Broken Hill Geological Modelling Project Using 3D-WEG Geological Editor

Final Report

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Abbreviations Used in the Report

20x20 Model – the 20km x 20km Broken Hill Geological Model as defined in Table 1

3D-WEG – 3D Web Editeur Géologique

46x51 Model – the 46km x 51km Broken Hill Geological Model as defined in Table 1

AGG – Airborne Gravity Gradiometer (Survey)

AHD – Australian Height Datum

BHEI – Broken Hill Exploration Initiative

BRGM – Bureau de Recherches Géologiques et Minières

GA – Geoscience Australia

GDA94 – Geodetic Datum of Australia 1994

gD – vertical component of gravity (from AGG data)

Gdd – vertical gradient of the vertical component of gravity (from AGG data)

GSNSW – Geological Survey of New South Wales

pmd*CRC – Predictive Mineral Discovery Cooperative Research Centre

MGA54 – Map Grid of Australia, Zone 54

NSW DMR – New South Wales Department of Mineral Resources

1 Executive Summary

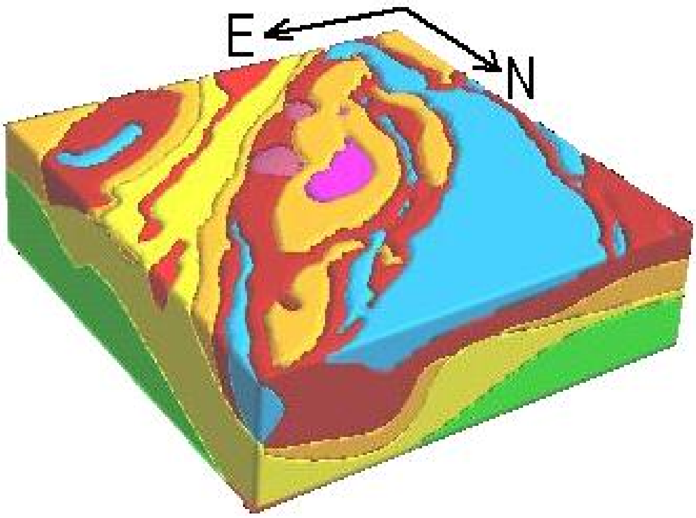
The ‘Broken Hill Geological Modelling Project Using 3D-WEG Geological Editor’ has applied the BRGM’s innovative geological editor to construct a 3D geological model of Broken Hill.

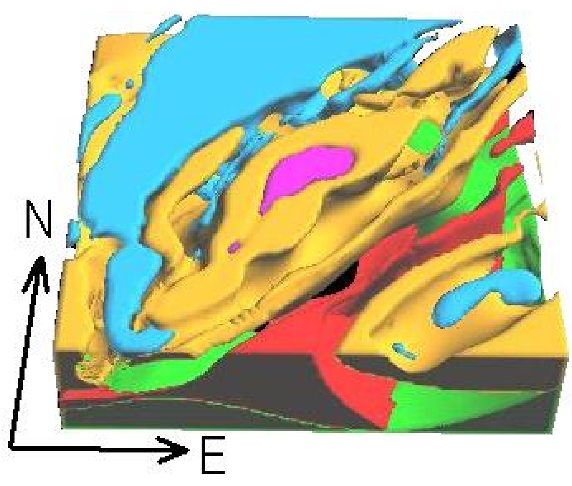
The Broken Hill model covers an area of 20km x 20km centred on the Broken Hill mining district. (A second model, covering a larger 46km x 51km area was also constructed, but only a small part of the project time was spent on the larger model). The Broken Hill model was developed using existing geological data from government and industry mapping, GIS and digital databases and the earlier 3D Pasminco Model (Archibald et al., 2000). No additional mapping was done. Never-the-less, this model is an interpretation of the Broken Hill geology by the authors, since the process of 3D-WEG 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. Since it is 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 very complex, and this complex geology has been captured into a coherent, fully 3D model during the short time of this project.

The model can be visualised within the 3D-WEG software, but has also been exported from the software as …

- A fully interactive web-site presentation, capable of being viewed in a standard web-browser (with a suitable VRML plug-in). A user can manipulate the model, turn selected units ‘on’ or ‘off’, apply ‘textures’, and can interactively visualise the model with rotate, pan and zoom controls
- Geological shapes. Wire-frame shapes, defined by triangulated surfaces, for each geological unit in the model. Exported in an industry-standard file format, and so suitable for import into other visualisation and analysis software.
- A voxel model. Voxels, again in an industry-standard file format, and recording the geology for each voxel, and also the geological ‘probability’ data reported from inversion.





A second important goal of the project was to assess the performance of the 3D-WEG software. Key findings from this assessment are …

- The editor is geologist-friendly software. The software has been designed such that the manner of working with geological observations is familiar to geologists. More importantly, we found that a geologist, using the software, ***is working as a geologist***. The geologist has the opportunity to be ***interpreting geology*** as an integral contribution to the process of building the 3D model.
- The geological editor builds a model ***from the raw geological observations*** – the contact points for the 'top' of strata, for example, and the orientation observations (dip & strike). This is a ***revolutionary development in geological model-building***, and a significant advance on the CAD approach of having to develop wire-frame shapes. Two radical consequences of this approach are 1: new observations can be easily added, and the model easily reconstructed to take account of those new data, and 2: this changes the whole approach to managing geological observations in corporate databases, since a raw observation can now be utilised again and again, in different projects, over many years.
- Inversion in 3D-WEG also uses an innovative approach. Joint inversion of gravity and magnetic data is possible, although the Broken Hill project used gravity inversion only. A traditional inversion approach is to iteratively adjust the model, and stop when some measure of error between observed and computed data is acceptably small – essentially achieving *one model* which matches the geophysical data. A key innovation in 3D-WEG inversion contrasts with this; when the error level becomes small, iterations continue, making further model adjustment, and so *can find many millions of models which match the geophysical data*. These many solutions can then be used to report the inversion results in terms of 'the probability of a formation' existing at any given location. In this way, the inversion process is able to quantify the uncertainty of the inversion solutions.

The 3D-WEG software is research software which is still in development. It is not yet commercially released software. Despite this, the software has a quite satisfactory level of finish, intuitiveness and robustness. Because the software is quite revolutionary, it does form a basis for further developing quite new approaches to managing geological observations, and using those to build interpretative models. Several areas have been identified for further development within a future R&D project. Potential areas include …

- Improved attributing of geological observations, and development of linkages between 3D-WEG and corporate databases used for geological data management.
- Size of model (number of geological observations) and Speed of Computation. The software currently builds quite complex models, and is able to use a modest number of observations to do this. As the number of observations increases, the compute-time also increases. Ultimately there will be a demand by users to build models using very large numbers of observations, and alternative modelling algorithms will be needed to implement this while still retaining practical computation times.
- Inversion Controls. Additional controls to allow the user to implement further constraints on inversions is recommended. In particular, being able to dictate that certain voxels cannot be modified – on the basis that those voxels contain factual observations – is an important area for further control of inversion processing.

2 Introduction

The Broken Hill Geological Modelling Project Using 3D-WEG Geological Editor is Project Number C6 of the Predictive Mineral Discovery Cooperative Research Centre (pmd*CRC). The project is an application of the 3D-WEG[1] Geological Editor software developed by the Bureau de Recherches Géologiques et Minières (BRGM[2]). The key goals of the project were …

- to evaluate the performance of the 3D-WEG Geological Editor – a radically new approach to 3D geological modeling developed over a ten year period by the BRGM.
- to use the existing digital geological data from the Broken Hill study area as input to 3D-WEG, to construct a cohesive 3D geological model, and then use the geological editor's geophysical inversion capability to invert both the ground and airborne gravity (gradiometer) data to further refine and test the accuracy of the model.

A further goal of the project was …

- to promote the outcomes from the work, and introduce the BRGM's Geological Editor technology to a wider audience of the Australian geo-science community, through a series of workshops to be conducted towards the conclusion of the project.

The project was undertaken by Intrepid Geophysics, with collaborative technical assistance from the BRGM. The BRGM also provided in-kind financial assistance to the project.

The principal sponsors of the project were …

- Geoscience Australia (GA)
- New South Wales Department of Mineral Resources (NSW DMR)
- Predictive Mineral Discovery Cooperative Research Centre (pmd*CRC)

In addition, the project was supported by …

- the *Innovation Access Programme* under the Australian Government's innovation statement, *Backing Australia's Ability*.

The support from this Innovation Access Programme grant was designed to achieve the third goal noted above … viz. fostering of international collaboration in technology innovation, and introduction of outcomes to Australian industry.

The project was developed over several months during 2003, and the research agreements were signed by the funding partners in early October, 2003. Project work commenced on November 5th, 2003, and was completed on June 30th, 2004. This final report documents all outcomes from the project, and records all activities undertaken during the project.

Workshops to introduce the 3D-WEG technology to the Australian geoscience community were conducted in Melbourne, Adelaide, Perth, Kalgoorlie, Canberra and Brisbane in late June, 2004.

[1] 3D-WEG: 3D Web Editeur Géologique … a Geological Editor developed by the BRGM.

[2] The Bureau de Recherches Géologiques et Minières (BRGM) is a national (and international) geological agency of the Government of France.

The Structure of this Report

This report is about *both* the 3D-WEG software itself, and the 3D model of Broken Hill geology developed by applying the software. The two themes are presented together. Within each of the main sub-topics, the general structure is …

- 3D-WEG - A note about the **3D-WEG approach** (to stratigraphy, for example)
- Broken Hill – The details for the **Broken Hill case study** (stratigraphy, structure, etc.)
- Discussion – Commentary, in part about geology outcomes from the Broken Hill case study, but more particularly about the performance of the 3D-WEG software as applied to the Broken Hill project.

2.1 Project Area

The Project Area is defined in the project agreement as the area of the Broken Hill FALCON™ Airborne Gravity Gradiometer (AGG) survey. At the commencement of the project it was agreed that all work would be done, and results delivered, using the standard national datum and projection …

Datum:	Geodetic Datum of Australia 1994 (GDA94)
Projection:	Map Grid of Australia, Zone 54 (MGA54)

Two models were developed during the course of the project.

The 20x20 Model

During the early to mid stages of the project, the software's management of complex networks of intersecting faults was faulty[3](!?). In order to continue working, a smaller area (20 x 20 km) was selected, wherein the geology was simpler(!?), and the structural complexity was reduced by taking into account just two major structures, viz. the Globe Vauxhall Shear and the Darling Fault. This is referred to as the **20x20 Model**. The project dimensions are noted in Table 1.

There were added advantages to using the 20x20 Model – in terms of computation speed. The interactive feed-back during model building was faster. Also, inversion processing was faster; or, more correctly, for a given elapsed compute-time, each voxel of the (smaller) model was visited and adjusted more frequently. Thus inversion of the 20x20 Model provided a more thorough assessment of 3D-WEG's inversion than would have been possible with the larger model. [One inversion on the larger model was executed for nearly two weeks!]

Where not explicitly stated otherwise, all work done, and outcomes documented refer to work done using the 20x20 Model.

[3] The problem with the networks-of-faults was remedied in the later stages of the project, and models built for the larger 46x51 Model.

The 46x51 Model

The primary goal of the C6 Project was to construct a 3D geological model covering the area of the FALCON™ AGG survey. Since a 3D-WEG project area must be a volume oriented parallel to the chosen coordinate system, a 46 x 51km area was needed to encompass the AGG survey area. This was created as a separate 3D-WEG project, and the earlier work from the 20x20 Model was transferred into the larger **46x51 Model**. The project dimensions are noted in Table 1.

Only limited inversion testing was done on this model. In this report, all reference to work done or results derived from using the 46x51 Model explicitly specify the '46x51 Model'.

Table 1. Coordinate limits of the two Broken Hill geological model projects areas – the 20x20 Model and the 46x51 Model.

The 20x20 Model				
West – East:	535,000mE	to	555,000mE	(GDA94, MGA54)
South – North:	6,450,000mN	to	6,470,000mN	
Top - Bottom:	1,000m	to	-5,000m	(AHD Geoidal Height)
The 46x51 Model				
West – East:	528,000mE	to	574,000mE	(GDA94, MGA54)
South – North:	6,438,000mN	to	6,489,000mN	
Top - Bottom:	1,000m	to	-5,000m	(AHD Geoidal Height)
Ground Level in the Project Area ranges from 126m to 400m (average 248m), so the upper limit of the 3D-WEG project box (+1000m) is several hundred metres 'in the air'.				

2.2 DEM

Elevation data from GA's 1995 Broken Hill Exploration Initiative (BHEI) airborne surveys (100m line-spacing) were downloaded, coordinate transformed to GDA94/MGA54, and gridded to 500m cell size. This grid was imported as the topography for the full 46x51 Model.

When the 20x20 Model was constructed (due to problems in management of faults), the modelling was further simplified by ***not*** using a DEM as the model surface. For the smaller 20km x 20km project area there is very little topographic relief, so for simplicity in modelling, a flat surface at RL = 250m was used as the topographic surface.

2.3 Geological and Geophysical Input Datasets

The following datasets were provided to the project by the principal project sponsors …

Geology

- 1:100,000, 1:50,000 and 1:25,000 scale geological maps of Broken Hill (NSW DMR)
- GIS mapping at 1:25,000 scale (NSW DMR Geological Survey mapping, ArcView)
- The Pasminco Model (Archibald et al., 2000), a 3D geological model of Broken Hill district, delivered as a FracSIS database.
- Interpretative cross-sections from the pmd*CRC C1 project (T. Lees)
- Associated geological reports
- Geoscience Australia (GA) geological structural database, Broken Hill
- NSW DMR drilling database, Broken Hill
- Petrophysical databases, summaries & reports, Broken Hill (GA, NSW DMR)

Note that the NSW DMR drilling database does not include the vast amount of company data along the Broken Hill line-of-lode. The modelling work did not ***directly*** use drilling data, but was done using the more regionally available datasets, such as the surface mapping, the interpretative Pasminco Model and regional cross-sections from the pmd*CRC C1 project. (The detailed mapping and extensive drilling data were used indirectly, since those data had been incorporated into the Pasminco Model and regional cross-sections from the pmd*CRC C1 project … which were in turn used in this project).

Seismic Data

- Image of GA's interpretation of the regional Broken Hill seismic traverse (Gibson et al, 1998), and seismic line location details
- Image of Archibald's interpretative line-work of the regional Broken Hill seismic traverse (part of the Pasminco Model, Archibald et al., op. cit.)

Gravity Data

- NSW DMR, pmd*CRC FALCON™ Airborne Gravity Gradiometer survey dataset
- GA ground gravity data, Broken Hill

Density data

- GA's Broken Hill Exploration Initiative (BHEI) physical properties database and associated reports and analysis

Magnetics Data, DEM

- 1995 BHEI Airborne Magnetic Surveys by GA – downloaded from GA as required.

3 3D-WEG – Introduction to the 3D Geological Editor

3D-WEG is a geological editor – a 3D geological modelling software package – developed by the BRGM. Unlike CAD-based packages which use shapes and surfaces to describe geological objects within a model, 3D-WEG describes a geological model in terms of …

- a *stratigraphic pile*, each series being either onlapping or erosional
- *geological contact points* (e.g. the points ascribed to the ‘top of Formation X’)
- *geological orientation data* (e.g. a vector v describes the ‘facing of Formation X’)

The software then ***builds a 3D model*** (Figure 1), based on the observations. The software includes all of the functionality that a geologist would traditionally require … such as the ability to readily input, and visualise, geology - in plan view (geological *maps*) and *sections*. New section views are easily created, and all sections rendered from the model are automatically consistent with all other sections and maps.

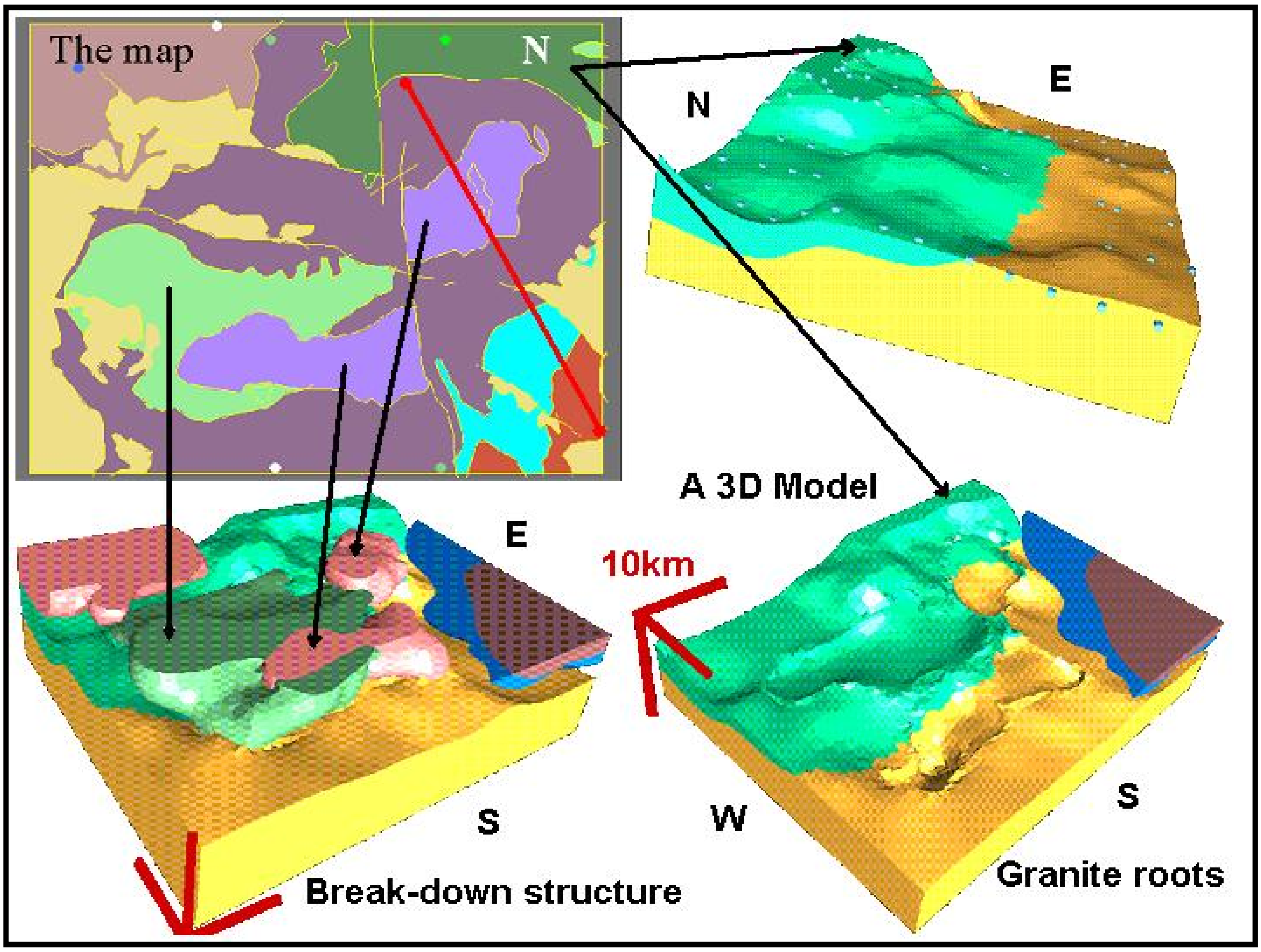


Figure 1. Example of the 3D-WEG 3D geological modelling. Authors: X. Charonnat, G. Courrioux, G. Martelet.

Features of 3D-WEG include …

- it was designed by geologists, for use by geologists. Some geological modelling packages are so sophisticated that they must be driven by highly skilled and trained operators. The designers of 3D-WEG had a vision that 3D-WEG should be able to be used by geologists, whose skills and passion were geology(!), not computer-aided drafting. This design objective has been achieved, and geologists rapidly become familiar with using 3D-WEG. The main interaction with the 3D model is via sectional views and plans through the model, concepts which all geologists are readily familiar with. (The model itself is a 3D model … but most geologists <u>*work with*</u> (2D) sectional views or plans of geology). There is a 3D viewer … but it is also very easy for the user to create any new 2D sectional view through the model.
- the geological <u>*observations*</u> are recorded. 3D_WEG works with the basic, raw observations that geologists measure … contact points, dips and strikes.
- <u>*new observations are readily incorporated*</u> into the modelling environment … and a revised model can be generated to take into account the additional data. (A weakness of the CAD style of model building is that new observations can require complex, manipulation of existing model shapes and surfaces in order to take account of the new data; 3D-WEG generates a revised model from the raw observations).
- <u>*hypotheses can be readily evaluated*</u> in the modelling environment. Just as a 'new observation' can be added, and a revised model generated … so too can 'hypothetical observations' be added by the geologist … to test an idea.
- a 3D-WEG geological model is a <u>*consistent, fully 3D model*</u> of the geology within the project volume. The geological model-building process honours the geological observations (typically input in 2D section or plan views) in a 3D sense; the geologist can view <u>*any*</u> section through the 3D model, and that section view will be completely consistent with any other intersecting sectional view through the model. [Regarding 2D / 3D, it is interesting to note … on the one hand 3D-WEG ensures 3D reality, and forces the model to be consistent in 3D, and assists the geologist in building a 3D model; at the same time, however, 3D-WEG easily caters to a geologist's preference for <u>*working with*</u> 2D sectional views and plans].
- 3D-WEG has a range of ways to bring geological observations into the modelling environment. These include simple 'mouse-click and edit attributes' in a 2D sectional view. A bit-map image (of a geological map, a hand-drawn section, seismic, …) can be registered in the view. Data can be imported from a text file. Drill-hole data can be imported from a text file. A range of export options are also available.
- 3D-WEG can <u>*invert gravity and magnetic data*</u> … with a radical new approach to inversion. A traditional approach to inversion is to iteratively adjust the model, each time measuring the error between observed and computed data. At some point when this error measure is acceptably small, iterations are stopped – and the process has yielded a single solution which is consistent with the observed field data. Whereas the traditional approach <u>*stops*</u> at this point, 3D-WEG <u>*effectively starts at this point*</u>, and continues to make adjustments, and so *explores that space of solutions that can explain the geophysical signature*. The software then reports the inversion results in terms of 'the <u>*probability*</u> of a formation' existing at any given location. In this way, the inversion process is able to quantify the uncertainty of the inversion solutions.

4 The Broken Hill 3D Geological Model

4.1 Preliminary Considerations – Broken Hill Geological Complexity

At the project start-up, a meeting was held between Richard Lane (GA), Terry Lees (Monash University / pmd*CRC) and IG and BRGM staff (AG). [Meeting in IG's offices, Nov 5th, 2003]. That meeting addressed the key issues of …

- available geological and petrophysical data for Broken Hill
- the main focus or *scale* of the modelling of Broken Hill using 3D-WEG.

Richard Lane presented results from his study of the ranges of density values across geological groups, formations and lithologies in the Broken Hill district.

It was noted that, although vast amounts of geological data have been recorded along the Broken Hill line-of-lode, there is a dearth of deeper drilling data away from that. A single regional seismic line across the project area does provide some deeper structural data.

The complexity of the geology of Broken Hill was noted, and this is reflected in the geological mapping of the district. At regional scales (1:100K, 1:50K) the geology is classified into the major geological ***groups*** and *formations*. At the detailed 1:25K (outcrop) mapping scale the rocks are assigned a lithology which is interpreted to formation and group level. Amphibolites and granitic gneisses have, until recently, been considered an integral part of the stratigraphy. It was also noted that there are differences between the published (traditional) geological maps and the equivalent data currently available in GIS; for example, there are many more structural dips/strikes recorded on the published maps which are not captured into the GIS.

There was a consensus that the most consistent set of geological information across the project area was that recorded at the major group level. This major classification is used in the 1:100K scale geological mapping, and in the Pasminco Model (Archibald et al., 2000). Furthermore, at this broad scale there is also a modest amount of petrophysical (density) data. On the basis of these considerations, it was agreed that …

- the Broken Hill 3D Geological Model of Broken Hill would be constructed in 3D-WEG using the *major group level geological units*.

4.2 Stratigraphy

4.2.1 Management of Stratigraphy in 3D-WEG

The stratigraphic column is an essential component of any geological map, since it records the time relationships of the strata. In 3D-WEG, the stratigraphic column is a fundamental control for the whole process of correctly rendering geological maps and sections.

Stratigraphy is defined in a two-step process …

- Formations are *created* … and attributes such as name and colour are assigned
- These are then assembled together in the correct order to make the *stratigraphic pile*

Note the following points about the stratigraphic pile …

- The order – from bottom (old) to top (young) – is a fundamental control which 3D-WEG uses to know which formation occurs at any given location in the project model space.
- Consecutive conformable formations can be grouped together in *series*. Geological conformity is broadly indicative of a shared geological history and structural control … and *an expectation that successive formation contact surfaces will have similar shapes*. 3D-WEG can take advantage of this expectation of similarity by grouping the relevant formations together in one series. The series is a fundamental 'package of geology' in the design of 3D-WEG … each series in 3D-WEG is computed independently from all other series.
- Each series is designated as having either an *onlapping* or *erosional* relationship to older series; this also is a fundamental control in 3D-WEG, used to determine which series is present when two or more series intersect with each other.
- The stratigraphic pile definition allows the user to specify whether geology contacts points will be the *tops* or *bottoms* of units; for the Broken Hill model, the contacts are *top contacts* for each unit.
- During the course of a mapping project, geologists might revise their understanding of rock relationships … and 3D-WEG allows the geologist to revise the order of strata, add new strata, and to modify the onlap or erosional classification.

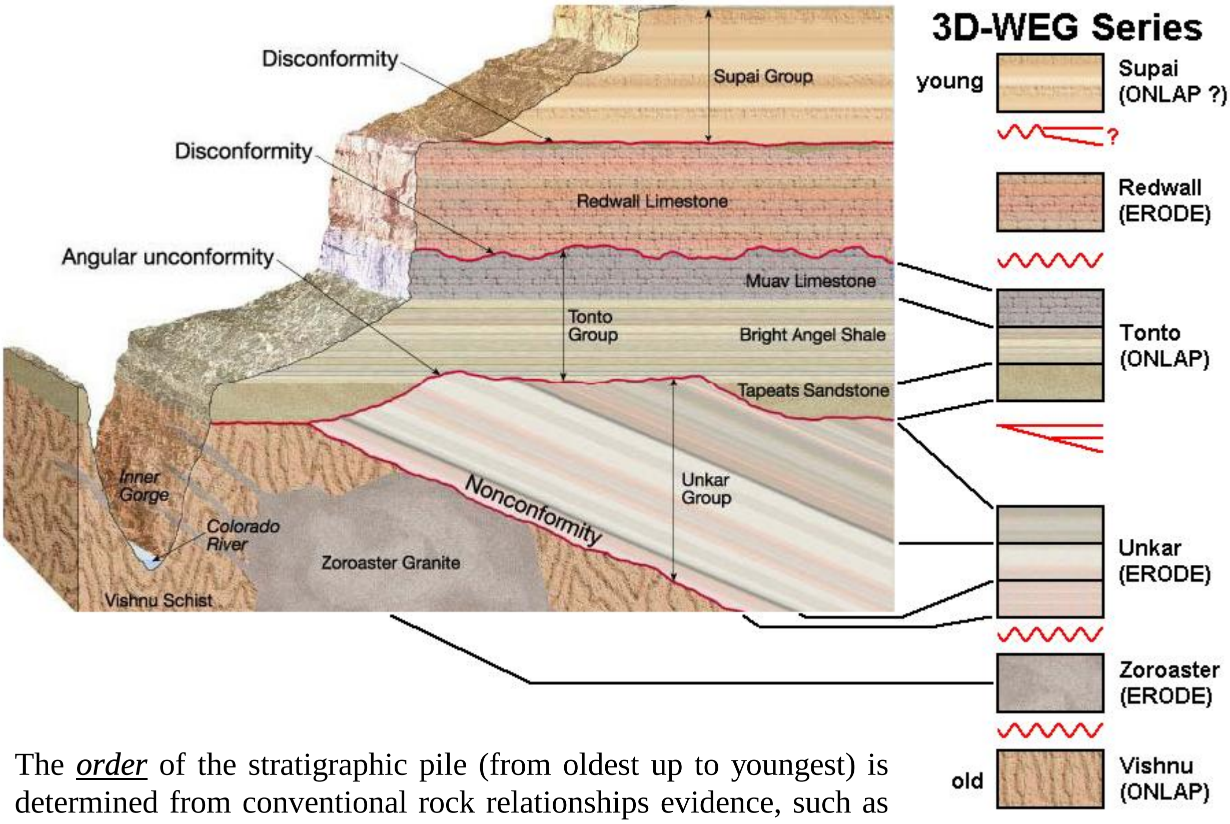
4.2.1.1 Geological Data: Contacts and Orientations

Having defined the stratigraphic pile of a project area, geological observations can be entered in to a 3D-WEG project. Two types of observations can be recorded …

- geological contacts – points which have a 3D position, and are assigned to a formation. A contact point in 3D-WEG is the top (or bottom) contact of the designated formation … e.g. the <u>*top of Broken Hill Group*</u>. Nothing is implied about what is 'above' this contact.
- orientations – are essentially <u>*facings*</u> (i.e. orthogonal to the geological surface, in the direction of stratigraphic younging). In effect, these are dip and strike data. As with contacts, these orientation vectors have a 3D position, and are assigned to a given formation. As illustrated below (Orientation Data in 3D-WEG), orientations can be recorded on map-views, or on section-views.

Geological contacts and orientation data are typically input in several map and section-views, and also in drill holes. See Section 4.4 (Building the Broken Hill 3D Geological Model).

Management of Stratigraphy in 3D-WEG



The *order* of the stratigraphic pile (from oldest up to youngest) is determined from conventional rock relationships evidence, such as cross-cutting contacts.

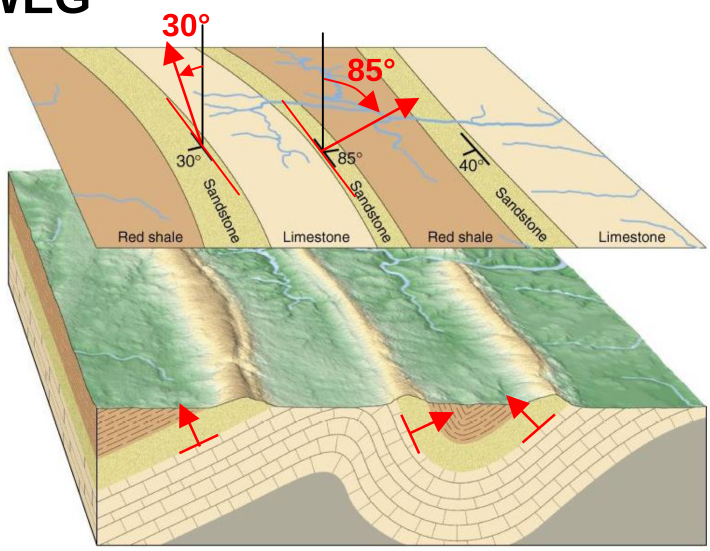
Some formations – with obvious conformable relationships – can be grouped together into *series*. A series may also consist of just a single formation. Each series is classified as being either *onlapping onto* or *erosional to* older series. 3D-WEG computes the geological surfaces for each series independently of all other series, and then uses the stratigraphic order and the onlapping / erosional relationships to determine which formation is present at each point. Note that intrusions typically have cross-cutting contacts, and are classified as 'erosional'!

Orientation Data in 3D-WEG

Orientations are essentially facings (i.e. orthogonal to the geological surface, in the direction of stratigraphic younging).

It is important to record orientations with the correct sense of 'up'; if some of the orientation data for a formation are incorrectly assigned an upside-down facing, then 3D-WEG's computation of the potential (or surface) for that formation could be quite convoluted!

From a topological view-point, *every surface* in 3D-WEG has *up* and *down* sides … so even faults and intrusives must have at least one piece of orientation data to define this *direction*.



4.2.1.2 3D-WEG's Computation of Geological Surfaces

3D-WEG draws geological maps and sections in a two-step process …

- compute the model
- render the geological surfaces from the model onto the required section

The process is – very simply – an interpolation process. The 3D interpolator in 3D-WEG is based on potential theory … and geological surfaces are treated as 3D iso-potentials of a potential field.

The **computation of a 3D-WEG model** is applied to each series independently of all other series; a matrix is constructed using all the geological contacts, and all the orientations (for each formation) of a series. The matrix is solved to define a 3D potential (field) which honours …

- the geological contacts – all of the contacts for a given formation lie on an iso-potential of the computed potential field
- the orientations – the orientations are treated as gradient-vectors (of the potential), and the computed potential is solved such that the field is always orthogonal to these vectors (gradients)

Note that – for the case of simple, conformable strata – there is some advantage from grouping those formations together into one series. Since the geological contacts and orientation data from several (conformable) geological horizons are all used together to compute a single potential (for the series), then – on the basis that more data makes for more reliable computation of the potential, and thus more reliable interpolation – 3D-WEG's ability to draw the geology correctly is improved.

The **rendering of geological surfaces** onto maps and sections requires repeated interrogation of the computed model in order to calculate the position of contacts between formations … then drawing these. The interrogation of the model essentially returns 'the *formation* at point *x*', and is based on …

- the *computed potentials for each series*, coupled with the additional factors of …
- the *order* of the stratigraphic pile, and …
- the *onlapping / erosional relationships* between series.

4.2.2 Stratigraphy used in the Broken Hill Model

The geology of the Broken Hill district is complex. There is a complex interplay between stratigraphy, structure, granitic and mafic (amphibolite) intrusions, metamorphism, and alteration. Structure includes retrograde shears, high-temperature shears, boudinage and transposition. In summary, Broken Hill geology presents a challenging test for 3D-WEG!

For more information on the geological setting, the reader is referred to Stevens, 1980; Willis et al., 1983; Stevens et al., 1988, and Gibson and Nutman, 2004.

The stratigraphy of the Willyama Supergroup in the Broken Hill Block is divided into groups that have some continuity across the entire area, then further divided into formations, often with less continuity. Figure 2 (from Stevens and Barron, 2002) shows the most recent stratigraphic chart, based on geochronology by Page et al, 2000, as well as stratigraphic relations, and modified from the earlier Geological Survey of NSW (GSNSW) synthesis (Willis, 1989). However, there is the possibility of major structures within the stratigraphy (Noble, 2000; Gibson and Nutman, 2004). The stratigraphy and high grade shear zones are discussed further in Section 7 (Discussion: Broken Hill Geology Outcomes).

Preservation of the original stratigraphy is variable. Sedimentary structures (such as graded bedding, although metamorphosed) are preserved in some domains. Elsewhere, small-scale structure such as transposition, is superimposed on poorly bedded and sometimes altered metasediments. Domains may be separated by retrograde shear zones or unmapped high grade shear zones, so that estimation of original sedimentary thickness, continuity and relationships between formations and groups is not reliable.

The stratigraphic pile, as originally formulated by the GSNSW, includes lithologies - such as granitic gneisses and amphibolites - that were regarded as *stratigraphy* and were therefore included in the definition of some formations and groups. Subsequently, although in several cases these were shown to be at least in part intrusive, there has been no revision to the stratigraphy. Complex structure (see Section 4.3.2) and the general lack of distinctive marker units (with local exceptions, such as Potosi gneiss and Ettlewood calc-silicate) means that the primary stratigraphic formations and groups, and their relationships, are not well understood. Geochronological constraints (e.g. Page et al., 2000) are helping to resolve some of the issues.

As noted in Section 4.1, given the complexity of Broken Hill geology, and the finite time allocated to complete the project, it was decided to base the 3D-WEG model on group-level stratigraphy (comparable with the earlier Pasminco Model).

- The stratigraphic pile for the 3D-WEG project was based on the succession defined by the GSNSW (Willis, 1989; Stevens and Barron, 2002; Figure 2)
- Given that relationships between the groups are not well known, and in some cases controversial, the stratigraphic units in the model were considered to be independent; i.e. each stratigraphic unit was considered to be a ***separate series***
- All series were designated to be *onlapping* relative to all older series, except for the Alma Gneiss; this intrusive unit was classed as being *erosional* (in order to be modelled with cross-cutting relationships to older series).

The units comprising the modelled geology are shown in Figure 2, and are briefly described below.

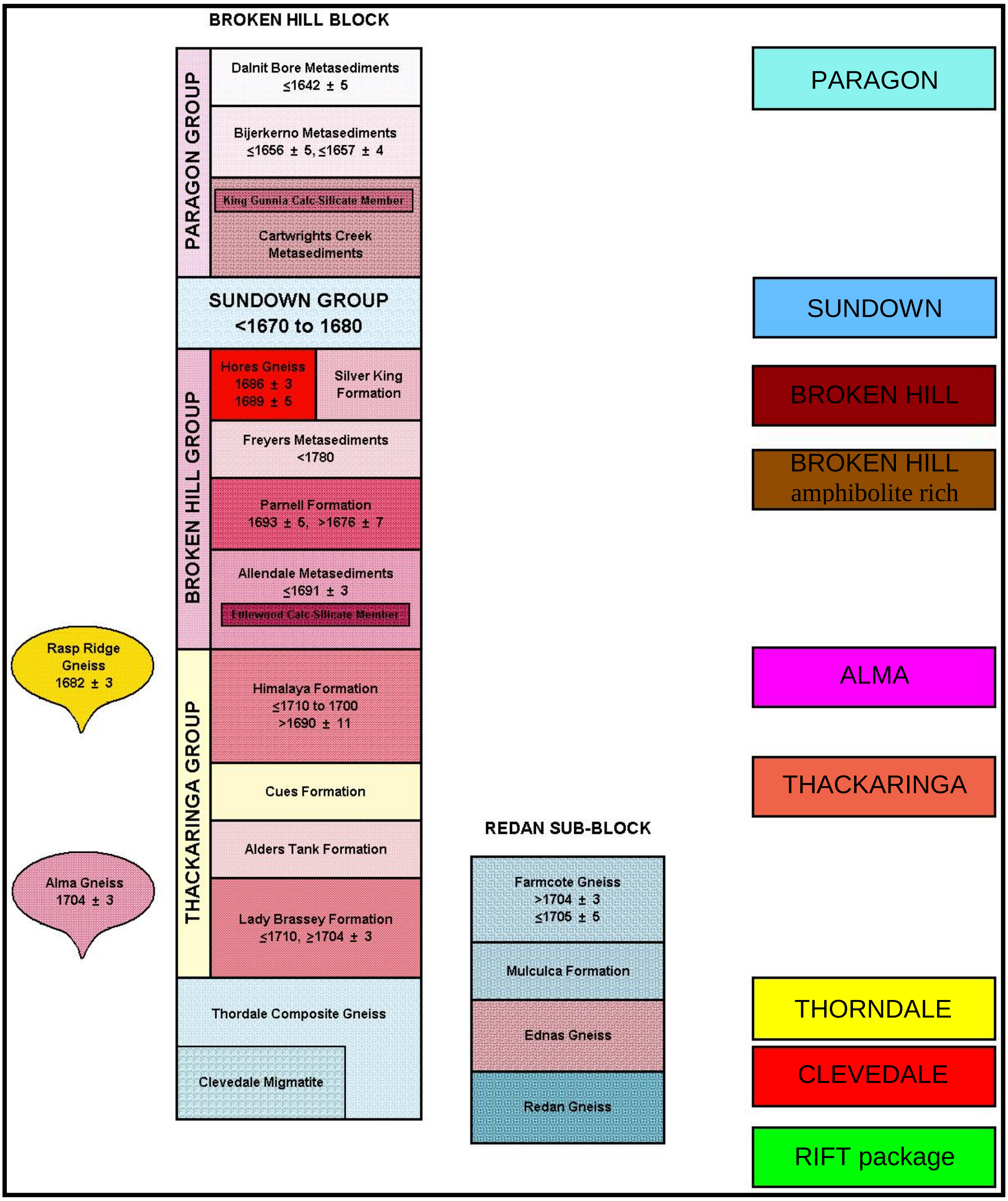


Figure 2. Stratigraphy and geochronology of the Willyama Supergroup in the Broken Hill district. (From Stevens and Barron, 2002, incorporating data from Page et. al., 2000, Stevens, 2000 and Page et. al., in press). The 3D-WEG Broken Hill geological model was constructed using only the broad group-level classification, shown at the right.

4.2.2.1 Rift

The Rift series was introduced from the interpretation of the Broken Hill regional seismic line (Gibson et al, 1998) and extended as a generally flat-lying, basal sequence throughout the model area. All geology below the top of the major reflector in the seismic section, and as extended through the model area, is grouped together as 'Rift'. Incorporation of this Rift unit from the interpreted seismic profile required reconciliation between the ***steeply dipping*** geology at surface (probably related to F2 folds with upright axial planes), and the ***low-angle*** reflector in the seismic.

In the 46x51 Model, it is assumed the Rift sequence is *equivalent* to the Redan sequence, which outcrops south-east of Broken Hill, and comprises Mulculca Formation, Redan Gneiss and Ednas Gneiss. These stratigraphic relationships are in fact unknown; this assumption conveniently simplifies the model, and avoids the need to introduce new series of unknown relationships into the stratigraphic pile.

'Basement' is not known from outcrop, nor has it been identified in seismic or other geophysical data; it has been omitted from the model. Analogy with the Mount Isa Inlier would suggest Barramundi basement (>1870 ma) sits beneath the sequence at Broken Hill. Logically, this basement would underlie the Rift sequence. For the purpose of this project, basement could be considered as part of the Rift sequence.

4.2.2.2 Clevedale Migmatite

The Clevedale Migmatite is a migmatitic and quartzo-feldspathic composite gneiss from the Darling Range, where it appears to occupy the core of a fold within the Thorndale Composite Gneiss, hence its' position at the base of the GSNSW stratigraphy.

4.2.2.3 Thorndale Composite Gneiss

This metasedimentary (psammite to psammopelite) quartz-feldspar-biotite-sillimanite ± garnet, cordierite gneiss has abundant pegmatitic segregations. It mainly occurs in the ranges east of Broken Hill.

In the Mulga Springs Creek catchment area north-east of Broken Hill, detailed mapping of the STEPHENS CREEK and MOUNT GIPPS 1:25,000 sheets (Stroud, 1989; Bradley, undated) of well-exposed Thorndale Gneiss and Thackaringa Group shows confusing differences between mapped geology, amphibolites (which appear to be at least in part intrusive), and interpreted geology.

4.2.2.4 Thackaringa Group

This group is defined as metasedimentary gneiss, composite gneiss and basic gneiss (amphibolite) with characteristic quartz-feldspar-biotite ('granitic') gneisses and quartz-plagioclase (typically albite) rocks.

Granite gneisses, such as the Rasp Ridge Gneiss, are regarded as part of the Thackaringa Group in the GSNSW legend. These may be granitic sills that are at least sub-parallel to stratigraphy. These granitic gneisses were not modeled separately from the Thackaringa Group. In hindsight, a separate Rasp Ridge Gneiss unit in the model may have improved the subsequent inversion results, since the bodies are distinctive, well mapped and have low enough density to cause gravity lows coincident with the bodies in several locations.

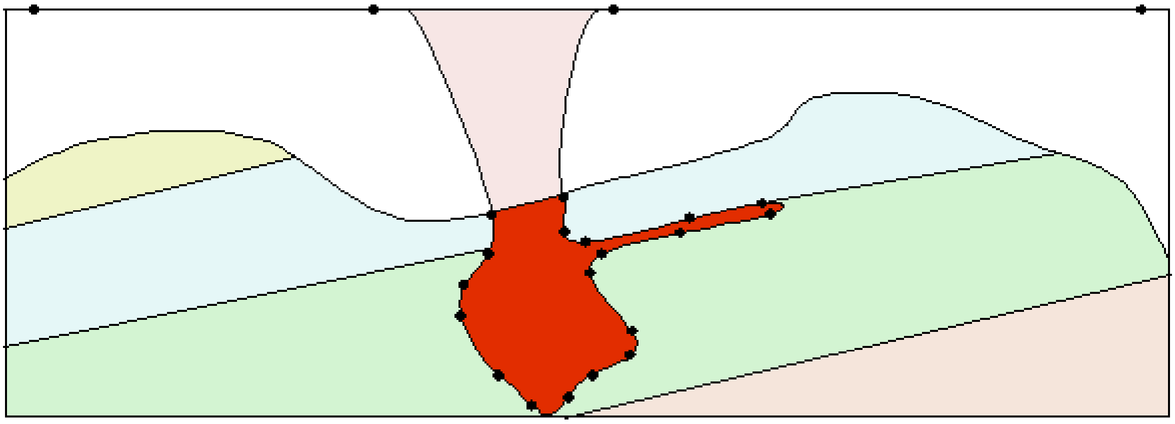
4.2.2.5 Alma Gneiss

Although actually part of the Thackaringa Group as defined, this K-feldspar megacrystic quartz-feldspar-biotite ± garnet gneiss has been identified as a discrete unit in the model. It is most likely to be a deformed granite, but conceivably could be meta-rhyolite. It is one unit which has a distinct (low) gravity signature.

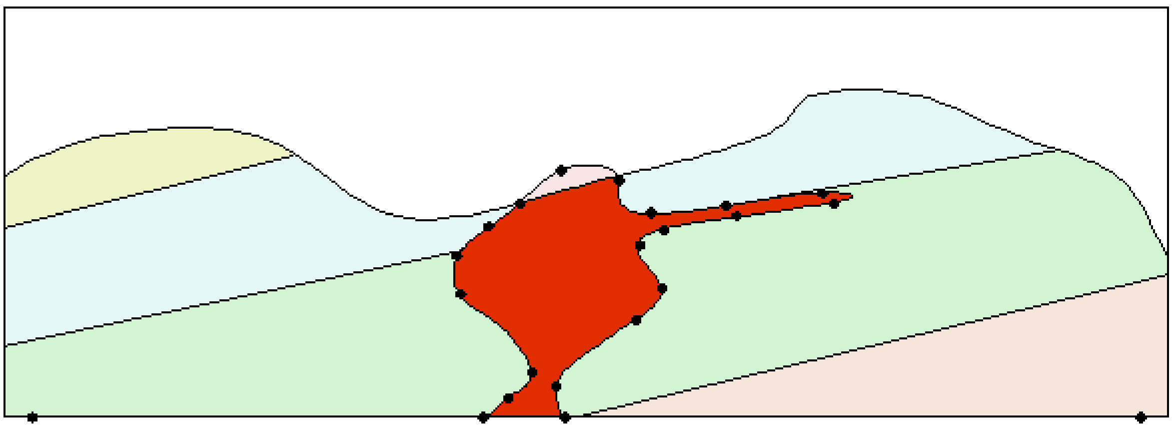
Managing Intrusives in 3D-WEG

The definition of the stratigraphic pile for a 3D-WEG project defines whether each unit has either an *onlapping* or *erosional* relationship to older units. This geological term is essentially defining the ***topological relationship*** between each unit and all older units. In a topological sense, an intrusive (typically) has a cross-cutting relationship with the strata that it intrudes – and in this sense, the intrusive (Alma, in this case) is classified in the stratigraphic pile as being 'erosional'(!) = cross-cutting.

Whilst it is obviously ***not actually*** erosional, the Alma intrusive is cross-cutting – which is, from the 3D-WEG viewpoint – the same as erosional. The Alma (where it occurs) can be considered to erode down into the older geological strata. Note that - ***where the intrusive is not required*** - it is constrained to be at the very top of the model (up in the air, where it has no effect on the model).



An alternative means of managing an intrusive is shown below; again the cross-cutting relationship – but in this case presented as a unit which 'erodes' up into the older strata. Note again that - ***where the intrusive is not required*** - it is constrained – this time at the very bottom of the model (where it also has no practical effect on the model).



4.2.2.6 Broken Hill Group

The Broken Hill Group comprises psammitic to pelitic metasediment with calc-silicate ellipsoids, amphibolite, and distinctive Potosi gneisses; it also hosts the lode horizon, consisting of various quartz-garnet and quartz-gahnite rocks.

A separate part of the Broken Hill Group - called ‘BH_DenseAmphib’ - was defined late in the course of the project. This was defined only in the area of the Thorndale Gravity High, and represents an unusually amphibolite-rich part of the sequence. It was introduced into the model in order to more correctly model this amphibolite-rich zone, and hopefully achieve an improved performance in the 3D-WEG inversion processing.

There is clear distinction between the underlying (Thorndale Gneiss, Thackaringa Group) metasediments across the entire Broken Hill area. The lower units are typically poorly bedded quartzofeldspathic psammites (‘FSM’) whereas Broken Hill Group and Sundown Group are well-bedded (often with graded bedding) pelite, psammopelite and psammite.

The Broken Hill Group is overlain by the Sundown Group, which is a similar metasediment but lacking amphibolite, ‘Potosi’ gneiss and lode rocks. The nature of the Broken Hill Group - Sundown Group contact is controversial and discussed later (Sections 4.3.2, 7.5).

4.2.2.7 Sundown Group

The Sundown Group comprises psammitic to pelitic metasediment with calc-silicate ellipsoids, but lacking amphibolite, Potosi gneiss and lode rocks. In the type area of the Sundown Hills north-west of Broken Hill, the Sundown Group contain locally abundant pegmatites and leucocratic gneisses.

4.2.2.8 Paragon Group

Mainly graphitic metasediments, phyllites and minor albitic psammites; this group is quite distinctive from the underlying units.

4.3 Structure

4.3.1 Management of Structure in 3D-WEG

4.3.1.1 Folds and Tilts

Folding and tilting of geological strata are represented in a 3D-WEG project by recording the raw geological observations – viz. geological contacts and orientations (Section 4.2.1.1). Using these raw observations, 3D-WEG computes a model which honours both the contact positions and the orientation vectors, and so is able to render the folded and tilted strata in a geological map or section.

In the most recent upgrade of 3D-WEG there are further improvements for managing folds, and the trace of a fold hinge line can be input, for example. None of this capability was evaluated in the Broken Hill Geological Modelling Project.

4.3.1.2 Faults

The location and attitude of a fault (surface) is recorded in 3D-WEG in a similar manner to describing a geological surface. Faults are defined in a two-step process …

- Faults are *created* … and attributes such as name and colour are assigned
- Faults are then *linked* to selected horizons of the stratigraphic pile

Having defined a fault, and those parts of the stratigraphic pile that the fault can intersect, the location and attitude of the fault is then recorded in the same way as any other geological surface viz. by entering the raw geological observations …

- fault 'contact' points (i.e. a location, equivalent to the contacts for strata) – points which have a 3D position, and are assigned to a specified fault.
- fault attitude or orientation. As for geological strata, a fault orientation is a vector which is orthogonal to the fault plane[4].

These contact and orientation observations for a fault simply describe a surface – the plane of the fault. There is no concept of describing the throw of a fault, or the sense of movement on this fault surface. The position of a given geological horizon either side of a fault is computed from the raw observations for that horizon on either side of the fault – and so *it is the geological observations that determine the sense of movement and the amount of throw on a fault.* The effect of the fault is to introduce a 'break', such that the geological surface for an horizon on one side of a fault is a different iso-potential horizon from that on the other side of the fault.

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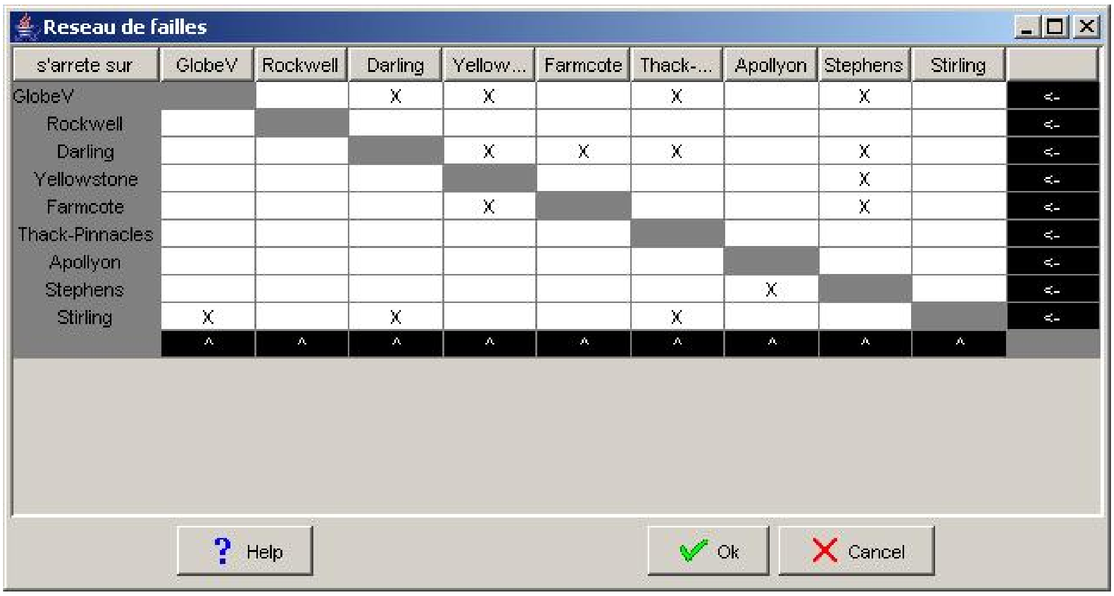
[4] Whilst there is no concept of *facing* for faults, 3D-WEG does never-the-less use orientation data for faults *as if they were a facing vector*. This is because every surface in 3D-WEG is computed as a potential, and so there is always a down-side and an up-side to any surface. The up/down direction of this 'facing' (for a fault) is unimportant … but it is important for the directions to be *consistent*; multiple orientation-data for a fault must consistently describe one side as 'up', and the other side as 'down'.

4.3.1.3 Networks of Faults

As noted above, a fault can be constrained to affecting only selected horizons within the stratigraphic pile. It is also possible to have a fault stop on some other fault. In 3D-WEG this is called a *network of faults*. The network is defined in a 2D matrix in which the relationship between every pair of faults in the model is assigned (Figure 3, Figure 4).



s'arrete sur	GlobeV	Rockwell	Darling	Yellow...	Farmcote	Thack-...	Apollyon	Stephens	Stirling	
GlobeV			X	X		X		X		<-
Rockwell										<-
Darling				X	X	X		X		<-
Yellowstone								X		<-
Farmcote				X				X		<-
Thack-Pinnacles										<-
Apollyon										<-
Stephens							X			<-
Stirling	X		X			X				<-
	^	^	^	^	^	^	^	^	^	

Figure 3. The ‘network of faults’ in 3D-WEG is managed via a table, wherein each fault can be described in terms of whether it ‘stops on’ each other fault or not.

4.3.2 Structure used in the Broken Hill Model

The Broken Hill Block is structurally complex. As this complexity is superimposed on a stratigraphy that is itself not well defined or constrained (Section 4.2.2), building a coherent model is a challenge. Rothery (2001) has reviewed of the structure of the Broken Hill region, with a focus on the Broken Hill lode.

Structural complexity arises from at least two orogenic episodes; the Delamerian Orogeny (c. 520-490 Ma), and the Olarian Orogeny (c. 1600 Ma). Effects of the Delamerian include the folding of Adelaidean sediments, and development of abundant retrograde shear zones. The Olarian Orogeny is associated with high-grade metamorphism and is characterised by one or two superposed fold events. Gibson and Nutman (2004) indicate an earlier (c. 1680 Ma) tectono-thermal event to explain introduction of amphibolites and synchronous extensional detachment of upper and lower plates at the Broken Hill Group – Sundown Group contact.

Major retrograde faults are ubiquitous in the Broken Hill Block. These are well mapped and comprise sericite-chlorite ± garnet, magnetite assemblages. Where dated, these have in many cases been shown to be of Delamerian age (c. 500 Ma., e.g. Hand et al., 2003).

High grade shear zones (with high-temperature mineralogy and therefore pre- to syn-metamorphism) in the area were first described by White et al., 1994. Since then, Noble (2000) describes a folded magnetic shear zone in the Broken Hill Synform; Gibson and Nutman (2004) describe the Broken Hill Group – Sundown Group contact as a mylonite, and Stevens (pers comm. 2004) has recognized a high-temperature shear zone in the Nine Mile area along the western edge of the Sundown Group.

These high grade shears are generally not visible in GSNSW mapping, and are not explicit in the model presented here. They are abundant along the line-of-lode, manifest in a variety of ways with various mineralogy and various kinematic indicators. The shear zones are in many cases represented as high strain zones within a pseudo-stratigraphy, that separate domains of coherent geology. The footwall of the line-of-lode is a good example of a highly attenuated sequence, containing a probable sheared-out sheet, possibly a tight to isoclinal fold, with a thin, sheet-like granite gneiss in the core, surrounded by Broken Hill Group.

The high grade shear zone of Noble (2000) has been built into the model as a revised contact between Thackaringa and Broken Hill Groups (see rationale in Section 7.4). This interpretation is quite different to that of Willis, 1989, based on the major change in sequence on either side of the high grade shear zone, which therefore is a major break. This then allows the lithologically similar, amphibolite-rich Cues and Parnell Formations to be equivalent. The implications of this change are discussed in Section 7.4. The Broken Hill Group – Sundown Group contact, described by Gibson and Nutman (2004) as a high grade shear zone, is implicit in the model as these groups are treated as separate geological series and therefore, as independent potential surfaces.

Other structural features are several generations of folding, including recently described sheath folds (Venn, 2001; Forbes and Betts, 2003). Transposition of bedding has been demonstrated by Hobbs (1966) while boudinage has been documented, particularly along the line-of-lode (Findlay, 1994). Although boudinage and transposition are recognised as occurring in Broken Hill, it is difficult to specifically build these into the model. The difficulty with transposition is that individual data points, for example bedding orientations, are typically steep and do not represent the form surface of a formation or group. Many bedding orientations may eventually average out, with high-frequency fold style on a longer wavelength form surface, but there are insufficient data to construct the model in this way.

The problem identified here is: What is the shape of the form surfaces? Prior work by Gibson et al, 1998, and Archibald et al, 2000, indicate overall gently dipping (but complexly folded) surfaces, and this premise has been adopted in the model. Although many observed orientations were entered into the model, there are insufficient 'fact' data points (observations) to constrain enveloping surfaces. In many cases, average or smoothed points were entered to honour the form surface from the interpreted plan and sections.

As noted in Section 2.1, two Broken Hill geological models were created:

- The 20x20 Model used just two retrograde faults - the Globe Vauxhall and Darling Faults - which do not intersect. The 20x20 Model was defined such that it was possible – to a first approximation – to reduce the structural complexity, and use only two major structures which were sub-parallel to the gross geological strike of the project area.
- The 46x51 Model covers the area of the AGG survey. The larger project area required an ability to model greater structural complexity. Major retrograde faults in the 46x51 Model are the Globe Vauxhall, Darling/Rupee, Yellowstone, Farmcote, Stephens Creek, Apollyon, Thackaringa-Pinnacles and Stirling Valley Faults/Shears. Many smaller retrograde faults are present, but only these major ones have been modeled.

The major structures in the 46x51 Model form a complex pattern of intersecting faults, with several faults ***stopping on*** other faults (Figure 4). See Section 4.3.1.3 and for Figure 3 for comment on 3D-WEG management of a ***network of faults***.

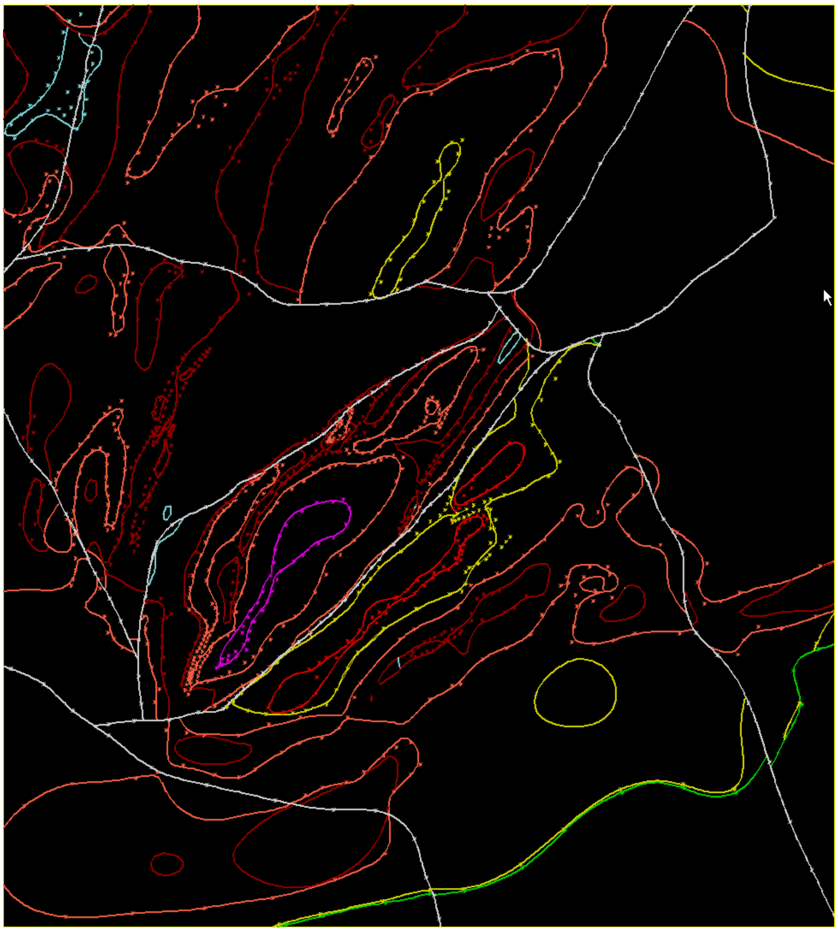


Figure 4. Plan view of the 46x51 Model of Broken Hill, showing the model geology, and in particular, the network of faults that were modelled in the larger Broken Hill model. (Image area: 46km x 51km).

4.4 Building the Broken Hill 3D Geological Model

4.4.1 What is a 3D-WEG Geological Model ?

A fundamental design feature of the 3D-WEG software is to be able to generate an answer to the following question:

For any point P(x, y, z) in 3D space, what is the geological formation present at that point ?

A ***3D geological model*** in 3D-WEG is ***a set of equations***, capable of answering this query. This is represented schematically in Figure 5. A 3D-WEG model is ***not*** a map, or a set of cross-sections or a series of 3D shapes defined by triangulated surfaces. All of these things can be generated from the mathematical model, and are views of the model, or representations of the model – but the model itself is the underlying set of equations.

Once a 3D-WEG project has been populated with data (geological observations), the software is used to ***compute the model***. This 'compute' process is a complete re-build of the entire model from the raw observations. Each geological series (and each fault) is defined by parameters …

- which describe (a series of) surfaces in terms of a ***potential*** or *field*,
- which honour the contacts and orientation data of that geological series (or fault)
- and from which the geological surfaces of that series (or fault) can be drawn to a variety of visualisation outputs.

The output from this computation is simply a complex set of equations, stored as large matrices – this set of equations is ***the model***.

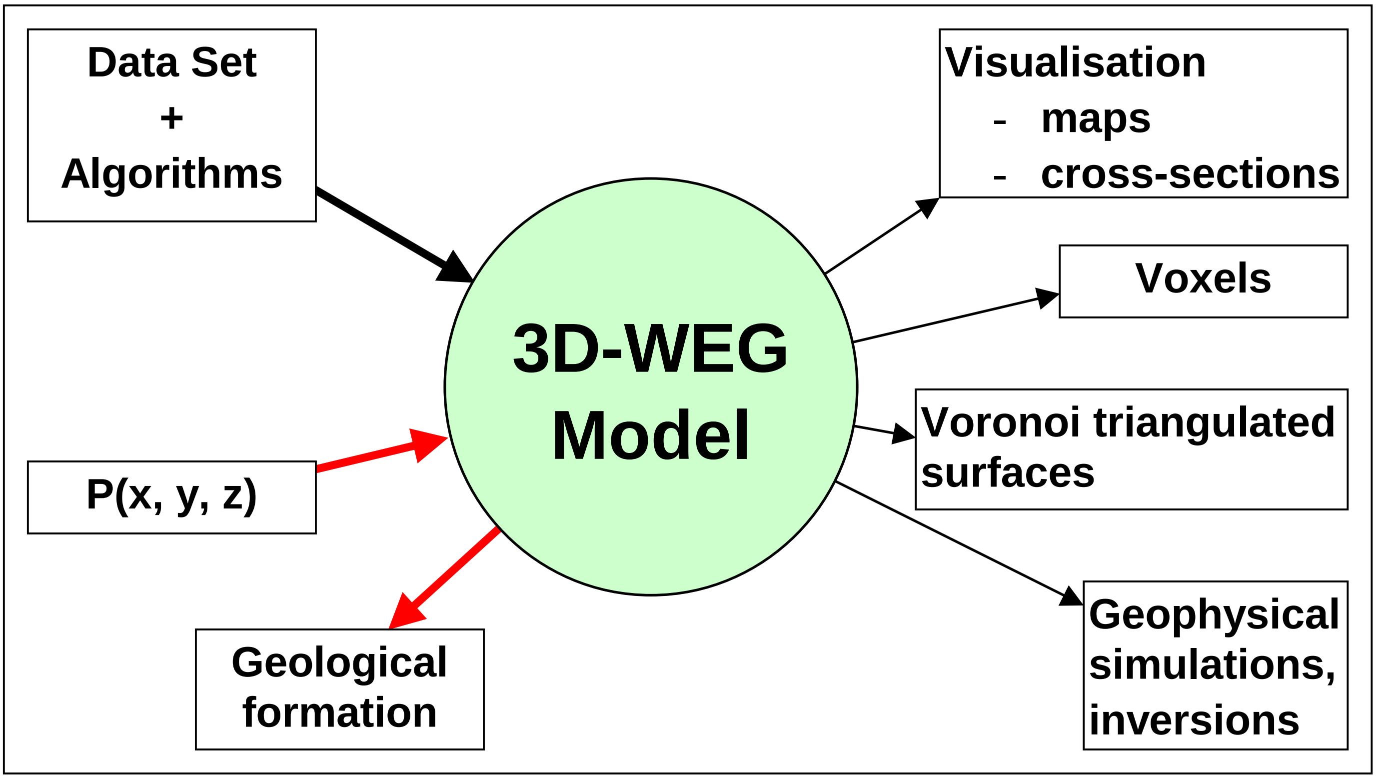


Figure 5. Schematic of the 3D-WEG Model. The essence of the model is that, for any point P(x, y, z) in 3D space, the model can automatically return the 'geological formation' which occurs at that point. Using this mathematical model, many other outputs can be generated, all of which are derived representations of the underlying model.

4.4.2 Geological Inputs

The following sources were used as inputs to the geological model …

- Maps of outcrop and solid geology. From geological mapping by the Geological Survey of New South Wales (GSNSW) at 1:100,000 scale and 1:25,000 scale. Map images were scanned from original sources.
- Map of interpreted solid geology from the Pasminco Model (Archibald et al., 2000), in turn sourced from GSNSW mapping at various scales. The map image was exported from the FracSIS database of this model.
- Interpreted regional geology cross-sections. Compiled and interpreted by T. Lees from personal mapping and re-logging of Broken Hill exploration drill core, Pasminco Mining (now Perylia Ltd.) line-of-lode detailed geology sections, GSNSW mapping and the regional sections used for the Pasminco Model. Compilation and interpretation was done within the related Curnamona C1 Project of the pmd*CRC. Images were scanned from original hand-drawn sections.
- Interpreted seismic section from the Broken Hill regional seismic line, with the interpretation of Gibson et al., 1998. In addition, Archibald's alternative interpretative line work (as used in the Pasminco Model) was used.

In all cases, these sources of map and section data were used as follows …

- Prepared GIF bitmap image files, trimmed to known coordinate extents. For maps this was the 3D-WEG project extents, in GDA94 / MGA54 coordinates. Sections were trimmed to known end-coordinates (GDA94 / MGA54), and clipped (top and bottom) to the 3D-WEG project extents.
- Created corresponding sections in the 3D-WEG project, and registered the relevant bit-map images in each section (for example, Figure 7 b).
- Geological contacts and orientation data were then directly digitised from the registered map and section images of geology (See Section 4.4.4 - The 3D-WEG *Input - Compute - Draw* Interpretation Process).

For the Broken Hill Geological Modelling Project, the intention was always to build a 3D geological model using *existing geological data* as inputs. There was no expectation or requirement to undertake additional field mapping or drill-core logging. The process of digitising from the bit-map images of geology is ***sampling the geology***; this sampling process – whether it be digitising existing geology, or actual field mapping - is critical to the outcomes that can be achieved in 3D-WEG model building.

4.4.3 Sampling Geology in 3D-WEG

Sampling (and interpolation) are fundamental aspects of the 3D-WEG software. Field mapping, or logging drill-core, are examples of ***sampling the geology***. Drawing a geological map or section is a process of ***interpolation***, attempting to predict from those sampled observations where some geological contact is expected to occur. In the 3D-WEG software, 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. It is necessary to comment on the frequency of sampling, because it was this aspect - more than any other - which required continual review and modification during the process of building the Broken Hill geological model.

Note …

- 3D-WEG does not necessarily need 'lots of data' to define some smoothly varying geological interface; the interpolation in 3D-WEG can be used to *fill-in the detail* between just a few points. It is important to take advantage of this … since adding data points does slow down computation.
- In general, 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. An appropriate combination of *enough contact points and structural orientations* will typically achieve a better result than 'many points on the geological boundary' (Figure 6).
- Conversely – and not surprisingly, of course – *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. Complex fold structures require definition by many points.

4.4.4 The 3D-WEG *Input - Compute - Draw* Interpretation Process

The building of a 3D model in 3D-WEG is partly a process of 'sampling the geology' as discussed above … but almost always it *also requires an interpretative process by the geologist*. This continual need to be 'interpreting the geology' is perhaps one of the most significant features of this software – because in essence this dictates that the software should be used by a skilled geologist (rather than a skilled CAD-package-user!). This interpretative process is encapsulated in the *input – compute – draw* cycle described below.

Having defined the stratigraphic pile, and also the faults, the basic process of creating the Broken Hill geological model was a repetitive cycle as follows …

- In the map-view, or one of the section-views, digitise a series of points from the registered bit-map image, and assign these contact points to the appropriate geological formation.
- Likewise, in selected places, also input orientation data – to define the facing (orientation) of the strata – and again assign each of these to the appropriate formation.
- Then compute the model, draw the geology from the model back onto the original working section or map … and review.

This cycle – *compute the model, and then review* – is essentially a process of testing the model against the geologist's expectations; the geologist will have certain expectations of what the geological section should look like (his/her 'interpretation' of the geology facts or observations) … and the rendered 3D-WEG geological model is continually evaluated against those expectations. For the Broken Hill project, the typical outcome from this cycle was …

- partly satisfactory results (expectations met!)
- partly *unexpected*(!) results (i.e. the geology was rendered differently from what the geologist might have predicted)

There were a variety of reasons for unexpected results, such as user inexperience (initially), and the model (in the early stages of the project) was not well defined in all three dimensions. The main reason for the model geology being plotted 'incorrectly' (compared to geologist expectations) was due to the complexity of the Broken Hill geology … and the inadequacy of the input data (at that point in time) to effectively describe that complexity. The solution was typically to add further data … in effect, increasing the frequency of the sampling of geology, as discussed above (Section 4.4.3).

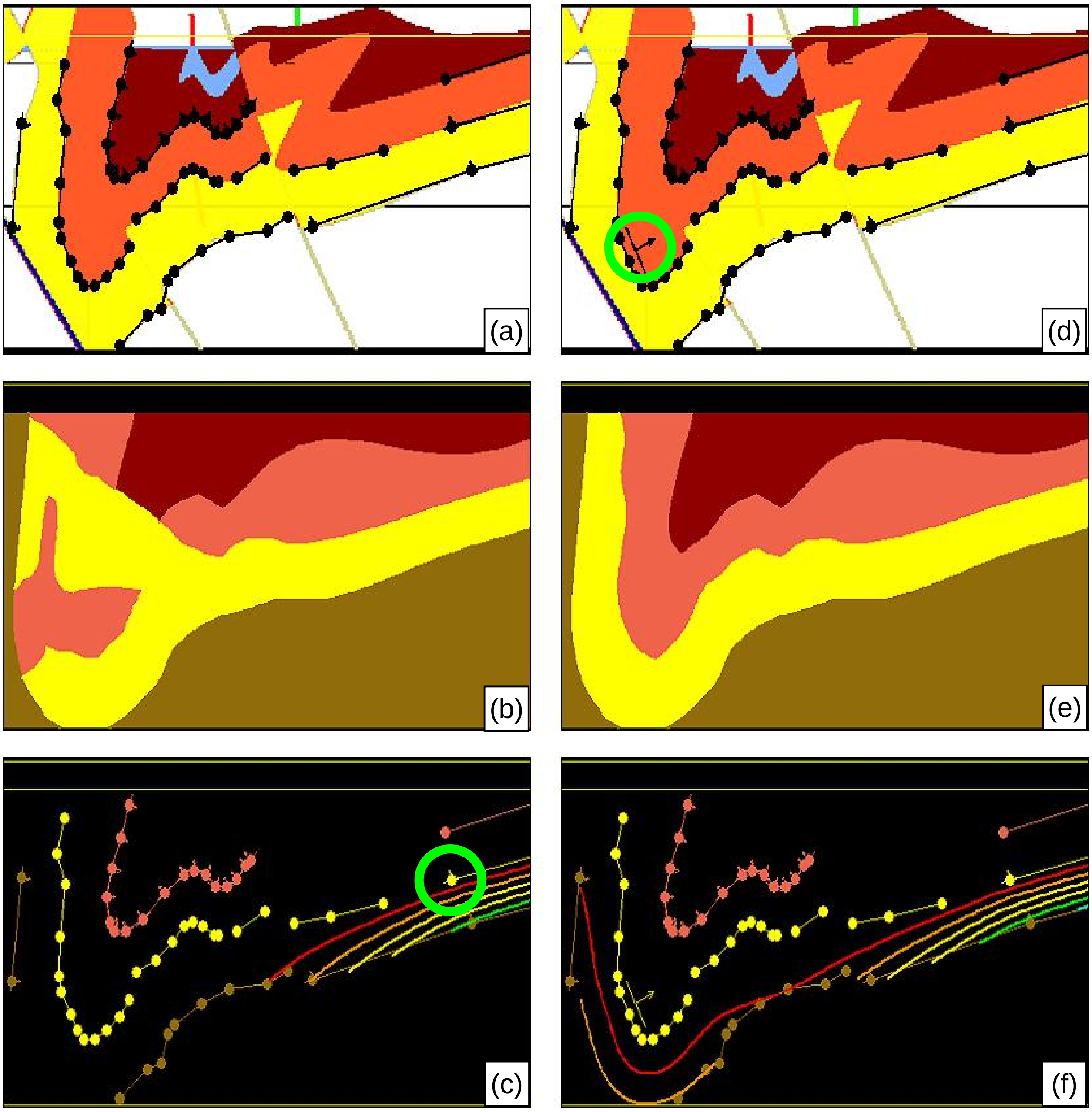


Figure 6. Orientation data have an important impact on the way the 3D-WEG computes a model in 3D space. In (a) part of an interpreted geological section is digitised (contact points shown in black), and the model is computed and rendered in (b) with unexpected! geological boundaries. By plotting the potentials of the yellow formation in (c), it can be seen that there is a well defined gradient at the right, but no 'potential' or gradient to the left side. There is only one orientation point for the yellow horizon, shown in (c). In (d), an additional orientation point is defined – with the result that the geology rendered from the revised model is much more 'as expected' in (e). The potential plotted in (f) for the revised model shows that there is a better-defined gradient in the plane of the section, and the yellow-geological horizon is more correctly plotted orthogonal to that gradient (in this case, approximately orthogonal to the section). By contrast, at the left side of (c) there is virtually no gradient in the plane of the section, so 3D-WEG renders the yellow horizon not orthogonal to the section, but, in this case, almost parallel to the section!

The comment above … 'the solution was typically to add further data' … requires explanation (since it may sound like a rather arbitrary process). A 3D-WEG model …

- will ***always*** produce a result which satisfies the ***observations*** that have been captured into a 3D-WEG project … but …
- ***may not*** produce a result which meets a geologist's ***expectations***.

Remedies for the latter case are …

- the geologist may elect to accept the 3D-WEG model; in effect, changing his/her expectations
- add observations. The geologist may be in the field, and can record further field observations. Alternatively, the geologist may be working from a reliable map or cross-section, and it may simply be that insufficient sampling of that map or cross-section has been achieved to completely capture the full details of some geological signature. (This is true of mapping anything – be it the magnetic field, air pressure, topography – or geology; in order to correctly model something ***in detail***, that something must first be ***sampled in adequate detail***!).
- add hypothetical observations ***to represent the geologist's interpretation***. It is frequently the case that it is not possible to capture further '***actual*** observations' … and yet the geologist has a reasonable basis for interpreting the geology in some manner which differs from the (current) 3D-WEG model. In the traditional world of drawing a map or section on paper, this geologist would (in this case) be using some ***hypothesis*** as the basis for drawing that map or cross-section. In the 3D-WEG world, it is necessary to express that hypothesis as 'hypothetical observations' (either hypothetical contact points, or hypothetical orientation data), and to add those hypothetical data to the 3D-WEG project. The model is then recomputed – and the hypothesis is tested by drawing and reviewing the resultant geological model.

Thus the Broken Hill 3D Geological Model produced in this project has been developed from the inputs described above, ***as interpreted by the authors*** (principally T. Lees). Initial data entry was from the listed geological maps, and from T. Lees interpreted sections. Revisions were then made, partly due to inconsistencies between plan and section (derived from different sources), and partly as a consequence of the geologist's evolving 3D re-interpretation of the project area mainly as a consequence of insights gained during the model-building process.

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 3D-WEG model; these observations were either additional samples from original maps or interpretative sections, or the geologist's hypotheses based on his evolving interpretation of that complex 3D geology.

[A weakness of 3D-WEG that should be addressed is that there is currently no effective mechanism for tagging the geologist's 'observations' with additional attributes – for example, to qualify those observations which are 'fact', and those which are 'hypothesis'].

It is worth commenting briefly here on several aspects of the 3D-WEG software which were important in this cycle of 'input-compute-render-review' …

- Just the simple fact that – immediately after adding some new observations – it is possible to re-compute the model, and re-draw a map or section view of the model is a revolution in the 3D geological model-building process. This immediacy of outcome allows the geologist to review the implication of the new observations, and choose to add further data or test alternative hypotheses.
- As the model becomes larger and more complex, the compute-and-render process does become slower. But there are several simple strategies that can be used to get a quick (approximate) output – suitable for rapid (immediate) review and modification. These strategies include computing only parts of the model (e.g. compute for selected strata, compute with or without faults, compute using only data from selected sections, etc.). Also it is possible to choose to draw only a small subset of a map or section, or to draw with a lower resolution – to achieve faster outputs.
- Unexpected results can cause some puzzlement. 3D-WEG computes a potential (field) to draw geological surfaces. It is possible to *draw the potentials* for a given horizon (Figure 6 c, f). The value of this tool is that it allows the user to visualise more clearly how the contact points and orientations (for an horizon) are being honoured by 3D-WEG, and clarifies for the user whether some points should be edited, or if additional points are needed.
- Unexpected results can often be better understood by viewing the modelled geology in some alternative section – at an angle. 3D-WEG allows a user to quickly and easily create a new section, and to render the current model in that view. The geology in the new section is guaranteed to be consistent with that rendered in all other section-views.

4.5 Visualising the Broken Hill 3D Geological Model

As noted in Section 4.4.1, the 3D-WEG 'compute' process generates a complex set of equations - stored as large matrices – which constitute the model. Each geological series (and each fault) is defined by parameters which describe a ***potential*** or ***field***, from which the geological surfaces of that series (or fault) can be drawn to a variety of visualisation tools. Outputs include …

- Maps and sections

  Any arbitrary section can be drawn through the model. This can include a non-linear fence-section, or a horizontal slice through the model. A geological map is simply the intersection of the DEM with the model.

- 3D views in 3D-WEG's '3D viewer'
- Shapes (triangulated surfaces) - built for each geological unit, and then exported as …

  T-surf files (Gocad format), suitable for import and visualisation in Gocad or FracSIS

  VRML files, for visualisation in a web-browser (with a VRML plug-in viewer)

- Voxels – a voxel model – with geology assigned to voxels – and exported as …

  Voxet files (Gocad format), suitable for import and visualisation in Gocad

Maps and Sections

Despite the importance of '3D' to model the full complexity of geology, geologists will continue to ***work with*** 2D views of geology – as maps and sections. As noted in Section 4.4.4, the rendering of maps and sections was used continually throughout the model building process, and it is in these 2D views that a geologist would typically perform the 'interpretative' process.

Section (and map) views are managed (in part) via a dialog, which allows various 'layers' of the plot to be turned 'on' and 'off' (Figure 7). Bitmap images (in *.gif and *.jpg formats) can be loaded into these section and plan views; for example, geology, gravity and magnetic images may be loaded, and each visualised in turn via user selection, with (for example) the geology rendered from the model onto these bitmap views.

A separate dialog manages the rendering of model outputs into section-views. The geology may be rendered as lines, or solid geology (Figure 7). It is sometimes useful to plot the potentials for a given geological series (Figure 6 c, f). The user can also control the drawing-resolution of these model views; a low-resolution view can be drawn ***quickly*** … which is useful for fast, approximate feed-back to the interpreter. The same rendering process can be used to render ***high quality images*** with fine drawing resolution … albeit rendered more slowly.

These plan and section views can also be rendered into 3D-WEG's ***3D viewer*** (Figure 8).

Shapes (Triangulated Surfaces)

Whilst the 2D-views are continually re-generated during the interpretative model-building phase, more complex 3D 'shapes' are made *after* the geological model is complete. This is a process of generating a 'shape' or 'surface' for each geological unit, the shape being defined by a triangulated wire-frame surface. The process could take an hour or more to compute. Having generated these shapes, these can be visualised in the 3D viewer (Figure 9), can be exported to a VRML file system for interactive visualisation (Figure 10), and can be exported in TSurf file format, suitable for import and further visualisation in other packages (Figure 11).

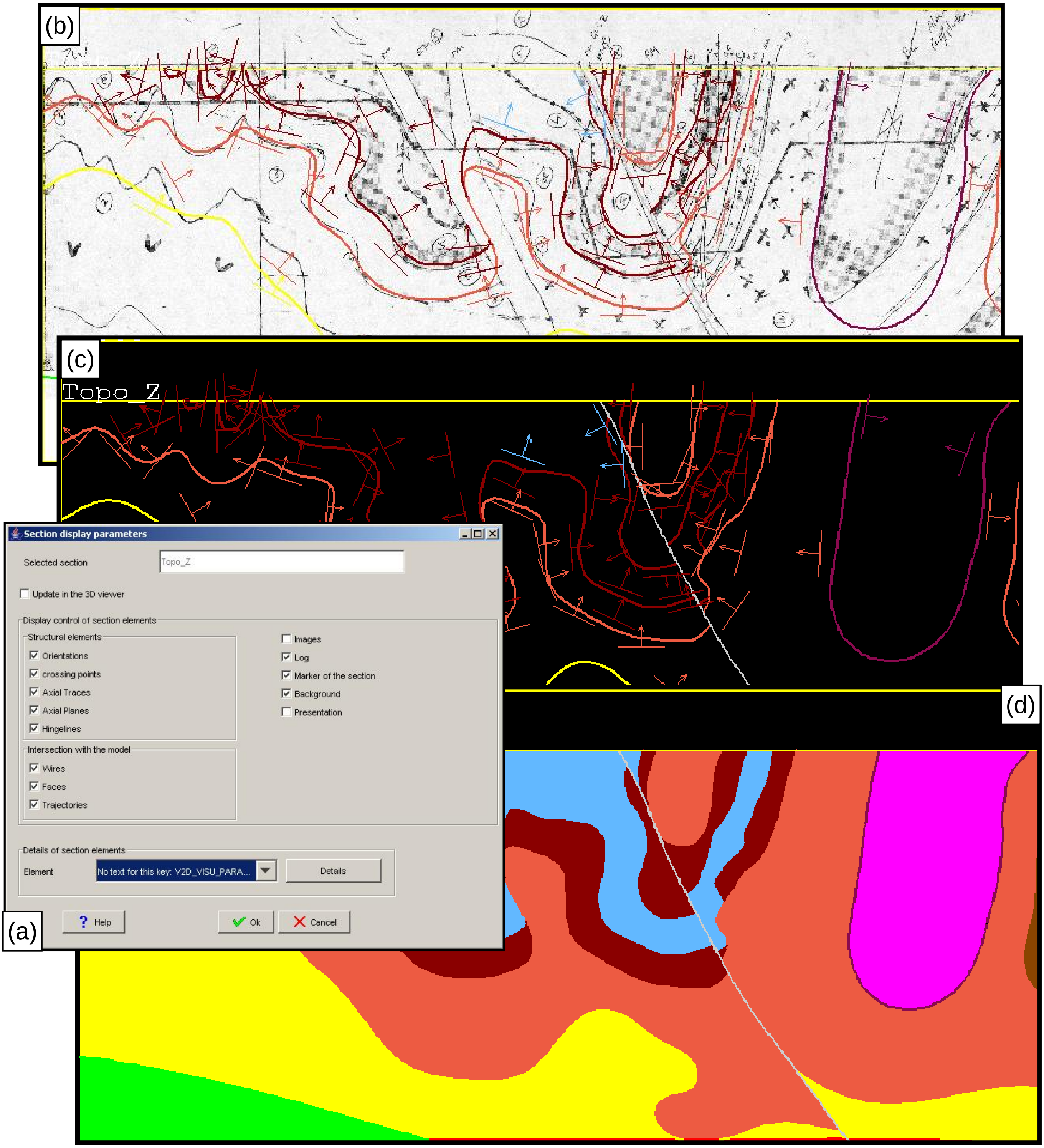


Figure 7. Part of the geological cross-section N7. Various 'layers' can be presented in 3D-WEG's map and section presentations, and each of these can be turned 'on', or 'off' (a). Image (b) shows the model geology rendered as lines onto the geologist's original working section. In (c) is the model geology as lines, together with the orientations data. Image (d) shows the model geology as solid-geology. The user can control the plotting resolution, to achieve either fast plots, or high resolution images, such as this one. Section length: 12.7km, V/H = 1.

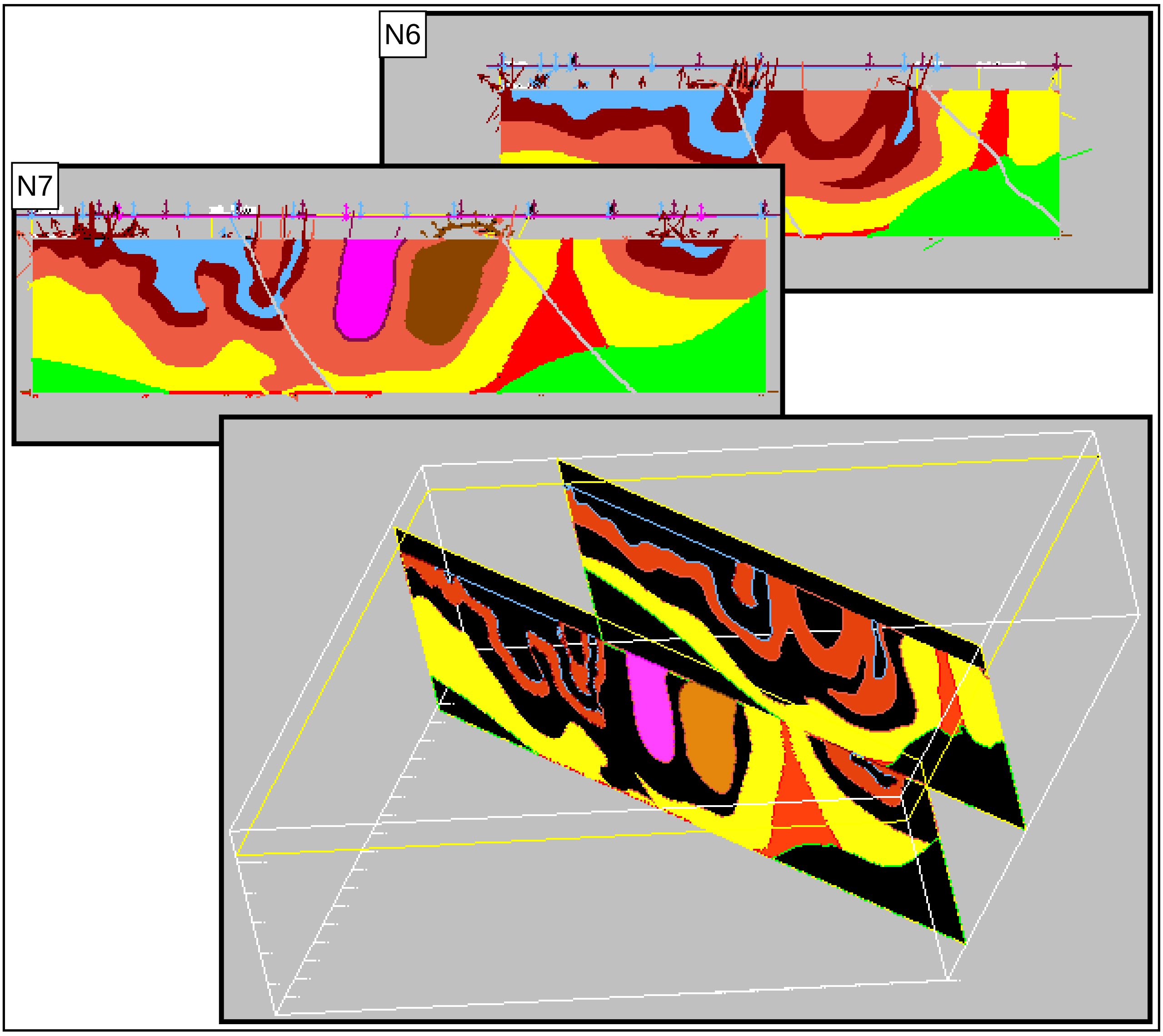


Figure 8. Sections N6 and N7, presented as solid geology sections, with selected parts of the solid geology also presented in a 3D view, which can be rotated. (Visualised in the 3D-WEG's 2D and 3D viewers).

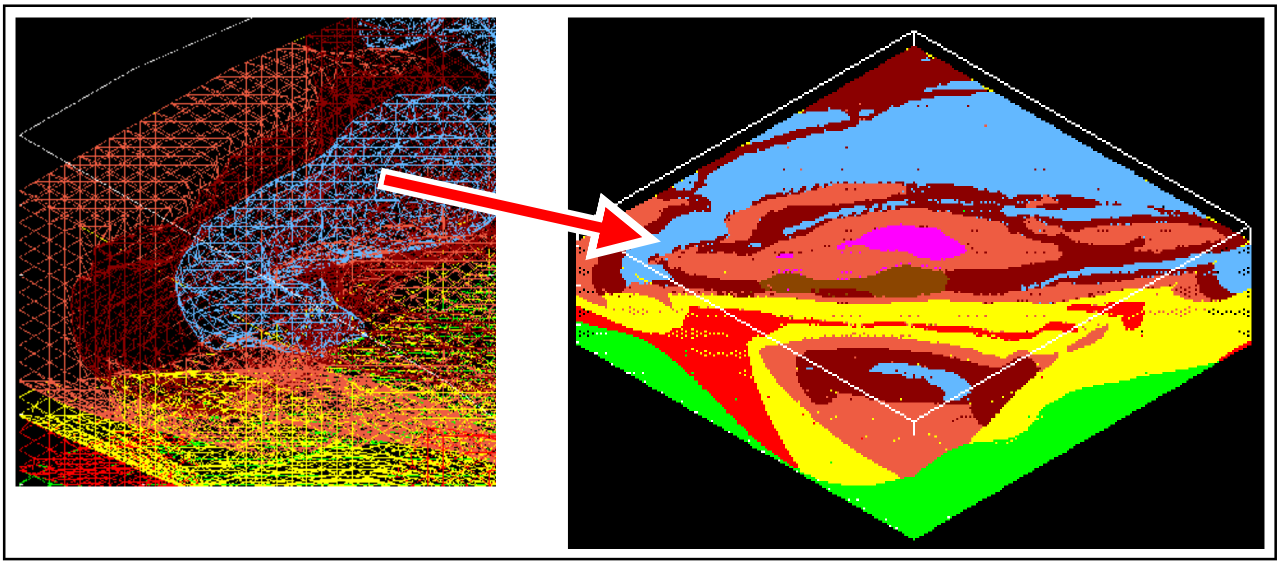


Figure 9. The 3D-shapes of geological units - generated as triangulated wire-frame surfaces – can be visualised in 3D-WEG's 3D viewer.

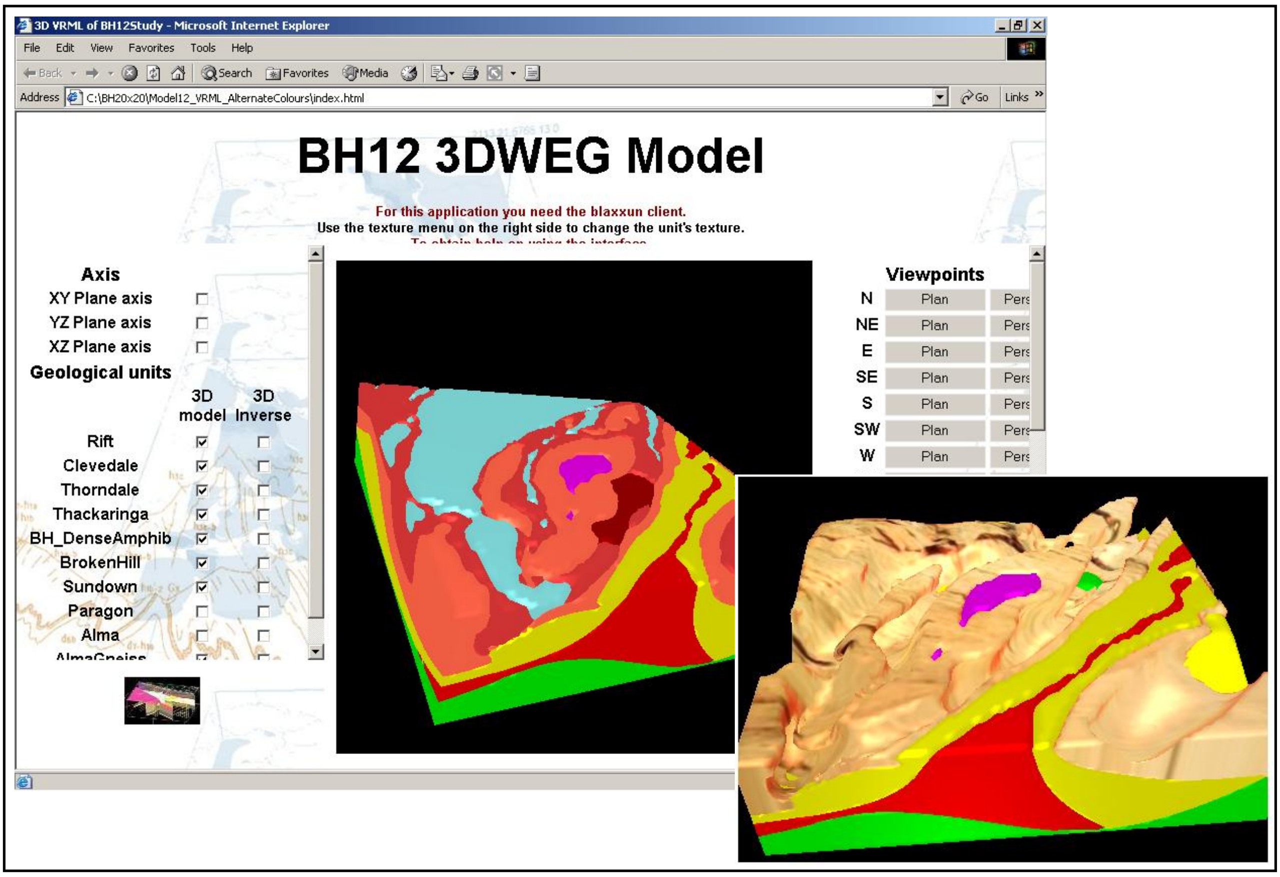


Figure 10. VRML web-browser visualisation of the Broken Hill Geological Model (20x20 Model). The 3D-shapes of geological units can be used to generate a 'complete web-site' representation of the 3D-WEG model in VRML file format. A standard web-browser, with a VRML viewer plug-in, can be used to manipulate the model: turn selected geology units 'on' or 'off', apply 'textures', and interactively visualise with rotate, pan and zoom controls.

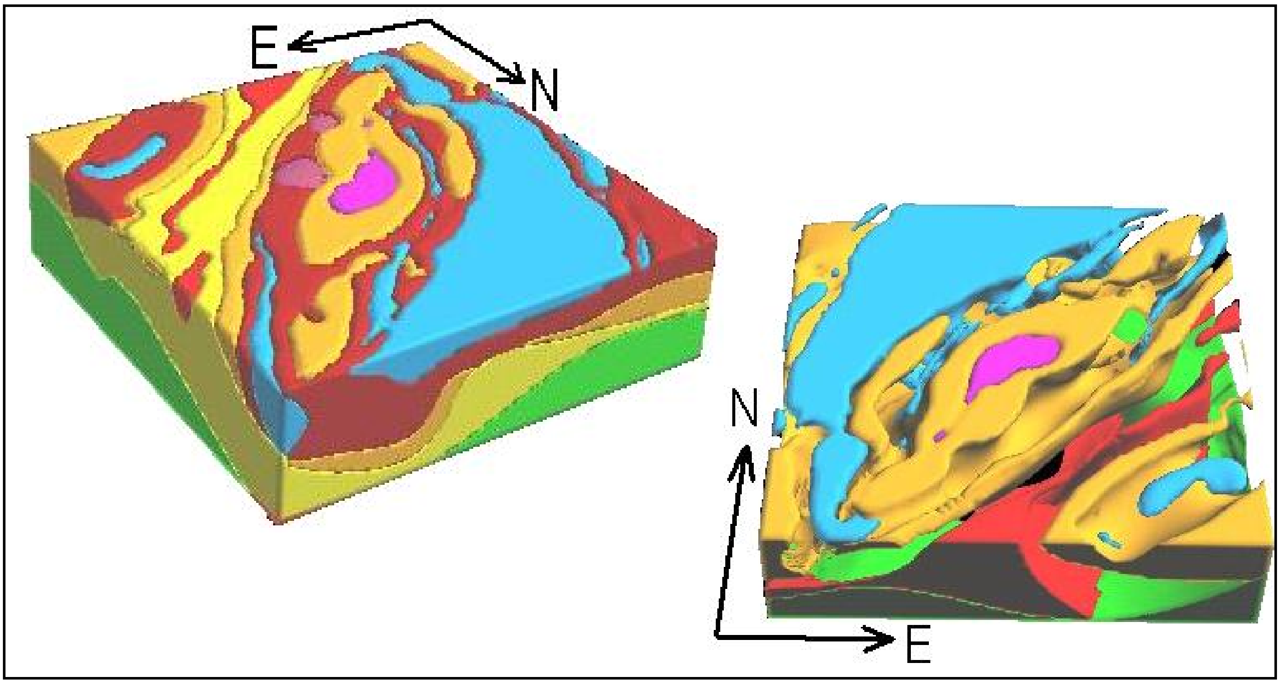


Figure 11. Perspective views of the Broken Hill Geological Model (20x20 Model) in Gocad. The 3D-shapes of geological units can be exported in T-Surf file format, and imported into alternative visualisation and analysis software, such as Gocad and FracSIS.

4.6 Exporting the Broken Hill 3D Geological Model

Having created, and saved the triangulated wire-frame shapes for each unit of the geological model, it is then possible - with just two mouse-clicks - to create a VRML file for interactive visualisation of the complete 3D model. This VRML file is a 'complete web-site' representation of the 3D-WEG model, able to be viewed in a standard web-browser, with a suitable VRML viewer plug-in. The user can manipulate the model, interactively turn selected units 'on' or 'off', apply 'textures', and visualise the model with rotate, pan and zoom controls (Figure 10). This very simple process provides an excellent, highly interactive representation of the model, which is ideal for rapid (web-based) communication of results to client-users.

Two additional exports were developed during the course of this project.

The same triangulated wire-frame shapes for each unit of the geological model can be exported as Tsurf-format files. This is an industry standard file format for 'triangulated shapes', and is suitable for import of the 3D-WEG model-shapes into Gocad and other visualisation software (Figure 11).

Inversion processing in 3D-WEG (Section 5) is based on a voxel representation of the model. The results of inversion are also managed (as probabilities for any given geological unit) in terms of the voxel model. The voxel model, and the inversion results, can be exported in Voxet file format. This industry standard file format for voxel model data is suitable for import into other visualisation and analysis software, such as Gocad and FracSIS (Figure 12).

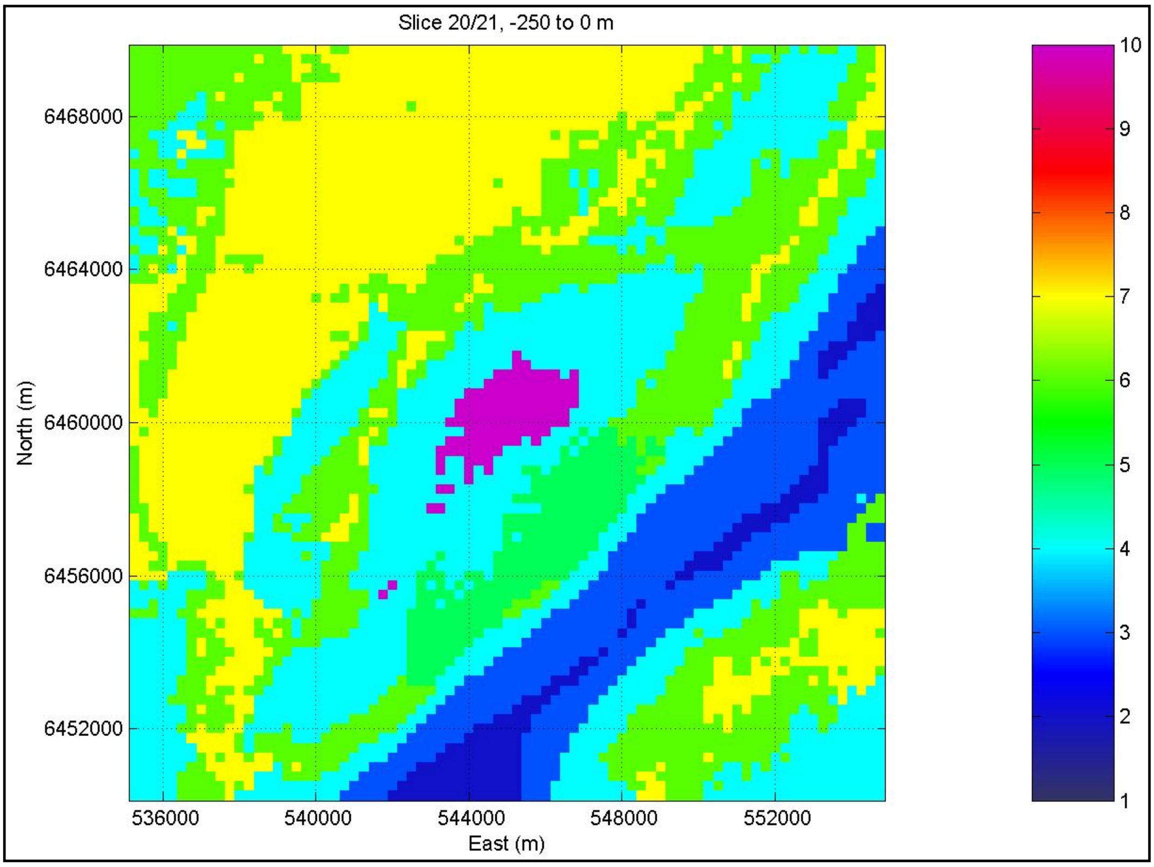


Figure 12. Image of 'most probable geology' for depth-slice (–250 to 0)m. Exported from 3D-WEG in Voxet-file format, and imported into Gocad for visualisation and analysis.

5 Inversion in 3D-WEG

Inversion in 3D-WEG is summarised here in dot-point form. For a more thorough treatment, see Guillen et. al., 2004. (This paper was prepared during this C6 Project). The following discussion is for the case of gravity inversion, using density as the physical property which is adjusted during the inversion iterations. Inversion requires the following preparatory steps …

- Potential field data (gravity) must be gridded, and clipped, to exactly match to the 3D-WEG project area, and the level adjusted (Section 6.1).
- Density values (the shape of the distribution, the mean and standard deviation – defining a probability density function) are assigned to each unit of the stratigraphy (Section 6.2).
- An initial 3D model must be computed.

The following important points about 3D-WEG inversion should be noted …

- Each inversion iteration makes a modification to *one voxel <u>only</u>*. Each simple adjustment is computed quite quickly, but the overall impact of each iteration is small.
- The inversion process is based on the Metropolis algorithm (a Monte Carlo method). The single voxel to be adjusted in each iteration *is selected randomly*. The assigned stratigraphic unit for this voxel may be changed to match that of an adjacent voxel – *on a random basis*. The assignment of a density difference value is by *<u>random selection</u>* according to the probability function defined for the relevant stratigraphic 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 3D-WEG inversion continues to iterate. Rather than simply finding *one model* which matches the observed data, the 3D-WEG approach is to explore a wide range of possible models – all of which have a computed response which 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 3D-WEG inversion process is …

- Voxelisation of the initial 3D geological model. The specially prepared potential field dataset dictates the (x, y) dimensions of the voxels; the z dimension is typically set to the same value, or may be set to some lesser value (for finer discretisation). For each voxel, the appropriate stratigraphic unit is assigned, based on the initial model. (Voxel centres and the assigned geology value are written to an ASCII file).
- For each voxel, compute the gravity effect observed at each gravity observation point, for the case of unit density.
- Assign density values to each voxel; density values are assigned randomly, based on the defined probability function for the relevant stratigraphic unit. Compute the gravity response of the initial model, and compare to the field data. Calculate the misfit. This is the misfit for the *current model*.
- Inversion iterations …
  - Select, at random, either a *frontier* voxel (on a geological boundary) or an *internal* voxel (entirely within a particular formation)

    If frontier: The assigned stratigraphic unit may be changed, and a revised density value assigned according to the appropriate probability function. If a change of stratigraphy is proposed, there is a further constraint: the basic topology of the model must not change. A grouping of voxels that is a single coherent 'zone' of some given formation must remain a single zone, and cannot 'split' into two or more zones. This forces the model to remain relatively coherent.

    If internal: A revised density value assigned according to the appropriate probability function.
  - Using the *change of density value* for the selected voxel *only*, compute the gravity effect (of this change) at each gravity observation point. Apply these changes to the computed gravity response, to generate the gravity response of the *new model*. Compare to the field data. Calculate the misfit.
  - Compare the misfit for the *new model* with that of the *current model*. Either keep, or reject, the proposed change to the model on the following basis …

    If the misfit is smaller – keep the proposed change

    If the misfit has increased – a probability function, based on the relative misfits of the *current* and *new* models, is used to randomly either keep, or reject, the new model.
  - If kept, record the changed voxel details to the inversion record file, update the current model.
  - Increment the iteration counter. Continue the above iteration cycle until the requisite number of iterations have been computed.
- Inversion Completion. After reaching the specified number of iterations, the inversion record file is analysed, and probabilities are computed for each voxel, and each stratigraphic formation … *the probability that any given voxel is a specified formation*.

5.1 Inversion Outputs

The primary output from 3D-WEG inversion are *voxel probability data*, stored in a series of files, one for each stratigraphic unit. These voxel probability data can then be used to generate various geological outputs – such as cross-sections and plans – which report the inversion outcomes in terms of '***the probability that a voxel is a given stratigraphic unit***' (Figure 13).

Three different presentations of *voxel probability data* are presented in Figure 13 a, b & c. For example, Figure 13 (c) is a plot of the 'probability to find Broken Hill Group' on the section shown, with high probability represented in white, and zero probability in black. The mean relative density (Figure 13 d), and the standard deviation of density (Figure 13 e) can also be reported in such cross-sections. These plots are an effective means of presenting the outcomes from an examination of perhaps several millions of possible models, all of which explain the observed gravity field.

Cross-sections such as those illustrated in Figure 13 can also be combined together to create a 'movie', consisting of a sequence of adjacent cross-sections. The 'movie' sweeps across the 3D-WEG project, and succinctly and graphically illustrates the probability results – derived from millions of models – all of which match the measured data.

These probability data can also be exported in voxel format, suitable for import into alternative display and analysis software package.

From a casual examination of Figure 13 (and other plots not shown), one might consider that the inversion results 'show support for the starting model' … and conclude that 'the starting model is a valid model' … or even *the* correct model.

But … is this correct ? Where such voxel probability data show a high probability for a given stratigraphic unit … is it possible to confidently pronounce that that part of the model is correct ?

One of the important goals of the Broken Hill Geological Modelling Project was to assess these inversion outcomes, and *attempt to understand the quality of the information reported in these voxel probability data*. Unfortunately no *quantitative* assessment of this was done during the project, since the ability to export and independently analyse the results was only delivered late in the project. Considerable *qualitative* assessment was done, however, using multiple inversion runs with varying parameters, and reviewing the range of plotted outputs.

5.2 Inversion Practical Expectations – a priori Information

It is well understood that there are an infinity of density distributions which could explain an observed gravity field. Thus, if some interpretation or inversion process finds just one solution which matches the data, it has one-to-infinity likelihood of being correct! The 3D-WEG software can explore 'the space of possible solutions' and find many millions of solutions which match the data … but does this really improve the likelihood of finding the 'correct answer' ?

As a consequence of this infinity of solutions, practical interpretation of potential field data requires some means of rejecting 'unrealistic' solutions … where 'unrealistic' basically means those solutions which do not match some *a priori* information.

Since one of the basic inputs to the 3D-WEG inversion process is a 'starting model' – which is presumed to have been developed from a range of geological observations – then the use of *a priori* information is an integral part of 3D-WEG's inversion.

An important consideration is 'how good does the starting model need to be ?'

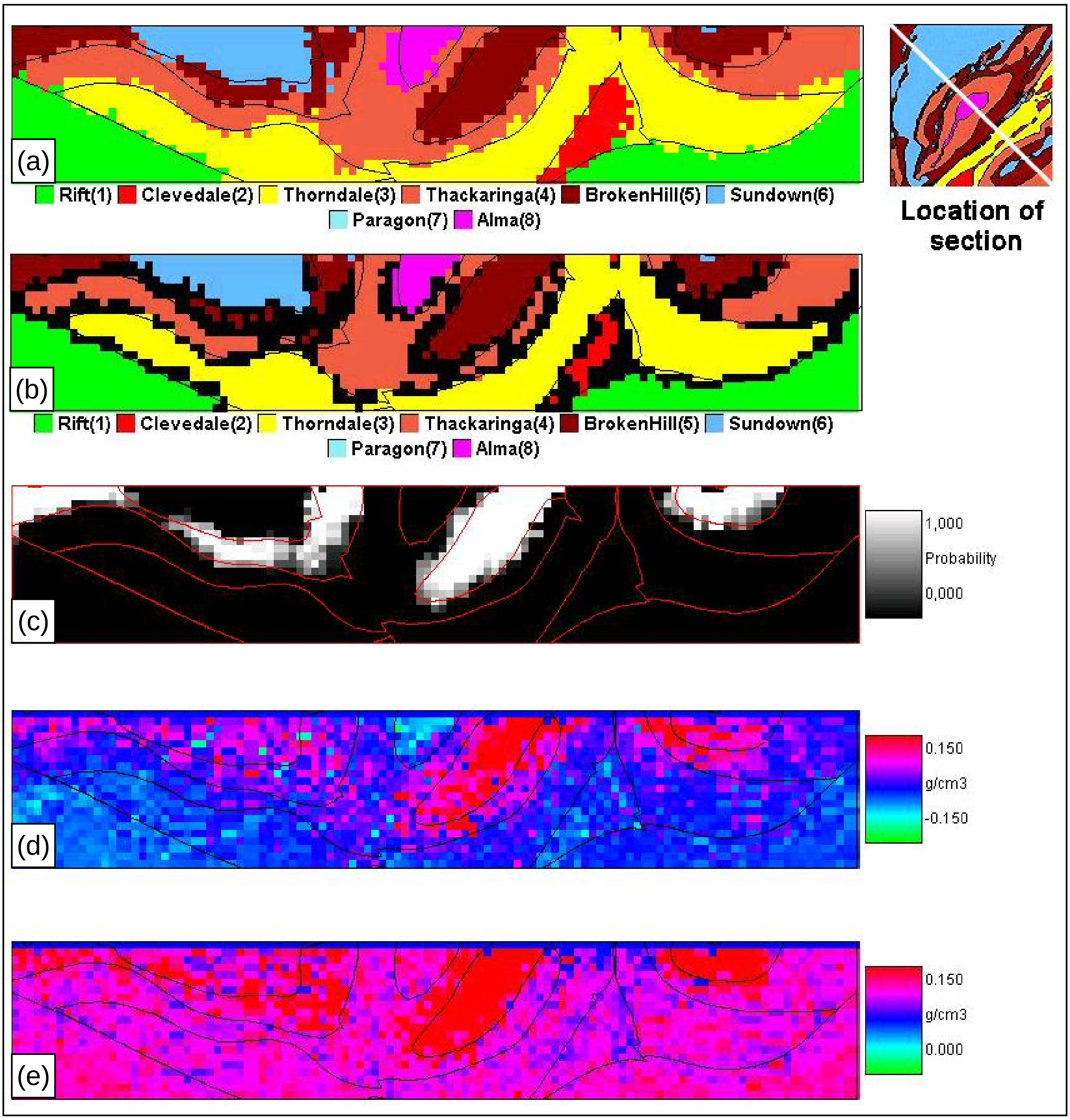


Figure 13. (From Guillen et al., 2004) NW-SE sections showing various products derived from the ensemble of acceptable models: (a) the most probable lithology; (b) the most probable lithology with areas where this probability is less than 0.95 shown in black; (c) probability of finding Broken Hill Group (black is zero probability whilst white is a probability of one); (d) mean relative density; (e) standard deviation of density. The lines shown on each section are the geological boundaries of the starting model. (Length: 28km; V/H=1)

Boschetti et al. (1999) demonstrated that their 'Mickey Mouse' model – by allowing just 10% variation in density – could be used to explain *<u>any</u>* gravity signature. The implication in this, then, is that if the geology is poorly understood – and, as a consequence, the 'starting model' is quite possibly incorrect - then it might be possible to invert towards a density distribution which is *closely founded on this <u>incorrect</u> model … but which never-the-less does reasonably <u>match the observed gravity data</u>*. (See also the discussion on density below).

To summarise …

- If the 'starting model' is wrong, there is a risk that inversion could yield misleading results; by achieving a good match to the observed gravity data, with a density distribution which is closely founded on that 'wrong' model … there is an implied 'geophysical support' for that 'wrong' model.

Conversely, if the 'starting model' is at least in part well constrained, and known to be approximately 'correct' (in part), then the inversion should be able to …

- Invert towards a density distribution which is (in parts) slightly modified from the starting model, and …
- Demonstrate that the geophysical data is broadly consistent with this now slightly modified model, thereby implying 'geophysical support' for this 'initially-reasonable-but-now-slightly-modified' model.

5.3 Inversion Practical Expectations – Density Data

The quality of the knowledge about the density data, and density ***contrasts***, is also important.

- If we ***know*** that two adjacent formations have the ***same density***, what will inversion tell us about the boundary between these two units ? The simple answer is '***nothing***'!

What if we take this simple case, and add some degree of ***uncertainty*** in our knowledge ?

- For example, we ***think*** that two adjacent formations have ***approximately*** *the same density*, but one formation has a variable content of amphibolite (say), and for the other formation we have very few measurements of the density … what will inversion tell us about the boundary between these two units ? The answer must be '***not very much***'! … and even if the inversion solution does seem to propose some geological outcome, *that outcome must be* ***qualified*** *by the degree of uncertainty* in the density data!

In summary …

- Relatively high or low density contrasts can yield distinctive and un-ambiguous results.
- Uncertainty in density implies a wide standard deviation (σ); inversion can proceed rapidly, inverting to a small misfit – but this 'fast and loose' approach does not really ***test*** the model. A narrow σ is more demanding, and more effectively tests the model.

6 Inversion of the Broken Hill 3D Geological Model

The two main goals of the Broken Hill Geological Modelling Project were …

- to construct a geological model of the study area.
- to use the Geological Editor's geophysical inversion capability to invert both the ground and airborne gravity (gradiometer) data from the project area to further refine and test the accuracy of the model.

Most of the inversion work done was applied to the smaller 20x20 Model. The faster processing of that smaller model permitted a much greater number of iterations (for a given elapsed processing time), and thus allowed more effective assessment of 3D-WEG's inversion processing. Only limited inversion processing was applied to the full 46x51 Model. Most of the inversion work used the ground gravity data; some test inversions were done using the airborne data.

Inversion in 3D-WEG can also be applied to magnetic data, and it is possible to do joint inversions of magnetic and gravity data. Neither of these were undertaken during this project.

6.1 Gravity Data for Inversion

Gravity data for use in 3D-WEG's inversion must be prepared as follows …

- must be Bouguer gravity anomaly data, in units of milligals
- the data are expected to have been recorded at a constant height above the model topography. This is typically 0m elevation (for ground level data). For the case of the AGG survey data, the mean terrain clearance was 80m.
- the gravity data must be gridded – and clipped – to *exactly match* to the 3D-WEG project area (Figure 14). In the voxelisation of the 3D geological model (at the start of the inversion process) the (x, y) voxel dimensions are matched to the cell size of the gravity grid. The z-voxel dimension may differ from these (x, y) dimensions. A regional background must be removed from the gravity data grid. The Bouguer gravity data contains (a) gravity signatures from the geology in the project area, ***plus*** (b) other gravity signatures due to geology on a broader, crustal scale (outside the model).

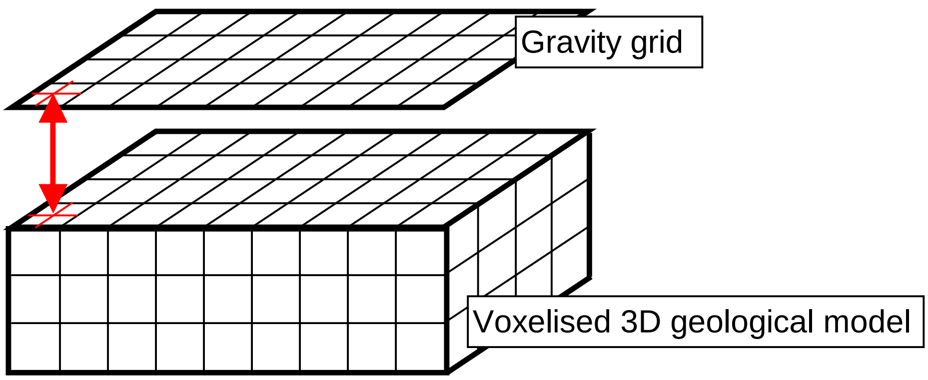


Figure 14. Gravity data must be gridded, and clipped, to exactly match to the 3D-WEG project area. At the start of the inversion process, the 3D geological model is voxelised; the voxel (x, y) dimension is matched to the gravity grid cell size.

See the sidebar 'Preparation of Gravity Data for 3D-WEG Inversion' (below) for further general discussion, and the following sections for specific details of the preparation applied to the Broken Hill gravity datasets; note, however, that no de-trending was applied to the Broken Hill gravity data.

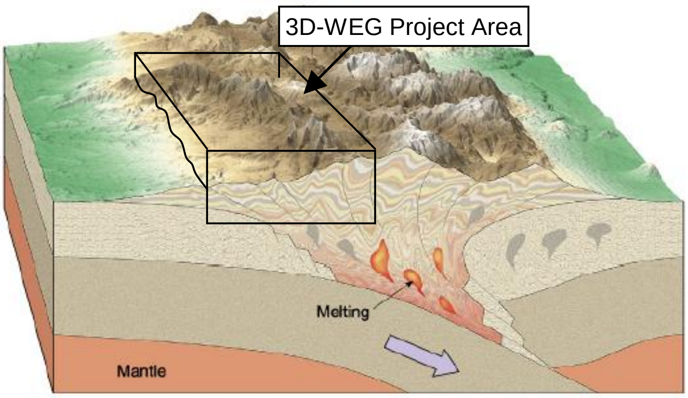
It is worth commenting on the fundamental importance of this preparation of the 'world-measured' gravity data. Quite simply, the continual comparison of the 'computed' gravity response to the 'world-measured' gravity response is at the very core of the inversion process; as a result, any error in the data preparation, will ultimately be expressed as some degree of error in the inversion outcomes – for example, the density distribution might become biased across the model as a consequence of the inversion process having to compensate for some inadequacy in the de-trending data preparation.

Preparation of Gravity Data for 3D-WEG Inversion

The Bouguer gravity anomaly map derived from field data will contain signatures from sources ***within*** a 3D-WEG project area, and from sources ***outside*** the project model. In order to correctly compare …

- the model's computed response to …
- field-measured data

those signatures from external sources must be removed from the measured dataset. This is achieved by de-trending (removal of long wavelength signatures), and a further zero-level adjustment.



The 'expected' gravity level that would be computed from a 3D-WEG model can be estimated using the formula for the gravity effect of an infinite horizontal slab.

$$g = 2\,\pi\,\rho\,G\,h$$

where g is milligals, ρ (g/cm^3) is the average density-contrast for the model, G = 6.673 (the universal gravity constant), and h (km) is the average height of the model. The average density for the model is not actually reported by 3D-WEG. A value can be readily computed, however. The start of the inversion process produces a voxel file, containing an (x, y, z) coordinate, and the assigned geology code for each voxel. Import this ASCII file into a spreadsheet tool (Excel, Intrepid), assign density values corresponding to each geology code, and compute the average density. Subtract this value from the 'reference density' (typically the Bouguer density value) to produce the average density contrast for the model.

Having computed the expected average gravity signature for the model, the field data should be adjusted to this same average level (by applying a DC-level-shift)…

$$\textit{Average gravity}^{\,Model} = \textit{Average gravity}^{\,Field\text{-}data}$$

The field data are now ready for use in inversion. The initial model response may or may not match well, but at least the model response level is approximately matched to the field data, and the computed misfit starts at an acceptably low initial misfit.

6.1.1 Ground Data

A ground gravity dataset of some 33,000 stations, and extending a small distance beyond the AGG survey boundaries, was supplied by Geoscience Australia. Within the area of the AGG survey, the widest station spacing for ground data was 2000m (Figure 15). The outlines of the 20x20 Model and the 46x51 Model are also shown in this Figure. Note that the dataset included detailed survey data from the Broken Hill Mine area, supplied by Perylia Limited (formerly Pasminco Mining) for use within the C6 project; with these data, there are broad areas where the spacing is 500m, or even less (e.g. 60 x 600m, and 25 x 100m).

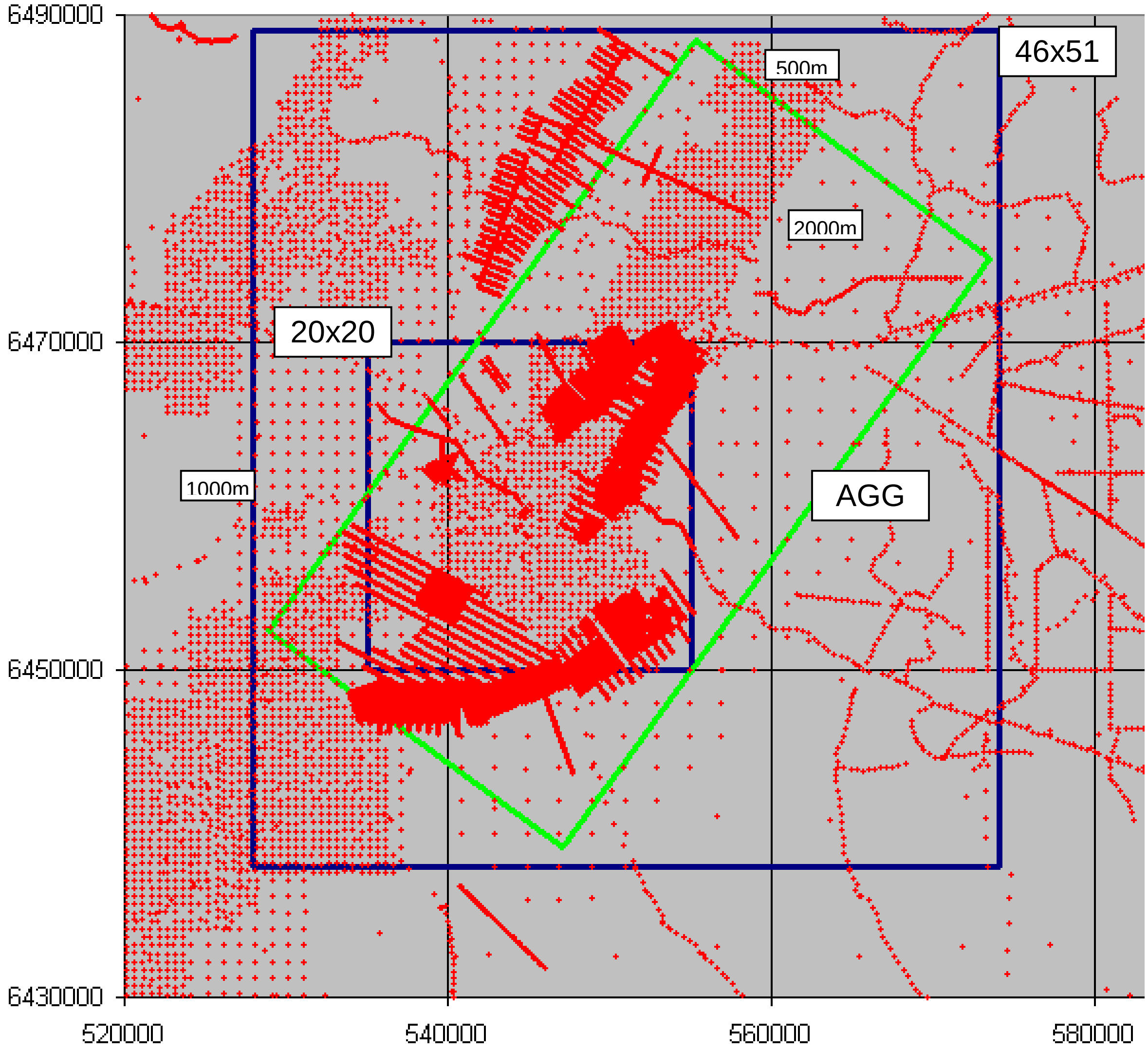


Figure 15. Ground gravity station locations for the Broken Hill district. The area of the AGG survey is indicated, and also the 20x20 Model and 46x51 Model areas. The maximum gravity station spacing within the AGG survey area is 2000m, but there are broad areas where the spacing is 500m, or even less (e.g. 60 x 600m, and 25 x 100m). Station spacing along roads is 400m. Grid coordinates are GDA94, MGA54.

Preparation of the ground gravity data for use in inversion (of the 20x20 Model) consisted of the following steps …

- Starting with the delivered point database, the Bouguer gravity anomaly was recomputed using a Bouguer density of 2.75 g/cm^3. No terrain correction was applied; this was considered unnecessary, given the mainly low topographic relief of the Broken Hill area.
- Gridded the Bouguer anomaly data to a grid cell-size of 250m, creating a grid of 80x80 cells, exactly registered to the 20km x 20km 3D-WEG project area (Figure 16).
- De-trend ? No. Examined the Bouguer anomaly grid, and elected to not apply any de-trending (to remove possible long wavelength features).
- Zero-level Adjustment ? Yes. Using the geology units reported for each voxel in the voxel-model (created from the Broken Hill 3D Model in the initial part of the inversion process), assigned the appropriate density value to each voxel, and computed the mean density for the model (2.80 g/cm^3). Since the specified reference density for the 3D-WEG project was 2.75 g/cm^3, the average density ***contrast*** for the starting model was +0.05 g/cm^3. For a 'slab' of 5.25km thickness and density contrast of +0.05 g/cm^3, the computed gravity signature would be +11.0 milligals; the Bouguer gravity grid was zero-level adjusted such that the average Bouguer gravity value for the grid was 11.0 milligals.

The resultant gravity image, based on these closely spaced gravity stations for the 20x20 Model area, is a quite high resolution image, which does sharply resolve several geological horizons and contacts (Figure 16 b, c).

Similar preparation was done to create a Bouguer gravity grid appropriate for inversion of the 46x51 Model, although only very limited inversion work was done with that model.

Some experimental inversion work was also done using a grid of ground gravity data which had been ***upward continued to 80m*** (to simulate a gravity signature measured at the height of the AGG survey).

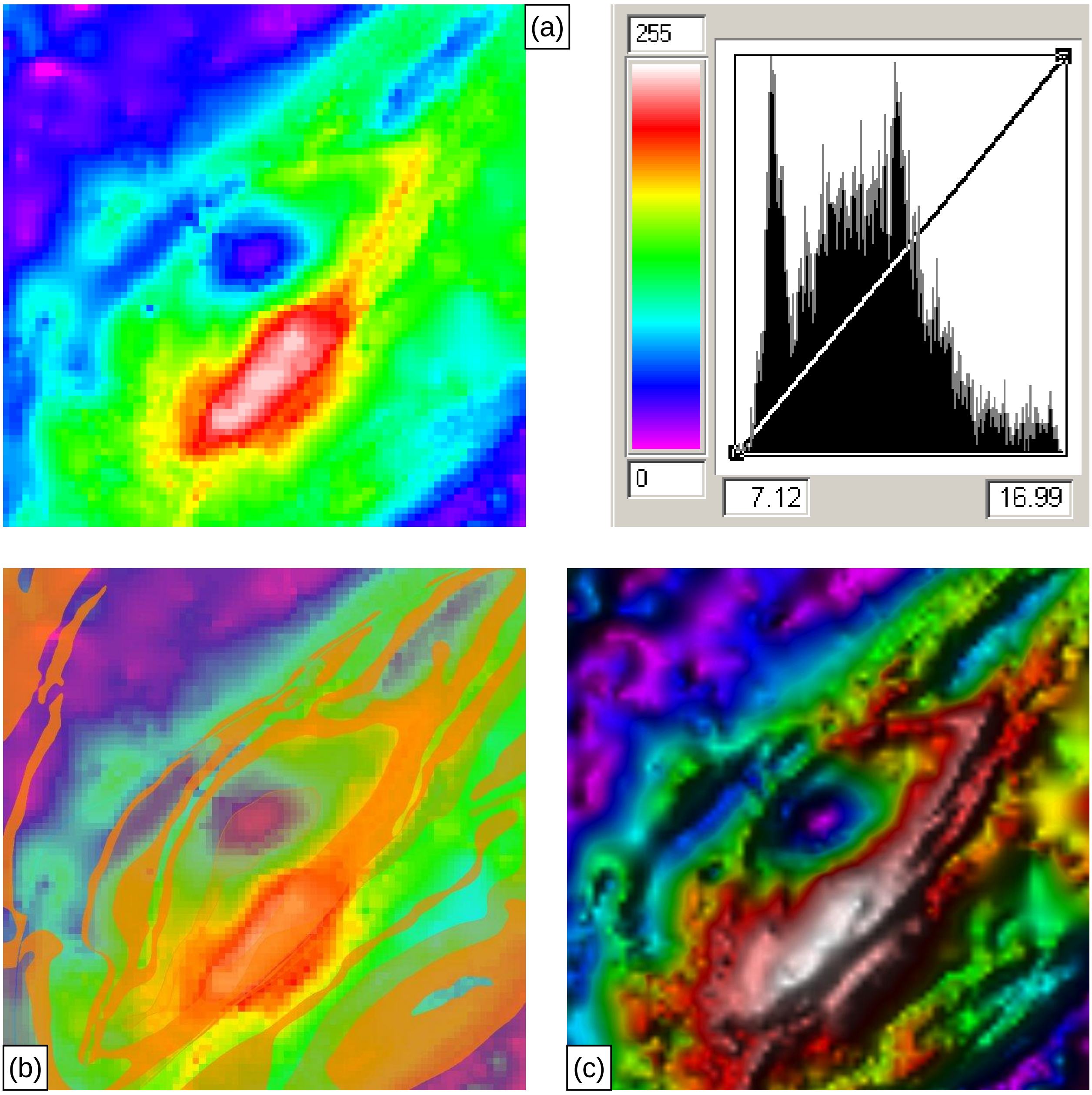


Figure 16. Bouguer gravity anomaly image for the 20x20 Model area, shown with linear colour stretch in (a), together with the histogram showing the distribution of data. The image also exhibits the 250m grid cell-size; the voxel model used in inversion has matching 250m voxels. The Broken Hill 3D Model is shown superimposed on the gravity image in (b), illustrating broad correlations between the geology and the gravity signature. The image, with WNW sun-illumination in (c) further highlights the geological information-content represented in the gravity data.

6.1.2 Airborne Gravity Gradiometer (AGG) Data

One of the goals of this project was to use the gravity data derived from an airborne gravity gradiometer (AGG) survey in 3D-WEG inversion processing, and so refine the Broken Hill 3D Geological Model. In the end, only very limited and experimental inversion work was done with the AGG dataset. The main reason for this limited use of the AGG data was due to some of the fundamental limitations of that dataset (discussed below); by comparison, the ground gravity dataset was a more appropriate dataset to use in the experimental evaluation of 3D-WEG inversion undertaken in this project.

The AGG survey was flown in February 2003 using the FALCON™ AGG system. Line spacing was 200m, and the nominal terrain clearance was 80m. The main outputs from the survey were grids of the *vertical component of gravity* (gD), and the *vertical gradient of the vertical component of gravity* (Gdd). Complete data from the survey (line-data, grids and reports) were made available by Geoscience Australia.

Lane et al. (2003) analysed the AGG data, and comment on the basic acquisition of the FALCON™ system, the processing then needed to derive these products, and the resultant limitations of the derived vertical component of gravity as a consequence of that acquisition and processing. A principal concern about the gD data is that it is a band-limited dataset; the necessity to apply filtering - to limit the effects of noise in the data - means that high-frequency signal is attenuated; and the fact that the fundamental acquisition is a relative rather than absolute measurement means that long wavelength information (longer than the survey dimension) are simply not recorded in the dataset. (It should be noted that FALCON™ processing can attempt to address the long wavelength limitation by incorporating the long wavelength component of the gravity signature from ground gravity survey data; results from such advanced processing were not delivered to this project).

Lane et al. (op. cit.) discuss the comparisons that can be made between the ground and AGG datasets, and there are some broad similarities.

From a viewpoint of 3D-WEG inversion, however, the measured gravity signature is expected to be that which can be computed from the geological model. Ideally, the gD derived from an AGG survey at 80m mean terrain clearance *should be comparable to ground data upward continued to that height.* In fact, there are significant differences between the upward continued ground data, and the gD data, and there are even greater differences between gD computed by two different methods! (Table 2 and Figure 17).

Table 2. Bouguer gravity anomaly minimum and maximum limits, and data ranges, for grids covering the area of the AGG survey. The limits and data range for the ground gravity data are for grids which were clipped to the AGG survey boundaries, shown as observed at ground level, and also upward continued to 80m, equivalent to the survey acquisition height for the AGG survey. The AGG data are the vertical component of gravity (gD) computed by two different methods (Fourier, and Equivalent Sources).

Dataset	Eff. Height	Min (milligals)	Max (milligals)	Data Range (milligals)
Ground gravity (at 0m)	0m	7.8	21.0	13.2
Ground gravity UC80m	80m	8.0	20.6	12.6
AGG gD by Fourier	80m	-4.9	12.2	17.1
AGG gD by Equiv Sources	80m	-2.9	4.9	7.8

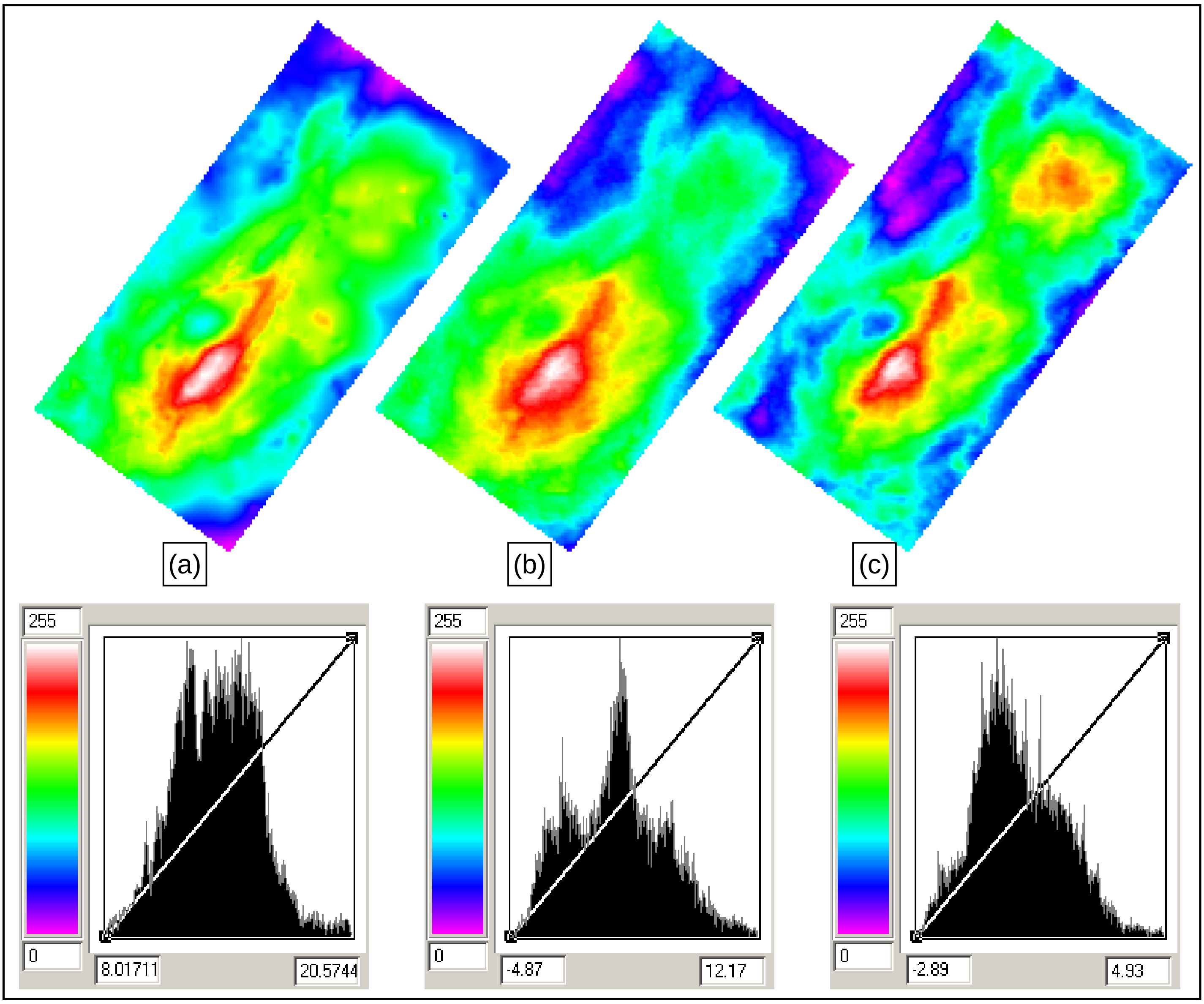


Figure 17. Grids of the vertical component of gravity for the area of the AGG survey. Image (a) is ground Bouguer gravity anomaly data, upward continued to 80m. Images (b) and (c) show the vertical component of gravity (gD) for the AGG survey; computed by the Fourier method (b), and by the Equivalent Source method (c). The histograms for the three datasets are shown. Survey extents: 44.6 km (SW-NE) x 22.5km (NW-SE).

Whilst some experimental work was done using the (AGG) gD data in 3D-WEG inversion during the early stages of the Broken Hill project, that early work was not systematically repeated in the later stages of the project (when a modified version of the inversion processing software was being used for systematic inversion analysis). The following comments can be made about the use of the AGG data in this project …

- The inversion software was modified to allow inversion to be applied to gravity data recorded at some specified height ***above*** the topography; previously only data at ground level could be used.
- The band limited nature of the (AGG) gD data make it unsuitable for use in 3D-WEG inversion; incorporation of signal content from ground data might remedy this problem.
- Inversion directly using the measured tensor data of the AGG system is a goal for future development of 3D-WEG; ground data would still be needed for long wavelength data.

6.2 Density Data for Inversion

6.2.1 Management of Physical Property Data in 3D-WEG

Physical property data, such as density and magnetisation, can be used to compute the geophysical response of a 3D-WEG model, and are used in inversion processing. Values are assigned to the stratigraphic units of a 3D-WEG project (Figure 18).

Rather than simply using an average value for each geological unit, however, the software takes into account *the statistical variation* which is always observed in the measurement of such data. Thus the *shape of the distribution* (e.g. Gaussian, lognormal, etc) is specified, together with the *mean* and *standard deviation*. A *reference density* value is also specified. This is typically the same as the density value used for the Bouguer processing of the gravity data, and is used here as the basis for computing density *differences*; differences, rather than absolute values, are used in 3D-WEG's forward modelling and inversion computations.

These inputs define *probability density functions* for each geological unit. In 3D-WEG's inversion processing, the assignment of *density difference values* to any selected voxel is by *random selection* according to the probability density function defined for the relevant unit (See Section 5, Inversion in 3D-WEG).

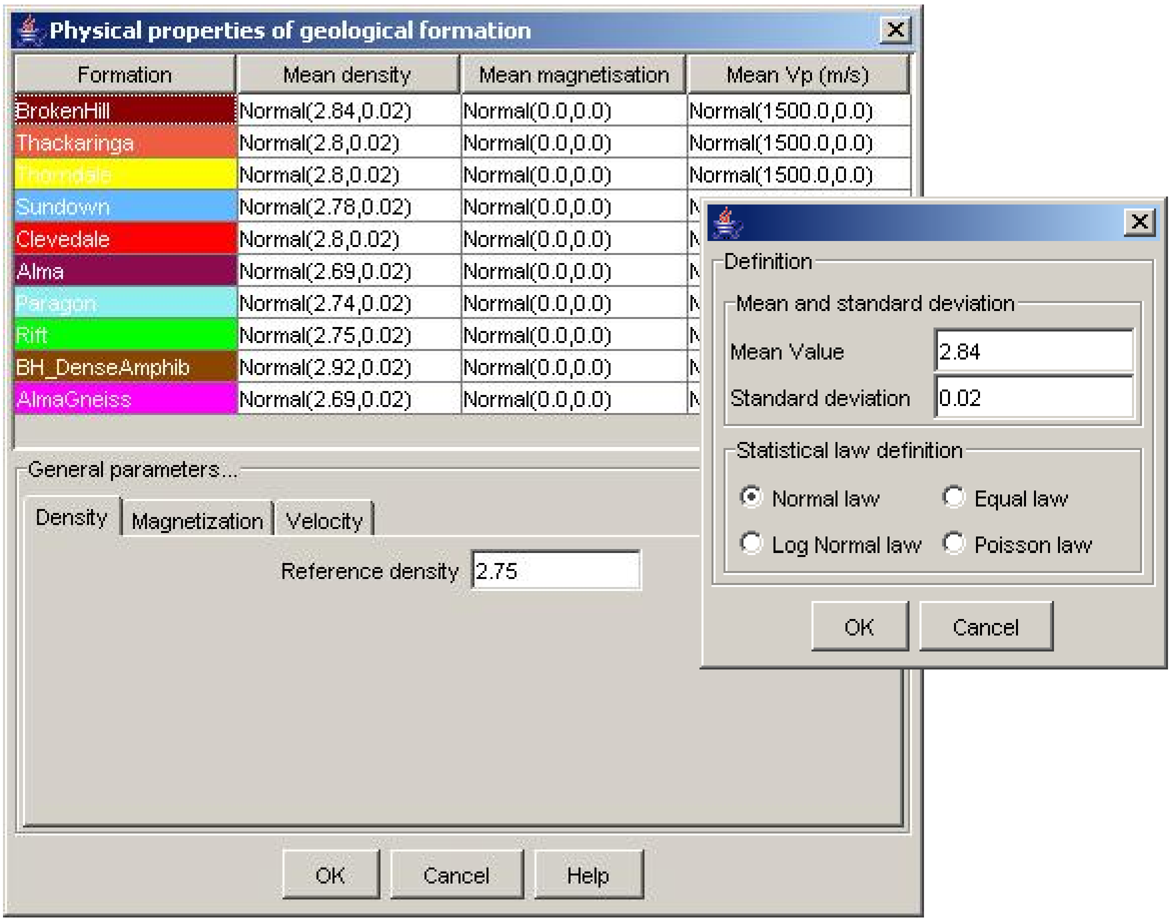


Figure 18. 3D-WEG's physical properties dialogs are used to assign properties to each unit in the stratigraphic pile in a project. The shape of the distribution is specified (normal, log-normal, …), together with a mean and standard deviation. Density differences for each formation are computed relative to a specified 'Reference density' value.

6.2.2 Broken Hill Density Data

The BHEI petrophysical database (Maidment et al., 1999), containing density measurements of drillcore and outcrop samples, was supplied to this project by Geoscience Australia. Lane et al. (2003) analysed those data, and reported mean density values, and standard deviation, for the main groups of Broken Hill stratigraphy (Table 3).

Table 3. Density values in g/cm^3 derived from measurements given in Maidment et al. (1999). Samples were assigned to the groupings on an exclusive basis from top to bottom. Samples from the Rasp Ridge Gneiss and Alma Gneiss were separated from the remainder of the Thackaringa Group samples. 'Contrast' is with respect to a notional background value of 2.82 g/cm^3. 'N' is the number of samples in each grouping. Table from Lane et al., 2003.

Grouping	Map symbol from 1:25,000 maps	Contrast	Median	N	Mean	Standard deviation	Minimum	Maximum
Younger mafic and ultramafic intrusions	bp,bx	+0.08	2.895	6	2.870	0.047	2.800	2.910
Retrograde schist	rm	-0.03	2.790	43	2.787	0.087	2.600	2.980
Pegmatite and Quartz	p,rp,q	-0.15	2.670	28	2.717	0.146	2.580	3.260
Iron-rich rocks	bif,qm	+0.48	3.295	16	3.270	0.256	2.690	3.580
Amphibolites	a,ag,ax	+0.23	3.050	67	3.071	0.164	2.760	3.500
Sundown Group	E,M,S,SE,rE,rM	-0.02	2.810	147	2.833	0.104	2.630	3.300
Broken Hill Group	BG,E,EM,FEM,FM,FS,FSE,Lq,M, S,SE,SM,bp,gq,rE,rSE	0.01	2.830	211	2.853	0.135	2.630	3.440
Rasp Ridge Gneiss	BG,BG2,Bc,EM,M,S,SE,rBm	-0.07	2.750	73	2.796	0.143	2.590	3.500
Alma Gneiss	Bc	-0.13	2.690	3	2.903	0.378	2.680	3.340
Thackaringa Group	BG,E,EM,FEM,FM,FS,FSM,M,PI,S ,SM,gq,BG2,rBm,rE,rEM,rM	-0.02	2.800	149	2.812	0.165	2.640	4.510
Clevedale Migmatite	Lf,rLF	-0.13	2.690	5	2.686	0.047	2.620	2.750

Some subsets of these data are plotted as histograms in Figure 19. Points to note from the histogram plots include …

- the data have an approximately *normal* or *Gaussian* distribution; the 'normal' law was chosen as the statistical law for the density distributions of all geological units.
- there is a wide standard deviation. This is in part due to the typical variability of density measurement on small samples, which may have been partly altered or weathered. Another important factor is that the 'group' classification combines together different geological formations, which will inevitably have density variations, one from another.
- there is significant overlap between 'groups' (Figure 19 d)

The analysis of Lane et al. (op. cit.) also noted …

- *pegmatites* have a strong negative density contrast. The widespread occurrence of these units in the Sundown Group would be expected to reduce the gravity response over that Group (Table 3, Figure 19 e, Figure 20)
- the strong positive density contrast of *amphibolites*, noting the concentration of such units in the parts of Broken Hill and Thackaringa Groups would give rise to elevated gravity response over those parts of those Groups (Table 3, Figure 19 f, Figure 21)
- the small numbers of samples (e.g. Clevedale Migmatite: 5!), their restricted spatial distribution, and also the relatively large standard deviation values (Table 3).

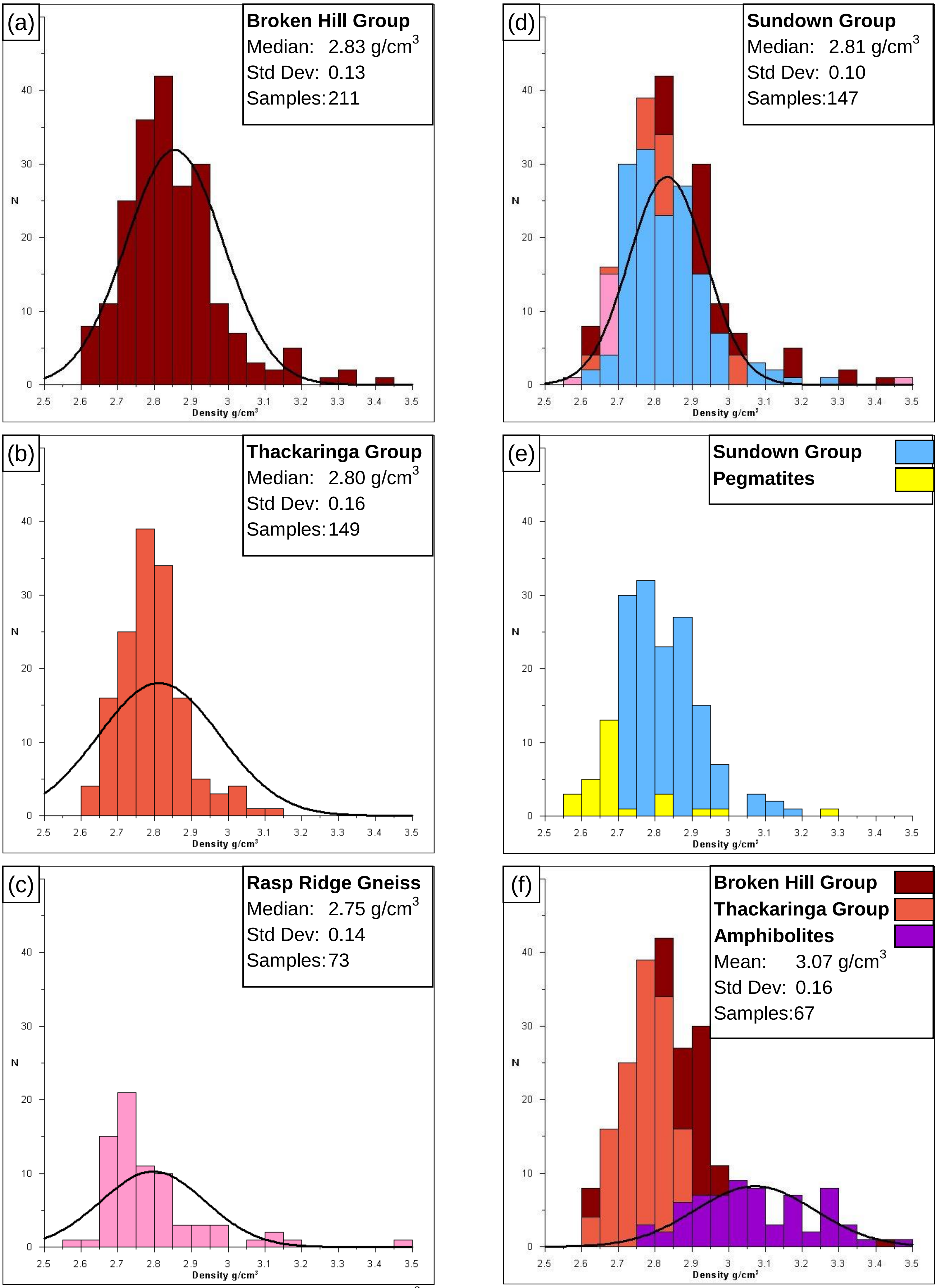


Figure 19. Histograms of density values in g/cm^3 from measurements given in Maidment et al. (1999). Note the wide standard deviation for samples from Broken Hill Group (a), Thackaringa Group (b) and Rasp Ridge Gneiss (c). The ranges of density values from different 'groups' do overlap, as illustrated in (d). In some areas of Sundown Group outcrop there are broad zones of pegmatites and K-feldspar rock which have lower density (e); these have the effect of lowering the 'bulk density' of those areas. In other areas (of Broken Hill Group and Thackaringa Group outcrop), as much as 40% amphibolite will have the effect of increasing bulk density (f).

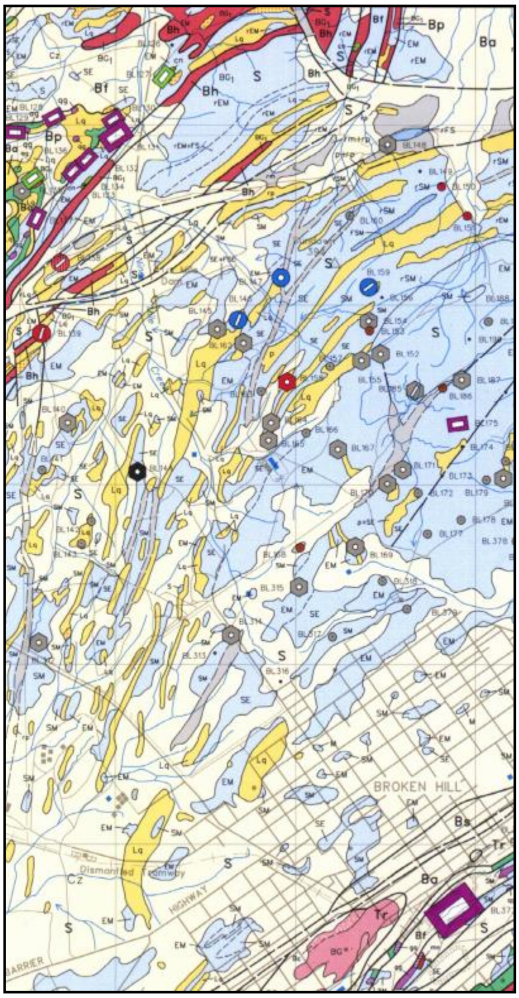


Figure 20. (above) In the area immediately north of the city of Broken Hill the Sundown Group rocks (light blue) contain significant volumes of pegmatites and K-feldspar rocks (yellow). The effect of the pegmatites would be to lower the bulk density of Sundown Group in this area. Geology from the GSNSW 1:50,000 interpretation (Bartholomaeus et al., 1995). Image area 5.6 x 11km.

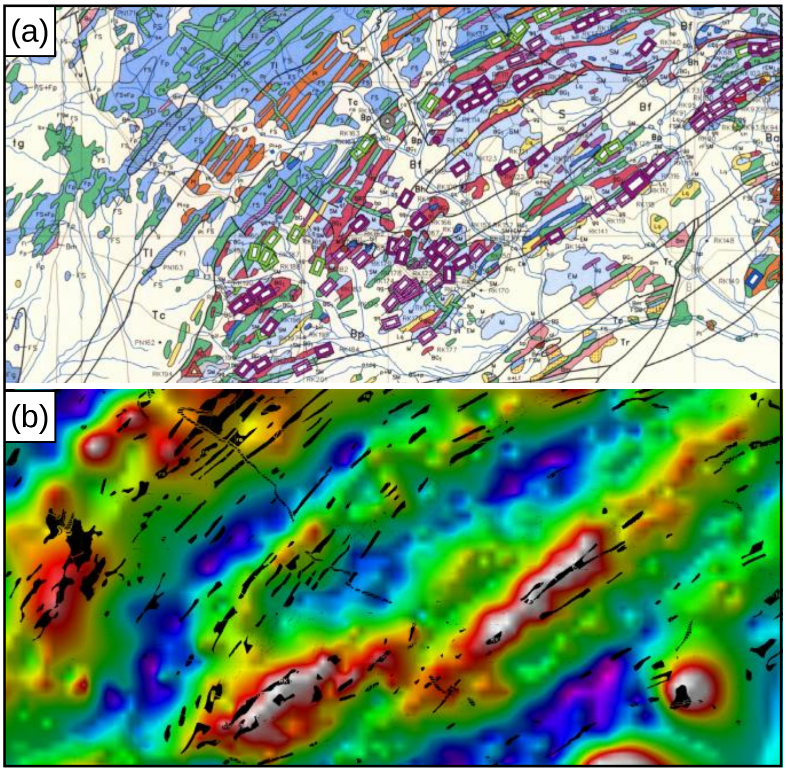


Figure 21. (above-right) The geological mapping (a) in the Little Broken Hill area (14km south-east of Broken Hill) shows the extent of amphibolites (green bands). The ground gravity data (b), which has been high-pass filtered, shows a strong correlation of increased gravity response in those zones of greatest concentration of amphibolite. Geology from the GSNSW 1:50,000 interpretation (Bartholomaeus et al., 1995). Image area 10 x 5km.

It is generally acknowledged that physical property measurements made on a ***modest number*** of ***small*** samples are hardly representative of ***bulk properties*** on a regional scale. Never-the-less, the values presented in Table 3 and were used as the basis for choosing ***initial*** density values for use in the 3D-WEG inversion processing. This choice was qualified by the rider that some units should be more dense than tabled (due to amphibolite), and the Sundown Group would be less dense (due to pegmatites). Thus, during the course of the project, some of the density values were modified as a consequence of observed poor fit between the computed model response and observed data …

- Some of the early inversion processing showed a persistent zone of misfit between the measured and inversion-computed model response along a north-east trending zone broadly coincident with an area of Thorndale Composite Gneiss and Clevedale Migmatite (Figure 22). The misfit was indicative of a mass-deficit in the model, and it was postulated that the originally assigned density values had not adequately accounted for the effect of high density amphibolites in these units. This misfit problem was eliminated by increasing the density of the Thorndale Composite Gneiss (from 2.73 to 2.80 g/cm^3), and of the Clevedale Migmatite (from 2.69 to 2.73 g/cm^3). Note also that the original value for the density of Clevedale Migmatite was based on just 5 samples (Table 3).

- The Thorndale Gravity High (anomaly ‘B’ in Figure 23a) is a distinct gravity anomaly that was not at all represented in the Broken Hill geological model. This gravity anomaly can be attributed to the high concentration of amphibolites in this area, estimated to be as much as 40% in these parts of the Broken Hill and Thackaringa Groups. It was decided that this distinctive feature of the gravity data should somehow be represented in the Broken Hill model – and assigned a density commensurate with the observed high concentration of amphibolites. (This was also deemed to be a test of 3D-WEG’s ability to incorporate a radical geological re-interpretation, and re-build the model from the revised observations). This revision was achieved by describing a part of the Broken Hill Group as being a ‘high-density component of Broken Hill Group’; a separate ‘unit’ was added to the stratigraphic pile for the Broken Hill model … called ‘BH_DenseAmphib’, and assigned a very high density value (2.92 g/cm^3). Geological observations were added to two sections, constraining the extent of this new ‘unit’ to the area where the Broken Hill Group contained a very high concentration of amphibolites in the area of the Thorndale Gravity High.

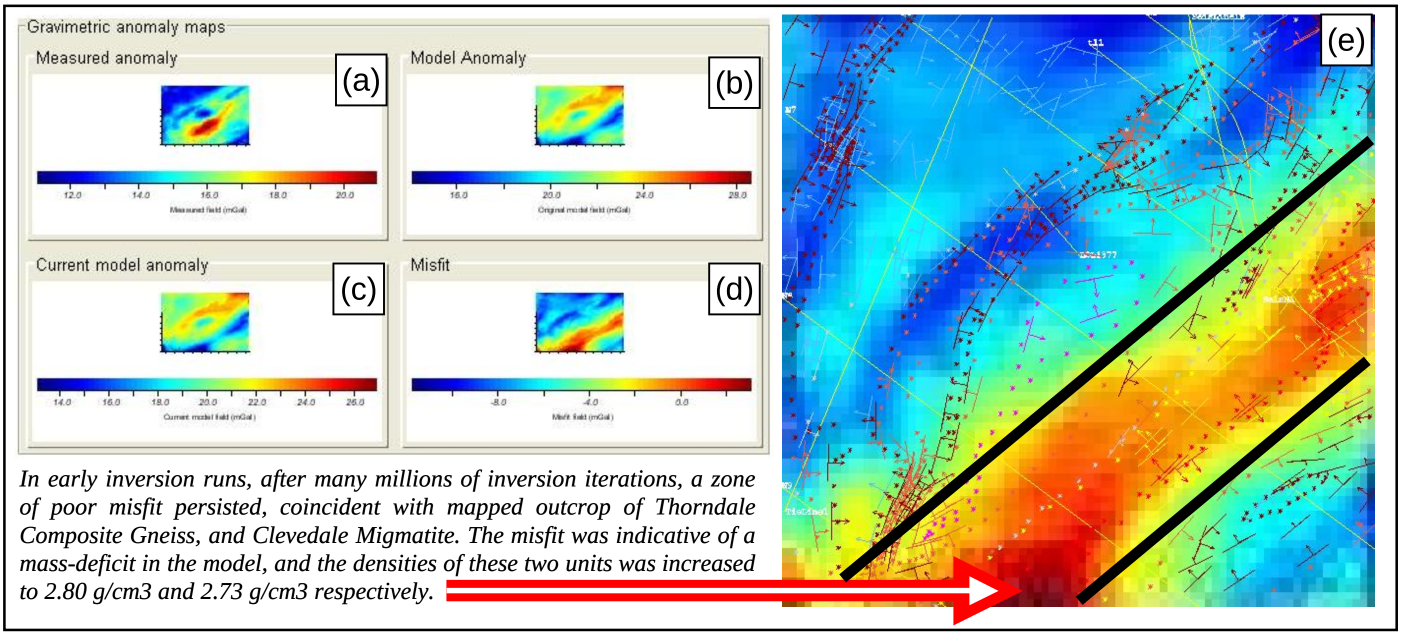
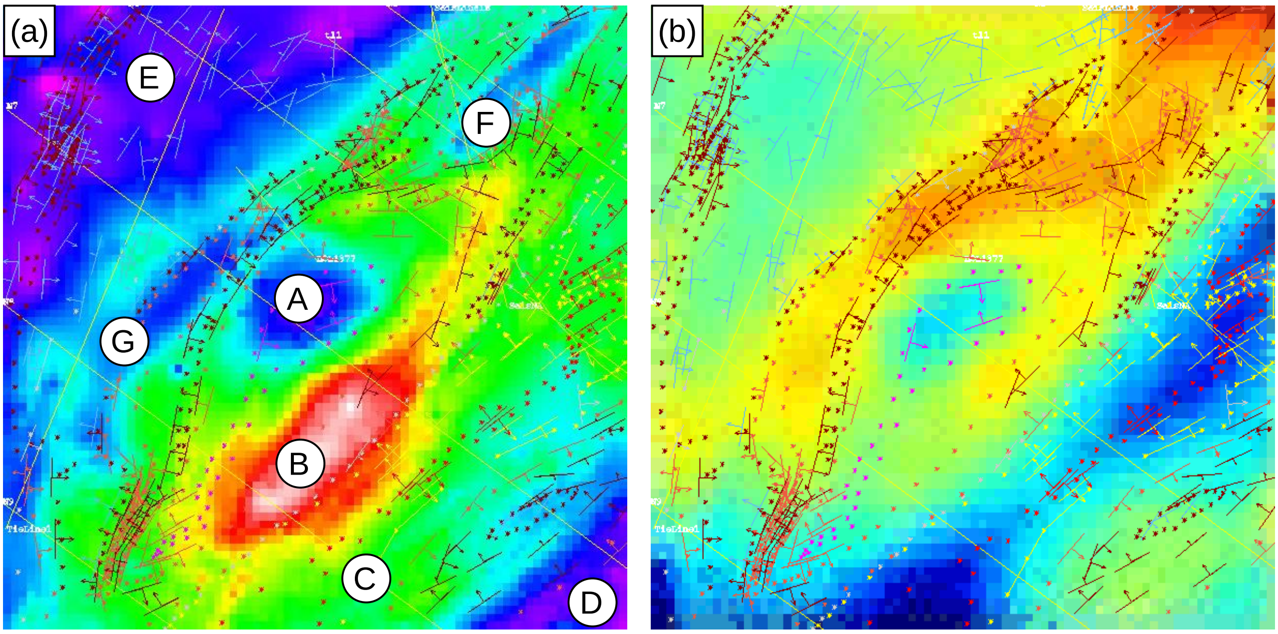


Figure 22. The feed-back screen from 3D-WEG’s inversion shows four images; the measured anomaly (a), the computed response of the starting model (b), the computed response of the ‘current’ model (c), and the current misfit (d). The misfit is presented again in (e). In early inversion runs, a NE trending zone of poor misfit persisted, even after millions of inversion iterations. This was indicative of a mass-deficit in the model, and the density of the Thorndale Composite Gneiss and Clevedale Migmatite was increased. The higher density in this area can be attributed to a locally higher concentration of amphibolites.



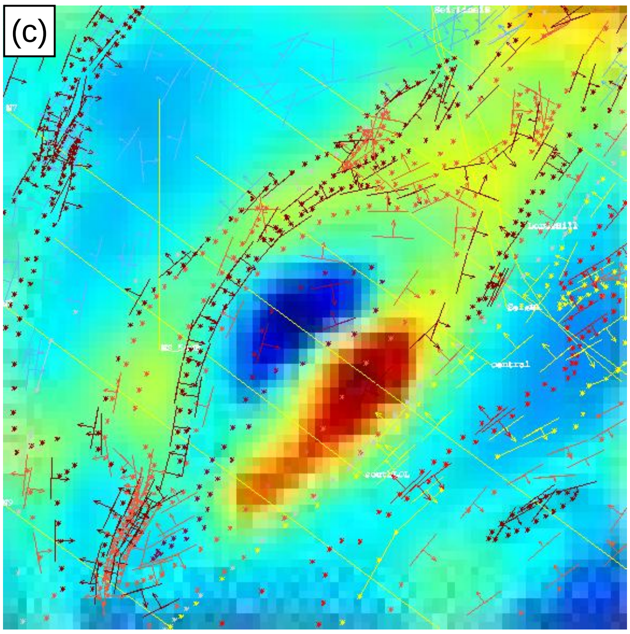


Image (a) is measured Bouguer gravity, and image (b) the computed gravity response of the starting model using original density values. Note several differences between the field and computed response: Whilst the Alma Gneiss (low, at A) can be seen in the model response, the Thorndale Gravity High at B is clearly not present in the model response; the gravity high is attributed to the concentration of amphibolites in the Broken Hill and Thackaringa Groups in this area. Other areas of discrepancy include: C – the north-east trending zone of mass-deficit discussed in Figure 22; D - a gravity low in an area where the lower density Redan rocks are present; E – an area of gravity low, attributed to the low density pegmatites in Sundown Group rocks.

The model was modified to improve the initial fit. A new unit was added to the stratigraphy to represent the 'dense-Broken Hill Group', and the densities of some units were modified. Image (c) is the model response for the final model.

The gravity lows at F and G are due to gneisses, which could be better modelled in future work.

Figure 23. Images of the measured Bouguer gravity anomaly (a), and the computed model response for the initial model, using original density values (b). The match between the two is poor. The model was modified by changing the density values for some formations – to better account for dense amphibolites, and low-density pegmatites (See final density values listed in Figure 24). A new stratigraphic 'unit' was added to represent the (locally) very dense amphibolite-rich rocks of the Broken Hill Group in the area of the prominent Thorndale Gravity High. The computed gravity response (c) for this modified model was considered to be an improved 'starting model' for use in 3D-WEG inversion processing. Image areas are 20 x 20km. The image colour stretches vary, but the gravity data range for all images is approximately 10 milligals.

- Figure 23 also shows other differences between the measured and computed responses. The density values for some units were further modified in an attempt to produce a model for which the computed 'starting-model-response' (Figure 23 c) was broadly comparable to the measured data (Figure 23 a).

The density values used in the final inversion processing of the Broken Hill geological model are those noted in Figure 24. The standard deviation was varied for different inversions runs; most runs used $\sigma = 0.04$ to 0.05 g/cm^3; one inversion test used a lower value ($\sigma=0.02$ g/cm^3).

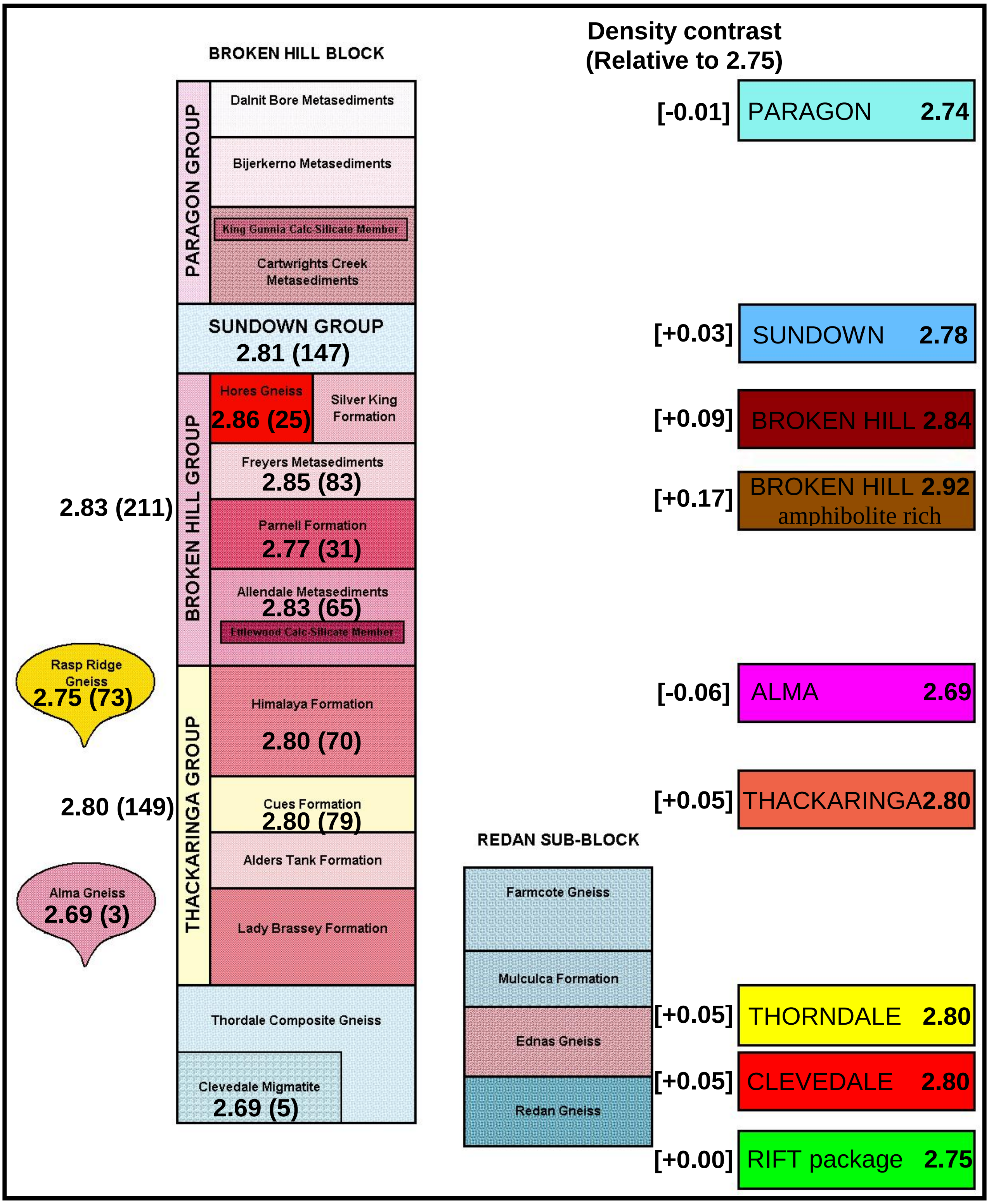


Figure 24. Density values in g/cm^3 from Richard Lane (Geoscience Australia, pers com), derived from data in Maidment et. al. (1999). Values in curved brackets are the number of samples measured for each formation. Shown on the right are the final densities used in the 3D-WEG inversion processing. Values in square brackets are the notional density contrast, relative to the reference density, 2.75 g/cm^3.

6.3 Inversion Results

Various modifications were made to the inversion part of the 3D-WEG software during the course of the project; some of those changes did impact on the performance of the inversion processing. For example, the controls on 'maintaining the topology of the model' were varied. In this environment of 'software-changes-in-progress', there is always the chance of bugs in the software yielding incorrect results; several inversions attempted during April and May seemed to be inverting correctly, but the outcomes were quite 'broken-up' … as if the model topology rules were not correctly applied. In early June a revised (beta) version of the software was delivered which fixed earlier problems; for consistency, all of the results discussed here were derived using that latest version of the software. (Inversions performed by Guillen during the early part of the project effectively utilised different inversion software, and are excluded from this discussion).

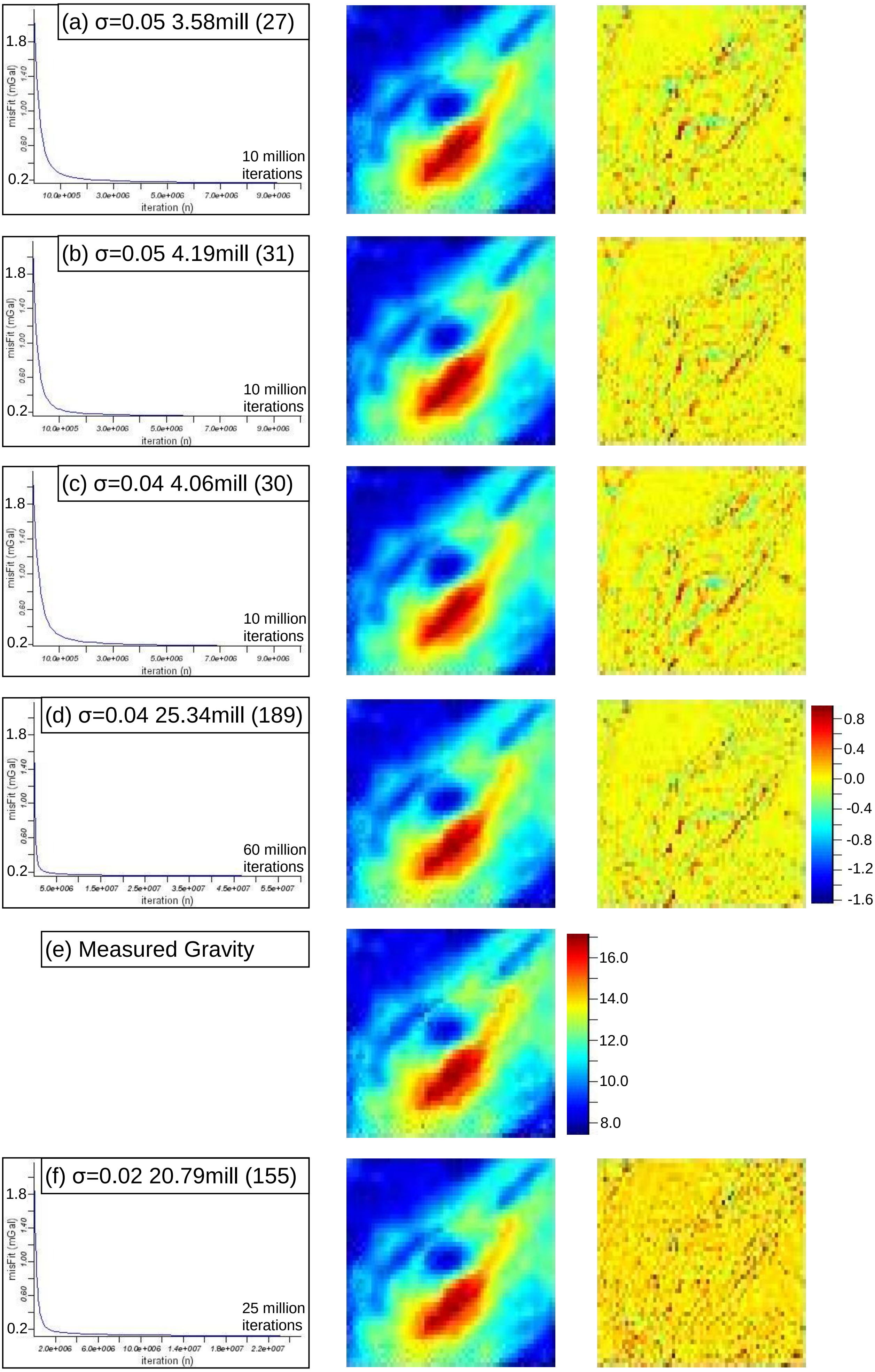
Five inversion runs were executed, using the 20x20 Model that was current in early June.

- This model ('Model 12') included the 'BH_DenseAmphib' unit, added to more correctly achieve gravity inversion results in the area of the Thorndale Gravity High.
- Densities were as shown in Figure 24.
- 250m^3 voxels were used; thus 80 x 80 x 21 voxels in the 20 x 20 x 5.25 km model space
- The 'average density contrast' (relative to the reference density of 2.75 g/cm^3) for this starting model was 0.05 g/cm^3. The 'expected gravity signature' for the model, with this density contrast, is 11.0 milligals (Based on the formula for an infinite horizontal slab … $g = 2\pi\rho G h = 2 \times \pi \times 0.05 \times 6.673 \times 5.25 = 11.006$ milligals).
- Ground gravity data were used, with a zero-level adjustment applied such that the 'measured' data level was matched to the expected gravity signature level for this model.
- Values used for the standard deviation, and total iterations, are shown in Table 4

Table 4. Parameters and performance measures for inversion runs performed on the 20x20 Model in early June. Run 5 used a much lower standard deviation (σ=0.02 g/cm^3). The number of iterations is shown in millions. For most runs, approximately 40% of iterations resulted in a 'saved model'. The 'per Voxel' column is a rough guide indicating how frequently each of the 80x80x21 250m^3 voxels in the 20x20 Model were adjusted. The time to invert is shown in hours and minutes.

Run	σ	Iterations (10^6)	Saved Models (10^6)	per Voxel	Time to Invert hh:mm
1	0.05	10	3.58	27	13:40
2	0.05	10	4.19	31	15:51
3	0.04	10	4.06	30	16:11
4	0.04	60	25.34	189	88:00 (3½ days)
5	0.02	25	20.79	155	59:00 (2½ days)

Figure 25. (next page) Inversion feed-back information for the five inversion runs. The first four runs (with wider standard deviation) are shown at the top of the figure, and the fifth run (σ=0.02) is at the very bottom. The labels repeat selected details from Table 4 … σ, 'saved models', and 'per Voxel'. For each run: the misfit graphs on the left show that the model response closely matched the data, and rapidly inverted towards a very small misfit value; the middle column of gravity images are the response for the 'current model' at the point of the last iteration; and the misfit image on the right is the difference between the 'current model response' and the measured gravity image (e).



(a) σ=0.05 3.58mill (27)
1.8
0.2
misFit (mGal)
10 million iterations
iteration (n)
(b) σ=0.05 4.19mill (31)
10 million iterations
(c) σ=0.04 4.06mill (30)
10 million iterations
(d) σ=0.04 25.34mill (189)
60 million iterations
0.8
0.4
0.0
-0.4
-0.8
-1.2
-1.6
(e) Measured Gravity
16.0
14.0
12.0
10.0
8.0
(f) σ=0.02 20.79mill (155)
25 million iterations

6.3.1 Inversion Runs with Standard Deviation 0.04, 0.05

Referring firstly to the first four runs listed in Table 4, note that these used σ=0.05 and σ=0.04 g/cm^3. These values should be considered in the following two contexts …

- At 0.05 and 0.04, these are much less than the standard deviation computed from the measurement of densities on drill core and sample … where typical values are 0.10 to 0.16 (Figure 19)
- On the other hand, referring to the notional ***density <u>contrasts</u>*** used in these inversion runs (and noted in Figure 24), the average density contrast value is about 0.05 g/cm^3 … so these values for standard deviation represent a 100% variability in our knowledge of density contrast values at Broken Hill!!!!

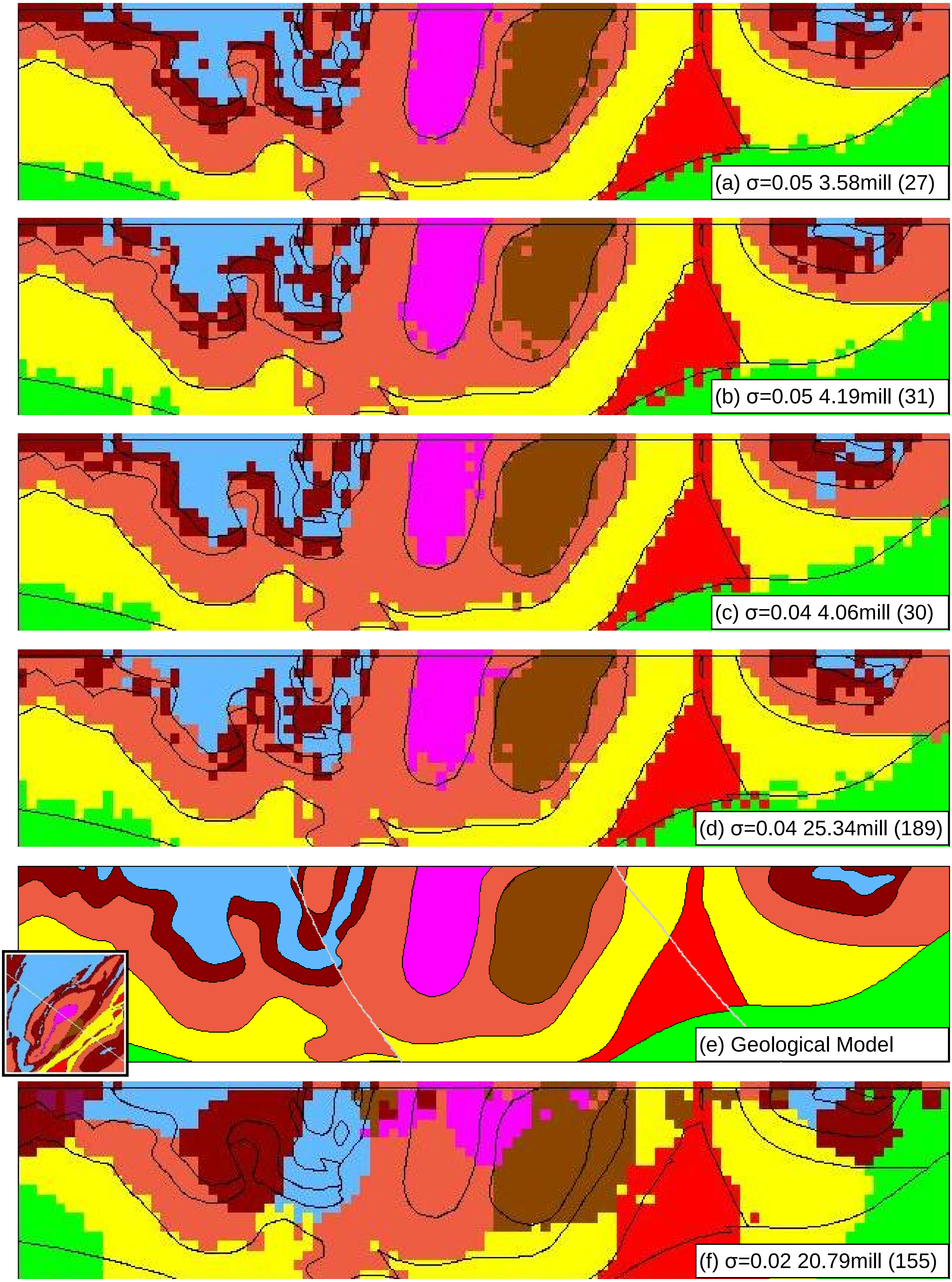
For all four runs, approximately 40% of the iterations resulted in a model that was 'saved'. For the fourth run, with 60 million iterations, some 25 million models were saved. For 250m^3 voxels, there were 80 x 80 x 21 = 134,400 voxels used in the inversion processing. For 25 million 'saved' models, we can estimate that – on average – each voxel was 'adjusted' 189 times.

Referring to Figure 25 a-d (above) all four inversion runs were 'good' inversions. For example, Figure 25 (d) shows part of the inversion feed-back for Run 4, with 60 million iterations; the starting misfit (graph) was low (approx. 2 milligals); after approximately 2 million iterations this had decreased rapidly to a very low misfit (just 0.2 milligals), and it remained at this very low level through to the 60 millionth iteration. The gravity response for the 'current model' at the point of the 60 millionth iteration is shown; this compares well with the measured gravity (Figure 25 e); in reality, the gravity response for the 'current model' was approximately unchanged from the 2 millionth iteration through to the 60 millionth iteration. Shown at the right is the misfit image – the difference between the 'current model' response and the measured gravity; this misfit is uniformly low across the entire area of the model … and again was mainly unchanged for the last 58 million iterations. Note the time taken for this inversion: approximately 3½ days.

The results from these four inversions are presented in terms of 'most probable geology' in Figure 26 a-d (below). There is a strong similarity for all four inversion runs … and there is (in many parts) a strong correlation with the starting model. Does this then imply ***strong support that the starting model is <u>correct</u>*** ? I believe the answer is ***<u>not necessarily</u>***!

Note firstly that for three stratigraphically adjacent units – Clevedale (red), Thorndale (yellow) and Thackaringa (tan) – the ***density value used in inversion was the <u>same</u>*** (all 2.80 g/cm^3; Figure 24). Thus inversion can yield ***<u>no information</u>*** about the two contacts between those three units; the inversion process has not changed these two contacts away from their starting model positions (Figure 26).

Figure 26. (next page) Plots of the 'most probable' stratigraphic unit (for Section N7) for the five inversion runs listed in Table 4. The labels in the figure repeat selected details from that table … σ, 'saved models', and 'per Voxel'. The different colours represent the stratigraphic units of the model geology, as per the legend in Figure 24. The 'most probable' geology for the first four runs (with wider standard deviation) are shown at the top of the figure, and the fifth run (σ=0.02) is at the very bottom. The starting model geology is shown in (e), and also by the black lines in all of the plots. There is a broad consistency for 'most probable' stratigraphic unit for the first four inversion runs with the wider standard deviation (a – d), and the inversion outcomes are also consistent with the starting model. For the fifth inversion run (f), the 'most probable' stratigraphic unit is very different; in this case, with a more restricted value for the standard deviation, the inversion process has significantly moved many of the stratigraphic boundaries away from their positions in the starting model. (Location of Section N7 shown in inset; Length: 24km; V/H=1)


(a) σ=0.05 3.58mill (27)
(b) σ=0.05 4.19mill (31)
(c) σ=0.04 4.06mill (30)
(d) σ=0.04 25.34mill (189)
(e) Geological Model
(f) σ=0.02 20.79mill (155)

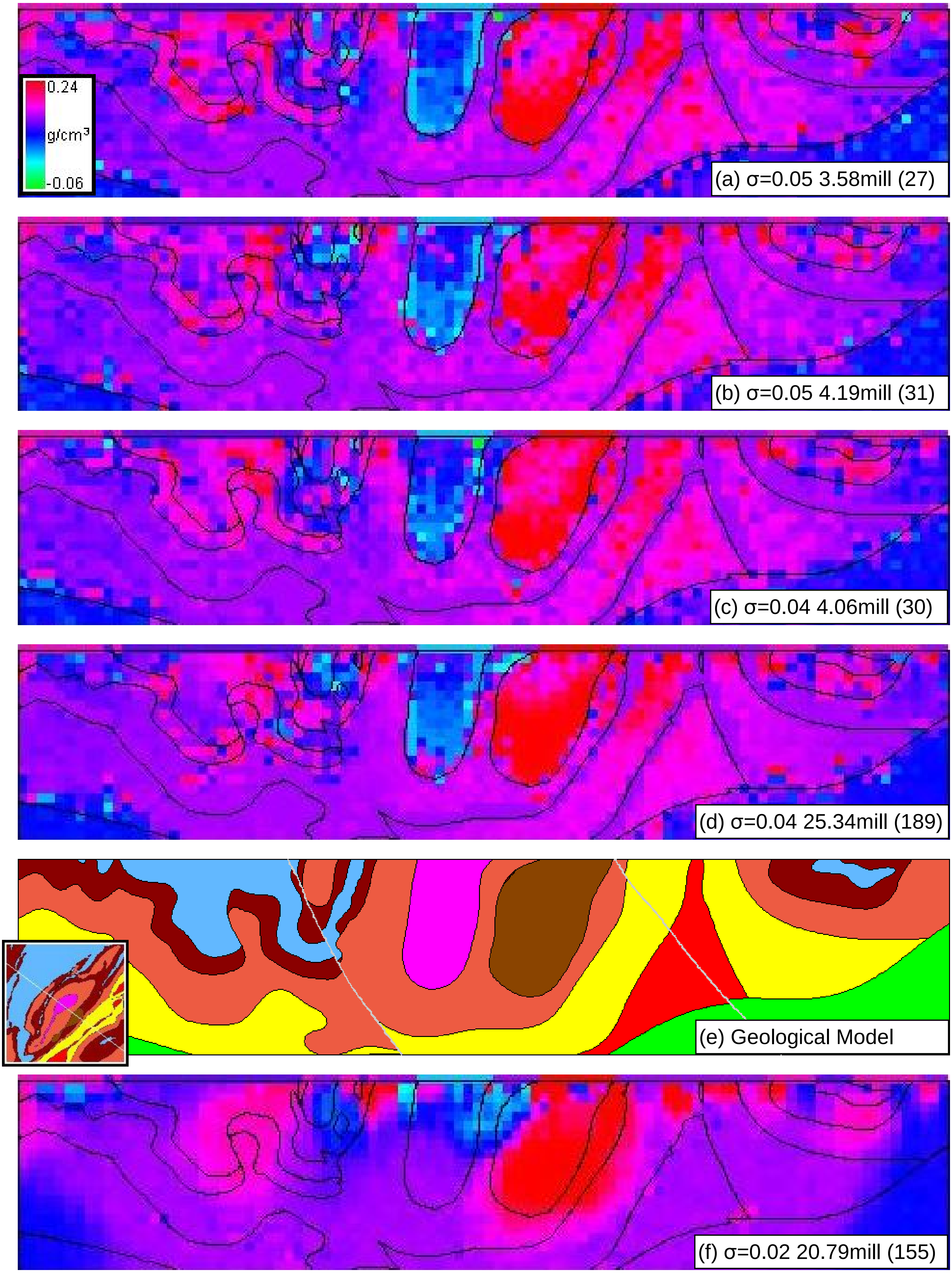

0.24
g/cm³
-0.06
(a) σ=0.05 3.58mill (27)
(b) σ=0.05 4.19mill (31)
(c) σ=0.04 4.06mill (30)
(d) σ=0.04 25.34mill (189)
(e) Geological Model
(f) σ=0.02 20.79mill (155)

Figure 27. (previous page) Plots of the 'mean density contrast' in g/cm^3 (for Section N7) for the five inversion runs listed in Table 4. The labels in the figure repeat selected details from that table … σ, 'saved models', and 'per Voxel'. The 'mean density contrast' for the first four runs (with wider standard deviation) are shown at the top of the figure, and the fifth run (σ=0.02) is at the very bottom. The starting model geology is shown in (e), and also by the black lines in all of the plots; the colours for the model geology are as per the legend in Figure 24 There is a broad consistency for 'mean density contrast' for the first four inversion runs with the wider standard deviation (a – d), and several of the density contrast boundaries are also consistent with the starting model. Note in these four images the occasional bright blue or red voxels, representing occasional extreme low or extreme high density values respectively. For the fifth inversion run (f), the 'mean density contrast' does have a broad similarity with the other plots. Note that in this case, with a more restricted value for the standard deviation, there are none of the 'extreme' low or high density voxels, but rather a smoother, more even distribution of density values. (Location of Section N7 shown in inset; Length: 24km; V/H=1).

Before considering further the 'most probable' geology, it is worth inspecting the 'mean density contrast' plots for these four inversion runs (Figure 27 a-d). Again, note the general consistency between the four plots. Note also the fairly obvious low-density Alma Gneiss (centre, in blues), and the large zone of higher density adjacent to this (the 'BH_DenseAmphib' zone, due to amphibolites, shown in red colours). With further examination of these distinct 'low' and 'high' density zones, it is also apparent that the inversion is ***not*** proposing a ***uniform density*** within those two zones. This variation of density (proposed by the inversion process) within a given stratigraphic unit is also seen in the Thorndale (yellow) and Thackaringa (tan) units; towards the south-eastern end of the section these units are depicted as being more dense, compared to lower density values in the north-western half of the section.

One very important aspect to note in these 'mean density contrast' plots are the occasional bright blue or red voxels, representing occasional extreme low or extreme high density values respectively. This is simply a consequence of the wide standard deviation used (σ=0.05 and σ=0.04); whilst most voxels will be assigned a density value which is near the mean (66% are within one standard deviation from the mean), there will also occasionally be values assigned which are 2 or 3 standard deviations above or below the mean. For example …

for Thorndale, with its mean density contrast = +0.05, and with σ=0.05 …

- occasional extreme low values could be $+0.05 - 3\sigma = -0.10$ (!)
- occasional extreme high values could be $+0.05 + 3\sigma = +0.20$ (!)

This degree of uncertainty in our knowledge of density data for Broken Hill does limit the effectiveness of inversion to 'test the validity of the model'; on the one hand, a wide standard deviation is needed in order to allow the inversion to migrate some areas of the model towards higher density values, and other parts of the model towards lesser values of density; these higher and lower areas are seen in the mean density contrast plots (Figure 27). On the other hand, the ability to occasionally use an extreme low value, or an extreme high value – particularly when assigned to a voxel at shallow depth – has a 50/50 chance of significantly improving the model (with a change to just one voxel). Whenever these extreme values result in 'an improvement to the misfit', those voxels (with their rather extreme values) will become one of the 'saved models'. Because of this rather wide standard deviation, the inversion can proceed with a rather 'fast and loose' approach, which can be guaranteed to rapidly invert towards a small misfit … but without really testing the boundaries of the model.

Returning to the 'most probable' geology plots (Figure 26 a-d), we can see very minor evidence that the inversion process is proposing some ***small*** changes to the boundary of Alma Gneiss (pink), and the BH_DenseAmphib unit (light brown). The inversion has also caused the Broken Hill Group (red-brown) to become rather broken up; in particular, see the north-western end of Figure 26 d (for Run 4, with 25 million saved models).

In summary, the inversion process is identifying some (small) inconsistency between …

- the model (this is the ***unknown*** in the equation, even though based on ***a priori*** data)
- the chosen density values (a known value ?)
- the measured gravity data (a known value ?)

… and the inversion process has attempted to resolve the inconsistency by inverting towards some alternative 'probable' model.

If we can confidently assert that the two 'knowns' in the equation (density and gravity) are indeed well-known, then the revised model proposed by the inversion result – suggesting (as it does) some minor changes to the starting model – could be considered to be a credible result.

For this (Broken Hill) project, however, there ***is*** a degree of uncertainty in the density data used (as expressed by a wide standard deviation), and there are overlapping ranges of density values for different units; consequently the credibility of the (only slightly revised) alternative model proposed by the inversion process must be qualified by the degree of that uncertainty. In summary …

- the inversion result (in this specific case) ***neither proves nor disproves*** the validity of either the starting model, or the proposed changes to the model
- it is possible to state that 'the measured gravity is broadly consistent with the Broken Hill model' (given what we know about the densities of each unit … which is ***not*** a lot!).

Consider again the 'mean density contrast' plots; the results for Run 4 are plotted again as Figure 28 (a). In particular note the general trend for the inversion process to have migrated density values at the north-western end of the section towards lower density values, compared to higher values at the south-eastern end of the section. As noted previously, this is seen within both the Thorndale (yellow) and the Thackaringa (tan) units. In the 'most probable' geology plot (Figure 28 b) the inversion result has proposed two small changes to geological boundaries; the boundary of the low-density Rift unit (green, 2.75 g/cm^3) is pushed upwards into the overlying Thorndale (yellow, 2.80 g/cm^3), and the boundary of the Thackaringa unit (tan, 2.80 g/cm^3) is pushed upwards into the overlying Broken Hill (red-brown, 2.85 g/cm^3). All of these changes are driven by the inversion process seeking to modify the density distribution in such a manner that the overall density of the north-western end of the section is decreased relative to the south-eastern end. How should these proposed changes to the density distribution be viewed ?

- are these proposed changes to the *density distribution* reasonable, and valid outcomes from the inversion process ?
- or … is there some problem with the preparation of the 'measured' data ? Has some regional trend been left in the measured data, when in fact it should have been removed ? … with the consequence that the inversion process is then left to adjust the density distribution (on a regional scale) in an attempt to account for this (regional) trend.

We have already stated that there is considerable uncertainty in density data. This last point now questions the degree of uncertainty in the second 'known' quantity in the inversion equation viz. the gravity.

Overall, these inversion results (for σ=0.04 and 0.05 g/cm^3) indicate that the gravity data are broadly consistent with the proposed starting model. For those units with a more distinct density contrast (the low-density Alma Gneiss, and the higher density part of amphibolite-rich Broken Hill Group) the inversion results do provide support for the model.

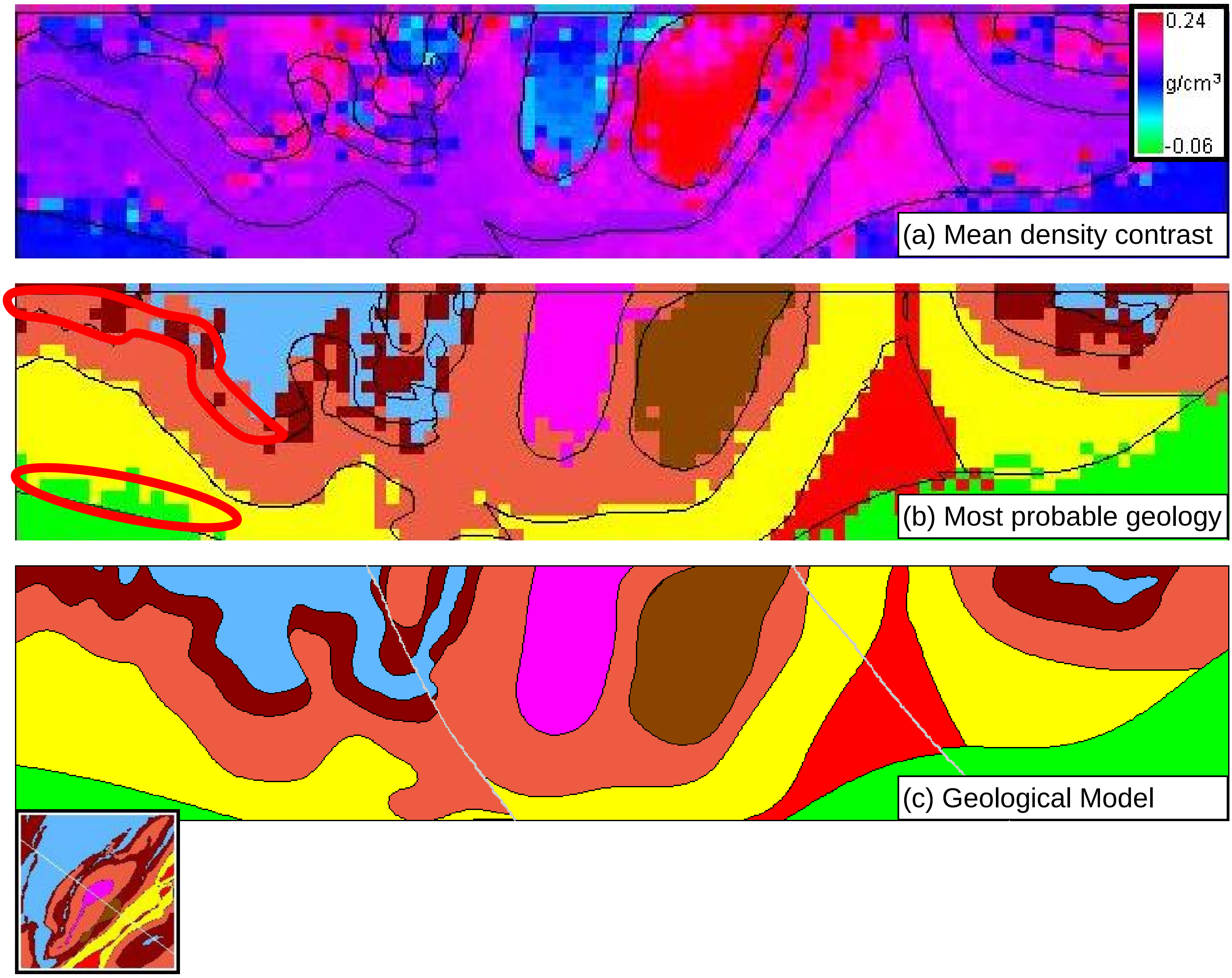


Figure 28. Plots of Section N7 showing inversion results for inversion Run 4 (See details in Table 4). The 'mean density contrast' (g/cm^3) is plotted in (a), and the 'most probable geology' in (b). The starting model geology is shown in (c), and also by the black lines in the other plots; the colours for the model geology are as per the legend in Figure 24. Inversion Run 4 used (σ=0.04), and 60 million iterations, resulting in 25 million saved models. The Thorndale (yellow) and Thackaringa (tan) units have lower density at the north-western end of the section compared to the south-eastern end. Note also that the boundary of the low-density Rift unit (green, 2.75 g/cm^3) is pushed upwards into the overlying Thorndale (yellow, 2.80 g/cm^3). Likewise the boundary of the Thackaringa unit (tan, 2.80 g/cm^3) is pushed upwards into the overlying Broken Hill (red-brown, 2.85 g/cm^3). All of these changes are driven by the inversion process seeking to modify the density distribution in such a manner that the overall density of the north-western end of the section is decreased relative to the south-eastern end. (Location of Section N7 shown in inset; Length: 24km; V/H=1).

One final comment about the 'mean density contrast' plots. Several plots show a band of relatively low mean density contrast along the geological contacts (e.g. Figure 28 a, above). This is presumably due to a bug in the software; it may be in the inversion processing (since 'frontier' voxels – on the geological contacts - are treated independently from 'internal' voxels), or it could be some problem in the computation of the 'mean density contrast' data, or rendering of the image.

6.3.2 Inversion Run with Standard Deviation 0.02

The fifth inversion run listed in Table 4 used a much lower value for the standard deviation for all stratigraphic units in the model ($\sigma = 0.02$ g/cm^3) … and the results were very different. For this run there were 25 million iterations, resulting in 20.79 million saved models (80% of iterations generated 'saved models').

The inversion feed-back (Figure 25 f) indicates that this was a 'good' inversion, very similar to the previous inversion runs. The results for Run 5 are plotted again as Figure 29. The 'most probable geology' plot (Figure 29 b) shows that the inversion results indicate a 'probable' model which is <u>*significantly different from the starting model*</u>.

This result would suggest that – <u>*if*</u> the density values are correct, and well known (with $\sigma = 0.02$ g/cm^3) – then *the starting model is <u>inconsistent</u> with the gravity data*.

It would be <u>*incorrect*</u> to state that the 'most probable model' as proposed by this inversion result is 'the correct model'. A basis of 3D-WEG software is that a priori data must be taken into account – and in this case – with the inversion results proposing radically different geological boundaries – there would be many parts of this proposed 'most probable' model that would not be consistent with parts of those a priori data.

Why is this inversion result so different from the previous results ? With $\sigma = 0.02$ g/cm^3, there is much less scope for 'extreme values' of density being assigned to voxels during the inversion process; the consequence is that the inversion is less able to reduce the misfit simply be modifying density values, and so there is a greater need for the inversion to 'change the geology and so propose a modified density value'. Thus geological boundaries are moved.

The plot of 'mean density contrast' for this inversion run (Figure 29 a) is interesting … and does seem to contain plausible information about the distribution of density. Note firstly that, with a more restricted value for the standard deviation, there are none of the 'extreme' low or high density voxels, but rather a smoother, more even distribution of density values. Note also …

- the high density zone (A, Figure 29 a). This coincides with the area of the Thorndale Gravity High. Although the geological boundary proposed by the 'most probable geology' (Figure 29 b) is inconsistent with geological mapping, it is clear that this distribution of density is quite compatible with the observation that a high concentration of amphibolites is mapped not only in the Broken Hill Group rocks in this area, <u>*but also in the adjacent Thackaringa Group and Thorndale Composite Gneiss rocks in this area*</u>. In other words, the inversion in this area has produced a quite credible 'distribution of density'.
- A similar effect occurs at B, Figure 29 a; the inversion has mapped out a zone of higher density in an attempt to be consistent with the gravity data; this was achieved by moving the boundaries of the higher density Broken Hill Group (Figure 29 b). Again, the geology is almost certainly incorrect, but the proposed distribution of density in this area may well be correct – and perhaps indicative of a locally increased concentration of amphibolite rocks in this area.
- The low-density zone of Alma Gneiss at C (Figure 29 a) does have a quite different 'boundary' compared to that mapped out in the starting model.
- The small, localised high-density zone at D (Figure 29 a) coincides with the Broken Hill line-of-lode. One could postulate that the three similar zones of localised high density at E might also be targets of potential commercial interest.

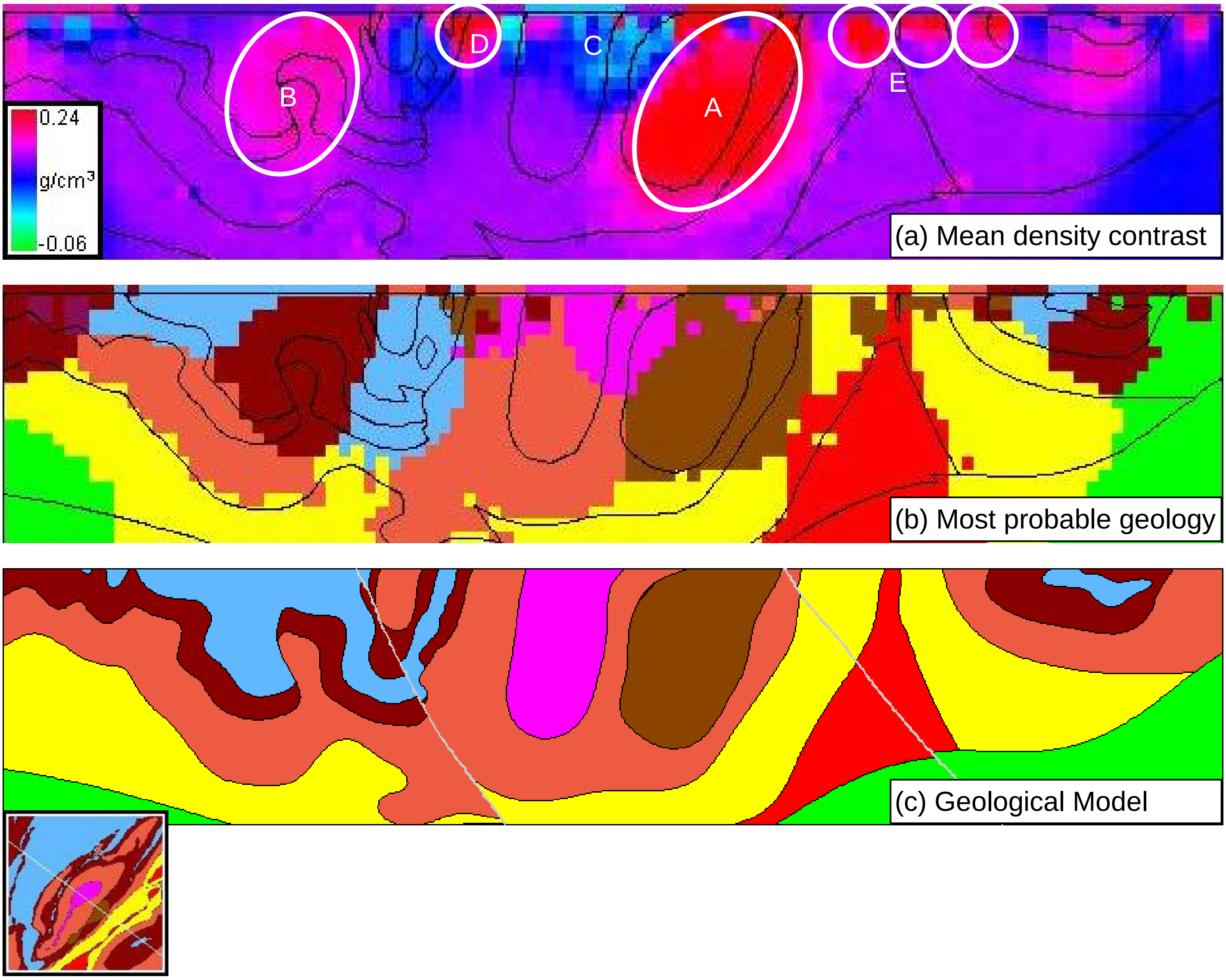


Figure 29. Plots of Section N7 showing inversion results for inversion Run 5 (See details in Table 4). The 'mean density contrast' (g/cm^3) is plotted in (a), and the 'most probable geology' in (b). The starting model geology is shown in (c), and also by the black lines in the other plots; the colours for the model geology are as per the legend in Figure 24. Inversion Run 5 used a lower value for the standard deviation (σ=0.02), and 25 million iterations, resulting in 20.79 million saved models. The 'most probable model' is very different from the starting model. The plot of 'mean density contrast' is quite similar to the 'most probable geology' plot (due to the low standard deviation value used). Because of the lower standard deviation value used in this inversion run, the inversion has been forced to move geological boundaries to a much greater extent in order to generate a distribution of density which is consistent with the measured gravity. (Location of Section N7 shown in inset; Length: 24km; V/H=1).

In summary, the inversion processing using a tighter standard deviation value ($\sigma = 0.02$ g/cm^3) does not 'support' the Broken Hill 3D Geological Model. This is almost certainly due to the fact that the model has grouped *rocks of __different__ density* into single units in the model; this inversion – with $\sigma = 0.02$ g/cm^3 - then restricts the range of densities that may be assigned to the voxels which contain those strata. The 'most probable geology' proposed by the inversion process is also incorrect, since it does not agree sufficiently with a priori geological observations. The distribution of density as shown in the 'mean density contrast' plots, however, does present a credible picture which could contribute to building a refined geological model. A model with a revised break-down of the geological units - attempting to define 'units' which contain more or less amphibolite, for example - would be more suitable for testing by inversion, since those revised geological units might be expected to have a more uniform density value.

7 Discussion: Broken Hill Geology Outcomes

Building the Broken Hill 3D Geological Model in 3D-WEG, and subsequent visualisation and review of the model, provided an opportunity to critically re-assess some of the assumptions (interpretations) in the geology, in terms of 3D geometry and continuity of the modeled units. As a result, there was some revision of stratigraphy, structure and geology within local areas.

7.1 Stratigraphy

The stratigraphy for the model was based on the GSNSW work (Figure 2). Assumptions made at commencement of the project - for example, that granitic gneisses and amphibolite were part of the stratigraphy - are now questionable. As a result, there are several places where interpretations in the earlier work may need to be revised (See expanded comments below).

The 'Rift' package is poorly constrained. The Rift is defined only from interpretation of the regional seismic section; there is an assumption that Rift is equivalent to the Redan sequence (Mulculca, Ednas Gneiss and Redan Gneiss), and that the Rift contains 'basement' (if it exists within the model volume). The Redan Gneiss is dated at 1700-1710 Ma, and is therefore approximately coeval with Thackaringa Group (Figure 2), although it is lithologically quite distinct.

In the south-east (Redan area), Clevedale Migmatite and Thorndale Gneiss are not present in their expected position - above the Mulculca Formation and below the Thackaringa Group. Instead, the Lady Brassey Formation is present as the lower unit of the Thackaringa Group, and is a time-equivalent to the Redan (Figure 2). The transition of Thorndale and Thackaringa southeastwards to a more proximal volcanic-dominated sequence does support the idea of a rift sequence.

7.2 Clevedale Migmatite

The Clevedale Migmatite crops out in the Darling Range. It occurs structurally beneath the Thorndale Composite Gneiss, and is distinguished from it by the proportion of quartzo-feldspathic melt. Migmatites occur sporadically through the high metamorphic grade rocks where the initial composition is felsic enough to melt; in some instances migmatites occur in the Thackaringa Group (K-Tank area) and Broken Hill Group (Nine Mile area).

In the model, Clevedale Migmatite is included as a stratigraphic unit, which outcrops in the Darling Range area, but is constrained to a thin layer away from the Darling Range. Upon review, it may have been preferable to treat the Clevedale Migmatite as a local intrusive (i.e. a local partial melt) rather than a stratigraphic unit. Reasons include …

- In principle, migmatites are just that – partial melts – and have no stratigraphic meaning;
- Migmatites are developed at a number of locations in the district (e.g. K Tank area) and are not ascribed to this sequence;
- In the Little Darling Creek area, the Clevedale appears to be discordant to bedding.

7.3 Line-of-Lode

The Line-of-Lode geology is well known in terms of gross geometry. The complexity and fine scale of interleaved ‘stratigraphy’ preclude detailed data entry and analysis in this (regional) model. An example is the thin but continuous sheet of granite gneiss in the footwall (south-east) of the lode that joins with the Rasp Ridge Gneiss as it is folded around the Broken Hill Synform (Figure 30). The thin, stretched fold limbs are too small to include at the scale of the model. The thin sheet of granite gneiss may be interpreted as a stratigraphic unit, or as an intrusive (sill), or as ‘pseudo-stratigraphy’ in a high-strain zone. The broad line-of-lode geometries indicate thinning and disappearance of major units towards the south-west, best explained by high-temperature shearing superimposed on a large-scale fold closure.

Some extremely attenuated units, such as the granite gneiss mentioned above, have not been modelled. Their absence from the model gives an appearance of discontinuity of these units, and misrepresents them in the visualisation of the model. The Sundown Group within the line-of-lode is an example of what - in plan and section - appears to be a relatively continuous but thin sheet within the high grade shear, but in the 3D-WEG model appears as a number of disjointed surfaces. Additional data points (cf. ***frequency*** of sampling, Section 4.4.3, Sampling Geology in 3D-WEG) would be needed to make the 3D-WEG model conform to the conceptual model of a folded sheet-like body.

7.4 High-temperature Shear Zone and Stratigraphy, Broken Hill Synform

The interpreted geology along the eastern side of the Broken Hill Synform is inconsistent with the structural data, and to some extent, the fact mapping. A significant thickness of the sequence (Rasp Ridge Gneiss and Cues Formation) and bedding trends are truncated along this contact (Figure 30); either an unmapped shear zone is present, or the folding is more complex than shown (a re-folded fold). The 3D-WEG model shows a different interpretation, honouring bedding trends.

Noble (2000) recognised a high-temperature (magnetite-biotite-sillimanite) shear zone, defined in the magnetics, and now known to extend from the eastern side of the synform around the Broken Hill Synform to the southern part of the line-of-lode. This shear zone is at the mapped contact between Alders Tank Formation (Thackaringa Group, ‘FSM’ lithology) and Cues Formation (Thackaringa Group, ‘SM’ lithology, amphibolite-rich). The Parnell Formation (part of the Broken Hill Group, amphibolite-rich ‘SM’ lithology) is remarkably similar to the Cues Formation.

The interpretation in the model is that Cues Formation (locally) is part of the Broken Hill Group, equivalent to the Parnell Formation. This implies that a refolded fold occurs within the Rasp Ridge Gneiss, with Broken Hill Group doubly folded around the Rasp Ridge Gneiss, contiguous with the Broken Hill Group folded around the northern nose of the Broken Hill Synform and interleaved and tightly to isoclinally folded Rasp Ridge and Broken Hill Group along the line-of-lode. An alternative explanation is that an unmapped (high grade?) shear zone truncates the sequence.

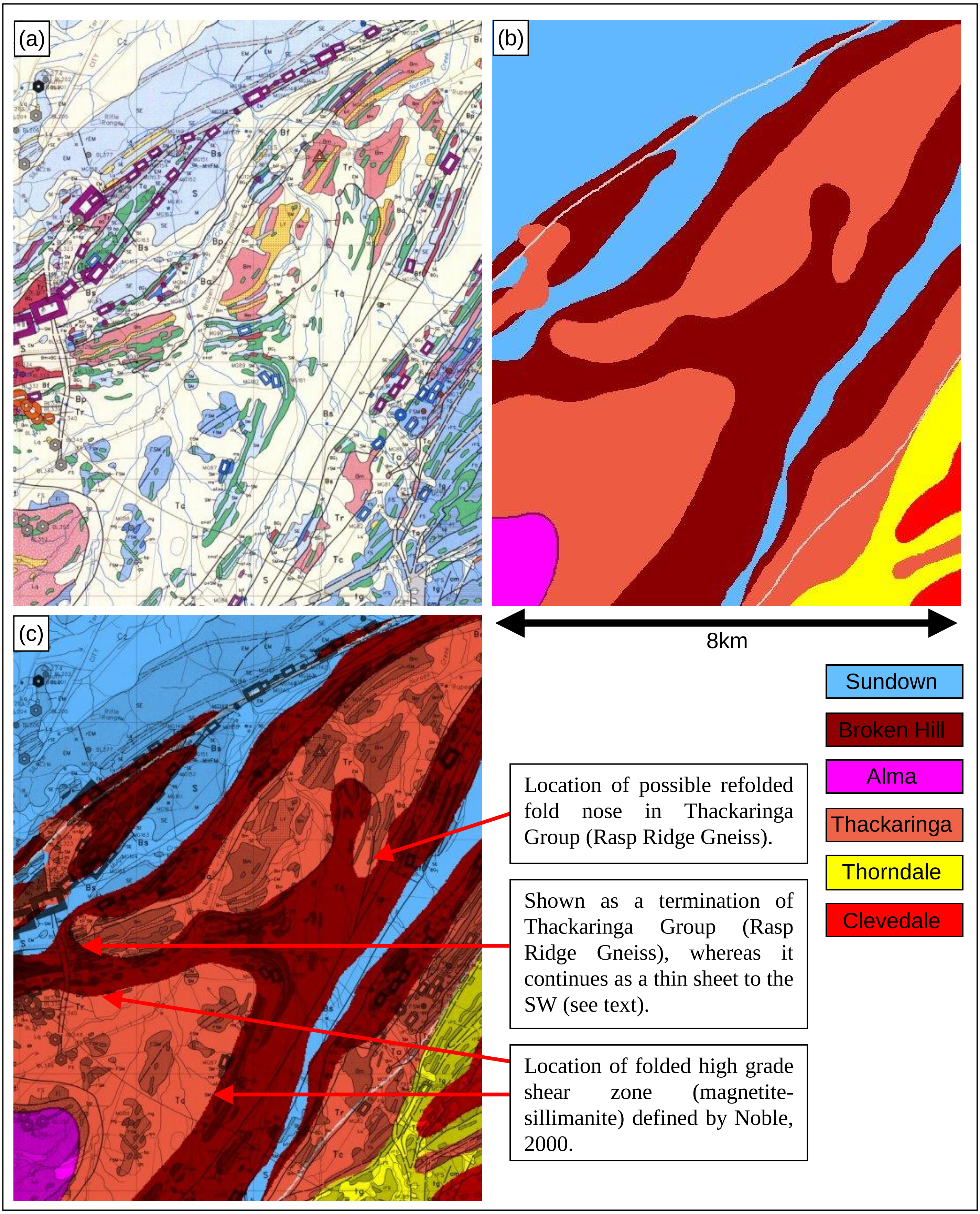


Figure 30. Geology of the Broken Hill Synform. Image (a) is geology from the GSNSW 1:50,000 interpretation (Bartholomaeus et al., 1995), and (b) is the geology rendered from the 3D-WEG model for the same area. Image (c) shows the revised interpretation of Thackaringa Group – Broken Hill Group contact, superimposed on the outline of 1:50,000 geology. All maps are for the same 8 x 10km area; Top left corner is 546000E, 6470000N (GDA94, MGA54).

7.5 Structure along the western edge of the Sundown Group

A number of thin, curvi-linear lenses of Broken Hill Group (with amphibolite and 'Potosi Gneiss') crop out amongst metasediments in the Nine Mile Creek area north-west of Broken Hill. Willis (1989) interprets the 'Freyers Metasediments' as part of Broken Hill Group within a grossly continuous, east-facing sequence. They are, however, lithologically indistinguishable from the Sundown Group.

An alternative solution, presented in the model (Figure 31), is that the lenses are *en echelon* tightly folded, possibly transposed crests of Broken Hill Group within the Sundown Group. This solution is structurally and geometrically feasible, and simplifies the stratigraphy, as the Freyers Metasediments become part of the Sundown Group.

7.6 The Thorndale Gneiss – Thackaringa Group Contact

Interpretation of the Thorndale-Thackaringa boundary appears to diverge from the mapped geology in some places, and differences between the groups seems at least partly based on presence of granite gneisses and quartz-albite rocks in the latter. The metasediments of these two groups are similar to each other, yet quite different to the overlying Broken Hill Group (see also discussion in Section 7.4). This can be shown in Figure 32.

7.7 Inversion

The outcomes from 3D-WEG inversion of gravity data is comprehensively analysed in Section 6.3, Inversion Results.

In general, the inversion results could be said to 'indicate that the gravity data are consistent with the Broken Hill 3D Geological Model' … but this claim is compromised by the reality that there is a ***high degree of uncertainty in our knowledge of the density values*** for the units used in the Broken Hill model. There are several problems related to density, and to the way in which this Broken Hill Geological Model was constructed …

- there are not many measurements of density - thus variability, uncertainty
- the ranges of densities for different units overlap so inversion results cannot be diagnostic
- the units in the model incorporate formations of differing density – thus further variability
- variable concentrations of pegmatites and amphibolites add to this variability, uncertainty
- some horizons with distinctive gravity signatures are not represented in the model

Some of the inversion runs do provide interesting results in terms of the probable distribution of density values, and these results could be used in building a revised model. In order to more effectively use gravity inversion, a revised model would need to be built – based on a revised stratigraphic break-down. That revision of stratigraphy would need to attempt to identify units within which there was some expectation of uniformity of density values. Given the overall complexity of Broken Hill geology, and the variability of concentrations of amphibolites and pegmatites, there would be practical difficulties in achieving this … but some attempt to address this would yield a model much more suited to inversion of gravity data than the rather coarse model built in this project.

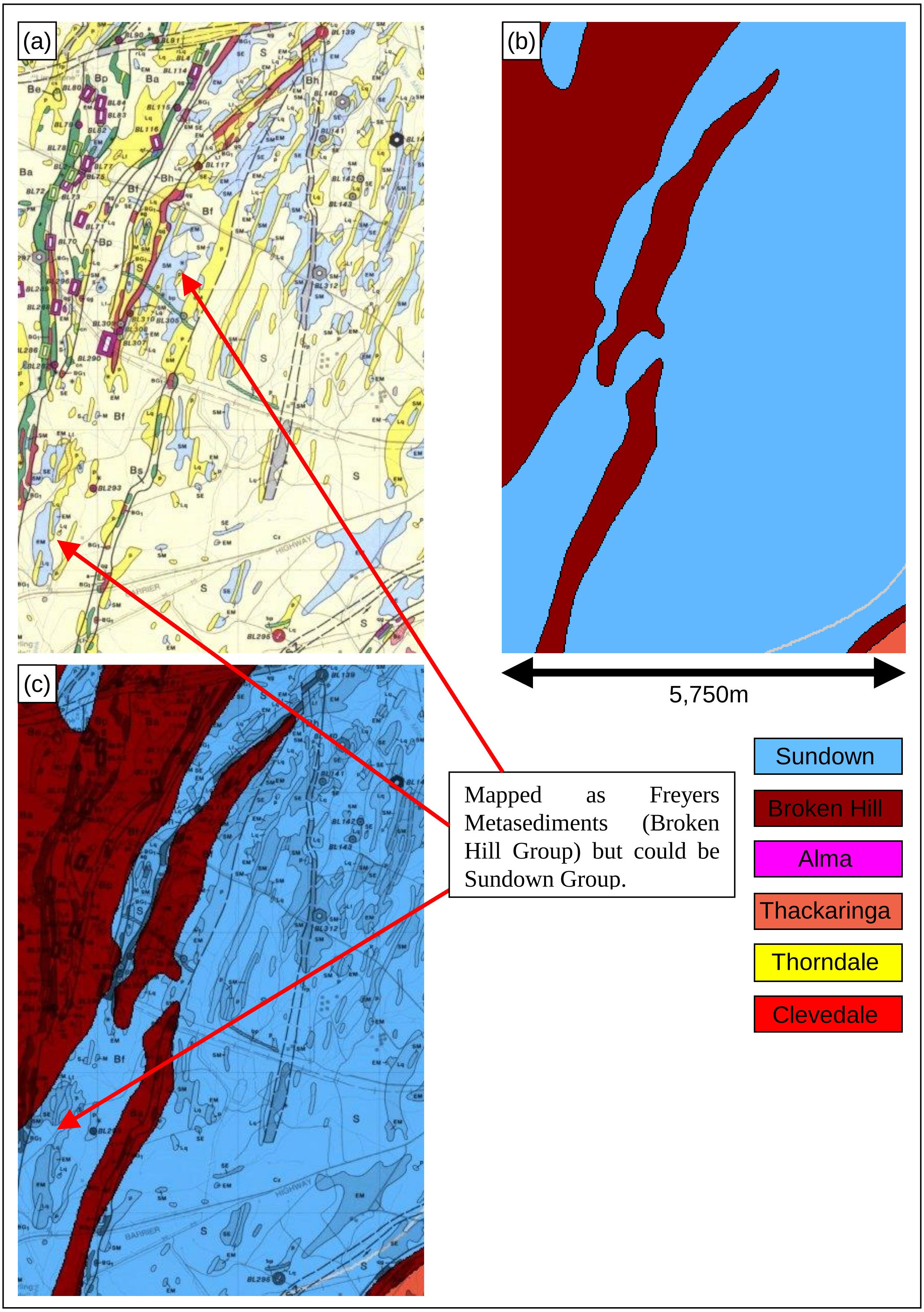


Figure 31. Geology of the western edge of the Sundown Group. Image (a) is geology from the GSNSW 1:50,000 interpretation (Bartholomaeus et al., 1995). Freyers Metasediments 'Bf' truncates against the Hores Gneiss 'Bh' at the top of the Broken Hill Group. Image (b) is the geology rendered from the 3D-WEG model for the same area. Image (c) shows the revised interpretation of the Broken Hill Group – Sundown Group contact, superimposed on outline of 1:50,000 geology. All maps are for the same 5.75 x 9km area; Top left corner is 535000E, 6470000N (GDA94, MGA54).

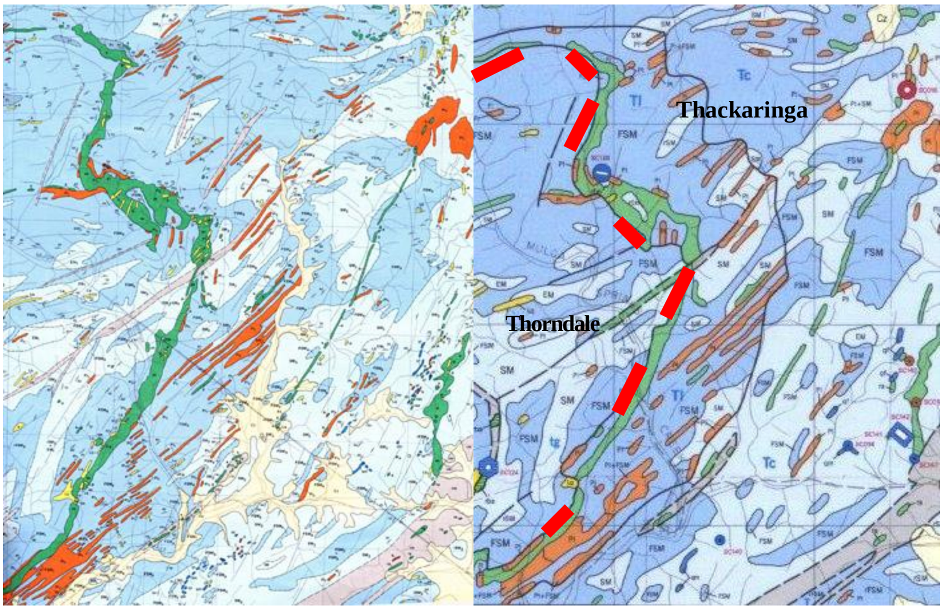


Figure 32. Geology of the Mulga Springs Creek area. Fact geology (left, from Stroud, 1989) against interpreted geology (right, from Bartholomaeus et al., 1995, after Willis, 1989). The interpreted Thorndale – Thackaringa boundary (red dashes) runs along the 'sea-horse' amphibolite, apparently at odds to the distribution of lithologies.

8 3D-WEG Performance

8.1 Strengths

There are three key aspects of 3D-WEG which make it revolutionary software in the practice of geological mapping and modelling.

Rebuilding the model from the geological observations

A major limitation of CAD-style 'models' of geology (wire-frame shapes and surfaces, etc.) is the difficulty of incorporating new observations, and so changing the model. A key goal at the outset of developing 3D-WEG was to create a tool that was used directly by geologists (rather than CAD experts), and which could easily incorporate new geological observations – and regenerate a revised model based on these new data.

The 3D-WEG software has achieved this goal with spectacular success.

In fact the success with which this has been achieved opens new doors for the overall management of geological observations by all organisations with an interest in the science of the structure of the earth. The traditional approach to geological mapping has been to record geology as hard-wired interpretations on maps and an occasional cross-section, accompanied by some explanatory notes. Even a GIS database is really an electronic copy of these hard-wired interpretative shapes.

Although drilling databases do document 'raw geological observations', traditional field mapping has generally not captured the raw data into a database; a few field observations of dips and strikes may be recorded – but the geology itself is typically left as an interpretative line on a map or in a GIS.

The advent of a software package that 'builds a model from the raw observations' introduces a paradigm shift. Suddenly the raw observations are worth capturing and managing in a fully attributed database … in the knowledge that those observations can be continually re-used – along with new observations – over a lifetime measured in years or decades.

Whilst the '3D-WEG software version 2004' may still have a way to go, the approach of the software in this regard is revolutionary, and will impact upon the earth science community's approach to recording and managing geological data observations.

Using 3D-WEG for geological interpretation – using geologist skills

A common complaint about the CAD-style of geological software is that a highly skilled CAD expert is needed to run the software – with the result that 'geology' is not 'done by a geologist'. Thus, a goal was to create an easy-to-use tool that was used *directly* by geologists.

In this goal also, the 3D-WEG software has excelled. Perhaps more importantly, however, the software goes beyond simply providing an easy-to-use environment in which a geologist can record observations and build a model. *The 3D-WEG environment is one in which a geologist can employ his/her interpretative skills*; in fact, it is likely that the software is used more effectively by a skilled geologist, with a highly developed interpretative understanding of the complexity of their project area. The 3D-WEG software allows the skilled geologist to use their understanding as a basis for developing an hypothesis – which is then easily incorporated into the model building process – and the hypothesis can be rapidly tested, reviewed and revised or rejected.

This interpretative cycle of using the software is discussed at length in Section 4.4.4 (The 3D-WEG *Input - Compute - Draw* Interpretation Process).

Inversion in 3D-WEG – integrating geology and geophysics

In addition to its 3D geological model-building ability, the 3D-WEG software also has a radical and innovative approach to inversion. One point to note about inversion in 3D-WEG is that it operates on a voxel-model, and ***each iteration makes an adjustment to just one voxel*** (selected at random).

Six features of 3D-WEG inversion are noteworthy …

- The universal problem with all interpretations of potential field data is that there are an infinity of solutions that 'match the data'. The universal solution is to reject those interpretations which are incompatible with ***a priori*** observations.

  Inversion in 3D-WEG is developed from the model-building process. Rather than being some alternative means of developing a model, inversion in 3D-WEG is dependent upon the 'starting model' that has been developed from the a priori geological observations. Thus, ***the use of a priori data is an integral part of inversion in 3D-WEG***. There is an underlying expectation that the 'model' must be a 'reasonable' model, and that the inversion process should explore that 'space of similar models' as a means of testing the validity of the model, and perhaps proposing refinements to the model.

  (The model cannot just be 'any old model'; there is no expectation that 3D-WEG inversion can simply start with any arbitrary model and magically invert towards the correct solution!).

- Conventional geophysical inversion software converts its starting model to a 'model of physical property' … for example, a model of density.

  In 3D-WEG the *inversion model remains a model of **geology***. The starting model (developed in 3D-WEG from a priori geological observations) is converted to a *geology* voxel model. Physical property values are assigned to each voxel on the basis of the 'physical property law for the geology of that voxel'. During inversion the geology of a voxel may change, or the physical property value of a voxel can be modified … but geology is retained throughout.

- A traditional approach to inversion is to iteratively adjust a model, each time measuring the error between observed and computed data. At some point when this error measure is acceptably small, iterations are stopped – and the process has yielded a ***single solution*** which is consistent with the observed field data.

  Whereas conventional inversion ***stops*** at this point (of 'acceptably low misfit error'), the 3D-WEG inversion effectively ***starts*** at this point, and continues to iterate, adjusting the model, and ***so explores that space of solutions that can explain the geophysical signature***.

- Because the inversion continues to iterate, it can locate millions of models - all of which are valid models (i.e. they can explain the geophysical signature). On the basis of these millions of models it is possible to report the inversion results in terms of probability (i.e. the ***probability that voxel 'v' has geological unit 'g'***). In this way, the inversion process is able to quantify the uncertainty of the inversion solutions.

- Joint inversions – of magnetic and gravity data – can be performed.

- Inversion in 3D-WEG is an effective means of integrating geophysical data (e.g. density and gravity) with geology … to work towards developing ***one model*** which is consistent with all of observations recorded in the independent datasets.

8.2 Limitations … and Recommendations

Only the more important issues (and recommendations) are itemised here. Some more general comments about the performance of the 3D-WEG software are noted in the following section.

1. Management of geological observations …

   - The need for additional attributes
   - The need to work with 'corporate databases'

   At the moment, geological contact points and orientation data are managed within the plan or section in which the point was input – and overall it must be said that the system works well! Creating observations, editing them, using them – all of these things work smoothly and intuitively … so why change this ?

   Two main reasons. Observations need to be more completely attributed, especially to make simple distinctions between 'hard facts' and 'hypothesis' data, for example.

   A second reason is that – in order for 3D-WEG to play a role in large organisations – it must work with the 'corporate databases'.

   Recommendation. As noted in Section 8.1 (Strengths), 3D-WEG has opened new doors as to how geological data might be utilised in many different ways over many years. Assuming that data are stored in a variety of industry standard databases, design work should be undertaken to define the protocols for linking between 3D-WEG and corporate databases, and adding revised dialogs in 3D-WEG to manage such database links.

2. Inversion Data Preparation

   A key part of inversion is the continual comparison between the 'computed model response' and the 'world measured signal' … but the preparation of the 'world measured signal' may perhaps be inadequate ? … resulting in the inversion needing to make adjustments when in fact the 'preparation' perhaps should have been more rigorous ?

   Recommendation. Review the 'preparation' procedures, and explore the possibility of using the first computed model response to apply automated de-trending and zero-level adjustment to the 'world measured signal'.

3. Inversion Control – Topological Issues

   The topological controls in 3D-WEG inversion were further modified during the course of the Broken Hill project. These (topological) controls have a significant impact on the outcomes from inversion – since they control the extent to which the boundaries of a model shape can change; a shape can be forced to remain more or less intact, or can be more free to change its boundaries. These controls are currently fixed in the code at compile-time.

   Recommendation. Bring the topological controls into the user dialog interface to allow user experimentation with these additional factors.

4. Inversion Control – Fixed Voxels

   At the moment 3D-WEG inversion does not make any changes to the top layer of voxels, on the basis that these are known from mapping. All other voxels are free to be modified (subject to maintaining topological integrity). There is a need for alternative strategies – available by user selection – to control which voxels can or cannot be adjusted during inversion.

   Recommendation. Implement a range of controls that will determine if the geology of a given voxel may be changed during inversion. Options could include …

   - Top voxels fixed
   - Voxels that contain a ‘fact’-attribute observation remain fixed
   - As above, but also select by section (e.g. only topo-z, and drill-hole observations)
   - Frontier voxels on a selected fault remain fixed (e.g. a well known fault is ‘fixed’)

8.3 General Performance Issues

The software used in the Broken Hill project was the ***research*** version of the 3D-WEG, the software is in ***continual development***, and it is ***not*** a commercially finished product … so there are a spectrum of small finishing issues that could be commented on. Most of these are minor, are known issues (i.e. known by the developers), and so are not itemised here.

A general comment that can be made is that – despite being non-commercial, research software, still in continual development – the software has a finish, intuitiveness and robustness that would be envied by many developmental products.

1. Robustness. The software crashes – occasionally. This is not unexpected for research software, and in general the robustness of the software was ***not*** an issue during the course of the project.
2. Intuitiveness (in the Interface). The software has an acceptable level of intuitiveness. There are – as in any software package – 'things-that-you-need-to-know' in order to use the software efficiently. In general intuitiveness in the interface was ***not*** a problem.
3. Geologist-friendly ? YES. Despite the fact that there are some quite radical aspects to 3D-WEG (see point 4 below) … 3D-WEG is never-the-less strongly oriented toward use by geologists. The underlying design of the software – with an emphasis on those things that are familiar to any practicing field geologist, such as a *stratigraphic column*, *map views* and *sections* – means that any geologist would quickly feel familiar using the software. On this point, the following are worth noting …
   - The model – once computed – always generates maps and sections that are consistent between themselves. A new section can easily be created through the model, to assist a geologist's visualisation of the model … and this new section will always be consistent with all other sections through the model.
   - Generating a new section-view through the model is easy. This new section may be used for input of new observations … so a geologist can readily 'propose some alternative hypothesis' … and input the hypothetical observations which define this hypothesis – regenerate the model quickly – and the review the modelled results derived from this alternative (hypothetical) dataset.
   - Equally – the data from such an hypothesis can easily be excluded, allowing the original model to be regenerated.
   - Despite the fact that there will be ***speed-of-computation*** issues as the model becomes more complex, there are several tricks available to the user to improve the speed of computation and review; for example, the model might be tested by modelling data from only one section through the model, rather than all data; modelling might be tested by temporarily excluding some strata, or excluding the effects of faults; it is possible to quickly render the model results for part only of a section-view, rather than having to render the model for the entire section, etc.
4. Sampling of Geology, and 3D-WEG's Interpolation. This is an area where users do need to develop an understanding of how 3D-WEG has been designed. The use of the 'potential field theory' is a radically new idea … and it does take some time to become familiar with how the definition of geological interfaces, and associated structural data – defined within 3D space - will be modelled by the software.

5. Speed of Computation. For simple models, the speed of computation is measured in terms of seconds through to tens of seconds. The ***rendering*** of a map-view or section-view of the model takes longer, however … but is still satisfactory for simple models. Note, however, that …

   - Speed-of-computation has been a problem for the Broken Hill project; the complexity of the geology demanded that many points are needed to define the geology.
   - The inclusion of faults (see point 6 below) also seems to slow the speed of computation for rendering views.
   - As previously noted, however, there are several short-cuts available to the user which allow the user to quickly test intermediate results by modelling only parts of the data, or rendering only partial views of a map or section, etc.
   - Rendering is partly scale-dependent, so that a complex area with many data points will be poorly rendered in comparison with a larger, simpler area. This can be overcome by zooming in to the complex area and rendering locally.

6. Faults – and Networks of Faults. The implementation of 'networks of faults' was delivered during the project – allowing faults to be defined as *stopping on* other specified faults. This now works well. There are still occasional problems in rendering geological strata close to faults; a likely bug in the software. Also there is a tedious need for every geological unit to be defined by at least one point on every side of every fault. Faults cannot terminate (as they do in nature).

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