3D Geological Map of the southern New England Orogen: Deep crustal structure

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ABSTRACT 3

INTRODUCTION 3

MODELLING WORKFLOW 5

PRE-MODEL PLANNING 6

Time/Resource allocation 6

Data availability, formats and quality 7

Standards 7

Modelling methodology 7

Software requirements 8

Model Scale/Resolution 8

Depth Extent 8

End uses needs 8

DATA SOURCING AND INTEGRATION 9

DATA INTERPRETATION AND GAPS ANALYSIS 10

Surface recognition of deep structure 10

Dip constraints on deep structures 11

Cross cutting relationships between deep structures 16

Data Gaps 19

REGIONAL STRUCTURAL ARCHITECTURE MODELLING 21

Workflow 21

CONFIDENCE MODEL 26

INTEGRATED MODEL (PRELIMINARY) 28

REFERENCES 29

Abstract

As the first step in developing a regional scale 3D geological map of the southern New England Orogen, a top-of-Palaeozoic surface and a number of deep crustal fault zones to depths of 20 to 30km have been modelled. The modelling process involved recognising deep structures and attempting to constrain their architecture using existing mapping and geophysical datasets. 4 major fault zones have been modelled: the Hunter-Mooki Fault System, the Peel-Manning Fault System, the Demon Fault and a previously unrecognised feature to the east of the Demon Fault, referred to here as the Drake edge. Due to limitations in available data, no faults have been modelled between the Peel and Demon Faults (Woolomin-Texas Block), despite there being clear evidence that major structures occur in the region. Further data collection or processing needs to be undertaken to provide enough constraint to recognise the strike continuity and down dip extent of fault zones in this area.

In addition to the modelled surfaces, a graphically representation of uncertainty has been developed using a system of 3D confidence level volumes. These volumes are based on containing points attributed with a numeric equivalent of confidence schemes applied to 2D mapping.

Introduction

This document gives an overview of the processes undertaken to develop the first pass 3D structural framework for the southern New England Orogen (SNEO) in northeast New South Wales. The model represents the first stage in developing a regional scale, solid 3D structural and stratigraphic map. It has been developed in parallel with the procedures or workflows set out here and will be further modified as the Geological Survey of New South Wales (GSNSW) continue to develop and refine its 3D mapping capabilities.

The development of a 3D map of the SNEO follows the completion of the New South Wales zone 56 seamless geology data set (Figure 1, Colquhoun et al. 2015) and is aimed to match the seamless dataset as closely as possible within the software, processing and interpretation limitations. The seamless geology dataset provides an internally consistent database of best available data. This reduced some of the data sourcing requirements in terms of compiling mapping over the area as well as sourcing available structural measurements. Furthermore, the attribution of objects within the database allowed for detailed querying and spatial selection to isolate and export specific line work from the database. In some cases however, the use of the exported line work was limited due to the node resolution of complex lines (Leapfrog and SKUA cannot deal with the high resolution of line work nodes in a model of this size) and also requirements of the 3D software (for example the requirement for fault surfaces to be extend to the model boundaries in leapfrog).

The model described here, has been developed in view of a number of key objectives:

1. Develop a regional scale structural framework to serve as the basis for more detailed infill modelling (structural, stratigraphy and basin volumes).
2. Further the recognition of strike extensive, and deeply penetrating fault zones.

3. Attempt to constrain and interpret the 3D geometry of the crustal scale structures, and their down dip intersection relationships.
4. Recognize where the gaps are in understanding and constraint of the crustal scale structural architecture.

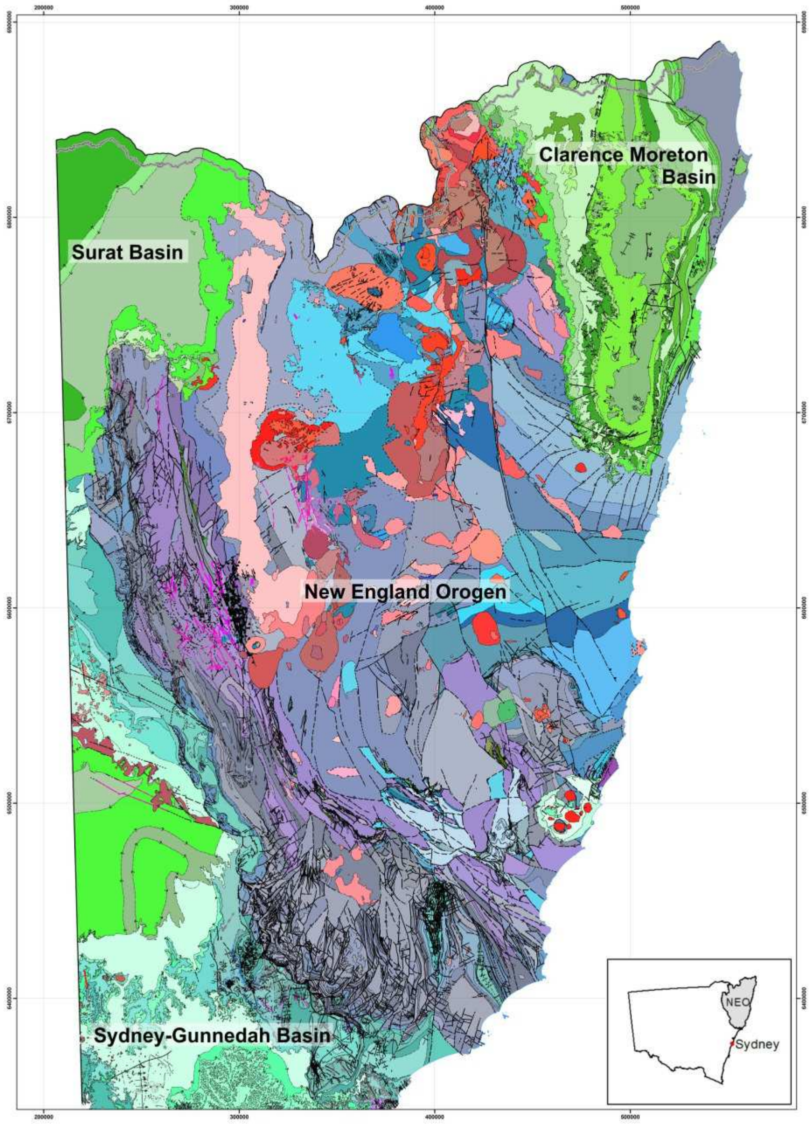


Figure 1: Solid geology map of the southern New England Orogen (SNEO) from the seamless z56 dataset (Colquhoun et al. 2015). The SNEO is overlain in the northeast by the Clarence Moreton Basin and to the west by the Surat Basin. To the southwest, the SNEO is thrust over the Sydney-Gunnedah Basin along the Hunter-Mooki Fault system.

Crustal scale fault zones provide a first order control of the regional scale architecture of orogenic provinces, and are also spatially associated with major hydrothermal ore systems. Orogenic provinces are commonly bound by strike extensive, and deeply penetrating fault systems. Internal lithological, age, magmatic bodies, structural and metamorphic discontinuities are also closely linked to major fault systems. In generating a regional scale 3D map, the first step must therefore be to recognize, constrain and interpret the geometry of, and relationships between these structures. The recognition of crustal scale fault zone also has more direct application in reducing search space for hydrothermal ore systems. Spatial association with crustal scale fault systems is a well-known characteristic of major hydrothermal ore systems (e.g. Groves et al. 1998; Betts & Lister 2002; Bierlein et al. 2006, Blenkinsop et al. 2008), the delineation of which is an important step in regional scale exploration targeting.

This document follows the modelling workflow used in the production of the current 3D model. It sets out the key planning decisions, the constraining data and sources of data as well as briefly summarising additional interpretation of source data undertaken specifically for this work. In addition to giving an overview of the current outcomes of the work, a summary of the method and outcomes of the generating the confidence volume model is also provided. It should be noted that the model being described is the first pass attempt to model the crustal scale structures of the SNEO, and as further described in the data interpretation and gaps analysis section, there are major areas of uncertainty where modelling is not possible without further data acquisition and geophysical modelling.

Modelling Workflow

The 3D mapping process under-development by GSNSW involves a broad project workflow (Figure 2) that sets out different stages of model development, with a series of sub-workflows that deal with specific aspects of the modelling. Sub-workflows are being developed for stages 4, 5 and 6 of the project workflow. Much of the work described here is focused toward stage 4a of the project workflow (Regional structural architecture modelling), and therefore on the requirements of developing regional scale structural framework around which the subordinate fault architecture and lithological modelling (sub-workflows 4b, 5a and 6a) is built. This workflow is detailed in the regional structural architecture modelling section.

The 3D project workflow recognizes the scalar and interlocking nature of orogenic provinces and basins, as well as the structures and stratigraphy contained therein. It aims to prioritize the large scale features then work down in scale to infill with increasing detail. That said it is expected that additional constraints and improvements in interpretation resulting from more detailed modelling will be fed back up the workflow to refine the large scale features where applicable.

A key feature of the workflow is the confidence model, and all stages of interpretation and modelling feed attributed point data into the confidence model. Any model produced will include a confidence model, irrespective as to whether subsequent stages of the workflow have been completed (i.e. if a model has been produced it will have a confidence model).

The outcome of the 3D project workflow is an integrated model. This may comprise as little as a crustal structure model and corresponding confidence models. However, it is intended that all models produced within the workflow can be visualized together to form a single, seamless model.

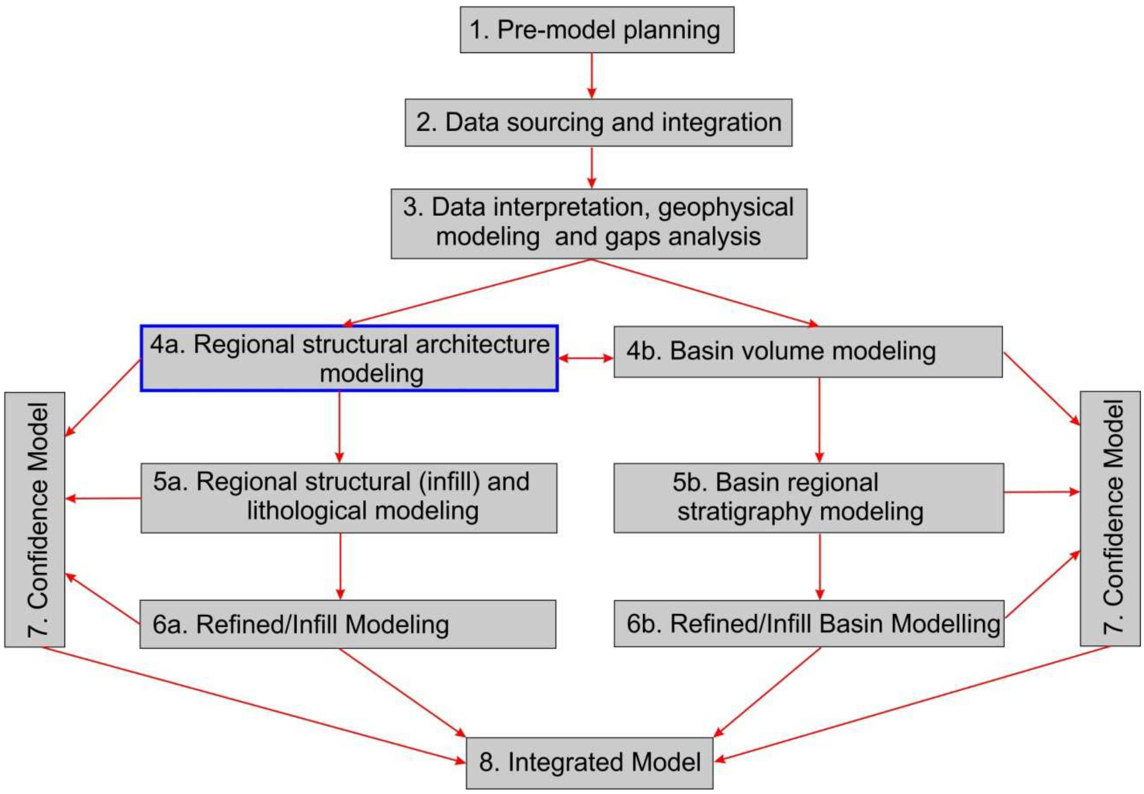


Figure 2: GSNSW 3D mapping project workflow. The work stage highlighted in blue is the primary focus of this document and the sub-workflow will be set-out in more detail.

Pre-model planning

There were a series of considerations examined prior to the commencement of this work that while largely applicable to modelling of crustal scale structures as documented here, had a broader perspective in regards to the overall GSNSW 3D program. One of the initial objectives at the commencement of the modelling program was that all models should interlock within a broad statewide framework and that all models should be consistent with the GSNSW seamless geology datasets. To attempt to achieve this requires consistency in standards between different models. As such the pre-model planning does have a broader, 'state-wide' perspective. What do we want to achieve it long term and how do we start to standardise our procedures?

The factors considered during the planning of the project are set out below.

Time/Resource allocation

How much time do we have to complete a model? Either the resolution, and scale of the model will need to be adjusted to the time available to construct the model or the time and resources will need to be made available to model to aimed resolution (e.g. more detailed models will require more time).

This consideration is dealt with in part by staging the modelling workflow to first construct a broad-brush structural/regional model with an aim of future infilling and refinement.

Data availability, formats and quality

What data types, distribution and quality are available in the objective area to be modelled? This will influence the resolution of the model, depth extent of modelling, time and resource allocation to digitize, translate, filter, interpret and produce derivative datasets from the raw data.

This question represents the biggest variable in the 3D program (as with most geological projects). The best solution (given we need to standardise many of the other model variable to allow seamless model integration), is we attempt to get as much constraint out of the data we have, but model uncertainty so the end user is provided with reliability information for different parts of the model. Unconstrained interpretation will exist in the model, but the end user can quickly and easily observe where they are. This will also serve as a graphical representation of data gaps.

Standards

What coordinate system is to be used? Will the model need to fit with other models and therefore need the same coordinate systems? Z axis positive upward or downward? How will objects be named in a consistent and manageable way.

Models are generated in GDA94, within their relevant zone or in the dominant zone where a model occurs crossing a zone boundary. This will minimize data translations during the production of the model. For purposes of model integration, a zone 55 translated version of a model may be produce when integration is required. Note 3D modelling software generally does not have variable projected coordinate systems. The user must ensure all objects imported into the software are in the same system.

Z axis values will be positive upward (some basin, seismic derived models use positive downwards).

Objects are named so that similar objects will group in a project tree in 3D packages or viewers. An example is: NEO_TBFN_Flt_SeamGeo_Peel, where `NEO' represents the model, `TBFN' represents the submodel, `Flt' indicates that the object is a fault, `SeamGeo' indicates it originates from the seamless geology and `Peel' is the name of the fault. Using this method, all the faults in submodel TBFN will group together in the project tree, making them easier to find and manipulate.

Modelling methodology

There are three basic end-member methods considered:

1. Develop a series of key cross sections in constrained areas (from seismic, drilling, geophysical modelling and surface mapping) then use surface map data and any intervening constraints to link the sections.
2. Work directly from seismic and drill holes, interpreting horizons and structures and linking with surface line work.

3. Work from surface mapping line work, constraining dip with structural measurements geophysical modelling, drill holes and seismic.

The SNEO crustal scale faults were modelled using a combination of methods 1 and 3.

Software requirements

Software used for modelling may vary according to methodology and model style. For example, SKUA can be used when modelling from seismic and boreholes, but does not deal well with complex geometry, while leapfrog can't deal with seismic but can be used to model complex geometry.

As in this case the large scale faults will be used to bound complex structural and stratigraphic geometries, leapfrog has been used to generate the faults. However, these faults could also be generated in SKUA.

There are also a range of other software packages used in support of the 3D applications. These are noted where used in the regional structural architecture modelling workflow.

Model Scale/Resolution

What level of detail of faults and lithological units is to be used?

In the GSNSW statewide models, lithology within orogenic provinces are grouped into geological periods. This tends to work at this scale in that there are not large numbers of complex surfaces, but the contacts between the age domains will provide a good representation of the folded geometry/enveloping surface.

Second and third order faults are incorporated into the model based upon their importance in controlling the geometry of the geological period interfaces. In most cases it is very difficult to build a contact without putting faults in that offset the contact.

Depth Extent

Large scale, low resolution models are probably best extended to 25 to 35km depth, but smaller scale models corresponding to 250k mapsheets are probably better modelled to 5 to 15km given the added detail and complexity in the models.

End uses needs

What are the model outputs likely to be used for and therefore what are the key features to be modelled? Features should be scale appropriate.

e.g. For minerals, large scale models should focus on recognising and constraining the geometry of strike extensive and deeply penetrating structures. They should also capture the regional stratigraphic architecture (fold plunges, dip directions).

For water resources the model should allow for estimation of stratigraphic volumes, dip directions, fault/flow barriers.

Data sourcing and integration

Constraining data used in the production of the crustal scale fault model is summarised in Table 1. The model is based dominantly on the seamless geology products and seismic lines.

The 9 second digital elevation model (DEM) dataset (Geoscience Australia) was regridded to a 1000m and used to produce a 3D digital terrain model (DTM). The reduced grid spacing is considered appropriate for the scale of the SNEO model, given the model area is 450 by 320km. More detailed grids at this scale require high end computer hardware, which will still have difficulty dealing with grids with spacing below 500m.

Seamless geology map products were sub-divided into geological province. The divisions were New England Orogen, Great Australian Basin (Surat and Clarence Moreton Basin) and Permo-Triassic basins. No Mesozoic igneous or Cenozoic igneous / sedimentary geology was modelled in the SNEO project. To provide an upper constraining surface for structural modelling of the SNEO, younger basin cover volumes needed to be subtracted from the DTM surface as to allow structures and lithological volumes to be terminated at the basement-basin interface. Therefore, constraints on the basement-basin interface were isolated (from seismic, drill holes, and surface structural measurements) to generate a basement surface.

Seismic constraint of the major crustal fault zones is dominantly along the west and south-western margin of the model (the Tamworth Belt). Only one, deep crustal seismic line exists (BMR91_G01), but the quality, particularly below 4 seconds is quite poor. The DPI Hunter Mooki Survey is the best quality seismic in the area, but none of the lines extend east across the Peel fault system. In the northern extension of the Tamworth Belt, below the Surat basin, as high quality 4 second seismic survey (MacIntyre survey) provides the best constraint on the dip of the Peel Fault, although relationships with the northern extension of the Mooki Fault (called the Goondiwindi Fault in this area) is not evident because of the shallow extent of the seismic.

Multiscale potential field gradients (Worms) were generated using WormE^{TM}, to examine their application to defining and constraining regional scale structures. Edges in the dataset have been processed at heights of upward continuation from around 800 to 68000m, however the dataset was filtered to remove the lower ~4000m of upward continuation to highlight edges with the highest upward continuation, and therefore representing the deepest penetrating discontinuities in magnetic susceptibility and density.

Data Type	Name	Source	Date	Notes
DEM	NEO_DTM_1000m	Geoscience Australia 9s DEM (GADDS)	2008	Regrid of the 9 second DEM data
Geological Map	1_Seamless_z56_NEO	GSNSW Seamless Geology	2015	Subset of the seamless geology z56 dataset.
Geological Map	6_Seamless_z56_GAB	GSNSW Seamless Geology	2015	Subset of the seamless geology z56 dataset.
Structural Data	NEO_Bedding	GSNSW Seamless Geology	2015	
Structural Data	NEO_Cleavage	GSNSW Seamless Geology	2015	
Structural Data	NEO_Flt_Ref_Demon	Babaahmadi & Rosenbaum 2013	2013	Estimated or digitised from published data
Seismic	BMR91_G01	Geoscience Australia	1991	1 line
Seismic	DPI Hunter Mooki 2007	GSNSW	2007	6 lines
Seismic	P06_MacIntyre	Pangaea Oil & Gas	2006	11 lines
RTP TMI Image	4_NEO_1VD_TMI_RTP_BBG	GSNSW	2015	
Bouguer Gravity	7_NSW_Geophys_Spherical_Cap_ Bouguer_Gravity	GSNSW	2015	
Multiscale edges (Gravity)	NEO_ME_Grav_800_to_12000m NEO_ME_Grav_14000_to_68000m	GSNSW	2014	
Multiscale edges (Magnetics)	NEO_ME_Mag_800_to_70000m	GSNSW	2014	

Table 1: Summary of source data used in the modelling of the crustal scale fault zones in the SNEO.

Data interpretation and gaps analysis

Surface recognition of deep structure

Comparison between the multiscale edges and seamless geology dataset recognises 3 major crustal scale fault zones (Figure 3: referred to as Edge A, B, C). A further deeply penetrating fault zone is also recognised in gravity edges, which corresponds to a series of discontinuous mapped faults and is thus interpreted to represent a major structural zone (Figure 3: referred to as Edge D).

Edge ‘A’ in figures 3 and 4 (Gravity and magnetics), roughly corresponds to the Mooki Fault System but generally occurs to the east of the mapped position of the fault. The Mooki Edge has a strike extent of >400km, and an upward continuation of up to 68km.

Edge ‘B’ in figure 3 and 4 (Gravity and Magnetics) roughly corresponds to the Peel-Manning fault system and has a strike length of >450km, and an upward continuation of up to 43km.

‘C’ in figure 4, is dominantly a series of breaks or offsets in NNW and NE trending magnetic edges that corresponds to the mapped location of Demon Fault. It’s strike length and relative level of upward continuation is more difficult to estimate (as it is not a continuous edge), however, truncation of edges appear to go as high as 65km of upward continuation, while offsets can be observed along a strike length of >300km.

The fourth deep feature marked ‘D’ in figures 3 and 4, does not correspond to any continuously mapped fault zone in the area. This feature is a major gravity and magnetic edge that does correspond to a discontinuous series of zones of mapped faulting and intrusive bodies. The edge also corresponds to the trend of a large number of known hyrothermal ore system occurrences at surface (Figure 5). Attributing this edge to the Demon Fault is difficult, as it is oblique to very clear surface expression of the Demon Fault (in mapping and topography). The Demon Fault also has an expression in the edges as ‘breaks’. Furthermore the hyrothermal ore-systems in the area do not appear to have a spatial relationship to the Demon Fault (Figure 5).

Dip constraints on deep structures

The interpretation of dip along the 4 major fault zones is based dominantly on seismic for the Hunter-Mooki and Peel-Manning systems, surface measurements for the Demon Fault, and Multi-scale edges for structure ‘D’. Figure 6 shows the distribution of seismic lines in the SNEO, although it must be noted that most of the seismic is targeting basin sequences overlying the NEO (Clarence Moreton, Surat and Gloucester).

The Hunter-Mooki Fault is clearly observed as a low-angle, east to north-east dipping system in all seismic lines that cross it (Figure 7 and 8). The interpretation of the dip Hunter-Mooki Fault in this work is consistent with previous seismic interpretations (Korsch et al. 1993, Glen & Roberts 2010). In most of the lines the fault is subparallel to bedding before steepening by 5 to 20^o and cross-cutting reflectors at a low to moderate angle. The point of refraction commonly corresponds to the location of splays from the fault, and also the horizontal location of the gravity and magnetic edge. In figure 7, the fault zone appears to broaden at depth. It is interpreted on the seismic images as hangingwall and footwall faults between which reflectors are difficult to distinguish and a zone of consistent seismic trace attributes occurs. The geometry of the fault and the initial parallelism with stratigraphy (reflectors) may explain why the gravity and magnetic edges corresponding to the fault occur to the east of the mapped surface expression. The magnetic and gravity edges better image steeper features, and low dip structures parallel to stratigraphy will not be detected.

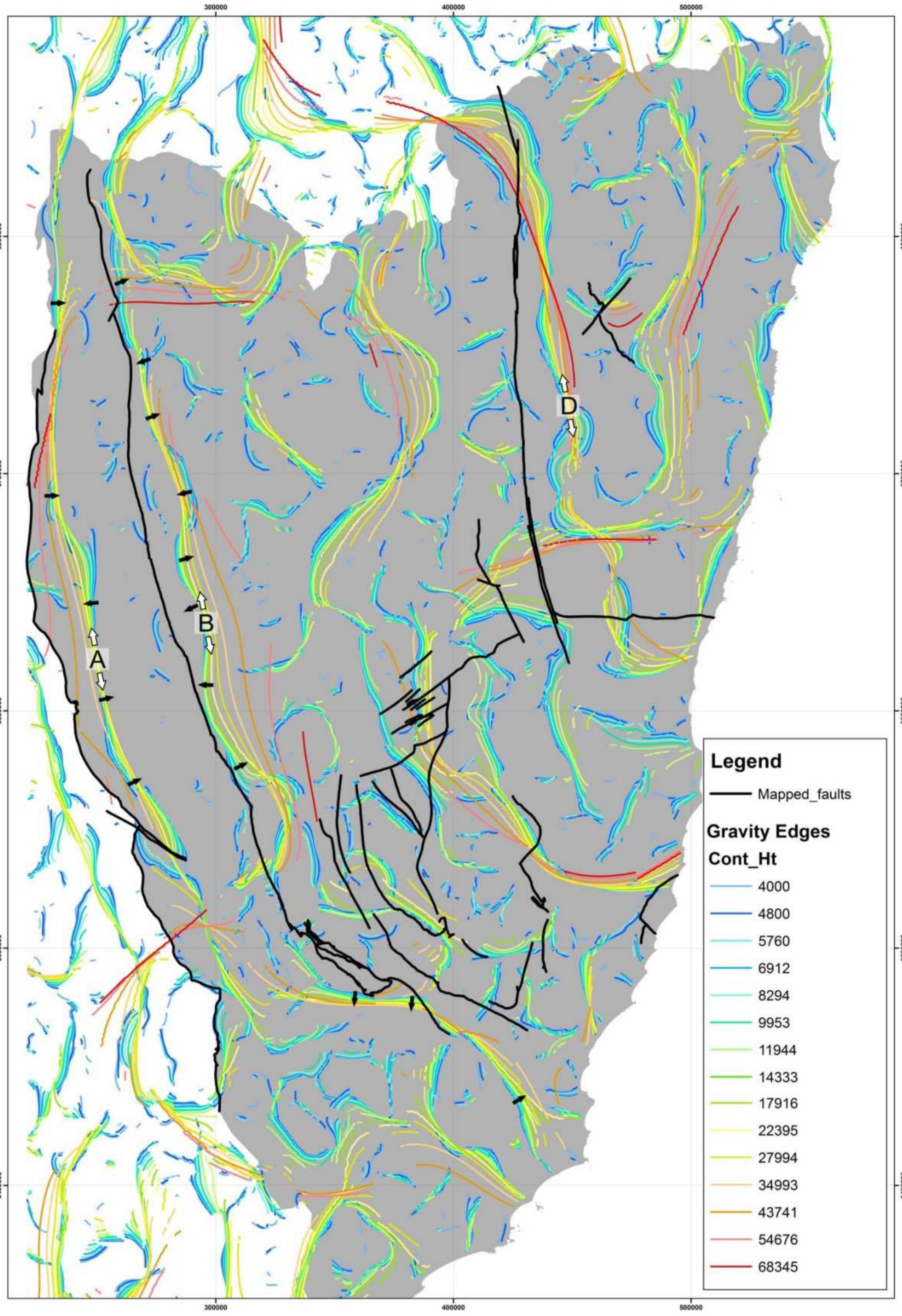


Figure 3: Multiscale potential field gravity gradients (Worms) with mapped major faults. Edge A is related to the Mooki Fault system. Black arrows represent dip direction of edge interpreted from low level upward continuation. Edge B is related to the Peel-Manning Fault system. Black arrows represent dip direction of edge interpreted from low level upward continuation. Edge D has not previously been recognised as a major structural zone but is considered not to relate to the nearby Demon Fault.

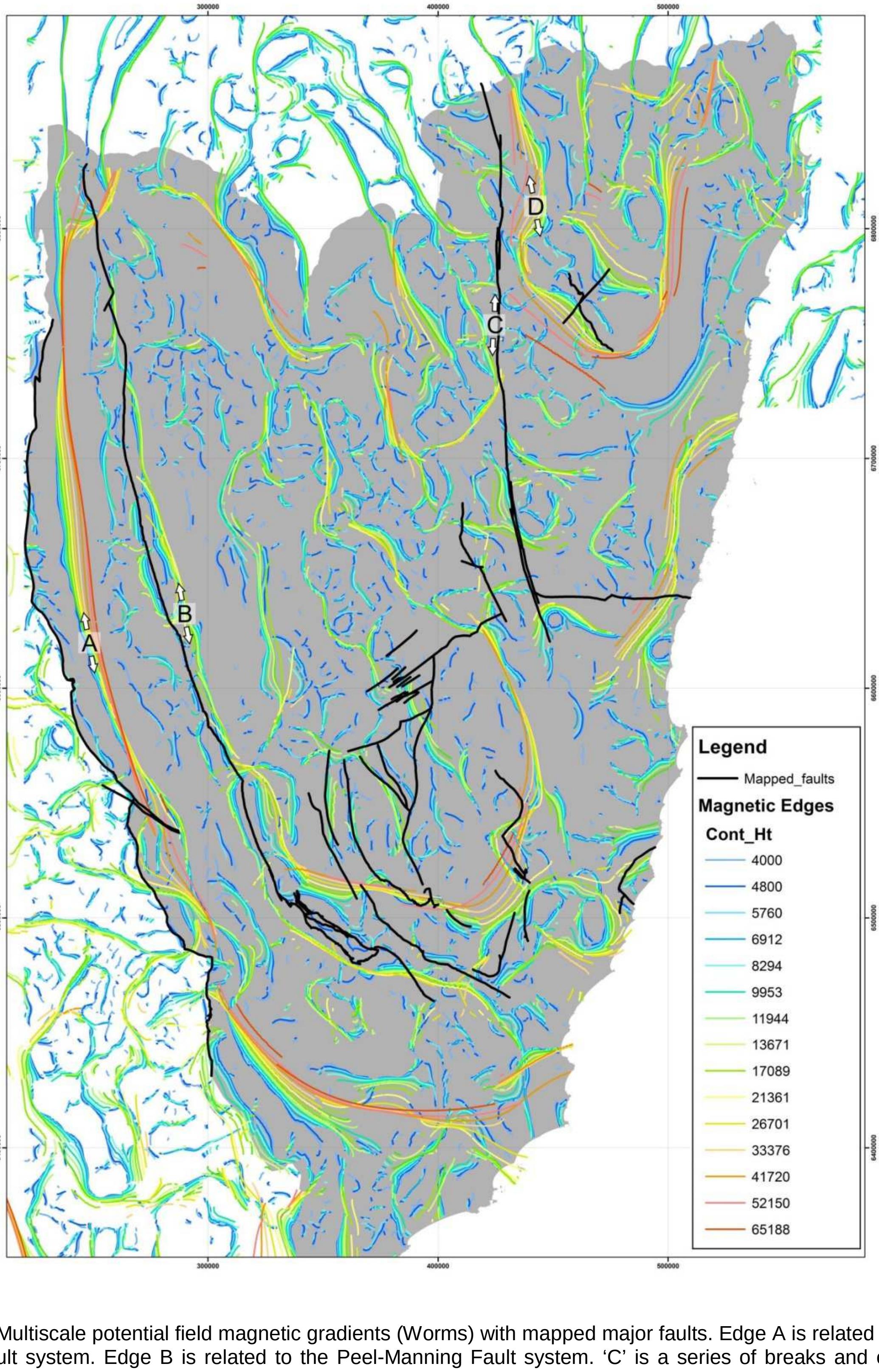


Figure 4: Multiscale potential field magnetic gradients (Worms) with mapped major faults. Edge A is related to the Mooki Fault system. Edge B is related to the Peel-Manning Fault system. 'C' is a series of breaks and edges related to the Demon Fault. Edge D has not previously been recognised as a major structural zone but is considered not to relate to the nearby Demon Fault.

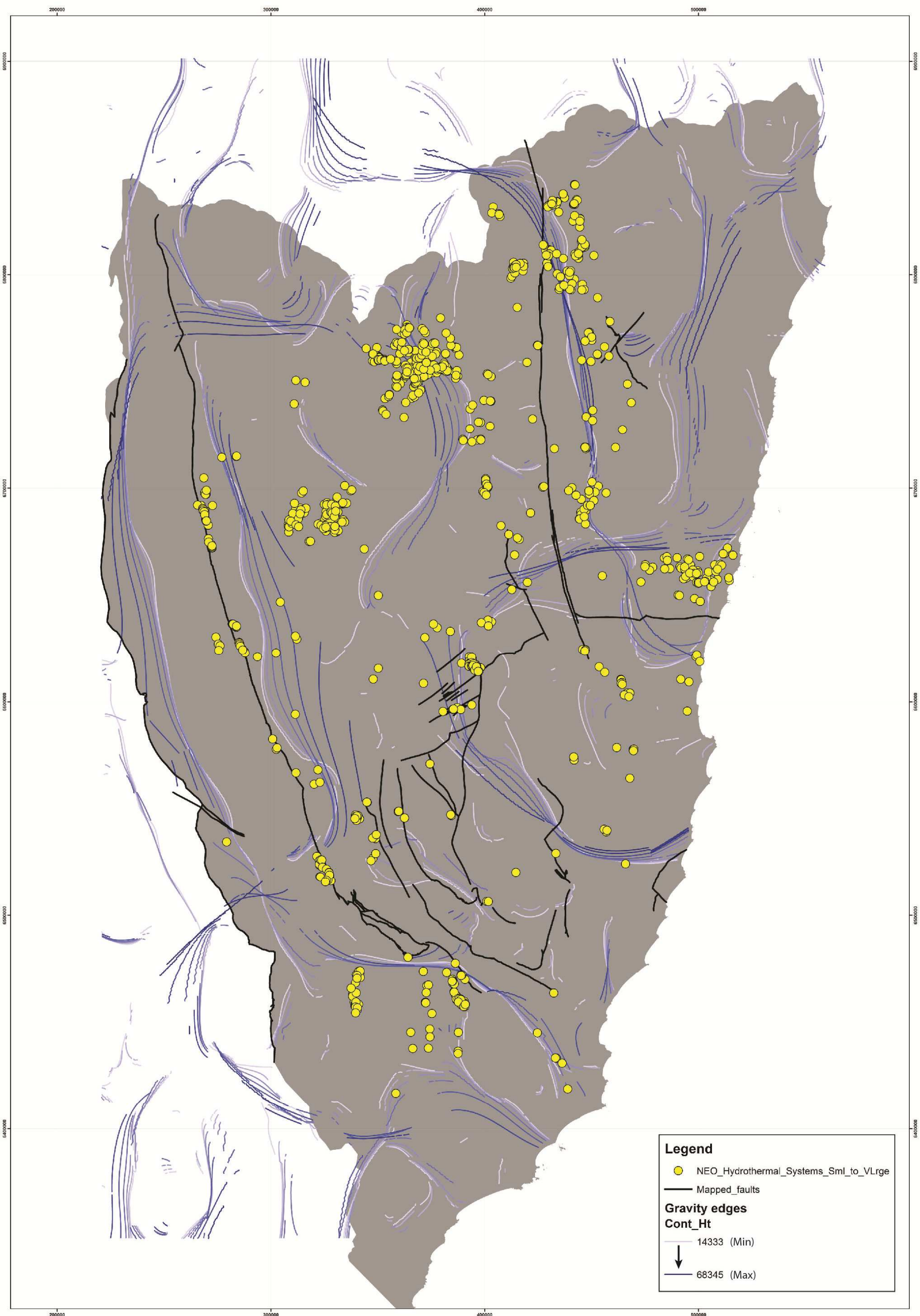


Figure 5: Multiscale potential field gravity gradients (Worms) with mapped major faults and locations of known small to very large hydrothermal ore systems (based on classification scheme of Downes et al. 2011). A good correlation exists between the deep edges and known systems. Note also the general lack of systems west of the Peel Fault.

Dip on the Peel-Manning Fault system is far more difficult to determine but based on the data used in this work, the best fit is steeply west. Previous interpretations have indicated both east and west dip (e.g. Korsch et al. 1993; Glen & Roberts 2010). The deep crustal seismic line that crosses both the Mooki and Peel Faults (DMR91_G01) images the Peel Fault very poorly (not unsurprising for a steep structure). The area corresponding to the Peel Fault in the seismic line is characterised by a loss of clear reflectors. The seismic trace attributes do assist to some degree in that the upper 2 seconds show a clear west dipping edge in the geometric attributes (Figure 7 B, C, D and E). It is difficult to project an east-dipping fault from surface given there is no significant break across a west-dipping zone of consistent geometric attributes immediately east of mapped fault position. The clearest indication of a possible west-dipping Peel Fault in this data is observed in the envelope amplitude, which highlights major changes in lithology (Figure 7 F). Truncation of low to moderate dipping boundaries can be interpreted against a west-dipping surface in this plot.

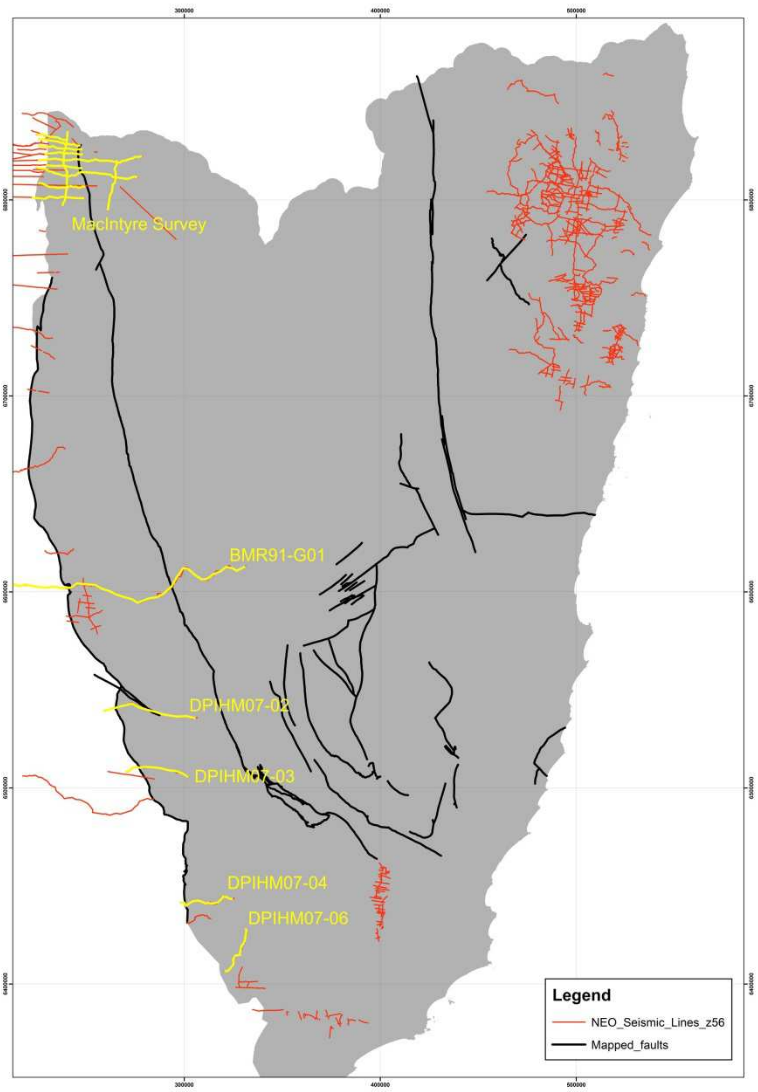


Figure 6: Seismic line location in the SNEO relative to mapped major faults.

The best evidence of a westward dip to the Peel Fault is in the MacIntyre seismic survey in the far north of the Tamworth Belt (below the Surat Basin) (Figure 6). Interpretation of this seismic data in this work, and also by Grieves (2007), indicates a westward dip to the Peel Fault (Figure 9). There are a total of 7 seismic lines in the MacIntyre survey that cross the Peel Fault under the Surat Basin along a 22km strike length. In all lines the interpreted Peel Fault dips west.

Dip estimates using the multiscale edges are largely consistent with the dip directions estimated from the seismic. The dip direction indicated by the low-level, upward continued edges does vary along strike on both the Mooki and Peel edges. The Mooki edge is interpreted to dominantly dip east, and the Peel edge dominantly west (Figure 3).

Dip and dip direction of the Demon Fault is constrained only by surface measurements and the dip of terminations in intersecting edges. Surface measurements published by Babaahmadi and Rosenbaum (2013) indicated the Demon Fault dips steeply east and west. Magnetic edges of intrusive bodies juxtaposed to the fault appear largely consistent with the surface measurements, however, the relatively shallow nature of many of these edges (and unreliability of dip estimates with higher upward continuation) means the dip at depth is unconstrained.

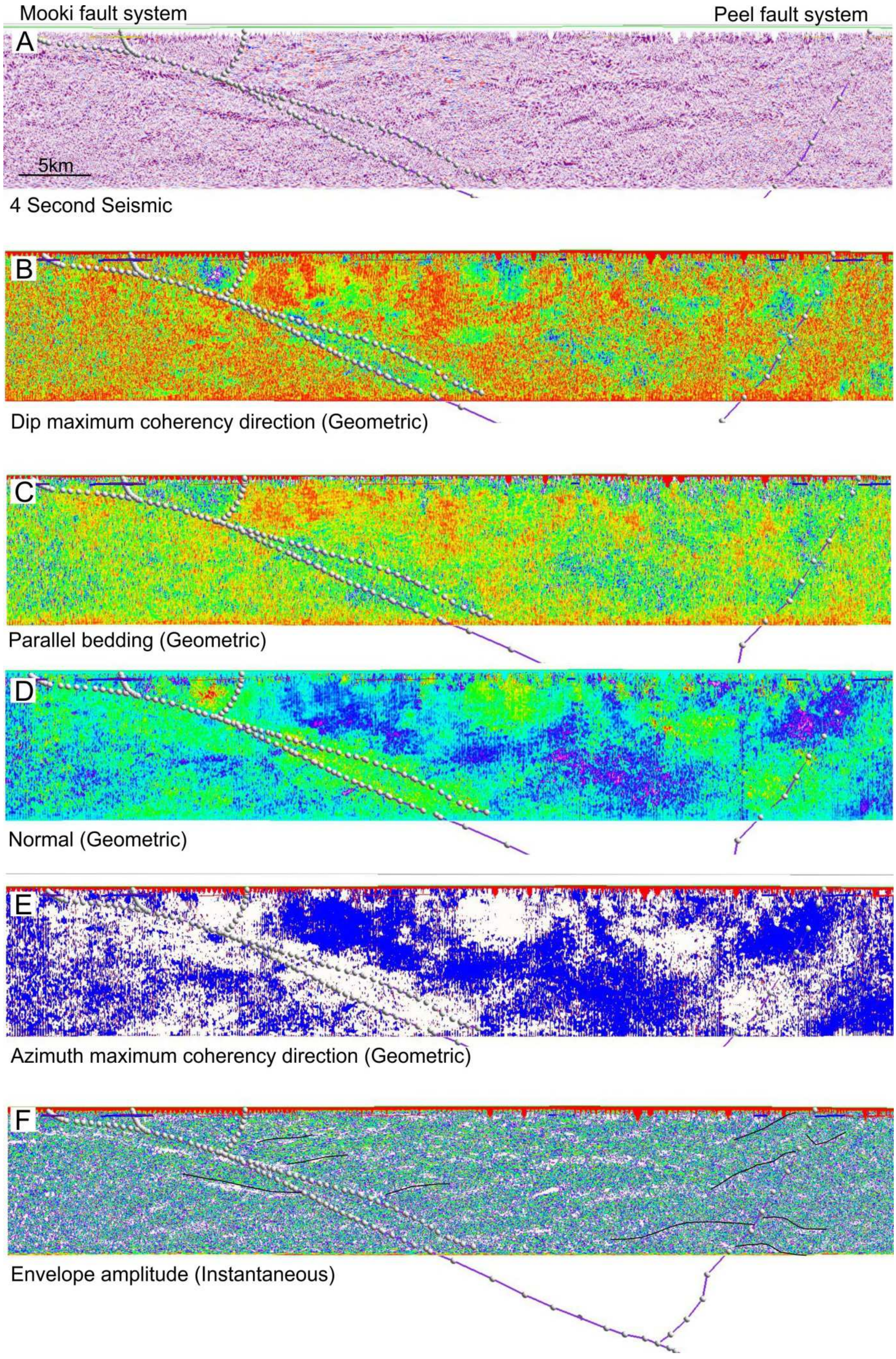
Dip on the fourth deep structure (D or 'Drake edge') is constrained only by dip estimates from the low level, upward continued gravity edges. There is some variability in the dip direction based on the lower levels of upward continuation. However, the fault zone is interpreted to dip steeply east. Dip of this fault at depth is unconstrained.

Cross cutting relationships between deep structures

The Hunter-Mooki and Peel-Manning Fault systems are the only faults in current dataset that are interpreted to intersect at depth. The Peel Fault System is inferred to terminate, or splay off the Hunter-System at depth because:

1. The Mooki appears to continue down dip east of the projected location of the Peel Fault based on the Seismic Trace Attributes in the 20 second BMR91_G01 line.
2. The Mooki Edge has higher upward continuation in both gravity and magnetics than the Peel Edge.
3. The occurrence of significant hydrothermal mineral systems around the Peel Fault and generally not further west (Figure 5), is consistent the relationship between orogenic gold systems and the deep fault architecture in western Victoria, particularly the relationship between the Moyston Fault (an east dipping thrust and major terrain boundary) and the west dipping listric faults in its hangingwall (See Cayley et al. 2011).

Figure 7 (below): Seismic Line BMR91-G01 crossing the Mooki and Peel fault systems with seismic trace attributes plotted to assist constraining the faults. A) 4 second seismic. B) Coloured by dip of maximum coherency direction. C) Coloured by zones parallel bedding. D) Coloured by Normal to maximum coherency direction. E) Azimuth of maximum coherency direction (Geometric attribute). E) Reflection strength or Envelope amplitude (instantaneous attribute).


Mooki fault system
Peel fault system
A
5km
4 Second Seismic
B
Dip maximum coherency direction (Geometric)
C
Parallel bedding (Geometric)
D
Normal (Geometric)
E
Azimuth maximum coherency direction (Geometric)
F
Envelope amplitude (Instantaneous)

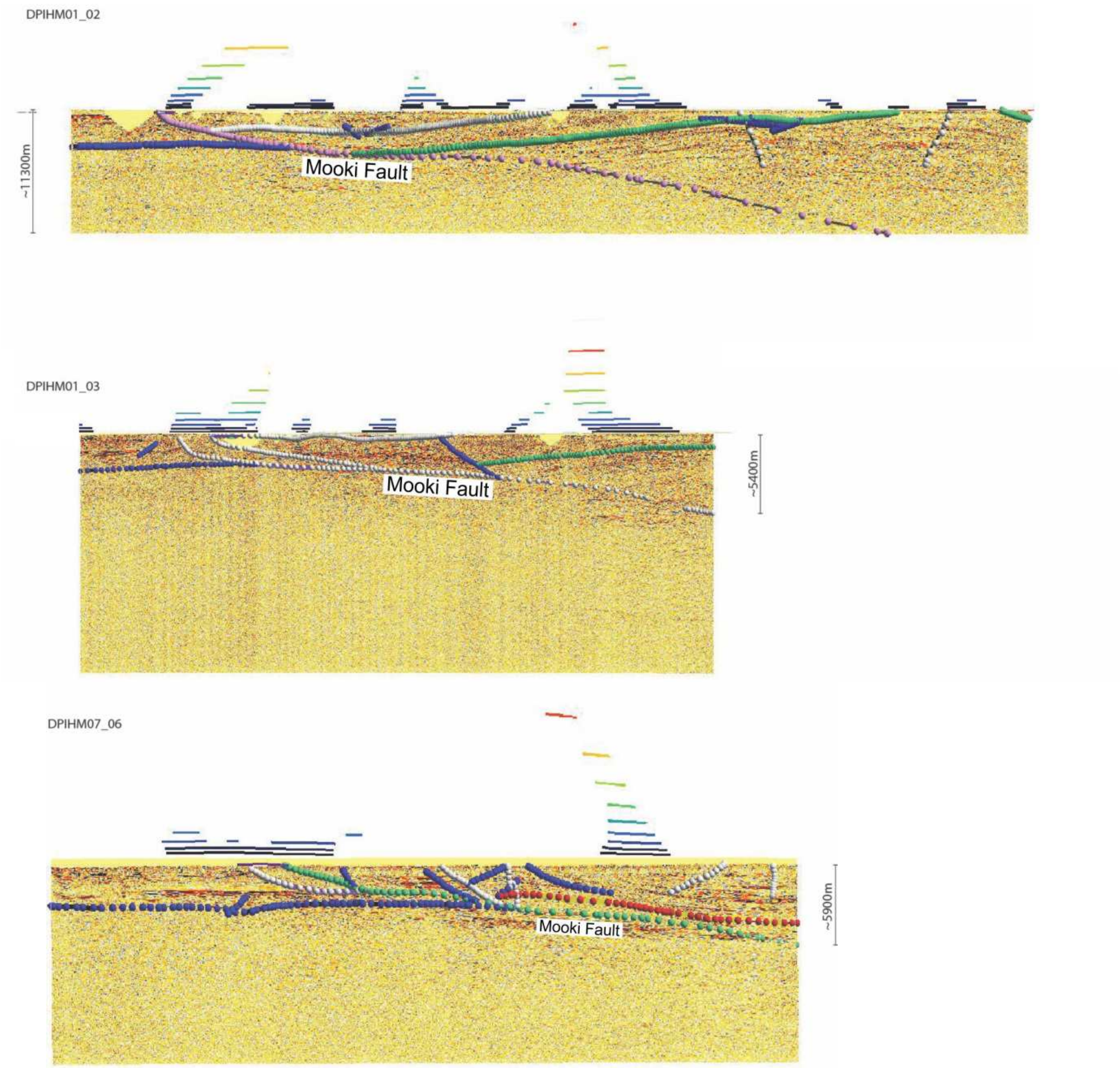


Figure 8: Interpretation of major structures in seismic lines across the Mooki Fault with gravity edges (worms) in section. Note depth estimate is provided for scale on each section. The Mooki Fault is a shallow east-dipping fault that is initially sub-parallel to bedding, that steepens and cross cuts stratigraphic reflectors at depth. The edges in the gravity data occur where the fault is steeper, and cross-cuts the reflectors.

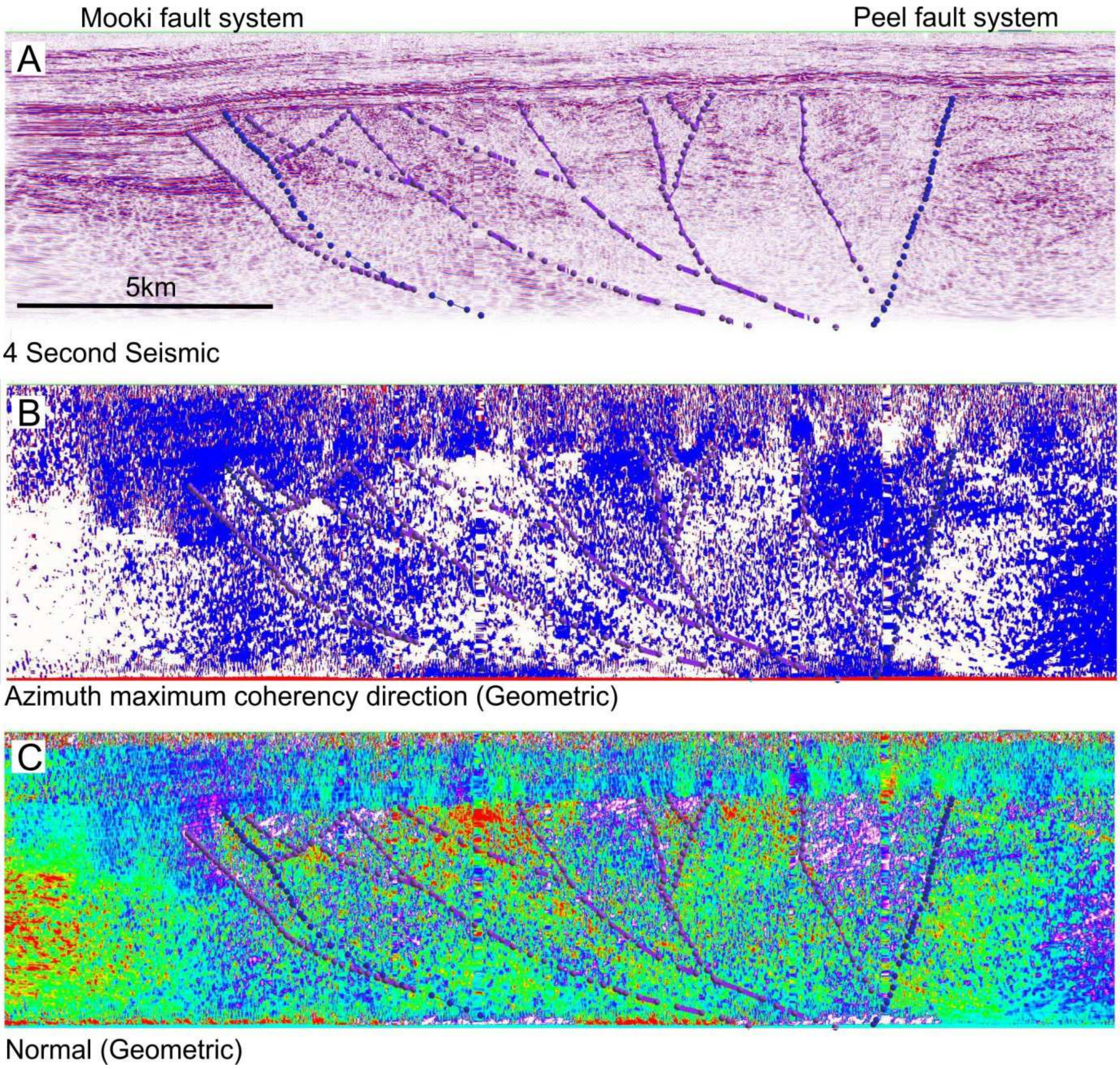


Figure 9: Seismic Line MacIntyre p06_04 crossing the Mooki and Peel fault systems with seismic trace attributes plotted to assist constraining the faults. A) 4 second seismic. B) Azimuth of maximum coherency direction (Geometric attribute). C) Coloured by Normal to maximum coherency direction.

Data Gaps

Much of the deep structure in the SNEO is relatively poorly constrained and a large part of the Woolomin-Texas Block contains insufficient data to model any large scale structure, despite evidence that crustal scale structures exist in region. Improving and expanding on the current model requires constraint in the following area's in particular:

1. Woolomin-Texas Block

   This regional contains a large number of structurally controlled mineral systems with good potential for further significant discovery. The gravity and magnetic edges, and particularly the correlation between deep edges known hydrothermal mineral systems and I-Type granite intrusions, indicate the presence of a deeply penetrative structural network. However, poor exposure and extensive intrusion has resulted in the scale of structures not being recognised at surface. The deep crustal architecture in this regional is also poorly understood, with most of the deep seismic restricted to the western margin of the province, and magnetic and gravity coverage over much of the area being of relatively poor quality.

2. Demon Fault-Drake Region

   The deep architecture of the Demon Fault, and the surface expression and deep architecture of the 'Drake edge' is poorly constrained. More detailed structural study of the region immediately east of the Demon Fault may provide constraint on the 'Drake edge'. Improved geophysical modelling and seismic acquisition would further constrain the deep architecture.

3. Southern Tamworth Belt

   While the Hunter-Mooki Fault is relatively well constrained along the western margin of the Tamworth Belt, its relationship to the Peel Fault and continuity to the east is relatively poorly constrained. Furthermore, the relationship between the Hunter Fault, the Sydney Basin and the Lachlan Orogen in the south is also poorly constrained. In this model, it is simply cut off along the line of its mapped termination. While high resolution magnetic data has recently become available in this area, the model depth required to constrain the fault probably require quality gravity data and/or seismic.

Regional structural architecture modelling

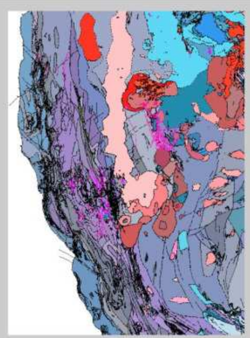
Workflow

The regional architecture modelling workflow (Figure 10) sets out the basic process and constraint requirements to generate a 3D map of deep crustal fault zones. This workflow was developed specifically for the New England Orogen model based around the available datasets and the quality of the available datasets. Further stages or sub-processes are likely to be added in future modelling where additional datasets and methods are available (e.g. modelling of magnetics and gravity).

Figure 10 (Pages 22 to 25): Workflow used to generate the SNEO deep crustal structure model.

Combination of seamless geology fault linework, magnetic and gravity multiscale edges and reflection seismic surveys used to identify mapped fault zones that are strike and depth extensive.

Software: ArcGIS, SKUA or Seisee



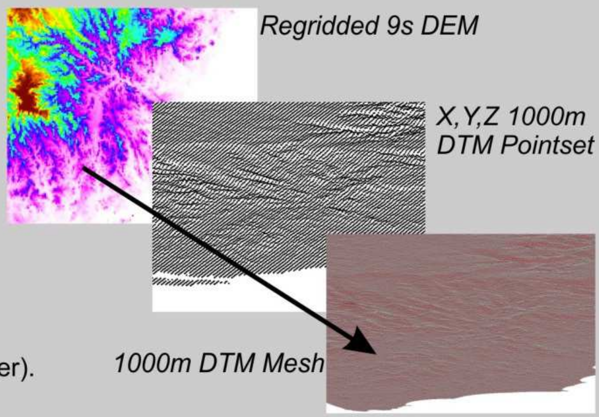
Seamless mapping

Filtered deep edges

Geoscience Australia 9 second DEM data converted to point (X,Y,Z) data and resolution reduced (to 1000m grid). Point data imported into leapfrog and used to generate topographic surface.

Software: ArcGIS (DEM to ascii pointset).
Leapfrog (Surface interpolation and clipping).

Subprocesses: Coord system translation.
Conversion of raster to point or multipoint data.
Surface clipping using geographic boundary cutters (e.g. Coastline, state border).



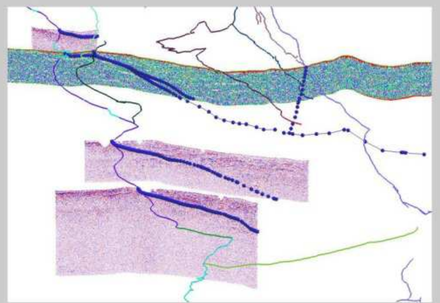
Regridded 9s DEM

X,Y,Z 1000m DTM Pointset

1000m DTM Mesh

Linework for individual faults extracted from seamless database and imported into Skua along with seamless mapping draped on DTM. Down-dip extension of target faults zones delineated along seismic lines.

Software: SKUA

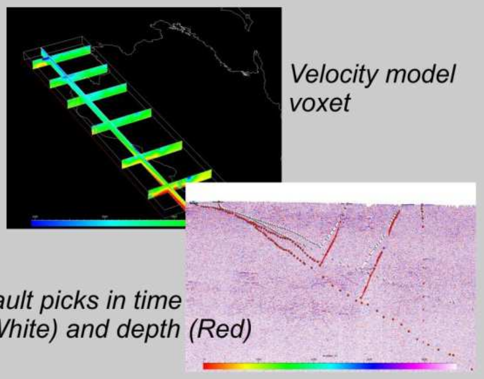


Seamless fault line work projected down dip on Seismic

Seimic linework time-depth conversion.

Software: SKUA, Excel

Subprocesses: Seismic Velocity data collation
Seismic velocity model generation



Velocity model voxet

Fault picks in time (White) and depth (Red)

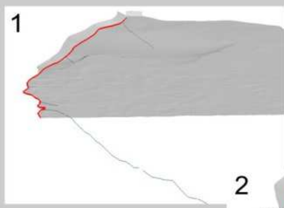
Option 1: Depth converted fault dip linework, along with surface linework imported into leapfrog.

Software: Leapfrog

Option 2: Depth converted seismic iterpretation used in combination with seamless mapping to generate cross sections which are then imported into Leapfrog and linework digitised.

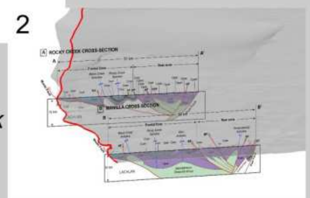
Software: ArcGIS, Illustrator or Coreldraw, Leapfrog

1



Direct imported seismic interp. linework

2

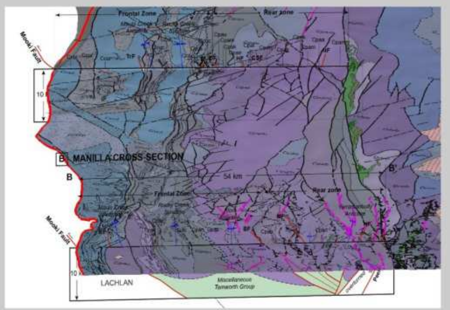


Seismic linework used to create cross sections

Georeference seamless geology map imported and draped on topographic surface along with line work shape files.

Software: ArcGIS, Leapfrog

Subprocesses: Export georeferenced province layers separately (e.g. NEO, GAB) or export with grid and georeference in LF.
Set elevation of imported line work shapefiles to topography.
Check line work against map for errors or draping issues.

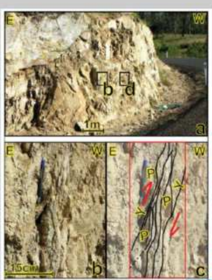


Map draped on DTM, check for errors in linework

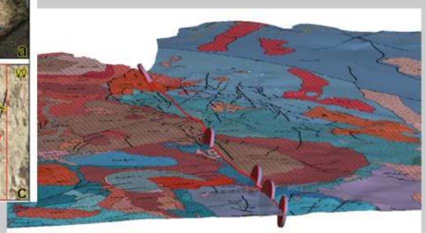
Collation of additional structural constraints: from seamless database or published work (papers or reports). Data formatted in spreadsheet and imported.

Software: ArcGIS, Excel, Leapfrog

Subprocesses: Generate 'Z' coordinate for each datapoint by importing as pointset, draping on DTM re-exporting. Merge with original data in excel/csv file.



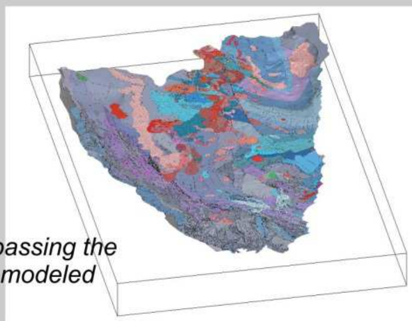
Published structural constraints (Babaahmadi & Rosenbaum 2013)



Structural constraints along fault

Set up geological model encompassing the objective X,Y,Z extents of the entire regional model and all the major faults.

Software: Leapfrog

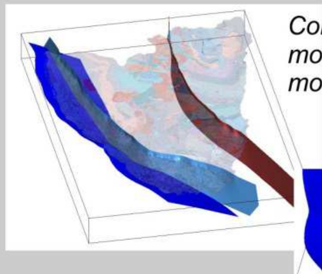


Geological model encompassing the entire region in which the modeled faults occur.

Generate individual faults as mesh objects using the regional geological model as extent.

Software: Leapfrog

Subprocesses: Faults constructed as new meshes from surface polylines, then dip polylines, structural data or constraining points added
Fault mesh <u>not</u> trimmed by DTM.

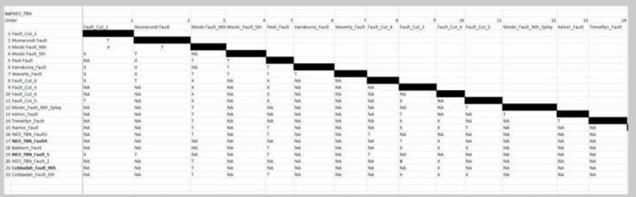


Constrained faults modelled to geological model extents

Fault surfaces constrained by imported linework, structural data and/or inferred datapoints

Devise a standard fault chronology for all the major faults to be used in the model.

Software: None, Piece of paper, spreadsheet......

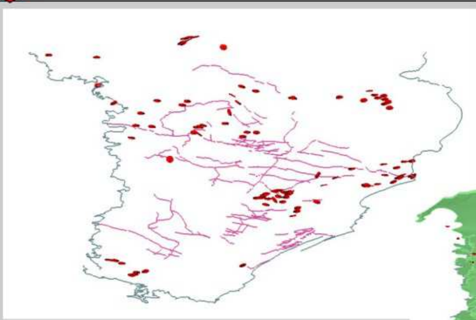


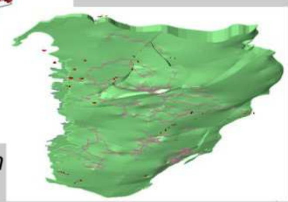
Complex fault chronology detailed in a spreadsheet.

Interpretation of basin-basement interface (using seismic, drillholes, surface linework and structural data), interpolation of basement surface.

Software: SKUA, Leapfrog

Subprocesses: Seismic basement Interp.



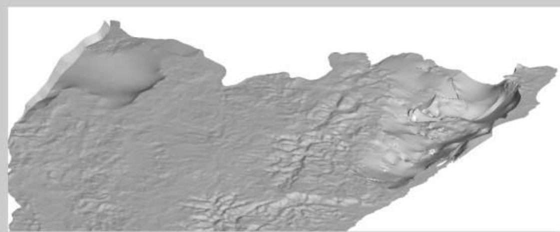


Basement surface interpretation

Subtraction of basins from DTM surface using the basement-basin interface surfaces generated in previous step (Generate a DTM mesh with basins removed).

Software: Leapfrog

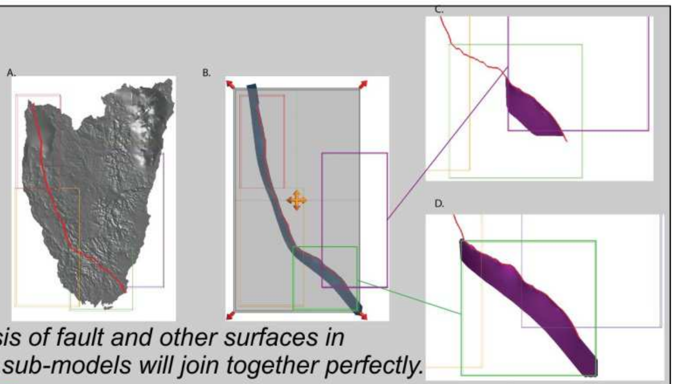
Subprocesses: Clip basin from DTM
Clip DTM from Basement volume
Stitch basement into DTM



Basins subtracted from DTM surface. Surface is now top of Palaeozoic and will provide an upper constraint for NEO structures and lithology.

Use fault meshes, and DTM mesh with basins removed, as basis in all sub-models (or for regional scale model), setting fault chronology as per the standard scheme divised.

Software: Leapfrog

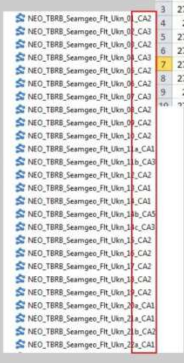


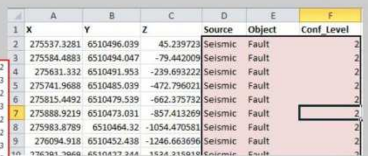
Using pre-made surfaces as the basis of fault and other surfaces in sub-models ensures all overlapping sub-models will join together perfectly.

All constraining line work should be attributed in object naming with confidence level. Export all constraining lines, points and structural data to spreadsheets and merge all data together using the confidence attribute and a new field corresponding to each node (X,Y,Z) in the spreadsheet.

Software: Leapfrog, SKUA (attribution in naming of constraining data)
ArcGIS (filtering and export of attributed map line work)
Excel

Sub-processes: File organisation and merging process. Merge all files of the same confidence level together (using dos) the import into excel and attribute in additional field against each X,Y,Z point.



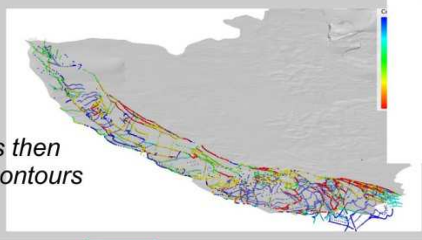


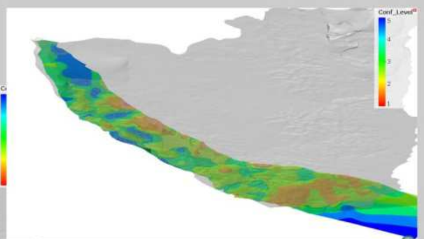
	A	B	C	D	E	F
1	X	Y	Z	Source	Object	Conf_Level
2	275537.3281	6510496.039	45.239723	Seismic	Fault	2
3	275584.4883	6510494.047	-79.442009	Seismic	Fault	2
4	275631.332	6510491.953	-239.693222	Seismic	Fault	2
5	275741.9688	6510485.039	-472.796021	Seismic	Fault	2
6	275815.4492	6510479.539	-662.375732	Seismic	Fault	2
7	275888.9219	6510473.031	-857.413269	Seismic	Fault	2
8	275983.8789	6510464.32	-1054.470581	Seismic	Fault	2
9	276094.918	6510452.438	-1246.663696	Seismic	Fault	2

Confidence level added to object naming, objects merged into spreadsheet and confidence added to each point.

Re-import the confidence attribute file into leapfrog and use to generate interpolation within the model volume.

Software: Leapfrog





Attributed point data which is then interpolated to produce 3D contours of confidence (volumes)

Completed model: export all faults, the topographic surface and confidence level volumes to DXF files and SKUA surface files.

Software: Leapfrog, SKUA

Sub-processes: Continuous surfaces generated in difference sub-models may require merging.

Final model surfaces for export

Confidence Model

The aim of applying an interpretation confidence mapping to the 3D modelling is to develop a standard system to visually represent constraint location, and constraint quality within models that is broadly similar to the representation of confidence in traditional mapping. The confidence model will allow end users to quickly identify areas of the model that that are well constrained, and those that are poorly constrained with a scale in between of incrementally reducing confidence.

Constrain confidence is rated on a 1 (high confidence) to 5 (low confidence) scale. The constraint attribution scheme used for all data types is shown in Table 2. Attributed constraints and imported into the model as points then interpolated to produce six 3D volumes.

In the current, deep crustal structure model, the structures as modelled are isolated, planar features that make a 3D volume confidence model somewhat difficult to produce for this model alone. As such the actual data used is from modelling of the entire Tamworth Belt (which is bound by the Hunter-Mooki and Peel-Manning Faults) and the Coffs Harbour Block/Clarence Moreton Basin (which is bound to the west by the Demon Fault and includes the Drake edge).

Table 2 (below): Standard confidence attribution scheme at July 2015.

Data Catagory	Data Type	Confidence Level	Numeric Value	Description
Map Data				
	Surface Map	Accurate	1	From seamless attributes
	Linework	Approximate	2	From seamless attributes
		Inferred	3	From seamless attributes
		Inferred Concealed	4	From seamless attributes
		Concealed	5	From seamless attributes
	Surface structural	Accruate	1	Measurement is on the contact/object being modelled
	measurements	Approximate	2	Measuremenet on a contact is inferred from nearby measurements
		Inferred	5	Measurement is estimated base on broad architecture and distal constraints on object strike and dip.
Dip Data				
	Seismic picks	Good-Good	2	Good quality seismic with good time-depth conversion
		Moderate-Good	3	Moderate quality seismic with good time-depth conversion
		Moderate-Moderate	4	Moderate quality seismic with moderate time-depth conversion
		Poor	5	Poor quality seismic and/or time depth conversion
	Drillholes	Accurate	1	Contact or specific fault zone recorded or observed in drill hole record
		Approximate	2	Contact or fault zone recorded or observed in drill hole record that is likely to be the target contact or fault
	Geophysical processing			
	Multiscale edges	Constrained	2	Contact/fault constrained by other data (Drill holes, Mapping, seismic)
		Constrained concealed	3	Contact/fault not exposed at surface but is consistent with other nearby contacts/faults or is evident in other datasets (e.g. seismic)
		Unconstrained	5	Contact/fault inferred only from the Mag or Grav data.
	Forward modelling	Constrained	3	Constrained by other data
	and inversion	Unconstrained	5	Not constrained by other data
	Geological Cross sections	Map Constrained	2	Section constrained by surface mapping and measurements, seismic and/or drillholes
		Map/Geophysics Constrained	2	Section constrained by surface mapping and geophysical modelling
		Seismic constrained concealed	3	Section produce from seimic data +/- drillhole data in concealed terrain.
		Map Unconstrained	4	Section produced only from surface data
		Unconstrained	5	Interpretive section where surface mapping or seismic data is unavailable.

Integrated model (preliminary)

Screen shots of the current deep crustal structure model are shown in Figure 11 with the confidence volume model. This model is to be further integrated with more detailed structural and stratigraphic models.

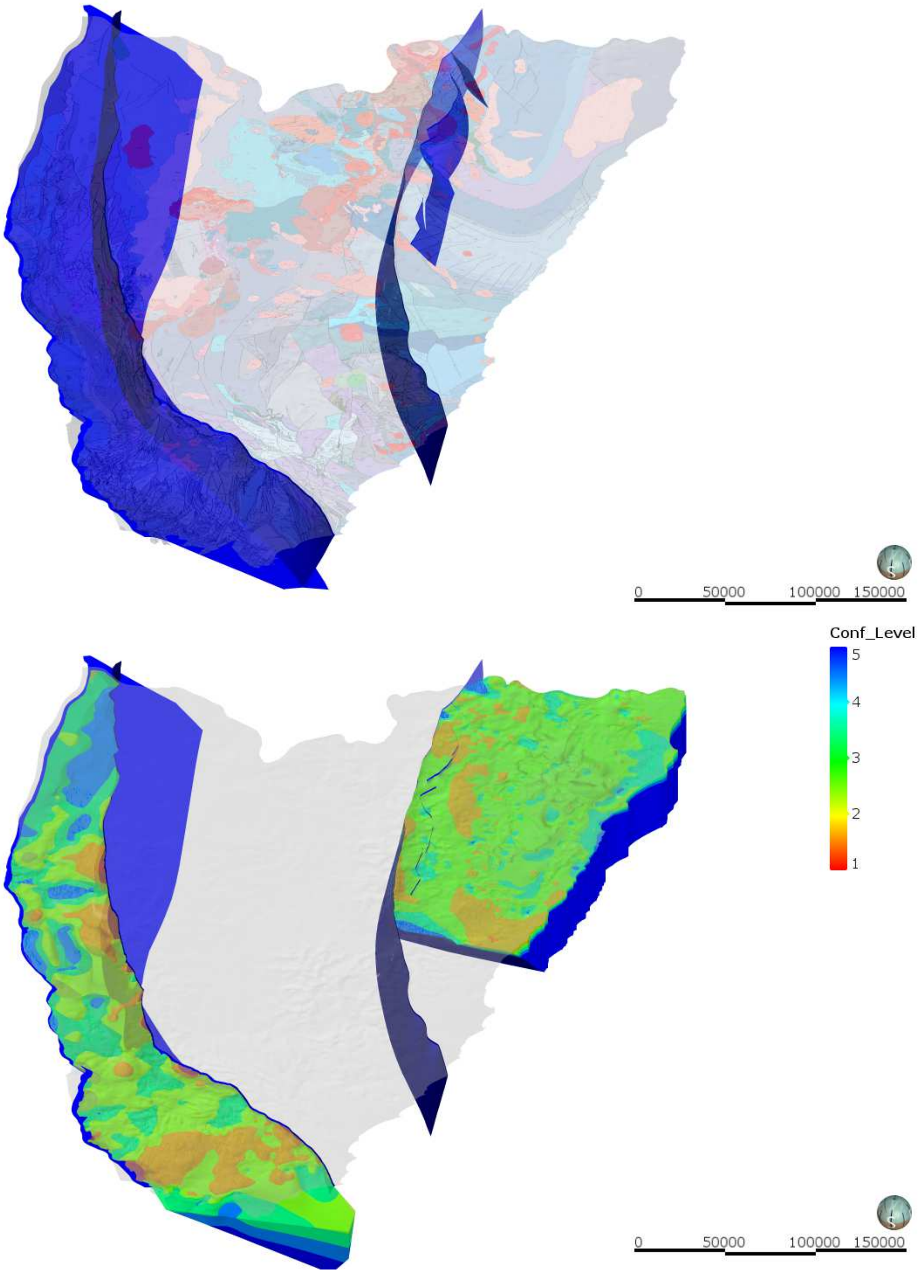


Figure 11: Screen shots of the current southern New England Orogen deep crustal structure model. A) Major Faults with semi-transparent seamless geology draped on top of Palaeozoic surface. B) Major Faults with confidence level volumes. 1 (red) is high confidence, 5 is lowest confidence.

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