# Audio-magnetotellurics (AMT) for steeply-dipping mineral targets: importance of multi-component measurements at each site

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**Summary**

Steeply-dipping mineralized bodies present a particular problem for audio-magnetotelluric (AMT) exploration. Such targets have little observable effect on currents flowing perpendicular to their dominant strike, thus TM-mode AMT data are not useful for target detection or delineation. The TE-mode and vertical-field transfer function data do detect such targets, and appropriately-designed surveys can define their geometries. The anomalous responses due to such targets are greater in the magnetic fields than in the electric fields. Conducting overburden suppresses the high frequency response, moving the anomaly maxima to lower and lower frequency with increasing overburden conductance. For optimal resolution of target geometries, all five AMT components must be measured at each and every site.

**Introduction**

As near-surface ore bodies are depleted, the exploration for economic minerals requires information from deeper depths. Electromagnetic (EM) methods have demonstrated their ability at imaging ore bodies, due to the high conductivity of interconnected sulfides. On the Canadian Shield, at depths below about 500 m the advantages of controlled-source EM (CSEM) methods are offset by the high cost of the logistical requirements, and the natural-source audio-magnetotelluric (AMT) method becomes an attractive tool.

AMT has advanced significantly since the early-1970s, when Strangway et al. (1973) developed CSAMT because reliable and interpretable AMT responses could not be achieved. Understanding of AMT source fields (Garcia and Jones, 2002) coupled with modern 24-bit AMT acquisition systems, new sensor designs, and robust time series processing algorithms, all developed over the last decade, means that high quality AMT responses can now be routinely acquired from 1-20,000 Hz with less than an hour's recording time. These responses can be analyzed for galvanic distortion effects, and the responses from the target can be modeled using 2-D, and recently 3-D, inversion codes to yield precise information valuable for mineral exploration objectives (e.g., Jones and Garcia, 2002).

In Canada over the last few years there have been in excess of 15,000 AMT soundings made for mineral exploration purposes, mostly in Voisey's Bay (Labrador), Sudbury (Ontario) and the Thompson Nickel Belt (Manitoba), particularly for regional mapping and for imaging structures at depths >500 m (e.g., Balch et al., 1998; Stevens and McNeice, 1998; Zhang et al., 1998).

Many Archean target ore bodies are steeply-dipping with widths that are smaller than their strike lengths or dip extents, such as Kidd Creek, Ontario (*Cu*, *Zn*, *Ag*), thus they can be approximated by 2-D models. Given such geometries, one can pose questions about appropriate survey design to image optimally the target bodies.

We show that such bodies have little effect on current flow perpendicular to their strike, the so-called *Transverse Magnetic* (TM) mode in 2-D magnetotellurics. Thus, in-line electric dipoles along a survey profile optimally oriented perpendicular to strike cannot detect steeply-dipping ore bodies. Currents flowing along the strike of the body, the 2-D *Transverse Electric* (TE) mode, are observable on the surface, which suggests acquisition by as many cross-line electric dipoles as possible for maximum resolution.

However, as well as the anomalous horizontal cross-line electric field from the body, there are anomalous vertical and in-line horizontal magnetic fields that can also be used to enhance resolution. The maximum anomaly in the magnetic field components is larger and at lower frequency than the electric field anomaly. Thus, greatest resolution of the body comes from acquiring all five components of the EM field at each AMT site, rather than a subset.

Finally, the effect of conducting overburden is to attenuate the high frequency anomalous response of the body, which is equivalent electrically to moving a body to deeper depths. A body below 50 m of overburden of 50 Ω.m resistivity has an equivalent frequency response to a body at 1,000 m or so on the exposed Shield. If the overburden is even more conductive, then the body becomes electrically deeper approximately related to the square root of the ratio of the resistivity of the Shield rocks (typically 5,000 – 50,000 Ω.m) to that of the overburden rocks.

**AMT response of steeply-dipping structures**

The generic ore body we have chosen to model is the Kidd Creek deposit in Timmins, northern Ontario, Canada. The schematic geometry of the deposit is shown in Fig. 1. Light green depicts mined out areas, and dark green shows unmined ore. The red body is the shape of our numerical body representing the unmined ore, with a width of 125 m at depths of 1400 – 3100 m and a dip of 6.7º). This body has a reported strike extent of 1200 m (Gilbert and Park, 1985), so with a length-to-width ratio of 10:1 means that a two-dimensional (2-D) approximation is valid for sites located over its center (Jones, 1983; Wannamaker et al., 1984).

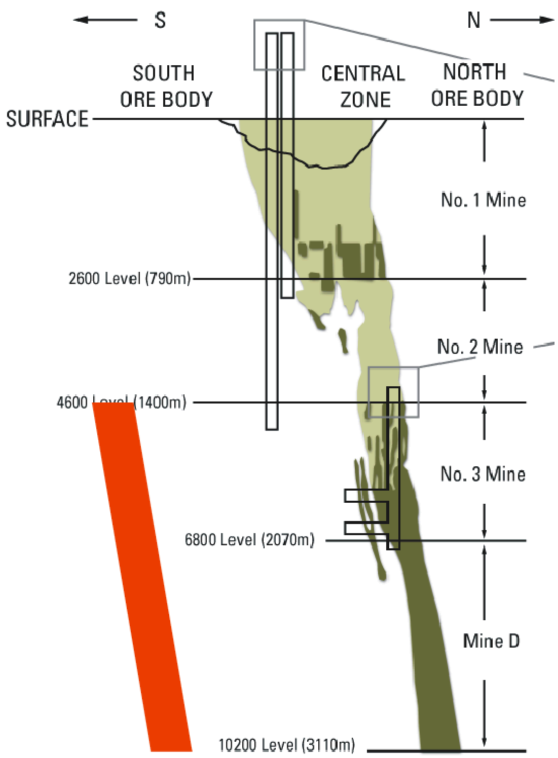


**Figure 1:** Kidd Creek deposit and numerical body

We assigned a resistivity of 10 Ω.m to the conductive target body, and it lies within a host rock of 10,000 Ω.m to a depth of 12.5 km, underlain by a lower crust of 1,000 Ω.m. There is no surficial overburden at this point.

Figure 2 shows the phase anomalies for the two modes of propagation in the 2-D case. These are the phase differences between a model with the conductive body compared to a model without it. We choose to portray phase differences as they are unaffected by galvanic distortions that plague the magnitudes of the electric field and cause static shifts in apparent resistivity curves.

For the TE case (Fig. 2 upper contour plot), there are two phase anomaly maxima, one at 100 Hz of -22º, and one at 6 Hz of +22º. The TM phase anomaly maximum (Fig. 2 lower contour plot) is at higher frequency, ~600 Hz, and shows asymmetry which is indicative of the dip of the body. However, in stark contrast to the TE phase anomaly, the TM maximum anomaly is only 0.5º, which is far below reliable detection (taken as 1º for the best data possible).

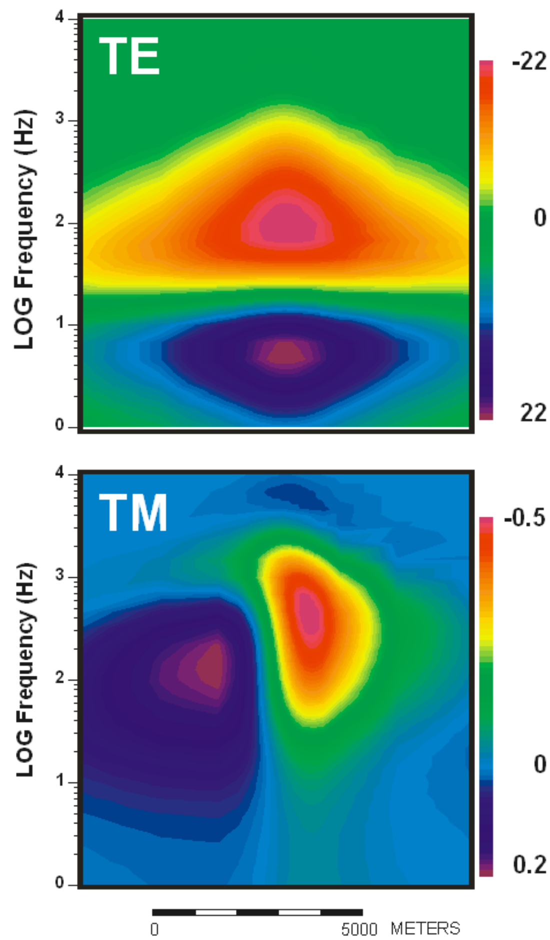


**Figure 2:** Phase anomaly due to body in TE (upper) and TM (lower) modes: Note difference in scale

The double maxima in the TE phase response occur because the anomalous electric and magnetic fields display maxima at different frequencies and with opposite sign. Figure 3 shows the spectra that would be observed at the site directly on top of the body. The maximum anomaly in the along-strike electric field is a 28% decrease at ~30 Hz. The maximum across-strike magnetic field anomaly is a 74% increase at a frequency of ~12 Hz.

The maximum anomaly in MT apparent resistivity is at ~20 Hz, and is an 85% decrease in resistivity. Clearly, most of this anomaly is coming from the 74% increase in magnetic field, not from the 28% decrease in electric field.

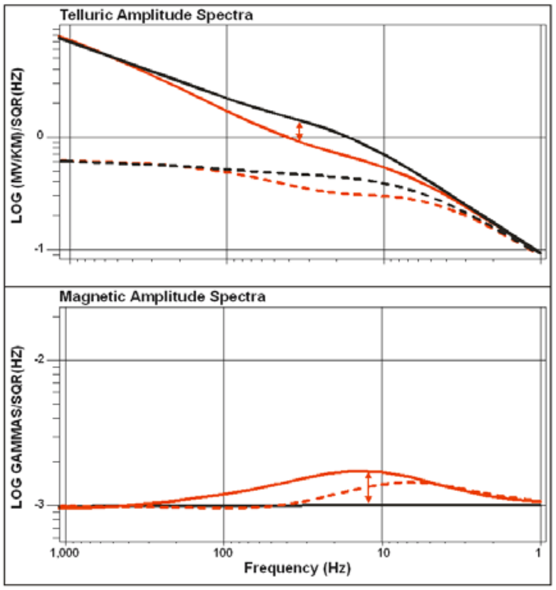


**Figure 3:** Electric and magnetic spectra that would be observed at the site on top of the body. The black lines are the TM-mode response (same as no body), and the red lines are for the TE-mode response. *Dashed lines* are the spectra with 30 m of 25 Ω.m overburden.

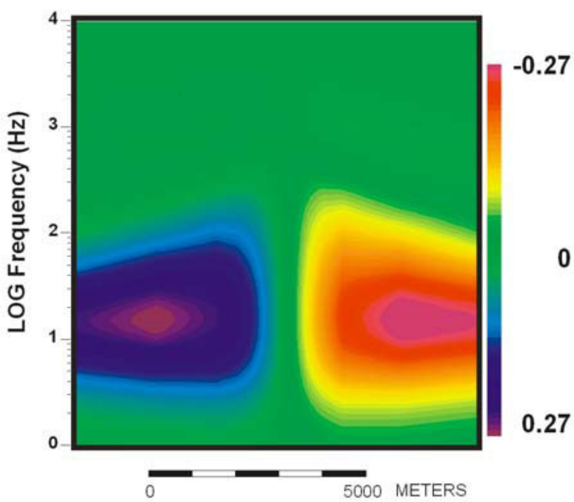


**Figure 4:** Real vertical field transfer function (TZr)

As well as the MT response, there is also a strong variation in the vertical magnetic field caused by the body. The real part of the vertical field transfer function (ratio of vertical magnetic field to the horizontal field perpendicular to strike), TZr, is shown in Fig. 4. The maximum anomaly occurs ~2.5 km away from the body at a frequency of ~12 Hz – the same frequency that displays the greatest anomaly in horiontal magnetic field (Fig. 3). The anomaly is 0.27, which is far greater than the typical noise value of 0.05.

**Effect of overburden**

When the target region is covered by overburden, the overburden attenuates particularly high frequency EM fields. For an overburden of 25 Ω.m with a thickness extent of 30 m (integrated conductance of 1.2 Siemens), typical for the region around the Kidd Creek mine, frequencies above ~10 Hz are strongly attenuated. Figure 3 shows the difference caused by the overburden (dashed lines). The maxima decrease both in amplitude and in frequency.

Compared to the no-overburden case (Fig. 2), the TE phase maxima shift downwards to frequencies of 40 Hz and 3 Hz, and the range decreases to ±15º from ±22º. TM phase is even more strongly attenuated, with a maximum of –0.06.

The vertical field transfer functions are also attenuated, with a range of ±0.16 instead of ±0.27 (Fig. 4), and the frequency of the maxima decreases to ~8 Hz.

**Body directly below overburden**

In the case that an ore body is subcropping beneath the overburden, there is sensitivity at high frequencies to its presence, but only for sites within the close proximity of the body. The phase and TZr plots are shown in Fig. 5.

The TM anomalous response is only visible at sites on top of the body - there is no response at sites off the body. The TM response over the body is due to the electrical connection between the overburden and the ore body. If that connection does not exist, i.e., if the ore body lies at a depth of 25 m below the base of the overburden, then there is no measurable TM response (anomaly <1º).

The TE phase response is very strong, and is visible over a distance range of >2,000 m at frequencies of ~100 Hz. The response is only marginally affected if the body is not subcropping, but is at a depth of 55 m.

The TF response is strong (±0.45) and visible over a distance range of >4,000 m. It maximizes at ~8 Hz, which is the frequency of maximum horizontal magnetic field anomalous response. In contrast, the maximum TE electric field anomalous response is at 200 Hz.

**Conclusions**

Steeply-dipping, electrically-thin ore bodies pose a problem for AMT detection and delineation. They have no reliably measurable TM response, but can have strong TE and TZ responses. Most of the anomalous response is visible in the anomalous across-strike magnetic field, rather than in the along-strike electric field.

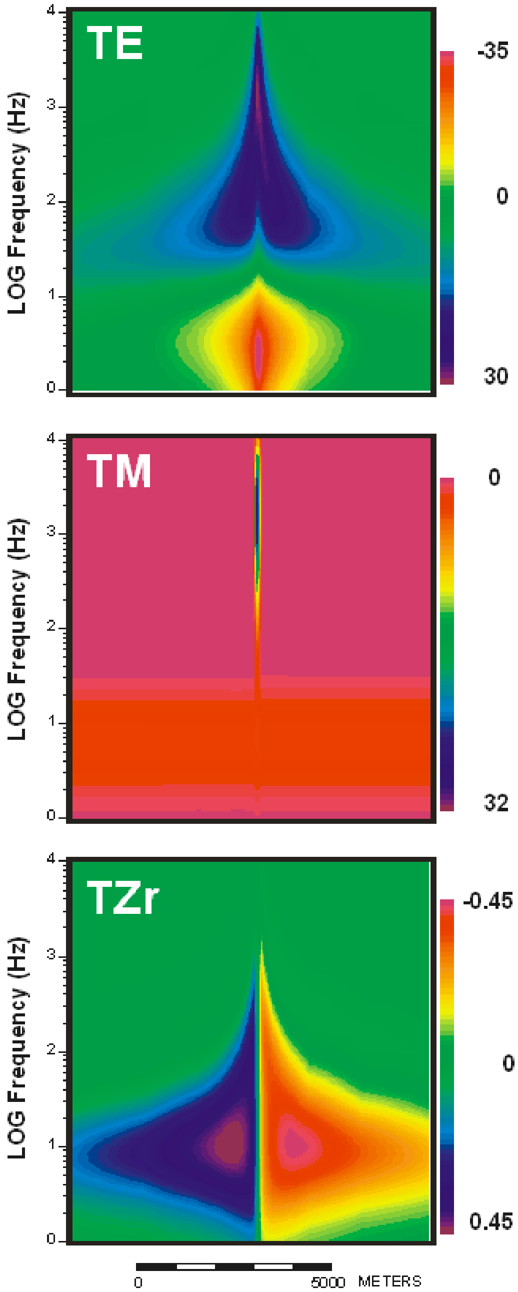


**Figure 5:** TE and TM phases and real transfer functions for a subcropping ore body

This behavior therefore necessitates measurement of all five components (*Hx, Hy, Hz, Ex, Ey*) at all AMT sites, rather than a subset of components. Acquisition of the four horizontal components also permits distortion analysis using the latest decomposition techniques (McNeice and Jones, 2001).

Finally, we advocate appropriate survey design prior to undertaking a survey. There is little point collecting data that are insensitive to your target!

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