The effect of discrete conductivity isotropy on electromagnetic surveys

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Summary:

The effect of discrete conductivity anisotropy on electromagnetic survey interpretation is examined with a numerical modeling study. Discretely anisotropic media are shown to mimic the characteristics of horizontally layered media, alter the apparent decay constants of conductors, and profoundly alter the amplitudes of the anomalous response. If unrecognized, the effects of discrete conductivity anisotropy on (mis)interpretation can be significant. The illustrations we present are representative of cases encountered in the Athabasca Basin in Canada.

Introduction:

The effect that large scale conductivity anisotropy has on electromagnetic data has been largely unstudied. Much of the research on anisotropy has been done assuming uniform anisotropic media (i.e. Collins *et al*, 2006), such as can be represented by a half-space or a layered earth. In such models, the anisotropy is considered to be continuous. However, in shield terrain, and particularly in metamorphic belts, anisotropy can be caused by folded and faulted conductors, often graphitic, which serve to generate a significant background response. In these cases, the scale of the anisotropy is often similar to the scale of the electromagnetic survey, and so the assumption of continuous anisotropy does not fully apply.

We present the results of a model study which shows that discrete conductivity anisotropy, where the scale of the anisotropic effects is on the order of the scale of the survey, even when the anisotropy is weak, can significantly alter the response of stronger, anomalous conductors. Starting with two simple half-sheets, we show that measured time constants are not intrinsic properties of the conductivity model, but also depend on the properties of the survey. We also show that anisotropic media can mimic the response of a layered medium, and that the apparent electromagnetic response of a conductor embedded in such a medium can appear to be significantly amplified in comparison to the response of such a conductor in free space.

If the effects we illustrate are not recognized as being due to anisotropy, the quality of geophysical interpretation can be seriously affected.

Background theory and method:

We use MultiLoop III, a mesh based electromagnetic modeling software package (Walker and Lamontagne, 2006), to simulate the effects of discrete conductivity anisotropy. MultiLoop III assumes the anomalous conductors can be represented as thin sheets (the mesh) in infinitely resistive background. To represent a conductor, the mesh is assigned a conductance that can vary as a function of position. The conductors are assumed to interact inductively, but cannot interact galvanically unless the meshes are explicitly connected.

The electromagnetic response of an isolated thin conductor is well known, and interpretation based on the isolated thin conductor model is typical of the current practice in the industry. When a conductor is energized by a time-varying field, currents will be energized in the conductor that will oppose any change in that field on it. The resulting decay rate of the currents is considered to be diagnostic of the conductance of the body.

In our study of discrete anisotropy, we begin with the example of conductor that is energized with a loop source with a step-off current. As the current is shut-off, an “inductive limit” current will be induced in the conductor which will oppose the change in shut-off of the field. After shut-off, the current will decay from the inductive limit due to resistive losses in the conductor.

As the current decays, a time-varying magnetic field is in-turn generated. Because the field is time-varying, it induces currents in nearby conductors to which it is coupled. If these conductors are separated by distances on the order of the scale of the survey, the effects of the interaction can be significant. When the background conductivity pattern is regular or semi-regular, the background assumes the character of being discretely anisotropic.

The effect of discrete anisotropy thus results from the initial coupling of the primary field with the conductors, and then with the subsequent interactions of the conductors amongst themselves.

The decay rate effect:

To illustrate the effect of discrete anisotropy in its simplest case, first consider a fixed loop that is located between two vertical conductors so that the primary field couples with each in the opposite sense. Next, consider the case where the loop is offset to the side so that coupling to both conductors is in the same sense.

The second case is the one that is most often encountered. Here, the time-varying decay will be in the same sense between the two conductors as with each conductor in isolation. When conductors are close enough together, the net conductance will be approximately additive. The time constant of the system (current decay-times) will increase.

In the first case, the coupling between the two conductors is opposite to the coupling of each conductor to itself. In this case, the decay of a current in one conductor drives the decay in the other, decreasing the time constant of the system, and reducing its effective conductance.

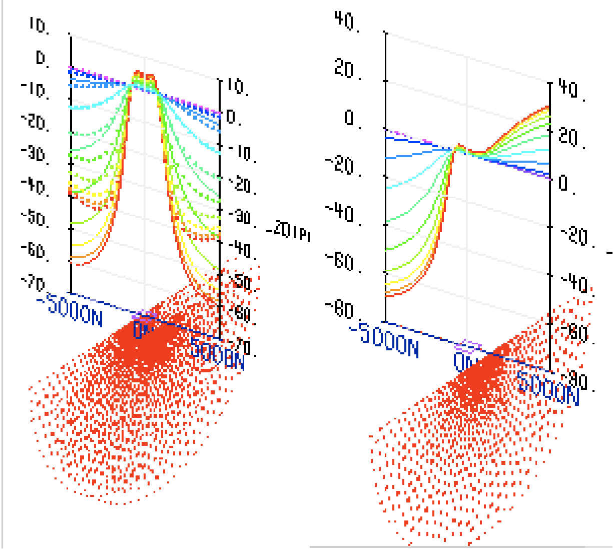

Figure 1: Simulated response for the case where the conductor is energized by the centred loop. The reponse of a single conductor is plotted on the right, and for the two conductors on the left. On the left plot, the solid lines illustrate the full response, while the dotted lines illustrate the superposition of the individual reponses of each conductor. The loop is centred at 0N, and the red tiles illustrate the conductor(s).

We illustrate this effect with a simple model representative of a case typical of those encountered in the Athabasca Basin in northern Saskatchewan. Here, the exploration targets are typically conductive meta-pelites located at depths often exceeding 500 meters. The meta-pelites exist in the crystalline basement under the resistive Athabasca sandstone. In the example illustrated, the conductors are 500 meters deep, and are located at +/- 800 meters on the profile. The conductors are represented by expanding pseudo-infinite half-sheets, each with 801 points and an extent of 20 km. The simulations use a 30 Hz UTEM (West *et al*, 1984) waveform and a 1000 meter square transmitter loop, with the response measured using a vertical magnetic dipole. Data are continuously normalized at a depth of 500 meters to the magnitude of the primary field.

Figure 1 illustrates the response of a single conductor, the coupled response of two conductors, and the superposition of the response of two conductors for the case when the loop is centered between the conductors. Note that the fully coupled response is larger than the superposed response from the two conductors: the decays reinforce each other due to the fact that the current excitation on each sheet has the opposite polarity.

In the Figures, channel 10 (early time) data are illustrated in red; late time data (channel 1) are illustrated in blue. The response was computed for the standard suite of ten geometrically spaced UTEM windows.

A detail of the response over the conductor is illustrated in Figure 2. Again, note that the fully coupled response (lines) is initially larger than the superposed response of the two conductors, with the decay of the coupled system being faster than the decay coupled from simple superposition. The coupling enhances the measured decay.

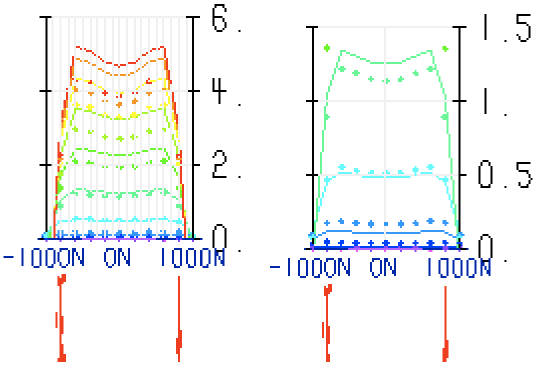

Figure 2: Detailed plot the simulated responses above and between the two conductive sheets illustrated in Figure 1 (left). Early times are plotted in the left graph and late times on the right, with the full response plotted as lines and the superposition of the individual responses plotted as points. The plate locations are illustrated in red below the line; note the cross-overs are shifted from the conductors.

Figure 3 plots the decay as a function of time (channel) that would be measured at a vertical receiver located at station 0 (centered between the loops) for the cases of the centered and offset loop. The decays for the individual conductors are plotted for comparative purposes together with the decays from the pair.

The decay of the individual conductors is less rapid than the decay of the pair of conductors. This observation is counter to the prevailing "rule of thumb", which would predict that the time constant of two parallel, well coupled conductors is greater than the time constant of either conductor, and can be approximated by the sum of the two since conductances are approximately additive. Such a view is valid only when the coupling of the current excitations to the transmitter and receiver is the same sign for each conductor. This is true for sounding geometries, and usually in cases when the separation between the conductors is small relative to the dimensions of the survey.

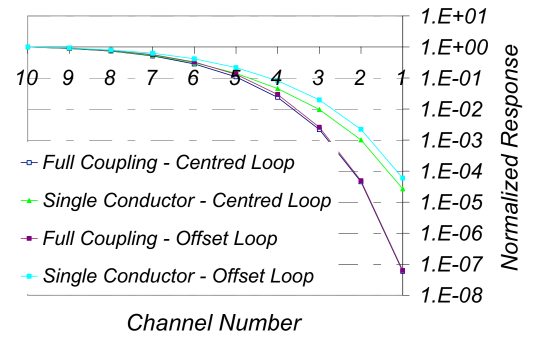

Figure 3: (Centered Dipole Receiver) UTEM decays for a vertical dipole at station 0N for the case of the loop centred between, and offset from, the conductors (normalized to channel 10). The decays of the fully-coupled response from the centred (blue line) and offset (purple line) loops are virtually identical..

Figure 3 also shows that for this model, the time-decays that would be measured by a receiver for the case when the loop is between the conductors and when it is offset from from them are almost the same. In the case where the loop is centered between the conductors, the more rapid decay is driven by the mutual interaction of the two current systems. In the case where the loop is offset, because the receiver is between the conductors, it is coupled in the opposite sense of the current systems on each conductor, and so measures the difference in the current systems. Thus the receiver senses an apparent decay which is different from the true decay of the currents. This is the principle of reciprocity in action.

To confirm this view, the decays are plotted for an offset receiver for the case of the centered and offset transmitter loop. As expected, the decay measured by the offset receiver for the case of the offset loop is slower relative to the cases of the isolated conductor (the conductances are approximtely additive), while the decay of the centered loop is as before. In the case of the centered loop, the rate of decay is approximately constant with position, while in the case of the offset loop, the measured decay depends on how the receiver is coupled with each of the current systems.

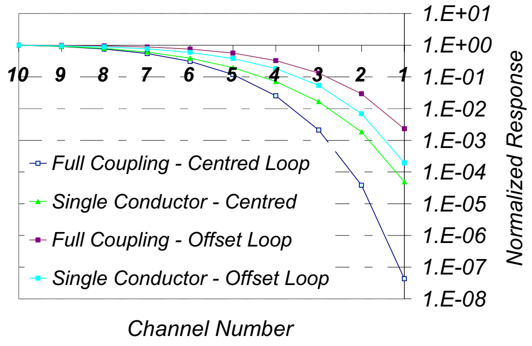

Figure 4: (Offset Dipole) UTEM decays for a vertical dipole at station 2200N for the cases of the loop centered between, and then offset from, the conductors.

Apparent anomaly enhancement:

Much of our understanding of geophysical interpretation is based on the decay of single conductor. It is also known that in practice, these single conductor decays can be significantly modified by the interactions with the surrounding media; two of the best known effects are shielding from overburden and enhancement from current channeling. Here we illustrate a third effect, namely apparent anomaly enhancement due to the effect of discrete conductivity anisotropy.

Figure 4 compares the UTEM magnetic field response of a single conductor using the geometry of the previous section with the response of a similar conductor in a discretely anisotropic medium. The conductor is a half-sheet with a conductance of 10 S. It is embedded in a medium populated by parallel 0.01 S conductors separated by 1000 meters.

Two effects are evident. The most prominent is the increase amplitude of the early-time responses (channels 10 to 6), in the vicinity of the conductor, while the late time decays are unaffected. The other effect is the migration of the cross-overs on the left side of the profile. Such migration is typically associated with currents diffusing as a "smoke ring" through a horizontally stratified medium. In the example presented (Fig. 5, right), the conductivity structure is entirely vertical, but an interpreter might infer the cross-over migration to indicate the presence of a weakly conductive overburden layer.

The enhanced early-time anomaly seen over the conductor is an apparition. The background anisotropic medium actually attenuates the response of the conductor. In Figure

6 (left), the background response of the 0.01S anisotropic model is plotted, showing the response is larger than the response of the conductor in free-space but smaller than the response of the anisotropic medium. The apparent response of the conductor is amplified, but the amplification is less than the amount simple superposition would suggest.

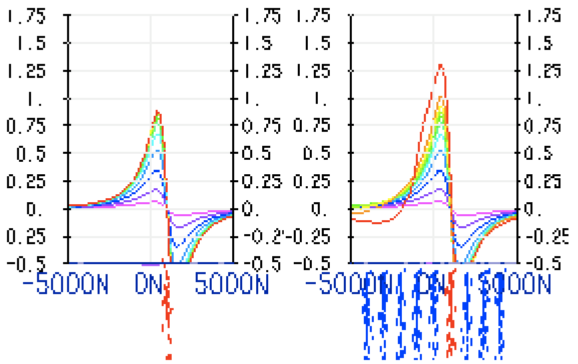

Figure 5:A comparison of the response of a single conductor in free space using the geometry and system parameters of Figure 1 (left), and the response of the same conductor where the background is discretely anisotropic (right). Response is plotted in nT. Channel 1 (late time) is plotted in magenta.

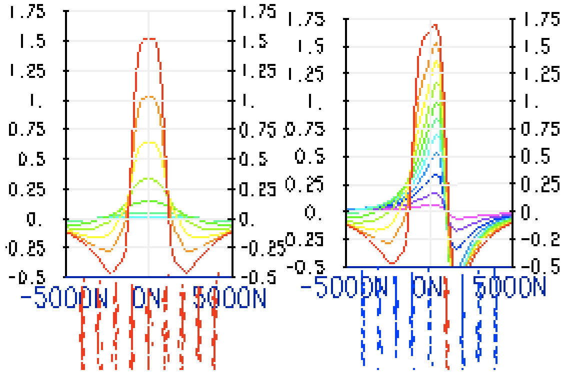

Figure 6: Left: The background response of the 0.01 S anisotropic model. Right: The response of the same conductor in a 0.1S anisotropic background. Response is plotted in nT.

Figure 6 (right) shows the response of the same conductor in a background where anisotropic sheets have a conductance of 0.1 S. In this case, the early-time apparent response of the conductor is approximately double the amplitude of the same conductor in free space. On the left part of the profile, there is evidence of current migration by virtue of the moving cross-overs. The cross-overs move outward from the loop with increasing time, and could be incorrectly interpreted as being due to a flat lying conductor. In this case, the apparent conductivity of the flat-lying conductor is larger than in the case illustrated in Figure 5 (right).

The effect of current migration is also seen in the uniformly anisotropic model illustrated in Figure 6 (left). In this model, the current is confined to flow in the vertical plane. However, the polarity of the current excitation is opposite to the left and right of the loop, and because the sensitivity to current excitation is strongest to currents under the sensor, it appears the current flowing on one side of the loop is matched by a return current on the opposite side. Sensitivity to current is flowing in a vertical plane, rather than returning in a horizontal plane is small, so the anisotropic case is difficult to differentiate from the horizontally layered one. Hence a vertically anisotropic medium can be misinterpreted to be a horizontally layered one.

Conclusions:

Our modeling study has shown that discrete conductivity anisotropy can have profound effects on the interpretation of electromagnetic data. Discretely anisotropic media can mimic horizontally layered media, and can increase the apparent amplitude of a conductor, particularly at early times. In addition, cross-over locations, which are often used to locate conductors, can be shifted when two strong conductors are present.

We have also shown that when multiple conductors are present, the measured decay constants are not an intrinsic property of the geo-electrical structure. Depending on the on the position of the transmitter and receiver, the measured decay rates may be significantly increased over the rate that would have been anticipated were the conductors isolated in free-space.

The background model with the equally conductive equi-spaced half-planes produces a migration on both sides of the loop, but the anomaly of a single conductive body embedded in a background of these conductors does not show any migration in the cross-over above it. The migration of cross-overs away from the loop observed over long conductors in the Athabasca basin cannot be explained by this type of model alone. More research is required to completely understand these effects.

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