Electromagnetic interpretation in complex geological environments

P. Walker, Geophysical Algorithms*
Y. Lamontagne, Lamontagne Geophysics Ltd.

Summary

Modern electromagnetic interpretation theory was built on the study of simple, isolated conductors located in homogenous media. We show how these assumptions do not fully apply for multiple conductors, or when the conductivity structures are complex. Examples are presented which illustrate how folding can distort the response of a conductor, how folding can shield target conductors, and how the borehole response of conductors is affected by resistive intrusions.

Introduction

The electrical setting of many geological environments is often complex. However, our understanding of electromagnetic interpretation is largely the result of work using simple numerical and analytical models. These models typically considered the response of isolated structures in homogenous media. As a result, our understanding of interpretation does not fully apply to data acquired in complex environments.

Of the numerical models that have contributed to modern interpretation, the thin plate model is arguably the most significant. Today, most electromagnetic interpreters use thin plate modeling software of one form or another. Studies of the thin plate have contributed not only to our understanding of induction, but also to effects such as overburden blanking and the interplay between current channeling and induction. The result of such studies has been a conceptual framework that has been in place over twenty years.

While modern exploration based on thin plate interpretation has been generally successful, this success has been muted in more geologically complex areas. We posit that one reason for this relative lack of success is that the conductors are neither simple nor isolated. Accordingly, the thin plate model does not fully apply. It follows that interpretation methodology derived from thin plate modeling also does not fully apply. A more complete formalism, both in terms of the modeling software and the interpretation theory is required.

We use MultiLoop III (Lamontagne Geophysics Ltd., 2006) to examine two cases where the thin plate model is limited. In the first, a fold shields a target conductor, while in the second, a resistor has intruded a target conductor. We show that while conventional interpretation concepts apply in part, they must be used with care, and with an understanding of the complexity introduced by these more complex environments.

Theory and Method

MultiLoop III solves for induction in thin sheets of variable conductance whose shapes can be represented by a tri-mesh. By representing structures as a mesh, it is possible to simulate very general geometries, including folds, conductors electrically connected to the overburden, multiple conductors electrically connected via faults, and conductors containing resistive intrusions. Although the electrical response is restricted to the thin sheet approximation, there is no other constraint on the scattering geometries.

The solution is constructed from a set of current vortex basis functions that are assigned to the mesh nodes. Each current vortex circulates around a mesh node such that adjacent mesh nodes will share common current segments. In the case where several sheets intersect to form a junction, the currents assigned to nodes on the junction are constructed to conserve the current flowing into and out of each sheet.

The scattering solution is based on a time-stepping integral equation for the excitation coefficients of the current vortices. The equation was derived for the frequency domain by Lamontagne and West (1971). Letting ρ represent the resistivity of the surface, ϕ the stream potential of the current, G the Green's function, μ_0 the permeability of free space, and t the time, then the stream potential is given by:

$$\rho\nabla^2 \phi + \mu_0 \partial/\partial t \int_s G\, \phi\, ds = \partial/\partial t\, B_p$$

where B_p is the component of the primary magnetic induction normal to the surface of the sheet. To implement the solution numerically using a step on response, the discrete form of stream potential is found from:

$$(\Delta t)\, \rho\nabla^2\phi + \mu_0 \int_s G\, (\Delta\phi)\, ds = \Delta B_p$$

where ΔB_p the step change in the primary induction on the surface, and is non-zero only for the first time step. Δt is the time stepping interval and $\Delta\phi$ is the change in the stream potential in the duration Δt. The solution is computed until the root mean squared amplitude of $\Delta\phi$ over the surface of the conductor is an inconsequential fraction of Δϕ computed on the first time step. Solutions for various waveforms are calculated by convolving the waveform against the step response.

Example 1: Scattering in folded structures

In this set of examples, the response of a syncline, and then response of a target within synclines, are simulated. This model study has application to interpreting data in metasedimentary environments.

Figure 1 shows geometry of a dipping syncline that has been energized by an offset loop and Figure 2 illustrates the resulting response. In Figure 2, the amplitude of the stream potential in the inductive limit has been plotted as colours superimposed on the mesh. Note that the profile response over the syncline resembles a thin plate over the limb closest to the transmitter, a reversed plate response over the limb farthest from the conductor, and a flattish zone between the two. The reversed response over the distant limb occurs because the limbs are electrically connected. The return currents from the vortex energized in the close limb return through the syncline’s more distant limb. The reversed response is the result of these returning currents being close to surface.

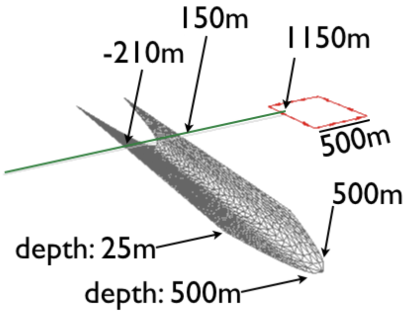

Figure 1: Geometry used to compute the response shown in Figure 2.

The approximately constant profile response over the centre of the syncline (it is continuously normalized) indicates the vertical magnetic field is approximately constant there. This is reminiscent of the response one would typically measure inside a shielded object such as a sphere. If the syncline were replaced by two plates representing its limbs, the shielded zone and the reversed plate response would disappear in favour of a second positively polarized plate response.

Synclines thus have the shielding characteristics similar to those of a closed object such as a sphere, or an overburden.

To test the shielding hypothesis, horizontal profiles of the vertical magnetic field response were calculated at two different depths in a pair of synclines. The profile locations and responses are illustrated in Figures 3 (near the top of the syncline) and Figure 4, deeper within the syncline. The profiles run through the plane that bisects the synclines and the loop. For clarity, the full mesh is not shown and only the nodes are plotted to illustrate the synclines.

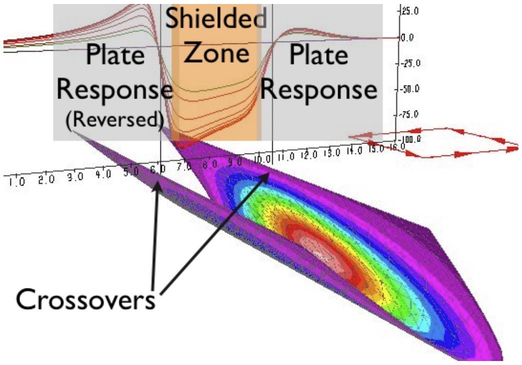

Figure 2: Simulated step response of a syncline showing the stream potential in the inductive limit.

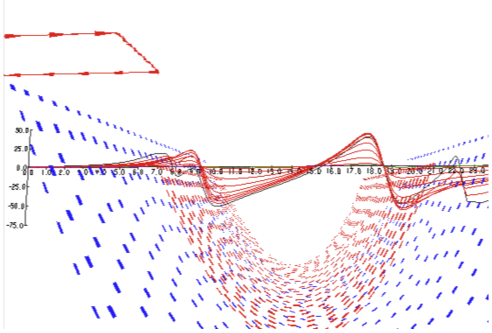

Figure 3: Upper Hz profile through the synclines

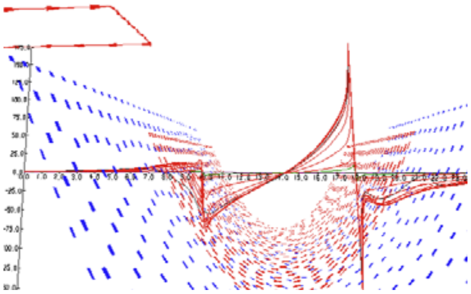

Figure 4: Lower Hz profile through the synclines.

Note the early time response in Figure 4 decays much more slowly than the similar early time channels in Figure 3. The slower decay at depth confirms shielding. Accordingly would expect the response of a target conductor located within a syncline to be attenuated compared to its response in free space. Figure 5 illustrates the response of a target plate within the synclines, while Figure 6 illustrates the response of an identical plate in free space. For the particular case illustrated, the response of the plate in the syncline is attenuated relative to its free space response by approximately 50%.

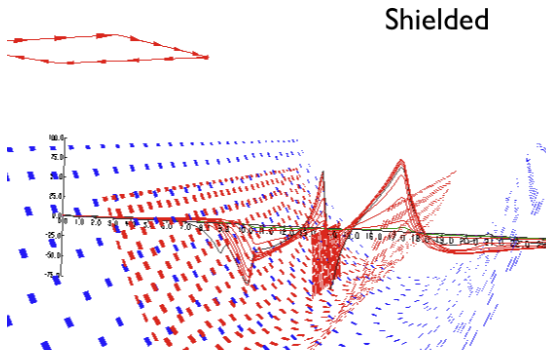

Figure 5: Hz profile (same depth as in Figure 4) with a plate present.

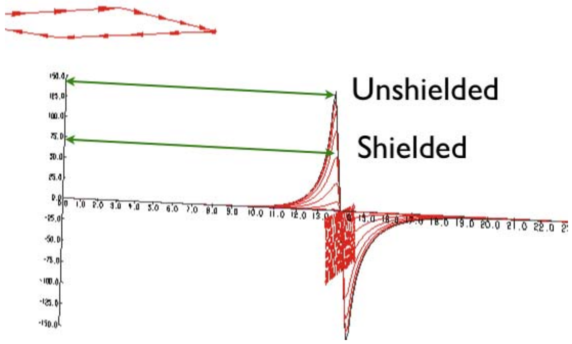

Figure 6: Hz profile of the free space response of the plate in Figure 5, with a comparison of the peak amplitude attained when shielded by the synclines.

Example 2: Scattering by intruded structures

When a resistive body intrudes a conductor, currents can be induced to circulate around the intrusion forming a closed loop. In borehole surveys where the borehole penetrates the intrusion, the conductor will generate an in-hole shaped anomaly even though no conductor is encountered in the borehole.

The basic character of the response of an intruded body is illustrated in Figure 7. The figure shows step response profiles of an annulus energized by an approximately uniform field. The profile runs close to the plane of the annulus, with Hx response shown in green. Since the profile is close to the conductor, the Hx response is a proxy for the current density of the conductor. The current is most intense near the outer edges of the annulus, and the sign reversal indicates the current is circulating in a vortex around the resistive core. Current decay begins at the outer edges of the conductor and propagates inward. The Hz response (red) has the same sign in the resistive core as in the conductor, and changes sign at the periphery of the conductor.

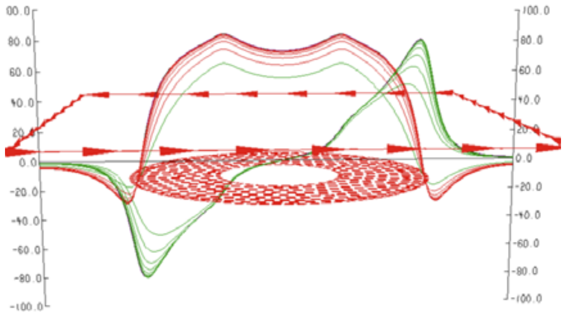

Figure 7: The Hx (green) and Hz (red) step response of an annulus.

To illustrate the effect of an intruded conductor on a borehole survey, the response over a fence of holes penetrating an annulus was calculated. The model geometry is illustrated in Figure 8, while the hole responses are illustrated in Figure 9.

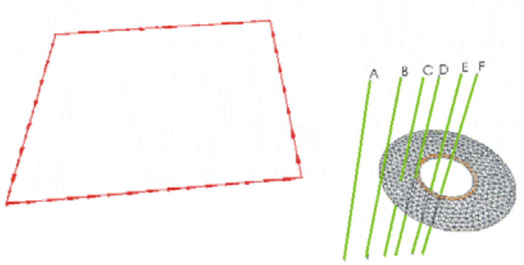

Figure 8: Model geometry used for the results in Figure 9

The profiles in Figure 9 run from outside the annulus (A) to its centre (F). The response, 9A, exhibits a reversal in the Hz component, and is typical of an off-hole response. In

(B) at the outer edge of the annulus, this reversal is sharper than in (A) because the length of the segment containing the reversed field varies as the distance of the hole from the conductor. Profiles C and D penetrate the conductor, and the effect of current migration on the secondary field is noticeable. Negatives are again due the presence of closed vortices that the borehole is outside of. Profiles E and F lie inside the resistive core, and so do not exhibit the obvious effects of current migration that are visible in C and D. Since profiles E and F lie entirely with the vortices, the response is positive with no crossovers.

To model a thin conductor with resistive intrusions, branch cuts must be added to the stream potential. A necessary part of the modeling algorithm is to recognize this and to automatically insert branch cuts where necessary. Representing intruded structures with thin plate models that do not naturally incorporate branch cuts is not feasible, and the calculated responses will be incorrect. The single branch cut in the annular model generated the positive responses shown in Figures 6E and 6F, and without it, those profiles would have been fundamentally different.

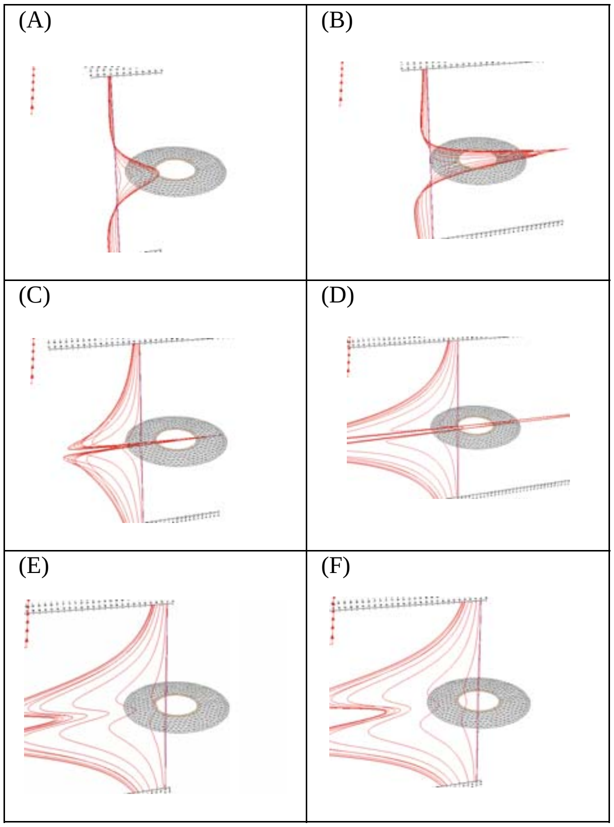

Figure 9: Hz response for the boreholes shown in Figure 8.

Conclusions

Modern electromagnetic interpretation is based on results from modeling simple, isolated conductors in homogenous media. We have presented two simple cases that illustrate the limitations of such models. It can be expected that such models will become progressively less valid as the distribution of conductivity becomes more complicated. The applicability of such methods to interpreting data acquired complex electrical environments must therefore be questioned.

The two cases that were presented illustrate some of the limitations of thin plate modeling and interpretation. In the first case, the effect of folds, and the response of a target embedded within folds was modeled. In the second case, complexity was introduced by simulating the response of a conductive target that was intruded by a resistive body. In both cases, the resulting responses were significantly different from what could have been predicted by assuming a target with a simple geometry in a homogenous medium.

The search for new mineral deposits is driving exploration into more geologically complex areas. In these areas, the electromagnetic characteristics of the ground are unlikely to match the assumptions upon which present interpretation theory is founded. Successful exploration in the future will depend on our ability to understand data acquired over these complex areas, and accordingly, on continued progress in electromagnetic interpretation theory and in developing germane modeling algorithms.

References

Lamontagne, Y. and West, G.F., 1971, EM response of a rectangular thin plate, Geophysics, **36**, 1204-1222.