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An example from the Paterson Orogen

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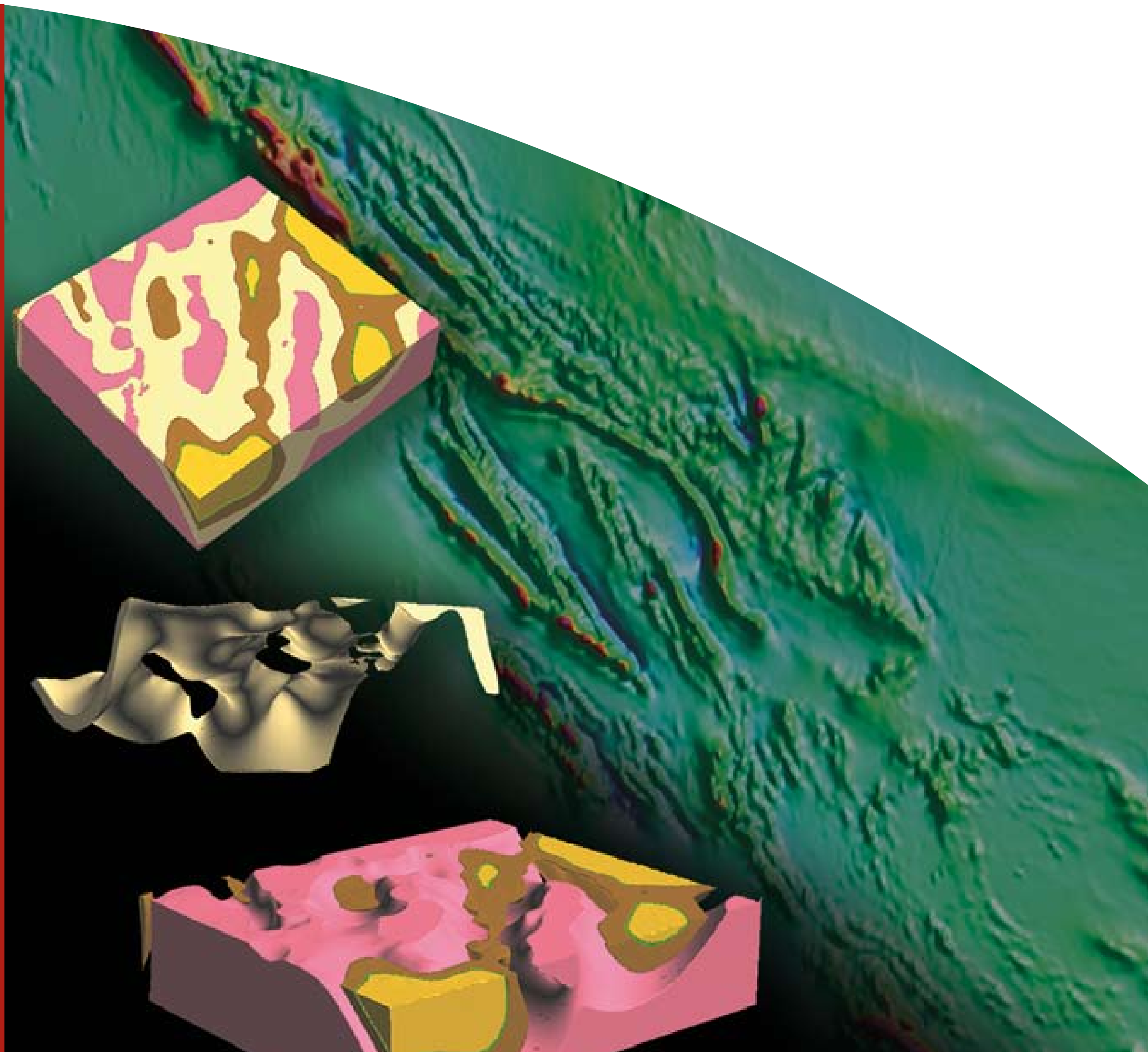

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by

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Contents

1. Introduction

The Paterson NGA project is using a number of tools to better understand the time-space evolution of the northwest Paterson Orogen in Western Australia. One of these tools, 3D GeoModeller, is an emerging technology that constructs three-dimensional (3D) volumetric models based on a range of geological information. The Paterson project is using 3D GeoModeller to build geologically-constrained 3D models for the northwest Paterson Orogen. This report documents the model building capability and benefits of 3D GeoModeller and highlights some of the geological insights gained from the model building exercise. The principal benefit of 3D GeoModeller is that it provides geoscientists with a rapid tool for testing multiple working hypotheses.

The Cottesloe Syncline district (Figure 1) was selected as the focus for a trial of the 3D GeoModeller software. The 3D model was built by members of the Paterson Project, as well as model building specialists within Geoscience Australia (GA). The resultant Cottesloe Syncline model, including two dimensional maps and images, was exported from 3D GeoModeller and transformed into a Virtual Reality Modelling Language (VRML), enabling a wide audience to view the model using readily available software. The VRML model requires the free Blaxxun Contact 5 plug-in to be downloaded and installed.

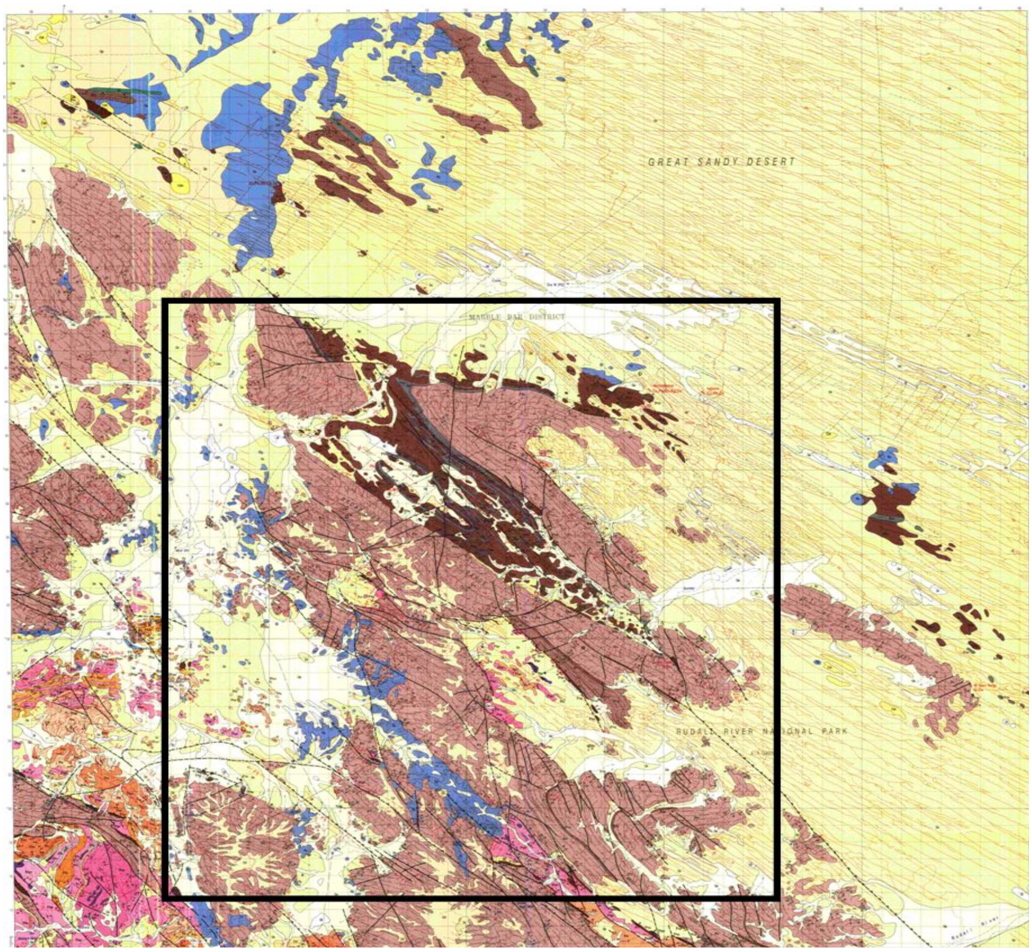

Figure 1: *Scanned image of the Broadhurst 1:100 000 geological map sheet (Bagas, 2004). The black outline shows the 3D model area (30 × 35 km). Rudall Complex - pink: Coolbro Sandstone - tan: Broadhurst Formation - brown: Paterson Formation - blue.*

2. 3D GeoModeller introduction

3D GeoModeller is a software tool for constructing 3D geological models. Geological boundaries within the models are defined by implicit mathematical functions that take into account the lithological contacts and orientation measurements supplied by the user. An integrated feature of the program is the ability to test and modify these models using potential field (magnetic and gravity) inversion once physical properties have been assigned to geological units.

3D GeoModeller (previously called 3DWEG) was originally developed by Bureau de recherches géologiques et minières, France (BGRM) as part of GeoFrance 3D. Geoscience Australia is a member of a consortium that includes Intrepid Geophysics, BRGM, all of the Australian State and Territory geoscience agencies, CSIRO, as well as other overseas government and commercial organisations. The purpose of the consortium is to foster development of 3D GeoModeller into a robust and versatile software package. Intrepid Geophysics is commercialising the software, and version 1.0 was released in late 2005.

3. Construction of 3D models

3D GeoModeller constructs models based on geological principles, geological observations and inferred information. The models are based on the following information:

- A stratigraphic pile with the geological units related by conformable, onlapping or erosional contacts.
- Geological contact point.
- Geological orientation data (i.e., strike and dip measurements).
- Faults.

The geological observations can be input in map view, section view, as drillhole information or as completely general 3D points. Following computation of the mathematical functions that define the boundaries of units within a 3D model, the results can be rendered and viewed in 2D as maps and sections or as a 3D model in 3D GeoModeller. Shapes (triangulated surfaces) can be built for each geological unit and exported in GoCad T-Surf format allowing for the import and visualisation in 3D packages such as GoCad and FracSIS. VRML files can be generated for visualisation in a web-browser. Voxel mesh (voxets) versions of the 3D geology model can also be created for visualisation or as an input to geologically constrained gravity and magnetic inversion or other volumetric application.

4. The Cottesloe Syncline 3D model construction and results

The Cottesloe Syncline model covers a 30 km x 35 km region in the Broadhurst 1:100 000 geological map sheet (Figure 1). The model area was selected based on the large proportion of outcrop with bedding orientations available at many locations. The geology of the region consists of Paleo- and Mesoproterozoic basement rocks of the Rudall Complex overlain unconformably by the Coolbro Sandstone and Broadhurst Formation of the Neoproterozoic Throssell Range Group (Bagas, 2004). The region has been affected by the Miles Orogeny at about 650 Ma (Durocher et al., 2003), which folded the sequence into a series of doubly-plunging, upright, northwest-trending synclines and anticlines with the cores of the anticlines exposing the multiply deformed Rudall Complex. Numerous, small displacement, north- to northwest-trending faults cross-cut the geology but the trend of the folds are not significantly disturbed. Unconformably overlying the Proterozoic units is the undeformed Permian Paterson Formation which infills a glacial paleotopography. Approximately one third of the area is obscured by Cainozoic sediments. This geological history was used to define the stratigraphic pile required to generate the 3D GeoModeller model. Figure 2 shows the interpreted relationships between stratigraphic units in the form of a schematic diagram and stratigraphic section. With the intention to better resolve structures within the model, the Broadhurst Formation was subdivided into three units, termed Broadhurst 1 through to Broadhurst 3. This subdivision is supported by outcrop within the Cottesloe Syncline but is absent in other regions of the map. This is either due to outcrop limitations in other areas or the units are laterally discontinuous.

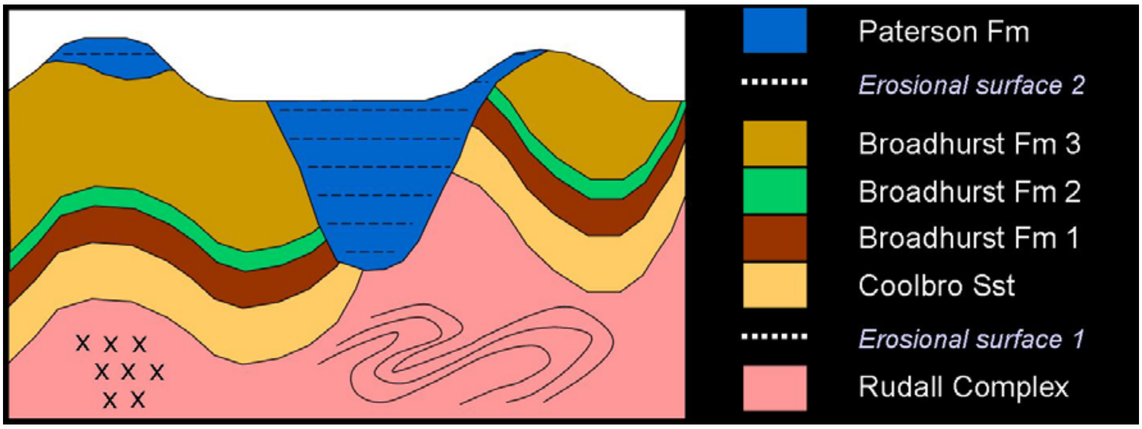

Figure 2: *Shows the interpreted relationships between stratigraphic units in the form of a schematic diagram and stratigraphic section.*

3D GeoModeller provides the ability to generate multiple models with a structured increase in the level of interpretative input. One of the principal intentions of constructing a 3D model of the Cottesloe Syncline area was to determine the capability of the software and the density of data needed to construct a model while maintaining scientific rigor. Therefore, two models were produced, the first model only utilising "observations" (e.g., lithological contacts, structural data) from the Broadhurst 1:100 000 map sheet, and the other based on an interpreted solid geology of the area produced by the project team (Figure 3). In the first model, only regions of direct juxtaposition of different stratigraphic units on the surface geology map were used. In contrast, all lithological contacts were accounted for in the latter model. This two-stage process in model building provides a progression from outcrop-only observations to greater levels of interpretation, with the outcrop-only model providing a "base" if the interpreted observations require later modifications. In both models, in areas on the map sheet where there were multiple close-spaced measured strikes and dips, representative measurements were used to level the frequency of data. The two resultant 3D models are shown in Figure 4 and consist of:

1. Outcrop Only (OO in VRML). Outcrop observations only.
2. Solid Geology (SG in VRML). Outcrop observations and solid geology interpretation included.

Problems were encountered in mapping the extent of the Paterson Formation, a relatively flat-lying unit that onlaps an erosional surface that in turn dissects the Proterozoic Throssell Range sedimentary rocks and underlying basement units. The available orientation information (undeformed flat-lying strata) for the Paterson Formation does not relate to the geometry of the erosional surface, and hence, cannot be used to infer the geometry of the base of the Paterson Formation. At the time the model was constructed it was not possible to include a zero thickness, non-depositional unit such as the erosion surface separating the Paterson Formation from the older units. As a consequence, the Paterson Formation in the VRML model is only shown for the outcrop-only model (OO in VRML) and a comparison of the model to the map shows that the model extent bears no relation to the mapped extent. Erosion surfaces are now able to be incorporated in 3D

GeoModeller, and hence, it is likely that incorporation of the Paterson Formation into the model would be far more successful if the exercise was repeated.

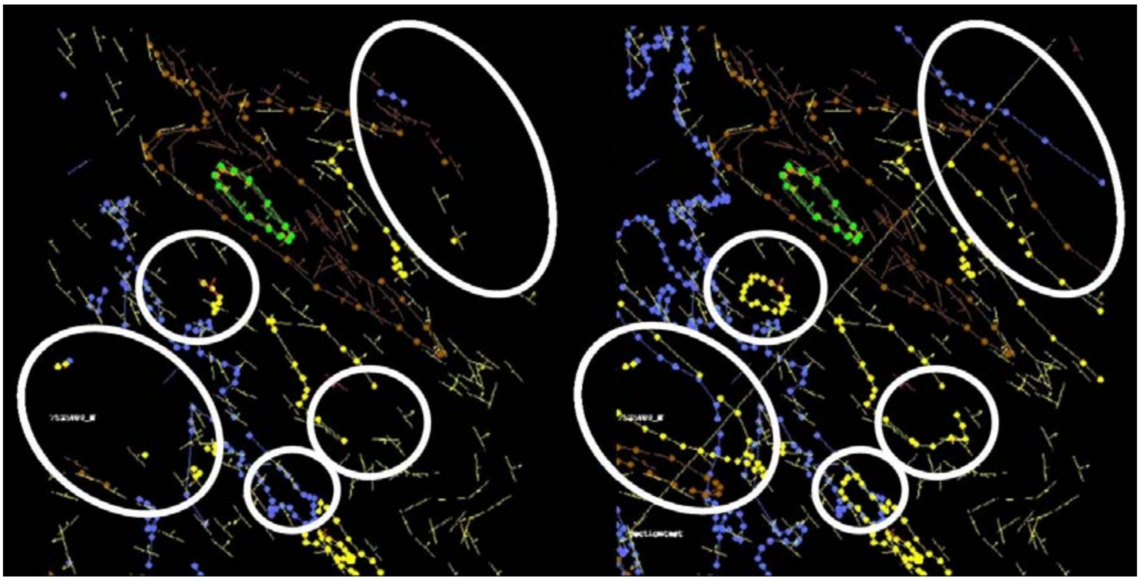

Figure 3: *Two snap-shots of the geological observations in the 3D GeoModeller interface. The one on the left shows the geological observations from the outcrop only model, while the one on the right shows the outcrop only observations as well as the additional observations from the solid geology interpretation. Points represent the geological contacts, while the structural markers represent the internal geological orientation data (dips and strike of strata). The white circles show regions where additional pre-Paterson Formation geological contacts were added. Note: 3D GeoModeller displays a thin line between geological contacts that are digitised as a string. These "construction" lines have no effect on the model (i.e., the boundary construction algorithm treats each geological contact as an independent observation).*

A comparison of the outcrop-only model with the solid geology model (Figure 4) shows a number of differences. The addition of interpretive boundary points had a very clear impact and resulted in a model with a closer match to the mapped outcrop. A comparison of the outcrop geology with the solid geology model (Figure 5), however, shows regions within the solid geology model where the lithology differs from the mapped outcrop. There are three possible reasons for the discrepancies. The first reason is the way 3D GeoModeller deals with the internal (dip and strike of bedding) observations. Examinations of the top surface of the models show that where a boundary observation was specified a unit boundary occurs. The program is, therefore, honouring all boundary observations. The internal observations, however, do not define the position of a unit boundary; they provide information on the space between boundaries. 3D GeoModeller, unfortunately, is unable to directly utilise these observations. The program can utilise measurements of the dip and strike of strata at internal locations, but cannot associate that dip and strike with the actual lithology. The knowledge implied by mapping away from unit boundaries can only be included by adding hypothetical boundary and structural points such that the outcome is seen to be consistent with the internal observations. The second reason for discrepancies between the model and the outcrop geology is that the quality of any mathematical interpolation method will naturally decrease towards the margins of the available data. These edge effects can be reduced by providing observations for the core region of interest within a larger region that provides sufficient "padding". This padding can be discarded later to leave the core of the model. The third reason for the discrepancies relates to our understanding of the geology and *a priori* geological assumptions discussed below.

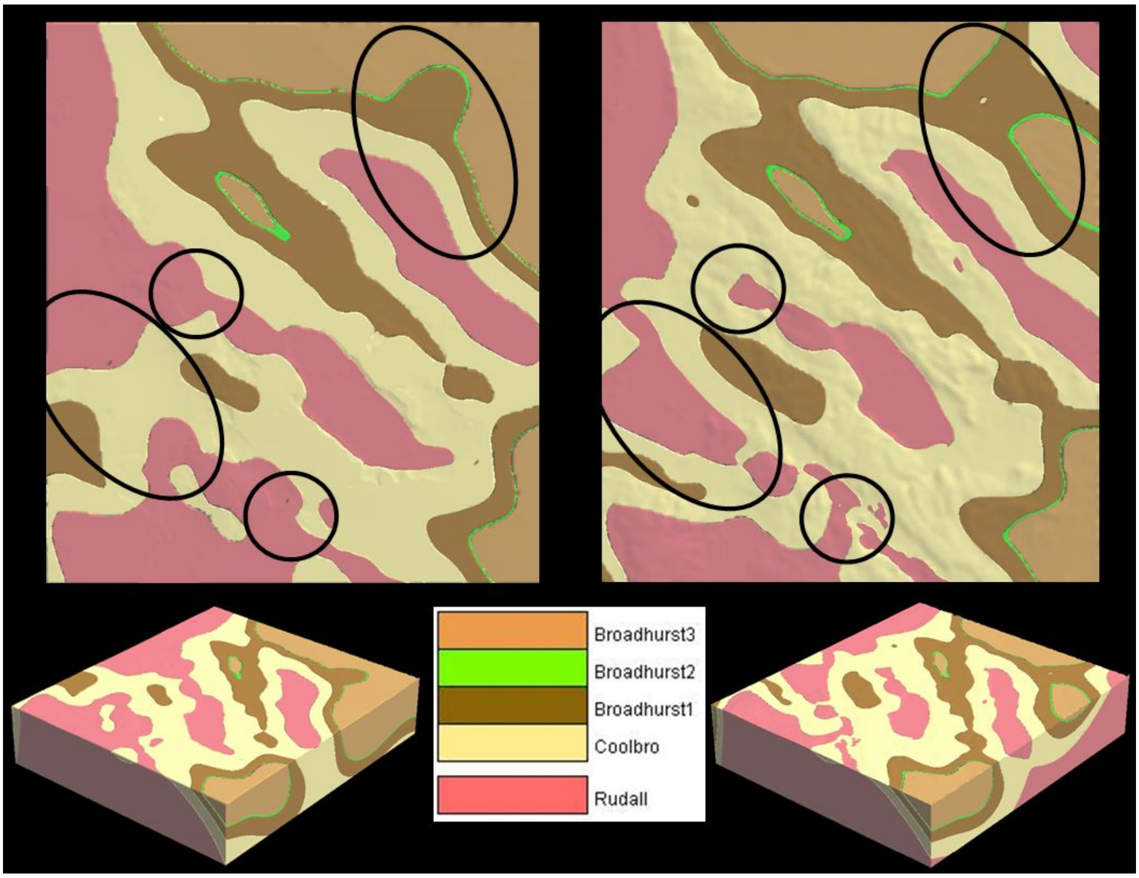

Figure 4: *Plan and perspective views of the outcrop only model on the left and the solid geology model on the right. The black circles highlight regions on the surface of the model that are different.*

In order to improve the 3D model, additional iterations involving input of more "hypothetical" boundaries and structural data on both vertical sections and the topographic surface could be undertaken to construct a 3D map that reproduced all aspects of the outcrop geology. Whilst it would be possible to impose a desired interpretative structural style, for example, on the resultant 3D map, it is important to question if the added effort will result in any new significant geological insight into a region. The results of the solid geology model indicate that in areas of fairly good outcrop, surface observations coupled with a modest input from an interpreted solid geology map are sufficient to produce a reasonable geological model. In applying this technique to undercover regions, however, far more interpretive information would need to be entered into the model due to the lack of direct observations. It is observed that construction of 3D models using cross-sections is significantly faster using 3D GeoModeller than with other 3D model-building methods used at Geoscience Australia . This allows for the construction of multiple 3D models based on multiple interpretations of the geology and consequently a better focus on geological rather than model-building issues.

The Cottesloe Syncline models described here were constructed using a developmental version of 3D GeoModeller (mid-2005). The functionality available at this time was restricted and it was not possible to test the geological models using potential field data. A second phase of model construction with a current version of the software would likely enable refinement of model 2 using the recently acquired 400 m line spacing aeromagnetic data and the 2 km spaced regional gravity observations.

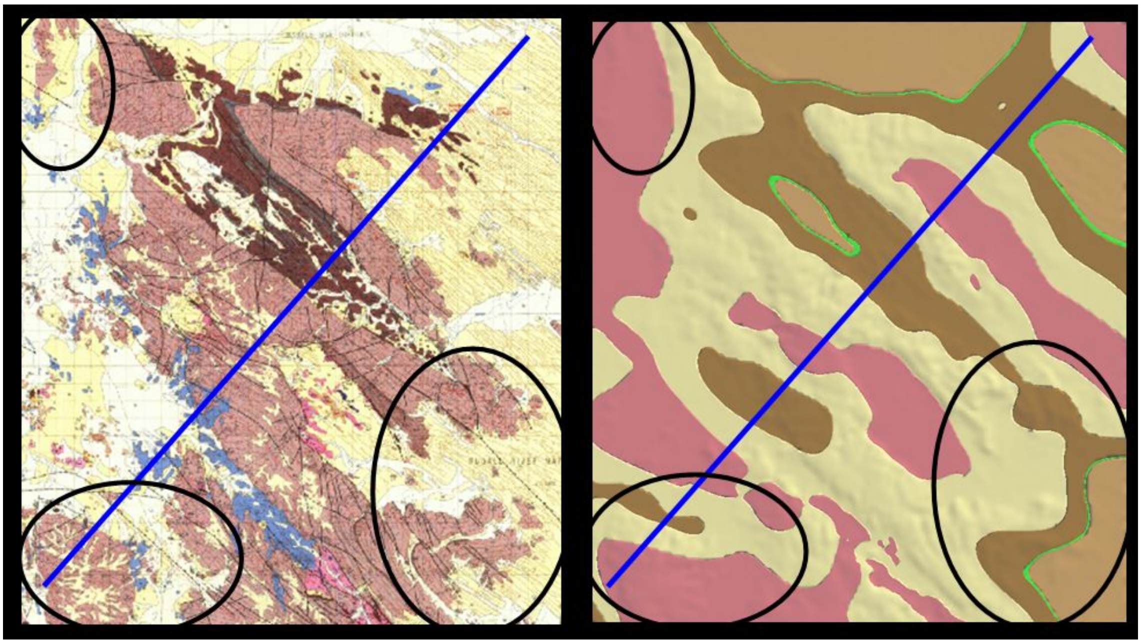

***Figure 5:** Comparison of the outcrop only model with the mapped outcrop. The black circles highlight regions at the surface of the model where the lithology differs from the mapped outcrop. The blue line shows the location of the cross-section in Figure 6.*

5. Geological insights gained from 3D model construction

Through the process of 3D model building a number of new geological insights were gained. Firstly, the exercise was carried out without incorporating any faults into the model. This approach tested the hypothesis that the majority of the architecture on the Broadhurst 1:100 000 map sheet, is the result of continuous folding of the Neoproterozoic units with only a minor contribution from regional faulting. The central parts of the solid geology model indicate that this hypothesis is valid. There are, however, inconsistencies between the outcrop geology and the modelled geology towards the edges of the model (Figure 5). All but the south-eastern corner can be attributed to edge effects due to the model not taking into consideration the lithology and structure outside the model boundary. In the south-eastern corner of the model, however, there is a significant difference between the mapped geology and the model results, which cannot be attributed to edge effects alone. This indicates that there is a gap in our geological understanding of that part of the map sheet. The difference between the model and the observed outcrop map pattern can be attributed to one of two reasons:

1. The available structural information is not of sufficient sample density to replicate tighter folding in this region in our model; or,
2. The outcrop geology cannot be explained by folding alone and it must be inferred that the area is affected by significant faulting.

Taking into consideration the scale of the Broadhurst map sheet and the thickness of the Coolbro Sandstone, the second reason is more likely. Hence, the modelling process has highlighted a region on the Broadhurst map sheet which may be significantly affected by faulting and thereby, in part, falsifying the initial hypothesis.

The 3D model has quickly produced 3D surfaces which honour the lithological and structural data and hence can be used to:

- Estimate the depth to geological units of interest.
- Show that the large scale structural vergence direction in the area is towards the southwest (Figure 6) i.e. in the southwestern corner of the model, one of the anticlines is overturned while in the rest of the model area, the southwest limbs of the anticlines are steepened. The presence of this vergence trend has been verified in the field.
- Communicate the doubly plunging nature of the folds far more effectively than a series of two dimensional cross-sections or plan map views.

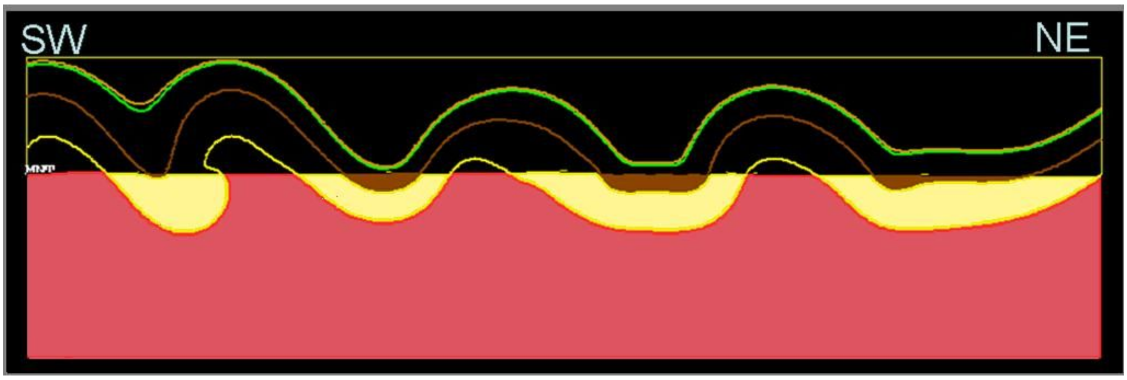

Figure 6: *Cross-section through the model area from the southwest to the northeast (see Figure 5 for location) showing fold vergence towards the southwest.*

6. A critique of the capabilities of 3D GeoModeller

The process of 3D model building using 3D GeoModeller differs from that which depends on more traditional engineering computer-aided drawing (CAD)-type software packages. In these packages, a series of 3D surfaces representing geological features are manually constructed from two dimensional cross-sections to define the 3D model. This process is very time consuming and when a modeller's ideas change, the resultant model is often difficult to alter to show the new direction in thought. In the same situation, a new model can be constructed using 3D GeoModeller every time a new piece of data is collected or hypothesised. Furthermore, 3D GeoModeller builds closed volumes for geological units whose boundaries exactly match their neighbouring units - there are no holes, or mismatches, such as are common with CAD-type software. In addition, 3D GeoModeller correctly identifies the point observations as the primary data. Such construction of models is necessary if they are to be tested through inversion of gravity and magnetic data. Through its design, 3D GeoModeller provides a more rigorous audit trail of observations and assumptions, and creates models that can be exactly reproduced given the same set of inputs. In particular, the trail forces assumptions to be addressed as questions, which exposes supported and unsupported geological interpretations.

A significant benefit of the 3D GeoModeller design is it should promote better integration of geology and geophysics, particularly geophysical inversion of geological models. Traditionally, cross-sections are generated based on geological knowledge and imported into a potential field modelling package. After changes are made, the resultant sections are exported from the potential field modelling package and imported into the geology modelling package. A revised 3D model is then painstakingly re-constructed. The time and effort involved is a significant disincentive for this approach. It remains untested whether 3D GeoModeller can realise the promise of its design.

3D GeoModeller is well suited to the task of constructing 3D models in areas of good outcrop where lithological unit boundaries and structural trends can be mapped and measured. In covered regions where such information is scarce, 3D GeoModeller can be used to construct multiple 3D models based on different interpretations of the geology at depth. The capacity to rapidly generate 3D models using 3D GeoModeller is particularly valuable in these circumstances of increased uncertainty. Several models reflecting different interpretations can be built and the implications examined.

Whilst there are many advantages, there are still issues that need to be addressed. The software performs well on continuously folded sequences with limited faulting such as the Neoproterozoic sedimentary rocks of the northwest Paterson Orogen. The current version of 3D GeoModeller, however, is not well suited to modelling terrains with multiple finite-extent faults. This poses difficulties for modelling shear zone dominated regions such as the Yilgarn Craton.

In summary, the speed and efficiency of constructing geologically-constrained 3D models using 3D GeoModeller indicates that it is an effective tool for investigating multiple hypotheses in fold-dominated geological regions with only simple faulting. With further development, the program may extend to modelling more complex regions and to testing the models through inversion of gravity and magnetic data.

7. Acknowledgements

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