

Interactive user-guided 3D inversion methods for direct geological interpretation of potential field data

David A. Pratt

Encom Technology Australia
David.Pratt@encom.com.au

Clive A. Foss

Encom Technology Australia
Clive.Foss@encom.com.au

SUMMARY

Interactive user-guided 3D inversion represents a methodology for interactive geological interpretation of potential field data. The method uses the direct application of geological principles of interpretation to the inversion of data. The interpreter interacts with the modelling process and guides the inversion to ensure that a model outcome is achieved that is consistent with both the geological knowledge and the data.

Three different methods are presented to highlight the value trade-off between the time cost of the work and the geological value of the outcomes.

An expert system method is introduced where the dominant focus is the rapid inversion testing of different geological styles for interpretation of specific magnetic anomalies. In this method the user only needs to select the anomaly and a geological style to start a complex 3D inversion.

Key words: Inversion, potential fields, magnetic, gravity, modelling.

INTRODUCTION

User-guided inversion is an interpretation methodology rather than an inversion algorithm and this paper shows how it is possible to use interactive inversion to produce meaningful geological outcomes. The importance of this methodology is highlighted when you consider that "every potential field model is an equivalent source solution". This statement reminds us of the inherent ambiguity associated with the interpretation of potential field data. The user-guided inversion methodology is designed to provide a practical solution to the ambiguity problem, by allowing the interpreter to apply a-priori knowledge as inversion constraints.

Three styles of user-guided inversion methods are presented and the relative benefits and limitations of each method are compared.

1. Enhanced Naudy methods for line data (2D)
2. Multi-body/multi-parameter 3D inversion
3. Expert system application of geological styles.

The contributions from each method differ in geological information value and quality and are contrasted with the labour cost of achieving the result.

ENHANCED NAUDY 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 (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.

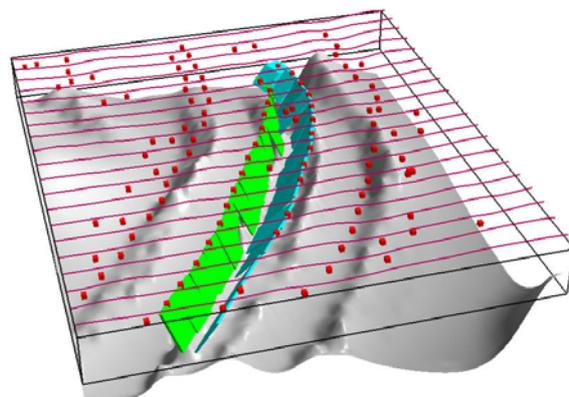


Figure 1. An example from the Elkedra survey where the AutoMag solutions have been interactively converted to their equivalent model representation to outline the limbs of a synclinal fold.

MULTI-BODY/PARAMETER 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 that can be created quickly and parameterised can be 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.

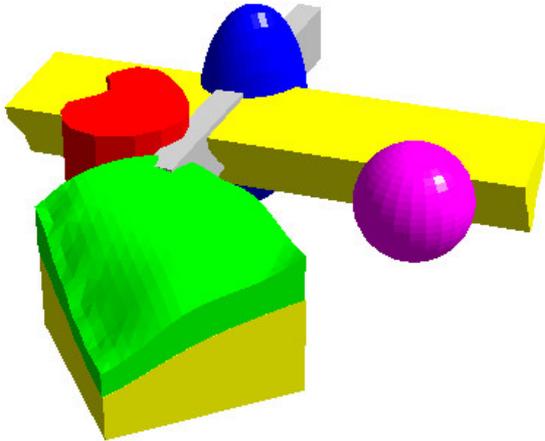


Figure 2. Simple shapes used for rapid editing and inversion including the sphere, ellipsoid, horizontal polygonal prism, plunging polygonal prism, tabular body and general polyhedron derived from individual surfaces.

This method is illustrated with a case history (Foss, 2003) where the method was applied to resolve a question of economic importance to future development of a coal mine. Figure 3 shows the modelling of a discrete anomaly, coincident with a steep hill. This anomaly is well matched by a thin cap of high susceptibility which was digitised to the terrain on each flight line over the hilltop, creating model strips 100 metres wide. Figure 4 shows an alternative model of greater depth-extent. The deeper part of this body broadens the anomaly, and to compensate for this it is necessary to reduce the width of the body. This model is slightly less successful in matching the observed anomaly, as can particularly be seen on the marginal profiles. There is however, little difference between the models in matching the central profiles, and it is clear that single profile inversion is not capable of discriminating between these models.

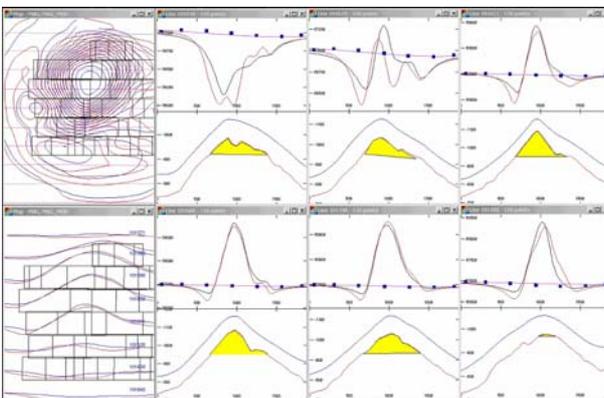


Figure 3 Anomaly 135 thin-cap model cross-sections

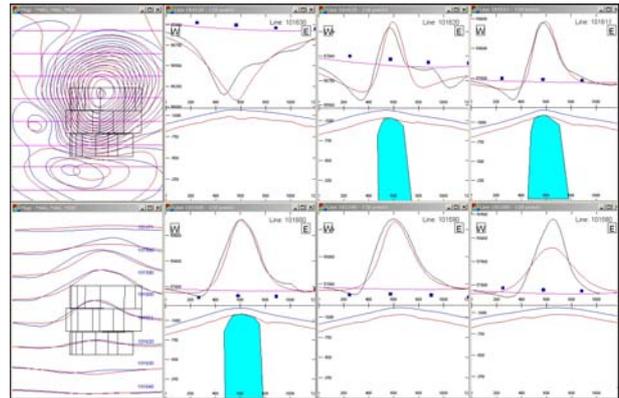


Figure 4. Anomaly 135 pipe model cross-sections

In the above example, the complex shape is developed from a series of polygonal cross-sections that are easy to create, edit and invert. In the case of the volcanic cap, the shape of the upper surface is determined by the terrain and remains fixed. There is some flexibility with the base, but the main inversion parameter is magnetic susceptibility and lateral extent.

Figure 5 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.

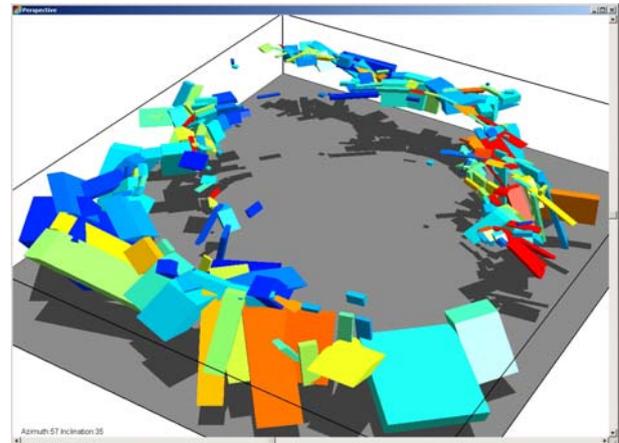


Figure 5. Multi-body inversion of dipping magnetic units surrounding a large granite.

In the above 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 6.

The inversion was also used to reconcile the regional gravity data (not shown) so that the final geological model could 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 7).

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.

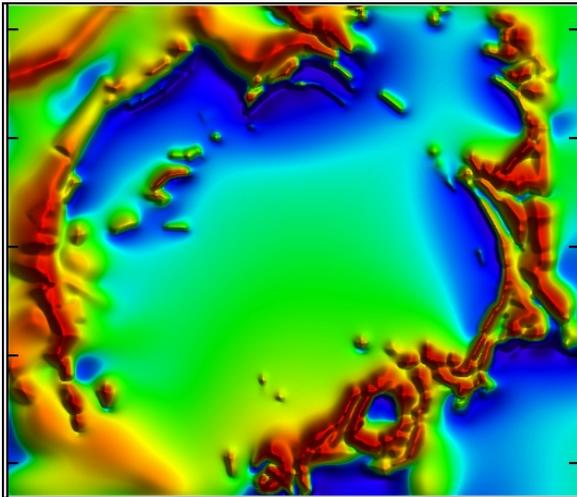


Figure 6. computed TMI from inversion model.

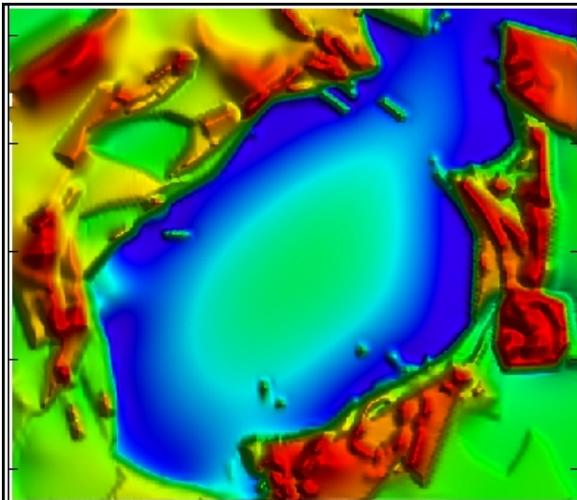


Figure 7. computed airborne equivalent G_{zz} from the inverted magnetic model.

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.

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.

The method is illustrated in Figure 8 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.

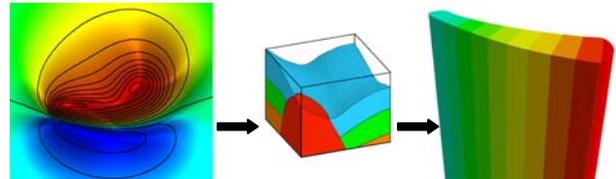


Figure 8. Illustration of the expert system procedure where the interpreter selects an anomaly, chooses a geological style and then performs the inversion to produce a geological model that is consistent with both the data and the geological style.

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 9 illustrates two geological styles. One shows a vertical fault that is defined by a break in the string. The second model 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.

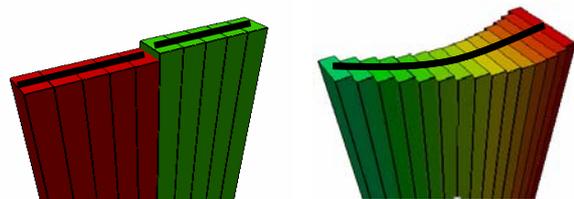


Figure 9. Illustrates the construction of 3D geological shapes from a sequence of linked blocks.

Figure 10 illustrates how the geological constraint is converted to a mathematical definition for shape. If we consider shape in terms of the depth along the unconformity it can take the values of (from left to right) clamped, assigned (known value), constant, sloping, smooth, curved, adaptive and faulted.

PARAMETER	PARAMETER SHAPE CONSTRAINT	CONSTRAINT VALUE
Depth		Dipping unconformity
Susceptibility		Constant susceptibility
Width		Loose change in boundary shape
Position		Smooth curve in model axis
Dip Angle		Clamp dip angle before inversion

Figure 10. The geological style can be defined in terms of the string shape (horizontal axis) and the inversion parameter (vertical axis).

The constraint type can also be applied to the properties of magnetic susceptibility, width, position and dip angle. This permutation of constraints provides the possibility of many different geological shape constraints.

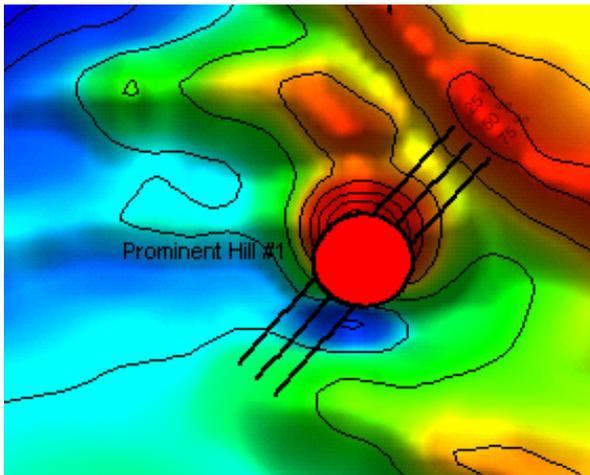


Figure 11. Expert system interpretation of the Prominent Hill anomaly using an elliptical shape constraint to replace the width parameter.

Figure 11 illustrates the application of the method to the magnetic anomaly associated with Minotaur’s Prominent Hill discovery.

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.

The method cannot be applied to all geological problems that 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.

CONCLUSIONS

Each of the user-guided methods discussed here provides the interpreter with a tool that can overcome the fundamental equivalent source limitation of potential field interpretation. By using geological principles to guide or constrain the interpretation, otherwise fuzzy results can be turned into effective geological models to improve exploration decisions.

Importantly, the geological interpreter maintains a direct connection between the model outcomes and the underlying geological principles. At the end of the process, the interpreter also has a good understanding of the sensitivity of various parameters such as depth, dip and physical properties. This knowledge becomes very important during robust geological debate on the design of the next drilling target.

ACKNOWLEDGMENTS

The authors wish to acknowledge Zhiqun Shi, Tony White, Alex Shamin and Blair McKenzie for their significant contribution to the development of the theory and software engineering behind each of these methods. The software products, Encom ModelVision Pro, AutoMag and Encom QuickMag Pro were used to produce the various examples that illustrate the principles of user-guided inversion.

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.
- 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.
- 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.