# Building 3D Geological Models Directly from the Data? A new approach applied to Broken Hill, Australia

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## ABSTRACT

With 3D geologic modelling, it is frequently difficult to incorporate new data, and to revise the geologic model. The potential field geologic modelling method described here automates the task of model building, and computes a model directly from data (the geologic observations). A geological interface (e.g., the upper surface of a geologic unit) is modelled as an iso-surface of a scalar potential field which is defined in 3D space. Structural data are treated as the gradient of the field. The interpolation of the field uses cokriging to take into account both contact and structural data, and generates surfaces that honour all of these data.

Since the model is computed directly from the observations, when new data are added to a project, a revised model can be quickly regenerated to take into account the new information. The method also exploits the regular structure of layered geology, by using a single potential to provide a set of sub-parallel surfaces to model a corresponding series of closely related horizons. For more complex geology, several potential interpolators are used; one for each different series of geologic strata. In this case, a unique geological model can be generated provided that the order of the stratigraphic succession of geologic units (the stratigraphic 'pile' or 'column'), and the onlapping or cross-cutting relationships between series are defined.

Several practical implementation issues designed to produce improved 3D models are presented. Faults can be taken into account. A network of faults—with some faults stopping on other faults—can be used. The regular geometry of fold structures can be described to improve the shape of interpolated folded surfaces. Gravity and magnetic data can be integrated with the model via inversion. These features are illustrated by application to the Broken Hill district.

## 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 (first done in 1801 by William Smith with his 'map that changed the world' (Winchester, 2001)). Geologic 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, and indeed such three-dimensional models are very sophisticated in areas where extensive drilling and 3D seismic mapping provide a wealth of data.

Much more commonly, however, we never have 'enough' data, and yet we require a defendable 3D model of a project area—for a range of environmental, hazard and resource exploration and development studies. The challenge, then, is:

- to build a 3D model—often with quite sparse data due to sparse sampling of the geology as a consequence of cover, or the expense of acquiring data at depth.
- then revise the 3D model as new data are progressively added, or our interpretive understanding of the geology evolves. New data are often slowly acquired over periods of years—during which the model should evolve.

It is this latter 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 geologic observations). A revision, then, implies (1) adding the new data, and (2) re-computing the model from the updated database. This new approach has been implemented in a new 3D geology modelling software package—3D GeoModeller (http://www.geomodeller.com).

In this paper, the 3D methodology 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 existing published geology, with further interpretation by the authors.


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

## THE METHODOLOGY

### Interpolation Requirements

A geologist who interprets the geology of an area typically is interpolating a line (in 2D) or a surface (in 3D) such that the interpolated shape—which represents a geological boundary - fits some set of geologic observations. In order to automatically compute a model directly from data, then, we need an <u>*interpolator*</u> to compute surfaces which represent geological boundaries or faults. The interpolator must be able to work with practical geologic data that can be observed in standard field-mapping practice as itemised below. Poor outcrop, and the expense of drilling, typically imposes constraints on the number and type of field observations that can be obtained.

Requirements for an interpolator include:

1. The position of a geologic contact or boundary is known at some (few ?) locations; the surface must be fitted *through* such points,
2. The attitude of the geology may also be measured, often at different locations. These orientation data (strike, dip and facing) can be represented as vectors, locally orthogonal to the geology. Since these orientation data may be recorded somewhere above (or below) the contact, and rarely <u>*on*</u> the contact itself, we need an interpolator which can take the orientation data into account … but *not* necessarily fit a surface *through* those data, and
3. We may also know other geologic data that was obtained from, or *within*, the unit (*not* on the contact). These data are more difficult to use, since they involve *uncertainty* … but nevertheless these data do define limits which the ideal interpolator must honour.

The complexity and unpredictability of geology make the task of interpolation challenging! It is also true, however, that geologic structures can be well-ordered and predictable, and so it is important to use an interpolation process that can exploit any regularity that may be present in the geology. Given the *layered* nature of geological strata-forming processes:

4. There will be circumstances where we would like to fit a *series of surfaces*, all of which are sub-parallel by virtue of their shared geological history; the interpolator should be capable of generating a *set* of geologic contact surfaces which have a layered (stratified) geometrical relationship to each other.

There is one further requirement:

5. There can be discontinuities (faults) in geological horizons; thus the interpolator must be able to model such breaks along arbitrary fault surfaces.

The problem, then, is to find (a set of) surfaces which respect the overall configuration of the 3D geologic framework. 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.

## Interpolation Method

There are several computational algorithms designed to fit a surface to position and orientation data; many are unsuitable for our purpose since they typically require all of the relevant data to be *on* the surface being fitted; we have noted that some of our data—which we must take into account—may be *above* or *below* the geologic contact surface that we want to generate.

The interpolator method that we have developed is based on **potential field theory**. A set of smoothly curving, sub-parallel geologic 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* (i.e. the *change* in potential) between any two points belonging to the same geologic interface is null. Orientation data represent the gradient or *derivative* of the field. The scalar field is then interpolated by **cokriging** the (null) increment data and their derivatives (Lajaunie *et al*., 1997). Interfaces (e.g., geologic contacts) 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).

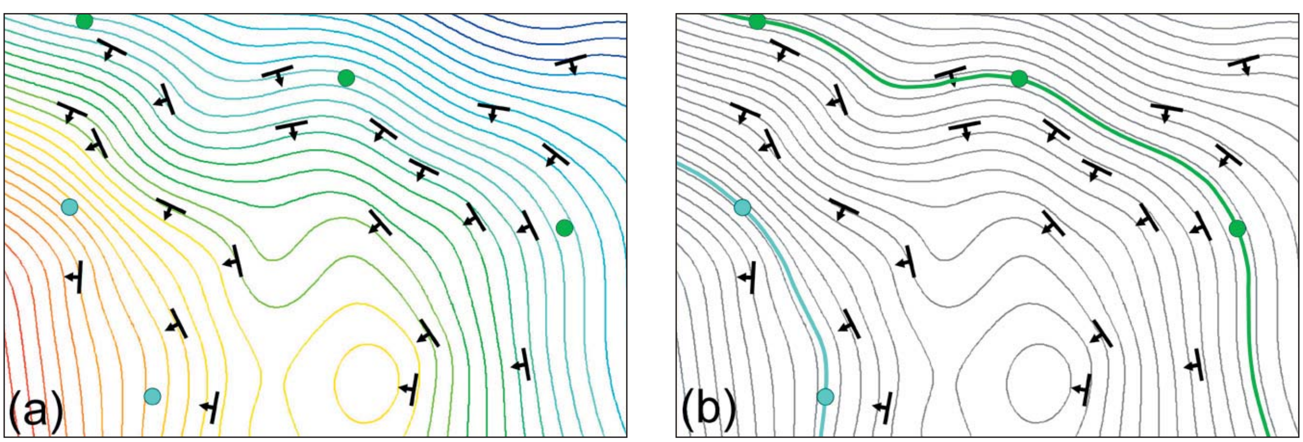


**Figure 2.** Map showing known geologic contacts (see black dots) for formations belonging to a single series, and also structural data. In (a) the potential field (interpolator) has been computed; note that structural data are all taken into account, with the field always orthogonal to the (structural)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

## Advantages of the Potential Field Interpolation Method

This solution is ideal for the case of layered geology. A series of surfaces—each at different iso-values of the interpolated scalar field—can be derived from the one interpolator. We refer to these layered strata as belonging to a geologic *series*[1]. If the rock relationships do support the premise of a shared geological history, then combining layers together into a single series has the big advantage that data from one horizon can influence the shape of other nearby horizons, and vice versa. The interpolator—being constructed from additional, relevant geological observations—is therefore an improved predictor of the shape of all geological boundaries 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. Whilst specific iso-surfaces, representing geologic boundaries, do not necessarily pass through any orientation data, nevertheless, all of the orientation data do exert an influence on the local attitude of those (nearby) iso-surfaces.

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. If the geologic structure is known to be complex, then the sampling of the geology must be high-frequency; the interpolated surface will honour the high-spatial-frequency signal content.

A potential also ensures no self-crossing. The premise for layered geology being combined into a single series is that the strata have all shared a common geological history; this precludes the possibility of significant erosional breaks and unconformities within a series. In the simplest case, each geological boundary within a series would represent a time-line, which cannot cross other time lines. The potential interpolator ensures this.

Finally, 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. The potential function allows us to immediately know 'which formation' is present at any arbitrary point *p* in 3D space. This is achieved simply by computing the value of the potential at the point *p,* and comparing it to the iso-values representing the various geologic interfaces. With reference to Figure 3:

- Let $v_1, v_i \ldots v_n$ be increasing values of potential corresponding to the different iso-values of *n* geologic interfaces in a series, being the 'tops' of geologic formations $f_1, \ldots, f_n$. Assume also that there is a cover formation $f_{n+1}$

[1]The term *series* is used here with a conventional English meaning viz. a 'sequence' or 'set' of geologic layered strata; it should not be confused with the chronostratigraphic usage of the term.

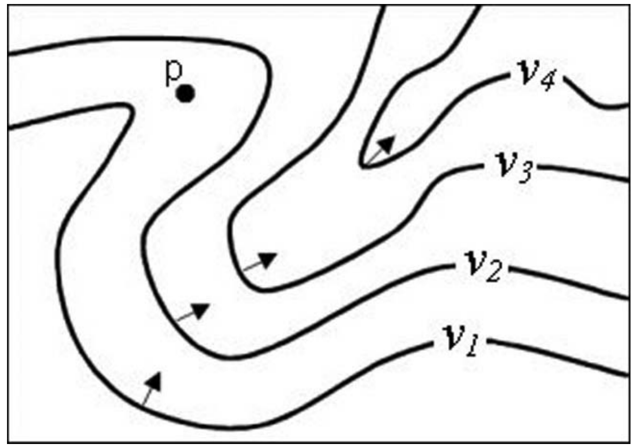


**Figure 3.** Determining the formation by using the interpolated potential field. For the point *p*, the potential has a value *V(p)*; by comparing this value with the iso-potential values used to model individual geologic formations, the geology at *p* is determined. In this case, $v_1 < V(p) < v_2 \ldots$ so *p* must be in formation $f_2$ (iso-potential $v_2$ represents the top of formation $f_2$).

- Let *V(p)* be the value of the potential at some point *p*

Then:

- If $V(p) <= v_1$ then p is in formation $f_1$
- If $v_i < V(p) <= v_{i+1}$ then p is in formation $f_{i+1}$
- If $v_n < V(p)$ then p is in formation $f_{n+1}$

## Advantage of Cokriging in the Interpolator

The interpolation uses cokriging, which is the best unbiased linear estimator, and provides a means of dealing with error in geoscience data. Error may be simple observational or spatial errors, but the term error must also be considered in the context of geological *signal* and *noise* … and these are typically scale-dependent. When mapping, a geologist must make a decision about the mapping-scale; a 1:250,000-scale map is very different from the 1:25,000 scale maps over the same area. With 3D geological modeling, the same decision must be made; essentially the process is one of defining the relationship between the dimension of a project, and the 'wavelength' of geological structures to be modelled. In our 3D modelling, this decision is quantified through the setting of the cokriging parameters.

Thus, for detailed *mapping* a geologist would include data which define the geology in detail, and draw interpretive boundaries showing the geological complexity. The same boundary and orientation data would be included in a 3D *modelling* project, and one would expect to produce a complex model which accurately honoured all available data.

The purpose of a regional map, however, is to generate an overview of the geology at the broader scale. Thus, the mapping geologist might 'average' the data, and draw a simplified interpretive contact. In 3D modelling the same outcome is achieved. When an area of detailed data are included in a regional modelling project, the interpolator (using the default cokriging parameters) *broadly* honours an *averaged* value of the observed data, and may *not* accurately honour the individual data points. The method can also provide an estimate of the error or uncertainty at all points. (Chilès *et al*., 2004)

## Modelling Complex Geology

The preceding discussion considered the case of simple, layered geology, and proposed the advantage of being able to model several horizons with a single potential. For the case where the geological history is more complex, and geologic horizons are not sub-parallel, separate potential interpolators must be used - one for each series of strata. For this case it is necessary to define the stratigraphic column, which records the chronological order of the strata, and also the series relationships (either 'onlap' or 'erode'). Where two geologic surfaces from different potential interpolators intersect, an 'erode' surface cuts across any stratigraphically older horizons, whereas an 'onlap' surface would 'stop' against the older surface (Figure 4). This coded information in the stratigraphic column is sufficient to ensure that a *unique* geological model is constructed from several overlapping potentials.

It is worth also noting that, from a topological viewpoint, the cross-cutting relationships of an eroded contact are no different from the cross-cutting nature of an intrusive contact; thus the 'erode' case is also used to model an intrusive.

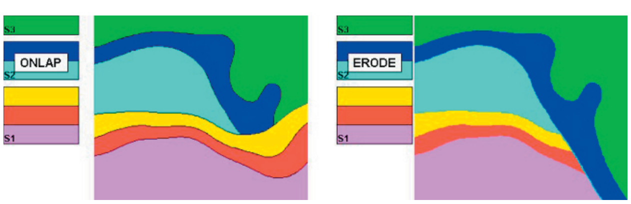


**Figure 4.** A 2D view of a geologic map or section consisting of three different *series* of geologic formations. Three interpolators (one for each series) can produce a unique geologic model only with reference to the model's stratigraphic column, which records the chronological order of formations and series, and the relationships between the series. On the left, series S2 'onlaps', and stops against the older S1 series. For the 'erode' case (right) the series S2 cuts across older formations.

## Faults

Faults are taken into account by (a) defining the location of the fault surface, and the limits of the fault's region of influence, and then (b) introducing discontinuous drift functions into the cokriging equations. The method, documented more fully in Chilès *et al*. (2004), is based on the work of Maréchal (1984), who used drift functions to model faults in 2D seismic data.

For each fault these discontinuous spatial functions model the shape of the influence of the fault. For a finite fault, with limits to the region of influence of the fault defined, the function has a value 0 on one side of the fault and decreases from 1 to 0 on the other side, scaled according to distance from the fault and distance from the edge-extents of the fault (Figure 5); for this case the relative displacement on the fault gradually decreases towards the edges (Figure 6c). Where no limits are defined, the shape of the function is a simple step (an infinite fault, Figure 5).

The fault surface itself is modelled in the same manner as any geologic interface; one or more data points define the location of the fault, and one or more orientation data define its attitude; the fault surface is then modelled using a potential interpolator which is constructed from these data.

In the modelling of faults there are two further practical details:

- A fault is typically restricted to affect only specified parts of the stratigraphic succession. This information is recorded in a table, which links faults with (geologic) series.
- It is possible to have a fault stopped by some other fault. Such a *network of faults* is also managed in a

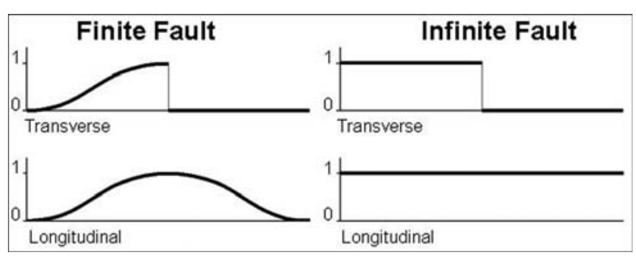


**Figure 5.** Profiles of the drift functions used in cokriging, in order to model faults. For a fault of finite extent, it is necessary to define limits to the region of influence for the fault; the drift function steps from 0 to 1 as it crosses the fault (*transverse*), but tapers back to 0 at the limit, some distance from the fault. Similarly, in the *longitudinal* direction (*along* the fault) the drift function approaches 0 towards the fault limits. In the simplest case there are no limits to the extent of a fault; an infinite fault.

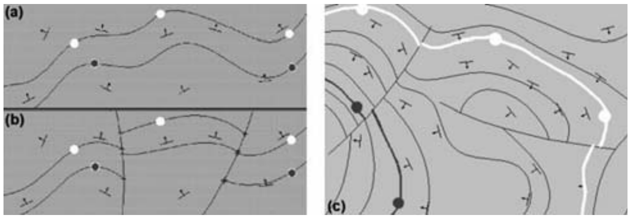


**Figure 6.** Examples of how faults can be modelled. *Contacts* for two formations belonging to a single series, and also *structural data*, are shown in (a) and (b). These data are modelled with no faults in (a), and with two faults added in (b); note that—on the basis of the two contacts being in a single series—the interpolator can reasonably predict a position for both contacts within the central fault block, despite the limited data available. Faults of finite extent are modelled in (c); the relative displacement decreases towards the edges.

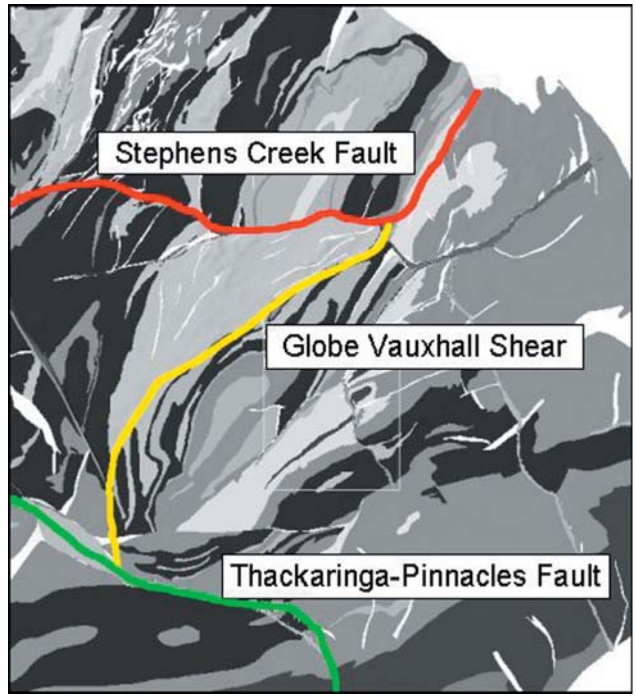


**Figure 7.** The geology of Broken Hill, showing three of the major shears in the district. The Globe Vauxhall Shear terminates against major faults to the north and south. This *network of faults* is defined in a table which shows the relationships between each pair of faults in a project.

table, in which the relationship between every pair of faults in the model is specified (Figure 7).

## Folds

The potential field method does not require any special treatment of folds. Fold structures, however, commonly are regular and predictable shapes, and it is useful to exploit any aspect of geology which can assist the process of interpolation. The structure of folds is used as follows:

- A fold axial surface is defined (Figure 8). As for any geologic interface, one or more data points define the location of the fold axial surface, and one or more orientation data define its attitude; the axial surface is then modelled using a potential interpolator which is constructed from these data.
- A section is constructed along this axial surface.
- A hinge line can be defined on this axial surface section view. By definition, a *hinge line* is the intersection between a (folded) geologic horizon and the fold’s axial surface.
- The shape of the fold is also recorded; anticline or syncline, and additional parameters including the inter-limb angle. On the basis of these parameters, additional orientation vectors are constructed which define the shape of the fold, and must be taken into account when the model is re-computed from the data.

# BUILDING THE BROKEN HILL 3D MODEL

## Scope of the Broken Hill 3D Modelling Project

The Broken Hill 3D Geological Modelling Project was designed as a demonstration of a new technological approach to geological modelling, to be completed within a six-month project life. The 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 mapping by the Geological Survey of New South Wales (NSW). 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

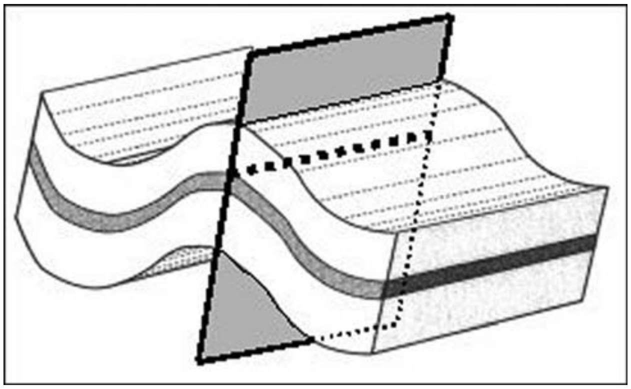

**Figure 8.** The regularity of fold structures can assist with interpolation. This diagram shows the fold axial surface, and the hinge line where a geologic formation intersects the axial surface. The hinge line, together with other parameters describing the shape of the fold structure, are then used in re-computing the model.

government and industry sources (see below). No additional mapping was done. Nevertheless, 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.

## Inputs to the 3D Model

The principal inputs (Figure 9) to the Broken Hill model were:

- the stratigraphy and mapping of the Geological Survey of NSW (mainly Willis, 1989),
- interpreted regional geologic cross-sections (author T. Lees: interpreted from published mapping and personal field-mapping and mine drill-hole logging by author Lees, under the auspices of the Predictive Mineral Discovery CRC's C1 research project),

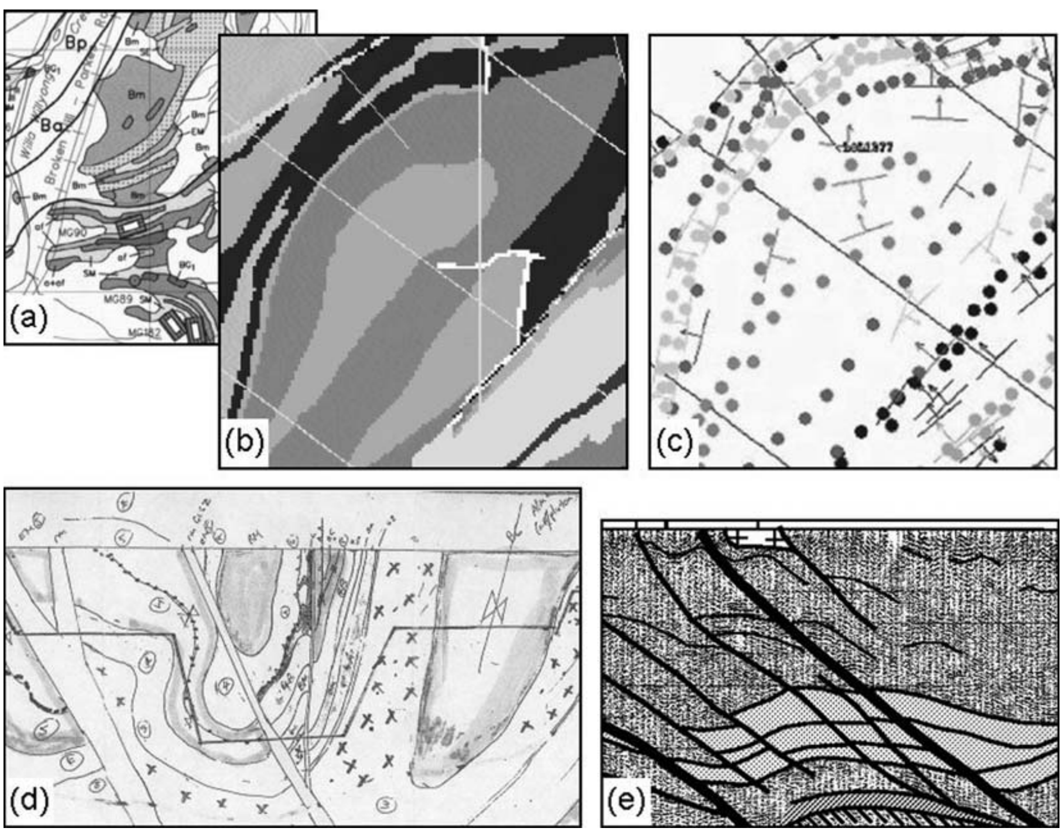


**Figure 9.** Inputs to the 3D model included published geology at various scales (a) from which geologic observations were digitised at the 'group' level of the stratigraphy (b, c). Digitised contact points are shown as spots in (c); dip and strike data, also derived from published geology maps, are shown with a strike-line and facing vector symbol. Input was also taken from the geologist's interpretive regional cross-sections (d) and seismic interpretation (e).

- interpretation from the Pasminco-Fractal study (Archibald *et al*., 2000, and Mason *et al*., 2003),
- unpublished data from the mine line-of-lode,
- the interpreted Geoscience Australia seismic profile (Gibson *et al*., 1998), and
- geological syntheses of the area (Stevens, 1980; Noble, 2000, Gibson and Nutman, 2004).

Given the planned scope of the modelling project—to produce a *regional* scale model - *selected* data were digitised from the regional maps and interpreted sections.

## Sampling Geology

Drawing a geological map or section is a process of *interpolation*, attempting to predict from *sampled* observations (e.g., field mapping, or logging drill-core) where some geological contact is expected to occur. In 3D model building, as in any field mapping exercise, the ability to predict or interpolate is wholly dependent on the quality and *frequency* of the sampling of the geology. In our experience the best result is achieved by a combination of just-enough points to define the geological boundary position, together with strategically located orientation data to guide the orientation of the geological surface that will be fitted through the observations. As the geology becomes more complex, more points are needed to define the geological structure; in other words, the sampling of the geology must be done at a closer sample spacing.

## Building the 3D Model

The building of a 3D model is partly a process of 'sampling the geology' as discussed above … but almost always it *also requires an interpretive process by the geologist*. This continual need to be 'interpreting the geology' is significant. There is no expectation that some computer software will successfully and automatically 'build a model'! The reality is that interpretive input from a skilled geologist is essential to build a model; the software is simply a tool to facilitate the model-building process.

The interpretive process is encapsulated in the *input—compute—plot - review* cycle described below. Having defined the stratigraphic pile for the project, and also the faults, the basic process of creating the Broken Hill geological model was an iterative cycle of:

- Input: In the map-view, or any of the section-views, digitise points at intervals along a geologic contact (thus capturing *geologic contact data*). Likewise selected *orientation data* may be input. (Note that there are options in GeoModeller for *importing* data from digital sources; this was not done for the Broken Hill study),
- Compute the model,
- Plot the modelled geology on the map or a section: Sections can be generated anywhere in the project area, and the model plotted to assist the geologist's assessment of the model, and
- Review: The geologist must review the model, and compare the model against known data—or against his/her expectations.

This cycle—*compute the model, and then review*—tests the model against the geologist's expectations, and is essentially an interpretive process. If the model contradicts some known data, then the geologist must add those additional observations, in order to take them into account when the model is recomputed. 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 recomputed and replotted 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 can evaluate alternative interpretations.

It is significant that by far the most 'geologist time' spent on the Broken Hill project was spent doing this cycle of 'input-compute-draw-review' … with the geologist continually working *as a geologist*, trying to fathom the complexity of Broken Hill geology in three dimensions, and continually adding further 'observations' to the GeoModeller model; these observations were either additional samples from original maps and interpretive sections, or the geologist's hypotheses based on his/her evolving interpretation of that complex 3D geology.

# THE BROKEN HILL MODEL—OUTPUTS AND INVERSION

The Broken Hill model produced in this project was developed from the inputs described above, *as interpreted by the authors* (principally T. Lees). The building of the model in three dimensions raised questions about earlier interpretations presented in various generations of published maps; the need to honour all the data inputs but also achieve a 3D integrity meant that several revisions of the regional geology were proposed during this model-building interpretive process. Notable revisions proposed by T. Lees are in the area along the eastern side of the Broken Hill Synform and the western edge of the Sundown Group.

It is worth noting that a model in this 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. Thus the model can be presented in full three-dimensional form (Figure 10), but it is also easily presented as 2D views. This flexibility is important. Building a model in 3D can expose the flaws of a simple 2D interpretation; it forces the interpreter to develop a more robust and coherent understanding of the geology. In practical terms, however, the actual process of working with the developing 3D model is often best achieved through a series of conventional—and simpler—2D views of the model (the map, and sections). Certainly all of the interpretive input in this project was done in 2D views—but then reviewed in various other 2D and 3D views.

## Outputs from the 3D Model

The (mathematical) model of Broken Hill was used to generate several outputs:

- Maps and Sections. Any surface that intersects the model-space is a *section*. The DTM (Digital Terrain Model, a topographic surface) is thus a section, and is used to create a conventional geologic map. Any arbitrary section can also be created, allowing the 3D model to be examined in any 2D view. Maps and sections were used throughout the (interpretive) model building phase, and section-plots were a standard output,
- 3D Views: the software has a 3D viewer, within which the geology data points, the orientation data (displayed as small 'discs'), and the 3D shapes of geological formations (see below) can be visualised from any angle,
- 3D Shapes: shapes for each geological formation, defined by triangulated surfaces, were generated and exported in T-Surf[2] file format, suitable for import and visualisation in Gocad, FracSIS, etc.,
- VRML files: for 3D visualisation using a VRML plug-in to a web browser, and
- Voxels: a 3D voxel model, with geology assigned to voxels, was generated and exported in Voxet[2] format, suitable for import and visualisation in Gocad.

A final component of the Broken Hill project was to demonstrate the application of gravity inversion to further refine and test the accuracy of the model. The voxel model was an important input to the inversion processing.

[2]T-Surf is an ASCII exchange file format, defined by Gocad software (http://www.gocad.com/), which describes surfaces and closed volumes in terms of the 3D coordinates of the vertices of triangles fitted to the surface. The Voxet format is also defined by Gocad.

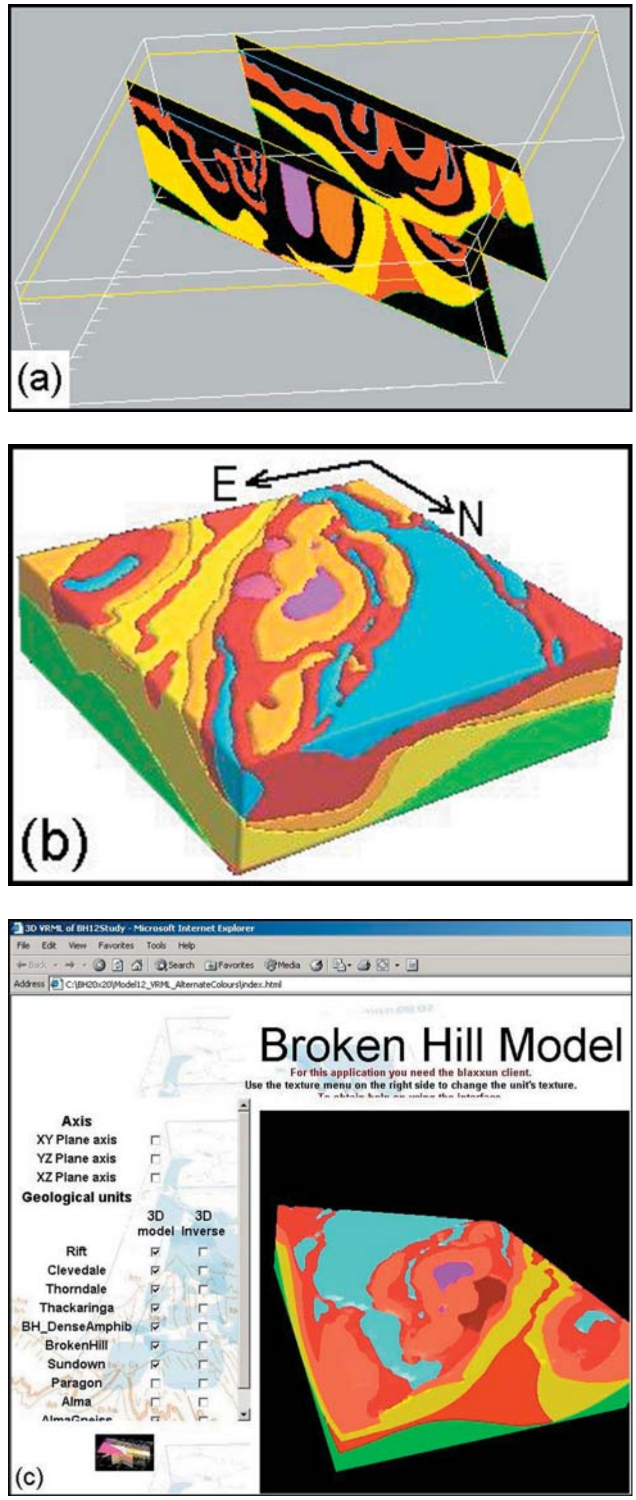


**Figure 10.** Outputs of the Broken Hill geological model. Conventional maps and sections can be drawn, and can be presented in perspective views (a). Full 3D models can be constructed and visualised, or exported in standard exchange format files suitable for import to other packages such as Gocad (b). The 3D shapes can also be used to create VRML files, suitable for viewing in a standard web-browser (c).

## Gravity Inversion of the Broken Hill Model

The purpose of generating realistic 3D geological models is often to provide a basis for further physical modelling and analysis. This might include investigation of ground-water characteristics, seismic hazard assessment, or thermal energy resource potential.

In Australia there are vast areas with little or no outcrop, and so the geology is often poorly understood. At the same time, these same areas often have good gravity coverage, and high quality magnetics coverage. Thus there is a strong interest in maximising the utilisation of these potential field data to improve geological understanding. Inversion of potential field data is often flawed by not having adequate models with which to begin the interpretation. Thus there is an interest to use an approach of (a) generating realistic models from all available sources of geological information (often not much!), and then (b) to use these models as a starting point for potential field inversion.

It is not the purpose of this paper to discuss inversion, but a summary is included here since the Broken Hill model was used to demonstrate an innovative approach to inversion which has been implemented in the GeoModeller software. For a more thorough treatment, see Guillen *et al*. (2004).

The inversion uses as a starting point what is expected to be a *realistic model of the geology*. On this basis there is an expectation that the misfit between the computed (gravity) forward model response and the field data will decrease relatively quickly, yielding a set of (inversion) models for which the computed geophysical response reasonably matches the field data. Practical comparisons can be made between a 'realistic' starting geologic model and the progressively revised voxel models generated by the inversion.

Inversion is performed on a voxel model of the *geology* rather than a model of some physical property, such as density. The *geologic unit* for each voxel is initially assigned from the starting model built by the project geologist; this may change during inversion. Physical property values are assigned to voxels using the parameters and statistical law which describe the distribution of that property for the given geologic unit.

Each inversion iteration makes a modification to one voxel only, or, optionally, to a small selection of voxels. The revised geophysical response due to each small adjustment of the model is computed very efficiently, and naturally the overall impact from a single iteration is small.

The inversion process is based on a Markov Chain Monte Carlo formulation, which is solely used to accept/reject each candidate model. The single voxel to be adjusted in each iteration is selected randomly. The assigned geologic unit for the selected voxel may be changed to match that of an adjacent voxel—on a random basis. The assignment of a density difference value is by random selection according to the probability function defined for the relevant geologic unit.

Whereas many inversion processes are designed to reduce the global misfit between the observed and the computed response, and then stop when the misfit has reached some specified low limit … the GeoModeller inversion continues to iterate. Rather than simply finding *one model* which matches the observed data, the approach is to explore a wide range of possible models—all of which have a computed response which have a known likelihood based on how well it matches the observed data; thus, potentially *<u>many millions of possible models are examined</u>*, and the inversion results are presented in terms of the probabilities … for example, the probability that a voxel *<u>v</u>* is stratigraphic unit *<u>s</u>*.

The inversion algorithm may be summarised as follows:

- for each inversion iteration, it randomly selects a voxel,
- it optionally changes the geologic unit and/or assigns a revised density value,
- it re-computes the model response,
- it compares the model with the field gravity data,
- if the misfit improves, the revised model is retained, and
- 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. With some millions of iterations, the global misfit typically decreases to some small error between the computed model response and the field data. By *continuing the inversion* for many more millions of iterations beyond this point, the models that are 'kept' are all *models which reasonably match the gravity data* … and these many millions of models can be used to report the inversion outcome in terms of probability.

The inversion trials for Broken Hill were inconclusive. Early inversions yielded poor results and required some revision of the model, and reassessment of the true density value of some formations. *<u>All later inversions achieved a good match between the model gravity response and the field data</u>*. These results must be qualified, however, by the reality that density values for the Broken Hill formations are not well known. For some formations the distribution of density values is bimodal due to local variations in the percentage of either dense amphibolite or less density quartz pegmatites.

An outcome from this work has been that we have recognised a need for inversion processing to be able to effectively manage these bimodal distributions of density, and have initiated experimental studies to implement an inversion option that allows for this.

## 3-D MODELLING AND DATA MANAGEMENT

The 3D modelling application presented in this paper is fundamentally designed as an interpretive tool to be applied by the project geologist. The software has been applied to a spectrum of tasks on a range of scales, and a small range of digital data input/output capabilities have been developed. We have a clear vision that this type of software must seamlessly integrate with an organisation's geologic data management to do the following:

- read geologic observations from databases,
- write back attributed data to those databases, and
- export lines and surfaces into the databases of GIS and presentation software.

Some of these data I/O requirements already exist in GeoModeller, and more are planned. It is worth commenting further about the input of digital data for 3D model building. In our experience to date, building 3D models needs an intelligent approach to selecting the data to be used. Simply importing *all available data* is often unsatisfactory. There are a variety of reasons for this. There can be quite trivial reasons, such as incompatibility between the stratigraphic nomenclature in the database compared to the modelling project, or the database may contain many micro-structural observations that are not immediately applicable for a regional modelling project. It is worth noting two other points:

1. When constructing a 3D model, it is often the case that there is little or no actual data in the third dimension. As with any uneven sampling problem, an abundance of data in one area cannot compensate for a lack of data in another, and it is—in our experience—unrealistic to generate 'high-frequency' models in zones of sparse data! In an area of good outcrop it may be possible to generate a high resolution map, but not necessarily a high-detail model beneath that. Thus it is not always possible to effectively use all of the mapping observations that are available; and we will be seeking to develop filters to assist the geologist in filtering the data, to select some, and reject others.
2. The GeoModeller software uses discrete *points* of geology. Some geologic databases record these, but there are also now vast repositories of GIS-geologic data recorded as *lines* of data. In many cases, a line in a GIS database is a combination of observation points and interpretation lines. In the GeoModeller software we would like to use the point (observation), but let the software (re)generate the line! To make best use of existing GIS data, we plan to develop tools to intelligently re-sample lines, and again give the geologist a filtering capability such that choices can be made about keeping or rejecting portions of these imported data.

## 3-D MODELLING AND DATA QUERYING/ PRESENTATION

In the future, we will provide some fundamental data presentation capabilities in the GeoModeller software. Already there is simple screen visualisation, and a capacity to produce a 3D VRML file—with little more than a click of a button! And presentation-quality printing of maps and sections is proposed. However, we see model-building as a process which must be integrated with other styles of data manipulation, querying and presentation, and so the export of standard interchange formats is a high priority. Several export formats are supported already, and more are planned.

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