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The magnetic relaxation effect on TEM responses of a two-layer earth

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Abstract

We have simulated ungrounded horizontal loop transient responses of a two-layer earth consisting of a magnetically viscous layer above (model 1) or below (model 2) a nonmagnetic layer. The transient responses of a two-layer magnetically viscous earth can be computed using the superposition principle because magnetic relaxation and eddy current responses are independent at electrical conductivities typical of the real subsurface. The transients are presented and analyzed in the form of $Y = f(h_1)$ functions, where h_1 is the upper layer thickness and Y is the response (at some fixed time) of a two-layer ground normalized to that of a uniform ground with its magnetic viscosity as in the upper (model 1) or lower (model 2) layer. In model 1, the Y function increases as magnetic viscosity grows in the upper layer while the latter is thinner than the loop size, but the magnetic relaxation responses of a thicker upper layer are almost identical to that of a uniform magnetically viscous ground. In model 2, the Y responses are likewise almost identical to that of a uniform magnetically viscous ground ($h_1 = 0$) as far as the thickness of the upper layer remains small, but they decrease, first slowly and then ever more rapidly, after the layer becomes 15–20% thicker than the transmitter size. The effective sounditng depth in a magnetically viscous ground being controlled by the size of the transmitter, it is reasonable to use geometrical sounding to resolve the vertical distribution of magnetic viscosity.

Keywords: TEM method; two-layer earth; magnetic viscosity; superparamagnetism; electrical conductivity

Introduction

The effect of magnetic viscosity of rocks on TEM data is an essential problem which has been solved through laboratory, field (Buselli, 1982; Dabas and Skinner, 1993; Kozhevnikov and Snopkov, 1990, 1995; Neumann, 2006; Neumann et al., 2005; Zakharkin et al., 1988), and numerical (Lee, 1984a,b; Kozhevnikov and Antonov, 2008; Pasion et al., 2002) experiments.

For the lack of *in situ* geological objects that would be documented well enough to allow comprehensive investigation of TEM responses of superparamagnetic ground at different loop configurations, the respective systematic numerical experiments are of special interest. This kind of modeling was applied before to magnetic relaxation effects on transient responses of uniform conductive, magnetically viscous ground (Kozhevnikov and Antonov, 2008).

A uniform magnetically viscous conducting earth is a basic model in many respects. It has provided an idea of how time-dependent magnetic susceptibility $\kappa(t)$ and resistivity ρ of rocks, as well as the loop configuration, influence the transient process. Namely, it has been found out that

– the magnetic relaxation and eddy current responses are independent at conductivities of the real subsurface, which makes it possible to compute the TEM responses of magnetically viscous conductors using the superposition principle;

– the responses of a magnetically viscous conducting earth change in an intricate way as a function of loop geometry and earth properties, but these changes exhibit certain features which may be useful guides to acquisition and processing of TEM data from a magnetically viscous environment.

The uniform-earth model can account for any volume of rocks which is uniform in magnetic susceptibility and resistivity and has a size several times the loop size. However, this model is only a rough approximation of the real subsurface. The next fundamental model to explore is obviously that of a two-layer conducting earth.

Choice of models and their general characteristics

The two-layer earth is a key model of layered media, in the same way as the uniform-earth model. Below we consider two important two-layer cases (Fig. 1).

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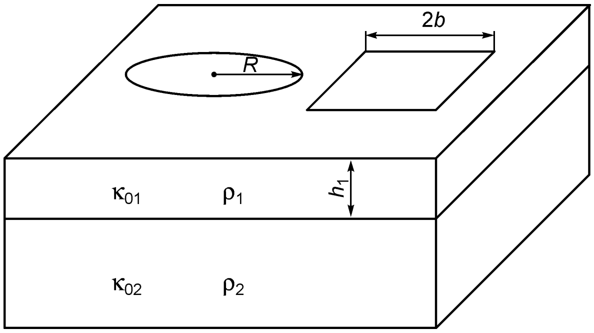

Fig. 1. A circular and a square loops on a two-layer magnetically viscous ground. ρ_1, ρ_2 are resistivities and κ_{01}, κ_{02} are static magnetic susceptibilities of upper and lower layers, respectively.

Model 1: a magnetically viscous layer lying over a nonmagnetic half-space of zero magnetic viscosity. This model is suitable for simulating diverse geological objects. The ground often contains large amounts of superparamagnetic grains of ferromagnetic minerals in which relaxation of magnetization shows up as magnetic viscosity. Superparamagnetic particles are either originally present in rocks, e.g., in basalt or tuff (Kozhevnikov and Snopkov, 1990, 1995; Urrutia-Fucugauchi et al., 1991; Worm, 1999; Zakharkin et al., 1988) or form as a result of weathering and other surface processes (Buselli, 1982; Emerson, 1980), or are generated by bacteria to further accumulate in soils (Linford, 2005). Human activity, especially if it is long-term, produces a layer of magnetically viscous deposits on the ground surface (Kozhevnikov et al., 1998, 2001; Linford, 2005). Superparamagnetic ground can have thicknesses of a few centimeters or tens of centimeters in the case of manmade effects on soil and rocks or hundreds of meters in natural cases as, for instance, in western Yakutia, where low-magnetic carbonate rocks lie under flood basalt and tuff (Kozhevnikov and Snopkov, 1995).

Model 2: a magnetically viscous half-space lying under a nonmagnetic layer. The model corresponds to the cases when thick layers of basalt, tuff, or other magnetically viscous rocks are buried under nonmagnetic sediments. It can be useful in engineering or archaeological geophysics, i.e., for investigation of relatively small natural or manmade objects, such as ancient metallurgical slag under recent sediments and soils.

Computing magnetic viscosity-affected TEM responses

There are two procedures for computing transient responses of uniform conductive superparamagnetic ground. In one code, the Helmholz equation is solved using the Fourier transform with allowance made for frequency-dependent magnetic permeability. This is a universal algorithm because it takes into account the interaction between eddy current and magnetic relaxation. The other code employs the linkage between viscous magnetization and the magnetic flux it induces in the receiver loop. This solution is simple due to the use of known analytical solutions but it is not rigorous as it neglects the eddy current-magnetic viscosity interaction.

These algorithms were implemented, respectively, in the Unv_QQ and MVIS programs which were described briefly in (Kozhevnikov and Antonov, 2008).

The two solutions are identical and exact in the case of noncoincident loops but differ when the transmitter and receiver loops are closely spaced (at 1 cm or less). In the latter case it is the first code that provides a correct calculation.

After having studied the transient responses of a uniform magnetically viscous earth (Kozhevnikov and Antonov, 2008), we are undertaking a similar investigation for a layered earth. Unlike the former of the above codes, the latter one needs additional comments.

The transient response of a uniform earth with time-dependent true magnetic susceptibility $\kappa(t)$ associated with magnetic relaxation after the transmitter current I_0 has been turned off is (Kozhevnikov and Antonov, 2008)

$$e(t) = \frac{1}{2} I_0 M_0 \frac{d\kappa}{dt}, \qquad (1)$$

where M_0 is the mutual inductance between two loops laid on nonmagnetic ground. In the case of single-loop or coincident-loop excitation and measurement, the M_0 inductance equals the loop self-inductance L_0.

The response of a layered earth includes apparent magnetic susceptibility κ_a instead of the true one. The apparent magnetic susceptibility is defined by the true susceptibility distribution and the loop configuration:

$$e(t) = \frac{1}{2} I_0 M_0 \frac{d\kappa_a}{dt}. \qquad (2)$$

In fact, calculating the apparent magnetic susceptibility reduces to calculating the magnetic flux through the receiver loop induced by magnetization of the earth with a known distribution of $\kappa(x, y, z)$. There exist analytical equations for some models, including that of a layered earth, which are useful for the consideration below. We consider them for the noncoincident (in-loop configuration) and then coincident loops.

In-loop configuration. The magnetic field of an ungrounded loop laid on a layered magnetic ground as discussed in (Blokh et al., 1986) corresponds to the case of an ungrounded receiver loop placed at the center of a transmitter. The receiver loop measures the time derivative of the magnetic field at the loop center, i.e., the measurement system is the same as in the TEM-TDEM method. The transmitter frequency and/or the earth conductivity are assumed to be low, such that the induction effects were negligible relative to the effects of magnetization. For a circular transmitter loop of the radius R on an N-layer magnetically viscous ground,

$$\kappa_a = \kappa_1 \left\{ 1 + \left(\frac{R}{h_1} \right)^3 \times \right.$$

$$\sum_{i=1}^{N-1}\left(\frac{\kappa_{i+1}}{\kappa_1}-\frac{\kappa_i}{\kappa_1}\right)\left[\left(\frac{R}{h_1}\right)^2+4\left(\frac{z_i}{h_1}\right)^2\right]^{-3/2}\Bigg\}, \tag{3}$$

where κ_i is the magnetic susceptibility, h_i is the thickness of the i-th layer, and $z_i = h_1 + h_2 + ...+ h_i$ is the depth of its base.

If the primary magnetic field is excited by a square loop with the side length $2b$, the apparent magnetic susceptibility is

$$\kappa_a=\kappa_1\Bigg\{1+\left(\frac{b}{h_1}\right)^3\sum_{i=1}^{N-1}\left(\frac{\kappa_{i+1}}{\kappa_1}-\frac{\kappa_i}{\kappa_1}\right)\times$$

$$\left\{\left[\left(\frac{b}{h_1}\right)^2+4\left(\frac{z_i}{h_1}\right)^2\right]\left[\left(\frac{b}{h_1}\right)^2+2\left(\frac{z_i}{h_1}\right)^2\right]^{1/2}\right\}^{-1}\Bigg\}. \tag{4}$$

The apparent magnetic susceptibility $\kappa_a(t)$ of a layered earth, with time-dependent susceptibilities of the layers, is found by using (3) and (4) together, where $\kappa_i(t)$ is used instead of κ_i. For instance, (3) becomes

$$\kappa_a=\kappa_1(t)\Bigg\{1+\left(\frac{R}{h_1}\right)^3\sum_{i=1}^{N-1}\left(\frac{\kappa_{i+1}(t)}{\kappa_1(t)}-\frac{\kappa_i(t)}{\kappa_1(t)}\right)\times$$

$$\left[\left(\frac{R}{h_1}\right)^2+4\left(\frac{z_i}{h_1}\right)^2\right]^{-3/2}\Bigg\}. \tag{5}$$

Magnetic viscosity of rocks is normally due to magnetic relaxation of superparamagnetic grains. Then (Kozhevnikov and Antonov, 2008),

$$\kappa_i(t)=\frac{\kappa_{0i}}{\ln(\tau_{2i}/\tau_{1i})}(B+\ln t),$$

where κ_{0i} is the static magnetic susceptibility, τ_{1i} and τ_{2i} are the lower and upper bounds of the relaxation time for the i-th layer, and B is a constant. The characteristic time of the experiment t (e.g., the delay time of the measured transient response) is most often within the gate $\tau_1 \ll t \ll \tau_2$. In this case one may assume that the gate is the same for all layers, i.e., for each layer $\tau_{1i} = \tau_1$, $\tau_{2i} = \tau_2$. Then, for a circular transmitter loop and a receiver loop at its center,

$$\kappa_a=\frac{\kappa_{01}}{\ln(\tau_2/\tau_1)}\Bigg\{1+\left(\frac{R}{h_1}\right)^3\sum_{i=1}^{N-1}\left(\frac{\kappa_{0i+1}}{\kappa_{01}}-\frac{\kappa_{0i}}{\kappa_{01}}\right)\times$$

$$\left[\left(\frac{R}{h_1}\right)^2+4\left(\frac{z_i}{h_1}\right)^2\right]^{-3/2}\Bigg\}(B+\ln t). \tag{6}$$

The corresponding equation for a square transmitter loop is

$$\kappa_a=\frac{\kappa_{01}}{\ln(\tau_2/\tau_1)}\Bigg\{1+\left(\frac{b}{h_1}\right)^3\sum_{i=1}^{N-1}\left(\frac{\kappa_{0i+1}}{\kappa_{01}}-\frac{\kappa_{0i}}{\kappa_{01}}\right)\times$$

$$\left\{\left[\left(\frac{b}{h_1}\right)^2+4\left(\frac{z_i}{h_1}\right)^2\right]\times\right.$$

$$\left.\left[\left(\frac{b}{h_1}\right)^2+2\left(\frac{z_i}{h_1}\right)^2\right]^{1/2}\right\}^{-1}\Bigg\}(B+\ln t). \tag{7}$$

Coincident-loop configuration. We failed to find in the literature analytical equations for calculating apparent magnetic susceptibility in the case of a coincident-loop system. However, we used a study of eddy current nondestructive testing (Sobolev and Shkarlett, 1967) to obtain formulas for the so-called extrinsic impedance Z_{ex} which is produced by the underlying uniform or layered (two or three layers) magnetic subsurface and is added to the self-impedance of circular coincident loops.

For a uniform earth with the relative magnetic permeability μ

$$Z_{ex}=j24\cdot10^{-7}\omega RW^2\frac{\mu-1}{\mu+1},$$

where $j=\sqrt{-1}$, R is the radius of the transmitter and receiver loops, in m; W is the number of coils in each loop; ω is the angular frequency, in s^{-1}.

Inasmuch as $\mu = 1 + \kappa$ and $\kappa \ll 1$,

$$Z_{ex}=j24\cdot10^{-7}\omega RW^2\frac{\kappa}{2}, \tag{8}$$

where κ is the magnetic susceptibility being $\kappa \ll 1$ in most of rocks.

For a layered earth,

$$Z_{ex}=j24\cdot10^{-7}\omega RW^2\frac{\kappa_a}{2}, \tag{9}$$

where κ_a is the apparent magnetic susceptibility.

It is convenient to express the extrinsic impedance through the introduced inductance M_{in} between the loops: $Z_{ex} = j\omega M_{in}$. With regard to (8),

$$M_{in}=24\cdot10^{-7}RW^2\frac{\kappa}{2}. \tag{10}$$

Equation (10) can be solved with respect to κ:

$$\kappa=\frac{2M_{in}}{24\cdot10^{-7}RW^2}. \tag{11}$$

Thus, (11) can be applied to find the true magnetic susceptibility of the subsurface from the measured extrinsic inductance between the loops laid on the surface of a uniform superparamagnetic ground.

Equation (11) makes sense also for a layered earth, but in this case it gives apparent rather than true magnetic susceptibility:

$$\kappa_a = \frac{2M_{\text{in}}}{24\cdot 10^{-7} RW^2}.$$

In the case of a two-layer earth,

$$Z_{\text{ex}} = j24\cdot 10^{-7}\omega RW^2 \frac{\mu_1(\mu_2-1) + (\mu_1^2 - \mu_2)\tanh\dfrac{3h_1}{2R}}{\mu_2(\mu_2+1) + (\mu_1^2 + \mu_2)\tanh\dfrac{3h_1}{2R}},$$

where h_1 is the thickness of the upper layer; μ_1 and μ_2 are the relative magnetic permeabilities of the upper and lower layers, respectively. Inasmuch as $\mu_1 = 1 + \kappa_1$, $\mu_2 = 1 + \kappa_2$, $\kappa_1 \ll 1$, $\kappa_2 \ll 1$, the latter equation becomes

$$Z_{\text{ex}} = j24\cdot 10^{-7}\omega RW^2 \frac{1}{2}\frac{\kappa_2 + (2\kappa_1 - \kappa_2)\tanh\dfrac{3h_1}{2R}}{1 + \tanh\dfrac{3h_1}{2R}},$$

whence, with regard to (9), one finds the apparent magnetic susceptibility of a two-layer earth measured with circular coincident loops:

$$\kappa_a = \frac{\kappa_2 + (2\kappa_1 - \kappa_2)\tanh\dfrac{3h_1}{2R}}{1 + \tanh\dfrac{3h_1}{2R}},$$

For a magnetically viscous earth,

$$\kappa_a(t) = \frac{1}{\ln(\tau_2/\tau_1)} \frac{\kappa_{02} + (2\kappa_{01} - \kappa_{02})\tanh\dfrac{3h_1}{2R}}{1 + \tanh\dfrac{3h_1}{2R}}(B + \ln t), \qquad (12)$$

where κ_{01} and κ_{02} are the static magnetic susceptibilities of the upper and lower layers, respectively. Then one can compute the coincident-loop transients associated with magnetic relaxation by substituting $\kappa_a(t)$ found with (12) into (2).

Figure 2 shows in-loop transient responses of a two-layer earth with h_1 = 10 m, $\rho_1 = 10$ ohm·m, $\kappa_{01} = 0.01$ SI units, $\rho_2 = 10^3$ ohm·m, $\kappa_{02} = 0$ (model 1) and h_1 = 10 m, $\rho_1 = 10^3$ ohm·m, $\kappa_{01} = 0$, $\rho_2 = 10$ ohm·m, $\kappa_{02} = 0.01$ SI units (model 2). In both cases the sizes of the transmitter and receiver loops were 100×100 m and 10×10 m, respectively.

First we calculated the eddy current response $e_1(t)/I$, assuming zero static magnetic susceptibility of the two layers in both models ($\kappa_{01} = \kappa_{02} = 0$), i.e., neglecting the magnetic viscosity effects.

Then we calculated the magnetic relaxation response $e_2(t)/I$, assuming $\kappa_{01} = 0.01$ SI units, $\kappa_{02} = 0$, and $\rho_1 = \rho_2 = 10^6$ ohm·m in model 1 and $\kappa_{01} = 0$, $\kappa_{02} = 0.01$ SI units, and $\rho_1 = \rho_2 = 10^6$ ohm·m in model 2. Inasmuch as eddy current

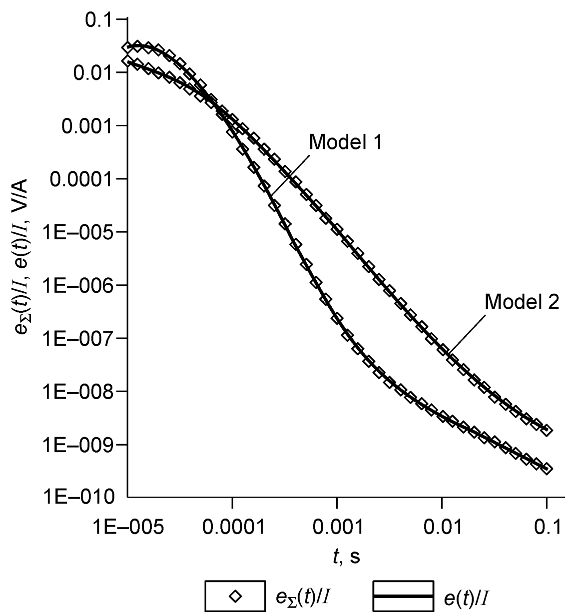

Fig. 2. In-loop transient responses of a two-layer earth computed with an approximate and a "rigorous" algorithms. See text for explanation.

decays rapidly in rocks with this resistivity, the contribution of magnetic relaxation in the transients is predominant already at early times.

Finally, we found the total response $e_\Sigma(t)/I = e_1(t)/I + e_2/I$ (Fig. 2). Figure 2 also shows the $e(t)/I$ responses computed using the Unv_QQ code taking into account the eddy current-magnetization interaction. This result supports the idea that the magnetic relaxation and eddy current responses are commonly independent in the real subsurface (Kozhevnikov and Snopkov, 1990; Kozhevnikov and Antonov, 2008), which makes it possible to compute TEM responses of magnetically viscous conductive ground using the superposition principle.

Presentation of the results

Interpretation of the results may be problematic because of incompatibility of the input data. For instance, the dissimilarity in the measured transient voltage loop configurations, properties of the two-layer earth, and the receiver delay times may reach several orders of magnitude. Therefore, we suggest applying special normalization to solve this problem.

The TEM responses for both models were normalized to the response of a uniform magnetically viscous ground, assuming the static magnetic susceptibility of the uniform earth κ_0 to be the same as in the upper (model 1) or lower (model 2) layers: $\kappa_0 = \kappa_{01}$ and $\kappa_0 = \kappa_{02}$, respectively. Thus, the normalized transient

$$Y = \frac{[e(t)/I]_{\text{two-layer}}}{[e(t)/I]_{\text{uniform}}}. \qquad (13)$$

substituted for the response $[e(t)/I)]_{\text{two-layer}}$ of a two-layer earth, where $[e(t)/I)]_{\text{uniform}}$ is the transient response of a uniform magnetically viscous earth. The thickness h_1 of the upper layer was normalized to the half-length of the loop side b or to the loop radius R in the cases of square and circular transmitters, respectively.

Results

The in-loop and coincident-loop transient responses obtained with the Unv_QQ and MVIS codes for the two models were as follows.

Model 1. We assumed the static magnetic susceptibility of the upper layer to be $\kappa_{01} = 10^{-3}$ SI units, $\kappa_{02} = 0$, and $\rho_1 = \rho_2 = \rho = 10^6$ ohm·m and computed the transients using the Unv_QQ and MVIS codes for the upper layer thicknesses h_1 in the ranges from 0.1 to 500 m and 0.05 to $5 \cdot 10^3$ m, respectively.

One experiment was for an in-loop configuration of a 100×100 m square transmitter loop and a 10×10 m receiver loop. See Fig. 3 for the normalized transient responses at three fixed times (t = 0.1, 1 and 10 ms) as a function of the normalized upper layer thickness.

We begin with the transients obtained using analytical equations (MVIS code). Note first of all that they were the same at any time (open circles in Fig. 3). The normalized signal increased proportionally to the square thickness of the magnetically viscous layer h_1 as long as h_1 remained within 15% of the loop size (side length). However, the response became hard to distinguish from that of a uniform magnetically viscous earth as the h_1 became half the loop size.

The transients computed with the Unv_QQ code differed at different times and h_1 thicknesses, and all differed from the MVIS result, the latter difference being inversely proportional to the thickness of the magnetically viscous layer. At greater thicknesses and/or time, the numerically computed transients approached those obtained with the MVIS code. At t = 0.1 ms and small h_1, the normalized transients were almost independent of the h_1 thickness (Fig. 3).

Let $e_1(t, h_1, \kappa_{01})$ be the magnetic relaxation-affected transient response of the magnetically viscous layer, $e_2(t, \rho)$ be the response associated with eddy current in the whole subsurface of the two layers, and $e_3(t, \kappa_{01})$ be that due to magnetic relaxation in a uniform magnetically viscous earth with its magnetic susceptibility same as in the magnetically viscous layer.

The normalized transient response obtained using analytical equations (MVIS code) is

$$Y_1 = \frac{e_1(t, h_1, \kappa_{01})}{e_3(t, \kappa_{01})}. \quad (14)$$

The normalized transient obtained using the Unv_QQ code is

$$Y_2 = \frac{e_1(t, h_1, \kappa_{01}) + e_2(t, \rho)}{e_3(t, \kappa_{01})} = Y_1 + \frac{e_2(t, \rho)}{e_3(t, \kappa_{01})}. \quad (15)$$

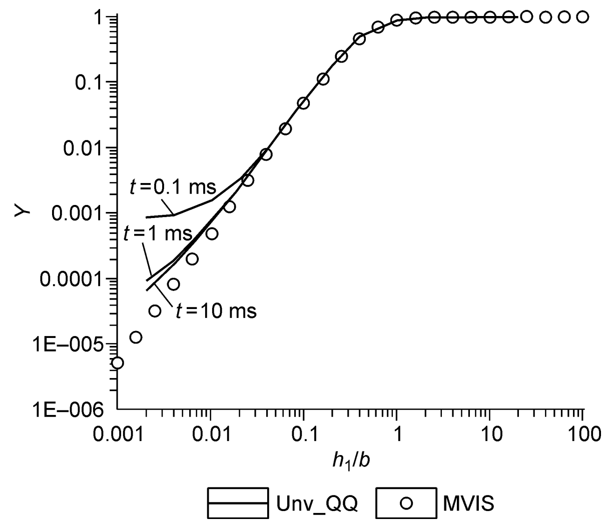

Fig. 3. In-loop transient responses of a two-layer earth $Y = f(h_1/b)$, with a magnetically viscous layer above. See text for explanation.

Comparing (14) and (15) sheds light on the behavior of the curves in Fig. 3. At early times and/or small h_1, the second term in (15) exceeds the first term, and $Y_2 < Y_1$. As the h_1 thickness and/or time increase, the relative contribution of the second term in (15) decreases, and $Y_2 \to Y_1$. Thus, the difference between the transients (Fig. 3) is due to the fact that eddy current relaxation effects are significant at small h_1 whereas the contribution of magnetic viscosity increases with h_1 and/or with time, to eventually become predominant.

In the experiment with the coincident-loop configuration, the model parameters remained the same as for the in-loop case. Note that the Unv_QQ code is designed for square-loop systems while analytical equations (MVIS code) for the coincident-loop responses of a two-layer earth are available only for circular loops. This problem is solved taking into account that coincident-loop transients of a magnetically viscous earth are identical for loops of any geometry and size if they have the same self-inductance L_0. It is reasonable to assume that the responses of the circular and square loop, with the same self-inductance, lying on a two-layer ground are identical as well in their magnetic relaxation component. See Fig. 4 for square ($2b$ = 100 m) and circular (R = 63 m) coincident loops with the same initial inductance.

The coincident-loop transients computed using analytical equations were identical at all times $Y = f(h_1/R)$, as well as in the in-loop case (Fig. 3), and the general pattern looked like that for the in-loop configuration. At $h_1/R < 0.3$, Y increased with h_1/R proportionally to h_1, and Y =1 at $h_1/R \geq 1$.

The $Y = f(h_1/b)$ curves computed using the Unv_QQ code for a 100×100 m coincident-loop system differed from those obtained with the MVIS code using equations (2) and (12) for a R = 63 m loop. The thinner the magnetically viscous layer the more divergent the $Y = f(h_1/b)$ and $Y = f(h_1/R)$ curves. The difference reduced as the layer became thicker, and Y =1 at $2h_1/R \geq 1$ for both configurations. The $Y = f(h_1/b)$ curves obtained with the Unv_QQ code being independent of time, the above reason for the discrepancy between the results does

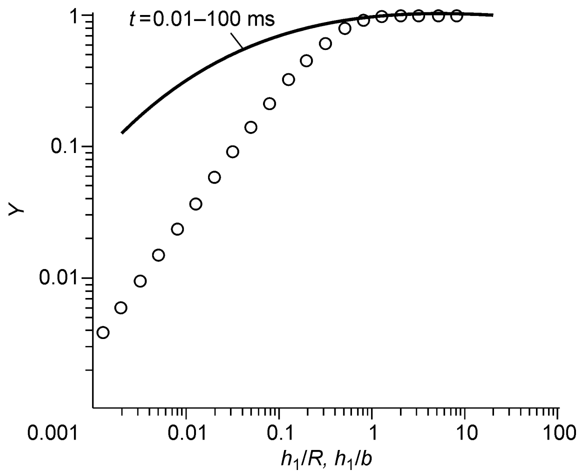

Fig. 4. Coincident-loop transient responses of a two-layer earth $Y = f(h_1/b)$, with a magnetically viscous layer above, for circular (R = 63 m) and square ($2b$ = 100 m) loops. Model parameters: $\rho_1 = \rho_2 = 10^6$ ohm·m, $\kappa_{01} = 10^{-3}$ SI units, $\kappa_{02} = 0$. Designations follow Fig.3.

not apply. A plausible explanation is that the mutual inductance M_0 between the coincident loops depends on the wire thickness when the transmitter and receiver wires are closely spaced (a few cm or closer). This dependence is taken into account in the MVIS code, because L_0 entering equation (2) is found a priori by analytical formulas. However, it is impossible to include the effect of the nearest vicinity of a coincident-loop wire in the Unv_QQ code for the reason that, in terms of physics, it gives the inductance between the receiver loop and eddy current rather than between the transmitter and receiver loops (Kozhevnikov and Antonov, 2008).

Model 2. The parameters of model 2 were as follows: $\kappa_{01} = 0$, $\kappa_{02} = 10^{-3}$ SI units, and $\rho_1 = \rho_2 = \rho = 10^6$ ohm·m. The modeling results are reported in the same order as for model 1.

See Fig. 5 for $Y = f(h_1/b)$ in the case of an in-loop configuration. The MVIS code again gave the same pattern irrespective of time (open circles). At a relatively small h_1 thickness ($h_1/b \le 0.1$–0.2), the response was the same as that of a uniform magnetically viscous ground: $f(h_1/b) = 1$ (Fig. 5). As h_1 increased, the signal decreased and decayed inversely to h_1^3 at $h_1/b \ge 1$.

Like the case of model 1, the numerical results were divergent and differed from the MVIS result as a function of time and h_1 thickness. The difference appeared when the upper layer became as thick as the transmitter loop size and increased with further h_1 increase, especially at early times. At late times, the transients obtained by the two codes coincided at any h_1.

Let $e_1(t, h_1, \kappa_{02})$ be the magnetic relaxation response of the magnetically viscous lower layer, $e_2(t, \rho)$ be the eddy current response, and $e_3(t, \kappa_{02})$ be that due to magnetic relaxation of a uniform magnetically viscous earth with its magnetic susceptibility same as in the underlying magnetically viscous layer.

The normalized transient response obtained using analytical equations (MVIS code) is

$$Y_1 = \frac{e_1(t, h_1, \kappa_{02})}{e_3(t, \kappa_{02})}. \qquad (16)$$

The normalized transient response obtained with the Unv_QQ code is

$$Y_2 = \frac{e_1(t, h_1, \kappa_{02}) + e_2(t, \rho)}{e_3(t, \kappa_{02})} = Y_1 + \frac{e_2(t, \rho)}{e_3(t, \kappa_{02})}. \qquad (17)$$

Again, the behavior of the curves in Fig. 5 becomes clear through comparing (16) and (17). When the upper layer is thin, the loop approaches the magnetic basement and the effect of magnetic viscosity dominates over that of eddy current. As the upper layer thickens up, the magnetic viscosity component of the total response decreases, and the eddy current effect is becoming ever more significant. The contribution of the second term in (17) predominates at early times ($Y_2 > Y_1$) because the two components decrease at different rates: the eddy current component as $t^{-5/2}$ and the magnetic relaxation one as t^{-1} (Kozhevnikov and Antonov, 2008). As the upper layer thins down and/or the delay time increases, the relative contribution of the second term in (17) decreases, and $Y_2 \to Y_1$.

The coincident-loop patterns computed using analytical equations (Fig. 6) were again the same $Y = f(h_1/R)$ at any time, and the normalized response looked generally similar to the in-loop response (Fig. 5). The response of the two-layer earth was identical to that of a uniform magnetically viscous earth ($Y = 1$) if the upper layer was relatively thin ($h_1/R < 0.2$–0.3), but Y fell ever more rapidly since $h_1 \ge (0.2$–$0.3)R$ as the layer was thicker. Unlike the in-loop transients which decreased as h_1^{-3}as the magnetically viscous basement grew deeper, the coincident-loop responses decreased exponentially as $Y \sim \exp(-h_1/R)$ at any h_1 and time.

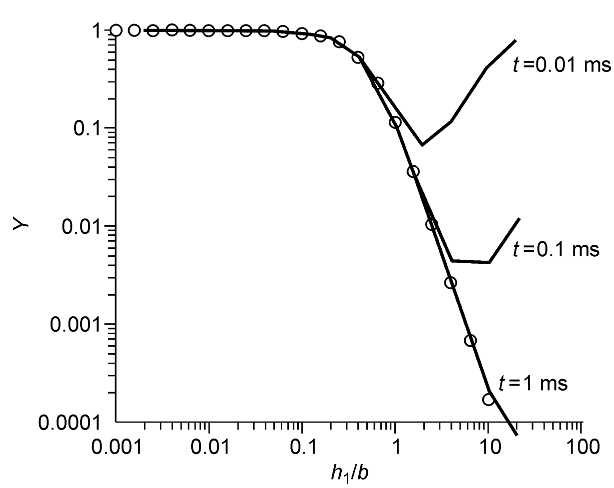

Fig. 5. In-loop transient responses of a two-layer earth $Y = f(h_1/b)$, with a magnetically viscous basement. Transmitter loop 100 m × 100 m, receiver loop 10 m × 10 m. Designations follow Fig.3.

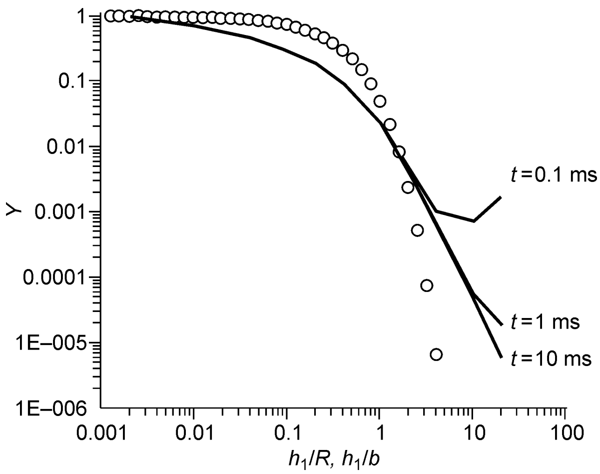

Fig. 6. Coincident-loop transient responses of a two-layer earth $Y = f(h_1/b)$, with a magnetically viscous ground below, for circular (R = 63 m) and square ($2b$ = 100 m) loops. Model parameters: $\rho_1 = \rho_2 = 10^6$ ohm·m, $\kappa_{01} = 0$, $\kappa_{02} = 10^{-3}$ SI units. Designations follow Fig. 3.

The Unv_QQ $Y = f(h_1/b)$ patterns for a 100-m coincident-loop system were generally similar to the MVIS ones for a R = 63 m loop, but differed in details. The difference between $Y = f(h_1/b)$ and $Y = f(h_1/R)$ has the same reason as in the in-loop case (see above). The more rapid fall of $Y = f(h_1/b)$ at $h_1 < 2b$ and its slower decrease at $h_1 > 2b$ prompts that the transients computed with the Unv_QQ code bear a systematic error.

Discussion

The reported results are interesting in two aspects. On the one hand, magnetic viscosity may be treated as geologic noise that interferes with TEM data in mineral (Emerson, 1980) and kimberlite (Kozhevnikov and Snopkov, 1995) exploration and in UXO (unexploded ordnance) detection (Barsukov and Fainberg, 2002; Pasion et al., 2002). In this case identifying the magnetic viscosity effect during data processing and estimating its possible magnitude on the basis of an a priori physical-geological model is useful as a guide in the choice of loop configuration while planning further TEM survey experiments.

On the other hand, magnetic viscosity of rocks *in situ* has geological implications, such as estimating the thickness (depth) of exposed or buried magnetically viscous layers. Or, magnetic viscosity effects may help identifying the rocks (e.g., basalt) that are mute in resistivity, chargeability, or seismic velocity patterns (Urrutia-Fucugauchi et al., 1991). For instance, magnetic viscosity is a critical parameter to discriminate between flood basalt and carbonate rocks in western Yakutia (Siberian Trap Province) which have resistivities of the same order of magnitude but basalts, unlike carbonates, bear abundant superparamagnetic grains (Kozhevnikov and Snopkov, 1995). The layer with superparamagnetic grains, be it exposed on the surface or buried under a nonmagnetic layer, may be too thin to be resolved in resistivity, magnetic, or other patterns (Kozhevnikov et al., 2001). However, with TEM soundings, one can "see" it, and more so, estimate its thickness and static magnetic susceptibility, provided that the loop configuration is chosen properly.

The resistivity interface may coincide or not with that between rocks of different static magnetic susceptibilities. Let h_{1tem} be the depth of the interface between rocks of the resistivities ρ_1 and ρ_2 and h_{1spm} be that for the magnetic susceptibilities κ_{01} and κ_{02}. The magnetic relaxation and eddy current effects being additive, the total response $e_\Sigma(t)$ is the sum $e(t) = e_1(t) + e_2(t)$, where $e_1(t) = e_1(h_{1tem}, \rho_1, \rho_2$, geometry, $t)$ is the eddy current component of the response, and $e_2(t) = e_2(h_{1spm}, \kappa_{01}, \kappa_{02}$, geometry, $t)$ is the magnetic relaxation component, while "geometry" stands for the loop shape and size.

In the problem of estimating h_{1tem}, ρ_1, ρ_2, the response $e_1(t)$ is the signal and $e_2(t)$ is the noise. Then, $e_1(t)$ divided by $e_2(t)$ is the signal/noise ratio, which is a handy parameter for comparison. One possibility to improve the $e_1(t)/e_2(t)$ ratio is to choose a configuration which shifts the balance towards the eddy current component. First we check this possibility with two-layer model 1 (a magnetically viscous layer above a nonmagnetic half-space). Let the model parameters be $\rho_1 = \rho_2 = 10^2$ ohm·m, $\kappa_{01} = 0.01$ SI units, and $\kappa_{02} = 0$, and the configurations be in-loop or coincident-loop, with R = 10 m and 2 m transmitter and receiver loops, respectively, in the former case.

The in-loop system provides a better signal/noise ratio, as it is evident from Fig. 7, *a* in which the $e_1(t)/e_2(t)$ ratio is plotted against the thickness h_1 for both loop configurations at t = 1 ms. At $h_1 > 10$ m, this ratio is minimum for both configurations and does not change on further h_1 increase, i.e., the layer looks like a uniform magnetically viscous earth. As the upper layer thins down, the magnetic relaxation component decreases while the $e_1(t)/e_2(t)$ ratio increases. At $h_1 < 10$ m, the in-loop configuration gives a better signal/noise ratio, the thinner h_1 the better (Fig. 7, *a*).

One has to bear in mind that these estimates are meaningful within the time range in which the transients are practically measurable. See Fig. 7, *b* for $e(t) = e_1(t) + e_2(t)$ as a function of h_1 at t = 1 ms, for both configurations. The dashed line shows the minimum transient signal (current-normalized) which is commonly measurable with the available systems at moderate noise. In-loop systems can hardly resolve transients at the transmitter current of 1 A, whereas the transients measurable by coincident-loop systems are one or two orders of magnitude or more above the minimum. Increasing the transmitter current and/or decreasing the time moves the $e(t) = f(h_1)$ curve up the y axis, to the domain where the in-loop configuration becomes able to measure the transients and thus to realize its advantage over the coincident-loop system.

The behavior of the $e_1(t)/e_2(t)$ ratio in model 2, with a buried magnetically viscous layer, is as follows (Fig. 8). Let the model parameters be $\rho_1 = \rho_2 = 10^2$ ohm·m, $\kappa_{01} = 0$, and $\kappa_{02} = 0.01$ SI units. The loop configurations are the same as in the case of model 1, and the delay time is t = 1 ms. The

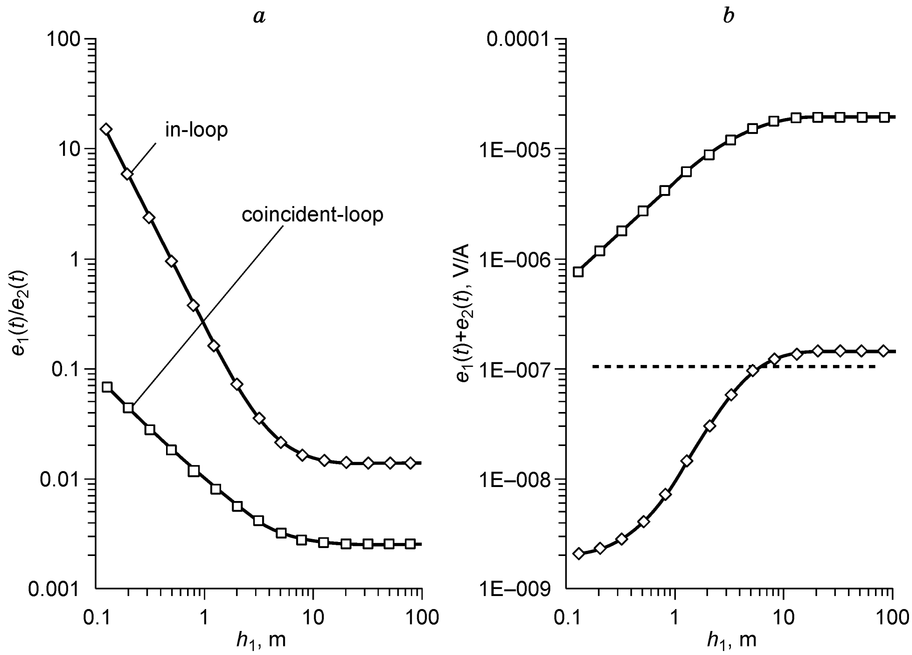

Fig. 7. Ratio (a) and sum (b) of eddy current and magnetic relaxation responses as a function of upper layer thickness. Model 1: a magnetically viscous layer above a nonmagnetic ground. See text for explanation.

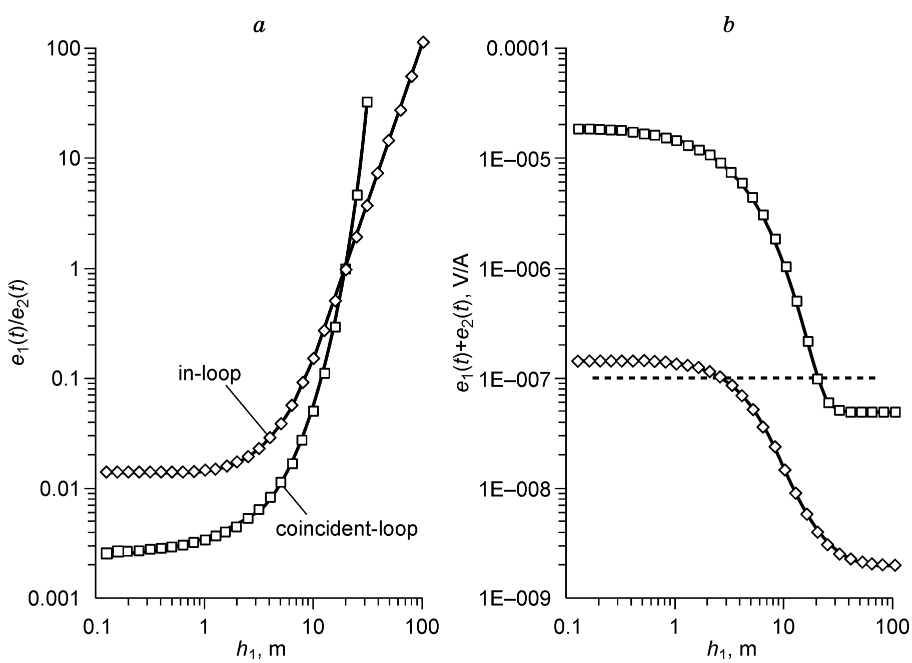

Fig. 8. Ratio (a) and sum (b) of eddy current and magnetic relaxation responses as a function of upper layer thickness. Model 2: a magnetically viscous ground below a nonmagnetic ground. See text for explanation.

depth to the buried magnetically viscous layer causes no influence on the signal/noise ratio as long as the upper layer thickness remains within 1–2 m but $e_1(t)/e_2(t)$ increases as it becomes thicker. At $h_1 < 10$ m, the ratio $e_1(t)/e_2(t)$ grows proportionally to h_1^3 for the in-loop configuration and to $\exp(h_1)$ for the coincident-loop configuration. The former configuration gives a better signal/noise ratio at $h_1 < 10$ m and the latter one is advantageous at $h_1 > 10$ m.

Figure 8, b shows the total responses for each loop geometry, where the dashed line marks the minimum measurable signal level. The advantages of the in-loop system do not work at the transmitter amperage within 1 A, but the signal is measurable with a current at least ten times greater.

Another way to reduce the magnetic relaxation effect is to place the loops above the ground surface (Barsukov and Fainberg, 2001). However, halving the effect requires a height above the ground no less than 15% of the transmitter size, i.e., 15 m for a 100×100 m loop and 4 m for a 25×25 m loop (see Figs. 5, 6, and 8). This way appears to be not very practical, at least in the case of loops larger than a few meters. It is pertinent to note that it was Buselli (1982) who first mentioned—but did not explain—the weak dependence of the magnetic viscosity component $e_1(t)$ on the loop height above the ground.

There is one important special two-layer case in which the loop is placed in the air at some height (h) above a uniform magnetically viscous ground. Like any model with a magnetically viscous layer below a nonmagnetic layer, the h_1 change of no more than 10 or 15% of the loop side length causes no effect on the transients. This is useful for mapping applications, such as in magnetic viscosity surveys for archaeological purposes, when the loop height is hard to control because of vegetation, relief, etc. The weak h_1 dependence of $e_1(t)$ is beneficial also for aerial TEM measurements in magnetically viscous terrains.

Instead of being noise, the magnetic relaxation responses ($e_2(t)$) may be informative, for instance, of the thickness of a magnetically viscous layer above a nonmagnetic one (Fig. 1). In this case the coincident-loop configuration is advantageous over in-loop systems due to its high sensitivity to the presence of superparamagnetic grains. We showed in (Kozhevnikov and Antonov, 2008) that the in-loop configuration is less sensitive to magnetic relaxation, but, besides this sensitivity, the two-layer models have to take into account the resolution with respect to h_1, i.e., variations of transients at small h_1 thicknesses. In model 1, the measured in-loop transients are proportional to h_1^2 and the coincident-loop responses are proportional to h_1, i.e., the in-loop configuration has a better resolution with respect to the layer thickness. In model 2, on the contrary, the thickness h_1 causes almost no influence on the signal as long as h_1 remains relatively small but the influence becomes significant when h_1 increases, especially in coincident-loop transients where $e_2(t) \sim \exp(-h_1)$. Thus, the coincident-loop configuration is more sensitive to h_1 change at large thicknesses, this being only one of its advantages. The curves in Fig. 8, *b* show the coincident-loop signal two orders of magnitude higher than that from the in-loop system.

There is another point worth of mentioning in conclusion, namely, the inverse TEM problem for estimating the magnetic viscosity parameters. This is a single parameter of the static magnetic susceptibility (Kozhevnikov and Antonov, 2008) in the case of a uniform magnetically viscous earth and the magnetic susceptibilities and thicknesses of the layers in the two-layer case. Unlike the induced polarization (Wait, 1982), magnetic relaxation in rocks is independent of the "normal" transient process. Therefore, time cannot be the depth controlling parameter in studying the vertical distribution of magnetic viscosity. Thus, the TEM sounding principle does not work in terms of magnetic viscosity but one can explore the depth dependence of κ by means of *geometric* soundings, as it is clear from equations (6), (7), (12) and Figs. 3 through 8.

Discussing the details of loop configurations applicable to estimate the parameters of a 1D magnetically viscous earth and the specific inversion techniques is beyond the scope of this paper. Note only that one has to find three parameters of a two-layer earth: the thickness h_1, and the static magnetic susceptibilities κ_{01} and κ_{02} of the two layers (Fig. 1). The three unknowns require at least three equations of the form defined by equations (6) and (7) for in-loop transients and by (12) for coincident-loop transients. From these equations it follows that one can control the sounding depth by changing the size of the transmitter loop, and, to certain extent, the loop configuration. Thus, at least three different configurations are needed to sound a two-layer earth, or two independent measurements if only one layer is known a priori to be magnetically viscous (the upper one in model 1 or the lower one in model 2).

Conclusions

The magnetic relaxation and eddy current responses are independent at conductivities common to the real subsurface, which makes it possible to compute TEM responses of a magnetically viscous conducting earth using the superposition principle.

A convenient way to present and analyze TEM data is to plot $Y = f(h_1)$ curves, where h_1 is the thickness of a magnetically viscous layer lying either above (model 1) or below (model 2) a nonmagnetic layer, and Y is the transient response of a two-layer earth normalized to the uniform-earth response at the same loop configuration.

The normalized transients Y increase with the thickness of the magnetically viscous upper layer (model 1) while it remains relatively thin, at a rate proportional to h_1 or to h_1^2 in the cases of in-loop and coincident-loop configurations, respectively. If the layer thickness is commensurate with or exceeding the characteristic size of the transmitter loop, its response is undistinguishable from that of a uniform magnetically viscous earth.

In model 2 of a thin nonmagnetic layer above, the Y responses are almost identical to those at $h_1 = 0$, i.e., on the surface of a uniform magnetically viscous ground. As the upper layer thickness (or the depth to the underlying half-space) becomes more than 15 to 20% of the characteristic loop size, Y begins to fall, first slowly and then ever more rapidly. At h_1 commensurate with or exceeding the characteristic loop size, Y falls at h_1^{-3} in the case of in-loop configurations and exponentially in coincident-loop measurements.

Coincident-loop transients are more strongly affected by magnetic viscosity than the noncoincident in-loop responses, both from a uniform and a two-layer earth. This is a drawback of the coincident-loop configuration in resistivity surveys but an advantage in surveys for magnetic viscosity.

Unlike the induced polarization, magnetic relaxation is independent of the "normal" transient process, and the TEM sounding principle is inapplicable to magnetic viscosity, which requires *geometric* soundings to be used to explore its depth dependence.

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