Magnetotelluric Investigation at McArthur River – A Preliminary Look at the Data

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Abstract

Fifteen audiomagnetotelluric (AMT) sites were located across the strike of the P2 Zone deposit at McArthur River to investigate the utility of modern AMT acquisition hardware and processing methodologies to image deep graphitic conductors that are commonly associated with major uranium ore bodies. AMT acquisition was undertaken in March of 2001 by Geosystem Canada Inc. and sites were accessed by a three man crew using snowmobiles and snowshoes. Each AMT site installation consisted of electrodes and induction coils that sample the Earth's natural electric and magnetic fields. High electrode contact resistance was encountered during the survey due to a thick frost layer. Initial processing of the data however suggests the dominant problem may be the low signal-to-noise ratio in the AMT band between 2 to 8 kHz. Preliminary analysis of the data at frequencies below 2 kHz indicates conductive structures at depths of 500 m in agreement with previous electromagnetic work in the area and known depth to basement estimates from borehole data. The preliminary images of subsurface electrical structure based on the AMT data also indicate a southeast dip in the basement consistent with geological sections in the area. The electromagnetic data suggest the presence of a deeper conductive feature southeast of the main P2 Zone conductor, although the site spacing is larger in the vicinity of the deeper conductor than in the vicinity of the P2 Zone conductor. The preliminary conclusion at this time is that AMT is a practical technique for exploration in the Athabasca Basin for conductors similar in nature to the P2 Zone.

1. Introduction

In March 2001, as part of the EXTECH IV project, an audiomagnetotelluric (AMT) survey was undertaken at McArthur River to assess: 1) the costs and benefits of utilizing state-of-the-art 24-bit acquisition systems for exploration in the Athabasca Basin; 2) the ability of modern data processing and inversion schemes to provide reliable subsurface images of the electrical conductivity structure in the Athabasca Basin; and 3) the applicability of surface sounding to infer subsurface regional fluid flow parameters of use to modern heat and fluid flow exploration models for the Basin.

AMT and controlled source AMT (CSAMT) studies have been conducted within the Athabasca Basin in the past (Matthews *et al.,* 1997). The spatial association of graphitic conductors (McMullan *et al.*, 1987; Madore and Annesley, 1997) with high-grade uranium deposits is the primary motivation for the use of EM techniques (McCready *et al.*, 1999). There are few published models and detailed interpretations of AMT data, collected within the Athabasca Basin to image the deep graphitic units. AMT acquisition hardware and processing algorithms have improved recently and the noise levels in the magnetic induction coils are now sufficiently low to provide adequate signal levels over the entire AMT bandwidth (20 to 20 000 Hz). With the advent of 24-bit recording systems and low noise coils, it is now possible to measure the natural signal over a broad range of frequencies, obviating the need for time-consuming deployment of a transmitter. The AMT survey deployed in March of 2001 was designed to image basement conductive features and alteration zones in the overlying sandstone. The survey was intended to include acquisition of data from both a regional line of combined audiomagnetotelluric and lower frequency magnetotelluric sites along the EXTECH IV seismic line, and a high-resolution acquisition component over the P2 Zone itself. Due to uncertainty regarding the distortion of the data related to high electrode contact resistance, it was decided that a larger data set should not be collected without first assessing the reliability of the existing data.

Expectation of good results was based not only on the recent advances in coil design, but also on the new generation of two-dimensional inversion procedures that provide robust images and improved fits to the data in short order. These techniques have been successfully utilized to detect basement graphitic units

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more than 4 km deep in the Western Canada Sedimentary Basin (Boerner *et al.*, 2000). Models based on magnetotelluric data are inherently non-unique because of the finite bandwidth and errors associated with the data. To address the non-uniqueness, increases in our knowledge of the rock properties constrain the allowable model parameter space. This is true for the electrical properties of the graphitic material and alteration zones surrounding the ore obtained through borehole measurements and X-ray analysis (Annesley *et al.*, 2001). Taken together, the improvements in AMT technology, extensive experience of the practitioners with the new technologies, and the increases in knowledge of the conductivity of the pertinent rock types, suggest the time is right to have a new look at AMT exploration in the Athabasca Basin.

2. P2 Zone Survey

The McArthur River uranium mine is situated in the southeastern part of the Athabasca Basin underlain by the western Wollaston Domain (Figure 1), approximately 70 km northeast of the Key Lake mill. McGill *et al.* (1993) and McGill (1996) have documented the geology and lithogeochemistry of the deposit. Most of the uranium mineralization is at depths of 500 to 570 m adjacent to the northeast-trending P2 reverse fault contact between footwall Athabasca Group and hanging-wall basement rocks (McGill *et al.*, 1993, McGill, 1996). The footwall basement rocks are composed of psammitic gneisses, psammopelitic gneisses, and meta-quartzites, whereas the hanging-wall basement rocks are composed mainly of sheared graphitic pelitic gneisses, and graphite-rich cataclasites and breccias. Several zones of pod- to carrot-shape mineralization make up the deposit, which is open at both ends. Broad zones of fracturing and brecciation are developed within adjacent rocks of the overlying Athabasca Group. The second zone of

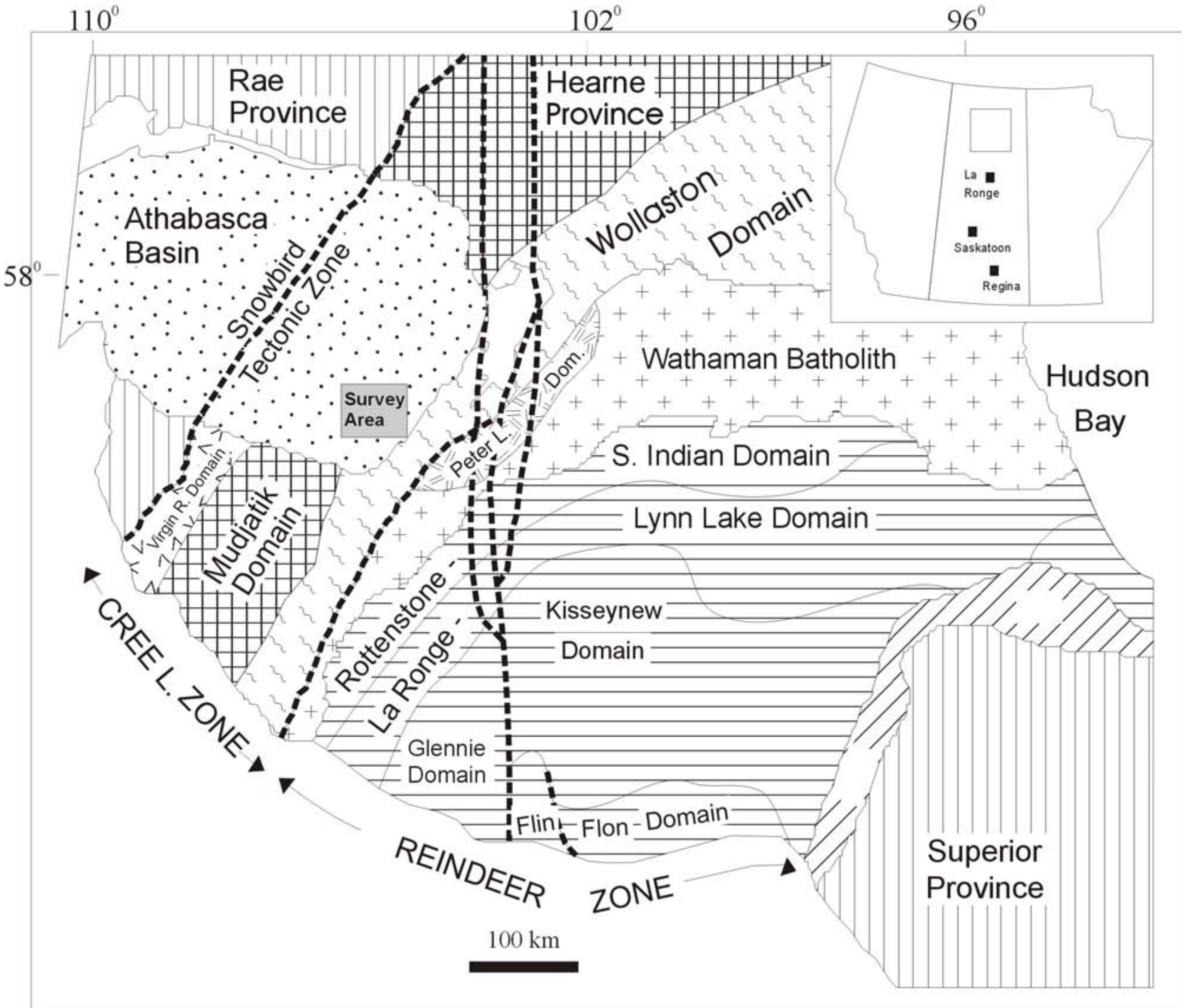

Figure 1 - Location of the McArthur River Survey area in northern Saskatchewan.

mineralization, known as the 'pelite mineralization', was discovered in 1996 along a deeper part of the fault structure, within pelitic gneisses thrust over meta-quartzites.

The P2 Zone is a few kilometres to the west of the high-grade P2 North deposit. The fifteen AMT site locations that comprise the survey at the P2 Zone are presented in Figure 2 and listed in Table 1. The experiment was undertaken in late March of 2001 and utilized snowmobiles and snowshoes to provide access for the three-person crew along the survey line. Geosystem Canada Inc. carried out the survey using two 24-bit ADU-06 acquisition systems manufactured by Metronix GmbH of Braunschweig, Germany. The magnetic sensors were BF-6 and BF-10 induction coils produced by Electro-Magnetic Instruments Inc. of California. Electrode dipole lengths were 50 m in length. The ground contact resistance of the electrodes was high, at over 100 kΩ. This is due to a thick resistive frost layer this time of year. Although logistical concerns were the primary factor in the choice of a winter survey, the extremely low water and clay content of the sand that forms the overburden in which the electrodes are seated indicates a high contact resistance would be encountered during the summer too. At such high contact resistances it is possible that the earth and wire form a capacitor with an appreciable frequency response within the highest measurement bandwidth. Also, coherencies between components of the magnetic fields suggest the natural signal levels were low at the frequencies above 1 kHz and below 10 Hz. Due to the low ambient signal levels and the possibility for capacitively coupled electrodes, the data above 1 kHz were excluded from further analysis in this paper.

Table 1 - ATM site locations.

Site	Latitude	Longitude
mac01_000	+57º 43' 31"	-105º 06' 42"
mac01_012	+57º 44' 07"	-105º 07' 07"
mac01_013	+57º 42' 56"	-105º 06' 10"
mac01_001	+57º 43' 34"	-105º 06' 44"
mac01_002	+57º 43' 28"	-105º 06' 41"
mac01_003	+57º 43' 37"	-105º 06' 46"
mac01_004	+57º 43' 24"	-105º 06' 39"
mac01_005	+57º 43' 40"	-105º 06' 48"
mac01_006	+57º 43' 21"	-105º 06' 36"
mac01_007	+57º 43' 46"	-105º 06' 51"
mac01_008	+57º 43' 16"	-105º 06' 30"
mac01_009	+57º 43' 53"	-105º 06' 53"
mac01_010	+57º 43' 11"	-105º 06' 23"
mac01_011	+57º 43' 59"	-105º 06' 57"
mac01_014	+57º 43' 04"	-105º 06' 18"

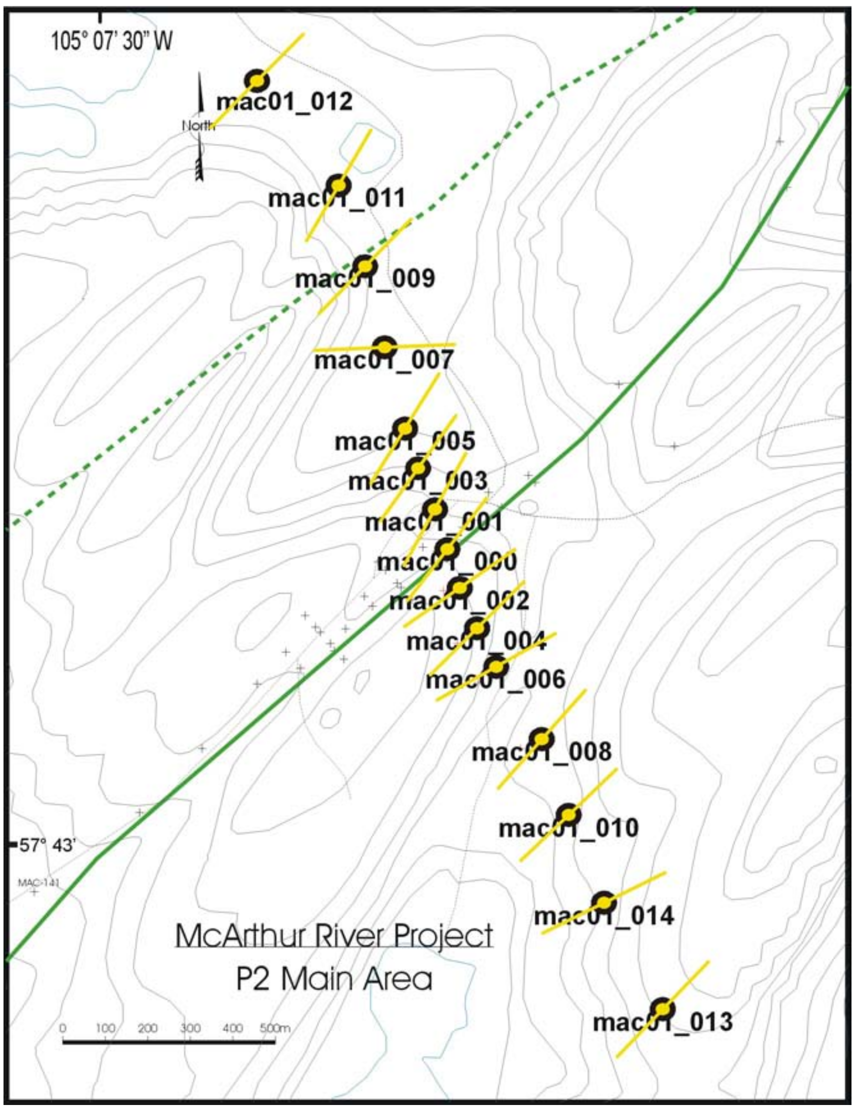

Figure 2 - Site location for P2 Zone AMT Survey. Green lines are known conductors and crosses represent nearby drill holes. The EM strike directions at 300 Hz are shown as yellow lines and indicate the alignment of two-dimensional conductive features beneath each site.

Depth to basement in the vicinity of this profile is around 500 to 550 m (McGill *et al*., 1993). The basement graphitic schists dip southeast and are expected to control the major portion of the AMT response. The overlying rocks of the Athabasca Basin contain numerous alteration zones and therefore may play a secondary role in the electromagnetic response. In the Athabasca sandstone associated with the P2 Main Fault are limonitic fractures with pyritic and clay alteration. Dips of fracture zones are about 45° in the basement and steepen sharply in the sandstone. The sandstone alteration at P2 Main differs from P2 North (the mine site) as follows. The P2 Main is characterized by steep open fractures in the upper sandstone without significant silicification, however the kaolinitic clay alteration may be conductive. The P2 North alteration is characterized by dravitic and tight silicified lower sandstone; fractures that feather out, and background, perhaps resistive, kaolinitic upper sandstone.

3. Data Processing

a) Robust Processing

Geosystem Canada Inc. collected three time series at each site with sampling rates of 40960, 4096, and 256 Hz. Coherent time series segments from each sampling rate were selected automatically for robust analysis to reduce the effects of bias due to noise. An iterative re-weighting scheme was used to provide a robust estimate of the apparent resistivities and phases used in subsequent analyses (Larsen *et al.,* 1996).

b) Decomposition

Determining if the electrical structure beneath the survey area is layered, or variable in two or three dimensions, is a critical preliminary step in the analysis. We have employed the method of Groom and Bailey (1989) to assess the validity of a simple model involving a two-dimensional (2D) regional electrical model affected by local, near-surface galvanic scattering. The Groom and Bailey methodology also provides a robust estimate of the electrical strike direction of a 2D model. The strike directions for data collected at 300 Hz (Figure 2) obtained using a decomposition in which all model parameters are allowed to vary with frequency, indicate structures striking at approximately 050º. In addition to galvanic decomposition, the tensor data collected at each site permit the computation of the phase that would be collected at any azimuth at each site. Contours of these synthetic phases for two sites (Figure 3) along any azimuth show that at longer periods there is a possible rotation of the strike direction.

c) Induction Arrows

For a 2D Earth, the electromagnetic field will propagate in two independent modes, one with an electrical field component along strike (TE-mode) and the second with the electric field perpendicular to strike (TM-mode). Complementary estimation of the direction of the TE-mode of induction can be made through an examination of the vertical field transfer functions. The ratio of the horizontal and vertical magnetic field data can be plotted as arrows such that an arrow points to 2D conductors (analogous to a 'crossover' in VLF analysis) and the length of the arrow is scaled to qualitatively indicate the strength of the subsurface conductivity contrasts. The reversal in directions of 100 Hz arrows (Figure 4) near site mac01_004 indicates the presence of a linear conductor striking approximately 050º. The magnitudes of the arrows in Figure 4 indicate moderate conductivity contrasts. At lower frequencies of 10 Hz (i.e. at greater depths) the arrows in the sites to the south are rotated suggesting a change in strike direction (Figure 5). This is consistent with the low frequency portion of the phase contour sections (Figure 3). Independent confirmation of the two-dimensionality of the data is apparent from an examination of the vertical field transfer functions plotted in strike coordinates in Figure 6. As predicted by a 2D earth, the Tx component (associated with the TM-mode) is small, whereas the Ty component (associated with the TE-mode) obeys a Hilbert Transform response, i.e. the imaginary portion of the complex response goes though zero at the frequency where the real part reaches a maximum or minimum.

d) Inversion

The MT response at any frequency represents a weighted combination of the effects from conductive bodies at all depths that scatter electric and magnetic fields. The depth of each conductive feature can be determined by forward and/or inverse modelling to produce a model that reproduces the data within a set tolerance. The decomposition and vertical field transfer functions indicate the data are 2D with a TE-mode aligned along an azimuth of 050º for the bandwidth between 1000 and 30 Hz. As 2D inversion is an underdetermined physical problem, constraints must be added to the process to stabilize the solution. Common to many 2D inversion techniques is the concept of Occam's Razor whereby only the structure required by the data is introduced into a model. Essentially the model found is the one that minimizes sharp conductivity contrasts whilst maintaining an adequate fit to the data. As such, one can be confident that structure inserted into the model is required by the data. These data were inverted using the smoothed inversion methodology of Rodi and Mackie (2001); the best-fit model of both TE and TM mode data is shown in Figure 7.

A prominent conductive feature in the model in Figure 7 is a bright conductor dipping to the southeast beneath sites 001, 000, 002, and 004. Such a location for the conductive structure is in harmony with the predictions based on the induction arrows (Figure 4). The resistivities in this unit may be as low as 1 Ω·m. The top of this feature is at about 500 m below surface and the highest conductivity appears to be at a depth of about 500 to 600 m. The second conductive feature at 600 to 700 m depth beneath sites 010 and 014 has the same attitude and size as the slightly shallower feature at 500 m. This deeper feature is beneath a portion of the line where site locations are less dense than over the shallower conductor and therefore fewer data indicate this feature. The top 100 to 200 m in the electrical section are poorly resolved due to the omission of high frequency data from the inversion.

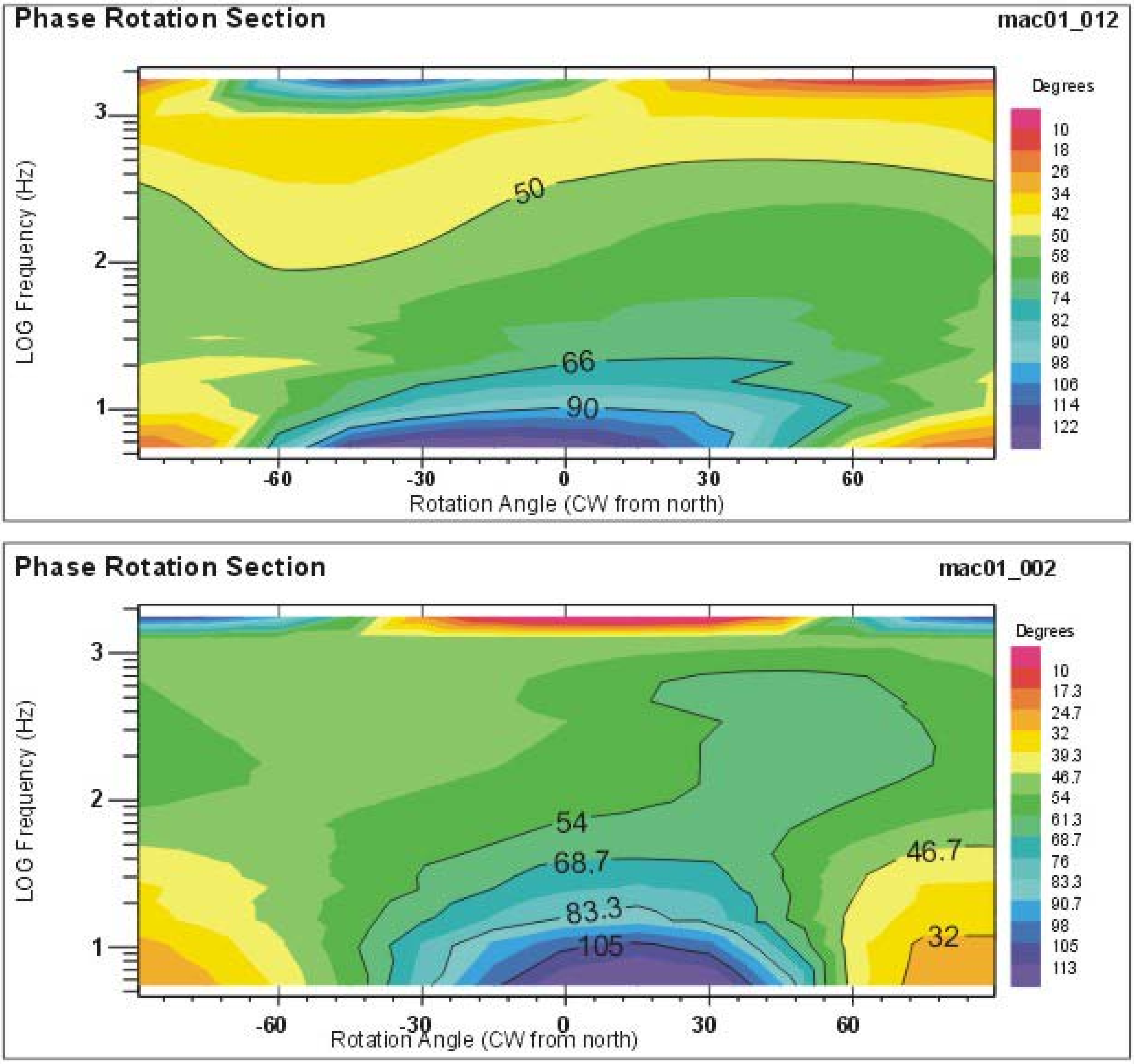

Figure 3 - Contours of the phases at all measurement azimuths for sites mac01_012 and mac01_002.

4. Discussion of Preliminary Model

The anomalies in the basement below 500 m depth are interpreted here as graphitic conductors. Drilled graphitic conductors are typically sheet-like, <1 to 20 m width, with massive to semi-massive graphite. They are associated with the brittle-ductile basement faults related to post-Athabasca faulting and uranium mineralization. The pelitic to semipelitic graphitic schists that host the mineralization, on the other hand, are typically tightly to openly folded, 100 to 500 m thick, and have a resistivity from <100 to 500 Ω·m. The graphitic schists are locally interbedded with other units. The resistive basement at the west end of the profile, with a contact somewhere in the general vicinity of station 009, is consistent with widespread quartzite units west of the P2 fault. The sandstone above the quartzite is also quite resistive because it tends to be more silicified in this area. The preliminary conclusion at this time is that AMT is a practical technique for exploration in the Athabasca Basin for conductors similar in nature to the P2 Zone

5. Acknowledgments

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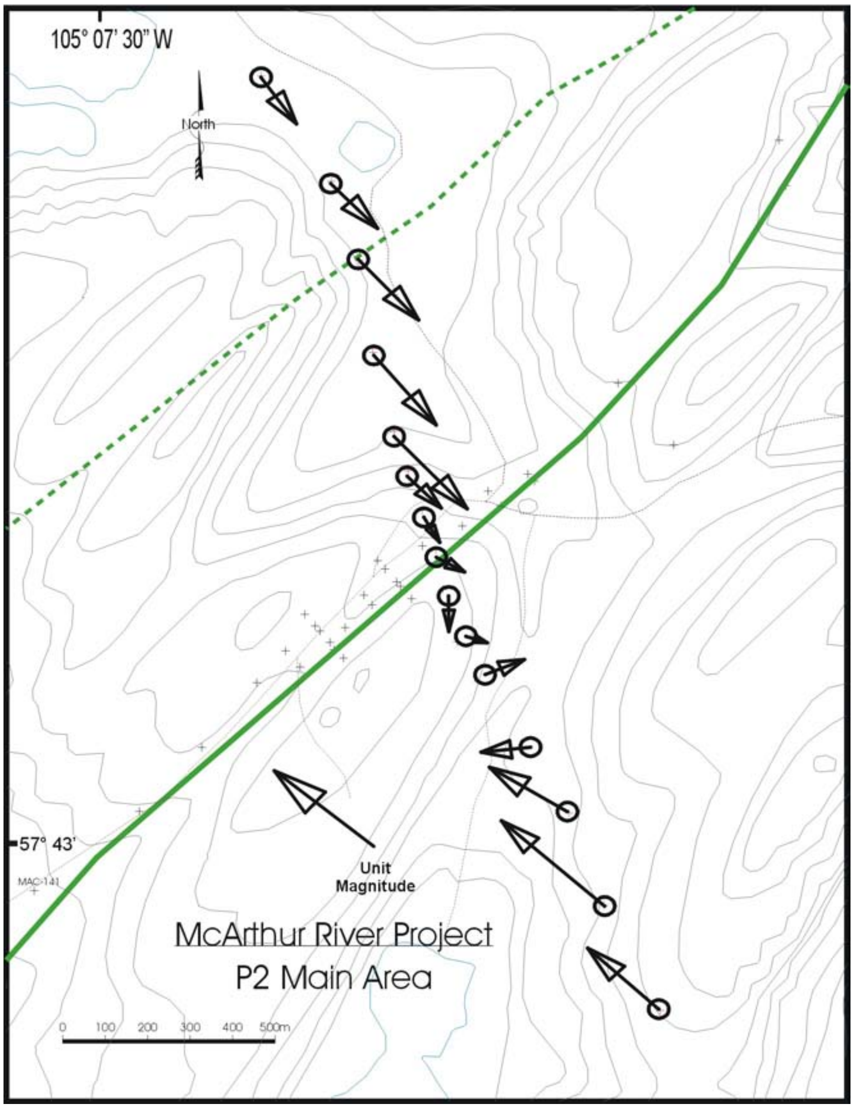

Figure 4 - Real induction arrows measured at 300 Hz plotted to point toward conductors.

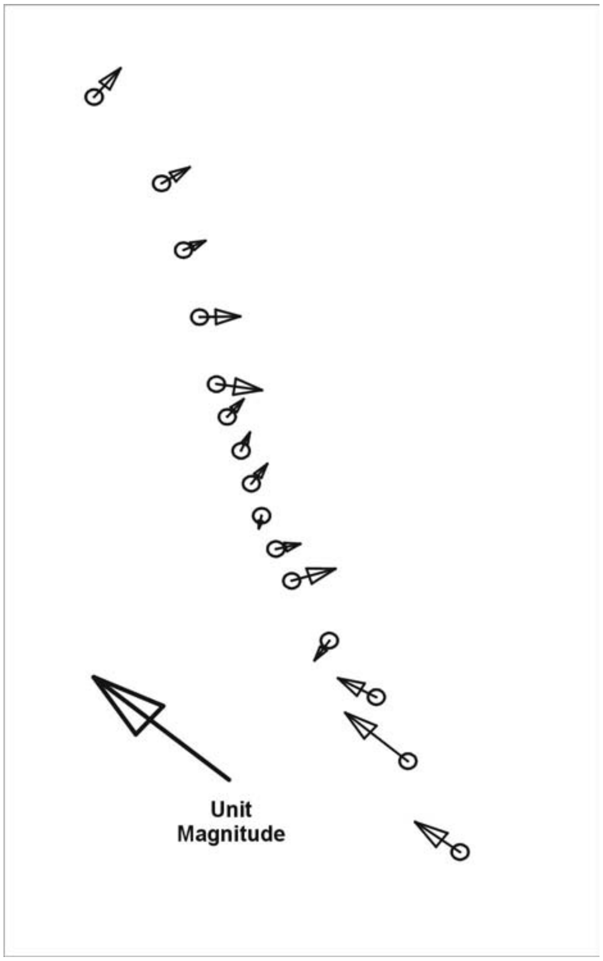

Figure 5 - Real induction arrows measured at 10 Hz plotted to point toward conductors.

6. References

Annesley, I.R., Madore, C., and Cutler, J. (2001): Petrographic and synchrotron X-ray analysis of carbonaceous material in graphitic pelitic gneisses, M-Zone, Saskatchewan, Canada; *in* Pierstrzynski, A. *et al.* (eds.), Mineral Deposits at the Beginning of the 21st Century, A.A. Balkema, p29-33.

Boerner, D.E, Kurtz, R.D., Craven, J.A., Ross, G.M., and Jones, F.W. (2000): A synthesis of electromagnetic studies in the LITHOPROBE Alberta basement transect; constraints on Paleoproterozoic indentation tectonics; Can. J. Earth Sci., v37, p1509-1534.

Groom, R. and Bailey, R.C. (1989): Decomposition of magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distortion; J. Geophys. Resear., v94, p1913-1925.

Larsen, J., Mackie, R.L., Manzella, A., Fordelisi, A., and Rieven, S. (1996): Robust smooth magnetotelluric transfer functions; Geophys. J. Internat., v124, p801-819.

Madore, C. and Annesley, I.R. (1997): Graphitic pelitic gneisses of the Paleoproterozoic Wollaston Group, Hearne Province, Saskatchewan; *in* Papunen, H. (ed.), Mineral Deposits: Research and Exploration – Where Do They Meet?, A.A. Balkema, p79-82.

Matthews, R., Koch, R., Leppin, M., Powell, B., and Sopuck, V. (1997): Advances in integrated exploration for unconformity uranium deposits in western Canada; *in* Gubins, A.G. (ed.), Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration, p993-1002.

McCready, A.J., Annesley, I.R., Parnell, J., and Richardson, L. (1999): Morphology, chemistry, and origin of carbonaceous matter from the McArthur River deposit, Saskatchewan, Canada; *in* Stanley, C.J. *et al.* (eds.), Mineral Deposits, Processes to Processing, A.A. Balkema, p251-254.

McGill, B.D. (1996): The McArthur River deposit – geological update; *in* Ashton, K.E. and Harper, C.T. (eds.), MinExpo'96 Symposium–Advances in Saskatchewan Geology and Mineral Exploration, Sask. Geol. Soc., Spec. Publ. No. 14, p95.

McGill, B.D., Marlatt, J.L., Matthews, R.B., Sopuck, V.J., Homeniuk, L.A., and Hubregtse, J.J. (1993): The P2 North Uranium deposit, Saskatchewan, Canada; Explor. Min. Geol., Can. Inst. Min. Metall. Petrol., v2, no4, p321-331.

McMullan, S.R., Matthews, R.B., and Robertshaw, P. (1987): Exploration geophysics for Athabasca uranium deposits; *in* Proceedings of Exploration '87, Ont. Geol. Surv., Vol. 3, p547-566.

Rodi, W. and Mackie, R.L. (2001): Nonlinear conjugate gradients algorithm for 2D magnetotelluric inversion; Geophys., v66, p174-187.

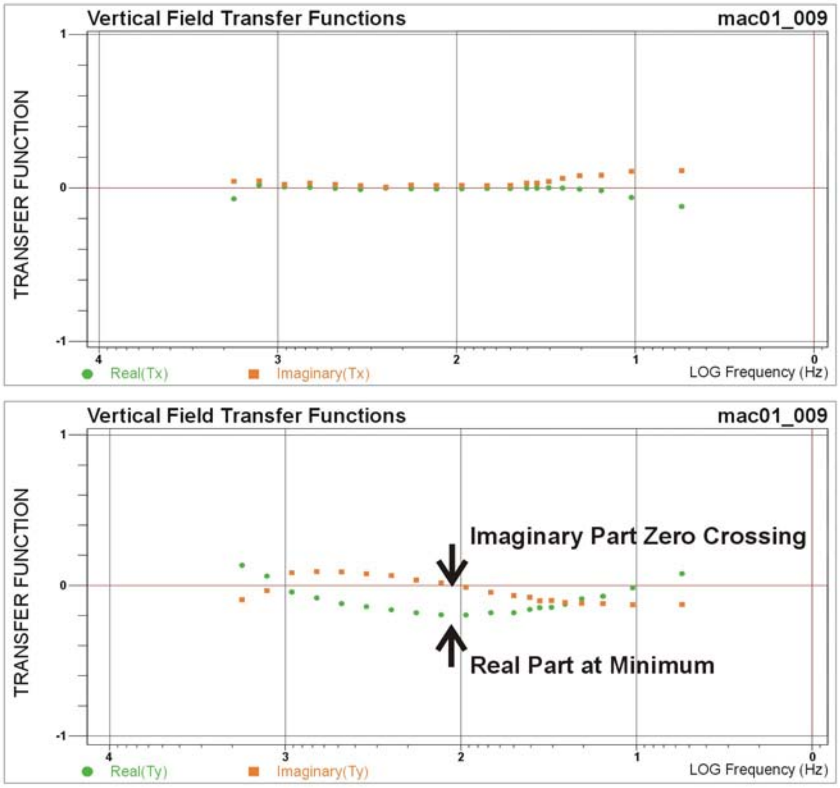

Figure 6 - The vertical field transfer functions for site mac01_009. A Hilbert Transform relationship between the real and imaginary portions of the Ty component is discussed in the text.

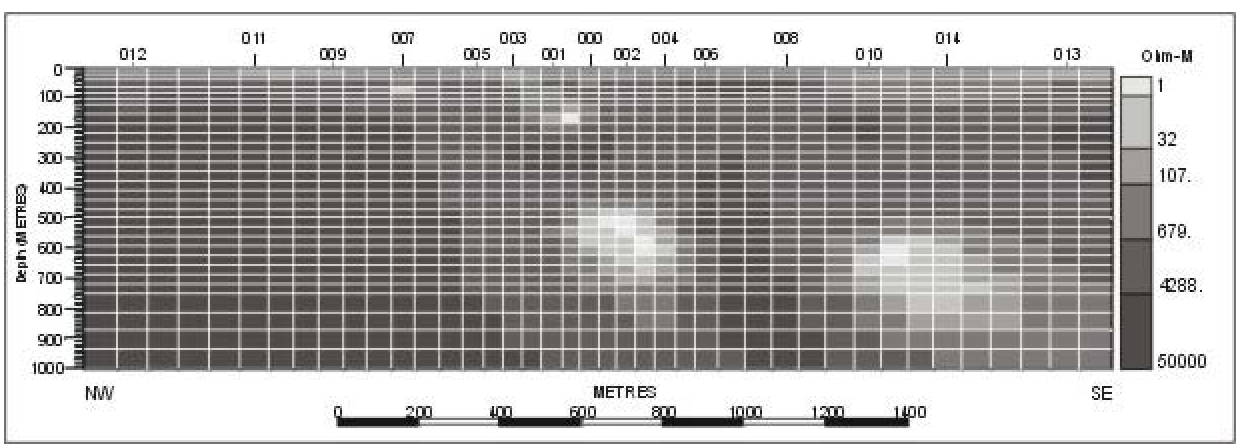

Figure 7 - Preliminary electrical conductivity model for the P2 Zone.