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On the excitation of magnetic signals by Love waves

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Abstract

The polarization method for recognition of seismomagnetic waves against a noise background is presented. The method is applied to detection of magnetic oscillations accompanying the propagation of surface Love wave after a strong earthquake. A specific property of the Love waves is that theoretically the Tolman-Stewart effect is alone responsible for the magnetic field that penetrates into the Earth's surface. Data from the Mondy Magnetic Observatory and the Talaya Seismic Station suggest that the arrival time, duration, period, and polarization of magnetic signals conform with the idea of generation of alternating electric currents due to fluid vibrations in pores and fractures of rocks under the action of the inertial force associated with the Love wave propagation.

Key words *Earth crust – Tolman-Stewart effect*

1. Introduction

The excitation of magnetic oscillations by seismic waves has attracted considerable attention for a long time (*e.g.*, Breiner, 1964; Eleman, 1966; Belov *et al.*, 1974; Iyemory *et al.*, 1996; Tsegmed *et al.*, 2000). The interest in seismomagnetic phenomena is motivated by the hope for advances in understanding mechano-magnetic transformations in the Earth's crust. The challenging task on this way is the detection of the rather small seismomagnetic signals against a noise background. Strong interferences hamper the collection of experimental data. Recently Tsegmed *et al.* (2000) proposed the polarization method for recognition of signals. The method is based on the fact that the magnetic signal has circular polarization in the vertical plane regardless of the particular mechanism of magnetic field excitation by the seismic wave. The polarization plane is perpendicular to the seismic wave front, and the rotation direction of the magnetic vector is controlled by the direction of seismic wave propagation.

In the present paper we describe the polarization method and apply it to the detection of the magnetic oscillations accompanying the propagation of surface Love wave after a strong earthquake. The selection of this type of seismic waves is not accidental. It is motivated by some special physical reasons. The Love wave is of immediate interest to the experimentalist because theoretically this wave induces the Tolman-Stewart effect in the Earth's crust, which is responsible for the magnetic field that is observable over the Earth's surface (Guglielmi, 1992, 1999).

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2. Mechano-magnetic transformations

The equation of the mechano-magnetic transformations in the Earth's crust makes it easy to understand our interest into the Love waves. Indeed, let us put $\boldsymbol{B}=\nabla\times\boldsymbol{A}$. The equation for the vector-potential $\boldsymbol{A}$ has the form

$$\hat{D}A = \boldsymbol{S} \tag{2.1}$$

where

$$\hat{D} = \partial/\partial t - \alpha\nabla^2 \tag{2.2}$$

is the evolution operator, and the term

$$\boldsymbol{S} = \alpha\nabla\times\boldsymbol{M} + \beta E_0\nabla\cdot\boldsymbol{u} + \boldsymbol{B}_0\times\boldsymbol{v} - \gamma\boldsymbol{a} \tag{2.3}$$

describes the underground sources of the magnetic field $\boldsymbol{B}(\mathrm{x}, t)$ (Guglielmi, 1999; Tsegmed *et al.*, 2000). We have used the following designations:

$$\begin{gathered}
\alpha = c^2\varepsilon_0/\sigma, \ \ \beta = \partial\ln\sigma/\partial\theta, \ \ \gamma = m_{ef}/e \\
M_i = (\lambda_1 p_{ll}\delta_{ij} + \lambda_2 p_{ij})\boldsymbol{B}_{0j} \\
p_{ij} = 2\rho c_t^2 u_{ij} + \rho(c_l^2 - 2c_t^2)\theta\delta_{ij} \\
u_{ij} = (\partial u_i/\partial x_j + \partial u_j/\partial x_i)/2 \\
\theta = \nabla\cdot\boldsymbol{u}, \ \ \boldsymbol{v} = \partial\boldsymbol{u}/\partial t, \ \ \boldsymbol{a} = \partial\boldsymbol{v}/\partial t.
\end{gathered}$$

Here the mechanical values $\boldsymbol{a}$, $\boldsymbol{v}$, and $\boldsymbol{u}$ are the acceleration, velocity and displacement of the rocks, p_{ij} and u_{ij} are the stress and strain tensors, $\boldsymbol{E}_0$ is the electric field associated with the terrestrial currents, $\boldsymbol{B}_0$ is the geomagnetic field, c_t and c_l are the velocities of transverse and longitudinal elastic waves, c is the light velocity, ε_0 is the permeability of free space, ρ and σ are the density and conductivity of rocks, e and m_{ef} are the charge and effective mass of the conduction ion in the porous fluid. The four terms in the right-hand side of eq. (2.3) have the following interpretation: the first accounts for the piezomagnetic effect, the second describes the modulation of the terrestrial currents by the seismic vibrations, and the two last terms describe the induction and inertial effects. The five phenomenological parameters of the model have the following interpretation: α is the diffusion coefficient, and β, γ, λ_1, λ_2 are the coefficients describing the conversion of mechanical energy into the energy of magnetic field.

We see that generally at least four mechanisms operate in the Earth's crust simultaneously and independently of each other. So we have a rather cumbersome superposition of fields. However, it is always interesting to select and clarify the limiting case when only one generation mechanism concerned prevails. And in this respect, the Love wave is especially interesting. A specific property of this wave is that, theoretically, the inertial mechanism alone is responsible for the magnetic field which penetrates into the Earth surface (Guglielmi *et al.*, 1996). Moreover, the Love wave makes it possible to switch on the least understood generation mechanism. The most striking feature of it is its universality. It operates in any conductive body and, therefore, it operates in the Earth's crust too. This simple and universal mechanism was brought into classical physics in 1936 by Darwin in his attempt to explain the Tolman-Stewart effect. Darwin's theory predicts that the coefficient of mechano-magnetic transformation γ is proportional to the mass of electron (*e.g.*, Landau and Lifshitz, 1984). This is true in the case of a metal. But in the case of the porous moist body, we expect that γ is proportional to some effective mass m_{ef}, which is many orders above the mass of electron (Guglielmi, 1992). It should be noted that the Tolman-Stewart effect was never observed in the laboratory using rock samples and we assume that it is practically impossible because the typical skin-length is many orders higher than the feasible size of a rock sample. Below we present our attempt to crack a problem by the full-scale observations.

3. Polarization method

It is common knowledge that observations of the seismomagnetic signals are impeded by the noise of magnetospheric origin. To suppress the magnetospheric interference, we have elaborated a special method based on the tapping of *a priori* information on the polarization state of seismomagnetic field (Tsegmed *et al.*, 2000). In this section, we present a general idea. The application of the polarization method to record magnetic wave that accompany the Love wave will be described in the next section.

We introduce the Cartesian coordinate system (x, y, z) such that the Earth's surface coincides with the (x, y) plane and the z-axis is directed upward (fig. 1). Let a plane $(\partial / \partial y = 0)$ monochromatic elastic wave travel in the positive direction of the x-axis in the lower half-space $(z < 0)$ supposed to be horizontally homogeneous. We are interested in the magnetic field $\boldsymbol{B}(x, z, t)$ in the upper half-space $(z \geq 0)$, where it obeys the Laplace Law $\nabla^2 \boldsymbol{B} = 0$ and the solenoidality condition $\nabla \cdot \boldsymbol{B} = 0$. We suppose that the field $\boldsymbol{B}$ is excited by the elastic wave, and it is linearly related to the mechanical variables. Then $\boldsymbol{B} \propto \exp(ikx - i\omega t)$, the solenoidality condition takes the form

$$B_x = \frac{i}{k} \frac{\partial B_z}{\partial z} \tag{3.1}$$

and the Laplace equation yields

$$\frac{\partial^2 B_z}{\partial z^2} - k^2 B_z = 0 \tag{3.2}$$

where $k = \omega / c_L$, ω is the frequency and c_L is the horizontal velocity of elastic wave (in the next sections c_L will be considered the velocity of Love wave).

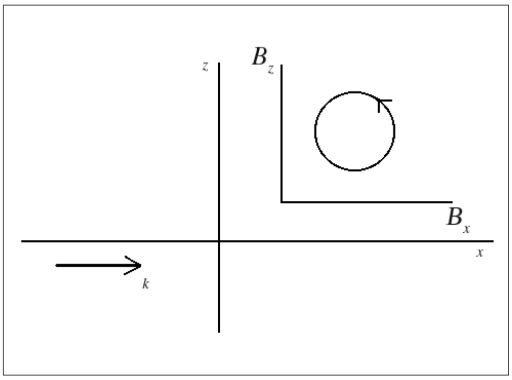

Fig. 1. Polarization of seismomagnetic oscillations (see the text).

The magnetic field tends to zero with increasing the height above the Earth's surface because the field sources are located beneath the surface. Hence, the eq. (3.2) gives $B_z \propto \exp \cdot (-kz)$. Substitution of this expression in (3.1) yields $B_z = iB_x$. As regards B_y component, it is negligible in comparison with B_x and B_z (in the particular case of the Love wave $B_y = 0$) Therefore we have

$$\boldsymbol{B} = \frac{B}{\sqrt{2}}(1, 0, i) \exp\left[k(ix - z) - i\omega t\right]. \tag{3.3}$$

This means that on the Earth's surface and above it the modulus $|\boldsymbol{B}|$ remains constant. The magnetic wave has circular polarization with counterclockwise rotation. The vector $\boldsymbol{B}$ rotates with the frequency ω in the vertical plane parallel to the direction of seismic wave propagation. These polarization properties are quite general. Besides, these properties are so specific, that one can try to use them for the detection of seismomagnetic signals.

4. Observations

An earthquake with magnitude $M = 7.9$ occurred on June 18, 2000, at a depth of 10 km with epicenter in the Indian Ocean (see the site of the IRIS Consortium at www.iris.washington.edu). To search for a seismomagnetic signal, we used data from the Mondy Magnetic Observatory (51.6°N, 100.8°E) and the Talaya Seismic Station (51.7°N, 103.6°E). The Mondy Observatory is equipped with a high-frequency digital three-component induction magnetometer developed at the University of Tokyo and kindly provided by Prof. K. Hayashi. The main parameters of the magnetometer are as follows: frequency range, 0.001-3.0 Hz; sampling rate, 10 Hz; GPS time synchronization; data storage on magneto-optical disks. The Talaya seismic station 200 km east of Mondy is equipped with a highly sensitive digital seismometer with a sampling rate of 1 Hz. Talaya seismic wave records were taken from the Internet (www.fdsn.org/station_book/II/TLY/tly_3.html). The epicentral distances to the Mondy Observatory and Talaya Station are, respectively, 7280 and 7269 km. The azimuthal aperture between these two points is 4.2º.

First, the seismogram was used to visually assess the arrival time (15:17:45 UT), characteristic period ($T = 23$ s), and amplitude (about 300 μm/s) of surface Love waves. The onset of waves corresponds to an average velocity of 3.6 km/s. Thus, the Love wave delay at Mondy is 3 s, *i.e.* it is small compared to the period of seismic waves. The distance between the observation points of magnetic and seismic waves is also small compared to the epicentral distance. Therefore, for simplicity, we will ignore the effects due to the difference between locations of the observation points.

For subsequent analysis, we transformed the initial numerical dataset to a coordinate system rotated about the vertical axis z in such a way as to bring the x-axis into coincidence with the tangent to the arc of the great circle passing through the epicenter and to direct it away from the epicenter. Moreover, the initial data were subjected to broadband filtering with a passband of 5-200 mHz in order to eliminate high-frequency noise and long-period trends. Finally, using the results of the preliminary visual analysis, we chose a frequency-time window containing Love waves and constructed the wave amplitude spectrum, after which we determined more accurately the carrier frequency ($f = 43$ mHz) and the time interval (15:13:20-15:25:00 UT) suitable for detecting seismomagnetic oscillations.

Figure 2 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 $\dot{B}_y$ are time derivatives of the horizontal and vertical components of the magnetic field, respectively. The seismogram dis-

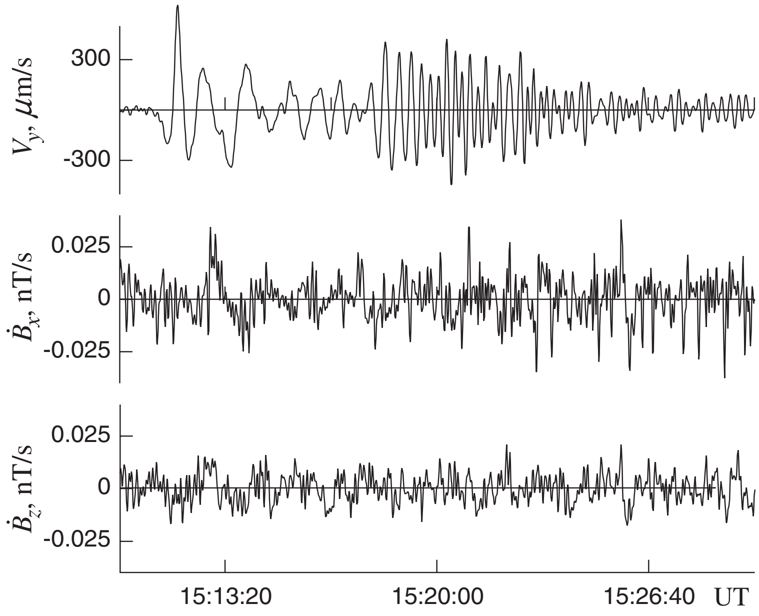

Fig. 2. Seismic waves and magnetic oscillations recorded at the Talaya Station and the Mondy Observatory, respectively, on June 18, 2000. Here, V_y is the transverse component of the displacement velocity, and $\dot{B}_x$ and $\dot{B}_y$ are the horizontal and vertical components of the magnetic field, where dots mean the differentiation with respect to time. The coordinate system is oriented in such a way as to make the x-axis parallel to the arc of the great circle that passes through the earthquake epicenter (see text).

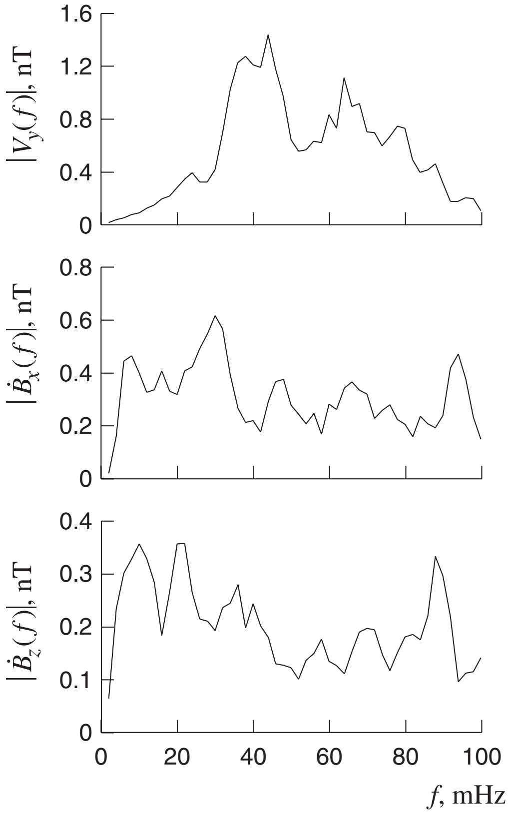

Fig. 3. Spectra of oscillations shown in fig. 2.

plays *quasi*-harmonic oscillations typical of Love waves in the far-field zone. The record of the magnetic field is severely complicated by noise. Against the background of this noise, the seismomagnetic signal cannot be detected by simple comparison of the oscillograms. We attempted to identify the seismomagnetic signal by the spectral method. Figure 3 presents the spectra of mechanical and magnetic oscillations in the time interval 15:16:40-15:25:00 UT. The mechanical spectrum exhibits a distinct peak at a frequency of 43 mHz. However, this effect is not observed in the spectra of magnetic field components.

Therefore, we applied the method of spectral polarization filtering based on the theoretical idea that the electromagnetic field of harmonic Love wave has the structure of an *H*-wave with a left-hand circular polarization in the vertical plane. The state of polarization can be conveniently described by the ellipticity parameter varying from -1 to $+1$ and chosen such that its value -1 corresponds to the left-hand polarization. The variation in the ellipticity of magnetic oscillations in the vertical plane at the frequency of 43 mHz is shown in the middle part of fig. 4. The lower plot shows the variation in the amplitude B of the circular component of oscillations with a left-hand rotation of the magnetic vector at the same frequency. As expected, the lowest values of the ellipticity and the highest amplitudes of magnetic oscillations with the left-hand circular polarization are observed during the passage of the 43 mHz Love wavetrain. This leads to the assumption that we have detected seismomagnetic oscillations with the amplitude $B = 0.02$ nT.

5. Discussion

The period, polarization, onset time, and duration of the detected magnetic oscillations are consistent with the concept according to which these oscillations are excited by Love wave. It is quite clear that the seismic waves are no more than a *causa instrumentalis*; *i.e.* they are only an external cause of the field generation, whereas the immediate cause is the current, and our task is to identify the current-generating mechanism. In the general case, this is a difficult problem because several mechanisms operate in the crust concurrently and independently of each other during seismic wave propagation. We chose the Love waves because the theory (Guglielmi *et al.*, 1996) leaves no other alternative and unambiguously indicates an inertial generation mechanism in this particular case.

This universal mechanism, describing by the equation

$$\frac{\partial}{\partial t}(\mathbf{B}+\gamma\Omega)=\alpha\nabla^2\mathbf{B} \qquad (5.1)$$

operates in the terrestrial and celestial conductive bodies which are in motion with time-dependent vorticity $\Omega = \nabla \times \mathbf{v}$. (The values $\mathbf{v}$, α,

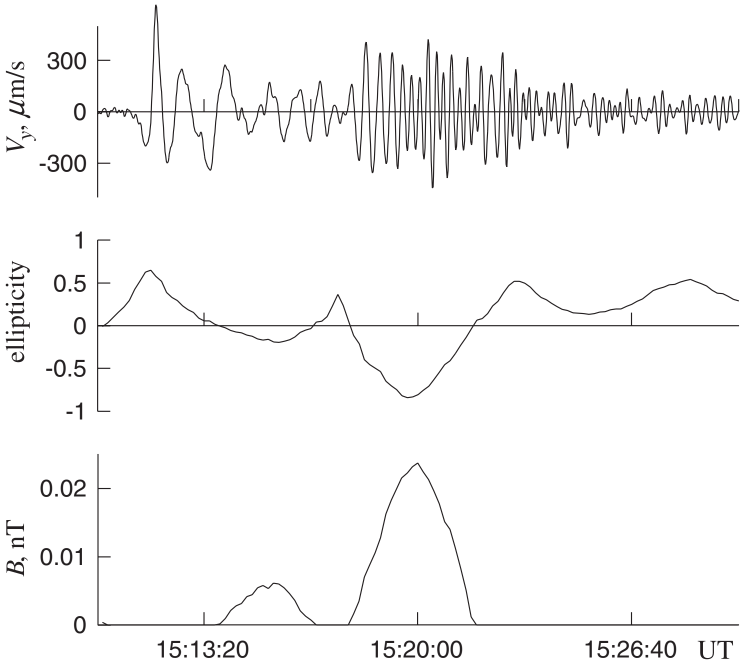

Fig. 4. Comparison of seismic oscillations V_y (*top* panel) with variations in the ellipticity of magnetic oscillations (*middle* panel) and the amplitude of magnetic oscillations with a left-hand circular polarization in the tangent plane (*bottom* panel).

and γ are defined above in the Section 2). For example, Sedrakian (1974) proposed that the magnetic fields of the neutron stars could be explained in part by the inertia effect. In his model the pulsar consists of the rotating superfluid of neutrons and protons, and the normal fluid of electrons. Because the angular velocity of neutron star is not constant, the protons move relative to the electrons creating the toroidal electric currents that produce extremely strong magnetic field. This is a sort of Tolman-Stewart effect.

We must realize that the Tolman-Stewart effect provides the generation of magnetic field in any conductive body, which moves with nonzero vorticity Ω. In this regard there is no question that the Love wave generates the magnetic field oscillations because $\Omega \neq 0$ during the passage of this wave. The real problem is the amplitude of magnetic oscillations, which is determined by the coefficient of mechano-magnetic transformation $\gamma = m_{ef}/e$. In a metallic conductor $m_{ef} = m_e$, where m_e is the mass of electron. Then $\gamma = -5.68 \cdot 10^{-12}$ kg/s·A, and it is likely that Eleman (1966) expected just this case when he rejected *a priori* the inertial mechanism as a possible cause of seismomagnetic signals. The electronic mechanism of conductivity operates in the Earth's core and lower mantle, and here the Tolman-Stewart effect is truly negligible. In the upper mantle the ionic conductivity takes place, *i.e.* $m_{ef} \approx m_i$. However, the Tolman-Stewart effect is also negligible in the upper mantle. The Earth's crust may be considered as an ionic conductor too, but $m_{ef} >> m_i$ because the inertial force sets in motion the porous fluid, and not just the conduction ion (Guglielmi, 1992). A rough estimate gives $\gamma \approx \rho_f K$, where K is the electrokinetic coefficient, and $\rho_f \approx 10^3$ kg/m^3 is the density of porous fluid. Laboratory experiments with the rock samples indicate that K varies from 10 mV/MPa to 10 V/MPa depending on the temperature and salinity of water and on the structure and saturation of the porous space. The coefficient of mechano-magnetic transformations γ varies correspondingly from 10^{-5} to 10^{-2} kg/s. Let us show that our observations do not contradict these estimates. One can see from eq. (5.1) that $\gamma \sim B/kV$, where $k = \omega/c_L$. According to our measurements $B \sim 2\cdot 10^{-2}$ nT, $V \sim$ $\sim 3\cdot 10^{-4}$ m/s, $c_L \sim 3.6$ km/s, so that $\gamma = 10^{-3}$ kg/s·A.

6. Summary

We have presented the polarization method for recognition of seismomagnetic waves against a noise background. The method is applied to detection of magnetic oscillations accompanying the propagation of surface Love wave after the strong earthquake. We have focused our attention on the Love wave because theoretically the Tolman-Stewart effect in the Earth's crust is responsible for the magnetic field that penetrates to the Earth's surface. Data from the Mondy Magnetic Observatory and the Talaya Seismic Station suggest that the arrival time, duration, period, and polarization of magnetic signal conform with the idea of generation of alternating electric currents due to fluid vibrations in pores and fractures of rocks under the action of the inertial force associated with the Love wave propagation. The estimated ratio of the amplitude of magnetic oscillations to the amplitude of Love waves is indirect evidence that the inertial mechanism of converting the seismic wave energy into the electromagnetic field energy is reasonably effective. We believe that the inferred result provides an additional basis for the interpretation of seismoelectromagnetic phenomena.

Our conclusion is as follows. In his 'Foreword' to the recent monograph *Seismo-Electromagnetics*, Prof. Uyeda (2002) said that «the earthquakes are nothing but physical phenomena». These are remarkable and optimistic words in the context of the earthquake prediction research. The specifics of such research is that the laboratory modeling of the pre-seismic evolution of the geophysical fields is practically impossible. This resembles in some respects the situation with the inertial mechanism of magnetic field generation. It is rather difficult to carry out laboratory measurements because the skin-length is many orders higher than the feasible size of a rock sample. We hope that our modest experience in an effort to detect the magnetic signal due to the Love wave may be useful for the prediction research as an example to crack a problem of the sort by full-scale measurements.

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