Joint inversion of Time-Domain Moving Loop EM and Electrical Resistivity Data: Athabasca Basin case-study

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Summary

The Athabasca Basin is a world-class uranium mining province with several high-grade and high-tonnage deposits. The development of mineralization is driven by hydrothermal fluid flow at the unconformity between basin sediments and basement metamorphic and magmatic rocks. This massive fluid flow is channelized by crustal faults in which graphite later precipitated. Graphite-bearing faults are highly conductive, and their host-rock is resistive, thus they are goods targets for electromagnetic (EM) inductive surveys. Fluid flow also led to the alteration of basin and basement rocks modifying their mineralogy and petrophysical properties, including resistivity. The resistivity contrast between fresh and altered rocks is recorded in the signal of galvanic direct-current (DC) resistivity methods.
Exploration of Uranium deposits in the Athabasca Basin therefore relies on localizing graphitic conductors and alteration halos, closely related to mineralization, using EM and DC methods. To evaluate the benefits of joint inversion of EM and DC data we inverted a line of Time Domain EM Moving-Loop survey, and a line of Pole-Dipole electrical resistivity survey. Inversion of EM data alone succeeds in identifying the location of graphitic conductors, while inversion of DC data alone is not able to recover information of resistivity contrasts close to the unconformity. Indeed, the signature of the graphitic conductors overprints the signal of objects nearby. Joint inversion led to a single geo-electric model fitting both datasets. The model obtained shows the conductive features identified with inversion of EM data, and resistivity contrasts unseen on separate inversions have been revealed down to 500m.

Keywords: Athabasca, Inversion, Electromagnetics, Uranium, Joint Inversion

Introduction

The Athabasca Basin hosts some of the biggest uranium deposits (e.g. Cigar Lake, McArthur River) in terms of grade and tonnage (Jefferson et al. 2007). These deposits are said unconformity-related. Uranium mineralization is found at the unconformity between Archean to Paleoproterozoic metamorphic basement rocks and the overlying Proterozoic basin sediments. The depth of the deposits is variable, but targets are commonly expected at a few hundred meters and there is usually no outcropping evidence of the underlying mineralization. Thus, geophysical methods are key to define drilling targets.
Mineralization is closely associated with graphite-bearing fractures that act as mineralizing-fluids conduits. Due to their high electrical conductivity, and their mineral content, these structures are called graphitic conductors. The contrast of resistivity with their host-rock is of several orders of magnitudes. Inductive electromagnetic (EM) methods are sensitive to such objects and are key tools on Athabasca uranium exploration projects. Processing of EM data acquired in Athabasca basin through inversion usually succeeds in identifying graphitic conductors. However, many conductors had been drilled without intersecting any mineralization. Indeed, occurrences of graphitic conductors alone are not enough to get a deposit. Deposition of uranium is associated with massive hydrothermal fluid flows at the unconformity, leading to extensive alteration of surrounding rocks. Alteration of rocks implies modification of their petrophysical properties (e.g. resistivity, density). Direct-Current resistivity methods (DC) are sensitive to the moderate contrast of resistivity between fresh and altered rocks (Nimeck and Koch 2008). But the response from alteration tends to be shaded by graphitic conductors' response. Increasing the drilling success rate relies on better defined targets. Identifying alteration haloes associated with graphitic conductors could indicate that favorable processes had taken place.

EM and DC methods, although they are both sensitive to electrical conductivity, carry different information. Taking advantage of their specific sensitivities in a joint inversion, we are expecting to constraint the extent of the graphitic conductors, allowing to model the resistivity contrast within sandstones, close to the unconformity, related to fluid flow and recorded in the DC data.

We are presenting a case-study of data acquired by Orano Canada Inc. in the Athabasca Basin. Results of separate inversions of EM and DC data are compared to the joint inversion of these datasets.

MATERIAL AND METHODS

The area of interest is in the eastern part of the basin. A Time-Domain EM (TDEM) Moving Loop, ground survey was acquired in 2015. Measurements of magnetic flux were made over several N-S profiles, perpendicular to previously identified magnetic and conductive trends on airborne data. For our work we selected as data the vertical component of magnetic flux over 15 time gates ranging from 0.1 ms to 2.0 ms over 26 stations, along a single line, with a spacing of 200m. Receivers were located 800m to the north of the 400x400 m^2 transmitter loop. Data from a Pole-Dipole survey acquired in 2016 on the same profile were available. The dipole length is 100m, and the current injections were made every 100m. Measurements with a geometrical factor above 100000 were discarded. The total length of the DC line is 5600m. Surveys configuration is shown in Figure 1.

Forward modeling of TDEM and DC responses were done using SimPEG codes (Cockett et al. 2015; Heagy et al. 2018). Modeling of Pole-Dipole survey was made in 2D, while TDEM modeling was made in 3D by extending a model defined on a 2D section. Different spatial discretizations are required for the two methods. Consequently, two different grids were created for forward modelling. A third grid was created for spatial discretization of inverse model parameters. Interpolation from grid of inversion to grids of forward modeling were made with cubic Non-Uniform Rational B-Splines (NURBS) interpolators (B_{em} and B_{dc}) (Bingol and Krishnamurthy 2019), see Equations 1 and 2. Instead of inverting directly the resistivity values (m_{em} and m_{dc}), we are inverting coefficients of our NURBS (m).

$$\mathbf{m_{em}} = B_{em}\mathbf{m} \quad (1)$$
$$\mathbf{m_{dc}} = B_{dc}\mathbf{m} \quad (2)$$

Sensitivity matrices (J_{em} and J_{dc}) are obtained on the grids of forward modeling. Using the chain rule of derivatives, it is easy to get Fréchet derivatives and gradient with respect to NURBS coefficients (J and ∇f), see Equations 3 and 4.

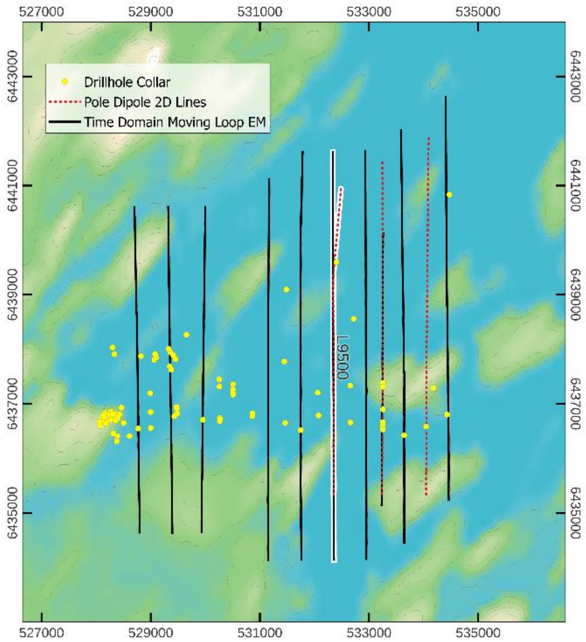

Figure 1. Map of ground TDEM Moving Loop, and Pole-Dipole surveys lines and drillhole collar locations. The two lines contoured in white, labelled L9500 were used for inversion.

$$J = B^T_{em}J_{em} \quad (3)$$
$$J = B^T_{dc}J_{dc} \quad (4)$$

A trust-region inversion algorithm (Conn et al. 2000, Nocedal and Wright 2006) minimizing the L2-norm of data discrepancy was used with a Gauss-Newton approximation of the Hessian matrix. The trust-region subproblem, Equation 5a and 5b (Δm corresponding to model perturbation, and r to trust-region radius), is solved with an iterative Lanczos method (Conn et al. 2000).

$$(J^TJ + \lambda I)\Delta\mathbf{m} = -\nabla\mathbf{f} \quad (5a)$$
$$\Delta\mathbf{m} <= r \quad (5b)$$

Three scenarios of inversion were tested for 30 iterations each. Two of them to fit separately TDEM and DC data and a third one attempting to fit both datasets jointly. The inversions were started with a homogeneous 1000 Ω.m halfspace.

RESULTS

Misfit decreased significantly for the three inversions. Predicted and observed data are very close, Figures 4 and 5. Both separate inversions show a resistive layer 400m thick overlying conductive anomalies, see Figures 3A and 3B. Conductive anomaly from the DC inversion, visible on Figure 3, is smooth and extended laterally. EM inversion, in Figure 3B, shows several sub-vertical conductive anomalies with sharp contrasts. Their depth is close to that of the unconformity from geological model based on drilling represented on Figure 2. Comparing Figures 2 and 3B, we see that some of the conductive structures visible on the EM inversion match with known graphitic conductors. The two structures located at grid coordinates -500m and 0 m are two branches of a single conductor identified by airborne EM.

Separate inversions give a good insight of the basement conductors, but we barely see the subtler contrasts in the sandstone that stays relatively homogeneous above the deep conductors. Moreover, DC forward responses computed from the EM model are not reproducing the observed Pole-Dipole data, Figure 4C. It is the same for the EM responses of the DC model, Figure 5A.

Joint inversion result gives a good prediction of both EM, Figure 5C, and DC data, Figure 4D. Conductive sub-vertical structures identified previously remain relatively unchanged in terms of resistivity, extent and location, Figures 3B and 3C. A horizontal layer of few hundreds Ω.m following the unconformity has been obtained. A lower resistivity at the unconformity could be expected as it constitutes a pathway for hydrothermal fluids. The first hundreds meters of the Joint Inversion model show lateral contrasts better focused than those on the DC inversion, especially outside the central part of the model between -500m to -1000m. However, interpretation remains tedious without a better geological knowledge of the area of interest.

Discussion

The model obtained by joint inversion of EM and DC, Figure 3C, data shows a good agreement with the geological model, Figure 2, built from drilling results in the area of interest.

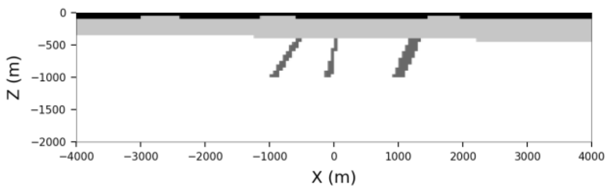

Figure 2. Section from geological model. Black: overburden, dark grey: graphitic conductors, light grey sandstones, white: basement.

Predicted data for both datasets are close to the observed data. As we hoped for, the joint inversion yielded better-focused lateral anomalies within the sandstone layer, improving the chances of identifying alteration halos.

Although conductors observed on joint inversion model, Figure 3C, are close to those of EM model, Figure 3B, the improved resolution in the sandstones carried by DC data influences their continuity and resistivity. The conductor at grid coordinate -2000m has the same location on both results but its resistivity decreased by an order of magnitude at depth on joint inversion model. The same trend can be observed for the conductors between grid coordinates 1000m and 2000m. The central conductors between grid coordinates -500m and 0m seem to be rooted to an underlying conductive structure.

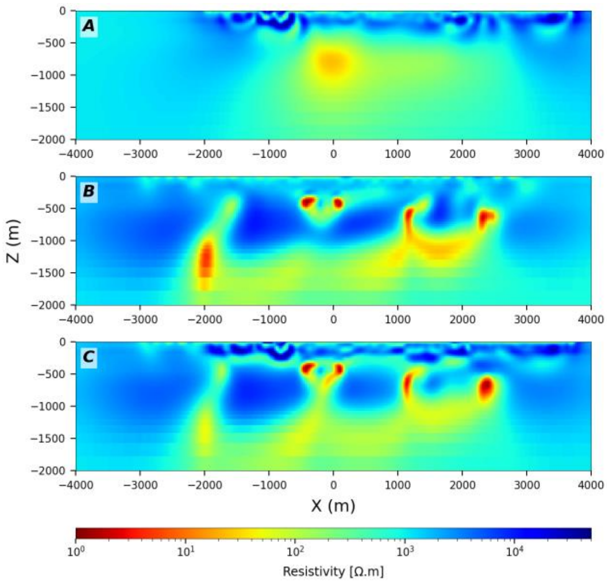

Figure 3. Resistivity Models obtained from inversions: (A) DC inversion result. (B) TDEM inversion result. (C) Joint inversion result.

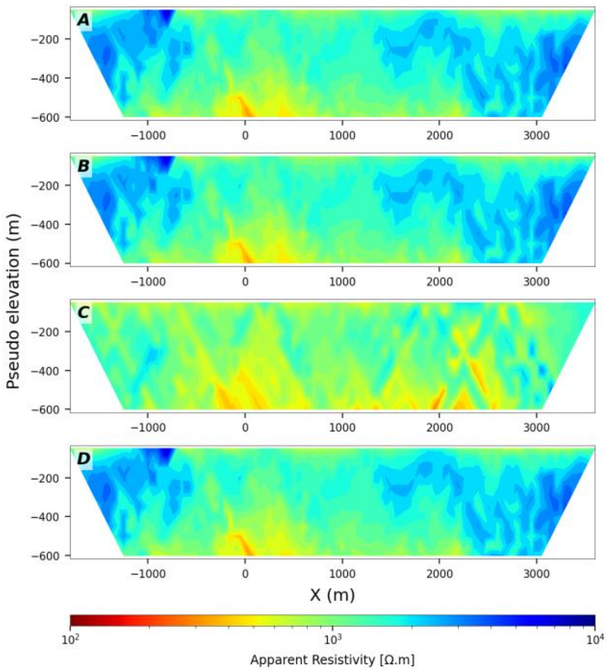

Figure 4. Pseudo-Sections of resistivity: (A) Observed Data. (B) DC Inversion result. (C) TDEM inversion result. (D) Joint inversion result.

Due to the structural pattern of the Athabasca basin, 2D inversion is acceptable. Indeed, basin sediments present layered structure, while basement rocks and faults are usually aligned along a trend across kilometers of distance when looking at the big picture. But on exploration project scale, structure strikes and length can vary. They can also be segmented. Modification in the methodology to fit large-scale 3D inversion is in progress, as to consider potential changes in structures geometry.

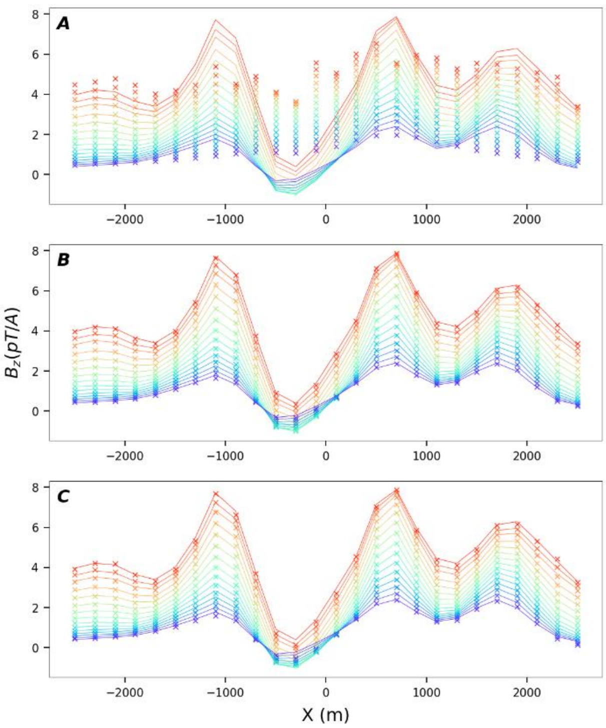

Figure 5. TDEM responses: Crosses correspond to observed data, plain lines correspond to predicted data (A) DC inversion result. (B) TDEM inversion result. (C) Joint inversion result.

Conclusions

Our results show that DC standalone inversion lacks details in the range of depth of sandstone layers. Result of EM inversion show well defined structures matching with graphitic conductors identified by geologists. It should be noticed also that EM model does not reproduce DC data and vice versa. By processing DC and EM data at the same time, our objective was to obtain a resistivity model fitting both datasets and improve resolution in the range of depth of sandstones. Our trust-region joint inversion algorithm succeeded in recovering a model satisfying the objectives.

The joint inversion model shows several anomalies of resistivity in the sandstones that were not revealed on separate inversions results. Another major improvement is the conductive structures following the unconformity. The graphitic conductors identified by drilling and EM inversion were also recovered on joint inversion results with improve continuity.

We now expect to upscale our methodology in 3D and include prior geological knowledge in our inversion workflow.

Acknowledgements

We are thankful to Orano Mining and Orano Canada Inc. for their financial support, access to data and feedback all along our project. We would like also to greatly acknowledge our colleagues Alessandro Vinciguerra and Serge Sambolian for their precious advice and support. Finally, we would like to thank all the stakeholders of the Chair Geomin3D involved in our work.

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