Integrating geological constraints in geophysical models

W.A. Morris, B. Spicer, P. Tschirhart, V. Tschirhart, M.D. Lee and H. Ugalde*[1]
MAGGIC, SGES, McMaster University, Hamilton, Ontario, Canada
[1]*Paterson, Grant & Watson Limited, Toronto, Ontario, M5H 3B7, CANADA*

Summary

There are three possible schemes by which one can compute geophysical models: discrete body, lithologic surface, and voxel mesh inversion. Each of these model schemes employs three attributes of the anomalous source body: location, geometry, and physical property contrast. The different computational approach employed by the three methods relating to source body geometry causes emphasis to be placed on either the geological or the geophysical data. The discrete body and lithologic surface methods are controlled by prior geological knowledge of the source geometry. In contrast the unconstrained voxel inversion method is driven by the geophysical data. The interpreter is required to decide which of these model schemes is appropriate to each specific problem. For example, when looking at diabase dike geometry in the Sudbury Basin the discrete body method must be used, When attempting regional geological mapping of the Baie Verte Peninsula the lithologic surface method is more practical. Finally, when attempting to model a complex fold structure a constrained inversion approach is most appropriate. Eventually it is anticipated that fully constrained inversions will actually incorporate elements of all three modeling schemes.

Introduction

Through the availability of a number of sophisticated software packages a geophysicist is now able to construct a range of hypothetical models of subsurface geological structures. In the process of developing these models the geoscientist attempts to incorporate all currently available information. This database might include gravity and magnetic surveys, physical property data, surface lithologic contacts with structure constraints, and occasionally borehole logs. Each element of this database contains information that can be used to help constrain the morphology of the proposed 3D geological model. Ideally having more information should help improve one's confidence in the computed model. However, it must be understood that the specific approach to modeling one adopts immediately imparts differential weightings on individual components of the database (Jessell, 2001).

All geophysical modeling schemes incorporate three fundamental attributes of the anomalous source body: a) its location in 3D geographically referenced space; b) its geometry; and c) its physical property contrast. Individual modeling schemes treat these attributes differently. As explained by Jessel (2001) there are essentially three types of geophysical modeling schemes: a) discrete object; b) lithologic surface; and c) voxel representation of a 3D volume. At one extreme the surface modeling approach favours geological constraints since one can readily incorporate known surficial geologic contacts and their geometry into the initial geophysical model. At the other extreme an unconstrained voxel inversion scheme is capable of defining lateral variations in physical property that may occur within what is considered "geologically" tobe a single lithological unit. Depending on the geological feature being modeled a discrete object approach can be advantageous. For example, consider the case of a diabase dike which is commonly associated with a discrete, well-defined magnetic anomaly. Using a simple dipping tabular body forces the contacts of the source body to be sub-parallel in agreement with the geological setting. An unconstrained inversion of this anomaly would result in a source body whose width increased with depth in direct contradiction to the known geological setting.

Through a series of examples we demonstrate that it is necessary for an interpreter to decide which modeling scheme is appropriate to the problem that they are considering. When developing a model the interpreter needs to use all available information (e.g. remote sensing imagery, dip and strike from EM and topographic data) in order to improve their model. We show how one can incorporate results derived from discrete body and lithologic surface models as inputs into the reference mesh for a subsequent constrained voxel inversion. Finally, we predict that as we progressively increase the number of constraints in our inversion models we will be able to map regions of localized alteration that exist in proximity to possible ore bodies.

Discrete Body Method

Sudbury Olivine diabase dikes

The Sudbury Basin Structure which is located at the juncture of the three tectonic domains (Superior, Southern and Grenville) is cross-cut by a suite of diabase dikes (Figure 1). Both age dating and tectonic evidence shows that emplacement of these dikes must predate the terminal deformation event recorded by the youngest Grenville deformation zone. Yet, transformation of an original near

DOI http://dx.doi.org/10.1190/segam2012-0487.1

circular impact crater to its current complex elliptical form must have involved extensive deformation. While most of this deformation has been attributed to Penokean age Orogeny (1.9Ga - 1.83Ga) (Riller, 2005). It is possible that some of this deformation may have occurred during the much younger Grenville deformation.

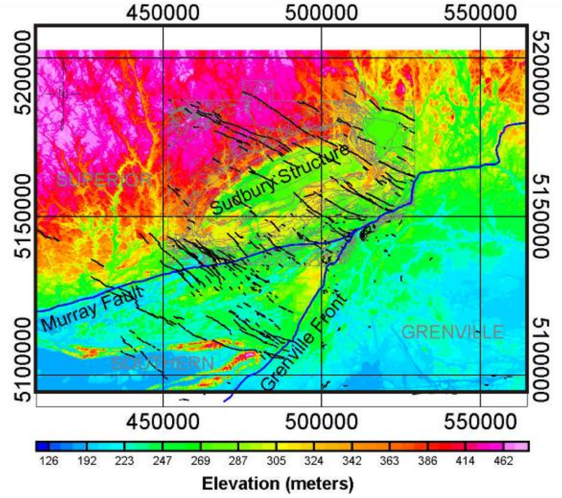

Figure 1: *Topographic image showing relationship of Sudbury Basin Structure to juxtaposition of Superior, Southern and Grenville tectonic Provinces. Locus of dikes (black lines) from compilation of regional scale geology maps.*

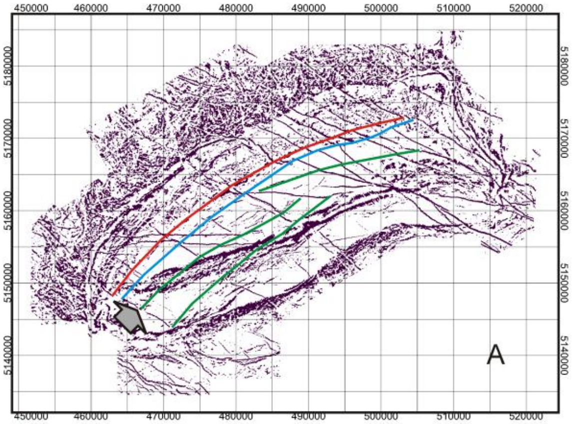

Figure 2: *Binary (black/white) image of first vertical derivative of aeromagnetic data accentuates outline of Sudbury olivine diabase dikes. Locus of faults was identified on basis of lateral displacement of dike anomalies. Only two faults (red and blue lines) exhibit strike slip displacement*

Upon emplacement the dikes would have formed an array of parallel flat sided tabular bodies. Any subsequent deformation should have produced systematic changes in the dip and strike of the dikes. As a result of their limited outcrop it is not possible to directly measure the dip of the dikes. However, the dikes are associated with very distinct magnetic anomaly patterns and as such it is possible to derive dike dip information from the magnetic data (Figure 2).

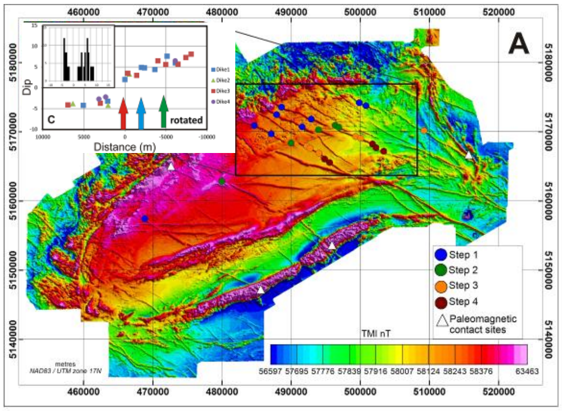

Figure 3: *Aeromagnetic map of Sudbury Basin Structure showing categorized location of model profiles. Inset plot of dike dip versus position across the Basin. Coherence of rotations from dikes indicates block rotation of slabs.*

In this instance a parameterised discrete object model scheme provides an ideal method of addressing the question about possible tectonic rotation of the diabase dikes. A dipping slab closely approximates the expected actual geometry of the dike. In seeking an optimum match between the observed and calculated magnetic field the only parameters allowed to vary were the dip, position (x,y,z location), the susceptibility and remanence intensity. This results in an estimate of the dip of the dike.

A complicating factor in this situation is that the dikes are remanently magnetised. This issue was addressed through an iterative modeling procedure. For the first pass through we used the published Fisher mean in-situ remanence direction for the dikes. Upon completion of the inversion we used the computed dip to rotate the remanence direction and then re-ran the inversion with the new remanence data. This procedure was repeated until there was less than 1 degree of change between inversions (usually less than 3 steps). Plotting the dike dip versus distance across the Sudbury Basin defined a systematic series of rotation steps (Figure 3). Dikes located nearer to the Grenville Front are rotated more than dikes further from the Front. In summary discrete body modeling of the Sudbury olivine diabase dikes indicates that the Grenville Orogeny produced scissor faulting in the adjacent Sudbury Basin.

DOI http://dx.doi.org/10.1190/segam2012-0487.1

Lithological Surface Method

The Baie Verte Peninsula

The Baie Verte Peninsula (BVP) of north-central Newfoundland represents the northernmost termination of the Appalachian mountain belt. While there have been numerous studies describing specific aspects of Baie Verte geology, the last geological map for the BVP was published by Hibbard in 1983. Geological outcrop on the BVP is highly variable. While the coast is often formed of tall cliffs with clear exposure, inland outcrop is generally less than 1% of the total area thus making it difficult to construct meaningful geological maps solely on the basis of outcrops.

Comparing Hibbard's map and the aeromagnetic data suggests the geology map needs revision. Geophysical map images contain information about contacts exposed at the earth's surface and the morphology of the source body in the subsurface. In this instance it was possible to construct an estimate of the 3D distribution of geological structure through the integration of a series of 2D profiles. The geophysical model on each of the profiles was constructed using a lithologic surface model scheme which employed known petrophysical constraints, mapped surficial geological contacts and where possible observed dip and strike observations. Linking subsurface contact information from a series of intersecting 2D profiles it is possible construct an estimation of the 3D geological structure.

Individual profiles were extracted from the high resolution aeromagnetic data. Initially each profile was modeled independently using contact information derived from a revised geological map which in turn was partly based on edge detection algorithms applied to the same magnetic data. Physical properties were assigned to each unit on the basis of measurements made on outcrop samples and bore core. The output of each model is a series of intersecting profiles each of which is compatible with both the known geological and geophysical information. To ensure geological continuity across the whole model it was necessary to iteratively adjust individual models within the constraints of the geophysical data. Given a sufficient number of profiles it is possible to extract contact surface information from individual lines to render the data as continuous 3D surfaces. Primary control with this lithologic surface scheme of geophysical modeling comes from the geological surfaces developed through the interpreter applying geological principles.

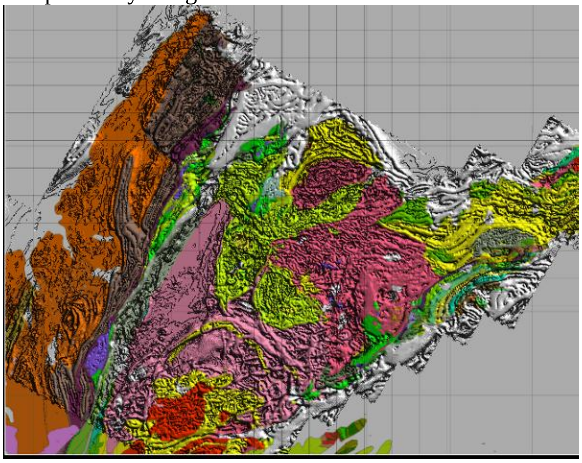

Figure 4: *Geological map for Baie Verte Peninsula overlain on greyscale image of aeromagnetic data. Numerous disagreements between trends in magnetic data and geology suggest map needs revision.*

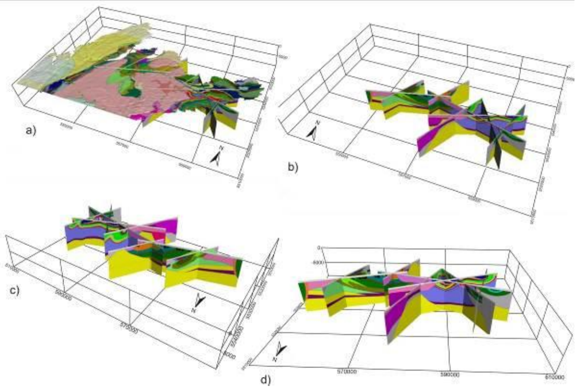

Figure 5: *Orthographic projection showing results of models developed for individual profiles and how they intersect with one another.*

Voxel Mesh Inversion Method

The Amer Fold Belt

The Thelon Basin is a late Paleoproterozoic, intracratonic, sedimentary basin located within Northwest Territories and Nunavut. Unconformably underlying the Thelon Basin the Amer fold and thrust belt comprises four early Paleoproterozoic sequences: Ps1: Ayagaq; Ps2: Resort Lake + Aluminum River + Five Mile Lake; Ps3: Three Lakes + Showing Lake; and Ps4: Itza Lake. Previous mapping of this structurally complex belt suggest that this structure is a broad southwest trending canoe-shaped synform. The Amer synform east of Amer Lake is outlined by the resistant Ayagaq quartzite and bounded to the east and south by thrust repeats of the quartzite. Outcrops of Ps2 through Ps4 group strata within the interior of this synform are sparse. So although the outer form of the synform is defined by outcrops of the Ps1 Ayagaq quartzite, the overall geometry of the structure is weakly defined.

DOI http://dx.doi.org/10.1190/segam2012-0487.1

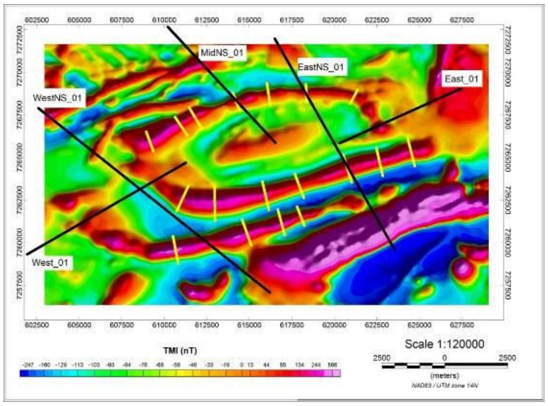

Figure 6: *Aeromagnetic anomaly map of the Amer synform. Short yellow lines are profiles that were modeled using a discrete dipping slab model.*

A compilation of high resolution aeromagnetic data outlines an east-west elongated bulls-eye pattern of aeromagnetic highs over the area of the synform (Figure 6). On the basis of one key outcrop it is known that the strongest linear aeromagnetic anomaly is associated an iron formation in the PS3 Three Lakes formation. Other more moderate magnetic anomalies are spatially associated with the Showing Lake formation. Given the very limited amount of outcrop it seems appropriate to interpret the interior structure using a voxel inversion model scheme.

In its simplest form voxel modeling is a numerical procedure that populates a subsurface mesh with physical property values from measured magnetic or gravity data with the condition that input data be reproduced within a specified error tolerance (Li and Oldenburg, 1996, 1998). The standard UBC-GIF MAG3D code includes provision for the interpreter to modify the depth weighting, and the "smallness" and "smoothness" of anomalous sources. In this approach all emphasis is placed on the geophysical data. Resulting unconstrained inversions of potential fields are non-unique. To overcome this issue one must incorporate physical constraints into the starting reference model to force pre-determined geologic form on the resulting output model. Li and Oldenburg (2000) first addressed this problem by allowing the interpreter to include geological dip and strike into the inversion. More recently, Williams (2008) followed by Spicer et al., (2011) have shown how incorporating prior physical rock property data, near surface lithological contact information and where possible borehole constraints can result in a more geologically appropriate model result.

Voxel modeling of the Amer synform provides an example of some progress and pitfalls of the inversion method approach. First, satellite imagery provided a detailed map of the surficial extent of the quartzite. This was included into the reference model as a non-magnetic region. Second, because a number of the limbs of the fold have linear segments it is possible to model these elements using the discrete object scheme. Integrating the output from individual profiles into a 3D volume provides a zone of magnetisation with predefined susceptibility bounds. While the resulting constrained model (Figure 7) does ably outline the geometry of the fold structure it also highlights some as yet unresolved issues. First, incorporation of geological constraints needs to be iterative. Where insufficient lateral control is placed on a source it will artificially widen with depth. Second, all of the potential field modeling schemes have difficulty with flat-lying laterally homogeneous strata.

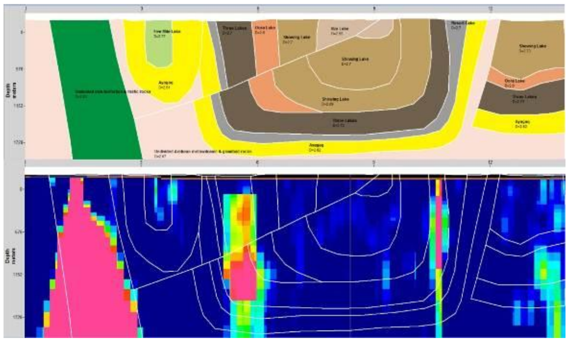

Figure 7: *A) Geological cross-section of the Amer synform with the Ayagaq quartzite in yellow. B) Slice through voxel inversion model. Colour coding linked to apparent susceptibility. Emphasises lank of sensitivity of model to flat-lying portions of the the fold structure.*

Conclusions

Different approaches to modeling of geophysical data will place emphasis on either the geological or geophysical data. Depending on the specific problem being examined there are cases where the interpreter should choose one specific type of model scheme.

Clearly future 3D geophysical modeling schemes must optimally integrate all geological, remote sensing and geophysical data. The geologic data that is available is often sparse. We need to apply similar concepts for modeling the geological data as we do to the geophysical data. Once we have achieved better integration of geologic, structural and geophysical data sets it will be possible to interrogate these models for possible mineral and oil resources.

Acknowledgements

Financial support for WAM was provided by a NSERC Discovery grant. NRCan TGI3 and GEMS programs have provided financial support for BS, PT, VT and HU.

DOI http://dx.doi.org/10.1190/segam2012-0487.1

http://dx.doi.org/10.1190/segam2012-0487.1

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2012 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Hibbard, J. P., 1983, Geology of the Baie Verte Peninsula, Newfoundland: Newfoundland Department of Mines and Energy, Memoir 2.

Jessel, M., 2001, Three-dimensional geological modeling of potential field data: Computers and Geosciences, **27**, 455–465.

Li, Y., and D. W. Oldenburg, 1996, 3-D inversion of magnetic data: Geophysics, **61**, 394–408.

Li, Y., and D. W. Oldenburg, 1998, 3-D inversion of gravity data: Geophysics, **63**, 109–119.

Li, Y., and D. W. Oldenburg, 2000, Incorporating geological dip information into geophysical inversions: Geophysics, **65**, 148–157, doi: 10.1190/1.1444705.

Riller, U., 2005, Structural characteristics of the Sudbury impact structure, Canada: Impact-induced versus orogenic deformation — A review: Meteoritics and Planetary Science, **40**, 1723–1740.

Spicer, B., B. Morris, and H. Ugalde, 2011, Structure of the Rambler rhyolite, Baie Verte Peninsula, Newfoundland: Inversions using UBC-GIF Grav3D and Mag3D: Journal of Applied Geophysics, **75**, 9–18, doi: 10.1016/j.jappgeo.2011.06.013.

Williams, N. C. 2008, Geologically constrained UBC-GIF gravity and magnetic inversions with examples from the Agnew-Wiluna greenstone belt, Western Australia: Ph.D. thesis, University of British Columbia.