Three-dimensional inversion of transient magnetotelluric data at Pasfield Lake, Saskatchewan

David Goldak[*], EMpulse Geophysics, Ken Witherly, Condor Consulting and Peter Kosteniuk, Kosteniuk Consulting

SUMMARY

A transient audio magnetotelluric (TAMT) survey was carried out in the Athabasca Basin of northern Saskatchewan as part of a uranium exploration program at Pasfield Lake.
Inspection of the TAMT data revealed a complex structural setting near the line extremities with a large conductive uplifted block in central portions of the lines. Two-dimensional (2D) inversion was helpful but failed to fit the data satisfactorily in the structurally more complex areas.
The results of 2.5D inversion (three-dimensional inversion on a single 2D profile) will be presented and compared to the original 2D inversions and known drilling. The 2.5D inversions show a much better fit to the measured data, returning models in good agreement with drill core defined lithology.
Additionally, three-dimensional (3D) inversion of airborne total field magnetic and airborne gravity gradient data was performed and clearly corroborates the presence of an uplifted basement under Pasfield Lake.
It would seem that the most likely source mechanisms to explain the Pasfield geophysical data and drill core to date are an explosive event in the form of a meteorite impact or a volcanic intrusive.

INTRODUCTION

The Pasfield Lake property is located in the proterozoic Athabasca Basin (AB) of northern Saskatchewan, Canada (Figure 1). The AB consists of mostly flat lying weathered and transported sediment, exceeding 1 km thickness in central parts of the basin. Archean “basement” is generally comprised of felsic gneiss, metavolcanic rocks and graphitic pelitic schist (Leppin and Goldak, 2005). Basement structures are usually near vertical due to the intense deformation that occurred during the Hudsonian orogeny.

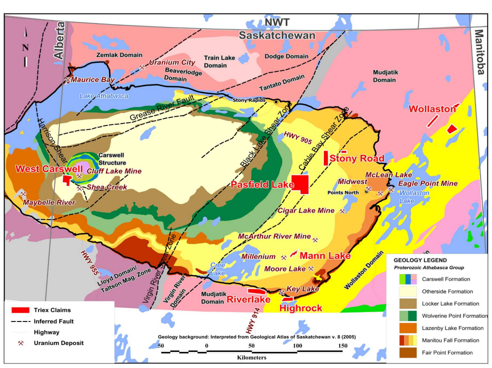

Figure 1: Athabasca Basin

With the unconformity exploration model (McMullan et al., 1987), electromagnetic methods are used to define conductive basement structures, usually graphitic schist emplaced along zones of structural weakness, while DC resistivity is used to map sandstone alteration as an indicator of fluid flow due to hydrothermal activity[*]. Where both are present, odds are increased of finding uranium mineralization in the reducing environment provided by the graphite (carbon).

A major structural basement feature, the Cable Bay Shear Zone (CBSZ), appears to intersect the Pasfield Lake property (Figure 1). However, the dominant geophysical response is characterized by a roughly circular conductivity/potential field anomaly located under the lake itself. Clearly visible even on regional scale potential field data, airborne surveys were conducted on more tightly spaced survey lines and better defined this feature (Figure 2).

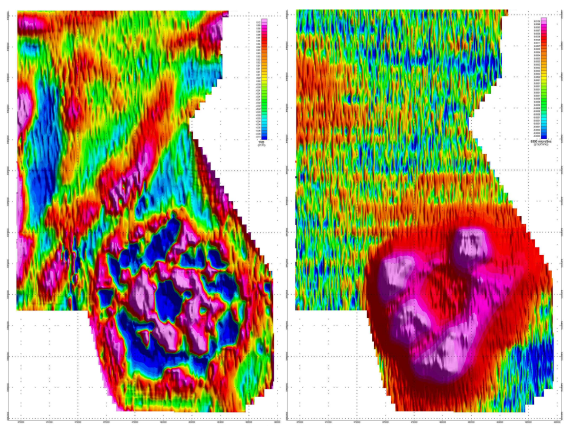

Figure 2: Calculated Vertical Magnetic Derivative and late time VTEM data

Since regional depth to basement is on the order of 900 m, and due to the high conductivity of the anomaly, a transient magnetotelluric survey was initiated to further explore the property to depth.

Our transient approach to AMT centers around the time localized recording of individual transient events in order to maximize Signal-to-Noise ratio (SNR). This is not a new idea, being implemented as early as 1976 by Don Hoover (Hoover et al., 1976) and many others (Kosteniuk and Paulson, 1988. Vozoff, 1991. Garner and Thiel, 1999).

However, our Adaptive Polarization Stacking (APS) algorithm is a relatively recent development (Goldak and Goldak, 2001) in which both the polarization properties of the source field and the SNR are properly reflected in the final earth response curves and error bars. A key feature of APS is that SNR can be enhanced (to an extent) through a time domain stacking of the transient waveforms, this reduces bias to negligible levels

[*]Although, TAMT data may also be used to map sandstone alteration in some cases (Nimeck and Koch, 2008. Powell et al., 2007).

even with difficult polarization characteristics (narrow angle sources).

Five-hundred and fourty five TAMT stations were collected on seven parallel lines, each line approximately 20 km long with an intra-line spacing of approximately 1.5 km. A nominal station spacing of 250 m was used with infill stations collected at 125 m spacing where warranted (Figure 3).

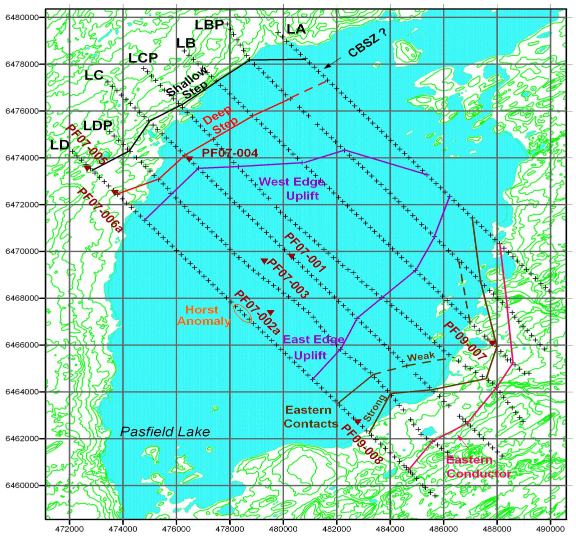

Figure 3: Base Map with interpretation based on tipper/2D inversion with drill hole locations

A high level of structural complexity was evident in the outermost 5 km of each survey line, but also at select locations within the conductive uplift. At the time of survey completion, our best inversion tool was 2D, this was carried out with the main emphasis placed on TE-Tipper and TM-Tipper inversions.

However, both sets of 2D inversions failed to re-produce the measured data in the structurally complex areas of the survey lines and produced somewhat disparate results. As is well known, picking drill targets based on 2D inversion in a 3D geologic environment is very challenging, enter 3D inversion.

IMPLEMENTATION

EMpulse Geophysics purchased the right to use the WSINV3DMT code (Siripunvaraporn et al., 2005) and partially funded the extension of which to include the tipper.

However, the code obtained was serial, capable of running on one CPU core only. Peter Kosteniuk parallelized the code by making estimation of the sensitivity matrix a parallel process. At a given frequency, the sensitivity matrix is now calculated at N_{core} stations simultaneously. Similarly, forward modeling is now a parallel process with up to N_{core} frequencies forward modeled simultaneously on separate CPU cores.

Note that WSINV3DMT fits the impedance tensor $\tilde{\mathbf{Z}}$ directly, as defined in equation (1).

$$\begin{bmatrix} \tilde{E}_x \\ \tilde{E}_y \end{bmatrix} = \begin{bmatrix} \tilde{Z}_{xx} & \tilde{Z}_{xy} \\ \tilde{Z}_{yx} & \tilde{Z}_{yy} \end{bmatrix} \cdot \begin{bmatrix} \tilde{H}_x \\ \tilde{H}_y \end{bmatrix} \tag{1}$$

Another quantity of interest is the magnetic field tipper $\tilde{\mathbf{T}}$, as defined in equation (2).

$$\tilde{H}_z = \tilde{H}_x \tilde{T}_x + \tilde{H}_y \tilde{T}_y \tag{2}$$

With our modest Linux based cluster of 24 AMD cores it's now possible to work with reasonably large data-sets (200 stations plus). A 2.5D inversion of the full impedance tensor and tipper at 18 frequencies (8 Hz- 20 kHz) and 79 stations ($N_{data} = 79 \times 18 \times 12 = 17,064$) with a model mesh of $20 \times 179 \times 26$ ($N_{model} = 93,080$) took approximately 12 hours per iteration. A total of six iterations were required to see that the minimum structure model was obtained. A goal misfit of 1.5 was used which very roughly corresponds to a fit of approximately 15 percent precision on $\tilde{Z}_{xy}$, $\tilde{Z}_{yx}$, 20 percent on $\tilde{Z}_{xx}$, $\tilde{Z}_{yy}$ and 10 percent on $\tilde{T}_x$, $\tilde{T}_y$.

A downside of our parallel approach is that the full sensitivity matrix must be assembled and stored in memory, hence the "heart" of our cluster is a 2P server with 64 GBytes of RAM.

3D INVERSION RESULTS

Shown in Figure 4 is the 3D inverted results using $\tilde{Z}_{xy}$, $\tilde{Z}_{yx}$, $\tilde{T}_x$ and $\tilde{T}_y$, for the southern-most line (Line D) with 2D inverted results directly below for comparison.

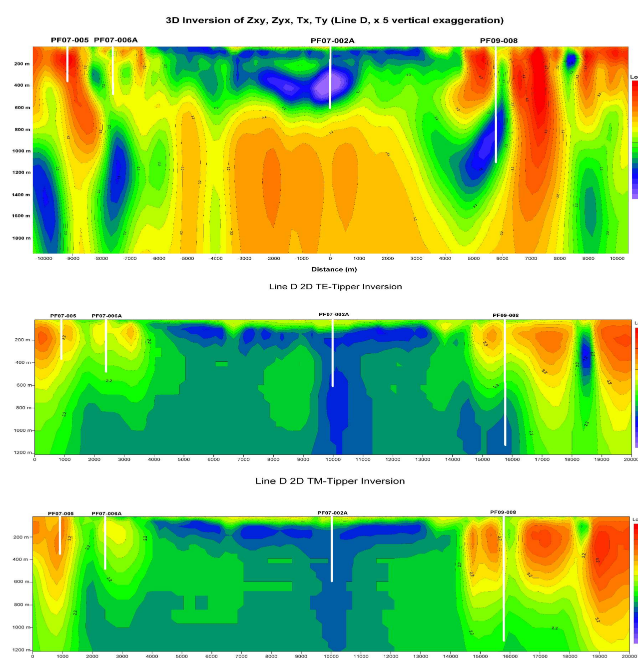

Figure 4: 3D/2D Inversions

3D TAMT Inversion

Perhaps the most striking difference is seen at the approximate line midpoint, where 2D inversion gives the appearance of a conductive anomaly extending to great depth whereas 3D inversion localizes the anomaly to the 300 to 500 m depth range. Drill hole PF07-002A was drilled to 614 m depth just 700 m to the north of the survey line, conductive material (graphitic meta-pelite) was recovered from 326 to 420 m depth, verifying the 3D anomaly localization.

A second drill hole, PF09-008 was drilled to 1155 m depth and was located directly on the survey line. The drill hole intersects a conductivity anomaly seen on the 3D inverted result, but mostly absent on the 2D inverted results. The drill-log for PF09-008 indicates a large amount of brecciation and fracturing in general but especially so below 400 m depth and passes through a strongly altered fault zone from 845 to 851 m depth. This would appear to explain the source of the anomaly seen on the 3D inverted results, which indicates a steeply dipping conductive zone beginning at approximately 600 m depth, with the core of the anomaly at approximately 900 m depth.

Such zones of high porosity are a source of "geologic noise" in the search for graphitic basement structures and/or clay altered sandstone.

A third drill hole, PF07-006A was drilled to 504 m depth and recovered only fine grained sandstone. Despite being near a lateral contact (Deep Step, Figure 3), the drill hole is located within a patchy zone of higher resistivity and did not extend deep enough to test the conductive anomaly at approximately 1000 m depth.

A fourth drill hole, PF07-005 was drilled to 360 m depth within a rather uniform zone of high resisitivity. Fractured sandstone was evident in the upper 275 m with the drill core becoming more competent as depth increased.

The remaining six lines were inverted separately in 3D and the results contoured to make plan view maps. Note that due to the relatively wide line spacing of 1.5 km, only the lowest frequency data would be expected to have any cross-line interaction. Therefore, 3D inversion on a per line basis should be as good as a grid based 3D inversion in this case, at least for the upper 700 m approximately.

Shown in Figure 5 is the result for the 300 m depth level. Drill holes that intersected graphitic meta-pelite are annotated with an "MP", both of which lie within conductive zones on the 300 m plan view. Furthermore, drilling found graphitic meta-pelite extending to greater depth in PF07-002A. This also agrees with the 3D inverted TAMT data where, at the 420 m depth level, the anomaly persists at the location of PF07-002A but is absent at the location of PF07-001.

PF07-003 on the other hand encountered no conductive meta-pelites and lies in a small zone of moderate resistivity. Although basement granite was clay altered in PF07-003, it appears that the meta-pelites have sufficiently high graphite content so as to provide a measurable resistivity contrast.

To get an appreciation of the 3D model variation of as a function of depth, the 880 and 1440 m plan view plots are shown

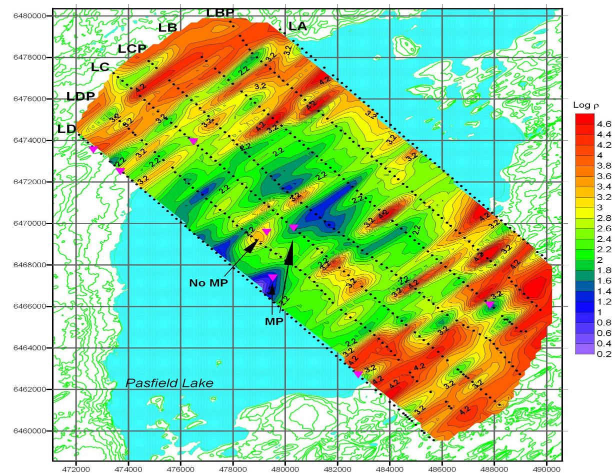

Figure 5: 300 m Plan View

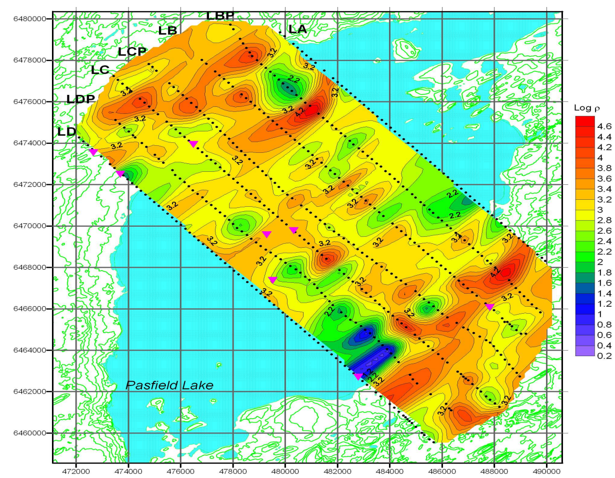

Figure 6: 880 m Plan View

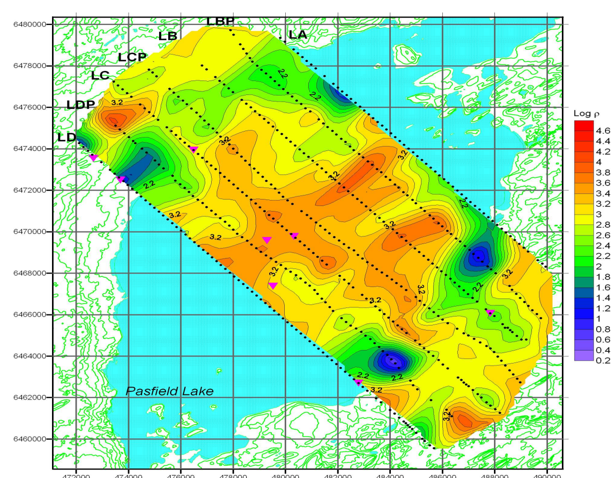

Figure 7: 1440 m Plan View

in Figure's 6 and 7 respectively. Note that plan view plots for depths less than 200 m are omitted as they mainly reflect conductive mudstone/lake fill sediment to which the VTEM data responsed almost singularly too.

Potential Field Data

Shown in Figure 8 are a portion of the 3D models derived from inversion of the total field magnetics and airborne gravity gradient data using the University of British Columbia Mag3D and Grav3D algorithms. A slice taken down TAMT line C is shown where indications of an uplift are evident, especially on the Mag3D model.

The margins of the uplift block as defined by the potential field data agree very well with those obtained from the 3D inversion of the TAMT data. An analysis of the TAMT data to greater depth is required to ascertain if any correlation exists with the very deep magnetic source material as defined outside of the uplift.

The potential field data are consistent with many previous studies over impact structures (Pilkington, 1992). Firstly, a relatively simple gravity low, due to a reduction in density caused by fracturing. Secondly, a more complex magnetic anomaly due to the effects of shock, heat and chemical processes that altered the magnetization of the source rock during and after impact.

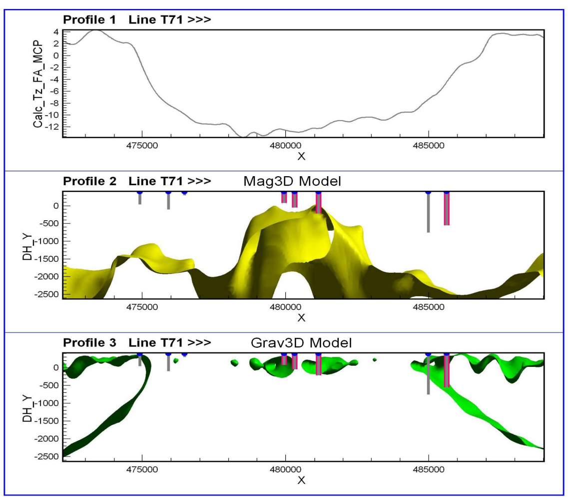

Figure 8: 3D Potential Field Inversion on Line C

CONCLUSIONS

3D inversion has significantly enhanced the interpretability of the TAMT data set at Pasfield Lake, fully revealing the structural complexities contained in the measured data. Good correlation with drilling and airborne magnetic/gravity 3D inversions provides further verification of the higher degree of confidence we may have in the 3D TAMT models.

With the exception of the graphitic meta-pelites in the uplift block, it appears that many of the conductive TAMT anomalies are simply due to zones of increased porosity. This high level of "geologic noise", presumably due to fracturing caused by the explosive event at Pasfield Lake, makes traditional exploration methodology difficult.

The possibilty of mapping graphitic meta-pelites within the uplift block is encouraging but requires more drilling to confirm this hypothesis.

The most prospective areas for further drilling may be on the edges of the basement uplift block, especially where meta-pelites are found. This is in direct analogy to the mineralization found at Carswell Lake, a well known impact structure and formerly producing mine approximately 250 km to the west.

In an effort to place confidence limits on the final inverted results, an analysis of the model variation with respect to the type of data being inverted needs to be conducted. It's been observed that some of the deep conductive features seen on a $\tilde{Z}_{xy}$, $\tilde{Z}_{yx}$ inverted model may move significantly or change in character on a $\tilde{Z}_{xx}$, $\tilde{Z}_{xy}$, $\tilde{Z}_{yx}$, $\tilde{Z}_{yy}$ inverted model. For this study, $\tilde{Z}_{xy}$, $\tilde{Z}_{yx}$, $\tilde{T}_x$, $\tilde{T}_y$ inverted models were chosen for presentation as these parameters are the most precisely measured.

Lastly, with the recent release of 12 core "Magny-Cours" CPU's by AMD (and commercial grade 6 core "Thuban" CPU's) the future looks bright indeed for small scale cluster computing†. This makes the relatively large effort required to program GPU video cards less desirable, especially since the sensitvity matrix calculation, the most time consuming part of the 3D inversion, is not readily amenable to GPU parallelism.

However, with recent CPU developments, it should be possible to triple the execution speed of the code for less than 20k CDN dollars. This would enable the routine inversion of 250 stations with 400 stations being a possibility, although probably not practically so.

ACKNOWLEDGMENTS

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†A 48 core CPU by Intel is expected in less than one year.