Deep electromagnetic imaging of the Bathurst No. 12 deposit: 3-D forward modeling, 2-D inversion and sensitivity tests

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Summary

A detailed three-dimensional (3-D) numerical electrical resistivity model of the Bathurst No. 12 deposit (New Brunswick) has been constructed using available geological and geophysical information. This model facilitates studies of the resolution capabilities of audio-magnetotellurics (AMT) at locating and defining mineral targets, and of methods of optimizing data acquisition. Different conditions were analyzed: presence of overburden, dimensions and positions of the ore body, and varying data sampling. The behavior of 3-D EM fields is compared with 2-D ones. The 3-D and 2-D responses are similar at high frequencies, but at low frequencies only those responses for current flow perpendicular to the body (TM mode in 2-D) are reasonably alike. The 2-D inversions show that the position and top of the 3-D ore body can be well resolved, but not the bottom and resistivity of the body.

Introduction

Audio-magnetotellurics (AMT) has been used increasingly in Canada to detect mineral targets at depth, with acquisition at over 15,000 sites in Voisey Bay, Sudbury Basin, and the Thompson Nickel Belt. AMT surveys have defined conductive targets, and demonstrated that AMT provides an efficient and useful tool for exploring conductive mining targets at depths beyond those conventionally targeted by EM methods (Garcia and Jones, 2001).

However, we wish to evaluate whether AMT is useful not only to **detect** but also to **delineate** conductive ore bodies. Some model-based studies have been done in the Sudbury Basin (Livelybrooks et al., 1996), but further work is required to achieve a better understanding of the applicability of AMT for mine-scale related problems.

Due to the complex geometry of ore bodies, 3-D modeling is essential, but reliable 3-D inversion algorithms that can be routinely applied to AMT data are not commonly available. Thus, 2-D inversions of 3-D data are widespread, but their limitations are poorly understood. During the 1980s papers were published studying 3-D effects (e.g., Wannamaker et al., 1984), and, more recently, other studies have shown the main limitations of 2-D inversions of 3-D data (e.g., Ledo et al., 2001). These studies give recommendations to avoid 3-D effects in 2-D interpretation, but these recommendations are not universally valid, and are not always taken into account. With AMT surveys being used to search for deep targets, 3-D studies and 2-D limitations needs to be revisited. However, the issue is no longer *how to avoid* 3-D effects, but rather *how to delineate* 3-D bodies by their MT responses and how to handle 3-D effects.

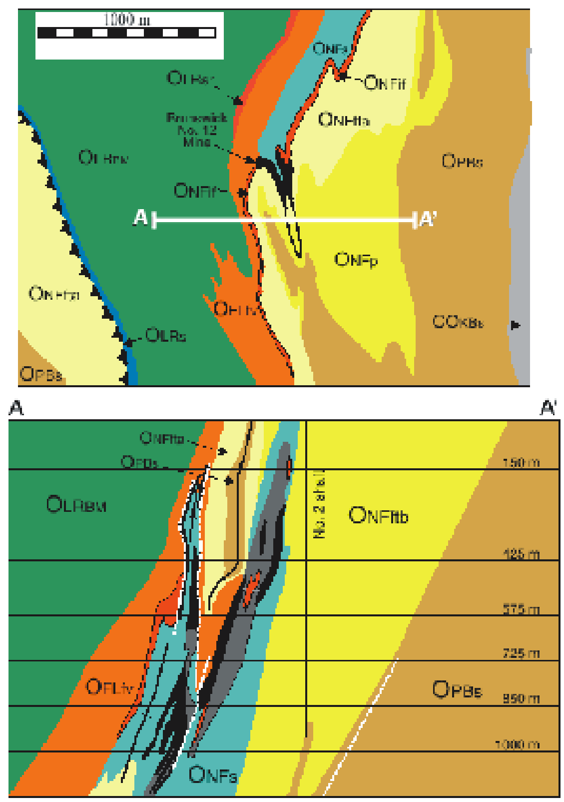

Figure 1: Geology map and section of the Bathurst No. 12 Deposit

The main questions are: Is AMT currently able to determine the geometry of ore bodies? What are the main difficulties? and, How we can improve field surveys and 3-D interpretations? To address these questions, we have constructed a detailed 3-D numerical model of an ore body and studied its AMT responses. Our aim is to provide recommendations for field survey design and data interpretation.

Our choice of an ore body for this study required as comprehensive a publicly-available information base as possible. Profiting from the recent and complete geological and geophysical information obtained at the Bathurst mining camp in New Brunswick (Thomas et al., 2000), we chose to simulate the Brunswick No. 12 Deposit, which is one of the largest massive sulphide deposits in the area.

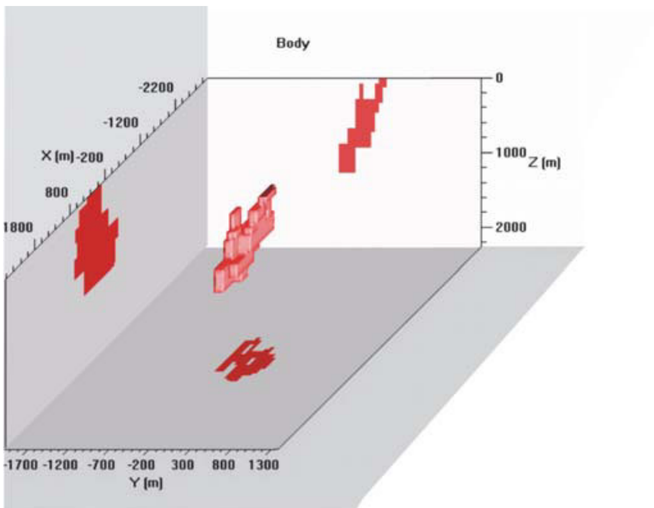

Figure 2: Outline of the 3-D body with projections onto the faces

Design of the 3-D model

Fig. 1 shows the geological map and a cross section of the Brunswick No.12 Deposit (from Thomas et al., 2000). The design of the 3-D numerical model took into account geophysical and geological information in Luff et al. (1992) and Thomas et al. (2000). Following Katsube et al. (1997), different host rocks were assigned different resistivity. However, here we discuss only the simplest case, comprising a conductive homogeneous ore body embedded in a resistive homogeneous half space. A thin (9 m) overburden covers the body and the eastern part of the model. Fig. 2 shows the constructed ore body, and a 2-D Y-Z slice through the body along a central profile is shown in model L in Fig. 4. The principal dimensions of the body are: depth to base: 1375 m; dip angle: 80^o; maximum width in X direction (N-S): 1300 m; in Y (E-W) direction: 250 m. Note that the body is directly below the overburden layer. Other 3-D models were constructed from this base one, by varying geometrical parameters, to study the effect of the length of the strike of the body.

Electromagnetic response of the model

The synthetic data were calculated using the 3-D forward code of Mackie et al. (1994), with the recent modifications of R. Mackie and J. Booker (pers. comm., 1999). The 3-D mesh was a compromise between model parameters (size and resistivity of body, its depth, overburden thickness and station locations) and computational limitations. In all cases, convergence was assured by increasing mesh size until the responses asymptoted to stable values. The final mesh size was 86 (E-W) x 99 (N-S) x 50 (vertical), with horizontal grid spacing in and near the body of 12.5 meters. The surface AMT responses at eleven frequencies (10,000 Hz - 0.4 Hz) were calculated. The validity of the 3-D responses was also tested by comparing the 3-D responses for a body with infinite length extent to 2-D responses derived using Wannamaker's code (Wannamaker et al., 1987). All models were calculated with the same mesh size. (For this mesh size the code required 1.5 Gb memory and 48 hours CPU time on a Sun Enterprise 450.)

Figure 3 shows the apparent resistivities and phases that would be obtained at stations located on a profile crossing the center of the body (Fig. 2) along the Y (E-W) direction. Although the body is 3-D, the X-direction can be considered the dominant "strike" direction given its elongated shape, and the XY data (RhoXY and PhaXY) are assumed to be quasi-TE-mode data, and the YX data (RhoYX and PhaYX) to be quasi-TM-mode data.

The most significant result is the behavior of the 3-D apparent resistivities at low frequencies; in the vicinity of the body they remain anomalously low compared with the 2-D response. The phases at sites over the body are high (near 78^o) but do not exceed 90^o. It is possible to fit each site's XY and YX data separately with different 1-D models, implying a causal relationship for this particular 3-D model. Causality is a necessary, but not sufficient, condition for the existence of an acceptable 2-D model: if the data were not causal, then no 2-D model could fit them.

2-D inversion of the 3-D data

Different 2-D inversion tests were made with various data subsets; inverting XY and YX data jointly, only XY or only YX, only phases or only resistivities, with different frequency ranges, and different site spacings. The inversions were undertaken using mainly RLM2DI (Rodi and Mackie, 2001). Smith and Booker's (1991) RRI code and Siripunvaraporn and Egbert's (2000) REBOCC code were also used, the latter to undertake joint inversion of XY, YX data and the vertical magnetic transfer function (TZ), and the models obtained were essentially similar to those from RLM2DI.

Table 1 summarizes the more significant tests and Fig. 4 presents the models obtained from 2-D inversion of the 3-D data from the central profile. The true 2-D section is shown in model L (Fig. 4), which is a Y-Z slice through the body along the central profile.

The best-fitting model obtained from joint inversion of all data did not yield a satisfactory fit; the final root mean square (RMS) misfit was 4.85. At frequencies <10 Hz, the XY data do not fit a 2-D model whereas the YX data do. The asymptotically decreasing RhoXY values at low frequencies at sites over the ore body (Fig. 3) are not compatible with a 2-D model. If the phases alone are inverted, a statistically satisfactory misfit can be achieved (RMS = 1.2), but the fit to the shapes of the phase curves is poor, suggesting that some data are overfit, whereas others are underfit. The inversion of YX apparent resistivities and alone produces a model with an acceptable misfit of 1.43 (case C, Fig. 4). Although the XY-data from each individual site can be fit with 1-D models, there is no 2-D model that can fit the XY-data alone; the best-fit model obtained (case D) has an RMS misfit of 9.56.

Other subsets were considered to study the effects of spatial sampling on resolution. The set “Body-l1”, with 16 sites (model G in Fig. 4), is obtained by doubling the spacing between the sites, and “Body-l1-2” is as “Body-l1” but without the sites over the body (models H to K). The results show that site spacing of ~½ of the body width is barely sufficient, and is a critical maximum limit. The misfit for set “Body-l1-2” is satisfactory, but, as there are no responses over the body, the final model shows weak detection of the body. The position and the top of the body are well resolved in contrast to the bottom and the resistivity of the body. These conclusions from RLM2DI were verified using RRI and REBOCC.

Table 1: 2-D inversions along the central profile

RLM2DI	Data inverted	iter	RMS	Case
Body-001 (22 sites, 50 m spacing over body) All frequencies	All	66	4.85	A
	Phases	28	1.2	B
	YX	62	1.43	C
	XY	19	9.56	D
Body-001 frequencies >10 Hz	All	49	3.98	E
Body-001 frequencies >100 Hz	All	53	2.85	F
Body-l1 (16 sites, 100 m spacing over body) All frequencies	All	76	4.59	G
Body-l1-2 (14 sites) All frequencies	All	86	3.76	H
	Phases	9	0.99	I
	XY	29	5.64	J
	YX	67	1.09	K

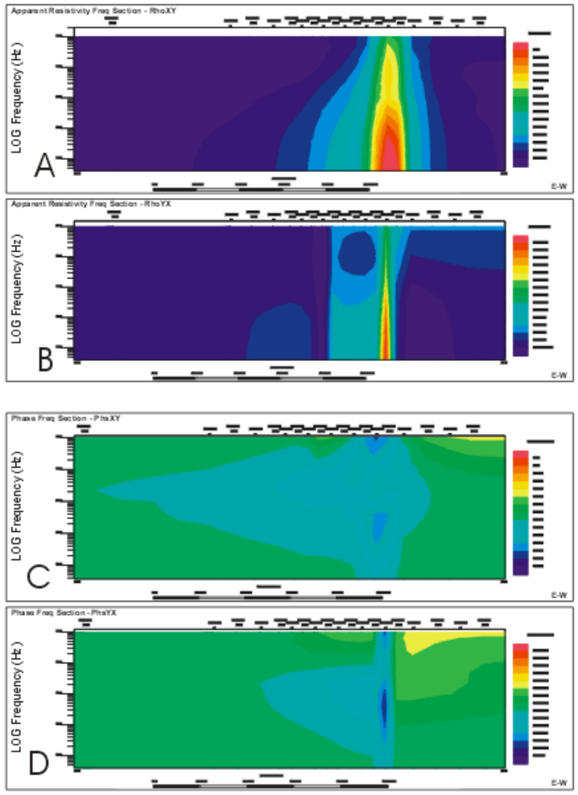

Figure 3: (A) RhoXY, (B) RhoYX, (C) PhaXY, (D) PhaYX, along an E-W central profile crossing the body.

Conclusions

From these initial results of our continuing study, we propose the following recommendations for the design of AMT surveys to detect and delineate ore bodies and for the interpretation of the acquired data.

For this 3-D body the anomalous horizontal magnetic field components are small compared to the 2-D case. Most of the anomalous response is in the electric field components. This suggests that an optimized field experiment could be planned with stationary magnetic sensors and multiple electric field measurements.

Site spacing must be sufficiently close to “see” the body; <½ the width of the body must be considered a maximum value for bodies similar to the one studied.

When interpreting data with a 2-D model, it must be kept in mind that the data corresponding to strike-parallel electric field (XY data in this example) are more sensitive to 3-D effects than YX data. If a 2-D inversion is attempted all the YX data can be considered when the profile crosses over the ore body, but only the high frequency XY data should be used. As a rule of thumb, frequencies down to one skin depth in the host can be used in TE, and to 1/10th of a skin depth in TM (Jones, 1983).

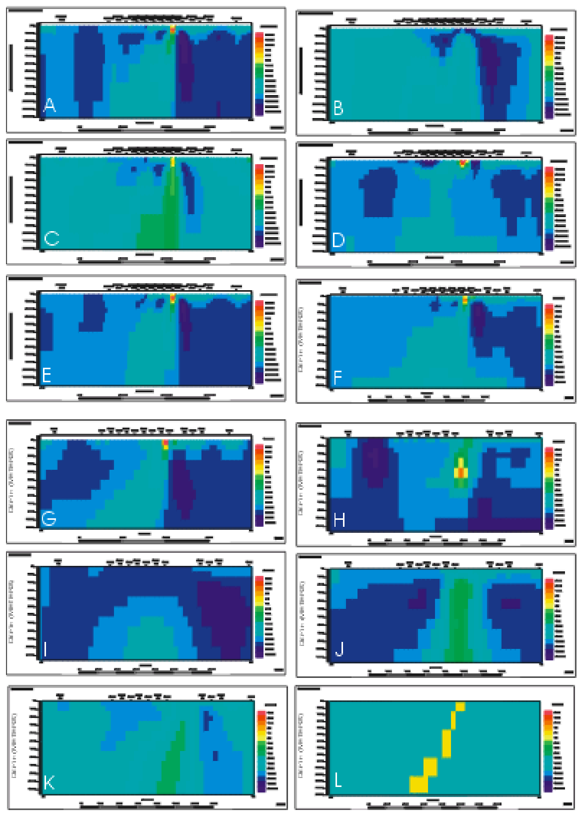

Figure 4: Final 2-D models obtained from 2-D inversion of 3-D data along the central profile. See Table 2 for details. The true 2-D section is shown in model L.

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