3D induction: fact or fiction?

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Summary

Three-dimensional electromagnetic induction by natural sources takes place in our three-dimensional world, but the question to address is whether a two-dimensional interpretation is sufficient or not, and uder what circumstances may one be lead astray. In this paper we analyse theoretical 3D audiomagnetotelluric responses over a numerical representation of the generic Canadian mineralized body found using EM methods, and also real data from northern Labrador. We demonstrate that a 2D interpretation is sufficient for exploration purposes for those sites over the middle of the body if the body is isolated electrically. However, when there is a large regional conducting structure nearby, such as an ocean or a sedimentary basin, then one must consider the effects of the mutual interaction between the mineralized body and the regional body.

Introduction

Just how important is considering induction in three-dimensions (3D) when interpreting AMT data over mineralized bodies? How valid is a 2D approximation? And how wrong will one be with a 2D model of a 3D structure?

In this paper we examine the 3D response of the typical "Canadian mineralized body", calculated using two different approaches: a full forward 3D solution by Mackie and Rodi (1998, submitted), as implemented as part of the Geotools package, and the extended Born-approximation of Habashy et al. (1993), as implemented as part of the PetrosEikon EMIGMA package.

Also, we analyze and interpret data acquired for Gallery Resources at Okak Bay, north of Voisey's Bay, Labrador. In contrast to the isolated body case, we consider the effects caused by the close proximity of the coastline.

Our conclusions are that for the most part a 2D interpretation is sufficient for industrial purposes, but that in certain circumstances a 2D interpretation is totally inappropriate.

Example 1 – Generic Canadian EM Target Body

The generic Canadian body found using EM is a VMS deposit of mainly pyrrhotite with a length of 500 m, a width of 150 m, a thickness of 25 m, and a vertically-integrated conductance of 1 – 300 Siemens (Boldy, 1981). The dollar value of the deposit is not a function of the conductance, but is a weak function of the width. The conductivity of pyrrhotite mineralization is far greater than that of any pyrite present, due to the interconnected nature of pyrrhotite compared to pyrite.

For the purposes of this test, we have assumed a target body at a depth of 250 m with a conductance of 25 Siemens, which, over a thickness of 25 m, means an internal conductivity of 1 S/m (resistivity of 1 ohm.m), within a resistive host of 10,000 ohm.m.

A comparison will be shown of 2D inversion of the 3D data outlining the problems and pitfalls, and demonstrating that, for the most part, a 2D interpretation of the data away from the ends of the body is sufficient for exploration needs.

Example 2 – Gallery Resources Data

As part of their exploration efforts in northern Labrador, Gallery Resources of Vancouver (web site: http://www.gallery-gold.com/) conducted an AMT survey of 48 sites over a region of about 10 square kilometres (Fig. 1), with a concentration of 12 sites in a one square kilometre region over an aeromagnetic anomaly (Fig. 2).

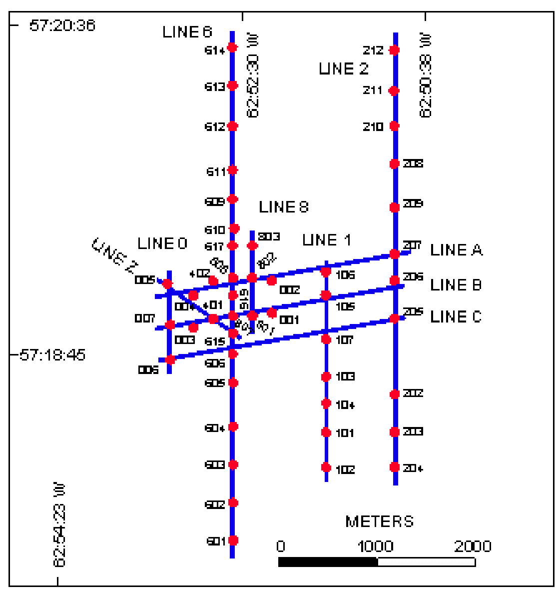


Figure 1: Locations of the AMT sites

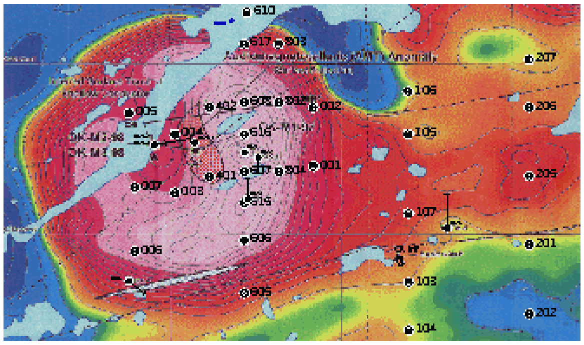


Figure 2: Locations of the AMT sites over the magnetic anomaly

The survey area is located some 25 km from Okak Bay in northern Labrador, and some 50 km from the deep waters of the Labrador Sea (Atlantic Ocean). Voisey's Bay nickel deposit, the largest nickel deposit in the world, is located 120 km to the SW, which explains the exploration interest in the region.

An interpretation provided by the contractor, shown below in Fig. 3, of the data from the fifteen sites along Line 6 prompted extension of the drilling program to a depth of 1500 m in order to intersect the large conducting anomaly interpreted to exist at a depth of 1 km.

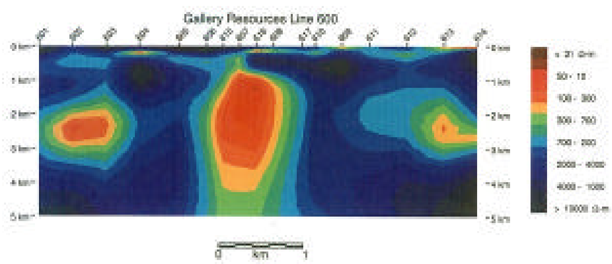


Figure 3: Model of Line 6 data provided by the contractor

The drilling program intersected sulphide (locally up to 10% pyrrhotite) mineralization at depths of 450 – 600 m, but showed no minerlization that could explain the major deep anomaly. Consequently, Gallery Resources and the GSC undertook a cooperative project to understand the AMT data by 2D inversion and 3D forward modelling.

The data at frequencies higher than 1 kHz was poor, particularly in the AMT "dead-band" of 1 kHz – 5 kHz, despite overnight acquisition. Consequently, these data were not used. In addition, non-inductive responses at frequencies lower than 10 Hz (see below) caused us to reject these data for further consideration. A Rho+ (Parker and Booker, 1996) prediction of the apparent resistivity curves from the phase curves showed that at low frequencies the rapid decay of the apparent resistivity curves is incompatible with the phase response (Fig. 4)

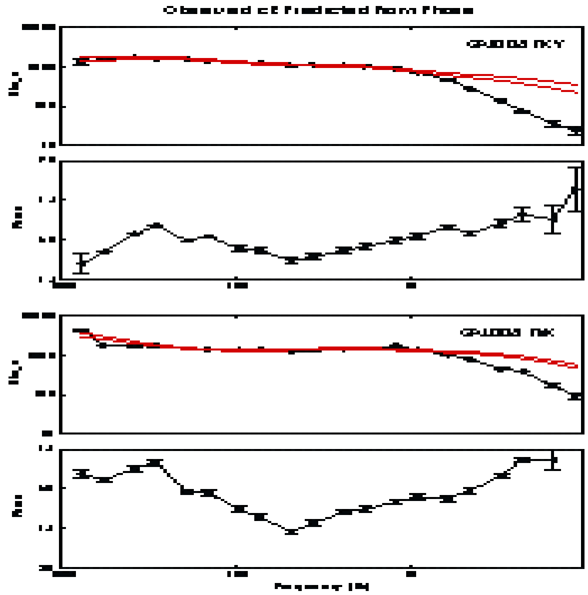


Figure 4: Observed apparent resistivity and phase data for both modes from site *GAL005* compared to the resistivities predicted by the phase curve using *Rho+*.

Accordingly, we rejected the low frequency data as suspect, and analysed and interpreted the AMT data in the two-decade band of 1,000 – 10 Hz.

Multi-site, multi-frequency McNeice-Jones (McNeice and Jones, submitted) tensor decomposition demonstrated that the strike directions were generally East-West. This was reasonably consistent with the induction vectors, although very poor data and calibration errors made quantitative interpretation of the transfer function responses impossible. At frequencies less than 36 Hz though, the real (reversed) induction arrows all pointed eastwards, towards the coastline. This was the first indication that perhaps a 2D interpretation of low frequency AMT data may be prone to serious error.

Two-dimensional inversions, using Mackie and Rodi's code, were performed on all lines, including an additional NW-SE Line Z which crossed the zone of interest obliquily. Inversions were performed of both modes simultaneously, and of each mode independently. The better fits from the independent modes, compared to using both modes, we take as evidence of the 3D nature of the dataset. Generally, we could fit the data to a normalized RMS of about 6, which, given the error floor of 2% in apparent resistivity and 0.56^{O} on phase, indicates a fit to within 12% in apparent resistivity and 3^{O} in phase on average.

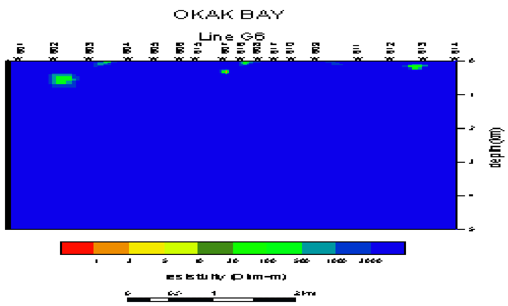
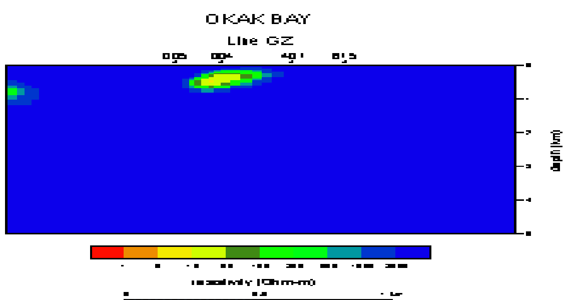


Figure 5: Mackie-Rodi inversion of the decomposed data from Line 6 (compare with Fig. 3).

The model we found for Line 6 data is shown in Fig. 5, plotted on the same scale but with different colour contours.

Note that none of the deep anomalies appear in this model, presumably as a consequence of limiting the data to 10 Hz rather than including all the suspect data down to 1 Hz. The model for the oblique line, Line Z, is shown below (Fig. 6), and an excellent image is observed of a region of enhanced conductivity, with resistivity below 50 ohm.m, within the



top kilometre.

Figure 6: Inversion of Line Z data

3D Composite

A pseudo-3D model was obtained of the target body by using the models derived from inverting the lines that cross the body (A, B, C, Z, 0 and 6). Four slices through the model are shown in Fig. 7, and a cutout of the body in Fig. 8.

Although this imaged body is not a true 3D body, but is a composite formed from 2D inversions, it is sufficiently precise for defining an exploration program.

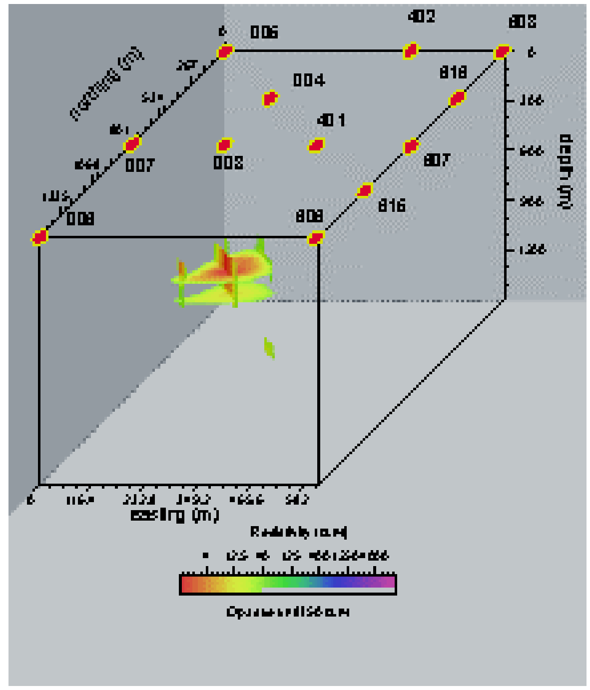


Figure 7: Four slices through the pseudo-3D model of the conducting body.

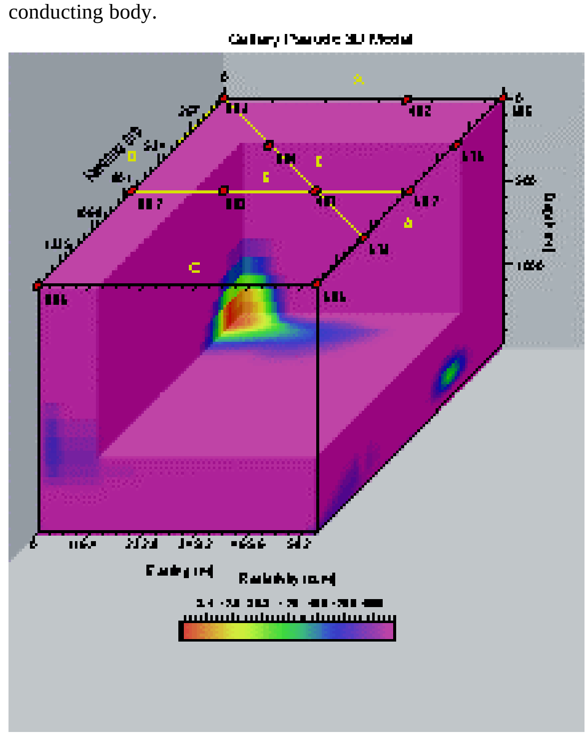


Figure 8: Cutout of the conducting body

One-dimensional Models

One-dimensional inversions of the decomposed data for the two modes and their average from the site on top of the body and close to one of the drillholes, *GAL004*, yielded a conducting layer in the upper kilometre with the following ranges of best-resolved model parameters:

Depth to conducting zone: **450 – 600 m**

Conductance: **1.85 – 2.15 Siemens**

This compares well with the well-log information which reports a mineralized layer intersected between 454.1 – 470.5 m depth with up to 10% disseminated sulphides, mainly pyrrhotite. If this 16 m thick layer is wholly responsible for the approx. 2 Siemens conductance anomaly, this implies an internal resistivity of approx. 8 ohm.m on average. Laboratory measurements on pyrrhotite suggest a mineral conductivity of 10^4 – 10^5 S/m, which implies, using Archie's Law with an exponent of two, that the averaged interconnected pyrrhotite content in this layer need only be 0.3%.

Three-dimensional Modelling

A three-dimensional model was constructed of a small-scale 2 Siemens mineralized body plus the very large scale Atlantic Ocean and Okak Bay. The forward calculations were performed using the *LN* approximation with PetrosEikon's EMIGMA code. Models were run of the *body-alone*, the *ocean-alone*, and the *body+ocean* in the frequency range 10,000 – 1 Hz.

In Fig. 9 is a plot of the three phase pseudosections for a profile crossing the body for the mode in which the currents are crossing the shoreline (regional TM mode). The top pseudosection is for the *body+ocean*, the middle one is for the body-alone, and the bottom one is for the *ocean-alone*. As would be expected, the *ocean-alone* is spatially monotonous showing a spatially-uniform phase response over the whole survey region with increasing phase with decreasing frequency. The *body-only* phase pseudosection shows that the EM response of the body has decayed by approx. 30 Hz, which is coincidentally the frequency at which the ocean is first sensed. However, when both the local mineralized body and the regional ocean are included together, there is an interaction between the two such that the phases at the sites sensing the anomaly increase dramatically with decreasing frequency (83^O at 1 Hz compared to 46^O). Clearly, the body is influenced by the relatively close proximity of the ocean currents.

The apparent resistivities are also perturbed, but in a perplexing manner, with the lowest frequency (1 Hz) value at 2868 ohm.m for the *body+ocean*, but only 1818 ohm.m for the *body-alone*. This effect does not qualitatively replicate the observations, of a strong decay in apparent resistivities but phases that appear unaffected, and may be a consequence of the LN approximation. Tests are being performed with the Inductive LN solution, and will be reported on at the workshop.

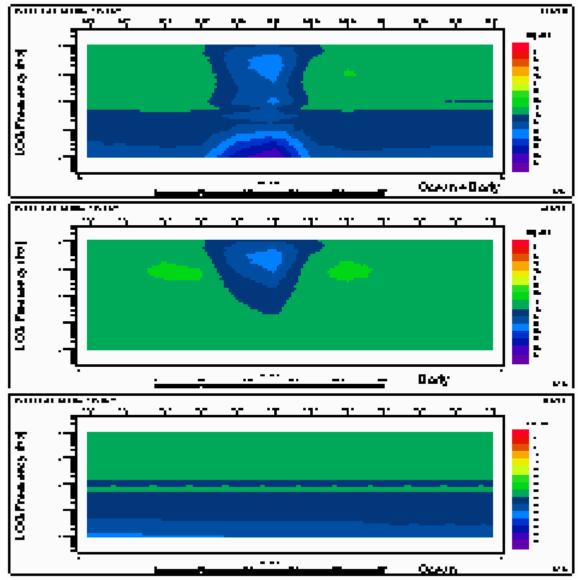


Figure 9: Phase pseudosections for the regional quasi-TM mode for the *body+ocean* (top), *body-alone* (middle) and *ocean-alone* (bottom).

Conclusions

Whether one needs to consider full 3D interpretation of AMT data for mineral exploration purposes is clearly a function of the complexity of the region. For a simple embedded mineralized body, a 2D interpretation of the data from sites over the middle of the body will give reliable geometrical information sufficient to define an exploration program.

However, in the "close" vicinity of a coastline, or indeed any major conducting feature such as a sedimentary basin, there may be significant mutual coupling between the currents induced in the ocean and the body to the extent that a 2D interpretation of the data may lead to highly misleading conclusions. A full 3D interpretation must be undertaken to understand the effects of the very large-scale regional conductivity structures.

Acknowledgements

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