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Deep electromagnetic imaging of the Bathurst No. 12 deposit, New Brunswick: three-dimensional forward modelling, two-dimensional inversion, and sensitivity tests

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Abstract: 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 capabilities of audio-magnetotellurics (AMT) at locating and defining mineral targets at depth, 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 behaviour of 3-D electromagnetic fields is compared with ones from a body of infinite length extent (a two-dimensional case). The 3-D and 2-D AMT responses are similar at high frequencies so 2-D modelling is sufficient; however, at low frequencies only those responses for current flow perpendicular to the body (the Transverse Magnetic mode in a 2-D case) are reasonably alike. The different 2-D inversions carried out in this study show that the position and the top of the 3-D ore body are well resolved in contrast to the bottom and the resistivity of the body.

Résumé : Un modèle numérique tridimensionnel (3D) de la résistivité électrique du gîte Bathurst No. 12 (Nouveau-Brunswick) a été élaboré d'après l'information géologique et géophysique disponible. Ce modèle facilite les études de l'utilisation de l'audio-magnétotellurique (AMT) pour la localisation et la définition de cibles minéralisées en profondeur ainsi que la mise au point de méthodes d'optimisation de l'acquisition des données. Différentes conditions ont été analysées : présence de mort-terrain, dimensions et position du corps minéralisé et espacement de l'échantillonnage des données. Le comportement des champs électromagnétiques en 3D est comparé à celui d'un corps de longueur infinie (cas bidimensionnel). Aux hautes fréquences, les réponses AMT en 3D et en 2D sont semblables, de sorte que la modélisation 2D est suffisante. Cependant, aux basses fréquences, seules les réponses à des flux de courant perpendiculaires au corps minéralisé (mode magnétique transverse dans le cas 2D) sont raisonnablement semblables. Les différents essais d'inversion 2D des données 3D réalisés dans le cadre de cette étude révèlent une bonne détermination de la position et du sommet du corps minéralisé, comparativement à ce qui en est de la base et de la résistivité de celui-ci.

INTRODUCTION

Over the last half decade, the natural-source, audio-magnetotelluric (AMT) electromagnetic method has been used increasingly in Canada to detect mineral targets at depth, with acquisition at over 15 000 sites in principally Voisey Bay, Sudbury Basin, and Thompson Nickel Belt. In both Voisey Bay and Sudbury, AMT was able to define conductive targets at expected depths, and demonstrate that AMT can provide an efficient and useful tool for exploring conductive mining targets at depths beyond those conventionally targeted by EM methods (Zhang et al., 1998; X. Garcia and A.G. Jones, Paper contributed at European Geophysical Society XXVI General Assembly, Nice, France, 26–30 March, 2001; Garcia and Jones, in press); however, as well as detecting the presence of a body, we wish to evaluate the economic potential of a possible mining target by estimating its geometry and internal physical properties.

Thus, the main purpose of our research is to demonstrate that 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 (e.g. Livelybrooks et al., 1996); however, further work needs to be undertaken 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 modelling is essential, but reliable 3-D inversion algorithms that can be applied to observed data are not yet available. Thus, 2-D inversions of 3-D data are common, but their limitations are poorly understood. During the 1980s, when 3-D modelling began to be developed, papers were published studying 3-D effects (e.g. Wannamaker et al., 1984a, b), and, more recently, other studies have shown the main limitations of 2-D inversions of 3-D data (i.e. Garcia et al., 1999; J. Ledo, P. Queralt, A. Martí, and A.G. Jones, in press). All of these studies give recommendations to avoid 3-D effects in 1-D or 2-D interpretation, but these recommendations are not always taken into account. At this time, when AMT surveys are now used to search for deep ore bodies, interest in 3-D studies and 2-D limitations has returned, but the issue is no longer in terms of "how to avoid" 3-D effects, but rather "how to delineate" the 3-D bodies by their MT responses and how to handle 3-D effects.

Taking the above into consideration, there are three main questions to answer for the MT community. Is AMT currently able to determine the geometry of these ore bodies? What are the main difficulties? How we can improve field surveys and 3-D interpretations? To address these questions, we have constructed a realistic, complex, and detailed 3-D numerical model of a particular well known ore body and studied the AMT responses that would be obtained over it. Our aim is to provide recommendations for field survey design and data interpretation.

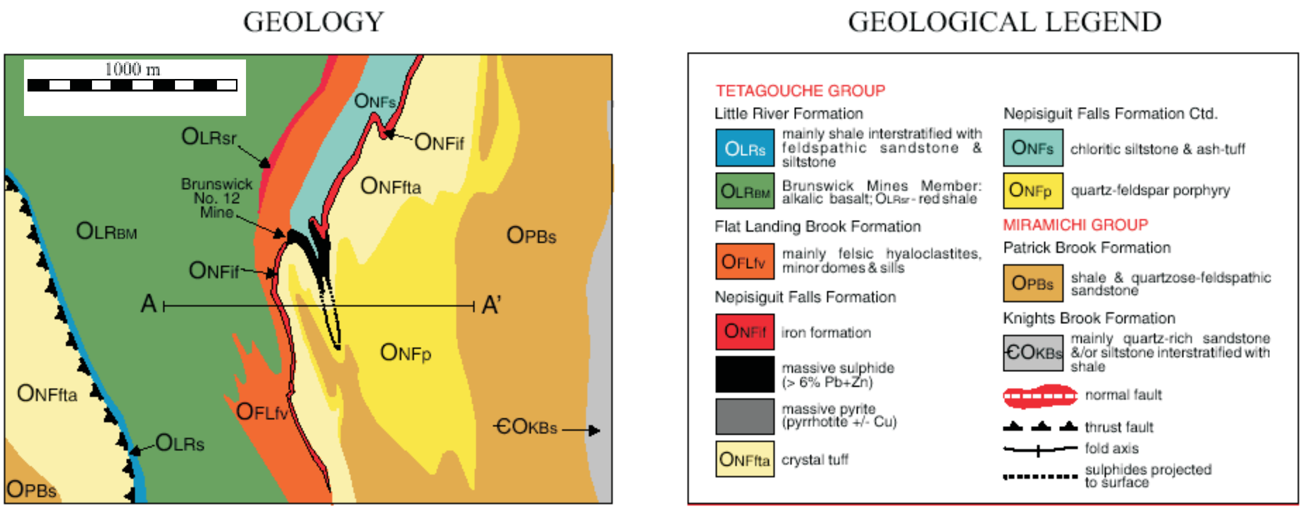
Our choice of an ore body for this study required as comprehensive an information base as possible, and that the information be in the public domain. Profiting from the recent and complete geological and geophysical information obtained at the Bathurst mining camp in New Brunswick (Thomas et al., 2000), we chose to simulate the Brunswick No. 12 deposit, which is one of the largest massive sulphide deposits in the area. By determining synthetic AMT responses of models of the Bathurst No. 12 deposit, for differing strike lengths and for different site sampling, we can investigate the main caveats of 2-D interpretation of 3-D data in a mining environment.

DESIGN OF THE 3-D MODEL

Figure 1 shows the geological map and a cross-section of the Brunswick No.12 deposit obtained from Thomas et al. (2000). The design of the 3-D numerical model took into account geophysical and geological information in Thomas et al. (2000) and references therein. Following Katsube et al. (1997), zones of different resistivity, corresponding to different host rocks, have been modelled; however, herein we present only the simplest case, comprising a conductive homogeneous ore body embedded in a resistive homogeneous half space. A thin overburden (thickness of 9 m) covers the body as well as the eastern part of the model. The shape of the body is irregular and was inferred from the plan views of the deposit at eight different depths, obtained from Luff et al. (1992). Figure 2 shows a sketch of the constructed ore body (note: not on equal length scales), and a 2-D Y-Z slice through the body along the profile in Figure 2 is shown in model L in Figure 4 (*see* Fig. 4, *below*). The principal dimensions of the body are: depth to base: 1375 m; dip angle: 80E; maximum width in X direction (north-south) is 1300 m and in Y (E-W) direction is 250 m. Note that the body is outcropping, i.e. directly below the sedimentary layer. Other 3-D models were constructed from this base one by varying geometrical parameters. These models were used to study the effect of the length of the strike of the body. Table 1 lists a summary of these different 3-D models.

Table 1. Summary of the different 3-D models considered.

3-D model	Y:X (strike)	Parameters
Body	1:4	Body: 2 Ω·m Hosting rocks: 1000 Ω·m Overburden of 100 Ω·m and 9 m thick Maximum depth z_{max} = 1375 m
Body-10	1:10	
Body-2-D	1:infinite	
Body-x	1:40	
Body-x2	1:2	
Body-z	1:4	As first case but z_{max}= 1125 m
Body-z2	1:4	As first case but z_{max}= 850 m
Bth-1bis	1:4	Body: 2 Ω·m Hosting rocks: 1000 Ω·m Without overburden Maximum depth z_{max} = 1375 m
Body-over	1:4	Body: 2 Ω·m Hosting rocks: 1000 Ω Overburden of 100 Ω·m and 75 m thick Maximum depth z_{max} = 1375 m



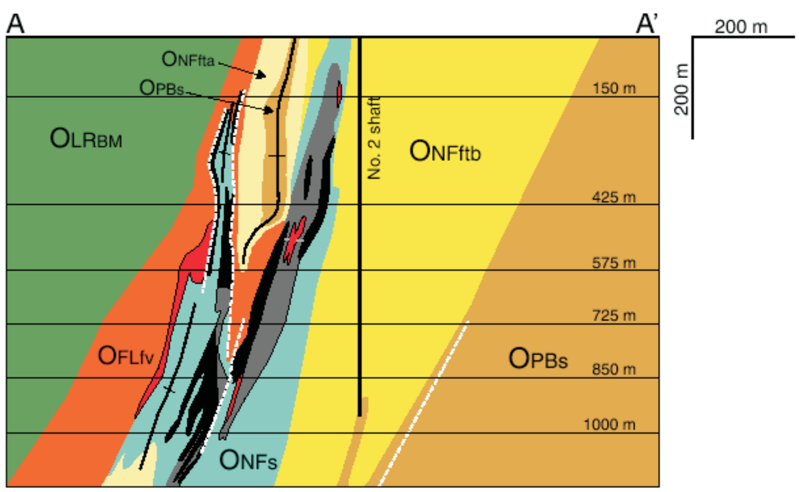


Figure 1.

Geology map and section of the Bathurst No. 12 deposit from Thomas et al. (2000).

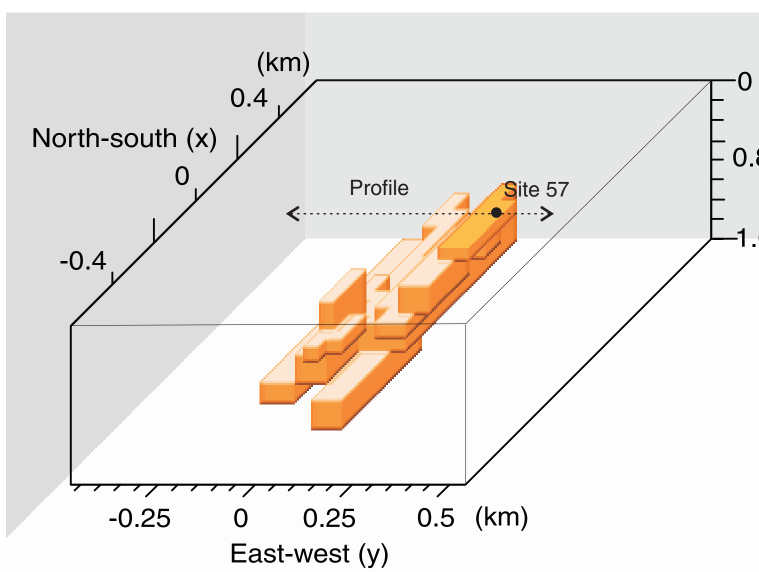


Figure 2.

Sketch of the ore body model used in this study. The profile of the 2-D models obtained, and the location of site 57, are shown.

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 used was a compromise between the model physical parameters (size of body and conductivity, its depth, the overburden thickness, and the station locations) and computational limitations. In all cases, convergence of the response was assured by increasing mesh size until the responses asymptotically reached stable values. The final mesh size was 86 (east-west) x 99 (north-south) x 50 (vertical), with a horizontal grid spacing in and close to the body of 12.5 m. The surface AMT synthetic responses at eleven periods between 10 000 Hz and 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 the 3-D models listed in Table 1 were calculated with the same mesh size. (For this mesh size, the 3-D code needs 1.5 Gb memory (RAM) and takes 48 hours to calculate the response at eleven frequencies.)

As a further test, a new proprietary version of the 3-D code (R. Mackie, pers. comm., 2001) was obtained and responses derived. The responses obtained using this new version were not significantly different from those from the public version, although the computing time increased drastically.

Figure 3 shows the apparent resistivities and phases, plotted as pseudosections with decreasing frequency down the ordinates to represent increasing depth, that would be obtained at stations located on a profile crossing the centre of the body (*see* Fig. 2) along the Y (east-west) direction. This model is named "Body" in Table 1. Although the body is 3-D, the X-direction can be considered as the dominant "strike" direction given its elongated shape. The XY data (RhoXY and PhaXY) are obtained from the ratio between the electric field in the X direction to the magnetic field measured in the Y direction. Conversely, the YX data (RhoYX and PhaYX) are obtained from the ratio between the electric field in the Y direction and the magnetic field in the X direction.

The most significant result is the behaviour of the RhoXY apparent resistivities at low frequencies; in the vicinity of the body they remain anomalously low compared with what would be obtained for a body with infinite length extent, i.e. the 2-D response. The phases at sites over the body are high (near 78°) but do not go out of the first quadrant (0°–90°). It is possible to fit XY and YX data separately with different 1-D models, which means that there is a special mathematical and physical relationship between the apparent resistivities and the phases at each site for this particular 3-D model. That they do obey this relationship, called causality or Hilbert transformation, is a necessary, but not sufficient, condition for the existence of an acceptable 2-D model. The important point is that if the data did not obey this relationship, then it would be impossible to fit them with a 2-D model, no matter how extreme.

TWO-DIMENSIONAL INVERSION OF THE THREE-DIMENSIONAL DATA

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

Table 2 summarizes the most significant tests and Figure 4 presents the models obtained. The true 2-D section is shown in model L of Figure 4, which is a Y-Z slice through the body along the profile. All the cases presented here correspond to inverted 3-D data of the central profile, and the models obtained should be compared with the 2-D slice in model L. The set called "Body-001" includes all 22 sites of this central profile. The best-fitting model obtained from joint inversion of all data and all periods did not yield a satisfactory fit; the

Table 2. Two-dimensional inversions of the central profile.

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

final root mean square (RMS) misfit between the synthetic 3-D responses and the 2-D model ones was 4.85 (a value of unity signifies a fit to within statistical tolerances). At frequencies below 10 Hz, the XY data do not fit with a 2-D model whereas the YX data do. The asymptotically decreasing RhoXY apparent resistivities at low frequencies seen in Figure 3 at the sites located over the ore body are not compatible with a 2-D model. If the phases alone are inverted, the RMS misfit that can be achieved is statistically satisfactory (RMS = 1.2), but the fit of the phase curves is poor. This suggests that some parts of the data are overfit, whereas others are underfit — a problem with correlated misfit residuals. The

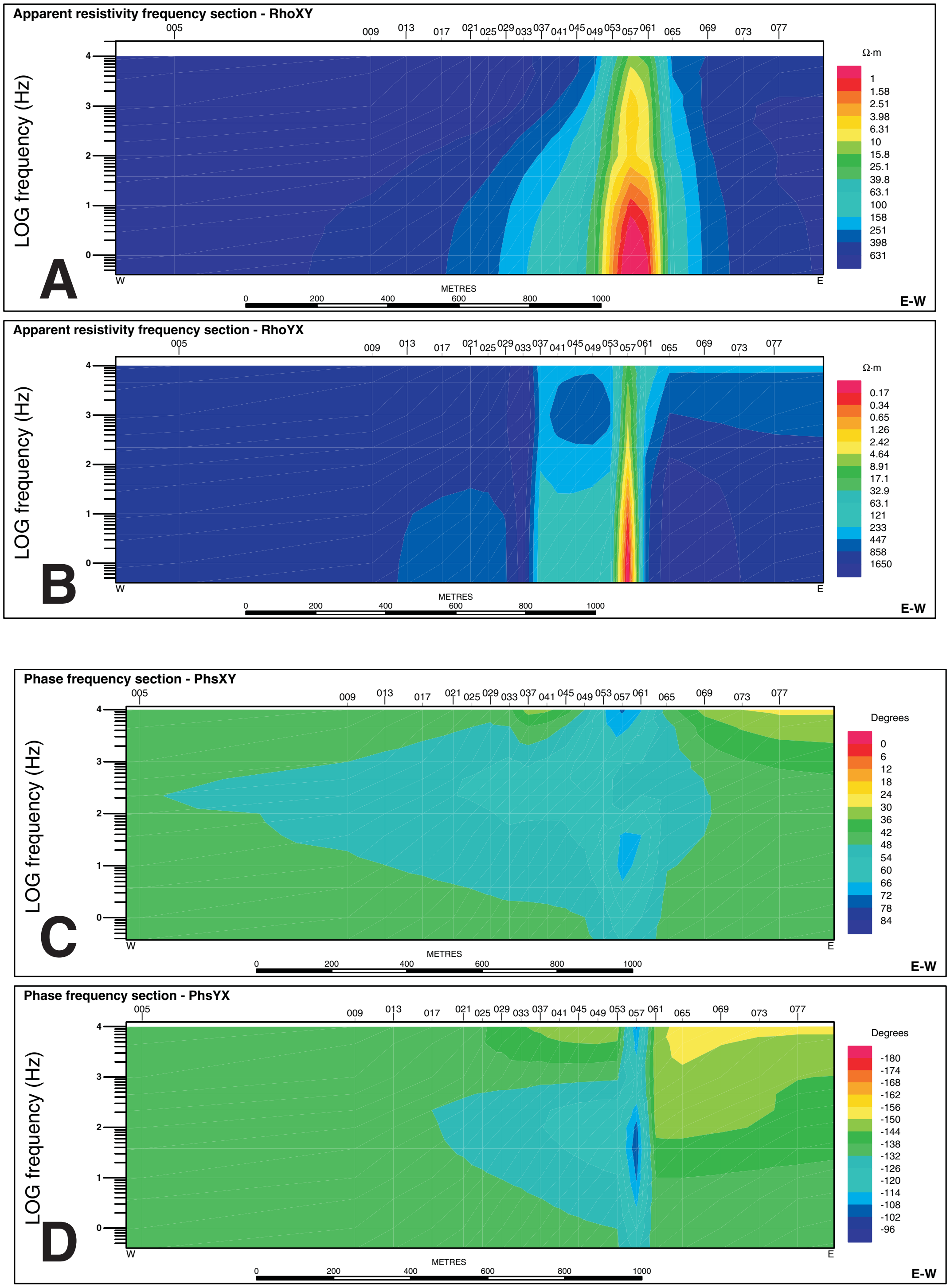


Figure 3. ***A***), ***B***) *Apparent resistivities;* ***C***), ***D***) *phases, across an east-west central profile crossing the ore body.*

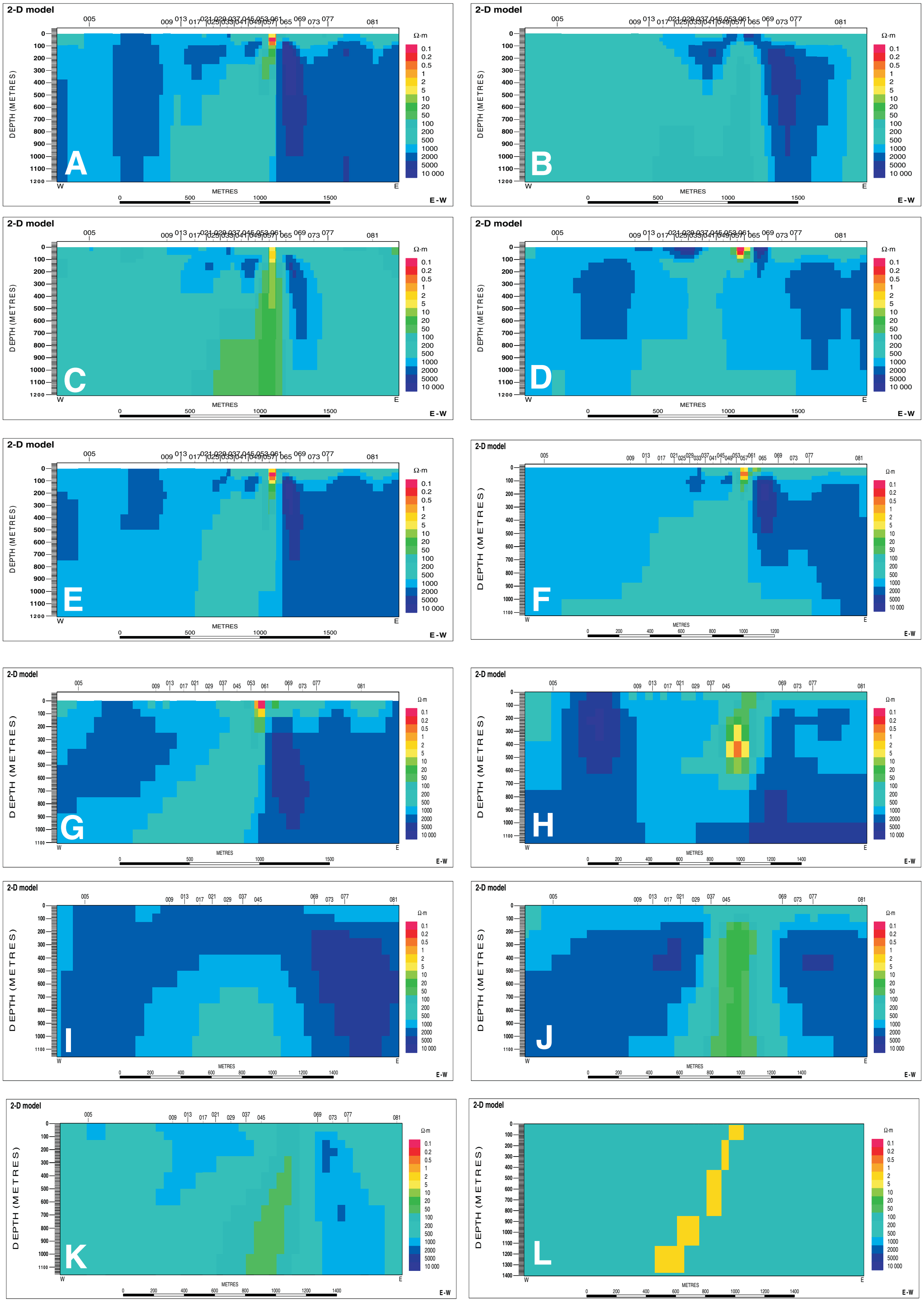


Figure 4. Key 2-D models obtained from the inversion of 3-D data along the central profile. See *Table 2 for details. The true 2-D section is shown in model L.*

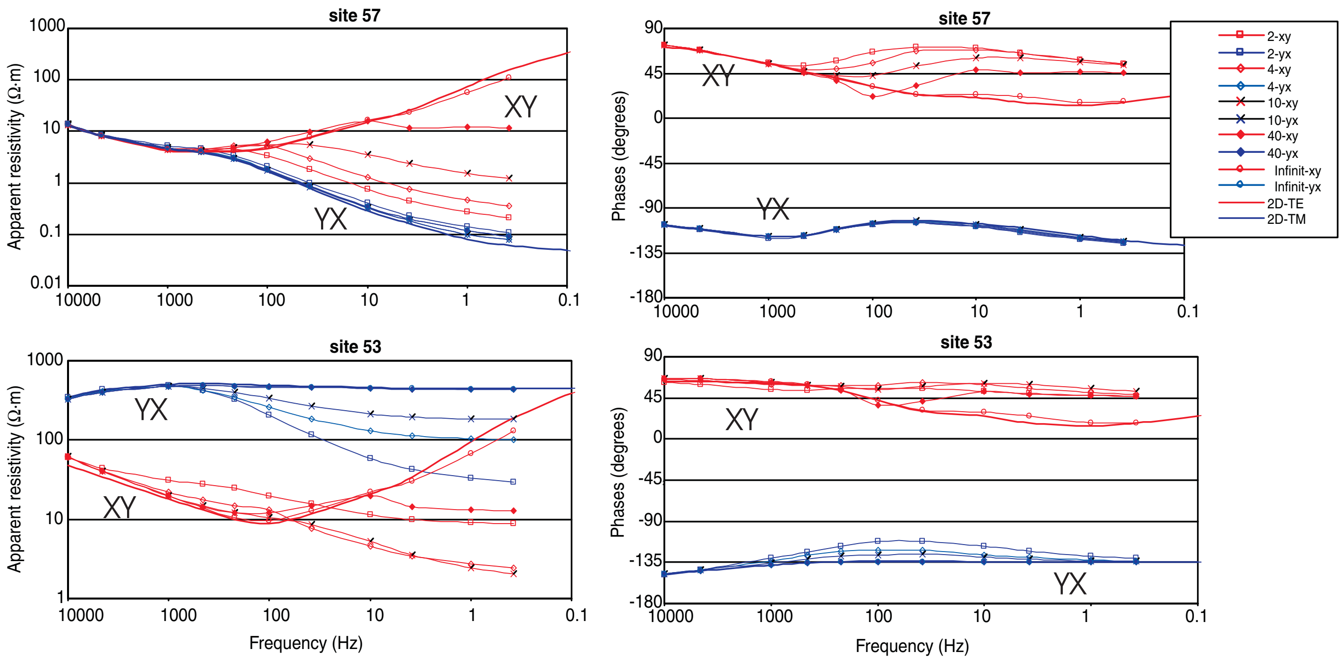


Figure 5. *Comparison of the responses for different 3-D models at two sites. Site 57 just over the body and at site 53, 50 m away. The figures in the legend indicated the length of the strike (X:Y). The label "2D" indicates the responses calculated by the 2-D forward code.*

inversion of apparent resistivities and phases corresponding to the YX data alone produce a model with an acceptable final RMS misfit of 1.43 (case C, Fig. 4); however, 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 inversions were performed using subsets of the high-frequency data. Using data above 10 Hz resulted in a final model with an RMS misfit of 3.98. Using only the data above 100 Hz (case F) shows a good fit to the data with an RMS misfit of 2.85.

In order to study the effects on resolution of spatial sampling, other subsets were considered. The set "Body-l1", with 16 sites (model G in Fig. 4), is obtained from the former one by doubling the spacing between the sites, and set "Body-l1-2" is the same as "Body-l1", but without the sites located over the body (models H to K). The results show that a sampling equal to approximately half of the body width is barely sufficient, and is a critical limit. The RMS misfit for the inversion of set "Body-l1-2" is satisfactory, but as the responses over the body are not inverted, the final model shows weak evidence of the body. Although the inversion strategy is different for every 2-D inversion code, the former comments referring to RLM2DI code were verified using the RRI and REBOCC codes. Moreover, the final models are similar. The position and the top of the body are well resolved in contrast to the bottom and the resistivity of the body.

BEHAVIOUR OF THE 3-D RESPONSES AND COMPARISON WITH THE 2-D RESPONSES

Figure 5 shows the apparent resistivities and phases for two sites along the central profile. Site 57 is located just over the ore body and site 53 is located 50 m to the east. At site 57 there is a contrast between the XY and YX data because the XY data are sensitive to the length of strike of the body, whereas the YX data are not. This behaviour holds for both apparent resistivities and phases. For site 53 both XY and YX data are sensitive to strike length. At high frequencies (above 100 Hz) the behaviour of the 2-D and 3-D responses are similar with the phases rising to 78° at 10 000 Hz. At lower frequencies, the 3-D YX data behave as the 2-D model (rising again up to 78°) but the XY data are completely different.

CONCLUSIONS

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

In these preliminary numerical studies there is only a small to negligible effect observed in the horizontal magnetic field components due to the presence of the body: the anomalous effect is almost solely in the electric field components. This suggests that to optimize the field experiment the magnetic sensors can remain in one location and multiple electric field measurements be made.

The site spacing must be close enough to 'see' the body; less than one-half of the estimated width of the body must be considered as a maximum value for bodies similar to the one studied.

When interpreting the data obtained with a 2-D model, it must be kept in mind that the data corresponding to the electric field measured parallel to the strike direction of the ore body (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 can be used.

For future work, we will consider studies with a nonuniform conductivity for the body and a halo zone.

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