Three-dimensional inversion of magnetotelluric data for mineral exploration: An example from the McArthur River uranium deposit, Saskatchewan, Canada.

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ABSTRACT

Blurb.

INTRODUCTION

A general trend in the mining industry is exploration for deeper targets. This is in response to the diminishing number of shallow, easily detected ore-bodies which remain to be discovered. The data-set considered here was acquired as part of the EXTECH IV project which investigated the applicability of various exploration methods for detecting and delineating deep uranium deposits in the Athabasca Basin of Saskatchewan and Alberta, Canada (see, for example, Jefferson et al., 2003). This multidisciplinary project was funded by the federal government of Canada, the provincial governments of Saskatchewan and Alberta, and uranium mining companies with operations in the Athabasca Basin. The desire was to ensure the future of uranium mining in the region, and thus the economic viability of the affected communities.

Uranium deposits are often linked to graphite. In the Athabasca Basin, the uranium is typically found at or close to locations where graphite concentrations associated with steeply dipping faults in the metamorphic basement rocks meet the unconformity between the sandstones of the basin and the basement (see, for example, Jefferson et al. 2006). The depth of the unconformity, and hence depths of possible ore-bodies, varies from 100 to 200 m at the known deposits at the eastern margin of the basin, to about 1.5 km in the centre of the basin. The deposit at the McArthur River mine is between 500 and 600 m deep. The spatial correlation of the uranium deposits with zones of graphite, and the high conductivities of the graphitic zones relative to both the metamorphic rocks of the basement and the sedimentary rocks of the basin, has meant that electromagnetic
techniques have been the favoured methods when prospecting for further deposits. This continues to be the case. For example, the use of new airborne time-domain electromagnetic systems to efficiently investigate the upper two or three hundred metres of the subsurface around the edges of the Athabasca Basin (Cristall and Brisbin, 2006), and the use of audio-magnetotellurics (AMT) to investigate down to depths of 500 m to 1.5 km towards the centre of the Basin (Craven et al., 2002; Leppin and Goldak, 2005; Tuncer et al., 2006).

Three-dimensional inversion of magnetotelluric (MT) data is becoming practicable. A number of inversion programs have been developed (Newman and Alumbaugh, 2000; Zhdanov et al., 2000; Mackie et al., 2001; Farquharson et al., 2002; Sasaki, 2004; Siripunvaraporn et al., 2005), and examples have been presented for mineral and geothermal exploration (Zhdanov et al., 2000; Mackie et al., 2001; Uchida et al., 2001; Farquharson et al., 2004). The data-set considered here was chosen for a further example for mineral exploration in general, and for uranium exploration in the Athabasca Basin in particular. The data were collected along a series of lines whose separations were only about two to four times greater than the spacing of the measurement locations along the lines. Data coverage over the approximately 5 by 8 km rectangular survey area was thus more uniform than is typically the case, meaning the data-set is well suited to interpretation and modelling as a whole. Also, the quality of the data is excellent. The particular question of interest in this study was how many of the data processing steps and compromises required by the current standard practice of line-by-line 2-D inversions are made redundant if 3-D inversion is used. Specifically, the form of the data used in the inversions presented here were simply the real and imaginary parts of all four elements of the impedance tensor, and the impedance tensor was with respect to an east-west–north-south coordinate system (that is, one not rotated to align with the approximate geological trend of the region). Impedances are, at least in principle, more desirable as data in the inversions than apparent resistivities and phases because their relationship to the conductivities in the Earth model are less nonlinear. Tensor decomposition and rotation to isolate sub-sets of the data that are consistent with 2-D inversion can be difficult, especially in typical exploration situations where the subsurface can be far from 2-D, and can lead to significant amounts of data being omitted from inversions. Also, in the inversions presented here, the data were not corrected for static shifts, nor were static shifts incorporated into the inversions. This was to test whether or not near-surface structure in the constructed models was meaningful or just “noise”, and to what extent deeper features were affected by this.
GEOLOGICAL SETTING

The data-set considered here is from the area around the McArthur River uranium mine in Saskatchewan, Canada (Figure 1). The mine is situated in the eastern part of the Athabasca Basin. This is a siliciclastic basin of relatively flat-lying, un-metamorphosed, late Paleoproterozoic to Mesoproterozoic strata mainly fluvial in origin (Jefferson et al., 2006; Figure 2). The basin unconformably overlies metamorphic basement comprising tectonically interleaved Paleoproterozoic metasedimentary and Archean to Proterozoic granitoid rocks. The McArthur River deposit is in a region underlain by the Wollaston and Mudjatik basement domains. Zones of graphitic metapelite are also present in the basement. These are correlated with both shear zones and ore deposits. The setting of the McArthur River uranium deposit is typical of unconformity associated deposits found worldwide.

The conventional model for deposits such as the one at McArthur River involves the mixing at the unconformity of oxidizing, uranium-rich basin fluids with reducing basement fluids circulating upwards along reactivated basement structures (Jefferson et al., 2006). The basin fluids react with basement graphite, causing precipitation of the uranium. The precipitation is localized to the intersection of the unconformity with graphitic shear zones in the basement. The sites of precipitation remain fixed for long periods of time, perhaps hundreds of millions of years. In addition, the precipitation zones are characterized by silicified caps and alteration halos that contain clay minerals including illite and kaolinite.

Figure 3 shows a schematic diagram of the McArthur River deposit. The unconformity between the sandstones of the Athabasca Group and the basement metamorphic rocks is between 500 and 600 m depth. The graphitic shear zone in the basement extends for several kilometres into and out of the plane of the figure. The uranium ore, however, occurs as a pod. It and the associated silicified cap and clay alteration zone only extend for tens of metres into and out of the plane of the diagram. The main, large-scale features can therefore be considered as fairly 2-D. But the uranium deposit and the associated mineralized zones, which are ultimately what is of interest, are definitely three-dimensional.

The concentration of graphite in the basement fault (Figure 3) means its conductivity ranges from 0.01 to 1 S/m (personal communication, Brian Powell, Jamin Cristall). This fault therefore gives the most noticeable feature in the MT data. In general, both the basin sandstone and the
basement metamorphic rocks are resistive by comparison, with resistivities greater than $10^3 \, \Omega \text{m}$. Increased graphite content on either side of the basement fault can increase the conductivities close to it. Also, the uranium deposit has a silicified cap, which is very resistive, and a surrounding zone of clay alteration, which can have an elevated conductivity relative to the unaltered basin rocks. The uranium deposit itself is too small to detect with MT data. However, the graphitic fault is easily detected, and it may be possible to distinguish a zone of increase conductivity associated with the clay mineralization. This clay mineralization is strongly correlated with the occurrence of uranium deposits along the graphitic basement fault, and could therefore provide the best means of locating further uranium deposits.

THE AMT DATA-SET

The data-set considered here was acquired at 135 locations distributed along 11 lines (Craven et al., 2003). The average spacing of measurement locations along the lines was 300 m. The average separation between the lines was approximately 800 m. The lines were oriented north-west–south-east to be perpendicular to the general strike of the graphitic basement fault zone. The survey area was a rectangle approximately 5 by 8 km. (The measurement locations can be seen in Figure 4.) Data were acquired in the frequency range 1 to 20,000 Hz using three Metronix 24-bit ADU-06 systems, one of which was deployed in a culturally quite location and used as a fixed reference, and using orthogonal 50 m dipoles and orthogonal magnetic field sensors. A strong harmonic noise source was apparent in the time series recorded at each site. Its origin is unknown, but was perhaps related to operations at the mine. The effects of this noise were removed with tuned comb filters, and robust MT responses were calculated using the technique of Larsen et al. (1996). The resulting data were of extremely good quality.

This data-set has previously been studied by Tuncer et al. (2006). They performed line-by-line 2-D inversions. The constructed sections showed conductive regions corresponding to the steeply dipping graphitic fault zones in the basement. These conductive features were fairly persistent from one section to the next, although their shape and depth extent did vary. Tuncer et al. also carried out 3-D forward modelling and inversion on the data-set. Although there were discrepancies between the 2-D and 3-D inversion results, Tuncer et al. concluded that neither did the 3-D results provide any information not present in the 2-D results, nor did they contradict the 2-D results.
INVERSION RESULTS

The 3-D inversion program used here is that of Farquharson et al. (2002). The inversion algorithm is a standard minimum-structure, Gauss-Newton algorithm. The program is parallelized to enable the computations for different frequencies to be done on different processors. The inversions were run on the 42 node cluster of the Geological Survey of Canada, Ottawa.

Impedances had been calculated for 40 frequencies ranging from 1 Hz to 20 kHz. For the inversions, 11 frequencies were chosen: 3.8, 7.0, 15.2, 31.8, 50.8, 71.3, 97.4, 177, 335, 637, and 1280 Hz. It was considered that a more closely spaced set of frequencies would not significantly add to the information content of the data-set being inverted, certainly given the crude discretization of the Earth model that the computational resources, although impressive, necessitated. Also, frequencies higher than 1280 Hz were difficult to model using the mesh which was chosen for the 3-D inversions.

The design of the mesh for the conductivity model of the subsurface necessarily involved a number of compromises. The chosen mesh comprised 60 × 70 × 40 cells in the west-east, north-south and vertical directions. (The mesh was not rotated to align with the average direction of the survey lines.) The centre of the mesh where the horizontal dimensions of the cells were all the same comprised 40 × 50 × 40 cells. The cell dimensions (in the layer of cells immediately beneath the Earth-air interface) in this region were 200 × 200 × 50 m. The lateral extents of the padding cells, 10 in each of the west, east, south, and north directions, increased by a factor of 1.1. The vertical extents of the cells increased by a factor of 1.1 from the 50 extent of the first plane of cells in the subsurface. There were 10 planes of padding cells up into the air whose vertical extents increased by a factor of 1.5. This mesh design was a compromise between a number of factors: (i) wanting the cell dimensions in the centre of the mesh to be less than the skin depth in conductive regions for the highest frequency considered; (ii) wanting the boundaries of the mesh to be further away from the central region than a skin depth in resistive regions for the lowest frequency considered; (iii) wanting the rate at which the cell dimensions increase into the padding zones, and the aspect ratios of the cells, to be small; and (iv) requiring that the storage for the model parameters and electric and magnetic fields (or vector and scalar potentials) for the mesh fit into the available computer memory. The most notable compromise was not having sufficiently small cells to model frequencies higher than 1280 Hz.
For the inversions discussed here, the starting model was a homogeneous halfspace of \(10^{-4}\) S/m. The coefficients of the “smallest” component of the measure of model structure (that is, the component measuring the closeness to the reference model), and those involving the east-west, north-south and vertical spatial finite differences were \(10^{-15}\), 1, 1, and 1, respectively. The reference model was a homogeneous halfspace of \(10^{-4}\) S/m, although the coefficient of this component of the measure of model structure makes the role of the reference model minimal. The trade-off parameter in the inversion algorithm follows a user-prescribed cooling schedule. Typically, six iterations were performed at a fixed value of the trade-off parameter, then its value was halved and the process repeated. This gives a procedure in which structure gradually appears and evolves in the model. The observations were assumed to be on a flat Earth-air interface. This is a small approximation as topography of the region around the McArthur River mine varied over only a couple of hundred metres. Finally, the variances generated from the processing used to calculate the impedances were used directly as the variances of the observations in the inversions.

Initially, inversions were carried out on individual frequencies, then on sub-sets of two and five frequencies. The results of these are not discussed here. However, their results were sufficiently encouraging that a sequence of inversions were carried out using the 11 frequencies listed above. It is the results from this that are presented here.

Figure 4 shows maps of the observed values of the real and imaginary parts of all four elements of the impedance tensor, and corresponding maps for the data computed for the final model in the inversion. (The circles on the maps indicate the measurement locations.) All 11 frequencies are shown at present; for the submitted manuscript, a selection of only two or three frequencies will be included. (It should be noted that not all frequencies were available at all the observation locations.) The correspondence between the observed and predicted data is visually good. This is true for all frequencies, for both the diagonal and off-diagonal elements of the impedance tensor, and for the real and imaginary parts of the impedances. The total number of data in the inversion was 10,040; the \(\chi^2\) measure of misfit for the final model was \(1.63 \times 10^6\). Although this is more than two orders of magnitude larger than the theoretical target misfit (which is equal to the number of observations), the fit between observed and predicted data shown in Figure 4 was considered satisfactory, especially given the coarser than ideal mesh. It is clear from the maps in Figure 4 that there is a general south-west–north-east trend to the features in the observations. However, there is also a significant amount of variation in these features along this trend.
Figure 5 shows the first horizontal layers below the Earth-air interface in the final conductivity model. The area of the images corresponds to the area shown in the data maps in Figure 4. That is, the panels in Figure 5 show the central area of the mesh comprising 40×50 cells, with the 10 planes of padding cells in each of the west, south, east and north directions not included in the images. The depths listed at the top of each panel is the depth in metres of the layer beneath the Earth-air interface. The colour scale for conductivity has units of S/m.

The top five layers (corresponding to the upper 300 m) of the model are dominated by what could be considered to be noise. This can possibly be attributed to static shift effects in the data. It is not clear whether this part of the model contains any meaningful information about the near-surface structure.

Between about 300 m and 1 km depths, the most noticeable pattern is the sequence of resistive bands that align with the gaps between the survey lines. It is thought that the data are essentially not sensitive to these parts of the model: the higher frequencies are influenced by cells closer to the observation locations, and the lower frequencies are more sensitive to cells at depth, not those off to the side of the observation locations. The more conductive areas in the model directly beneath the survey lines are a result of either genuine near-surface information or static shift distortion. No such information content or distortion is linked to the near-surface cells between the lines meaning the inversion assigns them conductivities which are commensurate with the Athabasca Basin sedimentary rocks.

Below about 700 m, and clearly below 1 km, an elongated conductive zone becomes apparent under the central and southern parts of the survey area, and a more localized conductive zone is present under the northern corner of the survey grid. The first of these two features corresponds to the graphitic fault zone in the basement. The conductive zone in the model initially exists in two distinct parts, before coalescing into a single linear feature at about 1.6 km. This may be influenced by the minimum-structure nature of the inversion algorithm, but is consistent with the variability of the observations from one survey line to the next. The second, localized conductive feature under the northern corner of the survey area corresponds to a second graphitic basement fault. This appears as a localized feature in the model because its influence is only present in observations from a small number of sites.
Figure 6 shows a sequence of vertical slices through the final conductivity model. The sequence progresses from the south-west corner of the area of the panels in Figure 5. The separation between slices is $\sqrt{2} \times 200$ m. The bottom 10 layers of cells are not included (neither are the 10 layers of padding cells in the air). The slices therefore extend from the surface to a depth of 2.9 km. The conductive zone associated with the graphitic basement fault is again clear. The south-eastward dip of the fault is apparent in these images. Conductive features at the northern and south-eastern extremities of the survey area are also visible, the northern one corresponding to the second graphitic basement fault. All these deep conductive features do not extend above depths of about 500 m to 1 km. The conductive features in the upper few hundred metres beneath the survey lines do appear to have a plausible structure to them which may suggest they are related to real subsurface features as opposed to being artifacts in the model because of static shift effects. Of course, the features in the model, especially those at depth, are very poorly resolve, both because of the nature of MT data, and because of the inherent smoothing tendencies of the minimum-structure inversion algorithm.

CONCLUSIONS

Impedances worked rather nicely. All elements, although unclear yet as to what the contribution of the diagonal elements was.

Near-surface structure in model, unclear to what extent this is believable, semi-believable, or just ends up being “noise” in the model. Intermediate and deep depths look good, so even if near-surface stuff is just “noise” doesn’t seem to adversely affect rest of model. Gaps in near-surface structure between lines: puzzling, but could just be that these parts of the model are not influencing the observations, and so revert to reference model (despite minimal influence of reference model in inversion).

Results of 3-D inversion somewhat different from 2-D results, and their inherent assumption of along-strike invariance. Features in 3-D inversion result come and go along strike, pretty much following the structure to be seen in the maps of the observations. And are probably a more faithful representation of the subsurface than what one achieves by implicit interpolation between 2-D inverted sections.

Conclusions about actual structure in model and how it relates to geology in the McArthur River area.
ACKNOWLEDGMENTS

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REFERENCES


Figure 1. The location of the McArthur River mine in Saskatchewan, Canada.
Figure 2. Geological map of the Athabasca Basin (from Jefferson et al., 2006). A much simpler map would be better.
Figure 3. Schematic geological section of the McArthur River uranium deposit. The graphitic fault zone extends for several kilometres into and out of the plane of the diagram; the uranium pod only extends tens of metres into and out of the diagram. (Personal communication, Jamin Cristall, Brian Powell.) *I shall make a publication-quality copy of this.*
Figure 4. Maps of the observations (left) and the predicted data for the final 3-D inversion result (right) for 3.8 Hz. The units for the impedance values are V/A. The observation locations are indicated by the circles. (Not all frequencies were available at all observations locations.)
Figure 4 (contd.).
Figure 4 (contd.).
31.8Hz, observed

31.8Hz, predicted

Figure 4 (contd.).
Figure 4 (contd.).
71.3Hz, observed

71.3Hz, predicted

Figure 4 (contd.).
Figure 4 (contd.).
Figure 4 (contd.).
Figure 4 (contd.).
Figure 4 (contd.).
3-D MT inversion, McArthur River uranium deposit.

Figure 4 (contd.).
Figure 5. Horizontal slices through the final 3-D conductivity model. The ?24? slices correspond to the upper ?24? layers of cells in the model. The area of the plots is the same as that for the data maps in Figure 4. The 10 planes of padding cells in each of the west, east, south and north directions are not shown here. The area shown correspond to 40×50 cells. The units for the colour scale are S/m.
Figure 5 (contd.).
Figure 5 (contd.).
Figure 5 (contd.).
Figure 6. Vertical slices through the final conductivity model. The sequence of slices moves from the south-west to the north-east corners of the part of the model shown in Figure 5. The separation between slices is $\sqrt{2} \times 200$ m. The bottom 10 layers in the model, and the 10 layers of padding cells in the air, are not shown. The depth range of these vertical slices is therefore from 0 to 2.9 km. There is no vertical exaggeration. The colour scale for conductivity is the same as that for Figure 5.
Figure 6 (contd.).
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Figure 6 (contd.).