

CREATING REALISTIC 3D GEOLOGY MODELS RAPIDLY, USING GEOPHYSICS TO TEST THEM

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ABSTRACT

The traditional method of recording and communicating an understanding of the geological structure of a region has been to create a map of the geology. Today there is a growing trend to use three-dimensional models of geology. One of the challenges with 3D geology modelling is that it is frequently difficult to incorporate new data, and revise the model. The potential field geology modelling method described here automates the task of model building, and computes a model directly from the data (the geology observations). The method has been implemented in the 3D GeoModeller software.

In this paper the modelling methodology is discussed in the context of a 3D geology modelling project completed at Broken Hill, in western New South Wales, Australia. Broken Hill is a world-class silver-lead-zinc resource, which has been mined for over 100 years. Our model covers an area of 20km x 20km centred on the mining district. The model was developed using published data from government and industry mapping, GIS and digital databases and an earlier 3D model developed by the mine's exploration team. The model is an *interpretation* of the Broken Hill geology, since the process of GeoModeller model-building - working in three dimensions as it does - requires the user to *interpret* the data being drawn together from different data sources in order to create a coherent 3D model of the geology.

The model was developed using the group-level stratigraphic classification for the Broken Hill district, as defined by the Geological Survey of NSW mapping. Being a regional scale model, much of the detailed mapping and mine-district work is not represented in the model. Never-the-less, even at regional scale the Broken Hill geology is complex, and this complex geology has been captured into a coherent, fully 3D model.

Both ground gravity and Falcon gravity data were used to test, refine and validate the final product by a process of constrained inversion. In this interpretative process, the model evolved showing successive improvements and increased understanding in less than 3 months.

1. INTRODUCTION

The traditional method of recording and communicating an understanding of the geological structure of a region has been to create a map of the geology. Geology maps often include a cross-section to provide some insight into the third dimension. More recently there has been a growing interest in constructing complete three-dimensional models of geology. Many 3D geology modelling packages are based on CAD systems. Criticisms of these systems include: (1) building a model can take a long time, (2) models tend to be inflexible, and difficult to change as new data emerge, and (3) some advanced systems require highly skilled users to achieve good results.

It is the second point - the need to revise the model - which has driven much of the development presented here. Depending on how a model has been constructed, it can be an onerous task to make changes. The solution that is proposed here is to automate the task, and *compute a model directly from data* (the geology observations). A revision, then, implies (1) add the new data, and (2) re-compute the model from the updated database. This new approach has been implemented in the 3D GeoModeller software.

In this paper the 3D methodology of the GeoModeller approach is discussed in the context of a modelling project completed at Broken Hill, in western New South Wales, Australia (Figure 1). Broken Hill is a world-class silver-lead-zinc resource which has been mined for over 100 years. A model (20 x 20 x 5km deep), centred on the mining district, was developed from the published geology, with further interpretation by the authors.

The model was then used as a 'starting model' for a series of gravity inversions. Despite uncertainty in the knowledge of density values for Broken Hill geology formations, the inversions produced some interesting results which should provoke reconsideration of the 3D geology model.



Figure 1. Location of Broken Hill, western New South Wales, Australia

2. METHODOLOGY

Geology interpretation typically requires *interpolation* of a line (in 2D) or a surface (in 3D) such that the interpolated shape - which represents a geology boundary - fits some set of geology observations. In order to automatically compute a model directly from data, then, we need an *interpolator* to compute surfaces which represent geology boundaries. The interpolator must be able to work with the typical data recorded in field geology practice:

- the position of a geology contact may be known or inferred at some locations; the interpolated surface must be fitted through such points
- more often a contact is not observed, but rather the geology formation *above* or *below* a contact may be known. This information is more difficult to use in a mathematical process since there is uncertainty.
- the attitude of the geology may also be measured, often at locations which are not *on* the geology surfaces that are to be interpolated, but are often within strata *above* or *below* a contact of interest.
- series of sub-parallel strata are often observed in geology; the interpolator should be capable of generating a *set* of geology surfaces which have a stratified geometrical relationship to each other.
- the interpolator must be able to model abrupt breaks in a geology contact surface due to faults

The problem, then, is to find (a set of) surfaces which respect the overall shape of the geology. Specific surfaces must pass through known sets of contact points, they must honour the directional vectors of orientation data points, and they must accommodate discontinuities at known faults. The interpolator must be general enough to model the surfaces of any arbitrarily complex 3D shape.

2.1 Interpolation Method

The interpolator method that has been implemented in GeoModeller is based on potential field theory. A set of smoothly curving, sub-parallel geology surfaces in 3D space can be seen to be analogous to a set of iso-potential surfaces of a scalar (potential) field. A unique solution for the 3D geometry of the interfaces between formations is obtained by assuming that:

- contact data for each interface lie on a potential field surface (an iso-potential)
- orientation vectors are orthogonal to a local tangential plane to the potential field

On this basis, the field *increment* between any two points belonging to the same geology interface is null. Orientation data represent the *gradient* or *derivative* of the field. The scalar field is then interpolated by cokriging the *increments* and their *derivatives* (Lajaunie et al., 1997). Interfaces are drawn as iso-values of the interpolated scalar field; iso-lines in 2D (Figure 2) or iso-surfaces in 3D. An overview of the potential field method and the cokriging of the potentials is presented in the following sections, but for a more complete discussion see Chilès et al. (2004) and McInerney et al. (2005).

2.2 Advantages of the Potential Field Interpolation Method

The potential field interpolation method is ideal for the case of simple layered geology.

- Strata with a consistently conformable relationship can be modelled with a single potential; modelling layers together has the big advantage that observed data from one horizon can influence the shape of other nearby horizons, resulting in an improved predictor of the shape of all geology contacts in the series.
- Measurements of strike and dip recorded anywhere within the series will all be taken into account at the point of their measurement.

- A potential field ensures smooth boundaries; the method provides a surface which is sufficiently curved to fit to the data, but has no more curvature than required.
- A potential also ensures no self-crossing. In the simplest case, each geological contact in a series would represent a time-line, which cannot cross.
- The physics and mathematics of potentials are well-understood. The mathematical form of a potential is an implicit function; it can be expressed in the form $f(x, y, z) = 0$. This formulation allows us to immediately know 'which formation' is present at any arbitrary point p in 3D space.

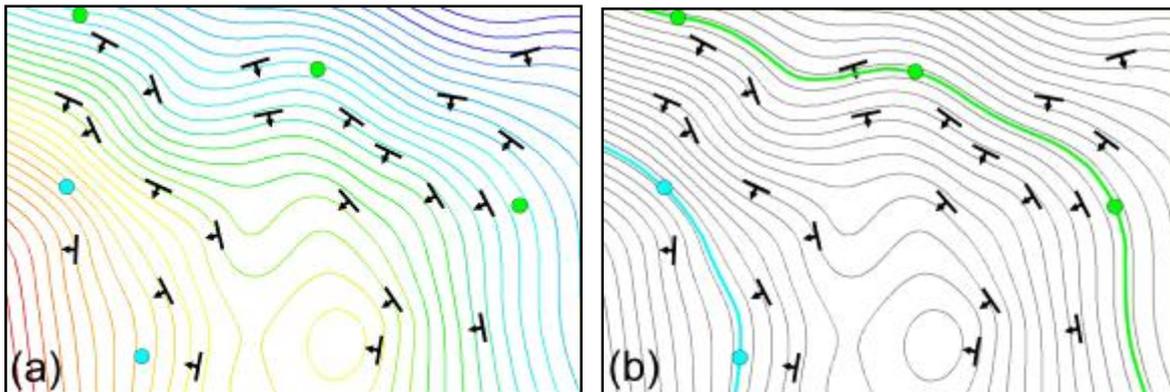


Figure 2. Map showing geology contacts for two formations belonging to a single series, and also structural data. In (a) the potential field (interpolator) has been computed; note that structural data are all taken into account, with the field always orthogonal to these orientation vectors. In (b) two iso-potentials of the field are plotted such that they pass through the two sets of geology contact points. Note that the interpolator has proposed a geology model which honours the contact data, but also takes full account of orientation data which are both above and below the particular geology contacts.

2.3 More Complex Geology – Multiple Interpolators

For the case of more complex geology, where horizons are not sub-parallel, then separate potential interpolators must be used - one for each series of strata. The stratigraphic column is used to record the chronological order of strata, and also the series relationships - either *onlapping* or *erosional*. Where two geology surfaces from different potential interpolators intersect, an *erosional* surface cuts-across stratigraphically older horizons, whereas an *onlapping* surface would stop against the older surface. This coded information in the stratigraphic column is sufficient to ensure that a unique geological model is constructed from several overlapping potentials. Note also that the cross-cutting relationships of an eroded contact are no different from the cross-cutting nature of an intrusive contact; thus the erosional case is also used to model an intrusive.

3. THE BROKEN HILL MODEL

The Broken Hill model covers an area of 20km x 20km centred on the Broken Hill mining district. It is a regional scale model, developed using the *group* level stratigraphic classification for the district, as defined by the Geological Survey of NSW mapping. Detailed mine-scale stratigraphic sub-divisions were not incorporated into the model. Even at regional group-level scale the geological structure is complex, however, and this complex geology was captured into a coherent, fully 3D model during the short time of the project.

The model was developed using existing data from government and industry sources (see below). No additional mapping was done. Never-the-less, the model is an interpretation of the Broken Hill geology by the authors, since the process of GeoModeller model-building - working in three dimensions as it does - requires the user to interpret the data being drawn together from different data sources in order to create a coherent 3D model of the geology.

3.1 Building the model

The building of a 3D geology model requires an interpretative process by the geologist. Having defined the stratigraphic pile for the project, and also the faults, the process of creating the Broken Hill geological model was an iterative cycle of:

- Input/Interpret: Using published maps and interpreted regional sections (Figure 3), points were digitised along contacts. Selected orientation data (strike and dip) were also input. A geologist's input is partly recording *observations of geology* that must be honoured by the model. The *interpretative ideas* of the geologist are also an important input to the model-building process.
- Compute the model

- Plot the model geology on the map or sections ... and review. Typically the geologist must return to add further input constraints from published sources, or revise interpretative constraints.

This cycle - compute the model, and then review - is one of testing the model against the geologist's expectations, and is essentially an interpretative process. If the model contradicts some known data, then the geologist must add those additional observations, in order that they are taken into account. Frequently, however, the geologist does not have additional data - but does have an understanding of the geology which is a valid basis for proposing that the current model cannot be correct, and needs to be adjusted. The geologist imposes his/her interpretation on the model simply by adding (hypothesised) contact data or orientation data. When the model is re-computed, and re-plotted in the section-view where the geologist has proposed this interpretation, the geologist can again review the model, and can observe how the shape of the model has been adjusted as a consequence of his/her interpretation. The geologist can also review the implications of this revised model in any other section view. Note that the geologist can test different ideas about the geological structure of the project area, and so evaluate alternative interpretations.

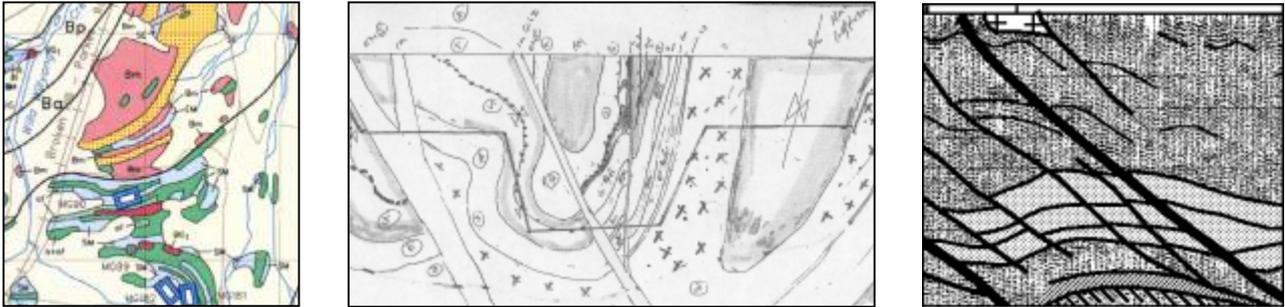


Figure 3. Inputs to the Broken Hill model were sourced from published maps, interpretative regional sections prepared by the geologist, and from interpreted regional seismic data.

3.2 Model Results

The model that is constructed in the GeoModeller software is not a set of shapes or surfaces, but rather a mathematical function in three dimensions. By interrogating this model-equation in various ways, a variety of visualisation outputs can be generated. The model can be presented in full three-dimensional form (Figure 4), but it is also easily presented as 2D views as maps or sections. Since each view of a model is derived from the same set of mathematical equations, then every section-view through the model is always coherent with any other view that might be derived from the same model.

The model can also be used as the basis for more advanced computational analysis. For example, realistic mathematical modelling of seismic wave propagation, or ground-water flow, should take into account the three dimensional structure of the earth. These 3D shapes can be generated from the model equations.

In the case of the Broken Hill project, a 3D voxel-model was generated from the mathematical model, and used as an essential input to inversion of the gravity data.

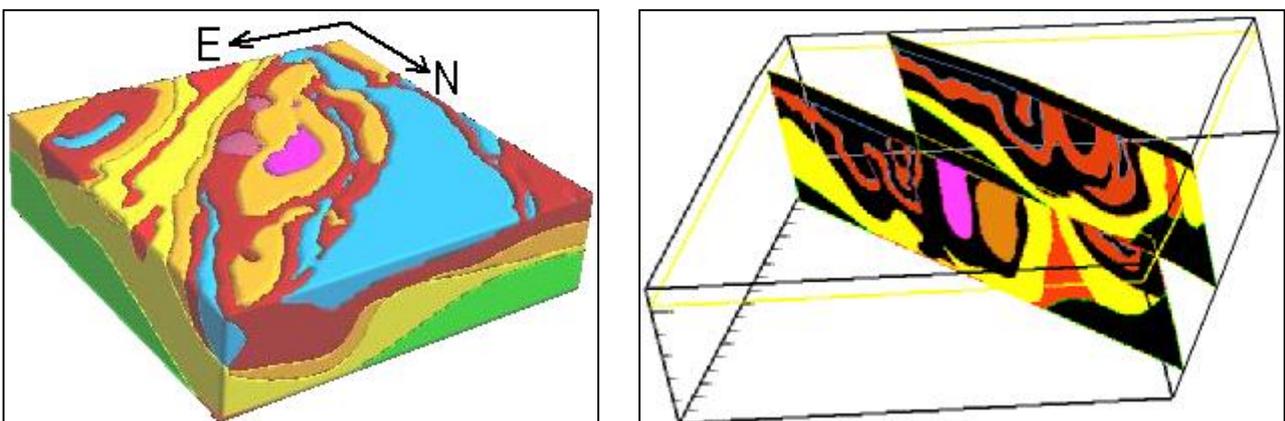


Figure 4. The model produced by 3D GeoModeller is a set of mathematical equations which can be interrogated to produce a range of outputs, including 3D shapes of each geology body, and 2D sections which can be viewed as maps or in 3D perspective views.

4. GRAVITY INVERSION TO TEST AND IMPROVE THE MODEL

Having produced a 3D model of geology, inversion can be used to test the validity of that model against independent datasets. For the Broken Hill project, a series of inversion runs were performed using ground gravity data. Some additional inversion tests used the 'gravity signal' derived from Falcon airborne gradiometer data.

The three principal inputs to an inversion of gravity data are:

- A starting model of the geology – which describes the formations present, and their 3D distribution
- Density data for each formation, in terms of the mean value, standard deviation and a distribution law
- Gravity data

Of these three, the field gravity data for Broken Hill was the most reliable. Much of the project area has gravity observations at 100m – 500m station spacing. Density values for each formation were poorly constrained. The database of measured density values is typical of many areas; relatively *few* samples, measured on *small* hand-specimens and core, resulting in a broad variability of the density measurements. For Broken Hill Group, for example, there were 211 samples, mean density 2.83 t/m³, standard deviation 0.13 t/m³. And thirdly, the geology model itself, although based on reasonable outcrop geology, is a highly interpretative model in the third dimension.

The methodology of inversion in the GeoModeller software is briefly described here. For a more thorough treatment, see Guillen et al. (2004). The inversion uses a voxel-model. For Broken Hill, voxels of 250m³ were produced from the 3D geology model. Initial density values are assigned using the defined distribution law and parameters for each formation, the forward model gravity signature is computed, and the global 'misfit' between field and computed values is deduced. An inversion run typically uses many millions of iterations, with each iteration making a modification to one voxel only, or, optionally, to a small selection of voxels. The process is based on a Markov Chain Monte Carlo formulation, which is solely used to accept/reject each candidate model. The inversion algorithm may be summarised as:

- for each inversion iteration, randomly select a voxel
- optionally change the geology formation and/or assign a revised density value
- re-compute the model response
- compare the model with the field gravity data
- if the misfit improves, the revised model is kept
- if the misfit is worse, the revised model may be kept or rejected (see below)

The last point - viz. keeping a model even though the misfit is worse - is designed to allow the inversion to move beyond local minima, and look for further solutions that might improve the fit.

Most inversion algorithms are designed to stop at a point where the global 'misfit' has decreased to some specified small error level, implying that the 'current model' is one for which the computed signature matches the observed field data. In GeoModeller, the inversion continues for many more millions of iterations beyond this point, defining further models which reasonably match the gravity data ... and these many millions of models can be used to report the inversion outcome in terms of probabilities.

4.1 Inversion Results

Several inversion runs were executed. Initial runs yielded poor results and required some revision of the model, and reassessment of the true density value of some formations. All subsequent inversions then achieved a good match between the model gravity response and the field data.

Using the many millions of accepted models from an inversion run, is it possible to compute a probability that voxel v is geology formation f . These probabilities are computed for every voxel in the model, and for each geology formation. Various parameters can be derived from these probability data; examples include 'most probable geology' (plotted in a section- view in Figure 5b), and 'mean relative density' (Figure 5c).

Results from two inversion runs are presented here. Both runs achieved a good match between the model gravity response and the field data, and both produced approximately 20-25 million 'accepted' models. The results from the two runs are very different, however. In the first, the standard deviation for the density distribution law for each geology formation was specified to be 0.04 t/m³. The result for one NW-SE section is presented as 'most probable geology' and 'mean density' (Figure 5 b, c). It is apparent that the inversion has achieved a fit to the observed gravity data *mainly* by modifying the density values, and – in many places – has not modified geology boundaries. This result suggests that - using a standard deviation of 0.04 t/m³ - the density values used in the inversion are poorly constrained, and the inversion process is not really *testing* the model.

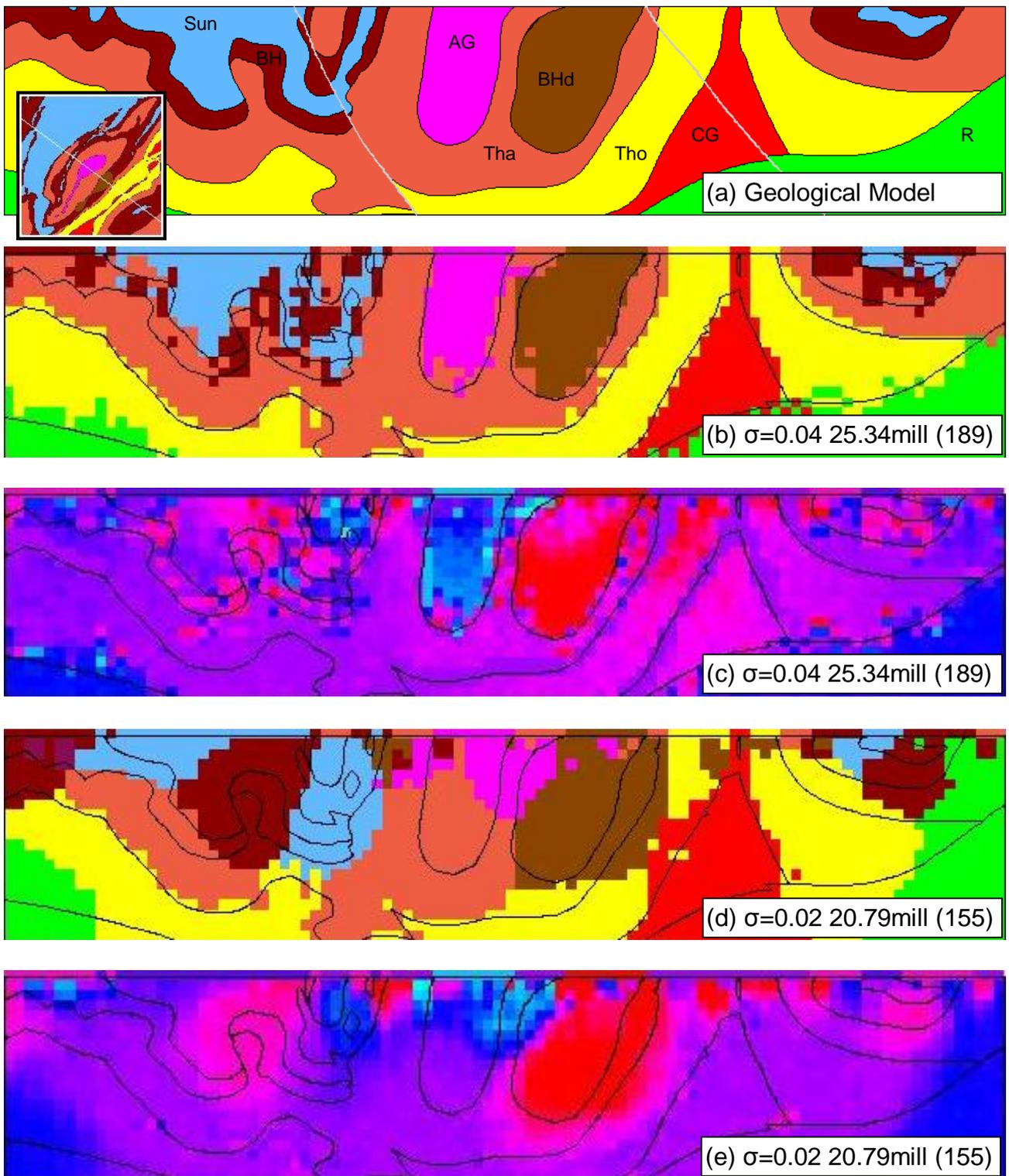


Figure 5. NW-SE section through the Broken Hill model (a), together with two very different inversion results, plotted as ‘most probable lithology’ (b, d), and ‘mean density’ (c, e). The first inversion (b, c) used a broad standard deviation ($\sigma=0.04$) for the density, and indicates that the inversion can produce a match to the observed gravity through *variations in assigned density*. In the second run (d, e) the standard deviation was narrower ($\sigma=0.02$), which forced the inversion to migrate *geology boundaries* to achieve a match to observed data. Also shown are the number of saved models for each inversion (approx. 25 million and 20 million respectively), and an estimate of the average number of times each voxel was adjusted during the inversions. Voxels used were 250m^3 . Geology: Alma Gneiss (AG), Sundown Grp (Sun), Broken Hill Grp (BH), amphibolite-rich Broken Hill Grp (BHd), Thackaringa Grp (Tha), Thorndale Gneiss (Tho), Clevedale Migmatite (CG) and the underlying ‘rift sequence’ (R). Mean density: red is relatively higher, blue is lower. The ‘start model’ for the inversions was the geology in (a), shown also by the black lines in the inversion plots. Location of section shown in inset; Length: 24km; V/H=1

In the second inversion run, the standard deviation for the density distribution law for each geology formation was more tightly constrained by using a value of 0.02 t/m^3 . The result for the same section is presented in Figure 5 d, e, and is very different. With the density value more tightly constrained, the inversion has been forced to achieve a fit to the observed data by migrating the geology boundaries (Figure 5d). This result suggests a radically revised geology structure. This provisional result from the inversion work does have weaknesses; in places, it is inconsistent with mapped geology. Never-the-less, it is a result which challenges the validity of the highly interpretative 3D model of Broken Hill.

An interesting aspect of this second inversion run is presented in Figure 6. The Thorndale Gravity High (Figure 6a) occurs in an area of dense, amphibolite-rich rocks. The Broken Hill model was revised to include an amphibolite-rich component of Broken Hill Group, having a relatively higher density. Figure 6b shows how the second inversion run has ‘grown’ the extent of the proposed zone of amphibolite-rich rocks. In Figure 6c it can be seen that the distribution of these proposed amphibolite-rich rocks is strongly governed by the zones of local gravity high ridges.

Again, although these are early experimental results from the GeoModeller inversion, the result is indicative that the method can use the geophysical data to ‘propose’ sound revisions of the geology.

An outcome from the Broken Hill project has been the recognition that geology formations are often a *mixture* of lithologies – with different physical properties - such as the metasediments and the amphibolite-rich components of the Broken Hill Group. On this basis, modifications have been implemented in the software such that the physical properties of a formation can be described in terms of such mixtures of lithologies.

8. REFERENCES

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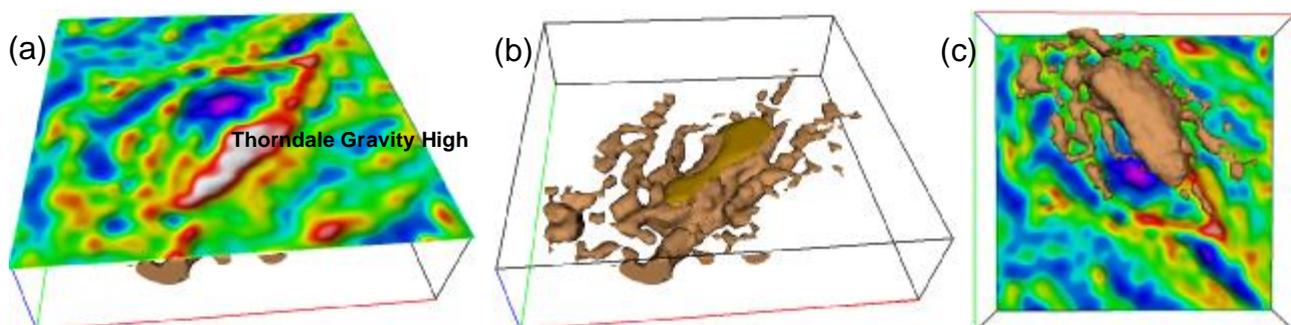


Figure 6. Image of Broken Hill gravity 1VD (a), and a perspective view of the distribution of the proposed amphibolite-rich ‘Broken Hill Dense’ unit derived from an inversion (b). Through inversion, the distribution of this dense material has ‘grown’ from the ‘starting model’, to be widely distributed along local gravity highs. A view from *beneath* the model (c) shows the strong relationship between the inversion result and the gravity signature. Project area is 20km x 20km.