Lithological classification of large-scale 3D inversion of airborne electromagnetic, gravity gradiometry, and magnetic data – A case study from Reid-Mahaffy, Ontario

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Summary

Multi-sensor airborne platforms capable of measuring electromagnetic, gravity, and magnetic data are now being deployed for mineral exploration. The availability of such systems poses a significant challenge for the exploration geophysicist: How do you generate a common earth model which satisfies all data? We address this with a case study from the Reid-Mahaffy test site in Ontario to demonstrate how our multiple 3D inversions of MEGATEM II time-domain electromagnetic, FALCON gravity gradiometry, and TMI data can be analyzed by self-organizing maps (SOM) to produce 3D pseudo-lithological models that can be used for geological mapping and improved exploration targeting. Our analyses are shown to be in good agreement with the known geology of the Reid-Mahaffy area.

Introduction

To improve mineral exploration success, there is consensus on the need to increase the "discovery space" by exploring under cover and to greater depths. For this reason, airborne geophysical data are essential as government-sponsored precompetitive data are supplemented with industry-acquired regional and prospect data. Airborne surveys typically contain hundreds to thousands of line kilometers of data with measurement locations every few meters, and often cover hundreds to thousands of square kilometers. Airborne systems are now being deployed with multiple sensors (e.g., Rajagopalan et al., 2007). For example, Fugro Airborne Surveys are now operating multisensor airborne platforms that simultaneously measure GPS position, LIDAR, radar altimetry, digital video, total magnetic intensity (TMI), gamma ray spectroscopy, FALCON gravity gradiometry, and electromagnetics (MEGATEM, TEMPEST, RESOLVE) (Figure 1).

Given the sheer volume of geophysical data produced from airborne surveys, most of it is only qualitatively analyzed (e.g., Oldenburg and Pratt, 2007); e.g., TMI data are more routinely interpreted for structure from first vertical derivative maps than from 3D inversion. AEM data are usually interpreted using a variety of filters or 1D methods, none of which can reliably recover 3D structures. This general lack of quantitative interpretation stems from the historic lack of "inversion capacity" for existing algorithms to invert entire surveys in 3D with sufficient resolution in sufficient time so as to affect exploration decisions.

In this paper, we rely exclusively on our suite of 3D inversion methods for airborne electromagnetic, gravity, and magnetic data that can be applied to entire surveys. With the availability of large-scale 3D inversions, there is a subsequent need to develop workflows for the integrated analysis and interpretation of different 3D models so as to identify subtle correlations, trends, and relationships indicative of mineralization systems. One simple targeting algorithm might be to find those cells that have specific relationships between their physical properties, e.g., a massive sulfide may be expected to have high density, high magnetic susceptibility, and high conductivity compared to its host. To aid such queries, a number of data mining methods have been developed, e.g., weights of evidence, and neural networks. Since these methods are supervised, they rely on a priori knowledge, training, or user subjectivity, none of which may exist or if it does, be relevant.

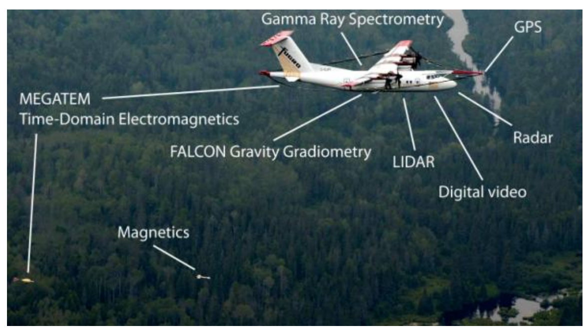

Figure 1. *Multisensor airborne platform operated by Fugro Airborne Surveys.*

We introduce self-organizing maps (SOM) (Kohonen, 2001; Fraser and Dickson, 2007) to analyze multiple 3D inversion models in an objective and quantitative fashion so as to recover 3D pseudolithological models. SOMs are advantageous because they can analyze complex, disparate, and sparse or incomplete geoscientific data, where relationships are nonlinear and data distributions are non-Gaussian. If one represents all model parameters from multiple 3D inversions as vectors in a data space defined by the total number of model parameters, SOMs provide nonparametric mapping that transforms the *n*-dimensional representation of these high-dimensional, nonlinearly related models to a 2D representation in such a manner that provides both an unsupervised clustering and a visual representation of the models' relationships.

Reid-Mahaffy test site, Ontario

Terranes overlain by conductive near-surface geology effectively distort if not mask the AEM response of the more resistive basement and deeper conductive targets which contain potential economic geology. For example, AEM-led exploration for Archaen bedrock conductors in Ontario (e.g., Kidd Creek analogues in the Abitibi greenstone belt) is often hindered by a conductive near-surface layer. The Reid-Mahaffy site is representative of Archean terranes in that it has a moderately conductive overburden overlying a resistive basement containing a number of conductive graphites and other bedrock conductors. It is located in the Abitibi Subprovince, immediately east of the Mattagami River Fault. The area is underlain by Archean (~2.7 ba) mafic to intermediate metavolcanic rocks in the south, and felsic to intermediate metavolcanic rocks in the north, with a roughly EW-striking stratigraphy. Narrow horizons of chemical metasedimentary rocks and felsic metavolcanic rocks have been mapped, as well as a mafic-to-ultramafic intrusive suite to the southeast (Figure 2). NNW-striking Proterozoic diabase dikes are evident from the aeromagnetic data. Copper and lead-zinc vein/replacement and stratabound, volcanic-hosted massive sulphide (VMS) mineralization occur in the immediate vicinity. The Kidd Creek VMS deposit occurs to the southeast of the test site (OGS, 2000).

3D MEGATEM II inversion

Our large-scale 3D AEM inversion is based on Cox et al. (2010), who introduced the concept of a moving footprint. Our frequency-domain modeling is based on the 3D contraction integral equation method (Hursán and Zhdanov, 2002). For time-domain AEM, system responses and sensitivities are obtained by Fourier transform of the frequency-domain responses and sensitivities, and are convolved with the transmitter or calibration waveform (Raiche, 1998). This enables us to accurately model and invert data from any AEM system. We use a regularized conjugate gradient method for minimizing our objective functional (Zhdanov, 2002). Here, we compare our 3D inversion results for DIGHEM and MEGATEM II dB/dt and B data from the Reid-Mahaffy test site. The DIGHEM frequency-domain helicopter EM data were inverted for a 3D conductivity model with approximately 240,000 cells that were 30 m x 30 m in the horizontal direction, and varied from 10 m to 70 m in the vertical direction. The footprint of the DIGHEM system was set at 400 m. The inversion was parallelized over frequency only on a workstation with five 2.3 GHz processors and 48 GB RAM. The a priori model for 3D inversion consisted of a 10 m thick, 10 ohm-m layer above an otherwise homogeneous 700 ohm-m half-space. Inversion run time was less than an hour.

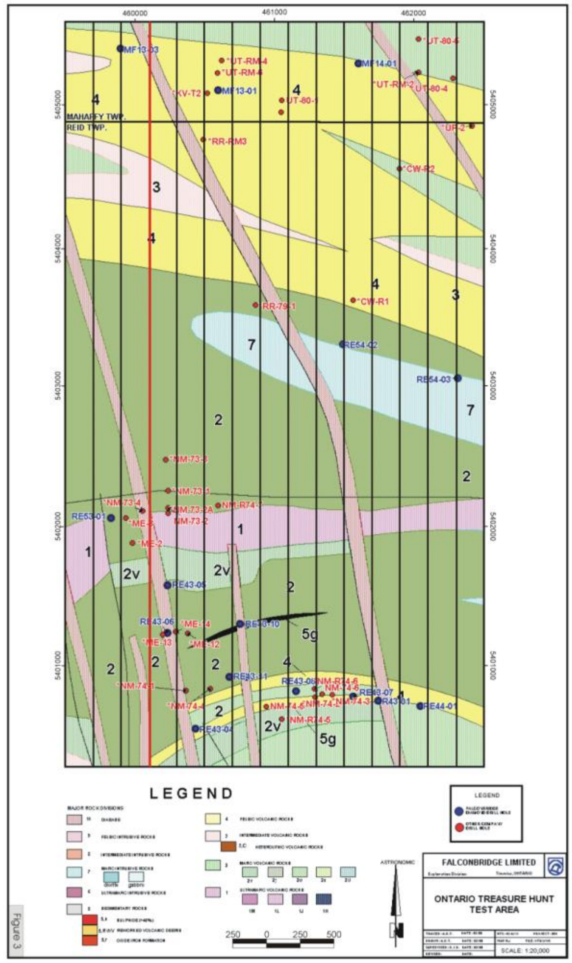

Figure 2. *Geology of the Reid-Mahaffy test site (from OGS, 2000). Line L50 is shown in red.*

The MEGATEM II fixed-wing time-domain system was configured at a 90 Hz base frequency with a 42% duty cycle half-sine transmitter waveform. The system recorded 20 channels (five on time, 15 off time) of in-line and vertical data 125 m behind and 50 m below the transmitter. Primary field stripping was applied to the data, and both dB/dt and B data were delivered. The survey was flown with a nominal 120 m ground clearance. Both MEGATEM II in-line and vertical dB/dt and B data were inverted for a 3D conductivity model with approximately 180,000 cells that were 50 m in the cross-line direction, 35 m in the in-line direction, and varied from 10 m to 130 m in the vertical direction. The footprint of the MEGATEM II system was set at 600 m. The inversion was parallelized over frequency only on a workstation with eight 2.3 GHz processors and 48 GB RAM. The same layered half-space model as per the DIGHEM inversion was used as the a

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priori model for the MEGATEM II inversion. Computationally, the only difference between dB/dt and B data occurs in the frequency- to time-domain transform. Since the Green's tensors were precomputed for the MEGATEM II dB/dt inversion, they were re-used for the MEGATEM II B inversion. Inversion run time was approximately three hours.

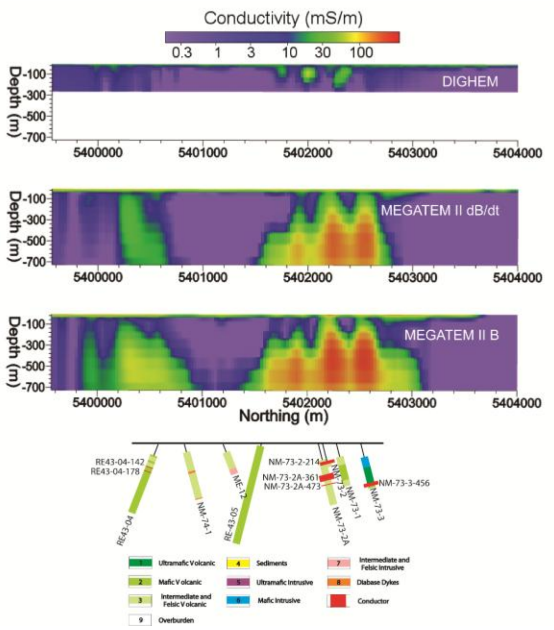

Figure 3. *Vertical cross sections through 3D conductivity models along line L50 obtained from 3D inversion of DIGHEM, MEGATEM II dB/dt, and MEGATEM II B data. The geology of the area, as identified from drilling, is shown in the lower panel (courtesy of OGS, 2000).*

Figure 3 shows a vertical cross section along line L50 of the conductivity models obtained from the 3D inversion of DIGHEM, MEGATEM II dB/dt, and MEGATEM II B data as compared to the known geology. As can be seen, all 3D inversions recover three discrete bedrock conductors beneath the conductive overburden. The presence of these conductors (as rocks) has been verified by drilling (OGS, 2000).

3D FALCON inversion

The FALCON airborne gravity gradiometry (AGG) system measures the horizontal curvature components of the gravity gradient (Lee, 2001). The full gravity tensor is then derived from these measured components. At Reid-Mahaffy, the ground clearance was nominally 80 m flown in a drape over the terrain. The measured gradients were processed by the usual multistep FALCON processing procedures. After the initial reduction of error due to the residual effects of aircraft motion, the data were demodulated and low-pass filtered with a sixth order Butterworth low-pass filter at a cut-off frequency of 0.18 Hz. The demodulated data were corrected for the self-gradient effects of the aircraft, and the tie-lines were leveled. These differential-curvature gravity gradient data were further processed to produce terrain-corrected data using a density of 2.67 g/cm^3, and thence the full gravity gradient tensor. In the processing, a low-pass filter with a cut-off wavelength of 300 m was applied to the data. Our large-scale 3D airborne gravity gradiometry (AGG) inversion is based on Wilson et al. (2011). Similar to Zhdanov et al. (2004), we use a regularized conjugate gradient method for minimizing our objective functional with focusing regularization (Zhdanov, 2002). The earth model was discretized to over 4.3 million cells of 25 m cubic dimension, and contained no a priori density model. Inversion was run for all seven gravity gradients. Figure 4 shows a 3D perspective of the density contrast model.

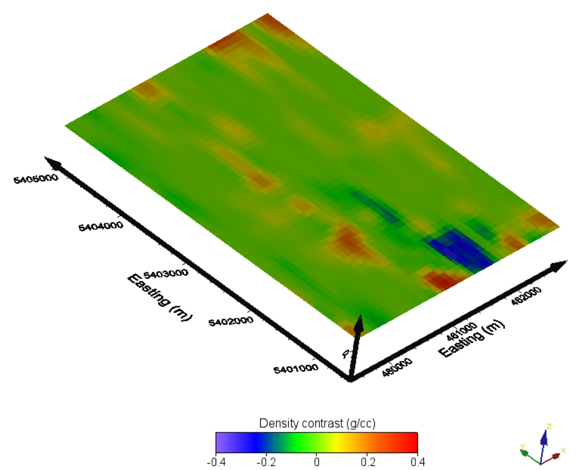

Figure 4. *Horizontal cross section extracted from 3D density contrast model obtained from 3D joint inversion of all seven FALCON gravity gradients.*

3D TMI inversion

Our large-scale 3D TMI inversion is based on a magnetic analog of our 3D AGG inversion (Wilson et al., 2011). Similar to Portniaguine and Zhdanov (2002), we use a regularized conjugate gradient method for minimizing our objective functional with focusing regularization (Zhdanov, 2002). We adopted the common assumption that there is no remanent magnetization, that the self-demagnetization effect is negligible, and that the magnetic susceptibility is isotropic. The earth model was discretized to more than 1.1 million cells of 25 m cubic dimension, and contained no a

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priori susceptibility model. Inversion was run for TMI only. Proterozoic diabase dikes dominate the TMI data, and these are evident from the 3D inversion (Figure 5).

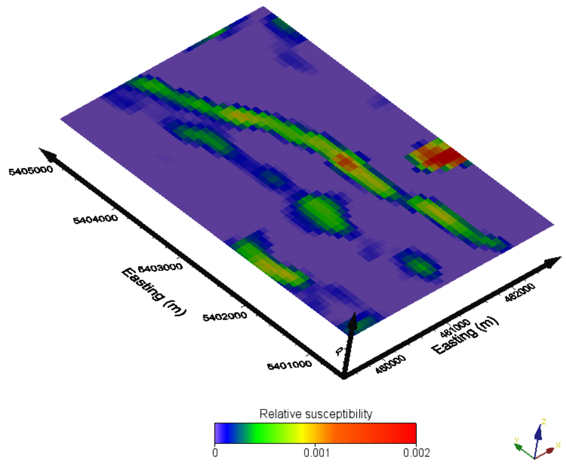

Figure 5. *Horizontal cross section extracted from 3D susceptibility model obtained from 3D TMI inversion. Note the NNW-striking Proterozoic diabase dikes.*

Lithological classification via self-organizing maps

The MEGATEM, FALCON, and TMI inversion results were all regridded to a common 3D earth model with over 212,000 cells. This multi-attributed 3D model was input to our self-organizing map (Fraser and Dickson, 2007). The inversion results were classified into eight lithological groups. The resulting model is shown in Figures 6 and 7. We have observed good agreement between our pseudolithological model and those results obtained from drilling (OGS, 2000).

Conclusions

It is important to extract maximum information from multiple 3D inversions via quantitative interpretation. To that end, we have demonstrated how self-organizing maps (SOM) can be used to produce 3D pseudolithological models from independent 3D inversions of airborne geophysical data. With no a priori information used in any of the 3D inversions or the SOM, we were able to produce a 3D geological model of the Reid-Mahaffy test site that corresponds very well with the known geology as inferred from drilling. While further research is needed, our approach bodes well for 3D integrated interpretations of multisensor airborne geophysical surveys.

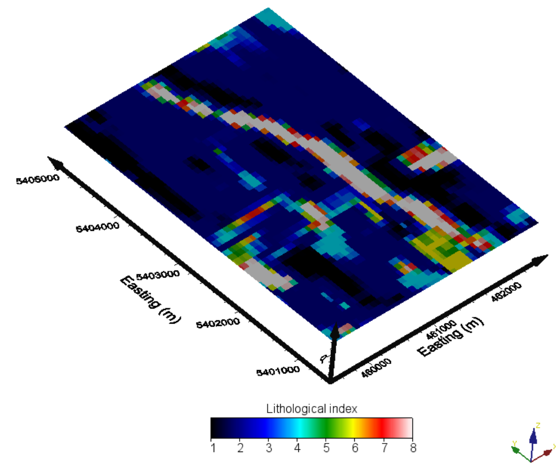

Figure 6. *Horizontal cross section at 50 m depth extracted from 3D pseudolithological model obtained from SOM analysis. The discrete units of lithology 8 (white) correlate with known Proterozoic diabase dikes.*

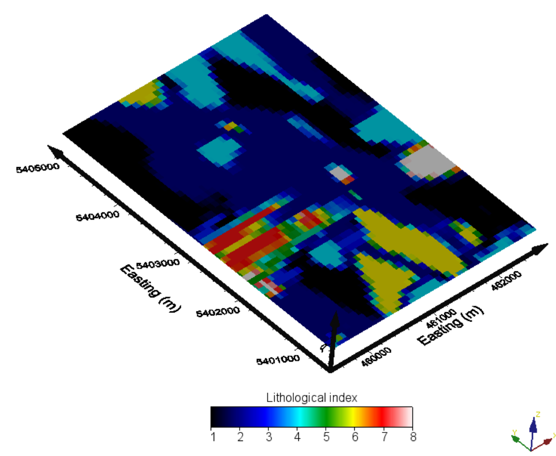

Figure 7. *Horizontal cross section at 100 m depth extracted from 3D pseudolithological model obtained from SOM analysis. The discrete units of lithology 7 correlate with known sulfide mineralization.*

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EDITED REFERENCES

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