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Magnetic relaxation of a horizontal layer: Effect on TEM data

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Abstract

We have modeled central-loop and coincident-loop transient responses of a magnetically viscous layer sandwiched between two nonmagnetic ones. The coincident-loop transients show exponential voltage decrease (at a fixed delay time), at any thickness h_2 of the magnetic layer, with an increasing depth to the latter (h_1) or the loop height if the layer is exposed on the ground surface. The patterns of central-loop transients are different from those of the coincident-loop ones and from one another for thin and thick magnetic layers. Namely, the voltage first rises to its maximum and then falls as the depth to the magnetic layer (h_1) increases, if it is thin: the thinner the layer, the more prominent the peak. If the layer is thick, the voltage decreases monotonically with its depth (or with loop height above the ground). Voltage grows, first rapidly and then progressively more slowly, at ever greater thicknesses of the magnetic layer in both loop configurations. At large h_2, the effect from the magnetic layer becomes similar to that from a magnetically viscous halfspace. These features of the transient responses have to be taken into account in planning and conducting TEM surveys, as well as in a geological interpretation of the TEM data affected by natural and/or man-caused magnetically viscous ground. In the general case, the turn-off of the transmitter current induces eddy current in the ground beneath the loop, which decays at a rate proportional to the ground resistivity. The eddy current decay and magnetic relaxation processes being independent at conductivities (resistivities) common to the real subsurface, the effect of the former can be allowed for using the superposition principle. This principle implies that the total response of a magnetically viscous conductor is a sum of the magnetic relaxation and eddy current components.
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Keywords: TEM survey; magnetic viscosity; superparamagnetic ground; three-layer earth; geometric sounding

Introduction

The effect of magnetic viscosity of rocks on transient responses is an essential problem in TEM surveys, which has been solved through laboratory, field (Barsukov and Fainberg, 2001, 2002; 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, 2009; Pasion et al., 2002) experiments.

The numerical experiments are of special value because there are no *in situ* geological objects that would be documented well enough to allow comprehensive investigation of TEM responses of superparamagnetic ground at different loop configurations. Earlier, we applied such modeling to explore the magnetic relaxation effects on transient responses of a uniform and a two-layer earth (Kozhevnikov and Antonov, 2008, 2009). It is, therefore, reasonable to continue the studies with a three-layer model. See Fig. 1 for a three-layer earth model with a circular transmitter loop of the radius R on the surface.

The magnetic viscosity of rocks, which is the subject of induction surveys, is normally due to a magnetic relaxation of superparamagnetic grains. Then (Kozhevnikov and Antonov, 2008, 2009),

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

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 ith layer, B is a constant, and t is the delay time. The characteristic time of the measurements (t) being most often within the gate $\tau_{1i} \ll t \ll \tau_{2i}$, one may assume that the gate is the same for all layers, i.e., for each layer $\tau_{1i} = \tau_1$, $\tau_{2i} = \tau_2$. The reported results were obtained assuming that $\tau_1 = 10^{-6}$ s, $\tau_2 = 10^6$ s.

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Below, we use the terms *magnetically viscous* and *magnetic* as synonyms to avoid repetitions of the words, and *nonmagnetic* as the antonym, though this is not right strictly speaking. There are no absolutely nonmagnetic rocks in nature: In addition to viscous magnetization, rocks always bear normal induced magnetization which decays very rapidly on the time scale of an experiment. This kind of magnetization component affects the signals measured in induction surveys (Blokh et al., 1986) but remains "mute" in transient responses.

The three-layer earth model we investigate consists of a magnetically viscous layer sandwiched between two nonmagnetic layers, i.e., this is a layered earth with an intermediate magnetic layer.

In the choice of the model, we proceeded from the following considerations. First, other three-layer models can be more or less accurately approximated by the earlier explored uniform magnetically viscous halfspace and two-layer models with a magnetic layer either above or below a nonmagnetic one (Kozhevnikov and Antonov, 2008, 2009). Second, the model with an intermediate magnetic layer accounts for real geological formations, such as tuff or lavas lying over and under nonmagnetic rocks. Alternatively, these may be archeological objects with a cultural layer buried under later deposits or fossil soils that bear superparamagnetic grains produced by bacteria. Finally, the model may be useful to describe responses of a surface magnetic layer measured by a TEM system lifted to the height h_1 above the ground. The latter configuration is applied in aerial geophysical surveys and can be employed for high-resolution magnetic viscosity mapping with a system being mounted on a small cart or some other vehicle. Furthermore, the receiver loops are placed above the ground to cancel the magnetic viscosity effects if the latter are considered as noise (Barsukov and Fainberg, 2001).

Thus, we measured the voltage induced in the receiver loop by magnetic relaxation of a horizontal layer in a nonmagnetic environment. In the real subsurface, however, each layer has its resistivity r_1, besides the parameters of the thickness h_i and the magnetic susceptibility κ_{0i} (Fig. 1). As the transmitter current has been turned off, there arises eddy current in the earth which decays at a rate proportional to the resistivity of the latter. Therefore, the transient responses are affect by both magnetic viscosity and eddy current. Yet, as we found out earlier (Kozhevnikov and Antonov, 2008, 2009), the magnetic relaxation and eddy current responses being independent at resistivities (conductivities) common to the real subsurface, one can compute the TEM responses of magnetically viscous conductors using the superposition principle, i.e., present their total as a sum of the magnetic relaxation and eddy current components.

Computing magnetic viscosity-affected transients

In our previous studies (Kozhevnikov and Antonov, 2008, 2009), we discussed two algorithms for computing transient responses of a uniform and a two-layer magnetic ground. In one code, the Helmholz equation in a boundary-value problem

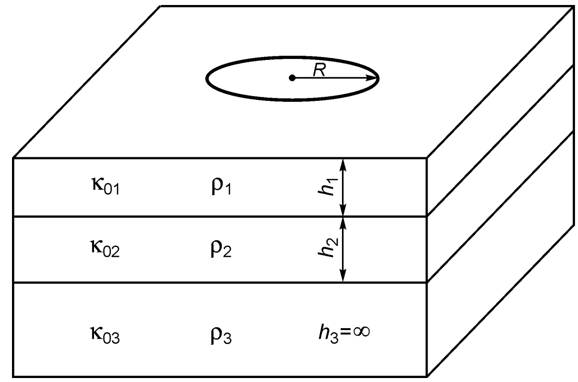

Fig. 1. A model with an ungrounded loop laid on a three-layer ground with a magnetically viscous layer. See text for explanation.

is solved using the Fourier transform with 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 equations but it neglects the eddy current-magnetic viscosity interaction and is, in this sense, not rigorous.

A comparison of transient responses of a uniform and a two-layer earth, computed with the two codes for the same loop configuration, shows that the two solutions are identical and exact in the case of noncoincident loops (with the transmitter and receiver loops spaced at more than a few centimeters) but differ when the loops are spaced closely, at 1 cm or less. In the latter case, it is the second code that provides a quality advantage.

Thus, we use the second code below because one of our objectives has been to compare the advantages and drawbacks of coincident and noncoincident (central-loop) configurations.

Note that analytical equations exist to calculate central-loop transients for both square and circular transmitters, but lack for coincident-loop responses with a square transmitter (Kozhevnikov and Antonov, 2009). Therefore, we here confine ourselves to the configurations with circular transmitters.

We computed the transients using time-dependent magnetic susceptibility $\kappa(t)$ (Kozhevnikov and Antonov, 2008, 2009). Namely, the transient response of a uniform earth with time-dependent intrinsic 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 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 inductance L_0.

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

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

Proceeding from the results reported in (Blokh et al., 1986), we showed (Kozhevnikov and Antonov, 2009) that for a circular transmitter loop and a receiver loop in its center laid on an N-layer magnetic ground,

$$\kappa_a(t) = \frac{\kappa_{01}}{\ln(\tau_2/\tau_1)} \left\{ 1 + \left(\frac{R}{h_1}\right)^3 \sum_{i=1}^{N=1} \left(\frac{\kappa_{0\,i+1}}{\kappa_{01}} - \frac{\kappa_{0i}}{\kappa_{01}} \right) \times \left[\left(\frac{R}{h_1}\right)^2 + 4\left(\frac{z_i}{h_1}\right)^2 \right]^{-3/2} \right\} (B + \ln t),$$

where κ_{0i} is the magnetic susceptibility, h_i is the thickness of the ith layer, and $z_i = h_1 + h_2 + ... + h_i$ is the depth to its base.

The coincident-loop responses of a two-layer magnetic ground measured with circular loops can be computed using an equation from (Sobolev and Shkarlett, 1967). With regard to magnetic viscosity, the time-dependent apparent magnetic susceptibility is given by (Kozhevnikov and Antonov, 2009):

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

where h_1 is the thickness of the upper layer and κ_{01} and κ_{02} are the static magnetic susceptibilities of the two layers, respectively.

In the case when the coincident loop configuration is placed at the height d above the surface, the magnetic susceptibility given by (3) has to be multiplied by $\exp(-3d/R)$. This is obviously a case identical to that of a system on a three-layer ground with a nonmagnetic upper layer. Then, d is actually the thickness of the upper layer, and, hence, $d = h_1$, while the upper layer in (3) becomes the intermediate one, with its thickness h_2 and the magnetic susceptibility κ_{02}. Correspondingly, the former second layer in (3) becomes the third layer, with its magnetic susceptibility κ_{03}. Finally, the apparent magnetic susceptibility of a three-layer subsurface with a nonmagnetic upper layer is

$$\kappa_a(t) = \frac{1}{\ln(\tau_2/\tau_1)} \times \frac{\kappa_{03} + (2\kappa_{02} - \kappa_{03}) \tanh \dfrac{3h_2}{2R}}{1 + \tanh \dfrac{3h_2}{2R}} \exp(-3h_1/R)(B + \ln t). \quad (4)$$

Now, assuming that $\kappa_{03} = 0$ and substituting the magnetic susceptibility found with (4) into equation (2), one can calculate coincident-loop transient responses of a three-layer earth with an intermediate magnetic layer.

Results

Inasmuch as the time at which the transient process is measured cannot be the depth controlling parameter in studying the vertical pattern of magnetic viscosity (i.e., the TEM sounding principle does not work in terms of magnetic viscosity), it is reasonable to use geometrical sounding (Kozhevnikov and Antonov, 2009). When applied to the discussed central-loop and coincident-loop symmetrical con-

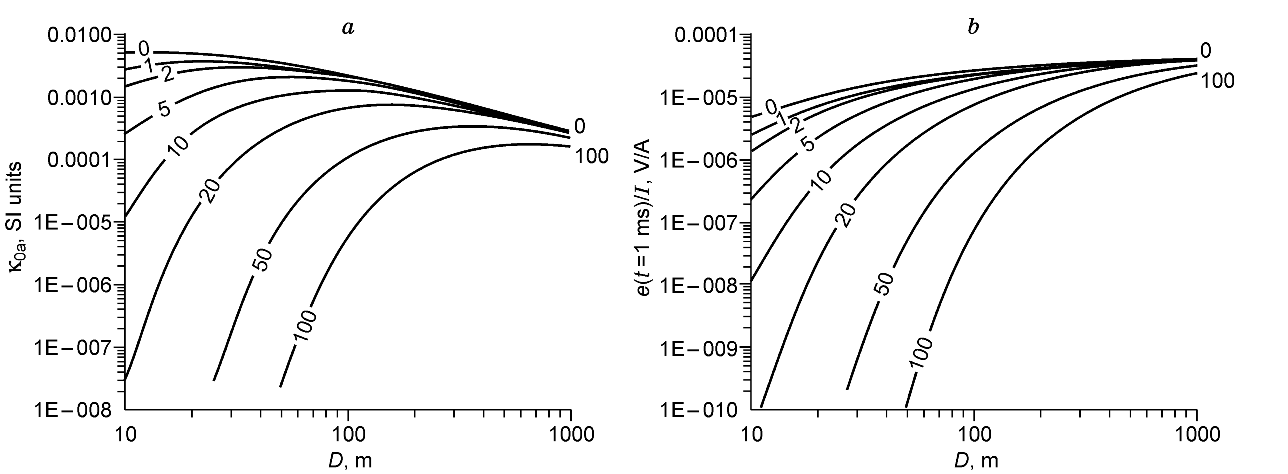

Fig. 2. Apparent static magnetic susceptibilities (*a*) and transient responses (*b*) of a three-layer earth with an intermediate magnetically viscous layer ($\kappa_{01} = 0$, $\kappa_{02} = 5 \times 10^{-3}$ SI units, $\kappa_{03} = 0$) as a function of transmitter loop diameter D. Coincident-loop configuration, circular transmitter, $t = 1$ ms. Thickness h_2 of the magnetic layer is 10 m, curves are labeled according to thickness h_1 of the upper layer (m).

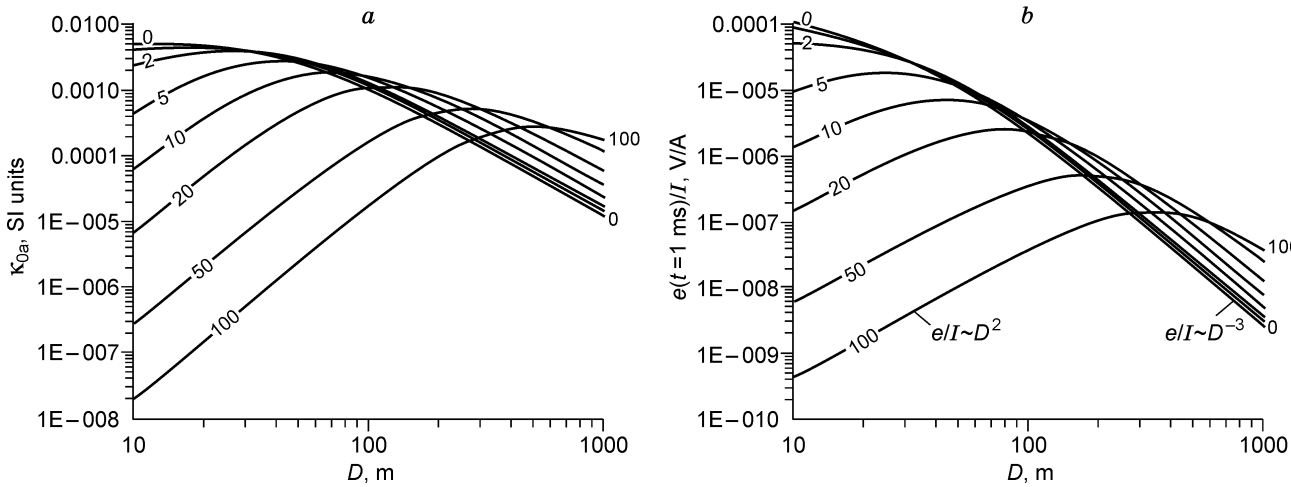

Fig. 3. Apparent static magnetic susceptibilities (*a*) and transient responses (*b*) of a three-layer earth with an intermediate magnetically viscous layer ($\kappa_{01} = 0$, $\kappa_{02} = 5 \times 10^{-3}$ SI units, $\kappa_{03} = 0$) as a function of transmitter loop diameter *D*. Central-loop configuration, receiver of effective area 10^4 m^2. Thickness h_2 of magnetic layer is 10 m, curves are labeled according to thickness h_1 of upper layer (m).

figurations, the effective sounding depth (analog of the array spacing) will depend on the transmitter's size (diameter, *D*).

See Figs. 2 and 3 for the computed transients for different transmitter loop sizes from 10 to 1000 m which are commonly used in TEM sounding and prospecting methods. In our modeling, we assumed the following parameters: a receiver in the central-loop configuration of 1×1 m in size and 10^4 m^2 in effective area; the thickness h_2 of the magnetically viscous layer 10 m, and the static magnetic susceptibility $\kappa_{02} = 5 \times 10^{-3}$ SI units. The current-normalized voltage (Figs. 2, *b* and 3, *b*) was calculated at $t = 1$ ms.

In order to understand how the transients depend on the depth to the intermediate layer (or on the system's height if it is above the ground while the magnetic layer is exposed on the surface), the thickness h_1 was let to vary from 0 to 100 m. This allowed us to explore the most typical models with thin ($h_2 \ll h_1$), medium ($h_2 \approx h_1$), and thick ($h_2 \gg h_1$) intermediate layers.

Coincident-loop configuration. In Fig. 2, *a* the apparent static magnetic susceptibility κ_{0a} is plotted against the transmitter size at different h_1 thicknesses. At relatively small loop sizes, κ_{0a} increases proportionally to *D*, the smaller the thickness h_1 the faster. Then $\kappa_{0a}(D)$ reaches a smooth maximum followed by a magnetic susceptibility decay on further *D* increase, while the difference between the curves progressively becomes less notable. At any diameter *D*, greater h_1 correspond to lower magnetic susceptibilities. The relative difference between k_{0a} calculated at different thicknesses h_1 obviously grows as the loop size decreases.

The plots of Fig. 2, *b* illustrate the behavior of voltage in the receiver loop as a function of the loop size and the depth to the magnetic layer. The voltage grows monotonically with the loop size, first faster and then ever more slowly. The relative voltage change associated with the h_1 change is inversely proportional to the loop size, and the curves coincide in the case of large loops. At a fixed *D*, the voltage decays as the depth to the magnetic layer increases.

Central-loop configuration. Figure 3, *a* shows the apparent static magnetic susceptibility vs. transmitter loop size plots labeled according to the thickness h_1. The $\kappa_{0a}(D)$ plots look like three-layer VES curves for K-type models.

At relatively small *D*, κ_{0a} grows proportionally to D^3 till its peak and then decreases proportionally to D^{-2}. In the transients obtained with a small transmitter, the magnetic susceptibility falls as the thickness h_1 grows. However, the large-loop responses show an inverse dependence pattern: the greater depths to the intermediate layer correspond rather to *greater* magnetic susceptibilities.

The voltage vs. loop size plots on the Fig. 3, *b* panel, labeled according to the thickness h_1, share similar features with the $\kappa_{0a}(D)$ curves. Namely, the voltage is lower when the upper layer is thicker at loop sizes within 100 m, but the dependence becomes inverse at greater *D*: the farther the magnetic layer, the larger the voltage. Like the above growth of κ_{0a}, this appears to be a surprising result, because intuitively one would rather expect the effect of the intermediate magnetic layer to decay with its depth.

Now let us see how the transient responses behave depending on the depth to the magnetic layer if the latter is buried, or on the height of the TEM system above the ground. We assume that the transmitter loop size is $D = 10$ m and as before, that the receiver loop lying in its center is 1×1 m, with the effective area 10^4 m^2. Below, we report modeling results for layers with their thicknesses from 0.001 to 10 m and the static magnetic susceptibility 0.01 SI units. As for the thickness h_1, it was allowed to vary from 0.01 to 100 m; the time was 0.1 ms.

Coincident-loop configuration. The coincident-loop transients plotted as a function of h_1, at different thicknesses h_2 (Fig. 4, *a*), show a monotonic increase with increasing h_1 at any thickness h_2. Each curve in Fig. 4, *a* fits the exponential dependence $e(t)/I = A\exp(-0.6h_1)$ where the initial amplitude, *A*, is proportional to h_2. The exponential voltage decay becomes notable (instrumentally detectable) at $h_1 > 1$–1.5 m.

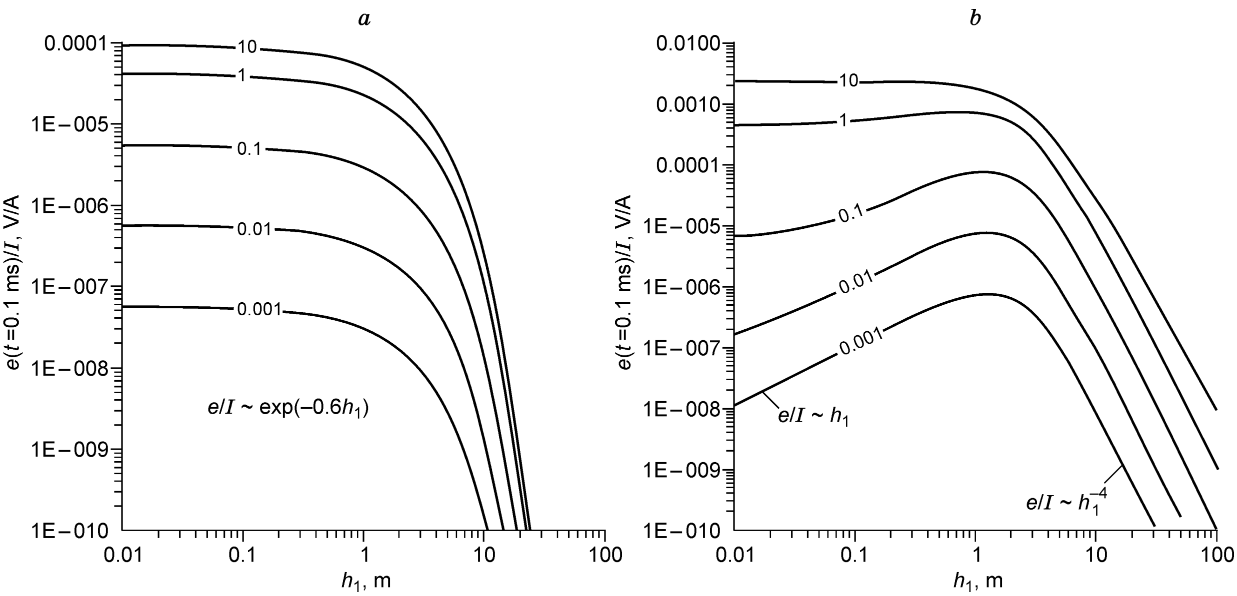

Fig. 4. The coincident-loop (a) and central-loop (b) transient responses of a subsurface containing a magnetic layer (κ_{02} = 0.01 SI units) as a function of h_1, at different thicknesses h_2; t = 0.1 ms. Transmitter loop diameter D = 10 m, receiver loop of effective area 10^4 m^2. Curves are labeled according to thickness h_2 of the magnetic layer (m).

Central-loop configuration. The h_1-dependent central-loop transients (Fig. 4, b), labeled according to the layer thickness in m, demonstrate patterns different from the coincident-loop responses. Namely, as the height of the system h_1 increases, the voltage first increases proportionally, culminates at $h_1 \approx$ 1–3 m, and, finally, falls exponentially as h_1^{-4}. The thinner the layer, the more prominent the voltage increase at small h_1 (in the range 0.01 to 2–3 m in that case). For instance, for a 1 mm thick layer, the voltage grows for about two orders of magnitude as h_1 increases from 1 cm to 1.5 m.

The effect dies out as the magnetic layer thickens up. At $h_2 > 1$ m, there is no voltage peak, and the transient responses look like those we obtained earlier for a two layer model with a nonmagnetic layer overlying a magnetic one (Kozhevnikov and Antonov, 2009). Namely, the voltage is invariable at small h_1 and then decays rapidly as the latter grows after having reached some "threshold".

Discussion

As we already wrote, intuitively it appears reasonable that a more deeply buried magnetically viscous layer would produce a weaker transient response, i.e., lower voltage. However, central-loop transients first rise as the depth to the magnetic layer increases and only then fall, after a peak.

Understanding why this is so will be easier with Fig. 5 that shows a transmitter loop and two thin layers: one on the ground immediately under the loop and the other buried at some depth h_1. In the former case, the primary magnetic field is orthogonal to the magnetic layer almost everywhere except the nearest vicinity of the wire. The magnetization of the layer is reduced by strong demagnetization, and, hence, the secondary magnetic field it produces is low. In the latter case, this is mostly the horizontal component of the transmitter's magnetic field that magnetizes the buried layer located at the distance h_1 from the loop (Fig. 5), the magnetization being rather high and directed along the layer. The voltage the magnetic relaxation induces in the receiver after the removal of the primary field is higher than in the case of an near-surface magnetic layer. As the distance to the magnetic layer increases, the magnetization induced by the primary field decays ever faster, while the voltage growth slows down correspondingly and eventually falls exponentially as h_1^{-4}.

The fact that the response of a buried magnetically viscous layer can be more than ten times that of an exposed one is critical for planning the surveys and interpreting the results.

It was suggested to reduce the unwanted magnetic relaxation effect by placing the TEM system above the ground (Barsukov and Fainberg, 2001). However, as we found out (Kozhevnikov and Antonov, 2009), the height for the case of a uniform magnetically viscous earth should be commensurate with the characteristic size of the transmitter. The magnetic relaxation effects can decrease significantly only when the TEM system rises high enough above the ground: the voltage will be, for instance, only twice lower if this height is 15% of the loop size. For this reason, the method would hardly be of broad practical use. As for the effect from a thin magnetic layer on the ground surface, its removal requires a height exceeding a half of the loop size. Otherwise, the signal will increase instead of decreasing, i.e., the geological noise will grow.

On the other hand, it is reasonable to measure transients from above the ground when the magnetic relaxation is not a noise but, instead, a subject of interest, as in the research of cultural deposits or exposed tuff and lavas. In the latter case,

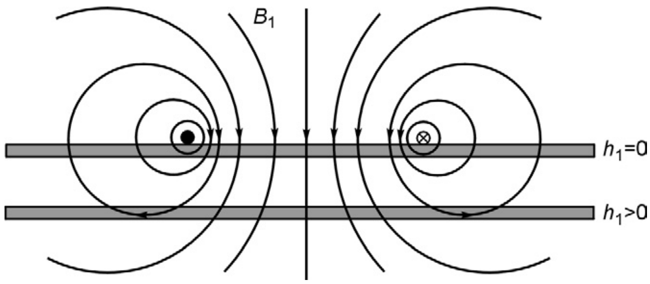

Fig. 5. Transmitter loop and a thin magnetic layer. The intermediate layer is mostly in a vertical magnetic field, and its magnetization is low when the loop lies on its surface ($h_1 = 0$), but it becomes strongly magnetized under the effect of the horizontal component of the loop's magnetic field when the loop lies at some distance away from the intermediate layer ($h_1 > 0$).

aerial TEM sounding can be more efficient than the ground surveys.

There is a certain ratio of the magnetic layer's burial depth to the loop size (Fig. 4, *b*) at which the voltage is the greatest. Thus, one can adjust the measurement system to make it more sensitive to magnetic relaxation through varying the loop configuration.

Unlike the central-loop data, the coincident-loop transients have no maximum in the h_1 dependences: the signal decreases exponentially with increasing h_1. Inasmuch as the transmitter size is the same in both cases, it is reasonable to attribute the difference to the receiver. The matter is actually in the inductance *M* between the two loops, which increases with h_1 when the receiver is placed inside the transmitter (if h_1 is not very large) and decreases if the loops coincide.

This difference between the loop configurations is not obvious, at least, it would be hardly predictable if looking into the loop—magnetic layer interaction in a "qualitative" way (Fig. 5). A more thorough analysis of this subtle difference between the two loop configurations being beyond the scope of our paper, we limit ourselves to a brief comment. The immediate vicinity of the transmitter wire is a special zone (Kozhevnikov and Antonov, 2008), and it would be interesting to see, by means of mathematical modeling, how the h_1 dependence of transients would change in this very domain while a central-loop configuration grades into a coincident-loop one. However, at this point we have no appropriate technique to simulate the magnetic relaxation-affected transients for the loop spacing of a few wire radii or less. Nevertheless, as the reported results indicate, it is not the proximity of a coincident-loop system to a magnetically viscous ground that matters. What really matters is rather the close transmitter-receiver spacing than the depth to the magnetic layer, contrary to what Lee (1984a,b) was writing and to what we ourselves were thinking before (Kozhevnikov and Antonov, 2008).

Conclusions

Due regard for magnetic viscosity of a layer sandwiched between nonmagnetic media is a topical problem in TEM surveys. We have investigated this effect through modeling with the use of known analytical solutions, for central-loop and coincident-loop configurations.

The coincident-loop transients show an exponential voltage decrease, at any thickness h_2 of the intermediate layer, as h_1 increases (h_1 being the depth to the latter or the loop height if the layer is exposed on the ground surface). The patterns of central-loop transients are different from the coincident-loop ones and from one another for thin and thick magnetic layers. Namely, the voltage first rises to its maximum and then falls as the depth to the magnetic layer (h_1) increases, if it is thin: the thinner the layer the more prominent the peak. If the layer is thick, the voltage decreases monotonically with its depth (or with loop height above the ground).

This unexpected behavior of the central-loop transients is due to demagnetization effects. The magnetization (and, hence, the magnetic viscosity effect) of a layer proximal to the loop is low because the layer is strongly demagnetized being in a vertical primary magnetic field. As the layer becomes more deeply buried, it is magnetized horizontally thus escaping the demagnetization, which increases the magnetic viscosity effect on the transients.

It remains unclear why exactly the voltage does not grow with h_1 in coincident-loop transients. We only hypothesize that the domain of the nearest wire vicinity (i.e., the transmitter–receiver spacing) may play a critical role.

In both loop configurations, voltage grows, first rapidly and then progressively more slowly, at ever greater thicknesses of the magnetic layer. At large h_2, the effect from the magnetic layer becomes similar to that from a magnetically viscous earth. These features of the transient responses have to be taken into account in planning and conducting TEM surveys, as well as in geological interpretation of TEM data affected by natural and/or man-caused magnetically viscous ground.

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