Synthetic modelling and joint inversion of gravity and seismic refraction data for overburden stripping in the Athabasca Basin, Canada

Mehrdad Darijani and Colin G. Farquharson, Memorial University of Newfoundland*

Summary

Gravity signatures from components of the footprints of uranium deposits in the Athabasca Basin of Canada are masked by the contribution to the measured gravity fields resulting from glacial sediments (overburden), in particular by the variable thickness of these sediments. In this research, 2D joint inversion of seismic refraction and gravity data is assessed as a means of reliably mapping overburden thickness, enabling density anomalies from deeper mineralization and alteration to be reconstructed through gravity inversion. Results show that the seismic refraction data provides an accurate estimation of the base of the overburden in the joint Earth model, which in turn leads to an accurate density distribution in the same model.

Introduction

Uranium is mostly found in unconformity deposits which are also typically high grade (Kyser et al., 2000). The largest, highest grade uranium deposits in the world are found in the Athabasca Basin of Canada (Jefferson et al., 2007). Exploration for uranium in the Athabasca Basin began in the mid-1960's with companies looking for sandstone-hosted and/or paleochannel-type uranium deposits (Gandhi, 1995). Initially exploration focused on the shallower parts of the Basin, but has recently moved to deeper areas of Basin (Tuncer et al., 2006; O'Dowd et al., 2006). Unconformity uranium deposits have traditionally been explored using EM methods based on a graphitic conductor model (Farquharson and Craven, 2009). Airborne magnetic data provide maps of basement geology based on the magnetic gradients between Archean gneiss and the Wollaston Supergroup metasediments (Thomas and McHardy, 2007). Ground and airborne gravity data can, it is hoped, detect alteration zones as either negative gravity anomalies (desilicified zones) or positive anomalies (silicified zones) which surround the small uranium deposits (Wood and Thomas, 2002; Thomas and Wood, 2007). Both magnetic and gravity data are affected by variations in the composition of basement rocks, alteration of the sandstone and basement rocks, and variations in the thickness and composition of the overburden.

Uranium deposits in the Athabasca Basin are normally associated with an alteration zone. Since the deposits are volumetrically small and located at depth with a poor density contrast with the host, the alteration zone is one of the most prospective targets for the gravity method. The problem is that the gravity signature of the alteration zone is influenced by the gravity signature of the overburden. In this research, ways to remove or take into account the overburden signature using the joint inversion of seismic refraction and gravity data are considered. This study is focused on the McArthur River uranium site in the Athabasca Basin, one of the highest grade uranium deposit in the world, but is relevant to wherever overburden is obscuring geophysical targets at depth.

Geological setting

The McArthur River area contains a variable thickness (0 to more than 100m) of Quaternary cover, dominated by till in drumlins and hummocky ground moraine, along with glaciofluvial sand and gravel in esker complexes. Beneath this overburden is an undulating bedrock surface affected by glacial erosion (Campbell, 2007). The bedrock consists of Athabasca Group sandstone of late Paleoproterozoic to Mesoproterozoic age. Underlying the sandstone by angular unconformity are metasedimentary rocks of the Wollaston Group, metamorphosed during the Trans-Hudson Orogeny. The McArthur River uranium deposit is situated at the intersection of this unconformity with the P2 Fault in the underlying basement. This fault zone, juxtaposing a hangingwall assemblage of variably graphitic pelite and semipelite over a footwall quartzite, exhibits up to 90m of post-Athabasca reverse fault reactivation.

Seismic velocity and density values increase with increasing depth. The average density of overburden in the McArthur-Millennium corridor is approximately 2g/cc. Sandstone has an average density of 2.43g/cc in the McArthur area. However, silicified and desilicified zones increase and decrease this density, respectively. Basement blocks have different density values. P-wave seismic velocity of overburden and sandstone have average values of 1000m/s and 4000m/s, respectively (Wood and Thomas, 2002; Juhojuotti et al., 2012).

Methodology

The inversion approach used in this research is that of the code of Lelièvre et al. (2012). This uses the minimum structure approach in which an objective function is minimized using a Gauss-Newton method. For a single dataset, the objective function can be written as

$$\Phi = \Phi_d + \beta\Phi_m$$

where β is the trade-off parameter which controls the relative contributions of the data misfit term (Φ_d) and the regularization term (Φ_m). The data misfit term is

$$\Phi_d = \sum_{i=1}^{N} \left(\frac{F[\mathbf{m}]_i - d_i}{\sigma_i} \right)^2$$

where N is the number of measured data d_i, $F[\mathbf{m}]_i$ are calculated data, and σ_i are the estimated uncertainties (Lelièvre et al., 2012). The regularization term is

$$\Phi_m = \alpha_s \|\mathbf{W}_s(\mathbf{m} - \mathbf{m}_{\text{ref}})\|_p^p + \alpha_m \|\mathbf{W}_m \mathbf{m}\|_p^p$$

where $\mathbf{W}_s$ contains cell volume information, $\mathbf{W}_m$ calculates model differences between adjacent grid cells, and α_s and α_m are constant values during the inversion which are used to adjust the relative amount of structure recovered in the physical property models. With two datasets in the joint inversion, the objective function can be written as

$$\Phi(\mathbf{m}_1, \mathbf{m}_2) = \lambda_1 \Phi_{d1}(\mathbf{m}_1) + \lambda_2 \Phi_{d2}(\mathbf{m}_2) + \alpha_1 \Phi_{m1}(\mathbf{m}_1) + \alpha_2 \Phi_{m2}(\mathbf{m}_2) + \Phi_j(\mathbf{m}_1, \mathbf{m}_2)$$

where the two Φ_d and Φ_m terms are the data misfit and regularization terms for each of the two data sets d_1 and d_2 and models m_1 and m_2, respectively. The Φ_j coupling term measures the similarity between the two models:

$$\Phi_j = \sum_i \rho_i \Psi_i(\mathbf{m}_1, \mathbf{m}_2)$$

where ρ_i is the coupling factor, and Ψ_i is a joint coupling measure. There are different types of possible coupling. In this research, we have used the fuzzy c-mean method in which we can specify a relationship between the physical properties that lies in discrete clusters (Paasche and Tronicke, 2007):

$$\Psi(\mathbf{r}, \mathbf{s}) = \sum_{i=1}^{C} \sum_{k=1}^{M} w_{ik}^f z_{ik}^2$$

where C is the number of clusters, M is the number of cells, and f is typically set to a value of 2. The terms z_{ik} and w_{ik} relate the model parameter set (physical property values) for the kth cell to the ith cluster (Lelièvre et al., 2012).

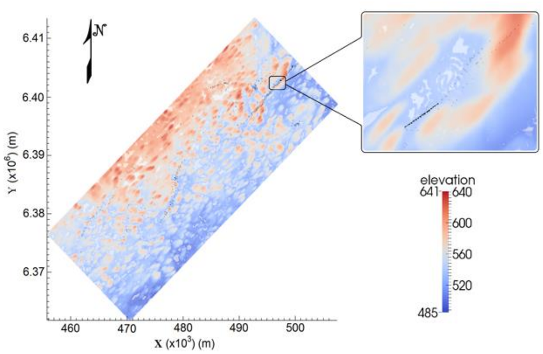

Figure 1: Topography of the McArthur-Millennium corridor. Inset shows location of survey line and seismic sources for synthetic modelling study.

Synthetic modelling and inversion of seismic refraction data

Two types of model, one with modest topography and one drumlin-shaped, were made. The upper layer is the overburden (v=1600m/s and d=2g/cc) and the lower layer is sandstone (v=4000m/s and d=2.42g/cc). Vertical sections were discretized by a triangular mesh. The advantage of this mesh, in comparison to a rectangular mesh, is the ability to easily include topography and arbitrary geological interfaces. Here, sections have more than 40,000 triangular cells. The maximum area of a cell is limited to 1 square metre. Although small cells increase computer run-time, they increase resolution and accuracy of the forward modelling.

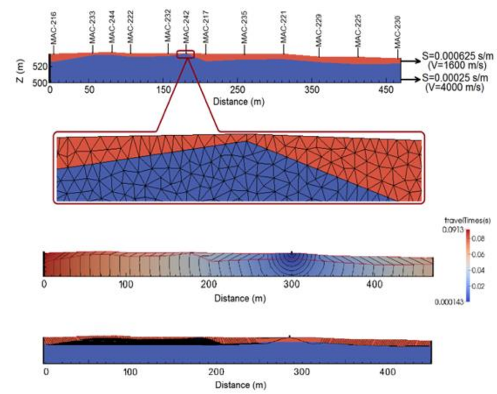

Figure 2: Top: model of glacial sediments (red, slow) over sandstone (blue, faster) based on true topography and base of glacial sediments interpolated between boreholes (labelled), and triangular mesh. Middle: propagation of a wavefront (travel-time contours) for one of the sources. Bottom: seismic ray paths between receivers and one of the sources.

The inset in Figure 1 shows the location of the survey line for the first model (modest topography) generated from using drill-hole data (Figure 2, top). Figure 2 shows the model and triangular mesh. Seismic first arrival travel-time data were synthesized using the code of Lelièvre et al. (2010). Distances between receivers (geophones) and sources were 2m and 50m, respectively. Figure 2 (middle) illustrates the propagation of a wavefront (travel-time contours) through the model for one of the sources and the corresponding rays.

Inversions were performed for seismic data using both L2-norm and L1-norm methods (Figure 3) using the code of Lelièvre et al. (2012). The L2-norm vertical section shows a good agreement with the original model. However, the interface between the two layers is not sharp, which is due to the L2 regularization. The L1-norm section shows a sharper interface. Figure 4 shows the travel-time vs distance plot of the refraction data for the true synthetic model and the data calculated from the inversion model. Fitting between observed and calculated data is good. However, the fit for the L2-norm result is slightly better than for the L1-norm result.

In order to test the modelling and inversion for the kind of topography that is more typical of the McArthur-Millennium corridor, a drumlin-shaped model was made (Figures 5, 6 and 7). Physical properties were the same as for the previous model; however, the shape of the interface between overburden and Athabasca sediments is varied. In Figure 5, small variations were considered for the interface, whereas Figures 6 and 7 demonstrate a bulge- and trough-shaped interface, respectively. Forward and inversion modelling were run for these models. Distances between receivers (geophones) and sources were kept at 2m and 50m, respectively. It can be seen that inversion results (using L1-norm method) show good agreement with true synthetic models, and there is a good fit between observed and calculated data.

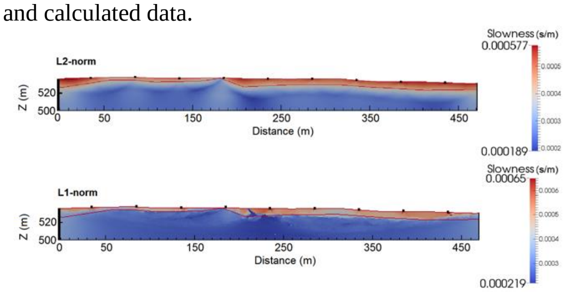

Figure 3: Earth models constructed from inversion of synthetic seismic data generated from the model in Figure 2 using L2- and L1-norm methods. Locations of sources indicated by squares. Red line indicates the glacial sediments-sandstone contact in the model used to synthesize the data.

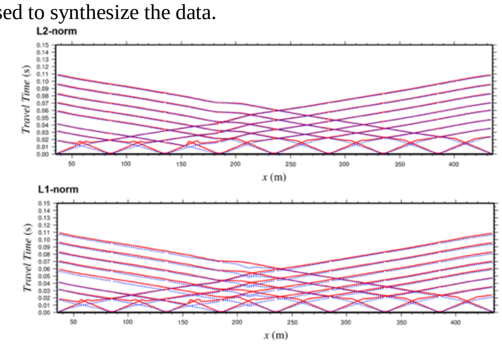

Figure 4: Travel-time vs distance plots of refraction data generated for the model in Figure 2 (red) and data calculated from the inversion model (blue) for both L2-norm (top) and L1-norm (bottom).

Joint inversion of gravity and seismic refraction data

Synthetic seismic travel-time refraction data and gravity data were generated for the drumlin-shaped model (Figure 8). Distance between gravity measurements was 10m. The results of the independent inversion of the gravity data using the L2-norm method are shown in Figure 9. The results of the corresponding seismic inversion are shown in Figure 5. There is a good fit between observed and calculated gravity data. However, the density vertical section does not resemble the true model at all. Figure 10 shows the models obtained by joint inversion using a coupling factor of ρ=1. Two clusters were defined as prior information for the joint inversion, namely, for upper layer: S=0.000625s/m and d=2g/cc; for lower layer: S=0.00025s/m and d=2.42g/cc. The fit between data is reasonable (Figure 11), and the approximate location of the base of the overburden can be clearly seen. In comparison to the independent inversion of the gravity data (Figure 9), the density model is much improved.

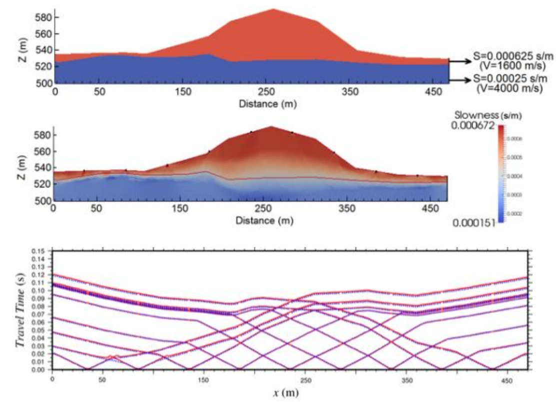

Figure 5: Top: model of glacial sediments (red, slow) over sandstone (blue, faster) based on conceptual drumlin topography. Middle: Earth model constructed from inversion of synthetic seismic data (L1-norm). Locations of sources indicated by squares. Red line indicates the glacial sediments-sandstone contact. Bottom: Travel-time vs distance plot of refraction data for true model (red) and data calculated from the inversion result (blue).

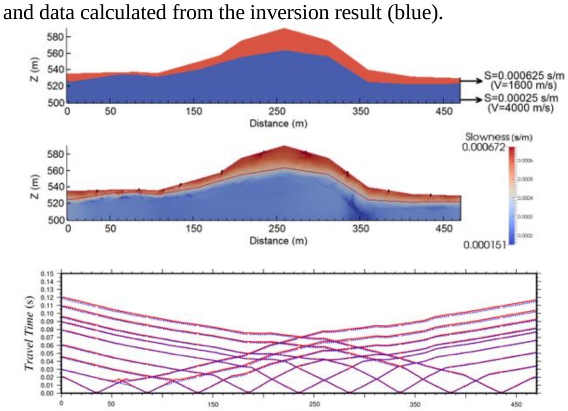

Figure 6: Top: Second drumlin model. Middle: Inversion model (L1-norm). Bottom: Travel-time vs distance plot of refraction data for true model (red) and for inversion result (blue).

Synthetic modelling and joint inversion of gravity and seismic data for overburden stripping

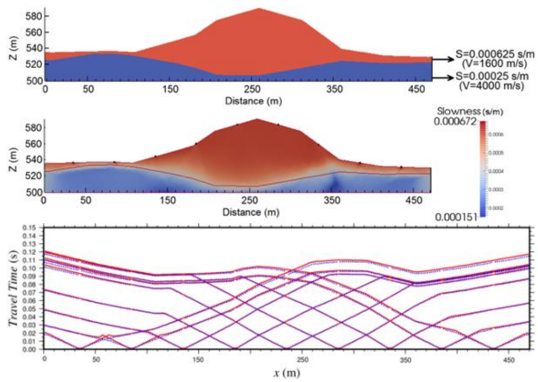

Figure 7: Top: Third drumlin model. Middle: Inversion model (L1-norm). Bottom: Travel-time vs distance plot of refraction data for true model (red) and for inversion result (blue).

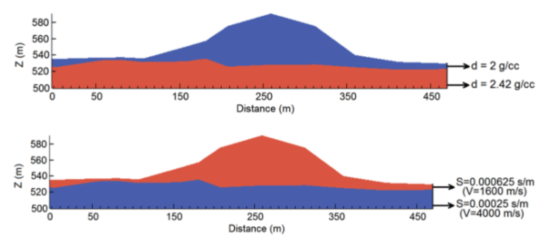

Figure 8: Model of glacial sediments (v=1600m/s and d=2g/cc) over sandstone (v=4000m/s and d=2.42g/cc) based on conceptual topography (drumlin).

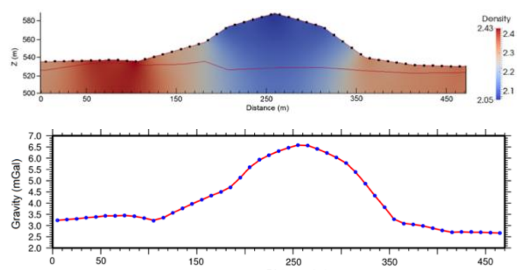

Figure 9: Top: Earth model constructed from independent inversion of synthetic gravity data (L2-norm). Bottom: Gravity data for the true model (red) and data calculated from the inversion result (blue).

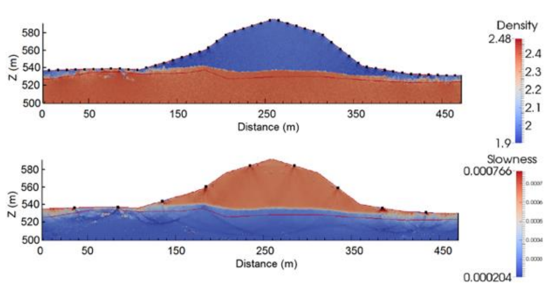

Figure 10: Density and slowness models constructed from joint inversion of seismic and gravity data (coupling factor ρ=1) (L2-norm).

Figure 12 illustrates the physical properties (slowness versus density) obtained after the independent and joint inversions for the models in Figures 5, 9 and 10. Physical properties belonging to each cell are indicated by a blue spot (more than 40,000 cells). For the joint inversion, two clusters can be seen which represent the physical properties of upper (S=0.000625s/m and d=2g/cc) and lower (S=0.00025s/m and d=2.42g/cc) layers.

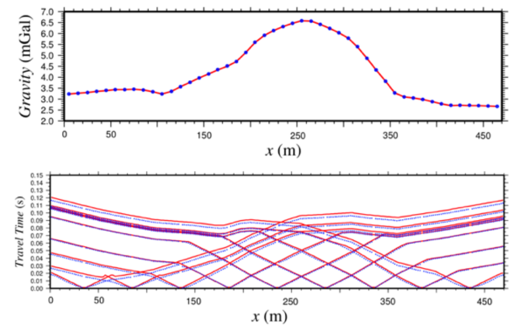

Figure 11: Gravity and seismic refraction data for the true model (red) and data for the joint inversion result (blue).

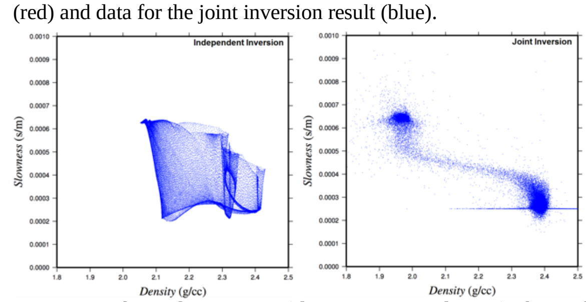

Figure 12: Physical properties (slowness versus density) obtained after the independent (left) and joint (right) inversions.

Conclusions

Alteration zones surrounding uranium mineralization are potential targets for the gravity method in the Athabasca Basin. The problem is that the gravity signatures from mineralization are masked by the overburden signature. We have demonstrated, through realistic synthetic examples, that the joint inversion of gravity data with seismic refraction data can accurately reconstruct the base of overburden in the joint Earth model, and hence the densities of the overburden and underlying bedrock.

Acknowledgments

The authors would like to thank the CMIC and NSERC for providing financial support through the CRD program. Also, this manuscript was improved by helpful and insightful reviews from Garnet Wood (Cameco

Synthetic modelling and joint inversion of gravity and seismic data for overburden stripping

Corporation) and Robert Hearst (AREVA Resources Canada Inc.). This is CMIC-NSERC Exploration Footprints Network Contribution #.