

User Guided Inversion & Visualisation of Interpretation Confidence

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SUMMARY

Potential field data inversion strategies can be broadly categorised as either following a pure processing approach or one that is geologically guided. The pure processing method is often defined as objective, whilst the geologically guided approach is subjective, the inference being that subjective is “not good”. Objective approaches are reproducible. If you apply the same parameters then you will get the same result, whereas subjective methods can produce a different result depending upon the starting model and processing path.

Pure processing methods transform the potential field data into information that generally resembles a fuzzy view of the geology. Examples include Euler deconvolution, Werner deconvolution, Naudy inversion and unconstrained UBC voxel inversions. Each of these methods uses simple geological concepts and tries to apply them to every anomaly. Some recent developments in the Euler method try to automatically determine the most appropriate structural index, but there is no guiding geological hand to arbitrate.

We use the term “user guided inversion” to describe the subjective inversion process where inversion is a tool used to help create a model that matches the geophysical data and available geological constraints. In this context inversion is a productivity tool to build a geological model, rather than an end in itself. As soon as we introduce appropriate geological thinking, the inverted parameter quality is improved for properties such as magnetic susceptibility, density, depth and boundary locations.

Geological constraints can be in the form of hard facts from drilling or outcrop data or deduced constraints. These are based on the concepts of geological mapping of the potential field data and the application of a regional geological environment that is appropriate for the survey area.

One of the challenges for the geophysicist is the need to transfer our understanding of the confidence in our interpretations to the geologist. We present some new ideas for quantifying and visualizing our interpretation confidence. The dominant parameters that we will use include sample density, sample quality, geological model confidence and algorithm confidence. 3D visualization of confidence superimposed on the geological model is introduced as a viable method for conveying the essence of the interpretation to a non-experienced user of the results.

INTRODUCTION

We have limited the discussion on user guided inversion to the context of exploration below cover where a steeply dipping basement geology is truncated at an unconformity and covered by rocks that are non-magnetic and have only limited lateral variation in density. In the magnetic case, the truncated surface of the magnetic rocks contributes approximately 80% of the amplitude of the associated magnetic anomalies.

In support of this assertion we introduce a simple model test for a bedded magnetic unit. The unit has the same top depth for all tests (50m), but the depth extent and dip are allowed to vary. Depth extents of 200, 500, and 1000 metres along with dips of 60, 70 and 80 degrees are used as test cases.

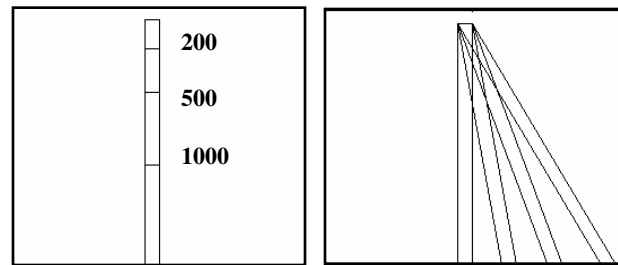


Figure 1. Test models used to produce data models for inversion with a vertical body of large depth extent.

A model with 5000 metre depth extent and vertical dip is inverted against the model data for each of the above cases and the results are illustrated in figure 2. In each case the red residual curve is less than 20% of the anomaly amplitude. Only at a dip of 60 degrees does the residual start to approach 20% of the anomaly amplitude.

These results confirm the dominance of the unconformity surface in the recognition and mapping of geological boundaries. If we accept this point, then the remaining magnetic response is made up of contributions from rocks at greater depth and interfering contributions from adjacent rocks. It follows that it is very difficult to deduce much about the magnetic property distribution below the unconformity without the constraints of a reasonable geological model.

We introduce different methods of applying the constraints of a geological model to an inversion process that varies from simple to complex. Each method relies heavily on the dominance of the unconformity surface to produce reasonable inversion outcomes.

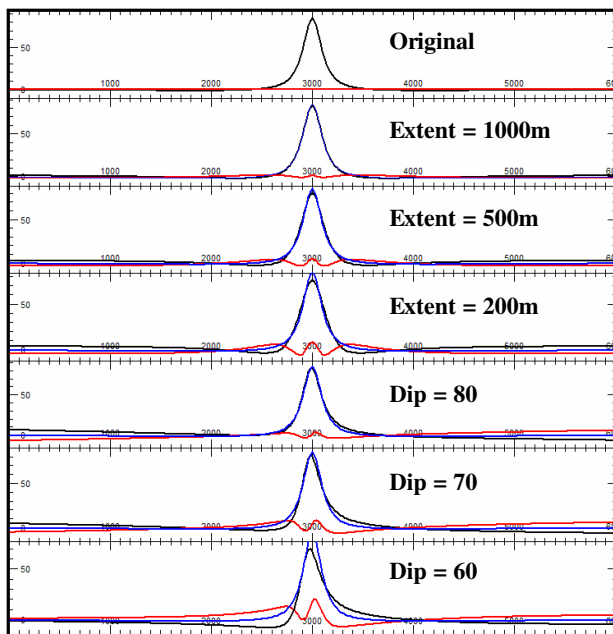


Figure 2. Inversion results (blue) against the test model data (black) and the residual difference (red) illustrate the dominance of the top surface (unconformity) of the model.

AUTOMATED METHOD

There are many automated methods of 2D and 3D interpretation where the primary objective is the determination of the depth to the magnetic source along with other physical properties. Examples include Werner Deconvolution (Werner, 1953), Euler 2D (Thompson, 1982), Euler 3D (Reid et al. 1990) and Naudy (1971). A specific implementation of the Naudy method called AutoMag (Pratt et. Al. (a), 2005, Shi, 1991,1993) is used to illustrate the integration of user-guided inversion into an automated method.

The Naudy method automatically locates each separable magnetic anomaly and determines the best fit for a simple geological edge or thick sheet solution. For an interpreter, this method has the same limitation as all other automated methods. The automation removes the interpreter from the procedure and hence limits confidence in the geological merit and numerical precision of the solution. Interpretation is an iterative analog process and this loss of contact with the process decreases the ability of the interpreter to make well informed decisions about the probable geological cause of the specific anomaly.

In the AutoMag case, solutions can be converted to specific geological objects that can be tested numerically for their success in explaining the observed magnetic field and visually for geological viability. This restores the link between interpretation and the appropriateness of a particular solution. An example from the Elkedra aeromagnetic survey in the Northern Territory, Australia, illustrates how a suite of individual solutions can be converted to a meaningful geological solution. In this case, solutions are combined to define the limbs of a synclinal fold.

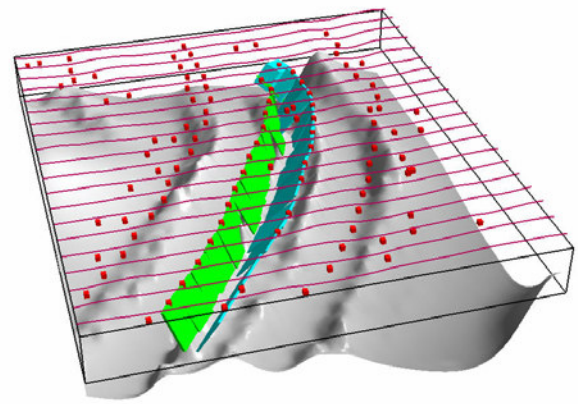


Figure 3. An example from the Elkedra survey where the AutoMag solutions have been interactively converted to their equivalent model representation to outline the limbs of a synclinal fold.

EXPERT SYSTEM METHOD

The manual creation of realistic geological models is time consuming and automated methods can only apply simple geological concepts to the inversion of potential field data. The expert system method was developed to fill a gap between the two extremes and provides geoscientists with a fast method for building 3D interpretive geological models (Pratt et.al. (b), 2005).

The method is illustrated in Figure 4 where the interpreter selects the magnetic anomaly for interpretation, chooses a geological style to be applied during inversion and then applies the inversion procedure. The process sounds simple, but it must be broken down into a series of small steps that mimic the processes that would be applied by an experienced interpreter. These include:

- Preliminary regional assessment
- Anomaly detection
- Anomaly interference detection (overlap)
- Assessment of shallow geological noise
- Isolation of the anomaly
- Secondary regional assessment
- Extraction of seed model from anomalous data
- Regularisation of seed model with the target style
- Iterative inversion against the target geological style.

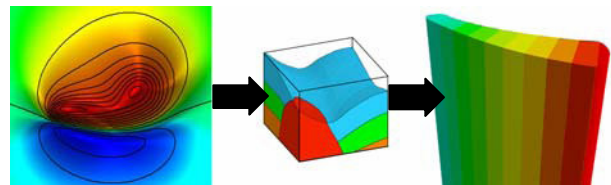


Figure 4. Illustration of the expert system procedure where the interpreter selects an anomaly, chooses a geological style and then performs the inversion to produce a geological model that is consistent with both the data and the geological style.

The inversion engine uses a minimisation criteria that balances the RMS of the data mismatch with the RMS mismatch in the geological style. This method frees the interpreter from having to tune every parameter that is associated with the target

geology and allows for rapid testing of minor changes in the style.

The concept behind a mathematical definition of geological style is managed by making some simple assumptions about the geology. These are:

- the upper surface of the model is terminated by an unconformity,
- the model can be approximated by a small number of tabular blocks,
- the blocks are connected by an invisible string that runs along the unconformity surface at the centre of each block,
- the vertical and horizontal path of the string are constrained by the geological style and
- other properties such as magnetic susceptibility, thickness and dip can be allowed to vary along the axis of the string in a way that is consistent with the geological style.

Figure 5 illustrates two geological styles. One shows a curved unconformity surface where the horizontal string position curves along the axis as its depth increases. The width of the blocks increase along the model axis. The second model shows a vertical fault that is defined by a break in the string.

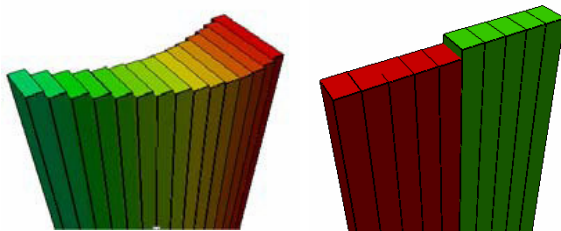


Figure 5. Illustrates the construction of 3D geological shapes from a sequence of linked blocks.

Figure 6 illustrates the application of the method to the magnetic anomaly associated with Minotaur's Prominent Hill discovery. The data was provided from the regional magnetic dataset of Australia by Geoscience Australia.

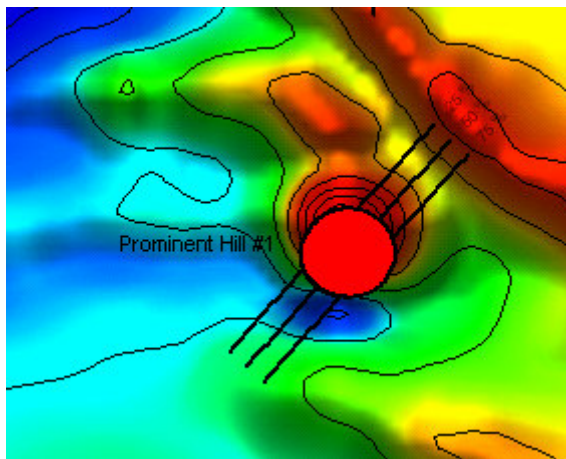


Figure 6. Expert system interpretation of the Prominent Hill anomaly using an elliptical shape constraint to replace the width parameter.

The method can be used to construct a wide range of geological models that are appropriate to rapid interpretation of large survey areas. The dominant target models in this application include dykes, folded volcanics and intrusive plugs.

Not all problems can be accommodated by the multi-body, multi-parameter method, but where it is applicable, it offers a very fast solution for important information such as depth, magnetic susceptibility and precise edge location.

MULTI BODY PARAMETRIC METHOD

The multi-body, multi-parameter method is designed specifically to allow the user to build geological models that are consistent with existing geological knowledge and the potential field data. Simple 3D shapes can be created quickly and combined to form almost any 3D geological model. Figure 7 illustrates a range of simple shapes that can be parameterised for rapid manual editing and inversion (Pratt, et.al. (a), 2005). Figure 7. Simple shapes used for rapid editing and inversion including the sphere, ellipsoid, horizontal polygonal prism, plunging polygonal prism, tabular body and frustum.

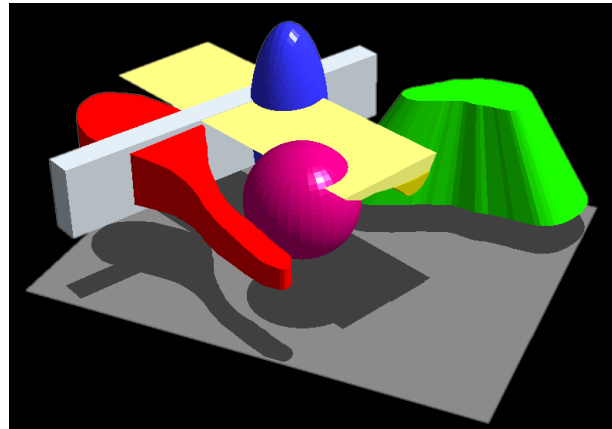


Figure 8 illustrates the results from a geological study of the Tanami region in the Northern Territory, Australia, where several hundred dipping magnetic units flanking a granite have been inverted to determine their depth, susceptibility and dip. Each body in the model is derived from a simple tabular body that is reconciled across all flight lines. In this case, the interpreter creates each body within the model and applies a geological decision regarding the orientation and strike length before using inversion to do the final model tuning. The computed response of the inversion is shown in Figure 9.

The inversion was also used to reconcile the regional gravity data (not shown) so that the final geological model can be used to simulate the expected outcomes from an airborne gravity gradiometer survey. A simulation of the BHP Billiton Falcon system was created for each of the original flight lines and then filtered to match the resolution of the Falcon system (Figure 10). Because access to BHPB Falcon gravity gradiometer survey data was restricted at the time of this exercise, it was possible to answer a range of questions regarding the probable geological outcomes from a large airborne gravity gradiometer survey.

CONSTRAINED UBC INVERSION

The University of British Columbia Geophysical Inversion Facility has developed voxel based smooth inversion software that can be run without any constraints to provide a continuous model of subsurface magnetic or density variations (Li & Oldenburg, 1996). It is widely used without constraints, but the best results are achieved when geological constraints can be applied to the inversion.

To illustrate this principle we use a case history from the San Nicolas VMS deposit in Mexico. The San Nicolas volcanogenic massive sulphide deposit was discovered in 1997 near Zacatecas, Mexico by Teck Corporation (Johnson et al, 1999). The target deposit has a high density, is truncated by an unconformity and is covered by up to 100 metres of sediments.

Figure 11 shows the results of an unconstrained UBC GRAV3D, gravity inversion where the isosurface response intrudes through the unconformity. Without constraints, the inversion ignores the knowledge of an unconformity.

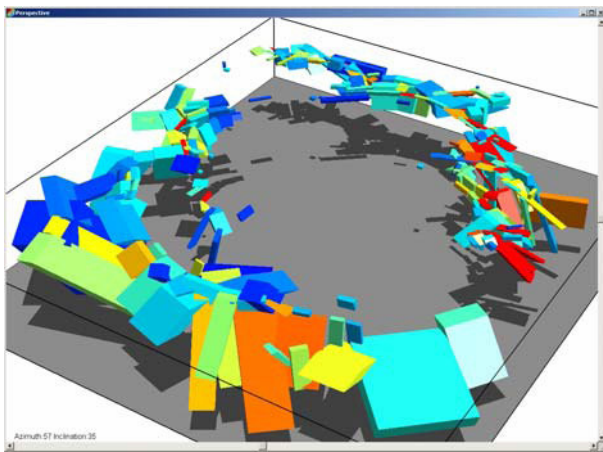


Figure 8. Multi-body inversion of dipping magnetic units surrounding a large granite.

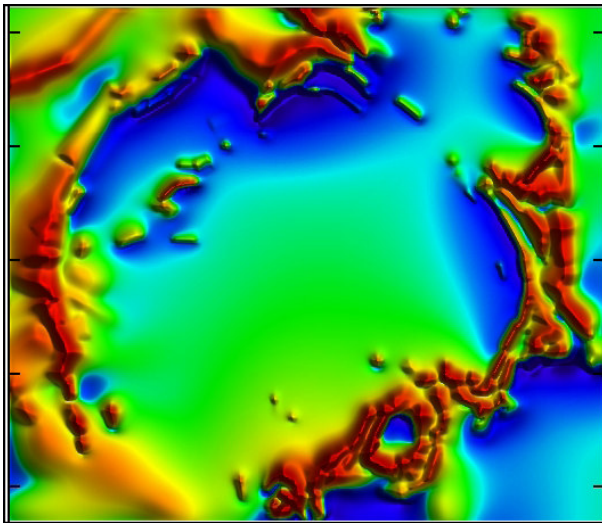


Figure 9. computed TMI from inversion model.

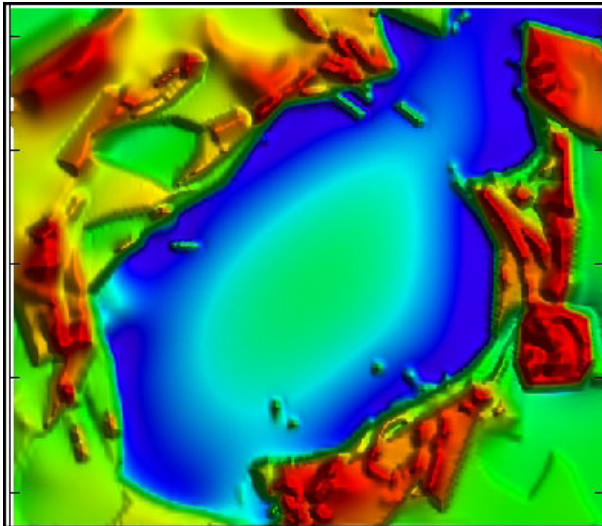


Figure 10. computed airborne equivalent G_{zz} from the inverted magnetic model.

Although the models have simple shapes, the examples above show that you can build complex geological models by using many different objects to build the ultimate model.

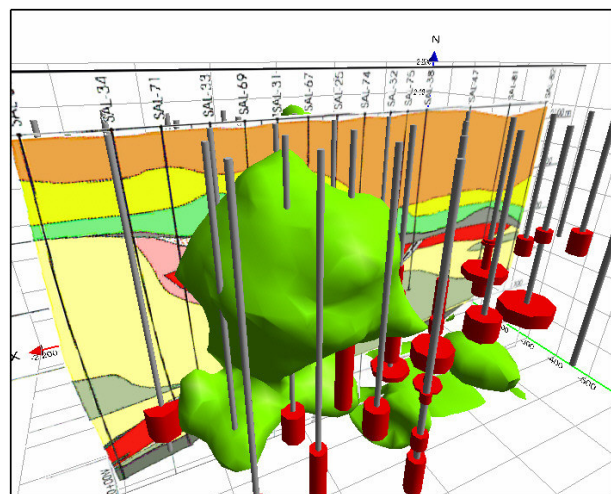


Figure 11 Unconstrained UBC inversion of the San Nicolas VMS deposit gravity data. The drillholes show the distribution of the Cu assays.

By using the simple target model, we calculated the depth using parametric modelling for both the magnetic and gravity data to provide the depth of cover constraint and then used the gravity model as a seed model to constrain the UBC inversion (Figure 12).

VISUALISATION OF CONFIDENCE

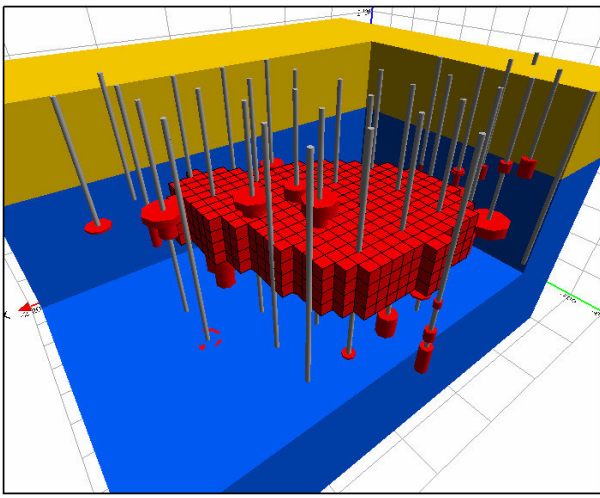


Figure 12 Parametric model used to constrain the UBC GRAV3D inversion. The model shows the overburden in yellow, basement rocks in blue and target in red.

The regional gravity field derived during the parametric modelling was subtracted from the gravity data prior to inversion and bounds placed on both the target and basement density ranges for the inversion. The results of the inversion are shown in Figure 13 and illustrate the improved target mapping when the unconformity model is used as a simple constraint. The blue body is the starting model derived by parametric inversion.

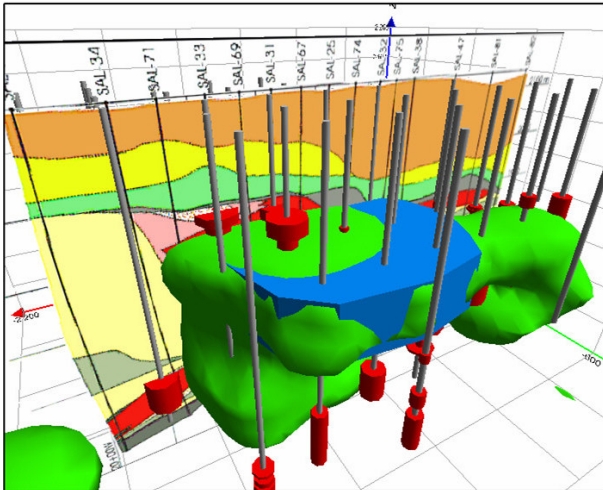


Figure 13 UBC GRAV3D inversion after the application of simple geological constraints and depth information derived by parametric inversion.

The above results were achieved without knowledge from a single drillhole, just the application of simple geological principles. As new knowledge is added with drillhole samples, the parametric models can be used to extend the zone of influence well beyond the hole to constrain further modelling of the deposit. The application of the two methodologies, could reduce the number of drillholes required to test this deposit style as long as there is a strong correlation between density and the commercial commodity.

Interpretation confidence is influenced by many factors that should be defined as part of the goals for each project. Our main focus covers the development of a working definition for a model based 3D confidence distribution and methodology for calculation and visualisation of confidence. Factors that also influence interpretation confidence include data density, data quality (especially for old surveys), geological model confidence, regional field separation, anomaly overlap and shallow geological noise.

At the start of this paper we propose the concept that it is very difficult to deduce much about the magnetic property distribution below the unconformity without the constraints of a reasonable geological model. In this section we explore this difficulty and provide a methodology for calculation and visualisation of interpretation confidence.

When geophysicists model their data through forward modelling or inversion, they quickly develop an understanding of the sensitivity of different parts of their geological model, but this knowledge is implicitly difficult to convey to a consumer of the model results. We propose a simple definition for the term inversion “confidence”. Anomalous magnetic material at each point below a magnetic anomaly (Figure 14) either exists or it does not exist. The confidence that it exists can be assigned a number between 0 and 1 where 0 means it does not exist and 1 means that we are 100% confident in its existence at this point.

A perfect inversion match does not mean that the result is truly representative of the magnetic properties of the subsurface. It indicates one of an infinite number of possible solutions, however, if the model is plausible, then we have a high degree of confidence in that distribution. In practice, we cannot achieve a perfect match and may accept a solution that has an rms (root mean square) match of 1 or 2 per cent as a good match for a 3D inversion. We can explore confidence by analysing the distribution of all model results that produce a match of 2 per cent or better.

We chose an elliptic pipe model as shown in Figure 14 for the purpose of the experiment and computed the results along a set of flight lines designed to simulate an airborne survey.

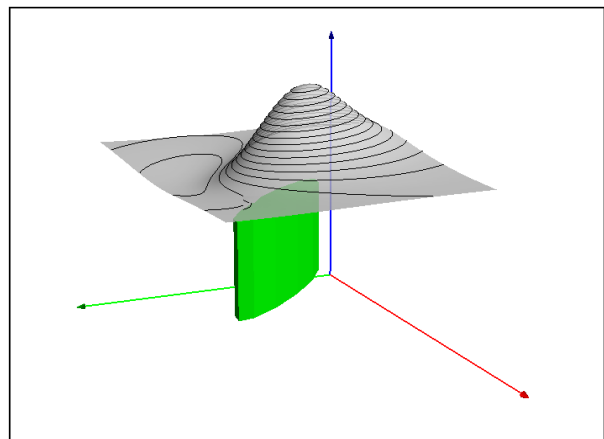
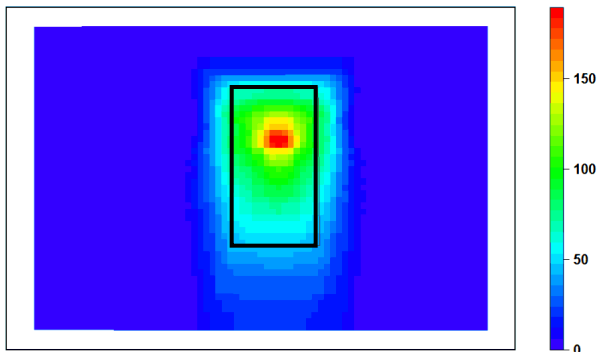


Figure 14 Elliptic pipe model with depth = 500 m below sensor, primary axis 200 m and secondary (strike) axis 1000 m. The 3D surface depicts the shape of the magnetic field above the model.

A total of 218 successful inversions were run using different starting models that perturbed the dip, depth, depth extent, axis length and map position. The results were binned into a 3D voxel model where the value of the voxel was incremented by 1 if the inversion model passed through the cell. Figure 15



shows the results of a vertical section through the binned voxel model near the centre of the elliptic pipe.

Figure 15 A colour coded slice through the voxel model showing the number of times inversion models occupied a cell in the voxel model. The rectangle shows the outline of the original model. The measurement surface is along the top of the dark blue rectangle.

Figure 16 shows the confidence distribution as a series of slices inside the original model where a cutoff threshold along each slice through the voxel model is set to 50% confidence. The combination of the model view and the confidence distribution conveys much of the information needed for use by a user that has not been involved in the model interpretation.

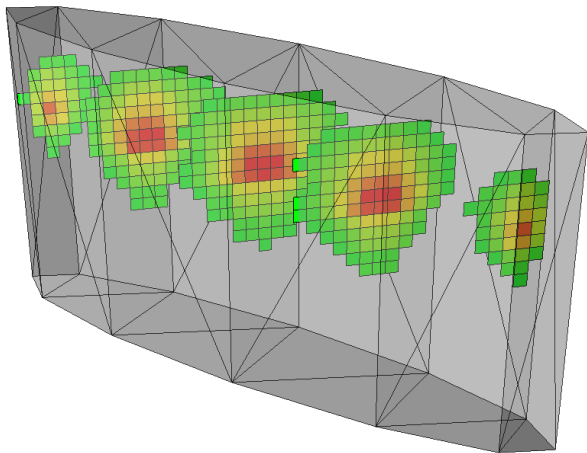


Figure 16 A multi-slice view of the confidence voxel model shown inside the original model where any confidence value below 50% is clipped from the slice.

The confidence cloud is reasonably contained within the original model for a threshold of 50 (~25%), but the maximum confidence is achieved at twice the depth from the surface. We originally expected the maximum confidence to be much closer to the dominant upper surface. The result can be explained by a combination of factors such as dip and depth extent interactions. For solutions with a small depth extent the top of the model drops to compensate. For solutions with a large depth extent, the top of the model rises to compensate. The maximum overlap zone is both beneath the top of most models and above their bases. With regard to horizontal offsets, limits in the possible dip ranges cause the sides of the

model to sweep a limited volume that retains the core of the model.

The confidence halo is only weakly elongate in the depth extent direction and the model provides a false sense of confidence that you can see the bottom of the pipe. In reality, a body with twice the depth extent would show very similar results.

There are some practical implications for exploration targeting that arise from these results. To have a high confidence of intersecting the source of the magnetic anomaly, you should target a drill hole at a central point that is almost twice the estimated depth to the model top. For the purpose of mapping depth to basement, you should take the top of the envelope at a confidence level of approximately 25%. In most depth to basement interpretations, the depth extent of the target anomalies is usually large and the depth underestimation influence cited above will not be relevant.

Figure 17 illustrates different voxel model views of the confidence distribution. At the 25% threshold, the isosurface maps the original target model very closely. At the 75% threshold, the isosurface maps the core high confidence zone and this is optimised for drill targeting as it is common to the majority of inversion models which fit the data with a 98 percent goodness of fit.

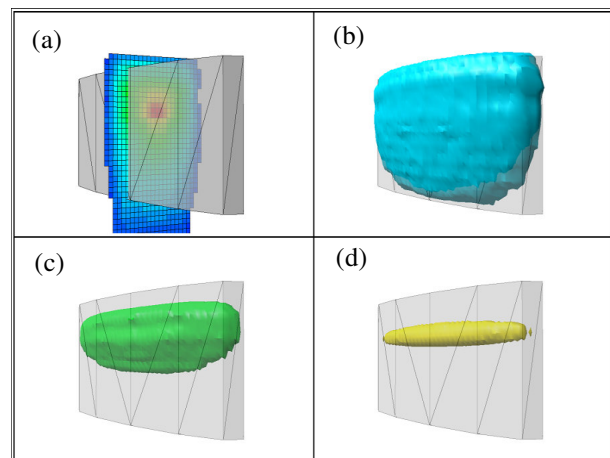


Figure 17 3D visualisation of confidence showing a slice (a), 25% isosurface (b), 50% isosurface(c) and 75% isosurface (d).

CONCLUSIONS

Our research shows the importance of using a geological model to constrain the ambiguity of magnetic and gravity interpretation. We have focussed on the unconformity model to illustrate that this simple constraint can produce quality outcomes. The automated Naudy method, expert system method, parametric inversion and UBC smooth inversion all produce significantly improved results when applied in a manner appropriate to the geological context.

We believe that the interpreter must be guiding the process at all steps to ensure confidence in the outcomes and the appropriate application of geological constraints. Without this interaction, the errors in depth calculations can be large and the proper location of drill targets compromised.

Visualisation of interpreter confidence we believe will provide an important communication tool between the geophysicist and geologist where results can be seen in shades of gray, rather than black and white. The biggest challenge is the automation of the visualisation process, but we believe that it is worth the challenge as improved communication of geophysical interpretation has to produce better exploration outcomes.

ACKNOWLEDGMENTS

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REFERENCES

Foss, C.A. 2003, Resolution of depth extent in modeling magnetic anomalies over shallow sources in rugged terrain. Extended Abstract, 16th ASEG Geophysical Conference, Adelaide, Australia.

Johnson, B., Montante, A., Kearvell, G., Janzen, J. and Scammell, R. 1999, Geology and exploration of the San Nicolas polymetallic (Zn-Cu-Au-Ag) volcanogenic massive sulfide deposit, In: Jambor, J.J. (ed), VMS and Carbonate-Hosted Polymetallic Deposits of Central Mexico, B.C. and Yukon Chamber of Mines Cordilleran Roundup, p. 45-54

Li, Y. and Oldenburg, D. W., 1996, 3-D inversion of magnetic data: *Geophysics*, 61, no. 02, 394-408.

Naudy, H., 1971, Automatic determination of depth on aeromagnetic profiles. *Geophysics*, vol. 36, pp. 717-722.

Pratt, D.A., McKenzie, K.B., White, A.S., Foss, C.A., Shamin, A. and Shi, Z., 2001, A user guided expert system approach to 3D interpretation of magnetic anomalies. (extended abstract) 15th ASEG Conference, Brisbane.

Pratt, D.A., Foss, C.A., Shi, Z., White, A.S., McKenzie, K.B., Gidley, P.R. and Mann, S. (a), 2005, Encom ModelVision Pro, Encom AutoMag - the 3D workbench for magnetic and gravity interpretation, Reference Manual. Encom Technology, 504 p.

Pratt, D.A., White, A.S., McKenzie, K.B., Foss, C.A., Shamin, A., Mann, S. and Gidley, P.R. (b), 2005, Encom QuickMag – Interactive expert system for 3D interpretation of magnetic anomalies. Encom Technology, 193 p.

Reid, A.B., Allsop, J.M., Granser, H., Millett, A.J., and Somerton, L.W., 1990. Magnetic interpretation in three dimensions using Euler deconvolution. *Geophysics* v. 55, pp. 80-91.

Shi, Z., 1991, An improved Naudy-based technique for estimating depth from magnetic profiles. *Explor. Geophysics*, vol. 22, pp. 357-362.

Shi, Z. and Boyd, D., 1993, AutoMag – an automatic method to estimate thickness of overburden from aeromagnetic profiles. *Bull. Aust. Soc. Expl. Geophys.* Vol. 24, pp. 789-794.

Thompson, D.T. 1982, EULDPH – A new technique for making computer-assisted depth estimates from magnetic data. *Geophysics*, v. 37, pp 31-37.

Werner, S. 1953, Interpretation of magnetic anomalies at sheet-like bodies. *Sveriges Geol. Undersok., Ser. C. Arsbok*, 43 (1949), no. 6.