exhibits a distinct peak at a frequency 23 mHz in the time interval 14:35:41–14:38:41 UT. However, this effect is not observed in the spectra of magnetic field components. So, we applied our method of polarization filtering based on the theoretical idea that the electro-

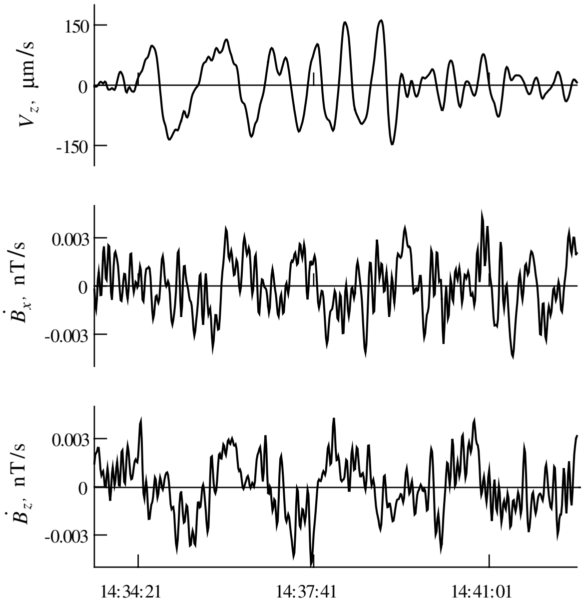

Fig. 4. The oscillograms of mechanical (top panel) and magnetic (bottom two panels) oscillations after broadband filtering.

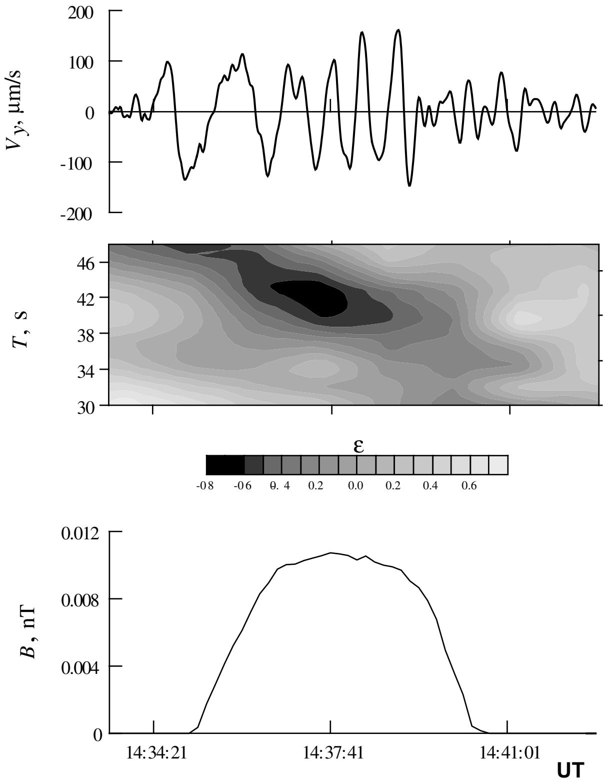

Fig. 5. Comparison of seismic oscillations V_y (top panel) with polarogram of magnetic oscillations (middle panel) and the amplitude of magnetic oscillations with a left-hand circular polarization in the tangent plane (bottom panel).

magnetic field of the Love wave has the structure of H-wave with the left-hand circular polarization. The state of polarization can be conveniently described by the ellipticity parameter ε varying from -1 to $+1$ and can be chosen such that its value -1 corresponds to the left-hand polarization. In the middle panel of Fig. 5 a polarogram of the magnetic oscillation is shown. We notice from this picture that there appears approximately at 14:37:00 UT a frequency band with the left-hand polarization and high ellipticity, whose central frequency is $f = 23$ mHz. The lower plot shows the variation in the amplitude of the circular component with the left-hand rotation. As expected, the highest amplitudes of magnetic oscillations with the left-hand circular polarization are observed during the passage of the 23 mHz Love wave train. The arrival time, duration, period, and polarization of magnetic signal conform to the idea of generation of the alternating electric currents due to the time-dependent shear motion of the rocks.

6. Conclusion

The main result of this work is that the Tolman–Stewart effect in the Earth's crust provides the generation of rather strong electromagnetic oscillations due to the fluid vibrations in pores and fractures of the rocks under the action of inertial forces associated with the seismic wave propagation and also with the shear motion in the earthquake centre at the very moment of main shock.

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