3D Geological Modelling for Geothermal Exploration in the Torrens Hinge Zone

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This paper describes 2D/3D Geophysical/Geological Modelling undertaken by the author for Torrens Energy in 2009, for the purpose of establishing 3D Geological Models of the upper crust within their Torrens Hinge Zone tenements in South Australia. Geological Models are a requirement for any Geothermal Energy explorer searching for Hot Dry Rock or Hot Sedimentary Aquifer targets. These Geological Models are assigned thermal parameters determined by field and laboratory measurements based on the lithologies included in the model. Heat resources may then be computed for the given volume based on the geological model and thermal rock properties. Whilst the studies were carried out for the purpose of creating temperature models and geothermal resource estimates, this document will discuss the geological models, geophysical investigations and tectonic implications generated by the study. Examples of Geological Models are shown from the Torrens Energy Port Augusta, Yadlamalka and Parachilna Geothermal Prospects, based over their GELs 230, 234, 235, 285 and 501.

Keywords: South Australia, 3D Geological Modelling, Geophysical Modelling, Heat Flow, Stratigraphy, Torrens Hinge Zone, Adelaide Geosyncline, Magnetics, Euler Deconvolution, Geothermal Energy.

Introduction and Geological Setting

The principle behind 3D Geological Modelling is to integrate existing geological and drilling information with geophysical data such as seismic, gravity and magnetics, in a 3D environment which will simulate the 3D geology of the region of interest by creating a 3D geological model which can then be used as an input for thermal modelling.

The Torrens Hinge Zone is a long but narrow (up to 40 km wide) geological transition zone between the relatively stable Eastern Gawler Craton "Olympic Domain" to the west and the folded sedimentary basin known as the Adelaide Geosyncline to the east (Drexel et al, 1993). The THZ is essentially a region of overlap between the Gawler Craton and Adelaide Geosyncline (Figure 1). In the study areas of the THZ, the Adelaidean and Cambrian sedimentary sequences are underlain at depths between 2,000 and 7,000m by Paleoproterozoic to Mesoproterozoic Gawler Craton Olympic Domain rocks (Matthews and Godsmark, 2009).

Heat flow values of over 90 mW/m^2 have been recorded in several wells drilled in the THZ. With several kilometres thickness of moderate conductivity sediments overlying the crystalline basement in this region, predicted temperatures at 5000 m are up to 300^{o}C in some areas (Matthews and Godsmark, 2009).

Data and Methodology

Available geological data included historic and Torrens Energy drillholes and South Australian (SA) geological mapping. Geophysical data comprised SA magnetic and Bouguer Gravity data along with recently acquired Torrens Energy and Geoscience Australia 2D depth-converted Seismic. Rock thermal properties were derived from laboratory measurements perfomed by Torrens Energy and top and downhole temperatures measured from drilling.

The Intrepid 3D Geomodeller suite was used to build the 3D Geological Model. The 3D Geomodeller software interpolates between geological boundaries, orientation data and drillholes to generate a 3D geological model that is flexible and readily adaptable with additional geological information. Geomodeller also supports faults and fold information into its interpolation. The final output can be discretised into a 3D "voxel" model of desired resolution to use in 3D Geothermal Modelling.

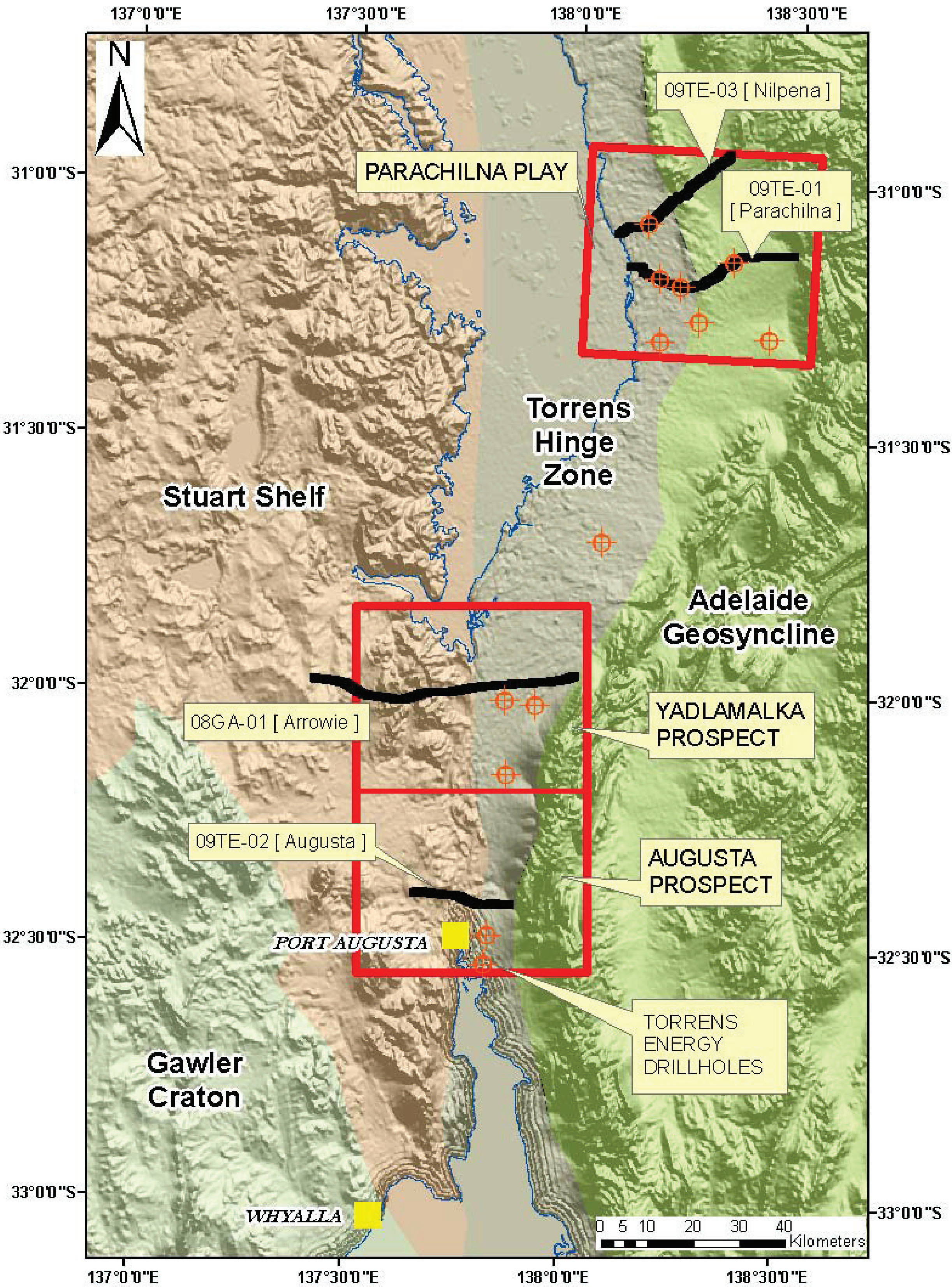

Figure 1. Map of Central South Australia showing tectonic elements and study areas together with Torrens Energy wells, seismic lines and prospects

Basic Modelling requirements

The following methodology was applied to construct a 3D Geological model. It relies heavily on interpretation and integration of many data types, as well as some creative thinking and intuition. All 3D geological models built by Geomodeller begin with 4 pieces of information. The first is a defined 3D volume of interest, set by rectangular coordinates of the target area, and a suitable depth dimension which will encompass (preferably) the heat source, basin thickness and topography. For both Parachilna and Port Augusta a depth below Mean Sea Level of 7km and a maximum of 1.5km above MSL to clear the range topography was deemed sufficient, giving an 8.5km thick model. The area covered in the Parachilna model was 50x45 km, and 50x80km over Port Augusta/Yadlamalka.

A surface topography is required for the model to compute the intersections of the geological interfaces at surface, ie to have an initial 2D section at which to input geological information and have it reproduced by the model computation for validation. Topography was imported into the models from SRTM DEM grids at 90 m resolution clipped to the Area Of Interest (AOI), Figure1.

The third and fourth requirements are the defined geology in the form of lithological interfaces and associated structural orientations, and a stratigraphic pile which defines the relationships between the lithologies. The latter is particularly important as contacts need to have relationships defined as either Onlapping or Erosional, as this determines whether interface isolines intersect or remain apart with respect to one another. Sequences of geological units such as found in sedimentary basins may also be grouped in onlapping series, whereas intrusives are always erosional and appear where required in the stratigraphic pile to best satisfy contact relationships. In strongly deformed regions, structural requirements may imply that lithologies must obey onlapping rather than erosional rules. A simplification of the stratigraphy was also created for ease of modelling (Figure 2), which essentially has grouped the Cambrian and Neoproterozoic sequences into their major tectono-stratigraphic units.

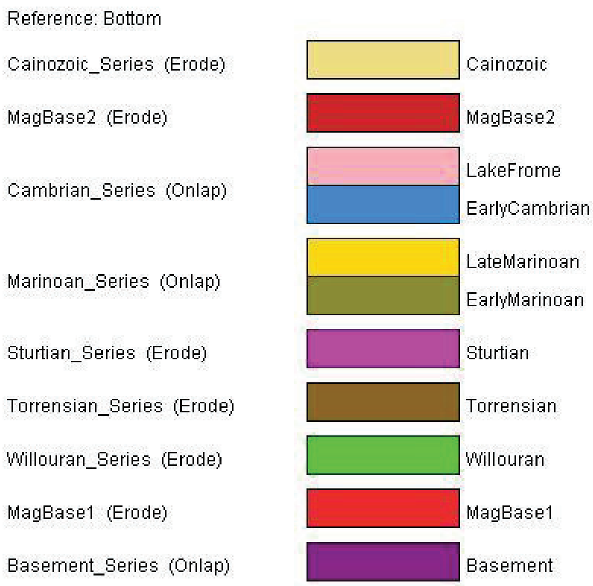

Figure 2. Simplified Parachilna Stratigraphy.

Geological information at surface came from importing simplified or grouped shapefiles derived from State 100k geology polygons, and assigning these to the simplified stratigraphic formations. Likewise orientation data, where known from mapping, have been supplied where possible and assigned to specific formations. Torrens Energy and historic diamond drillhole data have provided constraint in the 3rd dimension. Once again the geological logs of these drillholes were simplified to the stratigraphy and the drillholes imported using the import tools in Geomodeller (figure 3).

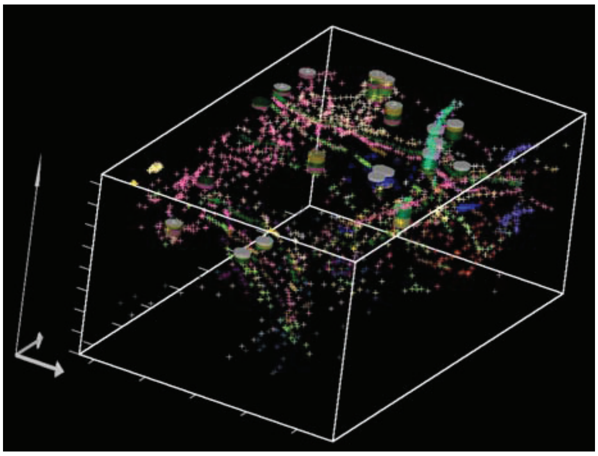

Figure 3. Port Augusta 3D Interface Points and Drillholes in Geomodeller project.

Supplementing Geology with Geophysics

Unless there is a complete coverage of mapped geological information at surface, it is unlikely that reliable models may be derived from surface mapping alone. To supplement the existing geological information, interpretation of four 2D depth-converted seismic lines, (two from the Parachilna area and two from the Port

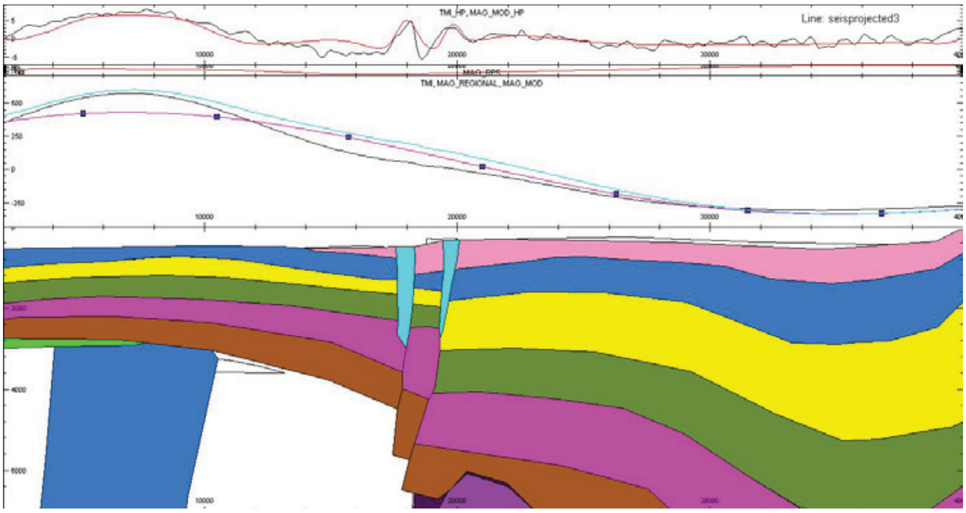

Figure 4. 2D Magnetics Model across Parachilna , showing main basin elements, possible magnetic intrusives and shallow fault-related magnetic bodies

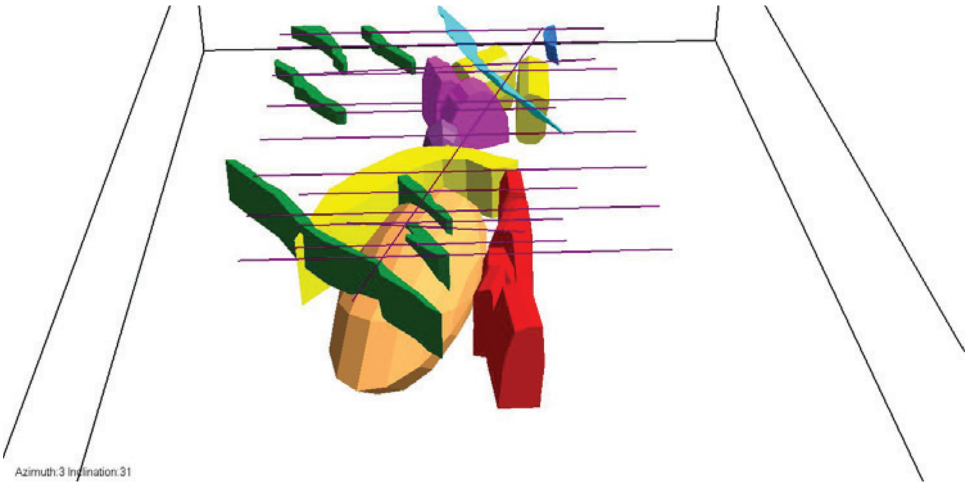

Figure 5. Persepective view of 3D Bodies derived from 2.5D Magnetic modelling within Augusta/Yadlamalka across Parachilna , including dykes, possible magnetic intrusives and sheet-like layers, probably thrusted Beda Volcanics.

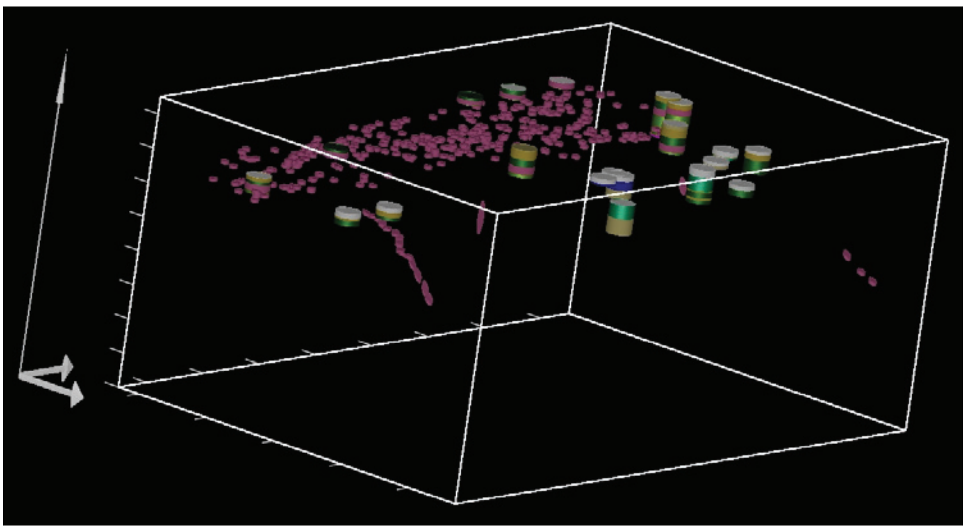

Figure 6. Depths to Base Sturtian, ie top Beda Volcanics, derived from Euler Deconvolution of Magnetics. Shown together with drillholes from Augusta/Yadlamalka prospects.

Augusta/Yadlamalka area), was performed (see Appendix 1). These were constrained wherever possible by drilling and outcrop information. These seismic sections were imported into Geomodeller as image backdrops along vertical sections through the model and the interpretation transformed into interfaces within these vertical sections.

The interpretation along these sections was augmented further in the Parachilna AOI by 2D modelling of state magnetic data along two lines adjacent to the 09TE-01 seismic line (figure 4). In the Port Augusta region, 2D magnetic modelling was also performed in order to obtain estimates of basement depth and magnetic body shapes and locations (figure 5). In each case images or actual 3D data points from the results were imported back into Geomodeller.

Euler Deconvolution of magnetic data was also used in this area to provide spot estimates of depth to shallow-dipping volcanic units, implying local estimates to the top of Willouran -age Beda Volcanics (figure 6). Additional scans using a larger window size revealed information about the shape and size of deeper magnetic bodies which correlate well with 2D magnetic modelling results. Finally, structural interpretation of both gravity and magnetic data was used to define fault traces in Geomodeller (see Appendix 2).

3D Geological Models

Computation time of the two 3D Geological models is dependent on the amount of data supplied. Results which are strongly biased to orientation data were treated with caution. Some additional inference of contacts and orientations was required to ensure geological consistency, especially near faults. Additional sections linking drillholes provided stronger cross-correlation of geological interfaces, especially in the Port Augusta/Yadlamalka area where data was widely spaced. Although in some cases actual outcrop geology was further from the area of interest than required, it was included to provide geological reality and well-defined constraints on modelling.

As faults also require orientation information to be computed in the modelling, their direction, dip and apparent movement was estimated either from seismic images or geological and geophysical images.

Parachilna

Emphasis on interpretation and modelling in the Parachilna area focussed on areas west of the Ediacara fault (Figure 7a, 7b, Appendix 2) where there is simpler geology according to the seismic data. In this area we see from modelling that the Early Cambrian to Adelaidean rocks transit from relatively flat-lying in the west to moderately east-dipping at the Ediacara fault contact.

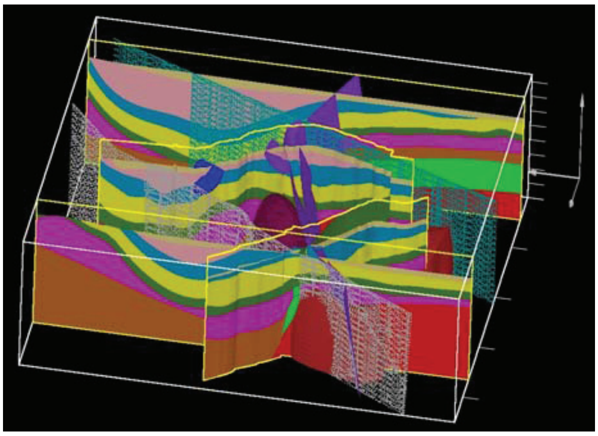

Figure 7a. Projected section view of Parachilna 3D Geology Model, view SE. Vertical. exaggeration= 2:1

The Ediacara fault zone changes in character from south to north. Our modelling shows it to be a steeply west-dipping feature, upthrown on the eastern side, which evolves in the south from a relatively simple antiform, to a complex horst structure involving several faults and possibly basement or diapiric material from the centre of the Parachilna AOI to its northern edge. Basement depths in the far west are predicted to range from 2km depth in the north to 5 km in the south. In the vicinity of the Ediacara Fault footwall basement depth reaches 6km, but this decreases to 2.5-3km in the far north. In the faulted horst blocks of the Ediacara Fault region basement or diapiric material may reach depths of 2km. East of the Ediacara Fault in the central and southern areas is a moderately folded disturbed region leading eastward into a very deep synclinal basin within the Cambrian – Adelaidean sequences adjacent to the range front fault. To the north of this area the model predicts less intense folding with flatter basin sequences, but still basin thicknesses of > 7km.

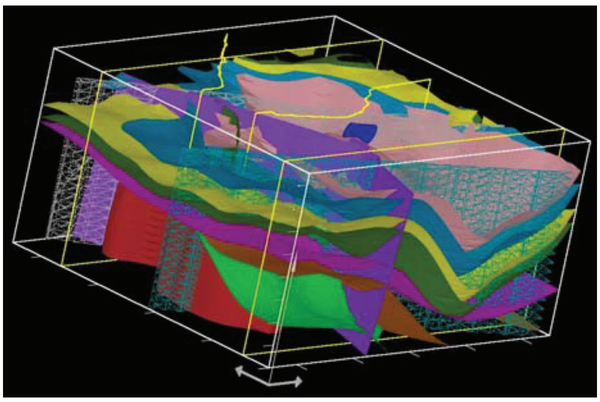

Figure 7b. Interfaces and Faults, Parachilna 3D. View NE, VE=3:1

Cainozoic erosional units tend to range in thickness from 300-400m and thin out in the vicinity of the Ediacara Fault hanging wall. Early to Middle Cambrian units of the Lake Frome, Unnamed, and Hawker Groups have been confirmed by deep drilling, whilst Adelaidean rocks of Marinoan to Sturtian ages are expected to lie beneath these based on their presence in the Ediacara Hills to the north in the fault zone and outcrops of these units to the west on the Stuart Shelf. Inference of Torrensian to Willouran rocks is based on the apparent presence of diapirs to the south and east, although these rocks are expected to thin out somewhere in this region. Torrensian rocks in particular may not appear anywhere west of the Ediacara Fault system. Basement has been largely undifferentiated in the Parachilna 3D model with the exception of what are inferred to be two large magnetic intrusives in the central parts and northwest.

Port Augusta/Yadlamalka

A very large area has been modelled in this study, which naturally implies a greater amount of both inference and uncertainty. To complement this is more complex geology and more drilling data, as well as much more diverse magnetic signatures and seismic imagery.

The interpretation on the seismic lines 09TE-02 (Augusta) and 08GA-01 (Arrowie) is still the subject of some debate, until such time as some specific drilling is performed along the lines and stratigraphic correlations are performed. The interpretation has been made through careful cross-comparison of nearby drillholes using Geomodeller as a guide, using logged depths to specific units and comparing how they are distributed across the area, and existing geological mapping.

Inferences have been made on the nature and distribution of the Willouran and Torrensian age rocks in a fashion similar to the interpretation at Parachilna, as well as deeper Proterozoic basement units. These inferences will be discussed in the next section.

The final 3D model is shown as sections and surfaces in Figures 8a and 8b. In general the stratigraphy is identical to that used at Parachilna, with the addition of several intrusive basement units of varying magnetic signature and a split of the Willouran-age rocks into Beda Volcanics/Backy Point Formation, general Willouran – age rocks and several thrusted Willouran – age slices. The overall trends modelled show an eastward – thickening wedge of sediments toward the range front, with possible down-thrown rift basins evolving closer to the range. To the northeast thrust faults occur sub-parallel to the Gairdner Dyke Swarm before the range front and are possibly facilitated by Callanna group evaporitic units and/or diapirism. To the east of these significant thrusts, closer to the range fault, sediments begin to dip more strongly or are deformed. Some deformation is also present immediately west of the thrusts on the footwall side, but this peters out as sediments become more flat-lying to the west.

In the south and south central areas in the vicinity of Port Augusta, the model predicts gently dipping Adelaidean rocks of 800 – 1200m thickness, overlying granitic or metamorphic basement, crossing a significant north-northeast trending basin-defining fault approximately 10km northwest of Port Augusta, coincident with the onset of a significant gravity low and a step in the magnetics and seismic images. Here the basin thickness increases to at least 2000m, dropping away gradually to 3000m approximately 9km west of the range front, before dipping away more steeply to 4500m at the base of the range fault. Deeper reflectors in the Augusta seismic section are enigmatic but their pattern is suggestive of rifting, the timing of which should be investigated further, if proven (see Discussion). Modelling results based on historical drilling near Wilkatana (central southern Yadlamalka prospect) demonstrate localised basins containing Cambrian sediments.

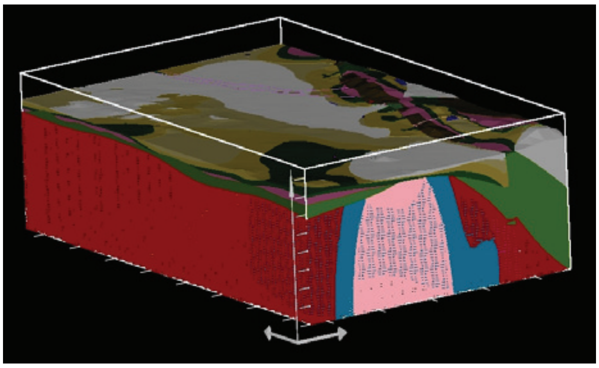

Figure 8a 3D volume model of Augusta/Yadlamalka. View NE, VE=3:1.

The northern parts of the model, described as Yadlamalka after the name of the station southeast of Lake Torrens near a major thrust zone, has similar gently dipping Adelaidean stratigraphy ranging from 600m thickness in the far west to 2300m before encountering a significant thrust fault which displaces Willouran volcanics close to surface, as evidenced by the Arrowie seismic section, drilling and magnetics. Unlike the more obvious extensional faulting regime exhibited farther south, basin units appear less disturbed, but a very marked angular unconformity exists between the sedimentary/volcanic pile and the basement, which comprises a series of west-dipping reflectors. East of the Yadlamalka thrust the sedimentary pile is moderately folded and of unclear composition and thickness. What is clear is that thrusting and compressional deformation has disturbed the Adelaidean sequences in more than one location. It is also speculated that Willouran/Callanna Group salt formations may again be principally involved.

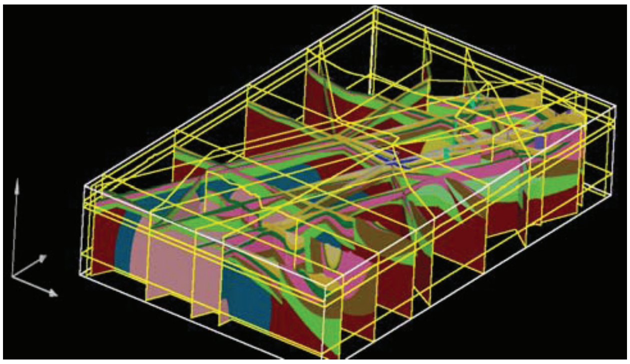

Figure 8b 3D section view of Augusta/Yadlamalka. View NW, VE=3:1.

In the northern part of the model magnetic modelling has suggested that a number of magnetic intrusives are present, along with slices of Willouran age volcanics. These have been emplaced into the model where most likely, but the remainder of the basement has been undifferentiated.

Partial modelling of the range to the east has been included to add both strratigraphic and structural control, but has been performed at a representative level only. Cainozoic strata also appear relatively thin in this region but have been included as a thin uppermost layer where evident.

Overall, the Early Cambrian to Neoproterozoic basin succession throughout the area remains relatively simple. Sequences dip gently eastward and thicken before the onset of thrusting, folding, or extensional faulting. Roughly midway across the model Torrensian lithologies are inferred to appear (see Discussion).

Discussion

Results and some of the methodology used in the Port Augusta/Yadlamalka area require some discussion due to inferences being made and the tectonic consequences of the modelled relationships

These inferences particularly concern the nature of the rocks within the basin sequences west of the range front fault. Torrensian/Burra Group rocks are not known to occur west of this structure or anywhere on the Stuart Shelf, however we have inferred from the seismic that Torrensian rocks pinch out or fault out fairly consistently 20-30km west of the range front, mainly at depths deeper than what has been currently encountered in drill holes. The implication from this is that Torrensian sedimentation is controlled by a second onset of strong rift-related extension closer to the Central Flinders Zone.

Willouran age/Callanna Group rocks have long been enigmatic in terms of their relationship to other rocks of the Adelaide Fold Belt and the Gawler Craton, but inferences on their distribution and geology have implications for understanding the early evolution of the rift zone and later deformation. Basaltic rocks of the Beda Volcanics have been encountered in many drillholes on the Stuart Shelf, mostly at shallow depths, but also may have been confused with older Gawler Range Volcanics (GRV) in some holes. These rocks and associated intertonguing sediments of the Backy Point Formation are thought to form the basal units of the Adelaide Fold Belt rift sequence. Exactly how thick these units are, and whether additional sediments lie beneath the volcanics, is unknown, however drillhole information suggests that the Beda Volcanics are probably only a few hundred metres thick, and their flat-lying nature suggests that they should form a good reflector in seismic data.

Both seismic lines in the area show good deep continuous reflectors just above or not far above the basement, but in places drillholes appear to have intersected Beda Volcanics well above the suspected top basement horizon, at another reflector. The Port Augusta seismic line even appears to show what may be another rift graben well beneath what is interpreted as Willouran, but until this is confimed by further studies we have assumed it to be basement, or at least GRV or similar age sediments. Elsewhere we have inferred that the Beda Volcanics are reasonably thick or probably have much larger proportions of Backy Point Formation beneath them for the purpose of modelling. The unmodelled other possibilities are that beneath the Beda/Backy Point rocks lie reasonable thicknesses of Mesoproterozoic rocks such as the Pandurra Formation and Gawler Range Volcanics (GRV), or that Torrensian and Sturtian rocks increase dramatically in thickness midway across the model, or both.

Further information was derived from the magnetics. Petrophysically, the Beda Volcanics are known to be moderately magnetic, but their flat-lying nature and probable magnetisation pattern means that unless they are tipped on their sides, the net effect is only to add a regional dc shift to the overall magnetic signal. High pass and analytic signal filtering of the state magnetics, however, has revealed where Beda Volcanics have been tipped on their sides and thrust to surface at the Yadlamalka thrust and Depot Creek on the range front, where they have been intersected at surface or in drillholes, with the thrust also visible in the Arrowie seismic section.

Euler Deconvolution of magnetics is based around automated scanning of changes in the magnetic signal in windows across a grid, with depth estimates to magnetic sources dependent on the size, intensity, and shape of bodies, and window size. Two different window sizes were used, the first scanning to depths of 2km and the other to 8km. The results of the shallower window targeted mainly the tops of the Gairdner Dyke Swarm, which are known to be Beda Volcanic equivalent ages. These are therefore by implication minimum depths to the base of Sturtian Adelaidean rocks in the west, where Torrensian rocks are not present, and base of Torrensian rocks in the east where the method detected thrusted Beda Volcanics. These results were statistically culled for reasonableness and proximity to dykes, thrusted volcanics or closeness to interception in drillholes.

The remarkable consistency of Euler depth trends in the west for the shallow scan gives credence to the notion that Beda Volcanics overlie deeper sediments and/or volcanics. The idea that Gawler Range Volcanics lie below the obvious basement unconformity seen in the Arrowie seismic is not supported by this model, unless east of the major volcanic flows on the Gawler Craton the GRV were deformed along with Hiltaba suite and eroded prior to either Mesoproterozoic clastic deposition or Willouran rifting. Similar notions apply in the Port Augusta area.

The deeper window targeted magnetic intrusions, by implication a maximum depth to basement across the area. Again these results were statistically culled and sorted by proximity to the inferred “tops” of magnetic body depths. These results, along with results of 2D magnetic modelling were interpreted to be from deep magnetic intrusives, possibly even Iron Oxide Copper Gold – bearing intrusives lying in the centre of the region (though perhaps too deep for drilling), rather than belonging to metasediments, GRV or younger volcanics. Further support for this notion came from examination of filtered magnetic grid images as described above.

Values from the deeper Euler and 2D magnetic modelling were input back into Geomodeller as the basis for intrusive 3D body shapes.

Results of 3D modelling in the Parachilna area are currently considered less contentious. The principal features for discussion are the nature of the magnetic anomalies, whether they indeed correspond to deep intrusives, or are related to diapirism bringing basement magnetic material to closer to surface, or a combination. The strong gravity anomaly running through the centre of the region suggests it is more likely to be basement reactivated along the Ediacara Fault. Once again the other major issue for consideration is the presence and distribution of Torrensian and Willouran rocks.

Conclusion

Two large 3D Geological models have been made of sections of the Torrens Hinge Zone in South Australia. The northern model near Parachilna shows moderately dipping Cambrian to Adelaidean sediments of thicknesses between 2000 and 4000m overlying unknown basement in the west. A modern active fault system, the Ediacara Fault, has uplifted basement locally and forms the boundary of a deep, moderately deformed north-south basin adjacent to the Flinders Range front.

The southern model between Lake Torrens and Port Augusta shows transitions between gently dipping Adelaidean sequences of up to 2300 m thickness with thrusted, deformed basins to the north and deeper rifted basins to the south. Evidence from seismic and magnetics suggests the presence of substantial sedimentary or volcanic sequences lying beneath Willouran Beda Volcanics and overlying deformed metamorphic or granitic basement with sharp unconformity.

References

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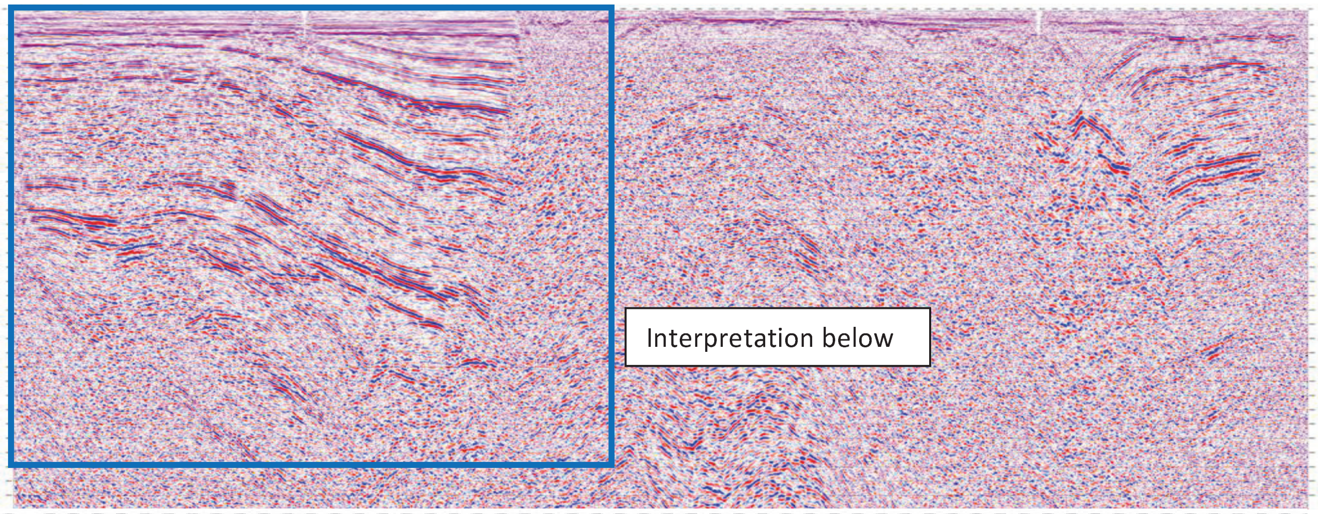
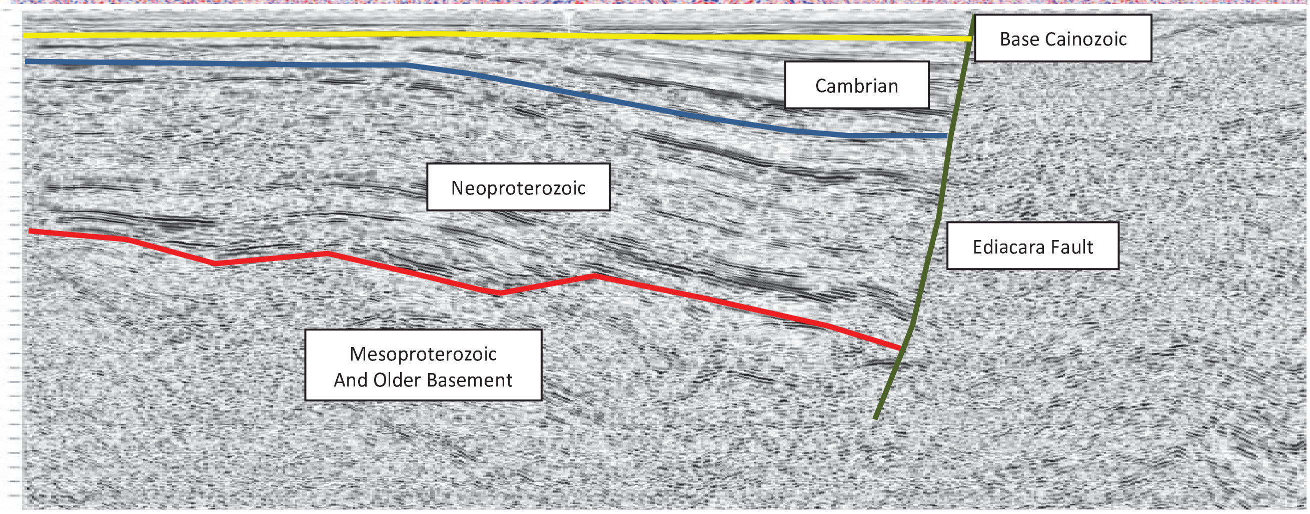
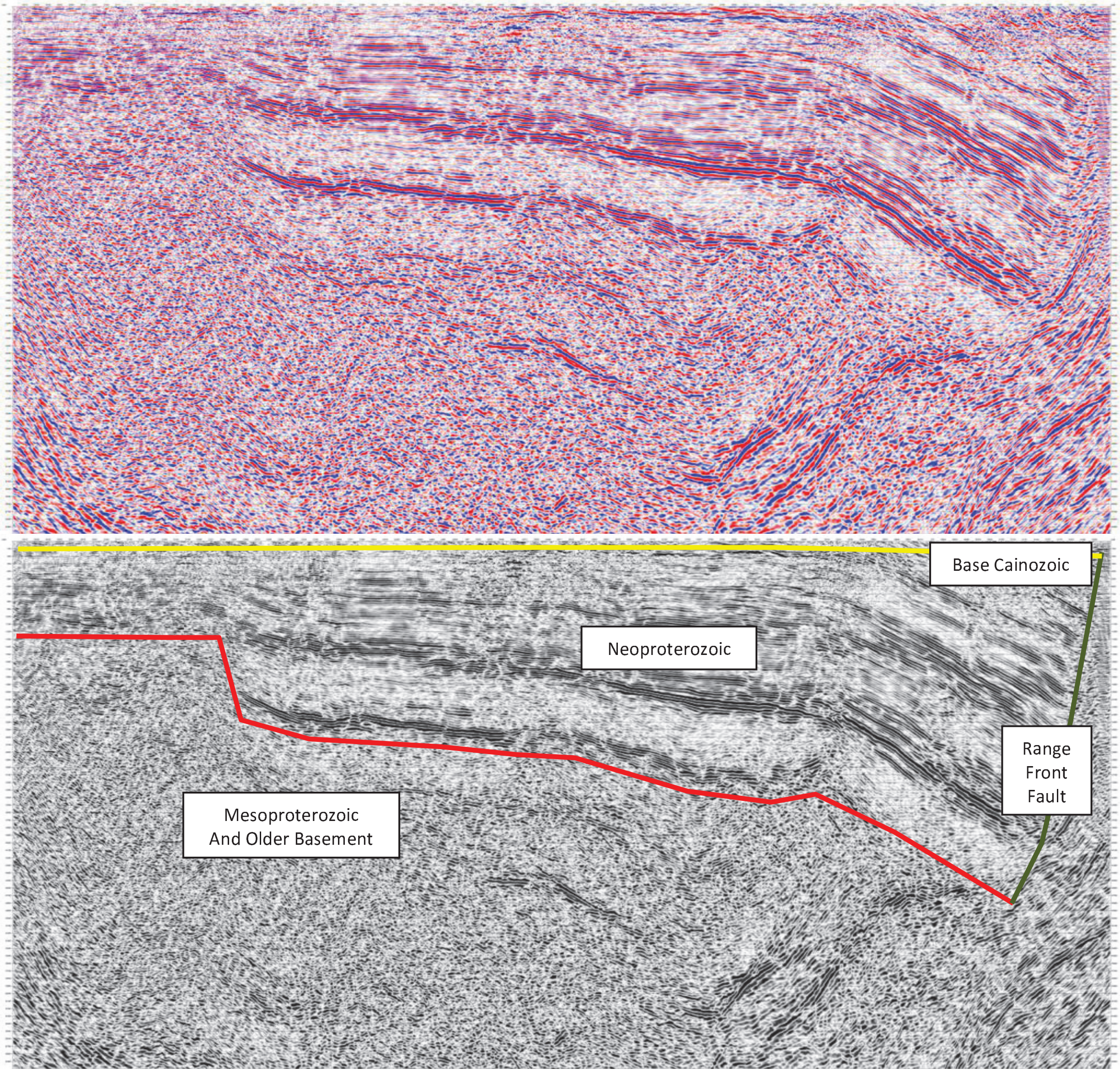
Appendix 1: Seismic Surveys and Results (after Matthews and Godsmark, 2009)

Parachilna Seismic Survey, completed January 2009

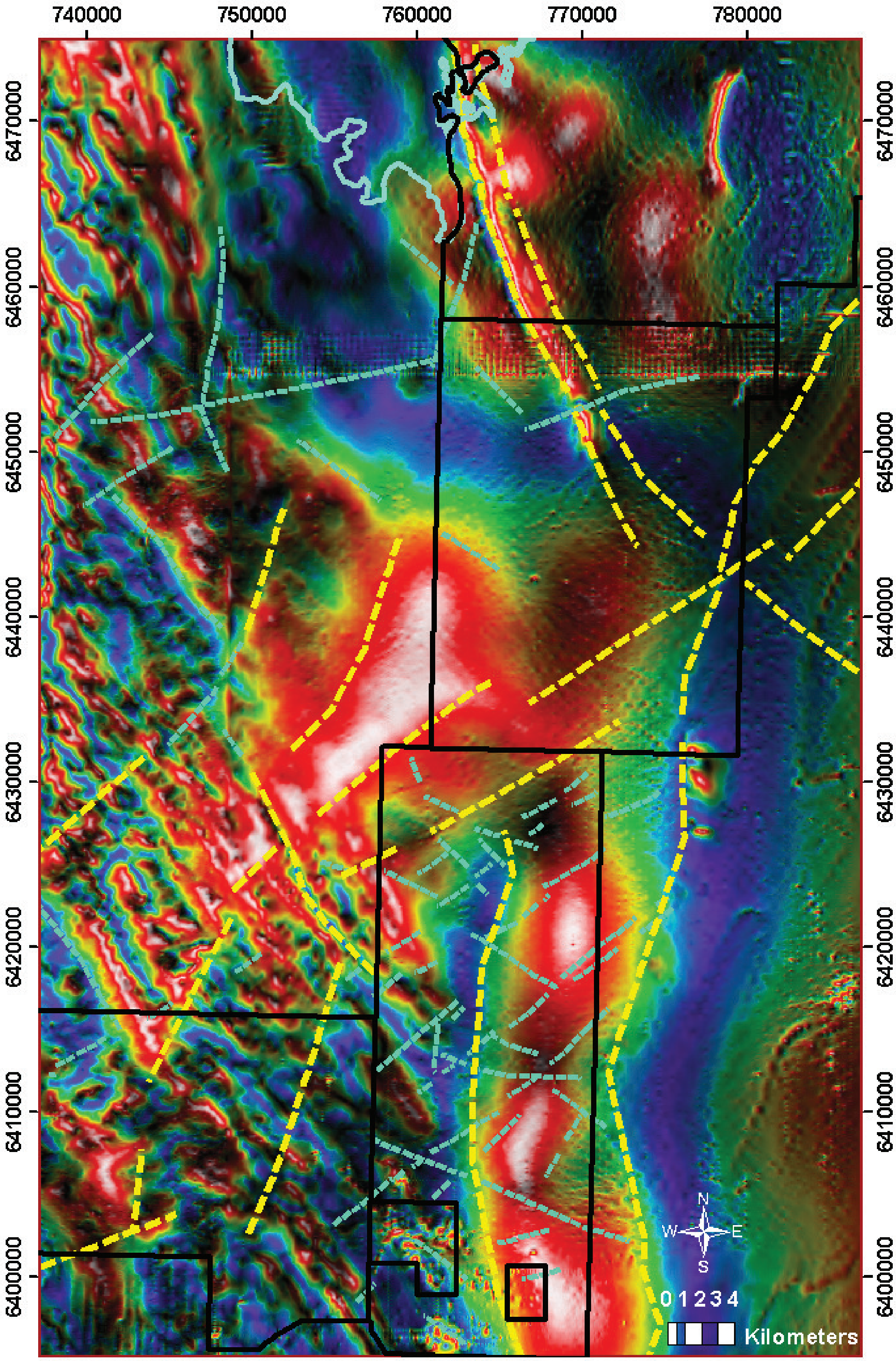




Port Augusta Seismic Survey, completed May 2009



Appendix 2: Fault Interpretation from Magnetics



Fault Interpretation (blue and yellow lines) of SA Magnetics in the Port Augusta/Yadlamalka area. Image is a Tilt Angle filter draped over Analytical Signal Amplitude. Torrens Energy GELs in black. MGA Zone 53.