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Case studies in integrated geological and geophysical 3D modelling: Value added to exploration and mining projects

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SUMMARY

The integration of geophysical with litho-structural models represents a valuable tool for better understanding of subsurface geometries of lithological contacts. Improved subsurface models add value to mineral exploration projects. Geophysical data is used to enhance and validate litho-structural models. The regular distribution of geophysical data allows lithologies and faults to be extended from observed locations into the subsurface. Geological models are validated and improved by comparison of the geophysical signal calculated from the model geology with the observed signal. Discrepancies between modeled and observed signals highlight areas requiring refinements of the geological model.
The case studies present examples of how iterative modeling from geological and geophysical data will result in an improved final product. The calculated geophysical signal from two distinct geological interpretations shows how well a certain litho-structural model conforms with the geophysical data. Applications are in determine the position of rocks of distinct physical properties, checking the geometry of faults and extending mapped structures into inaccessible/covered areas.

Key words: subsurface geophysical and structural modeling, iterative models, geometry of lithologies and structures

INTRODUCTION

The type of data input, Geophysical and geological subsurface models are distinct in terms of their data distribution and resolution, modelling workflows, and the time of their creation in the mine life cycle. As a result of this, the district- to deposit-scale 2D-4D models developed in support of mineral exploration and mining projects suffer from a poor integration between geology and geophysics. This contribution aims to demonstrate the advantages of increased cross-disciplinary collaboration in 2D-4D subsurface modelling.

A distinct advantage of using data acquired through geophysical surveys for modelling is the even distribution of data over an area of interest. For this reason, geophysical models may be constructed for early-stage exploration programs where the subsurface geology is ill-constrained. For this purpose, 3D inversion of geophysical data and semi-automatic interpretation routines are becoming increasingly popular for building geophysical models. However, automated inversions do not always result in geologically sound models.

With increasing geological data collected during an early-stage exploration programs, the geophysical models need to be revisited to determine how well the models conform to the acquired data. However, geological data are commonly irregularly distributed as a result of the distribution of boreholes, or the availability of underground or surface exposures. The 2D-4D geological model is, therefore, constrained in its lateral and depth extents by the location and density of observation points.

Despite the complementary nature of geophysical and geological data, available geophysical data are often not integrated in geological models (and vice versa). Without their proper integration, reconciliation of geological data (faults, contacts, stratigraphy) with geophysical data (maps, sections and block models) will remain a challenge.

In the presented cases, limitations imposed on litho-structural model by irregular data distribution are counteracted by the regularly spaced data from geophysical surveys. The case studies show examples of how iterative modeling from geological and geophysical data results in an improved final product. The models presented herein aim to determine the position of rocks of distinct physical properties, to evaluate fault geometry and to extend structures from mapped locations into inaccessible/covered areas.

CASE STUDIES

(1) Structurally constrained magnetic modelling & indirect targeting, NWT-Canada

The first example is a Fe-ore exploration project in the North West territories (NWT), in Canada. The area is within the Mackenzie sedimentary platform, which is filled by Late Precambrian sediments, including mixtites with abundant evident of glaciogenic deposition. Of interest for exploration is an Fe-formation within the Rapitan group (Yeo, 1986). Figure 1 shows the regional geology of the area of study. Of interest is the Precambrian Rapitan formation (Hr, dark blue). All the other formations are limestones and dolomites from Precambrian to Silurian and Devonian. The Rapitan formation includes the Fe-formation of interest (mostly hematite), which is covered by a very magnetic conglomerate, and underlain by a less magnetic conglomerate package. A 300m line spacing magnetic survey was flown over the area. Initial results were promising based on the preliminary assessment of "large magnetic anomalies". However, initial field recognition established that the Fe-formation was basically non-magnetic when compared to the 2 conglomerate units located above and below the formation of interest. Rather than just abandoning the dataset in search for other geophysical techniques, it was decided to perform 2.5D section modelling. Structurally, the area shows thrusts and faults but no major folding or tilting of sequences. Thus, by combining simple stratigraphic principles with the aid of the magnetic modelling we were able to discern areas where the magnetic conglomerate was at surface or buried (and thus the Fe-formation was likely still present underneath) from those areas where the less magnetic conglomerate was on top (and therefore the fe was already eroded).

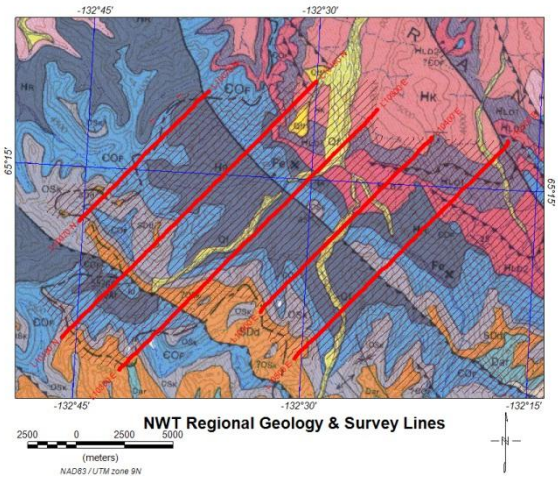

Figure 1: Regional geology, magnetic survey lines (black) and modelled sections (red) over the NWT case.

The construction of these sections required the close integration of structural geology to determine possible faulting directions, with geophysics to perform the actual model. This exercise allowed the exploration company to obtain a map of target zones with depth to top to the Fe-formation.

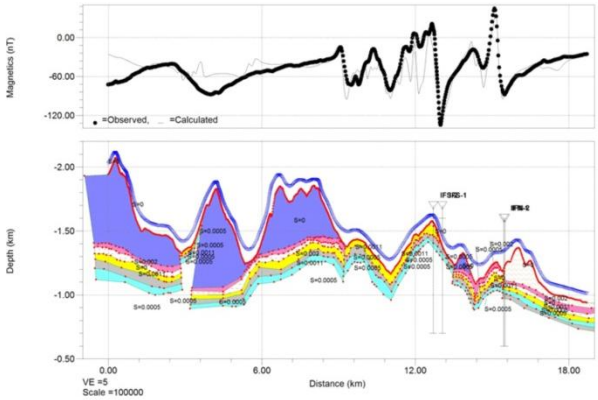

Figure 2: Example of one of the modelled sections (vertical exaggeration 1:5). Blue: younger (Silurian-Devonian) Carbonates; Pink: magnetic conglomerate unit; white: IF; yellow: less magnetic conglomerate unit underlying the IF; gray and light blue: other non-magnetic formations underlying the target Rapitan formation.

(2) 3D Geological modelling program in Mexico with geophysical support at depth

The second example describes an exploration project in Mexico. In this case there was sufficient geological data (surface mapping and borehole information) to build the base of a 3D geological model. However, the data was insufficient to constrain the continuation of some units at depth beyond the drilling constraints.

The 3D geological model was built in 2 stages:

1) Fault modelling: To create the structural framework of the geologic model, it is necessary to define the position and orientation of first order structures. Faults will be modelled from youngest to oldest, as the younger structure will offset the older structure. The modelled faults need to be extended to terminate at the model boundary, as the faults are subsequently used to subdivide the area of interest into fault blocks.
2) Lithology modelling: lithological contacts are modelled within each fault block separately. The position and orientation of lithological contact on surface and in boreholes are used to construct contact surfaces. Knowledge of the depositional environment (in weakly deformed sedimentary sequences) and dominant regional structures (e.g. orientation of folds and foliation in deformed rocks) is useful for extrapolating contact beyond observed extents.

After the basic model is built, it is checked for consistency. In this process variations in layer thickness and offset direction and quantity along faults are measured and verified. Figure 3 shows the regional geology over the area of study, as well as RTP magnetics.

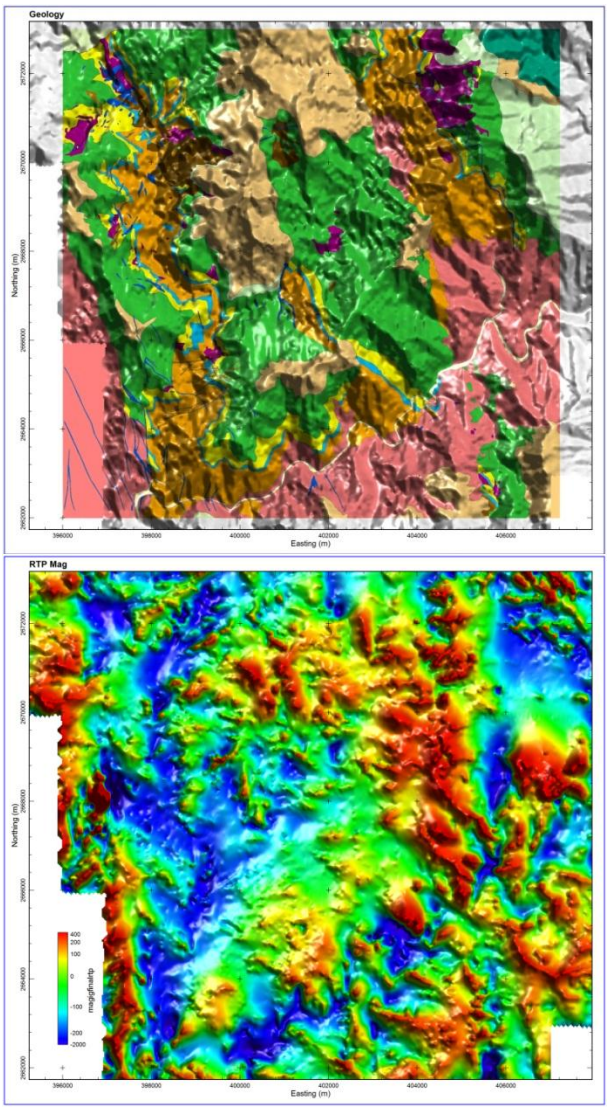

Figure 3: Top, regional geology (pink: granitic intrusives; green: andesites; orange and brown: rhyolites); Bottom: RTP magnetics. Both images are draped over topography.

The magnetic data shows a good correlation with structures and lithological units. The granites dominate the magnetic signal, whereas rhyolites follow low magnetic zones.
The geological model (Figure 4), especially the geometry of faults at depth, is validated using aeromagnetic data, by testing whether the modeled geometries can reproduce the observed geophysical signal. The validation is performed by extracting cross-sections from the geological model (Figure 5).
These sections serve as the basis for calculating the magnetic signature of the modeled lithologies. Magnetic susceptibilities for each of the outcropping rock types were varied, within given ranges to the respective lithologies, to best match the amplitude of the observed signal.

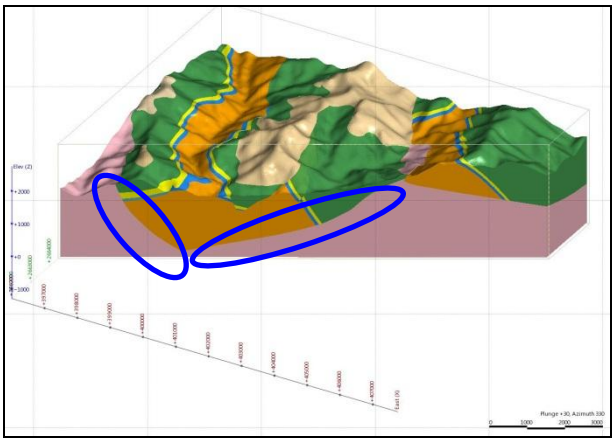

Figure 4: Oblique view of the initial 3D Lithology model. The areas marked in blue are the ones that require further control, since they are beyond borehole constrain.

In the first section, the calculated signal closely resembles the observed signal in areas where igneous rocks are exposed at surface (Figure 5A). A second section was extracted from the geological model and its modeled magnetic signal was calculated using the same rock properties as in the first section. In areas of surface exposure of the igneous rock, the calculated signal deviates significantly from the observed signal (Figure 5B). To adequately replicate the observed magnetic signal of the igneous rock, different susceptibility values are required for each of the sections. This suggests that the lithology marked as a single unit in the geological model varies significantly in its composition.
Variations in peak/low width and position between the calculated and the observed signal indicate a mismatch between the modeled and the "observed" geometry of lithologies. The thickness, dip and distribution of rock units, as well as the dip of faults are modified to better replicate the observed magnetic signature. This process adds detail to the existing interpretation
Using expected values for various compositions of volcanic and igneous rocks, we were able to determine to position of rock units at depth, especially by refining the contact geometry in areas lacking direct geological observations. Additionally, the forward modelling of magnetic data highlighted internal variations in rock units, instigating continuing studies into the subdivision of a previously assumed to be homogenous unit.
Correlation of litho-structural models with geophysical models can be significantly enhanced by acquisition of physical rock properties of each of the modeled lithologies.

(3) Greenfields Exploration program: Airborne EM & Structural interpretation

The third case we show is a greenfields exploration example where knowledge of local geology is mainly sourced from surface mapping. Aeromagnetic and EM data acquired in the area provide insight into the subsurface geometry of a structurally complex fold and thrust belt. This fold and thrust belt has been interpreted

as a series of parallel thrust faults as well as anti- and syncline trains. In this model we test for the possible locations of thrust faults dipping in the opposite direction.

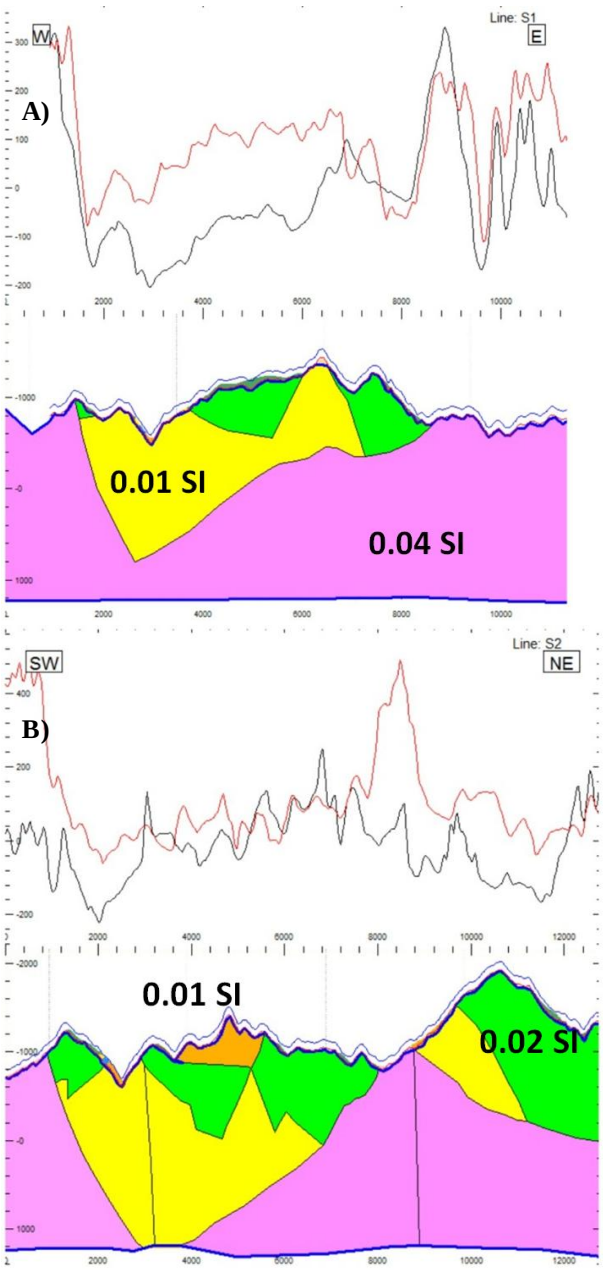

Figure 5. Sections extracted from the 3D Geological model and reproduced during a magnetic forward model. Pink: intrusives; orange and yellow: rhyolites; green: andesites. A) First section extracted. Notice the good match between computed and observed signal over the granite outcrops on the right; B) Second section extracted and computed with same physical properties as on A); notice that this time the computed signal over the intrusives in the middle does not match the observed.

By extracting a series of sections from the surface geology maps and simplifying the lithologies into geophysically distinct units (metasandstones, metagabbros and –iron formations), magnetic and EM data are modeled on these sections to determine the dip and position of conductive units and units with high magnetic susceptibility (i.e., iron formations). In the CDI EM sections, graphitic metasediments are modeled as inclined slabs. The distribution and geometry of the gabbroic units and iron formations are modeled from the magnetic data.

The geology model includes a series of thrust faults as well as anticline and syncline trains. The dip and direction of thrust faults are based on interpretation. The dip and extent of these physically distinct lithological units are modeled in a series of cross-sections from the aeromagnetic and EM data. The distribution and orientation of the lithologies provide constraints on the possible fault geometries. The case study identifies the location of possible back-thrusts, i.e. reverse faults dipping in the opposing direction as the majority of the thrusts in the fold-and-thrust belt.

CONCLUSIONS

This work highlights the improvements to lithology and structural models by using iterative feedback with geophysical modeling. It is often thought that the input from geophysics ends as soon as detailed 3D geological models are constructed from boreholes and surface mapping. However, geophysical models can successfully add value to these existing litho-structural models by:

1) Refining the distribution of rock units and the geometry of lithological contacts;
2) Testing structural interpretations (fault orientation and extent, magnitude of displacement);
3) Redefining the subdivision of units based on their magnetic signature;

The quality of integrated geophysical and geological models hinges on the constraints by physical rock properties. This means that lithological contacts can be modeled more accurately between units of highly contrasting rock properties. Large variations in rock properties within a single unit decrease the accuracy of modeled contacts. Structures can be modeled directly if they are associated with a change in rock properties, or indirectly if they shift the geometry between units of distinct physical properties. Although one can associate a small range of physical properties to the observed lithologies on surface and then iterate these properties within that range until the amplitude of computed and observed geophysical anomalies match, this would only work on a situation where the geological model is well known and constrained by boreholes. In all the more common situations where the dip of the geological units and their distribution at depth is unknown, the above methodology is insufficient.

REFERENCES

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