Toward the Study of the Piezomagnetic Effect of the Response of Magnetically Perturbing Bodies to Changes in Stresses in the Earth’ s Crust

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Abstract

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Corresponding Member of the Academy of Sciences of the USSR E. E. Fotiadi,
G. I. Karataev,
V. A. Larionov, V. G. Cheremisin

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In a number of our works on contemporary movements of the Earth' s crust, it was proposed to study the character of the variation of deep-seated stresses with time, on the basis of the ideas of potential theory, by observing temporal perturbations of gravitational and magnetic anomalous fields caused by certain gravitating and magnetically active bodies occurring at various depths (1,2). It was shown that in this way it is possible to study rather subtle effects of the response of perturbing bodies to changes in deep-seated stresses.

For the gravitational potential and its derivatives, corresponding analytical expressions were obtained for their temporal variations in connection with the deformation of a continuous perturbing medium and the nonconstancy of its density with time. The ideas of the theory and of the methodology of observing variations of the gravitational potential may also be transferred to the magnetic potential, taking into account some of its specific features.

If $\mathbf{J} = \mathbf{J}(r_0, t)$ is the anomalous field of magnetization of a perturbing body enclosed in a certain volume T at time t, and J is a superposition of the functions $J(p)$ and $p(t)$, $J(t) = J[p(t)]$, where $p(t)$ is the field of stresses acting on the anomalous body, then, according to (1), when the anomalous stresses p change over the interval dt, the magnetization field changes by dJ (which will be the piezomagnetic effect), and the vector $\mathbf{r}_0$ by $d\mathbf{r}$. In this case the material velocity of change of the magnetic potential, due simultaneously to deformation of the perturbing body ($d\mathbf{r}$) and to the change in its magnetization (dJ), may be obtained from the expression:

$$U^*(r_0, t_0) = \int_{T(t_0)} \left\{ \frac{\partial}{\partial t} \left[\frac{(\mathbf{J} \cdot \mathbf{l})}{l^3} \right] + \partial_i (c_i \cdot \psi) \right\} d\tau + (\operatorname{grad} U \cdot \theta), \qquad (1)$$

and the potential at time t

$$U(r,t) = U(r_0,t_0) + U^* dt, \tag{1'}$$

where $l = l(r_0, r_0', t)$ is the distance from the point (r_0, t_0) to the volume element $d\tau$ at the point (r_0', t_0); $\psi = (\mathbf{J} \cdot \mathbf{l})/l^3$; c_i is the velocity of displacement of the elementary particles of the perturbing body without rupture of its continuity (the deformation velocity); θ_i is the deformation velocity of the surface of definition of the function U; the sign ∂_i is the operator of partial differentiation with respect to the coordinates x_i; $\mathbf{r} = (x_1, x_2, x_3)$. In the case of homogeneous magnetization, according to Poisson' s theorem, for example for the Z-component of the magnetic field we have

$$Z^*(r_0,t_0) = Z_a \left(\frac{1}{J} J^* + \frac{1}{\rho} \rho^* + \frac{V_{sz}^*}{V_{sz}} \right), \tag{2}$$

where $Z_a = Z(r_0, t_0)$ is the anomalous field* for the state of the perturbing body at the instant t_0; V_{sz}^* is the material rate of change of the derivative of the gravitational potential in the direction of magnetization s and the z axis; V_{sz} is the anomalous effect from the gravitating body coinciding with the magnetic body at the instant t_0.

Analysis of equations (1) and (2) on a number of theoretical models has shown that the quantities U^* and Z^* are determined mainly by the change, with time, of the anomalous magnetization of the body caused by changes in stresses in the Earth' s crust. Deformations of the surface of the disturbing body and of the observation surface, in most cases, exert only a weak influence on the anomalous field. In this connection, assuming that $Z^* \approx \partial Z/\partial t = Z'$, we obtain expression (2) in the form

$$Z'(r_0,t_0) = Z_a \left(\frac{1}{J} J^\bullet + \frac{1}{\rho} \rho^\bullet + \frac{V_{sz}^\bullet}{V_{sz}} \right). \tag{3}$$

Since $\mathbf{J} = \mathbf{J}_i + \mathbf{J}_n$ and $\mathbf{J}_i = \chi \mathbf{T}_0 + \chi \mathbf{T}_j$ (where $\mathbf{J}_i, \mathbf{J}_n$ are the vectors of induced and remanent magnetization; $\mathbf{T}_0, \mathbf{T}_j$ are, respectively, the vectors of the intensity of the external field and of the internal demagnetizing field), and $\mathbf{T}_0 = \mathbf{T}_0(t)$, then $J^\bullet$, entering formula (3), is both a function of the piezomagnetic effect $J_p^\bullet = \dfrac{\partial J}{\partial p} \dfrac{\partial p}{\partial t}$ and a function of changes with time of the external magnetizing field. Assuming $T_j < T_0$ and taking into account that $J_i^\bullet = \chi^\bullet T_0 + \chi T_0^\bullet$, for the piezomagnetic effect we shall have $J_p^\bullet = \chi^\bullet T_0 + J_n^\bullet$. Then, putting $\rho^\bullet = 0$, since in the present paper we are interested only in changes with time of the magnetic properties of the disturbing body, instead of (3) we obtain:

* Here anomaly is understood as the difference between the normal and observed fields, with the usual field variations excluded.

$$Z'(r,t_0) = \frac{1}{f\rho}[(\mathbf{J}_i^{\bullet} \cdot \operatorname{grad} V_z) + (\mathbf{J}_n^{\bullet} \cdot \operatorname{grad} V_z)] =$$

$$= \frac{1}{f\rho}[(\mathbf{J}_p^{\bullet} \cdot \operatorname{grad} V_z) + (\chi \mathbf{T}_0^{\bullet} \cdot \operatorname{grad} V_z)] = \frac{Z_a}{J} J_p^{\bullet} + \frac{\chi T_0^{\bullet}}{f\rho} \operatorname{grad}_i V_z. \tag{4}$$

Hence the magnitude of the piezomagnetic effect $J_p^{\bullet}$, associated with the time variation of the stress field in the Earth' s crust, is determined by the formula

$$J_p^{\bullet} = \frac{J}{Z_a}\left(Z' - \frac{\chi T_0^{\bullet}}{f\rho} \operatorname{grad}_i V_z\right). \tag{5}$$

It is thus not difficult to see that the study of the piezomagnetic effect *in situ* can proceed mainly in two directions. On the one hand, observations of the change in Z can be carried out in two regions: 1) in the zone of anomalous gravitational and anomalous magnetic fields caused by one and the same disturbing body, and 2) far from such a combined anomaly (so to speak, in the normal field), for the purpose of recording variations of the induced magnetizing field. On the other hand, since the second term in formula (5) is nothing other than the rate of change with time of the vertical component of the induced external magnetic field $\mathbf{T}_0$, it follows that the second direction in the study of the piezomagnetic effect may consist in observing the difference of rates in the anomalous field and outside it, in the so-called normal field. Moreover, proceeding from the formulas given above, one may propose a number of particular methods of observation of the manifestation of the piezomagnetic effect. Thus, since

$$Z_a(r,t) = Z_a(r,t_0) + Z_a^{\bullet}(r,t_0)\,dt,$$

then

$$Z_a(r,t) = Z_a(r,t_0) + \frac{Z_a(r,t_0)}{J(r,t_0)} J_p^{\bullet} dt + Z_0^{\bullet} dt, \tag{6}$$

and the piezomagnetic effect will be

$$J_p^{\bullet} = \frac{\tilde{Z}_a(r,t_0) - Z_a(r,t_0)}{Z_a(r,t_0)} J(r,t_0), \tag{7}$$

where

$$\tilde{Z}_a(r,t_0) = Z_a(r,t) - Z_0^{\cdot}\,dt.$$

Hence the piezomagnetic effect can be obtained by simultaneous observation both in the anomalous and in the normal field, introducing into the observed values of the anomalous field $Z_a(r,t)$ a correction for the change in the external magnetizing field Z_0.

Finally, in the presence of intense variations of the external contemporary field, one may propose a method of observing the qualitative characteristic of the piezomagnetic effect. From (5), for $J_p^{\cdot} = 0$, we obtain

$$Z^{\cdot}(r,t_0)/Z_0^{\cdot}(r,t_0) = k(r,t_0). \tag{8}$$

Thus, if the rates of change (or variations) of the magnetic anomalous $Z^{\cdot}$ and normal $Z_0^{\cdot}$ fields are observed simultaneously, then their ratio, in the absence of the piezomagnetic phenomenon, must be constant, while in the case of its presence it must be variable. Plotting the graph $(Z^{\cdot}/Z_0^{\cdot};t)$, we shall observe a qualitative picture of the change in the quantity $Z^{\cdot}/Z_0^{\cdot}$ in connection with the piezomagnetic effect.

It is obvious that everything said for Z_a is transferred without restriction to the other components of the magnetic field.

It is not difficult to calculate the possible changes of the field Z_a in connection with the piezomagnetic effect. Thus, for example, according to Stacey' s theory (^{3}) and laboratory investigations (^{4}), for the piezomagnetic effect one may approximately write $dJ \approx C_{JJ}\,dp$ or $J_p^{\cdot} \approx C^{\cdot}_{JJp}$, where the magnetoturgic coefficient C_J varies within the limits from $1 \cdot 10^{-4}$ to $3 \cdot 10^{-4}$ cm^2/kg. If, per unit time, dp changes, for example, by 100 kg/cm^2 (i.e., by the magnitude of anomalous critical stresses during earthquakes), then dJ will correspondingly change by $1 \cdot 10^{-2}J$–$3 \cdot 10^{-2}J$. But according to (5), for $I_0^{\cdot} = 0$ we obtain $J_p^{\cdot} \approx \dfrac{J}{Z_a} Z_a^{\cdot}$; consequently, per unit time, during which the anomalous masses are involved in the process of compression—extension, the anomalous magnetic field will change by as much as 1-3%. Thus, if an anomalous body is located within the limits of an earthquake focus (within a radius of 30-50 km from the hypocenter), then changes of magnetic anomalies with an intensity of the order of 1000 γ in the situation preceding an earthquake can actually reach values of 10-30 γ. This is confirmed by our observations at the Baikal geodynamic test site in 1966 (Irkutsk region) and in 1968 (region of the mouth of the Selenga River, where before the earthquake the magnetic field decreased by 10-20 γ, and after the earthquake assumed a value close to the previous one).

Institute of Geology and Geophysics
Siberian Branch of the Academy of Sciences of the USSR
Novosibirsk

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Note: Figure translations are in progress. See original paper for figures.