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The magnetic relaxation effect on TEM responses of a uniform earth

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Abstract

Ungrounded horizontal loop transient responses of uniform conductive and magnetically viscous earth have been simulated using two different codes. One algorithm employs the relationship between viscous magnetization and the magnetic flux it induces in the receiver loop. In the other algorithm, the Helmholtz equation in a boundary-value problem is solved using the Fourier transform with frequency-dependent magnetic permeability. The two solutions are identical for noncoincident loops but differ when the transmitter and receiver loops are closely spaced (at 1 cm or less). In the latter case correct results are provided by the first code. The magnetic relaxation and eddy current responses appear to be independent at conductivities typical of the real subsurface. Therefore, TEM responses of magnetically viscous conductors can be computed using the superposition principle. Although transients change in an intricate way as a function of loop geometry and earth parameters, these changes exhibit certain patterns which may be useful at the stages of exploration and TEM data processing. In configurations where the receiver loop is laid outside the transmitter, the interaction of magnetic relaxation and eddy current decay causes sign reversal in transients. This reversal occurs at late times after an earlier sign reversal due uniquely to eddy current.

Keywords: TEM method; magnetic viscosity; superparamagnetism; conductivity; simulation

Introduction

Magnetic viscosity is a property of ferromagnetism. In rocks it is associated with superparamagnetism, or magnetic relaxation of ultrafine grains in ferrimagnetic minerals. Magnetic viscosity normally causes a much less effect on TEM data than eddy current. There are, however, natural and man-made objects in which the amount of superparamagnetic particles is as great as to make the magnetic relaxation response notable or even dominant over the conductivity-controlled eddy current response. This is the effect that cannot be ignored in data interpretation.

Magnetic viscosity is most often treated as geologic noise that interferes with TEM responses to be interpreted in terms of “normal” electrical conductivity (Buselli, 1982; Dabas and Skinner, 1993; Lee, 1984a,b; Pasion et al., 2002; Zakharkin et al., 1988; Zakharkin and Bubnov, 1995). On the other hand, there is evidence that magnetic viscosity effects in TEM measurements bear signature of genesis and structure of natural and man-made materials and near-surface processes (Barsukov and Fainberg, 1997, 2002; Kozhevnikov and Nikiforov, 1996, 1999; Kozhevnikov and Snopkov, 1990, 1995; Kozhevnikov et al., 1998, 2001, 2003). Therefore, it appears reasonable to learn how to (i) amplify or damp the magnetic viscosity response, (ii) image lateral and vertical magnetic viscosity profiles in shallow subsurface, and (iii) interpret the results in terms of rock physics and, possibly, magnetic mineralogy.

For this purpose, special tools are required for mathematical modeling of transient responses of magnetically viscous ground, in addition to laboratory and field experiments. The primary objective is to design forward modeling codes to be complemented in the long run with inversion algorithms.

An important contribution to the modeling experience belongs to T.J. Lee who derived analytical equations for transient responses of a conductive superparamagnetic ground (Lee, 1984b) and a thin superparamagnetic layer on top of a conductive nonmagnetic ground (Lee, 1984a). As Lee reported, the magnetic viscosity effect was stronger in coincident than in separate loops, especially, in the case where the superparamagnetic material was confined to a thin top layer of the ground (Lee, 1984a). Lee also showed that the coincident-loop transient response depended on the loop area

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as well as on the wire radius, and the wire-radius dependence was more evident in loops on a superparamagnetic ground (Lee, 1984a,b). Lee's equations (1984 a, b) derived for circular loops are critical for understanding the physics of superparamagnetism and are useful to predict the order of the expected effects but they hardly can make the basis for appropriate modeling.

Interest in the magnetic viscosity effect on TEM data has recently been rekindled in applications of UXO (unexploded ordnance) detection (Pasion et al., 2002). The models for UXO detection simulated in-loop transient responses of magnetically viscous materials obtained with a small circular receiver at the center of a relatively small circular transmitter. With small loop systems, the eddy current decay is usually so rapid that it has died out before the first time gate. However, with large square-loop systems in conductive terrain, which is a common case of TEM surveys, the conductivity effect can produce a pronounced response.

As far as we know, there has not been much literature on mathematical modeling of TEM responses of magnetically viscous ground. We failed to find publications that would discuss different models and compare their performance at different resistivity patterns and loop geometries. This modeling, however, will be an indispensable support to TEM soundings of a superparamagnetic ground which can make magnetic viscosity an inversion-derived parameter. We are trying to somehow bridge the gap by this study using the available literature on magnetic viscosity of rocks and our own results, which were partly reported elsewhere in brief communications (Antonov and Kozhevnikov, 2003; Kozhevnikov and Antonov, 2004).

Magnetic relaxation and its relation with induction transients

Assume that a transmitter of DC current I has been on indefinitely and the transmitter and receiver loops lie on nonmagnetic ground (Fig. 1). In this case, the magnetic flux Φ_0 induced in the receiver loop is $\Phi_0 = IM_0$, where M_0 is the coefficient of inductance between two loops on nonmagnetic half-space.

If there is a magnetic object in the loop vicinity, the primary magnetic field H_1 charges its any elementary volume with the magnetization J. The magnetized object induces the secondary magnetic field H_2 which adds $\Delta\Phi$ to the initial magnetism Φ_0. Correspondingly, M_0 changes for the value ΔM called introduced inductance. It either amplifies or reduces the initial inductance depending on loop geometry and magnetic susceptibility of the ground. Measuring ΔM can give information on the presence of a magnetic object and on its properties. The inductance that bears the effect of one or several magnetized objects (including magnetic half-space) is called effective inductance (M_e). It is convenient to write M_e as

$$M_e = \mu_e M_0, \qquad (1)$$

where μ_e is the effective relative magnetic permeability which allows for the response of magnetic objects in the loop vicinity and is $\mu_e = 1$ in their absence. There is always such μ_e that (1) fulfills exactly in the case of a horizontally uniform magnetic earth; otherwise, (1) is approximate.

As the current is turned off instantly at time $t = 0$, the primary magnetic field disappears immediately. Assume that the conductivity of the object and its host is so small that eddy current and the secondary magnetic field it induces decay rapidly on a time scale of the experiment and cause no effect on magnetization, but viscous magnetization decays slowly. Magnetic relaxation excites synchronous secondary magnetic field H_2 which induces the voltage $e(t) = -\dfrac{d\Phi}{dt}$ in the receiver loop.

In the case of single-loop or coincident-loop excitation and measurement, the magnetic flux equation will include the loop inductance L instead of the mutual inductance M.

Rock magnetism is often expressed via the magnetic susceptibility κ instead of the permeability μ. In the SI system, relative μ and κ are related as

$$\mu = 1 + \kappa. \qquad (2)$$

Correspondingly, their effective counterparts are related as

$$\mu_e = 1 + \kappa_e. \qquad (3)$$

Therefore,

$$M_e = M_0(1 + \kappa_e). \qquad (4)$$

The superparamagnetic decay on removal of the applied magnetic field is slow, and μ_e, κ_e, and M_e are thus time-dependent. Then, the magnetic flux can be written as Duhamel's integral:

$$\Phi(t) = I(t)\, M_e(0) + \int_{-\infty}^{t} I(\tau) \frac{dM_e(t-\tau)}{dt} d\tau.$$

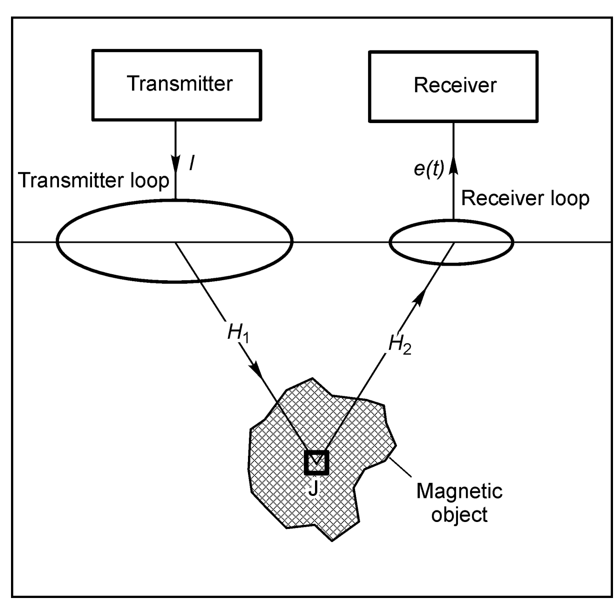

Fig. 1. Layout of TEM measurement system and magnetic object.