Geothermal Energy Prospectivity of the Torrens Hinge Zone: Evidence from New Heat Flow Data

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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 sedimentary basin known as the Adelaide Geosyncline to the east. It was hypothesized from first principles that the Torrens Hinge Zone should be prospective for high geothermal gradients due to the likely presence of high heat flow and insulating cover rocks. A method to test this hypothesis was devised, which involved the measurement of heat flow on a pattern grid using purpose drilled wells, precision temperature logging and detailed thermal conductivity measurements. The results of this structured test have validated the hypothesis, with heat flow values over 90 mW/m^2 recorded in several wells drilled. 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.

Keywords: Australia, Heat Flow, Thermal Gradient, Thermal Conductivity, Torrens Hinge Zone, Adelaide Geosyncline, Delamerian Fold Belt, Gawler Craton, Curnamona Craton, Engineered Geothermal Systems, Geothermal Exploration.

Introduction

For an area to be prospective for geothermal power generation there must exist high average geothermal gradients that indicate high temperatures at depths which can be economically drilled. In addition the heat must be able to be economically exploited. This requires the existence of suitable reservoir rocks with either high natural porosity and permeability, or the conditions that allow permeability to be artificially enhanced. Favourable economics are also driven by location, and the cost of bringing the power to market competitively. Geothermal resources are non transportable, making it desirable that resources be located proximal to a market.

There is a strong economic incentive to locate Enhanced Geothermal Systems (EGS) resources closer to the transmission system in southern Australia. In summary, the following criteria are optimal for a resource to be viable for economic geothermal power generation:

- High average geothermal gradient
- Suitable reservoir conditions, or the ability to economically engineer them
- A proximal market for the generated power

The surface heat flow and broad thermal conductivity structure (and thus the temperature field) of most of Australia are currently poorly understood. Preliminary estimates (e.g. Somerville et al, 1994; Chopra & Holgate, 2005) provided broad approximations of the Australian continent temperature field, but suffered from a sparse geographic distribution of heat flow and thermal conductivity data. Over most of the continent, these data are not available at sufficient spatial resolution to allow temperature modelling to a high degree of confidence.

South Australian Heat Flow Anomaly

The South Australian Heat Flow Anomaly (SAHFA; Neumann et al., 2000) is a region defined loosely by lines of longitude in the central to eastern part of the state of South Australia, encompassing reported elevated heat flow values, but also a number of low values evident in two higher resolution studies.

Prior to 1989 less than 30 published heat flow values were available for the whole of South Australia with, in many cases, hundreds of kilometres between measurements (Matthews & Beardsmore, 2007). This dataset enabled only the most basic understanding of the SA heat flow regime, and required sweeping assumptions to be made about the nature of the heat flow between data points. Two subsequent studies by Houseman et al (1989) and Matthews & Beardsmore (2007) collected heat flow data to a much greater spatial resolution in parts of the SAHFA.

Houseman et al. (1989) revealed that heat flow is variable by a factor of more than two in the Olympic Dam area, and that the highest values correspond to the locations of the Olympic Dam and Acropolis ore bodies, which represent shallow crustal radioactive heat sources (Figure 1). It is estimated that the mantle-derived component of heat flow (q_r) in the eastern Gawler Craton “Olympic Domain” (Figure 1; Ferris et al 2002), is as low as 20–30 mW/m^2 (Neumann et al., 2000). Therefore, the bulk of the surface heat flow anomalies in the Olympic Dam area must be due to the crustal component (q_c) of heat flow.

Matthews & Beardsmore (2007) obtained a similar spread of results in the south eastern corner of South Australia to that of the Olympic Dam study, with heat flow varying by a factor of three over the region. Furthermore, the Padthaway Ridge, a shallow crustal geological feature containing Palaeozoic heat producing granitoids - corresponds to the zone of highest heat flow.

The Olympic Dam and eastern South Australia examples illustrate that the SAHFA is not a zone of consistently high heat flow, and that it may be little different to the previously proposed Central Australian heat Flow Province (CAHFP e.g. McLaren et al., 2003). The concept is consistent with the idea that the Proterozoic CAHFP crust has a ubiquitous value of q_r, with broadly uniform tectonothermal history and heat production depth scale (Roy et al., 1968).

Geological Setting

The Torrens Hinge Zone

The study area is located within the Torrens Hinge Zone (THZ). Preiss (2005) described the THZ as a "zone of syn-sedimentary faulting and flexuring which separates the Gawler Craton [in the west]… from the rifted basins of the Adelaide Geosyncline to the east."

Preiss (2000) described the Adelaide Geosyncline (AG) as "a deeply subsident Neoproterozoic to Middle Cambrian basin complex…with a record of at least five major successive rift cycles." The Neoproterozoic portion of the geological time scale during which these sediments were deposited is locally known as the Adelaidean Period (Mawson & Sprigg, 1950), and the five rift cycles are broadly allocated to five sub-periods, named from oldest to youngest: Willouran, Torrensian, Sturtian, Marinoan and Cambrian (See Appendix 2).

The THZ is essentially a region of overlap between the Gawler Craton and Adelaide Geosyncline (Figure 1). Over the whole of the THZ, the Adelaidean and Cambrian sedimentary sequences are underlain at depths between 2,500 and 7,000m (de Vries et al, 2006), by the dominantly Mesoproterozoic Gawler Craton Olympic Domain (Ferris et al., 2002). In the south, the Palaeoproterozoic Barossa Complex (e.g. Preiss, 1993) also underlies the THZ.

To the east in the Adelaide Geosyncline proper, the sediments have been variably deformed by the Cambro-Ordovician Delamerian Orogeny (e.g. Preiss, 2000); with that region now part of the Delamerian Fold Belt (DFB). The competent nature of the Olympic Domain basement may have protected the THZ region from the full effects of the Delamerian Orogeny. Thus, while the Adelaide Geosyncline is now within the DFB, the THZ remains a "meridional belt of gentle folding" (Preiss, 2000; see Appendix 1).

Close to Port Augusta the earliest rifting phase of the Adelaide Geosyncline is marked by the extrusion of the mafic Beda Volcanics at around 827 Ma (Preiss, 2000).

Torrens Energy has undertaken two seismic surveys: one in the Parachilna Play, the other near Port Augusta, and the results (see Appendix 1) have confirmed the geometry of the Torrens Hinge Zone in the areas surveyed.

Thermal Conductivity in the THZ

As stated earlier, the Adelaide Geosyncline is a Neoproterozoic to Cambrian basin complex. The Geosyncline contains "a semi-continuous record of shallow-water sedimentation from the basal… rift succession with its associated basalts, through the shallow water sedimentary sequences of the Torrensian, the Sturtian, the Marinoan and the Ediacaran into the Early Cambrian…" (Foden et al, 2001).

Dominantly Proterozoic in age, the sediments of the Adelaide Geosyncline are generally more metamorphosed and less porous than most equivalent Phanerozoic sedimentary units, and this has previously led them to be overlooked as potential thermal insulators. Furthermore, the majority of the geographic distribution of these units is in the Adelaide Geosyncline proper, and as such the sediments there have undergone significant orogenic deformation and metamorphism during the Palaeozoic.

The vertical thermal conductivity of a rock can be greatly affected by factors such as the presence of tectonic fabrics or the tilting of bedding planes due to deformation (Clauser & Huenges, 1995; Beardsmore & Cull, 2001).

Thus the effects of deformation very likely reduce the thermal insulating ability of the sediments in the Adelaide Geosyncline region to the east of the THZ due to the effects of the Delamerian Orogeny. However, as discussed above, the THZ was largely shielded from the deformation associated with the Delamerian Orogeny and therefore also the majority of the negative effects of anisotropy on vertical thermal conductivity.

While sedimentary rocks are generally considered the best insulators, mafic volcanics also have low thermal conductivity. Thermal conductivity measurements on Holocene vesicular basalt rocks from South Australia were published by Matthews & Beardsmore (2007), with two values averaging 1.58 W/mK. A total of 19 samples were analysed from core samples of the mafic Neoproterozoic Beda Volcanics, located in the region immediately north of Port Augusta. The harmonic mean of thermal conductivities is 2.51 ± 0.26 W/mK (Musson & Alesci, 2007). The elevated thermal conductivity of these samples relative to their Holocene equivalents may be due to alteration and metamorphism plus the removal of most of the original vesicular porosity. However, the measured values indicates that the Beda Volcanics are still good insulators.

Structured Heat Flow Measurement Programme

As with other potential fields, the amplitude and wavelength of surface heat flow and temperature distribution are directly related to the magnitude and depth of the heat source. An intra-crustal heat

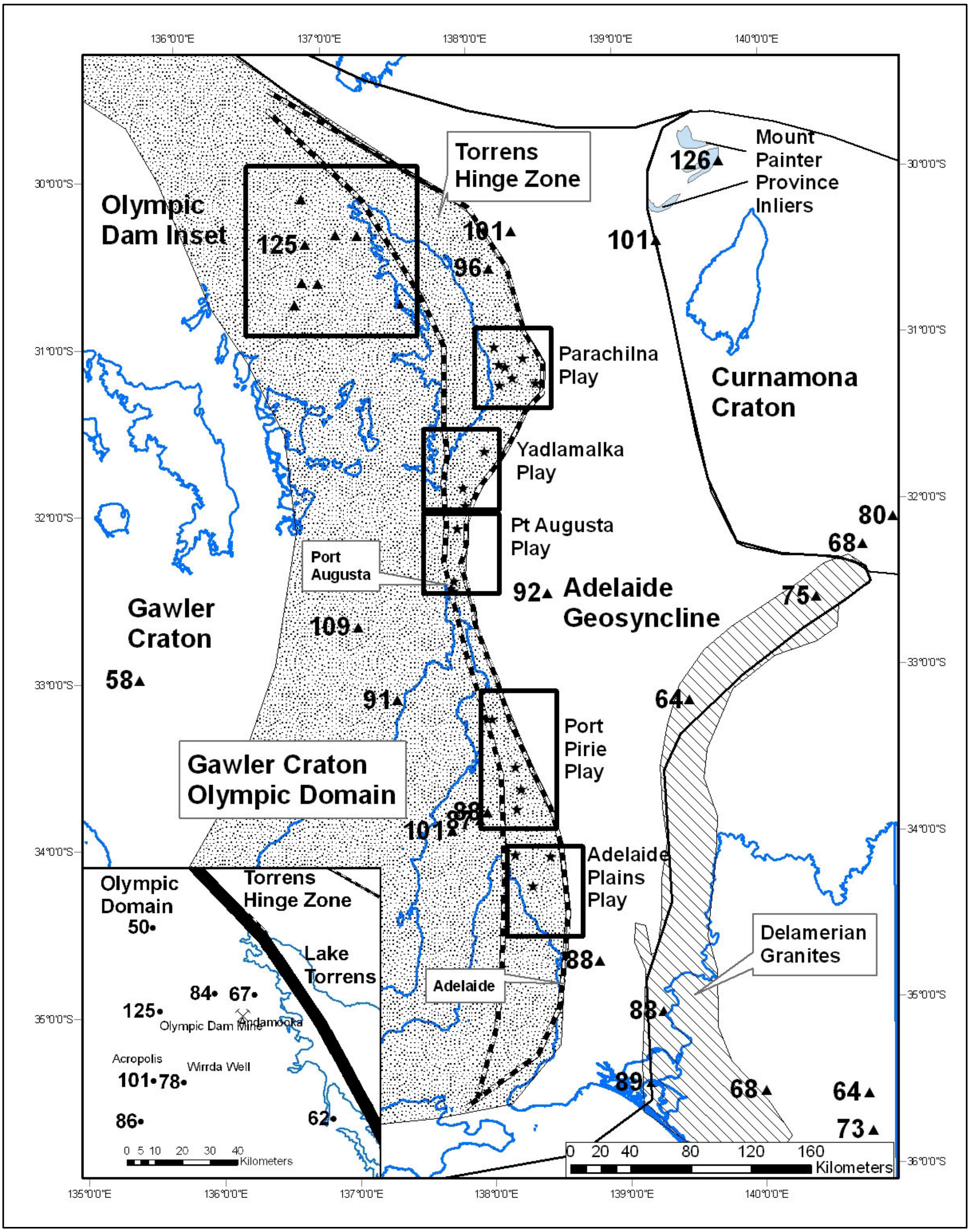

Figure 1: Key geological elements of central South Australia. The Torrens Hinge Zone is a narrow elongate transition zone between the Eastern Gawler Craton and the Adelaide Geosyncline. Heat Flow values are too widely spaced to gauge the true nature of the SA Heat Flow Anomaly. The inset shows values measured by Houseman et al (1989). Key: Triangles = Historic published heat flow values for the region; Stars = Torrens Energy wells. See figures 2a & 2b for heat flow results for Torrens Energy wells.

source should produce a surface heat flow anomaly with a wavelength in a similar order of magnitude as the depth of burial (e.g. Matthews & Beardsmore, 2006). Due to the status of the heat flow data set in Australia, with most values spaced hundreds of kilometres apart, it has been previously impossible to adequately delineate crustal heat flow anomalies.

The depth to crystalline basement in the THZ is estimated to be between 2.5 and 7 km depth (de Vries et al 2006). An effective test of this hypothesis therefore required heat flow data to be collected at a maximum spacing of about 10–15 km to facilitate reasonable accuracy for mapping of heat flow distribution (although this does not necessarily allow for local variations in lithology or rock thermal conductivity which can also contribute variation to surface heat flow distribution).

To test the hypothesis that the THZ contains areas of high heat flow and therefore likely high average geothermal gradients, a heat flow drilling campaign was designed in the Torrens Energy Geothermal Exploration Licences (GELs). Figures 2a and 2b show the locations of heat flow wells.

Data Collection

Each well was designed to reach a depth where the rock is competent enough to be fully cored for around 200m of continuous downhole depth. This involved rotary mud drilling through the mostly unconsolidated Cainozoic clays and sands, found to be up to 400 m deep, followed by diamond coring through the underlying Cambrian and Neoproterozoic sedimentary sequences.

Thermal Gradient Data

A temperature log from within each heat flow well was taken by measuring temperature at discrete depth intervals (0.05 - 2.00 m) from the surface to the bottom of each well. Sufficient time (at least five weeks) was allowed following completion of drilling activities to ensure thermal equilibration (Beardsmore & Cull, 2001). Temperatures were measured to a precision of ±0.001◦C and an absolute accuracy of ±0.01◦C using truck mounted logging tools either from Torrens Energy's in-house logging equipment or contracted from the South Australian Government Department of Water Land Biodiversity and Conservation (DWLBC).

Geothermal gradient varies with lithology. Heat flow remains constant across a geological boundary, and there is an inverse relationship between geothermal gradient and thermal conductivity.

Thermal Conductivity Data

The vast majority of the purpose-drilled heat flow wells contained at least 200m of continuous core section. To allow representative thermal conductivity profiles to be established, core samples were taken every seven to 14 metres on average throughout the cored section.

Up to three specimens were prepared and measured from each sample using a steady state divided bar apparatus.

Heat Flow Estimation

Heat flow can only be modelled over intervals with coincident thermal gradient and thermal conductivity data.

The following methodology was adopted to reach a heat flow determination for each well.

Three assumptions were made. These were that:

- Each conductivity value is representative of the rocks from which the sample was extracted.
- The boundary between one conductivity value and the next is the midpoint between measurement points.
- A dominantly conductive regime exists.

The thermal conductivity profile for each well was then used to model a theoretical temperature profile that would result from a given magnitude of heat flow in a conductive heat flow regime. The observed temperature log was plotted against this theoretical profile, and the magnitude of heat flow was adjusted until the modelled temperature profile best matched the logged temperatures.

Results

In total, 18 purpose-drilled wells and four existing wells returned 18 new heat flow values in the Torrens Hinge Zone, with two results pending and two inconclusive results, providing heat flow coverage for an area of approximately 6,500 km2 at a spatial resolution suitable for investigating heat sources in the basement.

The results of the heat flow study are presented in Table 1 and Figures 2a & 2b, and formed the major constraint for the hypothesis test.

The results of this structured test have validated the hypothesis, with heat flow values over 90 mW/m2 recorded in several of the wells drilled.

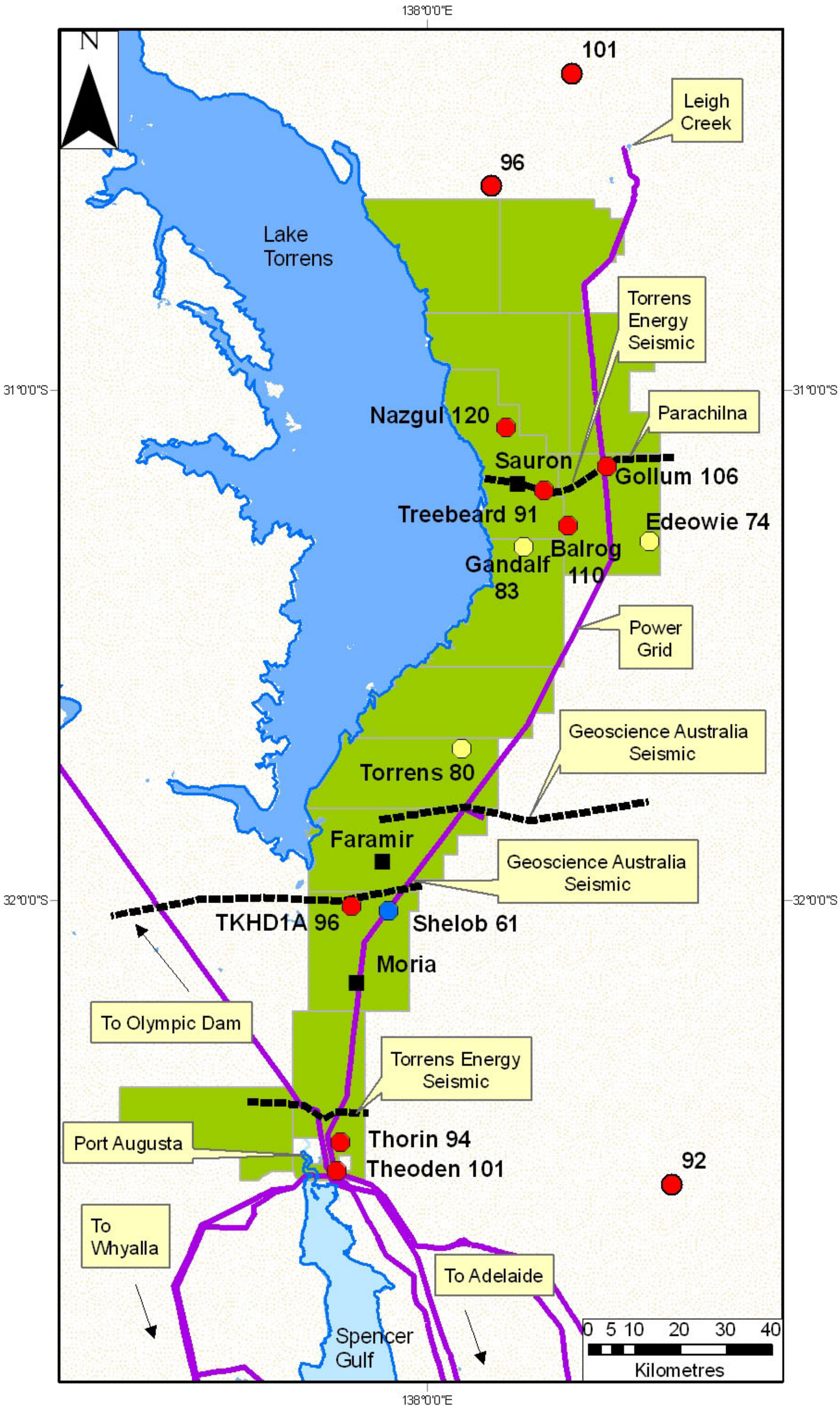

Figure 2a: Torrens Energy's northern tenement areas. The Parachilna Play was the first drilled by the Company, with the Port Augusta region drilled shortly after. Historical heat flow values are unnamed but labelled, with Torrens Energy heat flow wells named and heat flow values labelled. Key to all wells: Blue = < 70 mW/m^2; Yellow = 70 - 89 mW/m^2; Red = ≥ 90 mW/m^2. Black squares represent wells which are either awaiting results or have returned inconclusive results. See Table 1 for values.

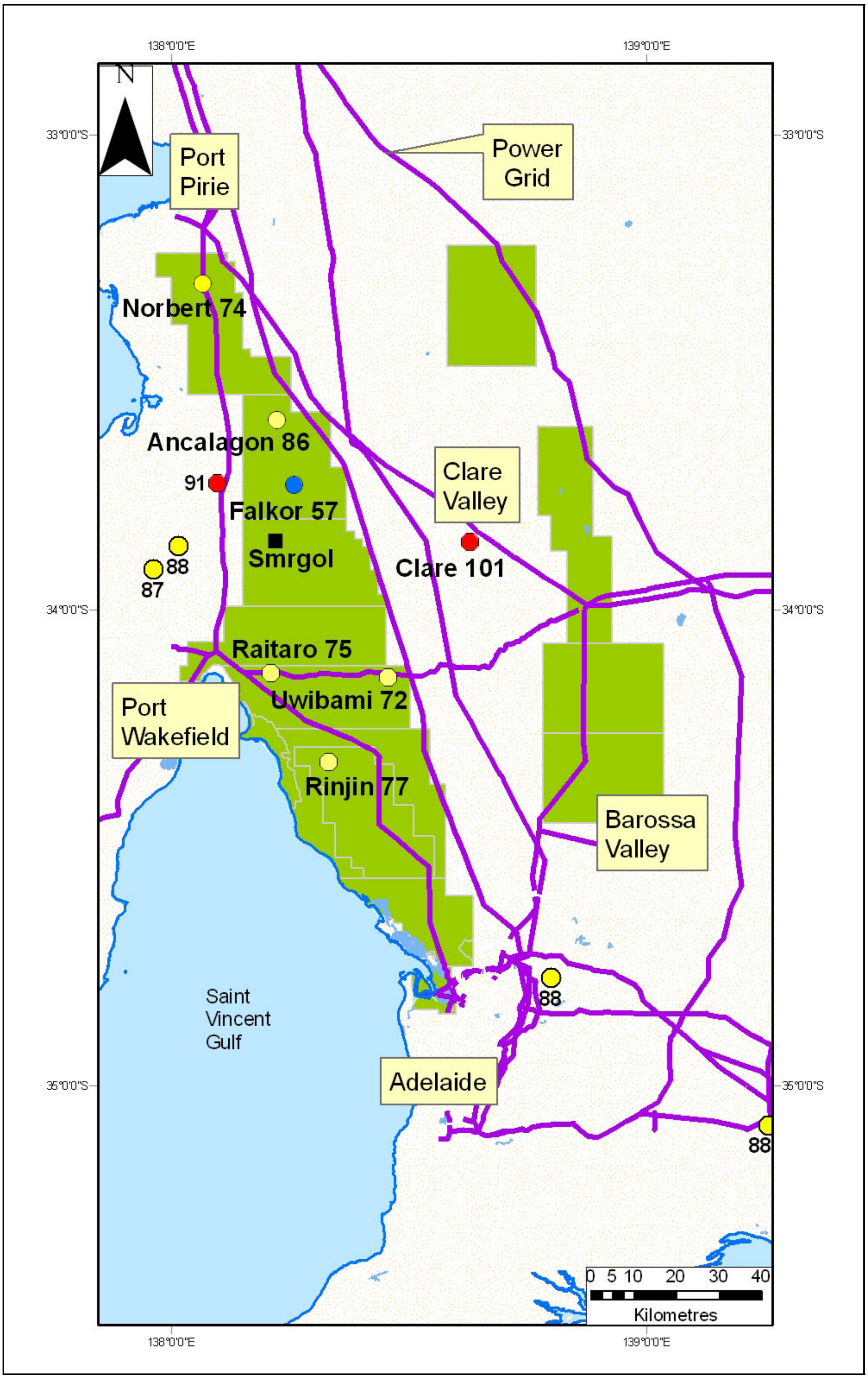

Figure 2b: Torrens Energy's southern tenement areas. The tenements are located in prime infrastructure position, stretching right to inside the city limits of Adelaide. Historical heat flow values are unnamed but labelled, with Torrens Energy heat flow wells named and heat flows labelled. Key to all wells: Blue = < 70 mW/m^2; Yellow = 70 - 89 mW/m^2; Red = ≥ 90 mW/m^2. Black squares represent wells which are either awaiting results or have returned inconclusive results. See Table 1 for values.

Discussion

Torrens Energy used the heat flow and thermal conductivity data to create temperature/depth models for several of the regions that were drilled. The primary tool utilized to estimate temperature was a 3D temperature inversion software module developed through collaboration between Torrens Energy and Hot Dry Rocks Pty Ltd.

Inputs into the software included:

- The 3D geological model of the region in question
- Extensive thermal conductivity measurements undertaken, plus the assignment of textbook values where necessary, with thermal conductivity values assigned to geological units in proportions based on published and interpreted geological data.
- Published data about internal heat generation in the rock column.
- Precision surface temperature and surface heat flow measurements.

The temperature modelling software operates on the principle of 'inversion'. Known information about surface temperature and surface heat flow is entered into the software module. The software then computes in three dimensions the simplest distribution of temperature that fits the observations, while respecting the laws of conductive heat transfer and the thermal properties of the geological strata. The temperature dependence of thermal conductivity is also taken into account.

Torrens Energy derived 3D temperature models in this manner for three of its projects – the Parachilna, Port Augusta and Yadlamalka Plays (Figure 1).

Conclusion

It was hypothesized from geological and conductive heat flow principles that the THZ is likely to be a region of high average geothermal gradients and thus prospective for EGS geothermal energy.

The heat flow drilling campaign designed to test the idea returned results that have validated this hypothesis.

With several kilometres' thickness of moderate conductivity sediments overlying the crystalline Eastern Gawler Craton basement in this region, plus its proximity to existing power infrastructure, the Torrens Hinge Zone is now considered prospective for economic EGS development.

Well	Heat Flow (mW/m^2)
Edeowie 1	74
Gollum 1	106
Sauron 1	Inconclusive
Nazgul 1	120
Balrog 1	110
Gandalf 1	83*
Treebeard 1A	91**
Torrens 1	80
TKHD1A	96
Shelob 1	61
Moria 1	Inconclusive
Theoden 2	101
Thorin 1	94
Rinjin 1	77
Uwibami 1	72
Raitaro 1	75
Norbert 1	74
Ancalagon 1	86
Falkor 1	57
Smrgol 1	Pending
Faramir 2	Pending
CLR 105 (Clare)	101

Table 1.

Surface heat flow measured in wells from this study.

**Gandalf 1 displayed a departure from a simple conductive heat flow inversion model. The best fit conductive model can be found by applying a heat flow of 116 mW/m² in the interval 375-433 m depth, and 83 mW/m² in the interval 433-545 m.*

***Treebeard 1A heat flow value is preliminary*

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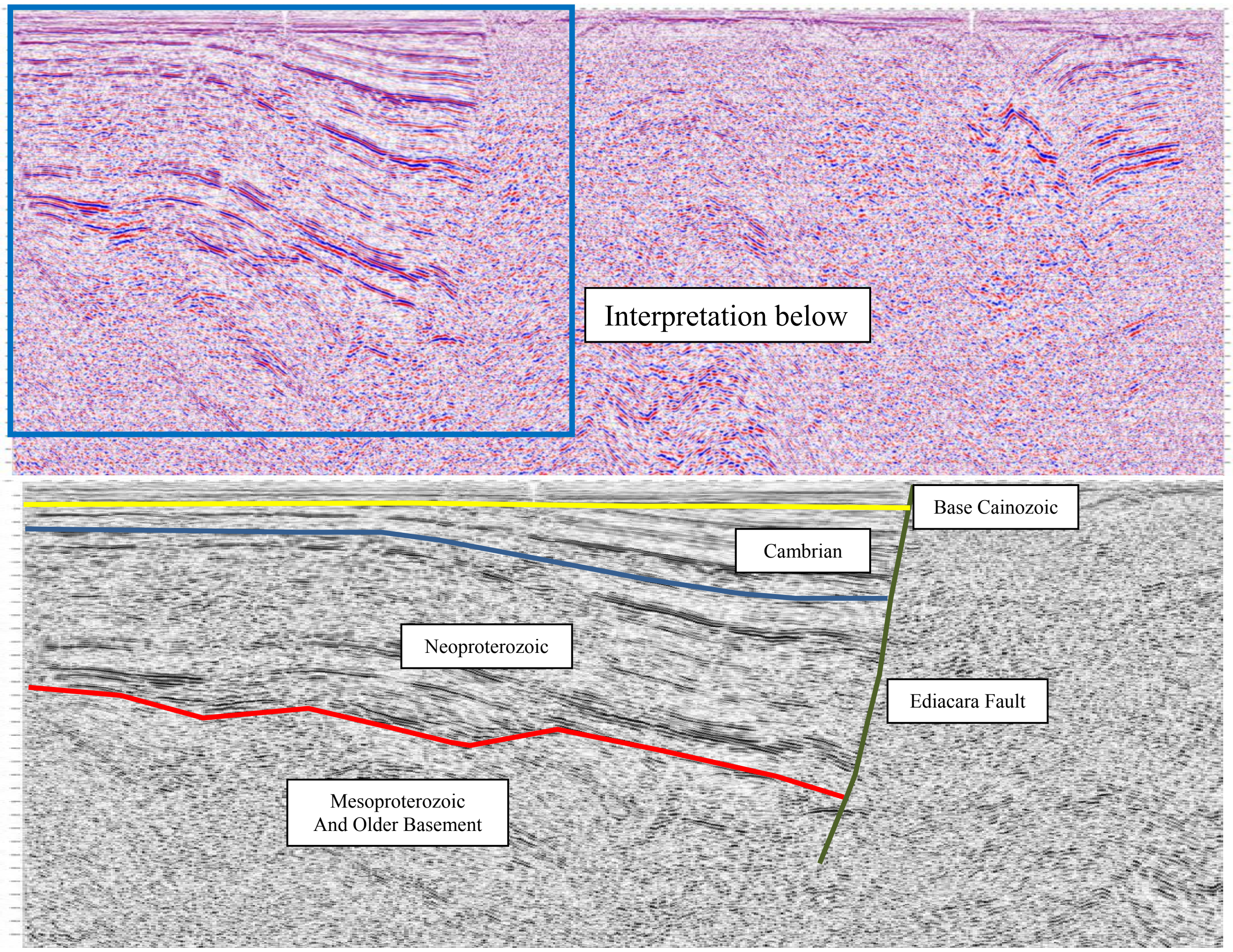
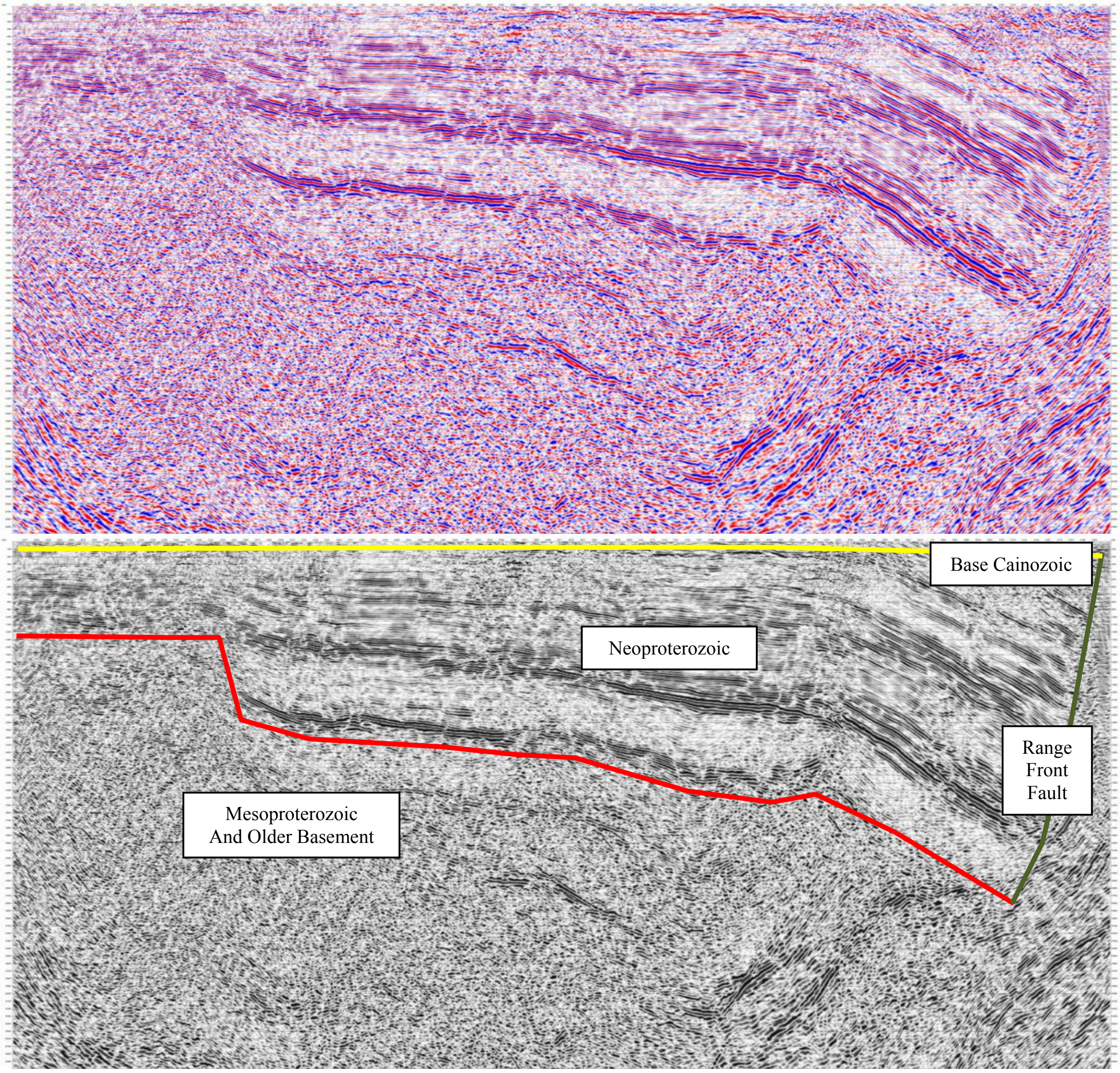
Appendix 1: Seismic Surveys and Results.

Parachilna Seismic Survey, completed January 2009



Port Augusta Seismic Survey, completed May 2009



Appendix 2: Generalised Stratigraphic Column for the Torrens Hinge Zone

Torrens Hinge Zone General Stratigraphy		
Age	**Group**	**Common Units Present**
Pleistocene/Holocene	Pirie-Torrens Basin	Undifferentiated Clays and Gravels
Oligocene-Miocene	Pirie-Torrens Basin	Neuroodla Formation
Eocene	Pirie-Torrens Basin	Cotabena Formation
Middle Cambrian	Lake Frome Group	Pantapinna Formation Balcoracana Formation Moodlatana Formation
Middle Cambrian	Unnamed Group	Wirrealpa Limestone Billy Creek Formation
Early Cambrian	Hawker Group	Wilkawillina Limestone Parachilna Formation
Neoproterozoic (Adelaidean, Late Marinoan)	Wilpena Group Pound Subgroup	Rawnsley Quartzite Bonney Sandstone
Neoproterozoic (Adelaidean, Late Marinoan)	Wilpena Group	Wonoka Formation Bunyeroo Formation
Neoproterozoic (Adelaidean, Late Marinoan)	Wilpena Group Sandison Subgroup	ABC Quartzite (incl. Corraberra Sandstone) Brachina Formation (incl. Tregolana Shale) Nuccaleena Formation
Neoproterozoic (Adelaidean, Early Marinoan)	Umberatana Group Yerelina Subgroup	Elatina Formation/Whyalla Sandstone
Neoproterozoic (Adelaidean, Early Marinoan)	Umberatana Group Upalinna Subgroup	Trezona Formation Wilmington Formation Angepena Formation Etina Formation
Neoproterozoic (Adelaidean, Late Sturtian)	Umberatana Group Nepouie Subgroup	Brighton Limestone Tapley Hill Formation (incl. Woocalla Dolomite Member)
Neoproterozoic (Adelaidean, Early Sturtian)	Umberatana Group Yudnamutana Subgroup	Wilyerpa Formation Appila Tillite Other equivalent Sturtian Glacials
Neoproterozoic (Adelaidean, Late Torrensian)	Burra Group Unnamed Subgroup	Saddleworth Formation
Neoproterozoic (Adelaidean, Middle Torrensian)	Burra Group Mundiallo Subgroup	Skillogalee Dolomite
Neoproterozoic (Adelaidean, Early Torrensian)	Burra Group Emeroo Subgroup	Rhynie Sandstone
Neoproterozoic (Adelaidean, Willouran)		Beda Volcanics Backy Point Formation Callanna Group
Mesoproterozoic Eastern Gawler Craton		Pandurra Formation Gawler Range Volcanics Hiltaba Suite Granitoids
Palaeoproterozoic		Barossa Complex