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Magnetic measurements in electrical prospecting by resistivity methods

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Abstract

The electrical resistivity and induced polarization (IP) methods are widely used in geological mapping, prospecting and exploration of mineral deposits, engineering geology, hydrogeology, archaeology, and geotechnical and environmental applications. Historically, these methods have formed the basis of the electrical prospecting technique. In these methods, a DC or low-frequency AC electrical current is introduced into the earth through a grounded transmitter line. The measured quantity is the electric field. However, if the earth's resistivity or chargeability changes horizontally, this change gives rise to an anomalous magnetic field, which is studied by the magnetometric resistivity (MMR) and magnetic induced polarization (MIP) methods, respectively. Along with advantages, some shortcomings are inherent in the MMR and MIP techniques. Apparently, the main drawback of these methods is that the magnetic fields of both the transmitter line wire and ground electrodes on the surface are several orders of magnitude greater than the anomalous magnetic field response. This introduces a significant "noise" to magnetic-resistivity data. We investigate the potential of using a circular electric dipole (CED) in magnetometric resistivity techniques. It has been found that the application of a CED, instead of a conventional transmitter line, dramatically enhances the signal-to-noise ratio.

Keywords: electrical prospecting; resistivity methods; magnetic field; DC; MMR; MIP; circular electric dipole

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Introduction

Resistivity methods (electrical profiling, vertical and dipole electrical sounding) and induced polarization (IP) methods have found wide application in geological mapping, prospecting and exploration of mineral deposits, engineering geology, hydrogeology, geotechnical problems, archeology, and environmental applications. Historically, they have formed the basis of the modern electrical prospecting technique.

As a rule, in these methods, a low-frequency DC or AC electric current is introduced into the earth using a grounded line (*AB*) (Fig. 1). The electric field and hence current distribution in the earth depends on the length of the line and the electrical resistivity distribution. The measured parameter is the electric field, which in practice is the potential difference between the electrodes of the grounded receiver line (*MN*). In the resistivity methods, the electric field is measured during current passage, and in the IP method, it is measured after the current is turned off (in pauses between current pulses). In the frequency-domain IP method, the amplitude and/or phase of the potential difference between the receiving electrodes is measured at one or several frequencies (Sumner, 1976); in the INFAZ VP method, the phase difference is measured at two frequencies (Kulikov and Shemyakin, 1978). Abroad the IP method involving measurements at several frequencies is known as the spectral induced polarization (SIP) method (Reynolds, 2011) or the spectral IP method. However, the currents flowing in the earth produce not only an electric field, but also a magnetic field. On the surface of a horizontally layered earth, the vertical component of the magnetic field of these currents is equal to zero. The horizontal component is not zero but does not depend on the vertical distribution of electrical conductivity and/or chargeability. If the earth's resistivity or chargeability changes horizontally, this change gives rise to an anomalous magnetic field, which is studied by the magnetic resistivity and induced polarization. These methods are used mainly abroad, where they are known, respectively, as the magnetometric resistivity (MMR) method (Edwards and Nabighian, 1991) and the magnetic induced polarization (MIP) method (Seigel, 1974).

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In the MMR and MIP methods, a magnetic field, or more often EMF, is measured in the receiver coil proportional to its rate of change. The horizontal magnetic-field component perpendicular to the line connecting the transmitter electrodes is usually recorded. Since the measurements are noncontact, these methods have an advantage over the traditional ones in cases where grounding of the receiving electrodes is difficult or impossible (arid regions, rocks, caving, loose rock, permafrost, etc.). Other advantages of the MMR and MIP methods are the possibility of studying bodies overlain by conducting sediments and the weak influence of near-surface inhomogeneities.

Magnetic-field anomalies result from the fact that the currents flowing in the earth are concentrated in areas of reduced resistivity or are expelled from areas of increased resistivity. Therefore, the MMR and MIP methods are particularly effective in searching and studying elongated bodies with a strike direction close to the line connecting the electrodes *A* and *B*. These are the so-called concentration type anomalies (Dentith and Mudge, 2014). In relative terms, their amplitude does not depend on the absolute values of the electrical parameters of the host medium and the anomaly-producing body, but only depends on their contrast.

MMR data are interpreted using a normalized parameter H_n that represents the ratio of the measured field H_{meas} to the normal field H_{norm} (calculated for a particular array, if necessary, based on topography): $H_n(\%) = (H_{\text{meas}}/H_{\text{norm}}) \times 100$. Values of H_n over 100% indicate an "excess" of current, i.e., the presence of a conducting "channel," and its values below 100% indicate a "deficit" of current, i.e., a body or a zone of increased resistivity.

Another parameter, MMR, is believed to provide better resolution. It is calculated by the formula: MMR $(\%) = 100 \times (H_{\text{meas}} - H_{\text{norm\_b}})/H_{\text{norm\_b}}$, where $H_{\text{norm\_b}}$ is the normal field calculated for some "basic" or "reference" point. Usually, the middle of the straight line connecting the transmitter electrodes is chosen as such a point.

Like any other methods, the MMR and MIP methods have not only advantages, but also advantages, which are rarely mentioned by those who "promote" or "propagate" these methods. Apparently, the main factor limiting the sensitivity of these methods is that, along with the anomalous field, on the surface there is a magnetic field that does not contain information on the medium being studied.

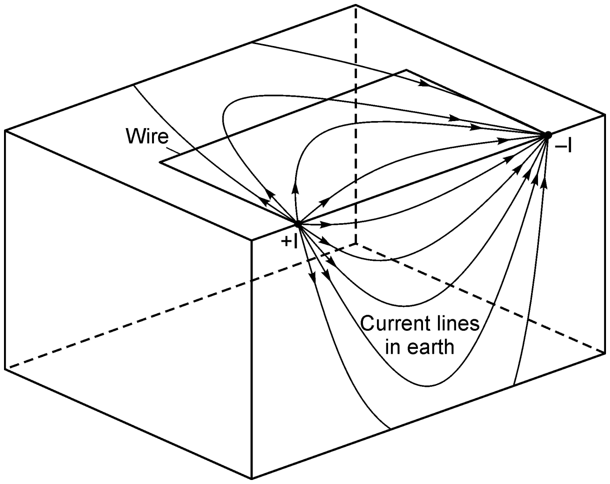

Fig. 1. General view of the array used in the MMR and MIP methods.

This field has several components. The first is the geomagnetic field, which exceeds the anomalous magnetic field by many orders of magnitude. Usually, this problem is solved by exciting the medium by a low-frequency alternating current and using an induction reception coil. The second component is the field of the wire connecting the transmitter electrodes, which in the context of this article can be called the primary field. In flat country, it is directed vertically. Its intensity is much higher than the vertical component of the anomalous field. Therefore, it is common to measure the horizontal component of the magnetic field or its derivative. And the final component is the "normal" ground field, which is directed horizontally. If the terrain is not flat, this must be taken into account when calculating the field of the wire and the normal field. In the calculation of the anomalous field, the errors in the determination of the geometry of the system are transformed into a "useful" signal, which is not such in fact. Since the anomalous field is much smaller than the field of the wire and the ground field, the error of the anomalous signal can be very large. This situation is similar to that in the study of frequency-dependent magnetic susceptibility (Kozhevnikov et al., 2014).

Usually, the above problem is noted in publications, but in practice everything depends on quantitative relationships. We propose a rather radical solution involving the use of a source that allows the introduction of the same current into the earth as the line, but does not have its own magnetic field. Such a source exists—it is a circular electric dipole (CED). CED theory and electrical prospecting methods, based on its application are described in many publications. Here we will only mention (Mogilatov and Zlobinsky, 2014) and the final work (Mogilatov, 2014). In these papers, the frequency-domain and transient modes are considered. The only exception is the early work (Mogilatov and Zlobinsky, 1995), which analyzes the constant electric field of a CED. In the present paper, the possibility of using a CED in direct current methods involving magnetic field measurements is investigated for the first time.

CED: definitions

By a circular electric dipole we mean an azimuthally uniform distribution of surface (in A/m) extraneous radial current grounded along circles of radii *a* and *b* used in theory (Fig. 2, left). For example, (Mogilatov, 1996):

$$j_r^{\text{ext}}(r) = \frac{I}{2\pi r} \cdot [U(r-b) - U(r-a)], \qquad (1)$$

where $U(x)$ is a Heaviside function. Obviously, of the greatest practical importance is the case where $a \to 0$, i.e., the inner