Mincor Georgina Basin Zn Modelling Project
Stage 2 Report: Generic Numerical Models for the
Georgina Basin – Structural Controls on Deformation
and Fluid Flow during compressional inversion

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Mincor Resources NL CONFIDENTIAL REPORT
Mincor Georgina Basin Zn Modelling Project

Stage-2 report: Generic Numerical Models for the Georgina Basin - Structural Controls on Deformation and Fluid Flow during compressional inversion

Confidential report for Mincor Resources NL

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Minerals Down Under Flagship

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Preface

This report is the print-out (reformatted) copy of the TWiki pages for the Generic Numerical Modelling Work, which is part of stage-2 work under the Mincor Georgina Basin Zn modelling project.

An executive summary is supplied to summarize the key predictions from the generic numerical modelling and the application of numerical modelling results to exploration targeting in the Georgina Basin is summarized in an exploration targeting section. The details of the results from these simulated stratigraphic and structural scenarios are covered by the respective TWiki pages (hardcopy print-out and html files are included on the attached DVD); TWiki (pages) is an efficient web-based project development, progress and reporting tool.

Note that the several important parts of the Mincor stage 2 works are not covered in this hardcopy report, due to their heavily data-oriented/electronic nature or collaborative effort. However, the data and outcomes of these works are reported by the TWiki pages (html files, images and attachments) on the DVD attached to this report. These work contents include:

- Geophysical Data and Worm Analysis (also see reports by Barry Murphy)
- 3D Geological model construction (assembling of data and interpretation in Gocad)
- New drill core data/sample collection and field visit
- Sample and thin section preparation and analyses

Please view these TWiki pages (as updated in April 2009) and follow the links.
Executive Summary

The stage 2 numerical modelling works are limited to generic models of simplified basin fault and stratigraphic architecture. The design and construction of a series of scenario models are based structural and stratigraphic data for the region, and also incorporated the ideas and advices from Bruce Groenewald and Richard Hatfield (Mincor Resources) and Barry Murphy (Fractore Pty Ltd).

The focus of the current modelling effort is on the structural and stratigraphic controls on fluid flow under an orogenic, convergent basin-inversion setting. The most important predictions of the models are:

- The fluid flow field purely resulting from the stratigraphic sequence of the model (i.e. assuming no faults and no deformation) would be dominated by slow upward fluid flow, driven by initial fluid pressure higher than hydrostatic gradients. Flow rates are very slow in the horizons below the hot shale (seal).

- The involvement of fault led to much greater fluid flow rates, several hundred times higher than the non-fault scenarios. However, without deformation, fluid flow field is dominated by upward fluid discharge along the faults and hence weak involvement of fluids in host rocks.

- The presence of the seal (fine grains Arthur Creek limestone and hot shale at its base) is important for preserving regional fluid pore pressure gradients and for focusing fluids into faults (fluid conduits) through the seal. This is important for generating higher flux/pore pressure perturbations in the Arrinthrunga unit near the faults (the fluid releasing “window” above the seal).

- Orogenic compressional deformation in the Georgina basin is the key reason for damage in host rocks, enhanced fluid flow into host rocks and more complex fluid flow patterns in faults (e.g. some down flow in addition to dominant upflow).

- Presence of pervasive stylolites in carbonate rocks in the region (Arrinthrunga, Thorntonia and Red Heart) represents an important sub-horizontal weakness (fabrics) in the system, resulting in anisotropic strength in carbonates rocks. The models show that the presence of both faults and stylolites, led to localized tensile failure, permeability enhancement and fluid flow in carbonate rocks near faults, in particular within the Arrinthrunga and Thorntonia units. The Arrinthrunga unit showed most extensive tensile failure and permeability enhancement, localised predominantly near faults and attracting significant fluids with greater flow rates. This is in clear contrast to the models with no faults and no stylolites.

- The NW-striking fault shows higher shear strain, volumetric strain (dilation) and more extensive permeability enhancement with increased fluid focusing than the NE-strike fault. Higher dilation occurs predominantly at fault intersections, along fault (NW-fault in particular) and fault tips (shearing-associated tensile domains)

- Dipping faults are more favourably oriented for localisation of shear strain and volumetric strain under ENE-WSW shortening than vertical faults, due to the
occurrence of clear reverse faulting. The NW-striking fault again displays greater shear strain and volumetric strain than a NE-striking fault.

- For dipping faults (NW-striking faults, in particular), there is a clear tendency for greater shear strain and volumetric strain development on the hanging wall side. In addition to higher localisation along faults, this is expressed as thin layers of higher shear strain and volumetric strain along stratigraphic contacts (top and base contacts of Arrinthurnga, Thorntonia and Red Heart contacts). Tensile failure and permeability enhancement also predominantly occur on the hanging wall side of the NW-striking fault (excluding shallower sandstone horizons), mainly in the Arrinthurnga unit but also seen in Thorntonia (see image below - dark gray indicates the locations of tensile failure and permeability enhancement).

- Intersection of a NW-striking fault and a NE-striking fault (both dipping) facilitates shear strain and volumetric strain localisation. Much greater volumetric strain (dilation) occurred in the hanging-wall-quarter block of the two intersecting faults (see image below) near the intersection, particularly at the top Arrinthurnga horizon. Tensile failure and permeability enhancement also predominantly developed in the hanging wall sides.

![Diagram of fault system](image_url)
Based upon the structural map and worm results, the WNW-trending fault graben with a cross faults is potentially an important structural style in the Georgina Basin. The results of fault-graben models suggest that WNW-strike graben faults experienced strong transpressional (sinistral shearing and large reverse faulting) deformation during the ENE-WSE shortening reactivation, displaying much stronger shear and volumetric strain localisation than the N-S or NE cross fault; a "pop-up" structure is developed for the central graben area. Higher shear stain, dilation, tensile failure/permeability enhancement are more favourably located in the hanging-wall area or inside-graben area. These correlate with the highest fluid flux localized asymmetrically toward the hanging-wall at the intersections of graben faults with cross faults.

Also note that the scenario of WNW graben faults with a N-S cross fault shows much greater dilation than in the WNW graben faults plus NE cross fault scenario (see images below).

The behaviours of WNW-trending fault horst structures with a cross fault are similar to those for the WNW graben scenarios, as stated above. The WNW-strike horst faults also display strong transpressional (sinistral shearing and large reverse faulting) deformation, leading to "pop-up" structure at the flanks of the fault horst. All the localisations (shear, dilation, tensile failure and permeability increase) are at the flank blocks of the horst structure (still hanging-wall sides).

A WNW-trending fault horst with a N-S cross fault also shows greater dilatation than a WNW-trending horst plus a NE cross fault (see images below).
Structural scenario models have been constructed for the area east of the Putta Putta Fault (PPF) and west of the Lucy Creek Fault (LCF). Three half graben scenarios (E-dipping PPF) and one half horst scenario (W-dipping PPF) were investigated. The key implications are:

1) The horst model (W-dipping PPF) exhibits much greater shear strain along the PPF and in the hanging-wall host rocks, in comparison with the graben model (E-dipping PPF). Higher dilation is also observed in the hanging-wall side of the PPF in the horst model.

2) In the horst model, vertical stratigraphic offset across the PPF is further increased by more than 250 meters due to reverse faulting, clearly greater than in the graben model. This suggests that reverse faulting along a W-dipping PPF during the Alice Springs Orogenic compression might have contributed to the development of the 400m stratigraphic downthrow across the PPF.

3) The most important prediction of this group of models is that fluids migrate more preferentially towards elevated stratigraphic horizons (see images below). These are the west side of PPF and east side of LCF, where exists ~400m stratigraphic elevation. In particular, in the horst models, the hanging-wall of the PPF and the elevated side coincide at the west side of PPF. Therefore, permeability enhancement and fluid flow focusing predominantly occurred in the west side of the PPF (Arrinthrunga, Red heart and Thorntonia horizons).
• Fault tip locations (shearing-generated tensile domains in particular) generally display high dilation, localized tensile failure/permeability enhancement and fluid focusing.

• Arrinthrunga seems to be the most important carbonate rock unit in the sequence in the Georgina Basin in terms of strain localisation and fluid flow focusing. All the models show: 1) higher shear and volumetric strain in the Arrinthrunga horizon (e.g. upper contact horizon), in particular fault hanging-wall sides; 2) most favourable carbonate sequence for tensile failure and permeability enhancement; 3) significant fluid flow into and through the unit, out of discharging faults with upward fluid flow.

• Thorntonia is the next important carbonate unit in the sequence. Tensile-failure, permeability enhancement and fluid flow focusing are most likely confined to relatively-smaller area (in comparison with Arrinthrunga) adjacent to faults on the hanging-wall side.

• Observations of drill core and outcrop rock lithologies indicate that Arrinthrunga has sandy or silty inter-beds (layers). Model results show that the presence of thin siltstone and sandstone layers in Arrinthrunga promotes the development of thinner tensile damage and higher permeability zones (for channelized flow out of faults) in the unit, particularly near its top contact boundary (see image below).
Preliminary exploration targeting outcomes in the Georgina Basin

The following preliminary exploration targeting outcomes have been derived from generic deformation and fluid flow numerical models (simplified computer simulations of complex geological processes). These outcomes do not yet incorporate all of the information expected to be derived from the 3D geological model building and data integration exercise which is still being completed. It is also important to note that these targeting outcomes reflect only the fluid localisation processes associated with deformation-driven fluid flow, using extremely simplified fault geometries, and do not yet take into account geochemical effects on mineralisation, or complex basin architecture and fault models. These models are intended to be the first step towards testing conceptual mineralisation process models in a greenfields zinc exploration environment, and the results should not be applied in isolation as a drill hole targeting tool.

Preliminary numerical modelling outcomes that can be used to understand the processes driving and localising fluids within the faulted Georgina Basin sequence:

- **Fault network and patterns.** Target horizons within Georgina Basin are buried under significant depths of cover and therefore the determination of fault strike and dipping directions is difficult. The potential field worm results and interpretation from the current project have provided new interpretations of, and practically imaged, the patterns of fault network (strike, dip, length and intersection relationship). We have used the geometries of the fault network derived from the worm results as the basis for relating numerical results to regional architecture.

- **Favourable locations (fault and fault intersections) for mineralisation.** The structural significance of a given fault intersection locality, in terms of deformation, dilation and fluid flow, is evaluated based on the numerical modelling outcomes. Simulations indicated that the following fault architectures are favourable for the localisation of shear strain and dilation localisation and focussed fluid flow (see Executive Summary and main report for details):
  - NW- or WNW-trending graben or horst with NS-striking cross faults (hanging wall sides/blocks of the graben or horst faults). Mostly to the south of the current tenement area at present, however may be revised once more stratigraphic information is available.
  - N-S trending fault horst (east of the W-dipping Putta Putta Fault) or graben (west of the W-dipping Putta Putta Fault); hanging-wall sides/blocks.
  - NW-trending graben faults with NE-striking cross faults (hanging wall side or blocks of graben faults) are considered as favourable structures in the eastern area of the tenement (including the Tarlton area).
  - In the western region of the Mincor tenements, where NW-striking faults predominate, the hanging wall sides of the NW-striking faults (with NE-striking cross faults) are considered favourable (e.g. the Phillip 2 area).
A series of locations within the basin, interpreted to contain structural geometries similar to those that best focused strain and fluid in the simulations, are summarised in the image below. These are considered to be potential sites for exploration targeting (drilling).
Model-suggested locations of drilling targets

- Existing drill hole
- GRJV hole (planned)
- Model-suggested locations
- Potential targets (outside tenement area)

50 km
Generic Numerical Modelling

Introduction

The stage 2 numerical modelling works will be limited to generic models of simplified basin fault and stratigraphic architecture as a first-pass investigation of the key processes associated with structural reactivation, the mobility and focusing of mineralising fluid within the basin sequences. Models will simulate the following scenarios/issues and evaluate the model predictions on the basis of modeled cumulative fluid flow and dilation outcomes. The following issues will be investigated via generic numerical modelling:

- Stratigraphic issues
- Effects of deformation
- Roles of faults
- Roles of fault graben versus horst structures

Model basis: geometry, properties and boundary conditions

- Link to: The Generic Model Basis page

Scenario models

1. Model set 1: basic effects of stratigraphy (no faults) with or without deformation
   - Link to: The Scenario model set-1 page

2. Model set 2: effects of vertical faults - without deformation
   - Link to: The Scenario model set-2 page

3. Model set 3: effects of vertical faults - with deformation
   - Link to: The Scenario model set-3 page

4. Model set 4: Investigation of permeability enhancement with deformation

   The models here investigate the impact of permeability enhancement with deformation. More specifically, in these models, an algorithm is incorporated, which allows rock
permeability to increase and reach the permeability value for faults when tensile failure occurs. The set 4 models include several sub-sets:

4a) Model set 4a: Permeability enhancement - no faults with deformation
   - Link to: The Scenario model set-4a page

4b) Model set 4b: Permeability enhancement - with faults and deformation
   - Link to: The Scenario model set-4b page

4c) Model set 4c: Permeability enhancement - with faults, deformation and "stylolites"
   - Link to: The Scenario model set-4c page

4d) Model set 4d: Permeability enhancement - effects of fault burying depth (with deformation and "stylolites")
   - Link to: The Scenario model set-4d page

4e) Model set 4e: Permeability enhancement - presence of siltstone and sandstone layers in Arrinthurunga
   - Link to: The Scenario model set-4e page

5. Model set 5: What happens when faults are not vertical but high angle dipping?
   - Link to: The Scenario model set-5 page: dipping faults

6. Model set 6: Simulation of a WNW-ESE trending fault graben with a cross fault
   - Link to: The Scenario model set-6 page: WNW-fault graben

7. Model set 7: Simulation of a WNW-ESE trending fault horst with a cross fault
   - Link to: The Scenario model set-7 page: WNW-fault horst

8. Model set 8: Graben and horst models for the Putta Putta Fault - Lucy Creek Fault area
   - Link to: The Scenario model set-8 page: the Putta Putta Fault - Lucy Creek Fault area
Model basis: geometry, properties and boundary conditions

Generic model design

- Based on regional structural outline (see image below), a plan-view model box of 10km by 10km is defined as the model plan view size.
- The model depth (thickness) is taken as 5 km.
- Models are with or without faults. In the models with two faults, a NW-strike and NE-strike fault is considered.
- Other faults and orientations are also considered (e.g. NS strike fault, fault graben/horst structures
- Regional shortening (tectonic contraction) direction is ENE-WSW
Simplified stratigraphic sequence

The table below illustrates the simplified stratigraphic sequence considered in the generic models:

<table>
<thead>
<tr>
<th>&quot;Grouped&quot; unit name</th>
<th>Rock</th>
<th>Conceptual depth for model (m)</th>
<th>Conceptual thickness in model (m)</th>
<th>Regional thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dulcie sandstone</td>
<td>quartz arenite, silty calcareous sandstone, and pebble conglomerate</td>
<td>800m</td>
<td>800 m thick</td>
<td>650m in typical section</td>
</tr>
<tr>
<td>Kelly Creek Fm</td>
<td>sandstone-dolostone-limestone-siltstone-conglomerate</td>
<td>1000m</td>
<td>200 m thick</td>
<td>typically 168m, but see 260m in ADD Mimica</td>
</tr>
<tr>
<td>Tomahawk Fm</td>
<td>sandstone, minor limestone, dolost, mudst, conglomer.</td>
<td>1160m</td>
<td>160 m thick</td>
<td>&gt;140m &lt;190m</td>
</tr>
<tr>
<td>Arrinthrunga Fm (incl. Euowie Sandstone member; 28-60m)</td>
<td>Limestone and dolostone</td>
<td>1640m</td>
<td>680 m thick</td>
<td>980m to 975m; max 975m seen in Huckitta</td>
</tr>
<tr>
<td>Arthur Creek Fm</td>
<td>Dolost &amp; Limest &amp; minor mudst (upper interval) Hot Shale</td>
<td>2270m</td>
<td>430 m thick</td>
<td>452m in typical sections</td>
</tr>
<tr>
<td></td>
<td>Dolost, minor sandst+conglom. (lower interval) Black Shale</td>
<td>2300m</td>
<td>30 m thick</td>
<td>0-30m (around Husst)</td>
</tr>
<tr>
<td>Thorntonia Limestone</td>
<td>Limestone, dolomitised limestone, dolostone with marl &amp; mudstone, local basal conglom., sandst &amp; greywacke</td>
<td>2500m</td>
<td>200 m thick</td>
<td>25 to &gt;110m, &gt;400m in fault block at Century</td>
</tr>
<tr>
<td>Red Heart Dolostone</td>
<td>Brown &amp; grey dolostone</td>
<td>2560m</td>
<td>60 m thick</td>
<td>9 to 126m, 9m in typical sections</td>
</tr>
<tr>
<td>Mount Baldwin Fm</td>
<td>Qz arenite &amp; sublitharenite, qz greywacke, siltst, shale</td>
<td>2700m</td>
<td>140m thick</td>
<td>60 to 230m; 120m in typical sections</td>
</tr>
<tr>
<td>Neoproterozoic rocks</td>
<td>predominantly: arkose, sandst, siltst, conglom., shale</td>
<td>4200m</td>
<td>1500 m thick</td>
<td>in excess of 1500m (?)</td>
</tr>
<tr>
<td>Palaeoproterozoic basement</td>
<td>Felsic/granitic gneiss, strong and massive/dense</td>
<td>6000m</td>
<td>1800 m thick</td>
<td>???</td>
</tr>
</tbody>
</table>

Numerical model mesh

The images below show one model geometry and mesh (with intersection NW-strike and NE-strike vertical faults). A series of other fault geometries are also simulated (e.g. no faults, single fault, dipping faults, deeply buried faults).
Geometries of a model with two vertical faults.

Numerical mesh of a model with two vertical faults.
Material properties

The material properties of the generic models are given in the table below.

### Generic model properties

<table>
<thead>
<tr>
<th>Unit name</th>
<th>Density (kg/m³)</th>
<th>Young’s modulus (Pa)</th>
<th>Poisson’s ratio</th>
<th>Bulk Modulus (Pa - Calc)</th>
<th>Shear Modulus (Pa - Calc)</th>
<th>Cohesion (Pa)</th>
<th>Tensile strength (Pa)</th>
<th>Strength to weakest joints</th>
<th>Joint for strike, Dip angle</th>
<th>Biax angle</th>
<th>Porosity (%)</th>
<th>Permeability (m²)</th>
<th>New Perm. order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault</td>
<td>2200</td>
<td>1.02e+10</td>
<td>0.15</td>
<td>4.76e+09</td>
<td>4.95e+09</td>
<td>1.00e+06</td>
<td>5.00e+06</td>
<td>2</td>
<td>15</td>
<td>3</td>
<td>20</td>
<td>1.0e+13</td>
<td>2</td>
</tr>
<tr>
<td>Dulcie sandstone</td>
<td>2310</td>
<td>3.50e+10</td>
<td>0.25</td>
<td>2.33e+10</td>
<td>1.40e+10</td>
<td>2.00e+07</td>
<td>5.00e+06</td>
<td>4</td>
<td>30</td>
<td>3</td>
<td>7.92</td>
<td>4.0e-15</td>
<td>2</td>
</tr>
<tr>
<td>Kelly Creek Fm (as above)</td>
<td>2310</td>
<td>3.60e+10</td>
<td>0.25</td>
<td>2.33e+10</td>
<td>1.40e+10</td>
<td>2.00e+07</td>
<td>5.00e+06</td>
<td>4</td>
<td>30</td>
<td>3</td>
<td>7.92</td>
<td>4.0e-15</td>
<td>2</td>
</tr>
<tr>
<td>Tomahawk Fm</td>
<td>2430</td>
<td>3.60e+10</td>
<td>0.25</td>
<td>2.33e+10</td>
<td>1.40e+10</td>
<td>2.00e+07</td>
<td>5.00e+06</td>
<td>4</td>
<td>30</td>
<td>3</td>
<td>7.92</td>
<td>4.0e-15</td>
<td>2</td>
</tr>
<tr>
<td>Arrinirra - dolomite lime</td>
<td>2490</td>
<td>6.50e+10</td>
<td>0.25</td>
<td>4.35e+10</td>
<td>2.60e+10</td>
<td>4.00e+07</td>
<td>1.00e+07</td>
<td>2</td>
<td>yes</td>
<td>30</td>
<td>3</td>
<td>12.35</td>
<td>1.5e-15</td>
</tr>
<tr>
<td>Arrinirra - siltstone or silty dolomite</td>
<td>2610</td>
<td>3.00e+10</td>
<td>0.2</td>
<td>1.67e+10</td>
<td>1.25e+10</td>
<td>1.00e+07</td>
<td>3.50e+06</td>
<td>6</td>
<td>yes</td>
<td>30</td>
<td>3</td>
<td>4.18</td>
<td>1.0e-18</td>
</tr>
<tr>
<td>Arrinirra - sandstone</td>
<td>2590</td>
<td>3.50e+10</td>
<td>0.25</td>
<td>2.33e+10</td>
<td>1.40e+10</td>
<td>2.00e+07</td>
<td>5.00e+06</td>
<td>4</td>
<td>yes</td>
<td>30</td>
<td>3</td>
<td>6.13</td>
<td>4.0e-15</td>
</tr>
<tr>
<td>Arthur Creek Fm - fine grain limestone</td>
<td>2650</td>
<td>6.00e+10</td>
<td>0.26</td>
<td>4.00e+10</td>
<td>2.40e+10</td>
<td>4.00e+07</td>
<td>1.00e+07</td>
<td>2</td>
<td>yes</td>
<td>30</td>
<td>3</td>
<td>3.21</td>
<td>1e-15 &amp; 1e-18</td>
</tr>
<tr>
<td>Arthur Creek - hot shale</td>
<td>2600</td>
<td>2.00e+10</td>
<td>0.16</td>
<td>9.52e+09</td>
<td>8.70e+09</td>
<td>8.00e+06</td>
<td>2.00e+06</td>
<td>7</td>
<td>22</td>
<td>3</td>
<td>2.5</td>
<td>1.0e-19</td>
<td>7</td>
</tr>
<tr>
<td>Thorntop Limestone</td>
<td>2620</td>
<td>6.00e+10</td>
<td>0.26</td>
<td>4.00e+10</td>
<td>2.40e+10</td>
<td>4.00e+07</td>
<td>1.00e+07</td>
<td>2</td>
<td>yes</td>
<td>30</td>
<td>3</td>
<td>1.50e-15</td>
<td>3a</td>
</tr>
<tr>
<td>Red Heart Dolomite</td>
<td>2780</td>
<td>6.60e+10</td>
<td>0.25</td>
<td>4.35e+10</td>
<td>2.60e+10</td>
<td>4.00e+07</td>
<td>1.00e+07</td>
<td>2</td>
<td>yes</td>
<td>30</td>
<td>3</td>
<td>2.08</td>
<td>1.0e-15</td>
</tr>
<tr>
<td>Mount Baldon Fm</td>
<td>2550</td>
<td>3.00e+10</td>
<td>0.25</td>
<td>2.00e+10</td>
<td>1.20e+10</td>
<td>1.50e+07</td>
<td>4.00e+06</td>
<td>3</td>
<td>30</td>
<td>1</td>
<td>5.99</td>
<td>1.0e-17</td>
<td>5</td>
</tr>
<tr>
<td>Keopeorosaurus rocks</td>
<td>2665</td>
<td>3.60e+10</td>
<td>0.25</td>
<td>2.35e+10</td>
<td>1.45e+10</td>
<td>3.50e+07</td>
<td>6.00e+06</td>
<td>3</td>
<td>30</td>
<td>1</td>
<td>1.86</td>
<td>1.0e-16</td>
<td>4</td>
</tr>
<tr>
<td>Paleosorosaurus basement</td>
<td>2630</td>
<td>7.00e+10</td>
<td>0.25</td>
<td>4.67e+10</td>
<td>2.80e+10</td>
<td>6.00e+07</td>
<td>1.50e+07</td>
<td>1</td>
<td>yes</td>
<td>30</td>
<td>1</td>
<td>1.23</td>
<td>1.0e-18</td>
</tr>
</tbody>
</table>

Notes:
1. Density and porosity: based on data for the Georgia basin
2. Permeability based on porosity and literature
3. Mechanical properties: based on average value for a rock type in literature (Turcotte & Schubert 1982; Lease & Vaidkun 1978)
4. Permeability unit: 1cm² = 1e-4 m²

Deformation and fluid flow boundary conditions

- A ENE-WSW regional shortening direction is applied to the models, based on the compression direction of the Alice Springs Orogen.
- The initial fluid pore pressures of all the models are ~60% of the lithostatic pore pressure.
- The top surface of the model is fixed with a pore pressure of 1e5 Pa, that is, free surface pore pressure.
- Fluid pore pressures on the vertical sides and bottom are free (i.e. impermeable fluid boundary conditions).
- Any variation from the conditions above will be indicated in specific model
Model set 1: basic effects of stratigraphy (no faults) with or without deformation

Model geometries

Three different model geometries for stratigraphic units are simulated here (see image below):

- **Geometry 1**: thin hot-shale layer (seal) extends to the whole model, and Arthur Creek limestone is modelled as aquifer (same permeability as other carbonate units)
- **Geometry 2**: thin hot-shale layer (seal) is only confined to about one quarter area of the model (the NW corner), and Arthur Creek limestone is modelled as aquifer (similar to the above)
- **Geometry 3**: thin hot-shale layer (seal) extends to the whole model, and Arthur Creek limestone is also modelled as a seal (based on massive/dense/low porosity feature of the rock seen in drill cores)

Key points of model results

- Without the presence of faults and a regional seal (hot shale or hot shale+Arthur Creek limestone), fluid flow in the stratigraphic sequence of the model is dominated by slow upward fluid flow, driven by initial fluid pressure higher than hydrostatic gradients. Flow rates are very slow in the horizons below the hot shale (the seal), but greater flow rates are seen in the sequence above the seal.
- The maximum flow rate in the cases above is about 1.2e-10 m/s (very slow), but adding deformation led to the increase of fluid flow rate by more than 30 times.
- Shortening deformation also led to change of fluid flow patterns, reflected by:
o Down flow emerged in shallow levels (due to deformation-related dilation), down to the top levels of Arrinthuranga, making fluid mixing possible.

o Clear lateral fluid flow patterns in deeper aquifer units (e.g. Thorntonia unit right below hot shale)

- The scenarios for the local presence of the seal (hot shale) show the possibility of much stronger lateral-upward flow along the edge of the seal. Flow rates are much greater than the models with a seal extending to the whole model. This is due to the preferential fluid escape out of the boundary of the seal unit.

- Without faults, the scenario with only hot shale as seal and the scenario with both hot shale plus Arthur Creek limestone as seal give very similar results. This is due to lack of conduits or connectivity between the regions above and below the seal.

Fluid flow patterns (images) from three model geometries without deformation
Fluid flow patterns (images) from three model geometries with deformation

Geometry 1

Geometry 2

Geometry 3

Total flux

Integrated flux

Flow vectors

Section plots of flow vectors

Arthur Creek

Max rate=4.076e-9 m/s

Arthur Creek

Max rate=1.216e-8 m/s

Arthur Creek

Max rate=4.99e-9 m/s
Model set 2: Effects of vertical faults - without deformation

Model geometries

In this set of models, we have considered three scenarios for vertical faults (see image below):

- 1 fault - NW strike
- 1 fault - NE strike
- 2 faults - NW and NE strike

The stratigraphic structure for these models is the one used for non-fault models, where hot shale plus Arthur Creek Fm form a regional seal.

Key points of model results

- Presence of faults establish the connectivity between the stratigraphic horizons below and above the seal (Arthur Creek limestone plus hot shale).
- Fluid flow rates are several hundred times higher than the non-fault scenarios
- Fluid flow field is dominated by upward fluid discharge along the faults
- There is a clear fluid flow pattern showing lateral fluid feeding into faults from carbonate rock units (Red Heart and Thorntonia, in particular)
- Fault tips appear to show higher fluid flux and flow rates, due to their favorable location to "suck" fluids from surrounding host rocks.
Fluid flow patterns (images) for the vertical fault models without deformation
Model set 3: Effects of vertical faults - with deformation

Model geometries

In this set of models, we again consider three scenarios for vertical faults (see image below), but in addition, the ENE-WSW shortening deformation is also considered:

- 1 fault - NW strike
- 1 fault - NE strike
- 2 faults - NW and NE strike

Key points of model results

- NW-strike fault shows higher shear strain and volumetric strain (dilation) than the NE-strike fault
- Greater shear strain and volumetric strain (dilation) at shallower levels where mechanical pressure is lower
- Fault intersection shows higher dilation
- Fluid flow is also dominated by upward fluid flow/discharging along faults
- In and around the NW-strike fault, down-flow is developed at shallow levels due to higher dilation there; no clear down-flow in the NE-strike fault
Fluid flow patterns (images) for the vertical fault models with deformation

Total flux

Flow vectors

Section plots of flow vectors

Arthur Creek
Max rate = 9.124e-8 m/s

Arthur Creek
Max rate = 3.6e-8 m/s

Arthur Creek
Max rate = 6.9e-8 m/s

Shear strain

Volumetric strain

21
Model set 4: Investigation of permeability enhancement with deformation

Model set 4a: Permeability enhancement - no faults with deformation

Model purpose

This model is to test whether there will be any tensile failure and permeability enhancement at all in a deformation model without faults. This provides an important reference point for comparison with the models containing faults.

Key points of model results

- The models with deformation but without faults do not show any tensile failure or permeability enhancement (see image below).
- The results remain the same even when "stylolites" (weak horizontal fabrics) are incorporated in carbonate units.
- This indicates homogeneous shortening deformation or high initial fluid pore pressure (60% of lithostatic pore pressure) or the presence of "stylolites" (weak horizontal fabrics) in carbonate units do not lead to tensile failure.
Model set 4b: Permeability enhancement - with faults and deformation

Model description

The models presented here are three fault scenarios with:
1) NW-strike fault,  
2) NE-strike fault,  
3) Both NW- and NE-strike faults.

Deformation-associated permeability enhancement mechanism is considered here. That is, the models incorporate an algorithm, which allows rock permeability to increase and reach fault permeability value when tensile failure occurs.

Key points of model results

- Faults resulted in tensile failure and permeability enhancement. This is in clear contrast to the no-fault models where no tensile failure/permeability enhancement took place.

- Permeability enhancement in host-rocks surrounding faults led to even greater fluid flow rates (now greater than in the model with both faults and deformation, but no permeability enhancement)

- Patterns of permeability enhancement around the two faults are different:
- **NW-strike fault**: more extensive permeability enhancement (along the fault, mainly in shallow levels but also in Arrinthrunga adjacent to the fault).
- **NE-strike fault**: less extensive permeability enhancement than the NW-strike fault. Permeability enhancement sites are mainly located in the tensile domains near fault tips (asymmetrically). In the central segment of the fault, only minor permeability enhancement is seen in the surface levels adjacent to the fault.

**Fluid flow patterns and permeability enhancement locations (images)**

1 fault (NW)  
1 fault (NE)  
2 faults (NW & NE)

**Total flux**

**Flow vectors**

**Section plots of flow vectors**

Arthur Creek

Max rate = 1.5e-7 m/s

Arthur Creek

Max rate = 1.7e-7 m/s

Arthur Creek

Max rate = 1.33e-7 m/s

*Dark gray indicates the location of permeability enhancement*
Model set 4c: Permeability enhancement - with faults, "stylolites" and deformation

Model description

- The models here also simulate three fault scenarios with: 1) NW-strike fault; 2) NE-strike fault; and 3) both NW- and NE-strike faults.
- Deformation-associated permeability enhancement mechanism is considered here. That is, the models incorporate an algorithm, which allows rock permeability to increase and reach fault permeability value when tensile failure occurs.
- In addition, the presence of "stylolites" (weak horizontal fabrics) in carbonate units is also simulated using the ubiquitous-joint module in FLAC3D.

Key points of model results

- Presence of "stylolites" (weak horizontal fabrics) in carbonate units significantly promote the occurrence of tensile failure and permeability enhancement. This highlights the potential roles or importance of stylolites (in carbonate units) in localizing rock tensile damage and fluids during the structural reactivation and inversion of the Georgina Basin.
- In contrast to the model without "stylolites", now important permeability enhancement occurred in Arrinthrunga.
- It is important to note that in the current scenario models, significant fluids come out of the faults and move through host rocks into the Arrinthrunga unit.
- Along the NW-strike fault, the permeability enhancement (tensile-fracture damage) areas enlarge upward from the the contact with Arthur Creek limestone (note the wedge geometry). An extensive permeability-enhancement layer develop along the top boundary of Arrinthuranga. The damage appears to be more extensive near the fault intersection.

- For the NE-strike fault, the permeability enhancement areas are asymmetric at its tips, as controlled by the asymmetric distributions of tensile domains due to shearing.

Fluid flow patterns and permeability enhancement locations
(see images below)
More section plots of fluid flow patterns from the model with 2-intersecting faults:

**NW-strike fault**

Section near intersection with NE-fault

Arthur Creek

Max rate = 2.4e-7 m/s

Section away from the intersection

Arthur Creek

Max rate = 2.4e-7 m/s
NE-strike fault

Section near SW end of the fault

Arthur Creek

Max rate = 2.4e-7 m/s

Section near the NE end of the fault

Arthur Creek

Max rate = 2.4e-7 m/s
Model set 4d: Permeability enhancement - effects of fault burying depth (with "stylolites" and deformation)

Model description

- The models here also simulate "blind" fault scenarios, exploring effects of various burying depth of fault top ends
- The cross-cutting geometry of a NW-fault and NE-strike fault is used here. Similar to some other model scenarios, the following structural factor and process are also considered:
  - Deformation-associated permeability enhancement mechanism.
  - Presence of "stylolites" (weak horizontal fabrics) in carbonate units.

Key points of model results

- Assuming buried-faults below Arrinthunga unit increased the development of tensile failure and permeability enhancement at the deeper levels (Arthur Creek, Thorntonia and Red Heart). This is accompanied with reduction of the damage at shallower levels. Tensile failure and permeability enhancement in Arrinthurunga remains extensive.

- Assuming deeper buried-faults below hot shale significantly increased the development of tensile failure and permeability enhancement in Thorntonia and Red Heart units. This seems to have resulted in major lateral fluid flow and mixing into Thorntonia and Red Heart, pointing to better mineralization potential in these units. Fluid flow in sequence above the hot shale became very limited in this scenario.

- In the cases where faults are buried even deeper below MT Baldwin or Neoproterozoic rocks, tensile damage and fluid flow became significantly reduced in the models (unfavourable for mineralization).
Fluid flow patterns and permeability enhancement locations (images)

**Faults terminating below Arrinthuranga**

Accumulative fluid flux

![Accumulative fluid flux](image)

Fluid flow vectors

![Fluid flow vectors](image)

Section plots of fluid flow vectors

NW fault (near intersection)

![NW fault](image)

Max rate = 2.327e-7 m/s

NW fault (away from intersection)

![NW fault](image)

Max rate = 2.327e-7 m/s

NE fault (near intersection)

![NE fault](image)

Max rate = 2.327e-7 m/s

NE fault (away from intersection)

![NE fault](image)

Max rate = 2.327e-7 m/s
Faults terminating below Hot Shale

Accumulative fluid flux

Fluid flow vectors

Section plots of fluid flow vectors

Faults terminating at deeper levels

Below Mt Baldwin

Below Neoproterozoic rock
Model set 4e: Permeability enhancement - presence of siltstone and sandstone layers in Arrinthurunga

Model descriptions

The models here compare the fluid flow results of three different scenarios for lithologies in Arrinthurunga Fm (see image below):

- 1. A homogenous carbonate rock Arrinthurunga
- 2. Silt-sandstone layers in Arrinthurunga
- 3. Sandstone-siltstone layers in Arrinthurunga

Key points of model results

- Presence of thin siltstone and sandstone layers in Arrinthurunga seems to promote the development of thinner tensile damage and permeability zones in the unit, in comparison with a homogeneous carbonate Arrinthurunga scenario.
Fluid flow patterns (images)

Fluid flow vectors on sections: NW-strike fault near intersection with NE-fault

Max rate = 2.4e-7 m/s

Max rate = 3.4e-7 m/s

Max rate = 3.2e-7 m/s

Arrinthuranga
Arthur Creek

Arrinthuranga
Arthur Creek

Sandstone

Siltstone

Siltstone
Model set 5: What happens when faults are not vertical but high angle dipping?

Model description

This group of models investigate the effects of dipping faults. The question interested here is: what happens to strain and fluid flow patterns when faults are high angle dipping at 70 degree (correlating with the vertical fault scenarios simulated in previous models)?

Eight model geometries are involved here, as illustrated by the image below:

- 1) Single fault: NW-strike and NE-dipping
- 2) Single fault: NW-strike and SW-dipping
- 3) Single fault: NE-strike and SE-dipping
- 4) Single fault: NE-strike and NW-dipping
- 5) Two intersecting faults: NW-strike (NE-dipping) and NE-strike (SE dipping)
- 6) Two intersecting faults: NW-strike (SW-dipping) and NE-strike (SE dipping)
- 7) Two intersecting faults: NW-strike (SW-dipping) and NE-strike (NW dipping)
- 8) Two intersecting faults: NW-strike (NE-dipping) and NE-strike (NW dipping)
Key points of model results (see images below)

- Dipping faults are more favourably oriented for localization of shear strain and volumetric strain under the ENE-WSW shortening direction, than vertical faults (previous models). This is particularly reflected by clear reverse faulting movement.

- NW-strike faults are more favorable orientated for the accumulation of shear strain and volumetric strain than NE-strike faults. This is clearly demonstrated by much greater strains and large reverse-faulting displacement along the NW-strike faults (rock units such as Arrinthrunga were uplifted or "popped up" at the hanging wall block of the NW fault).

- There is a clear tendency for greater shear strain and volumetric strain development on the hanging wall side (NW-strike faults, in particular). This is particularly interestingly expressed as thin layers of higher shear strain and volumetric strain along stratigraphic contacts (top and base contacts of Arrinthrunga, Thorntonia and Red Heart contacts).

- The tip locations of NW-strike faults show higher dilation in all the models.

- Intersecting fault scenarios facilitate the development of both shear strain and volumetric strain, with volumetric strains even more clearly enhanced. Much greater volumetric strain (dilation) occurred in the hanging-wall-quarter block of the two intersecting faults near the intersection, particularly at the top Arrinthrunga horizon (more along NW-strike fault).

- Permeability enhancement occurred in the following main locations as a result of tensile failure (combined effects of deformation and fluid pore pressures):
  
  o For the single fault cases:
    
    ▪ permeability enhancement predominantly occurs on the hanging wall side of the NW fault near the fault, mainly in Arrinthrunga unit but also seen in Thorntonia (excluding those area in the shallow sandstone horizon).
    
    ▪ permeability enhancement near the NE fault is much less or minor
    
    ▪ permeability enhancement on the footwall side is mainly confined to shallow sandstone horizons
For the two intersecting fault cases:

- permeability enhancement patterns are generally consistent with the feature stated above (e.g. hanging wall side and Arrinthrunga horizon), but
- permeability enhancement along the NE fault was increased, essentially due to interaction (effects) from the intersecting NW fault
- permeability enhancement on the footwall side was also increased on both faults (again due to fault interaction)

Features of fluid flow patterns:

- Strong fluid focusing and upward flow (from faults) into the permeability-enhanced locations on the hanging wall side of faults with two important stratigraphic horizons:
  - Arrinthrunga horizon (near fault and top unit levels - most important)
  - Thorntonia horizon (near fault and top unit levels - most important)

- The hanging-wall-quarter block of the two intersecting faults (near the intersection and top Arrinthrunga horizon, in particular) is the most important locations (also considering dilation patterns)

- Some downward fluid flow is seen in the shallower level near the NW fault (driven by "pop-up" high topography generated by reverse faulting along the NW fault). In a conceptual sense, this may suggest the possibility of fluid composition changes at the top shallower levels of Arrinthrunga.
Deformation and fluid flow patterns (images)

Shear strain patterns

Model 1  Model 2  Model 3  Model 4

Model 5  Model 6  Model 7  Model 8

Volumetric strain patterns

Model 1  Model 2  Model 3  Model 4

Model 5  Model 6  Model 7  Model 8
Section plots of fluid flow vectors (single fault models)

Model 1

Model 2

Model 3

Model 4

Section plots of fluid flow vectors (Two intersecting fault models)

Model 5

Model 6

Max. flow rate = 3.83e-7 (m/s)

Max. flow rate = 3.61e-7 (m/s)

Max. flow rate = 1.52e-7 (m/s)

Max. flow rate = 1.49e-7 (m/s)

Max. flow rate = 3.87e-7 (m/s)

Max. flow rate = 3.30e-7 (m/s)

Max. flow rate = 1.44e-7 (m/s)

Max. flow rate = 1.16e-7
Section plots of fluid flow vectors (Two intersecting fault models)

Model 7

Model 8

Max. flow rate = 3.4e-7 (m/s)

Max. flow rate = 3.58e-7 (m/s)

Max. flow rate = 1.1e-7 (m/s)

Max. flow rate = 1.21e-7 (m/s)
Model set 6: Simulation of a WNW-ESE trending fault graben with a cross fault

Model description

The models here simulate the WNW-ESE trending fault graben structures, which are possibly present in the Southern Georgina Basin on the basis of the worm results (suggested by Barry Murphy. Two models are designed here, one with a vertical NS-strike cross fault and the other with a vertical NE-strike cross fault. The geometries of the models are illustrated below:

WNW-ESE-strike fault graben

Key points of model results (see images below)

- Shear strain, volumetric strain (dilation) and faulting movement:
  - much greater shear strain localization along the WNW graben faults than along the cross fault;
  - among the two cross fault scenarios, a N-S cross fault shows relatively higher shear strain than the NE cross fault
  - the WNW graben faults experienced transpressional deformation during the ENE-WSE shortening reactivation, expressed as:
• strong reverse faulting movement (section view, see images below)
• sinistral shearing movement (plan-view)
• formation of "pop-up" structure (the central block confined by the two WNW graben faults)

  o the vertical N-S and NE cross faults show little vertical movements, with only minor strike-slip shearing as reflected by the patterns of plan-view tensile failure patterns.
  
  o Volumetric strains (dilation) are higher along faults and top-Arrinthruga horizon, with following details:

    • Highest dilation at fault intersections and tips
    • The scenario of WNW graben faults plus a N-S cross fault shows much greater dilatation than in the NE cross fault scenario. In this case, the top-Arrinthruga horizon between the two WNW graben faults and along N-S cross faults shows the highest dilation (together with fault tip and intersection locations). Note the occurrence of a relatively high dilation "pipe" along the N-S cross fault in Arrinthrunga (below the thin, very high dilation layer near the top Arrinthrunga horizon).

• The most important permeability enhancement and fluid flow locations are:
  
  o for the WNW graben faults, the hanging wall sides and fault tip locations (tensile domain locations for the sinistral shearing)
  
  o for the cross fault (N-S cross fault case, in particular), both sides and fault tip locations (tensile domain locations for the sinistral shearing); note the cross section plots below also reflects the effects of graben faults, even though the section is oriented to intersect the cross fault for illustration.
  
  o the features above mean that the inside-graben side of fault intersections (or hanging wall sides of the graben faults) are the most important locations for fluid focusing and mineralization, with the key stratigraphic horizons at:

    • near the top of the Arrinthrunga (most important);
    • Thorntonia unit (next important)
Deformation and fluid flow patterns (images)

Shear and volumetric strain patterns

NS-strike cross fault

NE-strike cross fault

Relative high dilation "pipe" along NS-fault in Arnhemland
Fluid flow patterns and permeability enhancement location
NS-strike cross fault

Max. flow rate = 0.4e-7 (m/s)

Fluid flow patterns and permeability enhancement location
NE-strike cross fault

Max. flow rate = 0.58e-7 (m/s)
Simulation of a WNW-ESE trending fault horst with a cross fault

Model description

The models here simulate the WNW-ESE trending fault horst structure. This type of structures could be present in the Southern Georgina Basin, similar to the scenario for a fault graben structures, due to the high angle natures of faults in this region. The suggestion of such models (by Barry Murphy) is also based on the worm results. Two models are designed here, one with a vertical NS-strike cross fault and the other with a vertical NE-strike cross fault. The geometries of the models are illustrated below:

Key points of model results (see images below)

- Results for the present fault horizon models are consistent with the fault graben models. The only major changes are reflected in the change of locations due to fault-dip-direction change (e.g. the hanging-wall side of WNW graben faults now becomes the footwall side of WNW horst fault). Some major features are listed below:
  - much greater shear strain localization along the WNW horst faults than along the cross fault;
among the two cross fault scenarios, a N-S cross fault shows relatively higher shear strain than the NE cross fault

the WNW horst faults also experienced transpressional deformation during the ENE-WSE shortening reactivation, expressed as:

- strong reverse faulting movement (section view, see images below)
- sinistral shearing movement (plan-view)
- formation of "pop-up" structure at the flanks of the fault horst (i.e. the central block became relatively deeper)

The vertical N-S and NE cross faults show little vertical movements, with only minor strike-slip shearing (reflected by the patterns of plan-view tensile failure patterns).

Volumetric strains (dilation) are higher along faults (fault intersection and tips in particular) and top-Arrinthuranga horizon

The scenario of WNW horst faults with a N-S cross fault shows much greater dilatation than in the NE cross fault scenario. In this case, the top-Arrinthuranga horizon on the hanging wall sides of two WNW horst faults and along N-S cross faults shows the highest dilation (together with fault tip and intersection locations). This is similar to the fault graben case, but the locations changed from the central block to the flank blocks.

For fluid flow, the outside-horst sides of fault intersections (or hanging wall sides of the horst faults) and fault tip locations (tensile domain) are the most important locations for fluid focusing and mineralization, also with the key stratigraphic horizons at:

- near the top of the Arrinthrunga (most important);
- Thorntonia unit (next important).

Questions/thoughts arose from seeing the horst fault model results:

- The stratigraphic units are deeper in the area east of the Putta-Putta Fault and west of Lucy Creek Fault, what caused this?
- Could reverse faulting movement during compressional reactivation under a horst framework be one of possibilities (the other possibility is growth/normal faulting plus sedimentation)?

- The current fault horst models show that a deeper central block in a horst framework can be developed as the result of reverse faulting movement.

**Deformation and fluid flow patterns (images)**

**Shear and volumetric strain patterns**

*NS-strike cross fault*

*NE-strike cross fault*
Fluid flow patterns and permeability enhancement location

NS-strike cross fault

Fluid flow patterns and permeability enhancement location

NE-strike cross fault
Graben and horst models for the Putta Putta Fault - Lucy Creek Fault area

Introduction and model description

This set of models investigate several structural scenarios for the area between the Putta Putta Fault (PPF) and Luce Creek Fault (LCF), an important area approximately situated in the central part of Mincor tenements. Drilling data (e.g. Hunt1, Baldwin1, NTGS HUC2) indicate that the stratigraphic units east of PPF and west of LCF have about 400m downthrow (deeper situated) with respect to both the areas west of PPF or the area east of LCF. This seems to suggest the presence of fault graben structure (according to most commonly perceived structural styles). However, the current worming results (detailed gravity worm) suggest that PPF could be high-angle west dipping. Therefore, this set of models simulate both graben and horst scenarios for the area. Four models are invested here (see image below):

- **Graben case 1**: PPF (east dipping) and LCF (vertical) form a graben with a NE cross fault (vertical, cross-cutting both PPF and LCF)
- **Graben case 2**: PPF (east dipping) and LCF (vertical) form a graben with a NE cross fault (vertical, cross-cutting PPF only)
- **Graben case 3**: PPF (east dipping) and LCF (vertical) form a graben with a NE cross fault (vertical, terminating at PPF)
- **Graben case 4**: PPF (west dipping) and LCF (vertical) form a horst with a NE cross fault (vertical, cross-cutting both PPF and LCF)
Model geometries for the Putta Putta Fault
– Lucy Creek Fault area

Key points of model results (see images below)

- Shear strain patterns:
  o For all three **graben** models (i.e. PPF dips toward east), all the faults display very low shear strains. For PPF, hanging-wall side show some shear strain localization (Arrinthrunga levels). LCF (vertical) shows even less shear strain, with some localization on both sides. The cross fault (vertical) show minimum shear strain localization.
  
  o For the **horst** model (i.e. PPF dips toward west), much greater shear strain occurred along the PPF. This seems to suggest that a fault-horst case is more favorable for reverse faulting under compressional conditions, than a graben case. It is interesting to note that clear shear strain localization (at several horizons within the Arrinthrunga unit)
occurred on the hanging-wall block of the PPF. In its foot-wall side, the top Arrinthrunga contact and the hot shale-Red Heart contact also show relatively higher shear strains.

- Also note that in the "horst" model, stratigraphic offset in depth on the both sides of the PPF is further increased by more than 250 meters. The maximum vertical offset here is > 650m. This suggest one of the possible explanations for how the vertical stratigraphic offset across the PPF developed, that is, reverse faulting along a W-dipping PPF during the Alice Springs Orogenic compression/inversion.

- Volumetric strain patterns:
  - For all three graben models, dilation mainly developed along faults at the relatively shallower levels. The highest dilation occurred at the southern ends of the PPF and LCF, at one side of the faults, which are most likely the tensile domains associated with some strike-slip shearing components.
  - For the horst model, higher dilation developed in Arrinthrunga (top Arrinthrunga levels, in particular) in the hanging-wall side of the PPF. Dilatation at fault ends are lower than in the graben models.

- Permeability enhancement and fluid flow patterns:
  - The most important prediction of this group of models is that fluids tend to migrate more preferentially towards elevated stratigraphic horizons (see section and plan-view plots). These are the west side of PPF and east side of LCF in the PPF-LCF area where ~400m stratigraphic elevation are reflected by drilling data. This fluid flow behavior explains:
    - In the graben models, both the hanging-wall sides and the footwall sides of the PPF (elevated stratigraphic side) show permeability enhancement and fluid flow focusing; note that little permeability enhancement below the Arrinthrunga unit.
    - In the horst models, the hanging-wall sides of the PPF and the elevated stratigraphic side coincide. Therefore, permeability enhancement and fluid flow focusing predominantly occurred in the hanging-wall side of the PPF, adjacent to the fault. It is important to note that permeability enhancement and fluid flow focusing here occurred not only in Arrinthrunga unit but also the Red heart - Thorntonia horizons, and the intensity is greater than the graben models.
  - Some other fluid flow features are:
- Fluid flow patterns asymmetry here is less than what was observed in the previous dipping fault models. This is probably because the PPF is higher angle dipping (80 degree versus 70 degree), and LCF and cross faults are both vertical here.
- The presence of the vertical cross fault has some impacts on permeability enhancement and fluid flow patterns (e.g. intersection locations), even though it has very minor effect on shear strain patterns.

Deformation and fluid flow patterns (images)

Shear strain patterns

Graben (Case 1)  
Graben (Case 2)  
Graben (Case 3)  
Horst (Case 1)  

[Images of shear strain patterns for different cases]
Volumetric strain patterns

Graben (Case 1)
Graben (Case 2)
Graben (Case 3)
Horst (Case 1)

Section-view plots of permeability enhancement and fluid flow patterns
Graben (Case 1)

Max. flow rate = 1.37e-7 (m/s)
Plan-view plots of permeability enhancement locations and flux patterns
Drill holes were logged (overview logs) and photographed by Yanhua Zhang, Bruce Groenewald and Warren Polma, on two separate field trips, were used to constrain the stratigraphic columns and provide distinguishing lithological and rheological properties which were used as the basis for grouping/splitting units prior to building the 3D geological model.

These drill hole logs were combined with existing logs to constrain the conversion and interpretation of the various seismic lines and potential field datasets (including the derivative worm data). The 3D model provides the integrated down hole lithology groupings in spatially referenced digital format.

A significant amount of data and pre-existing interpretations were sourced from the SEEBASE report (SRK) and the NTGS report entitled Geology and resource potential of the southern Georgina Basin. Many of the derivative products provided in the SEEBASE report had significant spatial location errors, with products such as the depth to basement DTM not being internally consistent with either the drill hole logs or the seismic data. There were also numerous drill hole location errors in the NTGS data. These errors had to be deciphered and corrected before any of this data could be incorporated into the new model.

The NTGS 400m line-spaced aeromagnetic dataset was reprocessed by Mincor's consultants and provided as a total magnetic intensity (reduced to pole) ER Mapper grid which CSIRO used to calculate the WORMS, which were imported directly into GoCAD to help constrain the location and dip of major structures within the 3D model. The worms were also provided to Barry Murphy to generate his derivative interpretation products (which are described in detail in a separate report, and were also integrated into the 3D model). A workshop was held where Barry Murphy's interpretations as well as the seismic and raw WORMS were interrogated to decide which faults were significant enough to be included in the regional 3D geological model.

Mincor also undertook a major detailed gravity survey on a 2 km square grid over their tenement packages, with infill to the existing Arunta survey conducted to the south by the NTGS so that the two detailed surveys could be stitched together seamlessly. This provided an excellent dataset for the calculation of the gravity WORMS, which were also incorporated directly into the 3D model, with further detailed interpretation and derivative products provided by Barry Murphy for integration into the 3D model.

The historic seismic lines proved very difficult to obtain from the NTGS. Initially only 3-4 lines were available from the NTGS (sourced by Bruce Groenewald) and these were only available in paper format and PDF as two-way time images, and reliable spatial co-ordinates for the line end points were also not available (initially). Without depth converted images or
constraining petrophysical data it was nearly impossible to incorporate and use this data in the 3D model. It took approximately 8-10 weeks before the majority of seismic lines were sourced from the NTGS, and the X, Y corner points of the lines were known with any certainty, however the Z (vertical) spatial control was still a problem. Eventually several of the seismic line datasets were provided in digital SegY format, in which, while the resolution of the data was not as good as the PDF’s, the location data was better. It took a further week of QC and data integration before the seismic line data were confidently co-located with the drill hole and other geological datasets in 3D. Once this was done a decision was made (with Mincor) to use the drill holes to manually constrain the two-way time to depth conversion of the seismic data, rather than go to the time and expense of reprocessing the original seismic data, assuming the original data could ever be located. It must be noted that while this manual stretching (and double checking via approximating the (unknown) petrophysical properties of the units is reasonably accurate it lacks the precision of reprocessing the original data, thus accuracy errors of +/- tens of metres on the scale of the seismic sections are to be expected. For the sake of this model however, this error was deemed to be acceptable to Mincor.

• Throughout the data compilation phase described above, Bruce Groenewald was compiling a series of cross sections through the southern Georgina Basin utilising the drill hole data and SEEBASE surfaces as a starting-point from which to refine a series of more detailed 2D geological interpretations. These cross sections also formed a critical input into the 3D geological model build and were the basis for resolving some of the 3D geological interpretation issues that arise when generating a 3D geological model for a very large region with sparse data.

Building the 3D geological Model

All of the available data was imported into and spatially registered in GoCAD (a 3D geological modelling and GIS package). Regular meetings and workshops (every week or two) were held at CSIRO with Bruce Groenewald and other representatives of Mincor throughout the data compilation, importing and interpretation process.

• Where the data was available in digital format it was directly imported into GoCAD (with some requirement for grid conversions etc).

• Some drill hole data required conversion from paper logs to digital format (completed by CSIRO), and most needed significant spatial QC before it could be used reliably.

• The SEEBASE datasets (including the flawed depth to basement model) were imported into GoCAD and required significant and ongoing debugging and modification before these could be used in the final 3D geological model.

• The magnetic and gravity WORMS were imported directly into GoCAD and used to interpret the location and dip/dip direction of major faults.

• The various seismic line data were imported as spatially registered PDF’s as they became available, and once constrained (see notes above), were manually located and stretched to approximate the depth conversion from 2-way time. The seismic lines were interpreted, in 3D, constrained by drill hole logs and informed by the WORM interpretations as well as the Mincor cross section interpretations (which were also imported and registered in GoCAD once they were complete).

• Barry Murphy’s derivative WORM products and interpretations were used (in conjunction with other datasets) to interpret and rank the most important structures, and to decide which structures should be included in the 3D geological model.

• The 3D fault architecture was constructed first. This provided a framework upon which the stratigraphic variations could be interpreted using 3D Geomodeller software. This software enables geological surfaces (such as lithological contacts) to be automatically modelled
based on a set of geological rules, and subsequently reiterated rapidly as new data becomes available. This software, and model building methodology, significantly reduces the 3D geological model building time and allows for rapid automatic revision of the geological model when new data becomes available, rather than the traditional manual rebuilding of models which often takes as long to complete as the original model build.

- The subsequent 3D stratigraphic contact surfaces were then exported back to GoCAD where the surface intersections were cleaned up and the final model with all supporting data was delivered.
- The 3D geological model was also provided as a 3D PDF, and all model surfaces were provided separately in DXF format to enable them to be easily imported into other 3D modelling packages as required by the client.