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GEOPHYSICS

Remote Determination of Zones of Direct and Reverse Magnetization of Rocks in Past Epochs

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The possibility of remote detection of the zones of direct and reverse magnetization of rocks in the past epochs related to inversions of the magnetic field is considered based on the Faraday effect in the course of radar sounding and recording of the magnetic component of reflected signals.

The solution to this problem determines the moments of geomagnetic field inversion and the duration of its stable states if the age of the rocks in the section studied is known. The elements of the paleomagnetic field and hence the zones of direct and reverse magnetization are traditionally determined on the basis of laboratory investigation of the residual magnetization of spatially oriented rock samples. At present, the number of such samples is possibly estimated at a few million. Sampling of oriented samples is a labor-consuming operation, which is not always possible without drilling of special boreholes. New possibilities of research in this and other fields of geophysics appeared after we suggested a radar sounding method with recording the magnetic components of reflected signals using highly sensitive magnetometers based on the Josefson effect [1]. Previously, we demonstrated the possibility to use this effect for remote detection and location of the boundaries formed by inversions of the geomagnetic field in ice [2] and rock sequences [3]. These boundaries in ice can reliably be determined by comparing the results of radar sounding of electric and magnetic fields. Direct or indirect reference data are required for their identification in rock sequences.

A polarized electromagnetic wave changes the location of the polarization plane by angle $\varphi = WlB_l$ (W is the Verde constant) over its trajectory l (during the reflection from the interface boundary and back) along the magnetic induction component B_l. (Henceforth, we shall use the terms “signal” or “pulse,” the succession of which is studied in radar sounding and can be presented as a superposition of plane monochromatic waves.)

We shall consider a layer with boundaries at depths h_1 and h_2 formed by two sequential inversions of the geomagnetic field that can also enclose other (usually stronger) reflecting boundaries. This implies uniform properties of the layer in terms of the value and direction of the residual magnetization (and, consequently, magnetic induction), because inductive magnetization within this layer is also the same. We assume that the signal propagates in the forward and reverse (after reflection) directions along the z-axis. We shall measure the rotation angles of the polarization plane of the reflected signals. Two methods are possible. The first method requires other (at least one) reflecting boundaries in the layer at depth h_i from the upper boundary of the layer. Then, under the simplest assumption about the existence of one additional boundary at depth h_2, we get two necessary equations in series

$$\varphi_1 = W \cdot 2(h_2 - h_1)B_z,$$

$$\varphi_2 = W \cdot 2(h_3 - h_2)B_z,$$

where φ_1 and φ_2 are rotation angles of the polarization plane of the signal on the path from h_1 to h_2 and back from h_2 to h_3. From this, we calculate the Verde constant W for the studied layer in situ (assuming for a while that it is constant within the layer) and the vertical component of magnetic induction B_z in the layer, because the h_i values are known from the results of radar sounding. The estimate of the absolute value of the vertical component of magnetization requires a correction for the inductive component of magnetic induction μZ, where Z is the vertical component of the present-day geomagnetic field intensity. The magnetic permeability $\mu = 1 + \chi$ can be set to unity in the SI system if we are not considering magnetic rocks, magnetite ores, ferruginous quartzites, and so on. The relative error due to the neglect of magnetic susceptibility would be equal to $0.0n\%$, on average.

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The sign of B_z remains unknown: the rotation angle of the polarization plane of the signal depends only on the absolute value of the corresponding component of magnetic induction. In order to determine the sign of B_z, let us magnetize by a given mean value ΔB_z the volume of rocks in which the trajectory of the signal to the reflecting boundary and back is located. The direction of magnetization will either coincide with the present-day direction or be opposite to it. Let us change stepwise the value of magnetization in time. We shall get two more pairs of equations

$$\varphi_1 = W \cdot 2(h_2 - h_1)(B_z \pm \Delta B_z),$$

$$\varphi_2 = W \cdot 2(h_3 - h_2)(B_z \pm \Delta B_z),$$

which will allow us to determine W for the layers with thickness $(h_2 - h_1)$ and $(h_3 - h_2)$, thus obtaining a more precise estimate for the entire layer.

The following versions are possible.

1. Inductive J_r and residual J_n magnetizations coincide in direction. If we additionally magnetize samples in the same direction (henceforth, we consider the vertical component of magnetization and the intensity of magnetizing field), the magnetic induction and rotation angle of the polarization plane of the signal increase, but the sign of J_n remains indefinite. We cannot exclude that J_r and J_n have opposite signs. J_r significantly exceeds J_n and determines the response of the rock to magnetization.

2. Magnetization in the direction opposite to J_r and J_n. In this case, the total value of magnetic induction and the rotation angle of the polarization plane of the signal would first decrease with an increasing magnetizing field (the latter parameter down to zero at the moment of compensation of the total magnetization by the magnetizing field) and then increase. It is clear that the directions of the residual magnetization and present-day magnetic field coincide in this case.

3. The residual and inductive magnetizations are directed oppositely. The direction of the magnetizing field coincides with the present-day magnetic field. If $|J_r| > |J_n|$, the total magnetic induction and rotation angle of the polarization plane of the signal increase with an increasing magnetizing field and it is impossible to indicate the sign of the residual magnetization. If $|J_r| < |J_n|$, the total magnetic induction and rotation angle of the polarization plane of the signal would, first, decrease with the increasing magnetizing field. Angle φ decreases to zero at the moment of compensation of total magnetization by the magnetizing field. Then they begin to increase. Thus, it is clear that the residual magnetization is directed opposite to the present-day geomagnetic field.

4. The residual and inductive magnetizations are directed oppositely. The direction of the magnetizing field is opposite to the present-day field. If $|J_r| > |J_n|$, the total magnetic induction and rotation angle of the polarization plane of the signal would, first, decrease with an increasing magnetizing field. Angle φ decreases to zero at the moment of compensation of the total magnetization by the magnetizing field. Then they begin to increase. Hence, residual magnetization is directed opposite to the present-day geomagnetic field. If $|J_r| < |J_n|$, the total magnetic induction and rotation angle of the polarization plane of the signal would, first, show unlimited positive correlation with the magnetizing field. Hence, the direction of the residual magnetization coincides with the magnetizing field.

We should add that when the magnetizing field compensates for the total magnetization, the rotation angle of the polarization plane of the signal decreases to zero if the layer studied lacks other mechanisms leading to rotation of the polarization plane of the signal. If such mechanisms exist, angle φ decreases to a minimum and then increases. In this case, its value is described by a linear equation with a constant term, which indicates the existence of another mechanism (or other mechanisms) for rotation of the polarization plane of the signal. Here and above, we assumed that the ΔB_z value is known and can be greater than B_z. Let us calculate it as the mean value over the path of the signal motion between the h_1 and h_2 boundaries of the layer:

$$d\Delta B_z = \frac{2\pi J R^2 dh}{[(R^2 + (h_2 - h_1)^2]^{3/2}}.$$

After integration over the path from h_1 to h_2, the mean value of ΔB_z would be equal to

$$\frac{\Delta B_z}{h_2 - h_1} = \frac{2\pi J}{[(R^2 + (h_2 - h_1)^2]^{1/2}}.$$

Neglecting R^2, which should be specified small, we get

$$\Delta\varphi = 4\pi J W,$$

$$\varphi = 2\pi W(h_2 - h_1)B_z + 4\pi J W(h_2 - h_1)$$
$$= 2\pi W(h_2 - h_1)(B_z + 2J).$$

The second method can be used when there are no intermediate boundaries in the layer studied. The method is similar to that applied above and consists in magnetization of the region containing the trajectory of the signal motion. Then,

$$\varphi_0 = W \cdot 2(h_2 - h_1)B_z,$$

$$\varphi = 2\pi W(h_2 - h_1)(B_z + 2J).$$

These equations allow us to determine the Verde constant and the absolute value of the vertical component of magnetic induction B_z. By varying the value and direction of the electric current in the magnetizing loop, it is possible to determine the sign of B_z using the method described above. The current in the magnetizing loop should be significant for notable variation in the rotation angle of the signal polarization plane.

A common problem in investigation of the paleomagnetic field based on samples and remote sounding (in situ) is the account for further variations of the initial magnetization. Magnetic cleaning is possible in our case because generation of a magnetic field with varying intensity, direction, and the required dynamic of temporal variation in the given rock volume does not pose principle difficulties.

Let us try to estimate numerically the possibility of practical realization of the suggested idea based on the estimates of the Verde constant for ice. Owing to high homogeneity of ice columns, low signal absorption, and more reliable identification of interfaces formed by geomagnetic field inversions, glaciers are most favorable for studying the elements of the geomagnetic field in the last ~20 Ma (the age of the beginning of Antarctic glaciation [4]) based on measurement of the rotation of the polarization plane of the signal caused by the Faraday effect with the simultaneous detection and identification of other mechanisms participating in this process and estimation of their combined contribution. Assuming that the density and aggregate state of the matter do not generally influence strongly the value of the Verde constant, we shall use three different approaches.

1. In the optical range for different glasses, the Verde constant is located within (0.01; 1 min/G · cm) with a probability of >0.9 [6]. The minimal value (0.01 min/G · cm) corresponds to a 5% significance level. In water at T = 20°C, it is equal to 0.0154 min/G · cm. We shall use this value. The two latest inversions of the magnetic field occurred 78 and 91 ka BP. According to our estimates [7], the ice thickness increased by 715 m during this time. Then, at B_z = 0.5 G, W = 0.0154 min/G · cm = 0.026°/G · m, and assuming that the path length (in the direct and opposite directions) is equal to1430 m, we shall get the rotation angle of the polarization plane of the signal equal to 18.6°.

2. In the ionosphere at a frequency of the field equal to 24–144 MHz, the rotation angle of the polarization plane of the signal determined from signal fade is equal to 180° with intervals of ~10 km [8]. Then, W = 0.036°/G · m and the rotation angle of the polarization plane would be equal to 25.7°.

3. According to [9], the rotation angle of the polarization plane at the South Pole is equal to 90°. Assuming B_z = 0.5 Ts and ice thickness equal to 2800 m [9], we obtain W = 0.032°/G · m.

According to [10], the error in the measurement of the rotation angle of the polarization plane does not exceed 0.06° at a frequency of 101 MHz. Thus, even according to the modest estimates of the Verde constant, the rotation angles of the polarization plane are significant and can be reliably measured: even if $h_2 - h_1$ is only 50 m, the rotation angle reaches 1.5° and can be increased by additional magnetization. We note that it is possible to use multiple reflections of the signal and correspondingly increase the length of its path under favorable conditions.

Magnetization of rocks over the trajectory of the signal propagation also occurs during radar sounding with unipolar pulses of the magnetic field. Their attenuation due to absorption can be estimated and excluded. In our case, this effect can be avoided or significantly attenuated by using pulses of a magnetic field of different polarities and equal amplitude in the course of radar sounding.

Thus, based on measurements of the rotation angle of the polarization plane of the signal caused by the Faraday effect in the level formed by two sequential inversions of the geomagnetic field, one can distinguish the direction and value of the remanent magnetization. From this, it is possible to determine remotely (i.e., without collection of oriented samples) the location and alternation order of the zones of direct and inverse magnetization in the ice or rock column.

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