ISSN 1028-334X, Doklady Earth Sciences, 2006, Vol. 411A, No. 9, pp. 1470–1472. © Pleiades Publishing, Inc., 2006.
Original Russian Text © V.S. Yakupov, M.V. Yakupov, S.V. Yakupov, 2006, published in Doklady Akademii Nauk, 2006, Vol. 411, No. 5, pp. 680–683.

GEOPHYSICS

Remote Determination of the Direction to the Geomagnetic Pole in Past Epochs

V. S. Yakupov, M. V. Yakupov, and S. V. Yakupov

Presented by Academician G.F. Krymskii, May 29, 2003

Received February 1, 2006

DOI: 10.1134/S1028334X06090303

The possibility of remote detection of the direction to the geomagnetic pole in past epochs is considered on the basis of using the Faraday effect in the process of radar sounding and recording of the magnetic component of reflected signals.

The results of paleomagnetic investigations made it possible to distinguish the drift of continents and trajectories of their motion in past epochs. These results facilitated significantly the development and formation of the modern paradigm of geology: tectonics of lithospheric plates. The elements of the paleomagnetic field, in particular, magnetic declination, are determined traditionally from the laboratory analysis of residual magnetization of rock samples taken with indication of their spatial orientation. Sampling of oriented samples is a labor-consuming and sometimes impossible operation without borehole drilling. New possibilities in this and other fields of geophysics appeared after our suggestion of the method of radar sounding with recording of the magnetic component of reflected signals using high-sensitivity 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 geomagnetic field inversions in ice [2, 3] and rock sequences [4, 5]. Reliable identification of these boundaries is possible by comparing the results of radar sounding of electric and magnetic fields in ice. Direct or indirect reference data are required for their identification in the rock sequences.

A polarized electromagnetic wave[1] changes the location of the polarization plane by angle $\varphi = \mathrm{W}LB_L$ over its trajectory to and from L (during the reflection from the interface boundary) along the component of magnetic induction B_L, where W is the Verde constant. In order to determine the Verde constant, we can change the length of the pathway and change in stepwise manner the intensity and direction of the magnetizing field, where the trajectory of the signal motion is located. Let us consider two versions (the simplest and the general one) of the problem conditions, which are sufficient to understand the sense of the suggested solution.

Suppose that the studied layer is homogeneously magnetized, lacks other interfaces, and represents the first layer from the top. Let us preliminarily determine the thickness of layer h and magnetic induction B_H in the direction of the resultant of the horizontal components of the inductive and residual magnetization using radar sounding with closely located emitting and receiving dipoles. With this end in view, we shall separate the emitting and receiving dipoles, conserving their coaxial alignment so that the direct signal (in the air) and lateral signal (in the earth medium) are resolved. Next, we move the receiving dipole along the circle with the center at the location of the emitting dipole and simultaneously measure the rotation angle of the polarization plane of the signal with respect to the direct signal. It would be maximal when the radius of the emitting dipole location coincides with the direction of B_H. Measuring the rotation angle of the polarization plane of the signal at two different distances between the emitting and receiving dipoles located along the found azimuth, we get

$$\varphi_1 = \mathrm{W}_H L_1 B_H, \quad \varphi_2 = \mathrm{W}_H L_2 B_H.$$

From here, we calculate the Verde constant in the horizontal direction W_H in situ and the absolute value of B_H along the resultant of the horizontal components of the inductive and residual magnetization. Determination of the true direction to the geomagnetic pole in the past epoch (either north or south) requires a correction related to the inductive component of magnetic induction μH, where H is the horizontal component of the

[1] "Signal" or "pulse" designates a signal whose characteristics and propagation succession are studied by radar sounding and which can be presented as a superposition of plane monochromatic waves.

Institute of Cosmophysical Research and Aeronomy, Siberian Division, Russian Academy of Sciences, Merzlotnaya ul. 29/5, Yakutsk, 677010 Russia; e-mail: ikfia@sci.ru

intensity of the present geomagnetic field. With account for the residual magnetization J_n, magnetic induction (its horizontal component, for definiteness) in the SI system of units is equal to

$$B_H = \mu_{\text{eff}} H = H + \left(\chi + \frac{J_{nH}}{H}\right) H = \mu H + J_{nH}.$$

Here, μ_{eff} is the effective value of magnetic permeability, J_{nH} is the horizontal component of residual magnetization, which is one to two orders of magnitude greater than inductive magnetization χH. If we do not consider magnetic rocks (magnetite ores, ferruginous quartzites, and others), magnetic permeability can be specified equal to unity. The relative error due to neglecting magnetic susceptibility would be equal to $0.0n\%$, on average. Thus, if necessary, we can operate with the values of the present-day magnetic field intensity $H_i \approx B_i$. Then, $B_H = H + J_{nH}$. The sign of B_H usually coincides with the sign of H.

Thus, the vector of the horizontal component of residual magnetization is determined as the difference between vectors B_H and H, and one of the main problems of paleomagnetism is solved in this simplest case.

We note that, if we determine the direction to the pole in the past and use the independently determined trajectory of the pole's motion, we can indicate whether the pole is north or south and estimate the age of the rocks or at least determine the respective epoch of the rock layer formation. In order to find possible anisotropy of the Verde constant and estimate the Verde constant, one has to measure the rotation angle of the polarization plane of the reflected signal with respect to the direct signal at a close location between the emitting and receiving dipoles, which makes it possible to determine the direct signal in the air:

$$\varphi_1 = W_Z 2hB_Z.$$

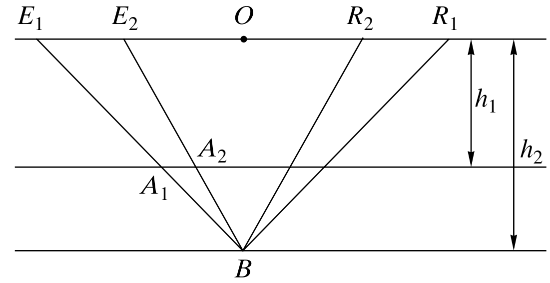
It was assumed here that the distance between the dipoles is small and that the signal propagates in one direction and back (after reflection), practically vertical directions, i.e., along the Z axis. Next, we magnetize the region containing the trajectory of the signal motion by the mean value along the trajectory ΔB_Z by means of a circular loop with current I and radius R. It would be equal to

$$\frac{1}{h}\int d\Delta B_Z,$$

where

$$d\Delta B_Z = \frac{2\pi I R^2 dh}{(R^2 + h^2)^{3/2}}.$$

Integrating this value over the distance from 0 to h and neglecting R^2, which is reasonably taken to be small, we get that the mean value ΔB_Z is equal to $\frac{2\pi I}{h}$.



(E_i and R_i) Positions of emitting and receiving dipoles at different distances between them; (h_1) thickness of overlying rocks; (h_2) depth of the lower boundary of the studied layer; $A_1B = L_1$, $A_2B = L_2$; magnetic dipole is located at point O symmetric with respect to E_i and R_i.

After increasing the magnetic induction by this value, we get

$$\varphi_2 = 2W_Z h\left(B_Z + \frac{2I}{h}\right) = 2W_Z h B_Z + W_Z \cdot 4\pi I$$

After solving the last two equations, we calculate W_Z and B_Z.

Let us consider a more general case. Let us assume that the layer studied is not located at the surface. We also assume that this layer is homogeneous and does not contain any interface boundaries. Let us locate the emitting and receiving dipoles close to each other and carry out preliminary determination of the depths of the upper and lower boundaries of the layer formed by two sequential inversions of the geomagnetic field. Next, we separate the emitting and receiving dipoles at a sufficiently large distance, at which the possibility of recording the reflected signals from the needed interface boundaries is still possible. For simplicity, we assume that the velocities of the signal in the layer and in the overlying and underlying rocks are the same, as was observed in homogeneous rock sequences, e.g., in ice columns. Let us determine the Verde constant using the lateral signal by measuring the rotation of the angle of the polarization plane with respect to the direct signal in the air. By measuring the angle of the rotation of the polarization plane at two values of the distance $2X_0$ between the emitting and receiving devices (figure), we get

$$\varphi_1 = W \cdot 2L_1 B_{l1}, \quad \varphi_2 = W \cdot 2L_2 B_{l2}.$$

Here, the length of trajectories of the signal in the studied layers L_1 and L_2 is known, which allows us to calculate the Verde constant W assuming that it does depend on the direction of the signal. The horizontal component of magnetic induction and residual magnetization in the studied layer would be equal to $B_{H1} = \frac{B_{l1}X_{01}}{L_1}$ and $B_{H2} = \frac{B_{l2}X_{02}}{L_2}$. They should be different due to different contributions of the vertical and horizontal components of magnetic induction over trajectories L_1 and L_2. The account for this difference would allow us to calculate W more precisely.

The Verde constant and elements of the paleomagnetic field can also be determined by measuring the rotation angle of the polarization plane of the signal at different (discrete and, better, multiply changing) values of the magnetic field. Then, at one distance between the emitting and receiving dipoles, we get

$$\varphi = \mathrm{W}LB_l,$$

$$\varphi_1 = \mathrm{W}L(B_l + \Delta B_l),$$

$$\varphi_2 = \mathrm{W}L(B_l + 2\Delta B_l).$$

From this, we find $\Delta B_l = If(x_i)$, where I is the current in the magnetic loop, which is known; x_i values determine geometric parameters of the loop and its location relative to the emitting and receiving dipoles. Next, we find the Verde constant and the value of the horizontal component of the resultant magnetic induction B and residual magnetization J_n. Introducing a correction for the inductive component of magnetic induction using the method described above, we find the horizontal component of residual magnetization. Changing the sign of ΔB_l by increasing or decreasing the angle of rotation of the polarization plane of the signal, we determine its sign, and thus, determine the direction to the geomagnetic pole.

Remote determination of the direction to the magnetic pole in the epoch between two specific sequential inversions of the geomagnetic field in time by means of radar sounding and recording of the magnetic component of the reflected signal already solves the main problem of paleomagnetism. The general problem of the study of the geomagnetic field using both the method of samples and the method of remote sensing in situ is accounting for the further variations of initial magnetization. In our case, magnetic cleaning is possible, because there are no principal difficulties in the formation of a magnetic field with different intensities, directions, and required time variations in a given volume of rocks. We note that comparison of the Verde constant obtained from variations in the length of the signal trajectory and from magnetic induction variation along the trajectory allows us to find the existence of other mechanisms governing the rotation of the polarization plane of the signal and determine their joint contribution.

We recall that remote detection and determination of the depth of the interface in ice and rock sequences caused by inversions of the geomagnetic field is also possible even from the air [2, 4]. According to the data in [6], the rotation of the radio pulse polarization plane in the Antarctic ice column can be as large as tens of degrees. Among the possible mechanisms of the rotation of the signal polarization plane without estimates of their possible contribution, ice crystal orientation with the C axis in one predominant direction is preferable. Thus, owing to high homogeneity of ice columns, low signal absorption, and greater reliability of distinguishing inversion boundaries formed by inversions of the geomagnetic field, glaciers are the most favorable object for investigating the rotation of the signal polarization plane due to the Faraday effect with simultaneous identification of other mechanisms involved in this process and for finding their total contribution in the angle of the rotation of the signal polarization plane.

Simultaneous magnetization of rocks over the signal trajectory occurs during radar sounding with unipolar magnetic field pulses. This signal generally attenuates, because it is absorbed. This can be taken into account and excluded. A simpler method of avoiding additional magnetization of rocks during radar sounding with unipolar magnetic field pulses is the application of pulses of different polarities and equal amplitude.

Thus, radar sounding with recording of the magnetic component of reflected signals allows us to locate the interfaces formed by inversions of the geomagnetic field. Variations in the relative position of the emitting and receiving dipoles make it possible to determine the direction to the geomagnetic field in past epochs on the basis of the Faraday effect by means of stepwise variation of the magnetic field and its direction with simultaneous variation in the angle of rotation of the polarization plane of reflected signals and other signals. This can be done in any layer available for radar sounding with the boundaries formed by inversions of the geomagnetic field and other processes.

REFERENCES

1. V. S. Yakupov and S. V. Yakupov, Dokl. Earth Sci. **385**, 565 (2002) [Dokl. Akad. Nauk **384**, 815 (2002)].
2. V. S. Yakupov and S. V. Yakupov, Dokl. Earth Sci. **393**, 1309 (2002) [Dokl. Akad. Nauk **393**, 256 (2003)].
3. V. S. Yakupov, M. V. Yakupov, and S. V. Yakupov, RF Patent No. 2 257 596, Byull. Izobret., No. 21 (2005).
4. V. S. Yakupov, A. N. Khramov, M. V. Yakupov, and S. V. Yakupov, Geomagn. Aeron. **44**, 517 (2004) [Geomagn. Aeron. **44**, 1 (2004)].
5. V. S. Yakupov, A. N. Khramov, M. V. Yakupov, and S. V. Yakupov, RF Patent No. 2 245 564, Byull. Izobret., No. 3 (2005).
6. V. Bogorodskii, Ch. Bentli, and P. Gudmandsen, *Radioglaciology* (Gidrometeoizdat, Leningrad, 1983) [in Russian].