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Geothermal Systems Assessments and Their Use in Conductive Regimes

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ABSTRACT

Geothermal Systems Assessments offer a holistic approach in delineating geothermal resources with the methodology synonymous to that proposed by Magoon and Dow (1994) in their Petroleum Systems Analysis volume.

Four critical risk areas are identified which are related to four geological factors: heat flow (conductive and advective), thermal resistance (insulation), reservoir characteristics (void connectivity and prevailing stress regime) and access to a working fluid (usually water or steam). These parameters are examined and applied to the onshore Canning Basin in Western Australia.

INTRODUCTION

Geothermal exploration aims to make an assessment of the geothermal potential of a site by assessing the likelihood of each of the main components of a geothermal system being present, namely: the availability of water, the likelihood of *in situ* permeable aquifers or rock units susceptible to artificial permeability enhancement; and the likelihood of elevated temperatures at drillable depth.

The concept of a Geothermal Systems Assessment (GSA) was first suggested by Cooper & Beardsmore (2008) who based their risk methodologies on the Petroleum Systems Assessments of Magoon & Dow (1994). A recent report by Driscoll *et al*. (2009) on the geothermal potential of the onshore Canning Basin of Western Australia has been used to demonstrate the application of GSA to real world situations.

Temperature data are regarded by many in the geothermal community as being the lynchpin to the commercialisation of any given geothermal resource. However, caution should be maintained with respect to the validity of temperature datasets as they are often collated from other sources—most notably the petroleum industry—and collected as ancillary data. Data quality issues including uncorrected bottom-hole temperatures and un-equilibrated thermal regimes associated with drilling fluids can lead to erroneous outputs. In addition, a number of personnel within the geothermal community utilise geothermal gradient methodologies to assess geothermal potential of an area, and this can introduce significant errors given the energy potential of a well cannot be accurately expressed as a single geothermal gradient. By incorporating precision temperature log data with reliable rock property measurements of lithologies penetrated within the well (including thermal conductivity, diffusivity, specific heat, density and radioactive isotope concentrations), heat flow can be calculated. 1D, 2D and 3D conductive heat flow modelling, temperature prediction and mapping outputs can thus be produced.

Whilst temperature/heat flow is obviously an important parameter in defining a geothermal resource, it is paramount to have a detailed understanding of the tectonic stresses and rock properties of any given area, particularly in relation to Engineered Geothermal Systems [EGS] reservoir characterisation. With regards to Hot Sedimentary Aquifer [HSA] systems, reservoir forward modelling techniques—including seismic sequence stratigraphy—used in conjunction with magnetotelluric surveys can be utilised to better understand the sub-surface plumbing characteristics of an area of interest.

Water is a valuable commodity, and it is therefore essential that 'access to water' issues be addressed in the early stages of planning a geothermal project. Hot Dry Rocks Pty Ltd (HDRPL) undertook a study to quantify the volumes, rates and quality of water required at successive stages of exploration, development and production of deep geothermal resources.

CANNING BASIN GEOLOGICAL SETTING

The intracratonic Canning Basin is located in northern Western Australia, covering an area in excess of 595,000 km^2 of which approximately 430,000 km^2 lies onshore (Figure 1). The onshore part of the basin is bounded by three Palaeoproterozoic to Neoproterozoic terranes (the Kimberley Block to the north and the Pilbara and Musgrave blocks to the south), and to the east and south-east by the Amadeus and Officer basins.

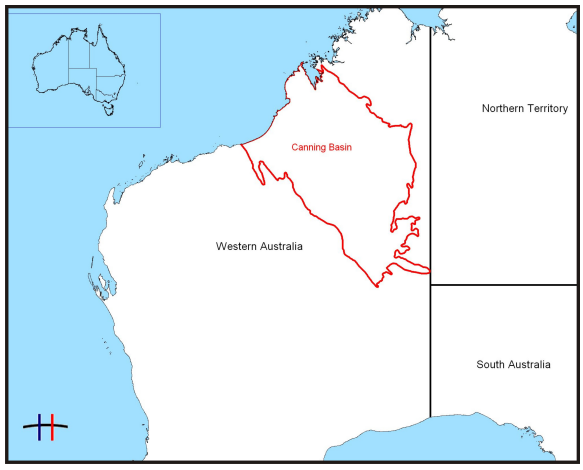

Figure 1: Location of the Canning Basin in northern Western Australia.

Seismic and other geophysical data identify a north-westerly Palaeozoic structural grain in the onshore portion of the basin, and a number of tectonic elements are recognised (Hocking *et al*., 2008; Figure 2). A fault-bounded rift dominates the northern Canning Basin and is subdivided into two depocentres—the Fitzroy Trough and the Gregory Sub-basin. A number of faulted terraces flank

these depocentres (the Lennard Shelf, Betty Terrace, Balgo Terrace, Barbwire Terrace and Jurgurra Terrace). The southern Canning Basin comprises the Crossland Platform and Broome Platform, and two broad sag basins—the Wallal and Kidson sub-basins. The boundaries between the structural elements are typically syndepositional fault zones which have been active at various times during the Palaeozoic to Mesozoic.

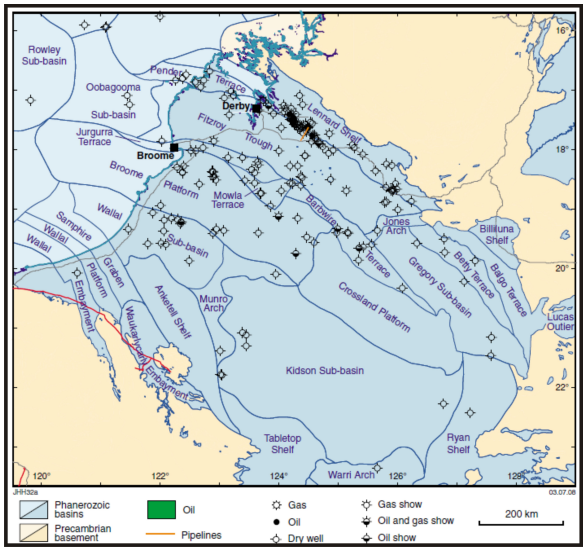

Figure 2: Basin subdivisions and tectonic elements of the Canning Basin (from Hocking *et al*., 2008).

Data derived from the OZ SEEBASEv2 project (www.frogtech.com.au) suggest in excess of 18 km of gently deformed Lower Ordovician to Lower Cretaceous sediments have accumulated in the deepest section of the Canning Basin—the Gregory Sub-basin. Sediment thickness in the main southern depocentre—the Kidson Sub-basin—is not as pronounced, typically in the range 5–6 km thick. Both the Fitzroy Trough and Kidson Sub-basin began subsiding in the Early Ordovician, however only the former continued subsiding during the Late Devonian and Early Carboniferous (Middleton, 1990).

The regional stratigraphic framework of the Canning Basin (Figure 3) is almost entirely derived from subsurface petroleum datasets as much of the basin is covered by a thin Cainozoic veneer. The Canning Basin has a multi-phase depositional history spanning the Early Ordovician to Cretaceous; thus the sedimentary architecture is complex with formations being both spatially and temporally restricted in the basin. Four major phases of deposition are recorded (Hocking *et al*., 2008): Ordovician–Silurian (marine to marginal marine, and evaporitic sequences); Devonian–Early Carboniferous (marine, reefal, and fluvio-deltaic deposition in the north, and marginal marine to terrestrial in the south); Late Carboniferous–Permian (non-marine to marine, and glacial deposition); and Jurassic–Early Cretaceous (mostly non-marine).

HEAT FLOW RISK

Heat flow modelling provides a firm basis for accurate extrapolation of temperatures to depth, as it takes the thermodynamic principles of heat transfer into account.

Heat flow at the Earth's surface is a power unit and is a function of heat generated within the crust plus heat conducted from the mantle. The thermal state of the crust can be expressed at the surface in the form of heat flow units (mW/m^2) and it is generally assumed that heat is transported to the surface by conductive means over much of the Earth's surface. In a conductive heat regime the temperature T, at depth z is equal to the surface temperature T0 plus the product of heat flow Q and thermal resistance R, such that:

$$T=T0+QR \qquad (1)$$

where $R=z/\lambda$ (average thermal conductivity between the surface and z).

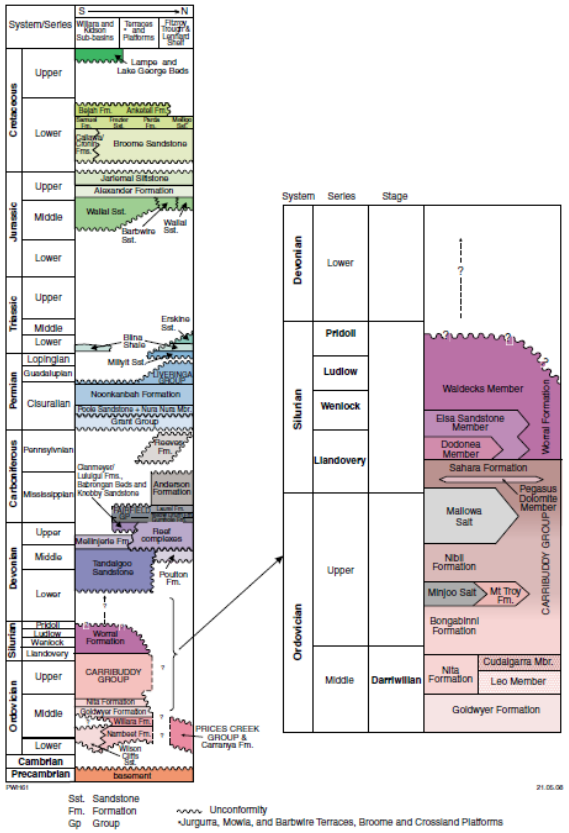

Figure 3: Stratigraphy of the onshore Canning Basin (from Hocking *et al*., 2008).

Consequently the most prospective regions for geothermal exploration are those that have geological units of sufficiently low conductivity (high thermal resistance) in the cover sequence combined with high heat flow.

Heat flow is a product of temperature gradient and rock thermal conductivity and is therefore a modelled value (not directly measured). The modelling of heat flow is a precision skill that requires a detailed understanding of physical conditions in the bore hole and the physical properties of the rocks; including advective processes that may influence bore temperature (such as groundwater flow) and the temperature dependence of conductivity.

Heat flow estimates are only as accurate as the data that have been used to generate them. It is therefore important that the temperature and conductivity data used to model heat flow represent as closely as possible the actual thermal conditions.

Driscoll *et al*. (2009) utilised HDRPL's proprietary 1D conductive heat flow modelling software to build heat flow models for selected wells in the Canning Basin. Required input data include downhole temperatures (corrected to

approximate equilibrated conditions where sufficient information is available) and thermal conductivity data of representative formations.

Verification of Well Temperatures

Temperature modelling and extrapolations undertaken solely using temperature gradients derived from the reported well temperatures measured during the drilling process can underestimate the true virgin rock temperature of the formations at depth. Temperature data reported in petroleum reports are often of unknown quality. In order to ensure the most accurate data are used in the thermal modelling process, corrections (such as Horner Plots) can be applied to time series data recorded during logging processes.

The Horner Plot method (Horner, 1951; Lachenbruch and Brewer, 1959; Hermanrud *et al*., 1990) corrects the bore hole temperature for the cooling effect of the drilling process using the parameters of recorded bore hole temperature, the time since the last fluid circulation, and the time elapsed between the end of drilling and the cessation of fluid circulation. The accuracy of the correction depends on the reliability and accuracy of the reported temperatures and times. More than one recorded temperature from the same depth is required for a Horner Plot.

Temperatures reported in the well completion reports of 113 wells in the Canning Basin were assessed and, where sufficient information was found, Horner corrections were applied. The corrected temperatures were used in the thermal models for these wells. Temperatures recorded during drill stem tests (DSTs) were also accepted as accurate representations of virgin rock temperature, and used in the thermal models. For all other temperature data it was not possible to apply corrections; however uncertainty values were ascribed to each temperature datum.

Surface Temperatures

Ground surface temperature is an important constraint for well heat flow models. Average surface temperature for each well was determined from annual mean air temperature data derived from the Australian Bureau of Meteorology for the Canning Basin. These data were corrected upwards by 3°C to account for surface insolation effects, following the findings of Howard and Sass, 1964. Surface temperatures for offshore wells were modelled using bottom water temperature (BWT) as a function of water depth and latitude (Beardsmore and Cull, 2001).

Rock Thermal Conductivity Measurement

Thermal conductivity is the physical property that controls the rate at which heat energy flows through a material in a given thermal gradient. In the S.I. system of units, it is measured in watts per metre-Kelvin (W/mK). In the earth, thermal conductivity controls the rate at which temperature increases with depth for a given heat flow. The thermal conductivity distribution within a section of crust must be known in order to calculate crustal heat flow from temperature gradient data, or to predict temperature increase with depth for a given heat flow.

Steady-state thermal conductivity measurements were undertaken by Antriasian (2009) for 50 representative samples from lithologies of the Canning Basin using HDRPL's portable electronic divided bar thermal conductivity apparatus.

As rock thermal conductivity is highly dependent upon lithology, some manipulation of the measured data was undertaken by Driscoll *et al*. (2009) to ensure that conductivity values utilised in the 1D heat flow models best represented the typical lithologies found within the basin. The 50 measurements of thermal conductivity included a number of measurements on 'pure' lithological samples such as 'shale', 'sandstone', etc. Where formation descriptions in well logs indicated mixed lithologies, a conductivity value for these formations was estimated from the weighted harmonic mean of the conductivities of the 'pure' lithological components. This process is described in Beardsmore and Cull (2001).

Derived thermal conductivity values for each Canning Basin formation, as used in the 1D heat flow models, are shown in Table 1.

Estimating Lithologies at Depth

1D heat flow models for temperature prediction at depth require detailed lithological data, and associated rock thermal conductivities, for all formations down to the modelled depth. Driscoll *et al*. (2009) used wire-line log data and well completion reports to constrain lithologies within the drilled portion of the heat flow models.

The lithologies and thicknesses of deeper formations were estimated using other available data. Driscoll *et al*. (2009) utilised existing deep wells to estimate the thickness of individual formations as a ratio of the entire stratigraphic column. OZ SEEBASEv2 depth-to-basement estimates for all wells were used to constrain the overall thickness of the sedimentary section, to which the formation-specific ratios were applied.

In order to make this methodology as robust as possible, wells that reached total depth within the sedimentary sequence were tied to the nearest deep well that intersected basement. This process assumed that the sedimentary units within the sedimentary pile would continue laterally between the wells in a relatively constant ratio. Whilst simplistic, this methodology provides one of the few mechanisms to estimate the likely thickness of deep units for which there is a paucity of data.

In summary, whilst there is some uncertainty in the estimated thickness and distribution of non-intersected formations within the Canning Basin, Driscoll *et al*. (2009) used all available data to make reasonable assessments on a regional scale to minimise the uncertainty.

Estimating Basement Heat Generation

Heat generation is best determined from the analytical measurement of uranium, thorium and potassium within rock samples. As it is not possible to obtain basement samples for all 274 wells in the Canning Basin, Driscoll *et al*. (2009) assessed the heat generation of rocks within and adjacent to the Canning Basin using data from the Geoscience Australia geochemical database (OZCHEM). Heat generation values estimated from these data have been incorporated into the 1D heat flow models for this study.

As no geochemical data were available for the Canning Basin, samples from the Halls Creek and Kimberley regions were utilised, assuming that similar rocks may partly comprise the basement of the Canning Basin. Heat generation ($\mu W/m^3$) for each sample was estimated using an assumed rock density and the isotopic abundance method as described in Beardsmore and Cull (2001).

Table 1: Summary of rock thermal conductivities by formation for the Canning Basin, as used for 1D heat flow modelling in this report. Uncertainty range derived from Antriasian (2009).

Formation	Formation Conductivity (W/mK)
Alluvium	1.42 ± 0.14
Broome Sandstone	3.12 ± 0.07
Jarlemai Siltstone	1.57 ± 0.17
Alexander Formation	2.70 ± 0.11
Wallal Sandstone	3.12 ± 0.07
Erskine / Culvida Sandstone	3.12 ± 0.07
Blina Shale	1.28 ± 0.19
Millyit Sandstone	3.12 ± 0.07
Liveringa Group	2.70 ± 0.08
Noonkanbah Formation	1.57 ± 0.17
Poole Sandstone (Tuckfield Member)	3.12 ± 0.07
Poole Sandstone (Nura Nura Member)	3.12 ± 0.07
Grant Group Unit A (Carolyn Formation)	3.07 ± 0.28
Grant Gp Unit B (Winifred Formation)	2.61 ± 0.30
Grant Gp Unit C (Betty Formation)	4.17 ± 0.08
Lower Grant Gp (Reeves Formation)	5.83 ± 0.22
Anderson Formation (Unit A to C)	2.58 ± 0.21
Fairfield Group (Laurel Formation)	2.27 ± 0.19
Fairfield Group (Yellow Drum Formation)	2.81 ± 0.15
Fairfield Group (Gumhole Formation)	2.25 ± 0.12
Fairfield Group (Luluigui Formation)	2.27 ± 0.22
Nullara Limestone	3.33 ± 0.02
Windjana Limestone	3.13 ± 0.02
Clanmeyer Siltstone	2.23 ± 0.13
Knobby Sandstone	3.97 ± 0.33
Napier Formation	2.51 ± 0.47
Virgin Hills Formation	2.51 ± 0.47
Pillara Limestone	3.14 ± 0.14
Gogo Formation	2.51 ± 0.47
Tandalgoo Sandstone	2.23 ± 0.14
Poulton Formation	2.50 ± 0.13
Worral Formation	2.50 ± 0.13
Carribuddy Group (Unit A Sahara Formation)	2.98 ± 0.30
Carribuddy Group (Unit B Mallowa Salt)	4.89 ± 0.32
Carribuddy Group (Unit C Nibil Formation)	3.64 ± 0.63
Carribuddy Group (Unit D Mt Troy Formation)	2.07 ± 0.29
Carribuddy Group (Unit E Bongabinni Formation)	1.78 ± 0.07
Nita Formation	2.03 ± 0.35
Goldwyer Formation	2.03 ± 0.35
Willara Formation	3.24 ± 0.20
Nambeet Formation	2.03 ± 0.35
Basement (Schist)	2.76 ± 0.29
Basement (Gneiss)	3.29 ± 0.11
Basement (Metasediment)	4.01 ± 1.00
Basement (Granite)	3.36 ± 0.26
Basement (Basalt)	1.80 ± 0.18
Basement (Metabasalt)	1.80 ± 0.18
Basement (Metagabbro)	1.80 ± 0.18
Basement (Metasediment–Gabbro)	2.49 ± 0.59
Basement (Uncertain)	3.36 ± 0.42
Basalt intrusions	1.80 ± 0.18

Median heat generation results for granite, gneiss and sedimentary rock samples adjacent to the Canning Basin are shown in Table 2.

Table 2: Summary of heat generation estimates for selected rock types around the Canning Basin.

Lithology	No of samples	Assumed density (g/cm^3)	Heat generation ($\mu W/m^3$)	
			Range	Median
Granite	20	2.68	0.15–11.73	2.68
Gneiss	3	2.65	1.87–2.75	2.42
Sedimentary	6	2.5	1.84–3.71	2.48

The data suggest that the uranium content of granites, gneiss and sedimentary rocks around the Canning Basin is not greatly elevated. The resulting median heat generation estimate for granite is slightly below global average (Beardsmore and Cull, 2001) and well below those described underlying the Cooper Basin of South Australia (~10 $\mu W/m^3$, McLaren *et al*., 2003). The median value may change with further geochemical sampling of basement rocks beneath the Canning Basin.

Heat Flow Determination

Driscoll *et al*. (2009) incorporated temperature data and measured rock thermal conductivity data to estimate heat flow in each given well. Data were incorporated into the model and heat flow was adjusted until the predicted temperature profile best fit the reported temperature datasets, allowing for uncertainty margins. Driscoll *et al*. (2009) constructed 1D heat flow models for 101 wells in the Canning Basin.

Heat flow for the Canning Basin ranges from 20 to 160 mW/m^2, with a median value of 68 mW/m^2. However, the distribution of these data is biased by local concentrations of well locations, especially in the northern portion of the basin. Figure 4 details the 1D heat flow model for the Kidson 1 petroleum well.

Reliability of Heat Flow Data

Modelled heat flow is highly dependent upon the quality and quantity of temperature data. For each temperature datum, an uncertainty range was estimated based on the type of datum and the information known about it. For example, a well constrained Horner corrected or DST temperature may be assigned a narrow uncertainty range centred on the corrected value. Uncorrected BHT values, however, were assigned a very low or zero uncertainty on the 'negative' side and a much larger uncertainty on the 'positive' side to reflect the fact that these data are very likely to understate the true temperature conditions. Heat flow models were constructed so that predicted temperature profiles passed as near as possible through the mid-point of the error bars on all temperature data (Figure 4

demonstrates an example of this methodology when applied to the Kidson 1 petroleum well).

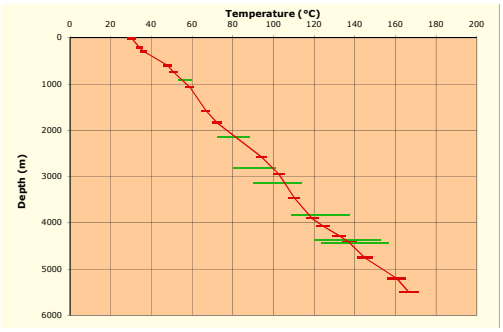

Figure 4: 1D heat flow model for the Kidson 1 petroleum well. The green circles represent individual temperature data; the green lines represent the degree of uncertainty; the red line is the predicted temperature profile for a heat flow of 60 ± 1.9 mW/m2.

Modelled heat flow values were ascribed a relative reliability ranking based on a qualitative assessment of the well temperature data (Table 3 and Figure 5).

Table 3: Reliability ranking scheme for the 101 wells modelled in the Canning Basin.

Reliability Ranking	Temperature Data
1	One BHT datum
2	Several BHT data
3	One DST or Horner corrected temperature
4	Several DST or Horner corrected temperatures
5	Both DST and Horner corrected temperatures

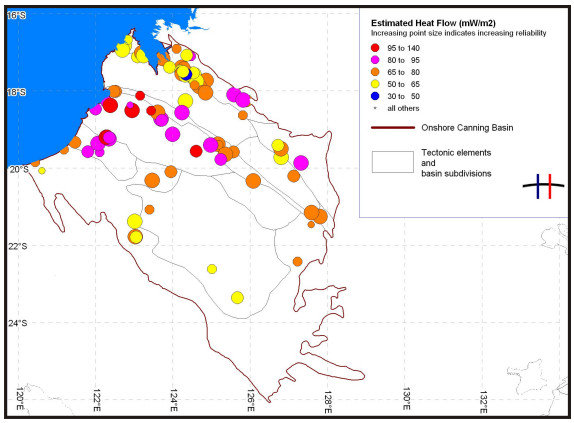

Figure 5: Estimated heat flow for 101 wells in the Canning Basin. The relative reliability of data is illustrated by point size.

Of the 101 wells modelled in this study, 20% were ascribed a reliability ranking of 1 or 2.

To ensure robustness of ensuing modelling, Driscoll *et al.* (2009) excluded wells with a reliability ranking of 1 or 2 from assessments of the spatial and magnitude distribution of heat flow and temperature projections. Thus, where data quality was poorly constrained, or where there were no well penetrations, graphical representations of the data appears blank (Figures 6, 7 and 8). In addition, the radial distance of influence of each well was limited to 75 km.

Spatial and Magnitude Distribution of Heat Flow Data

The spatial distribution of heat flow models is illustrated in Figures 5 and 6.

There is a paucity of relevant data for the Canning Basin. Large portions of the central, south and south-west of the basin (approximately 50% of the total area of the onshore basin) have not been drilled, have vintage datasets, or lack geological data that can be utilised for geothermal prospectivity assessment.

In general, those parts of the Canning Basin for which data exist show increasing surface heat flow towards the central areas. The lowest heat flow (<65 mW/m^2) is centred on the Fitzroy Trough, Gregory Sub-basin and Kidson Sub-basin (although only one well was modelled in the Kidson Sub-basin). This trend may be related to increased sediment thickness in these depocentres. Areas of lower heat flow also occur on the margins of the basin, most notably the Munro Arch and southern portion of the Anketell Shelf on the southern margin, and the Pender Terrace and Lennard Shelf on the northern margin.

Heat flow increases to >80 mW/m^2 in the central basin areas, most notably on the Broome Platform and Wallal Sub-basin. Other relatively high heat flow areas include the Mowla Terrace, Jurgurra Terrace and Barbwire Terrace.

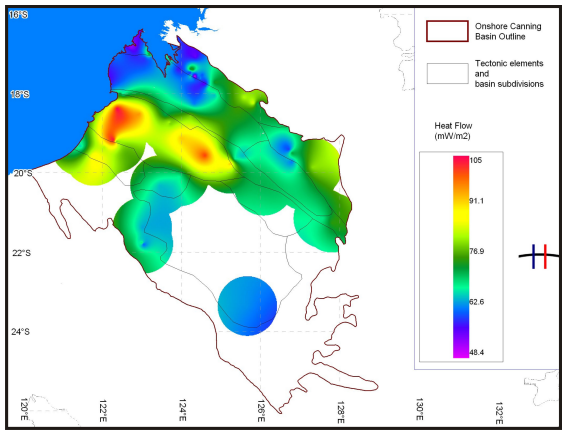

Figure 6: Gridded heat flow values for the onshore part of the Canning Basin. Each well was assumed to represent an area encompassing a radius of 75 km from the well. Those parts of the basin in which there are no wells, or where the reliability of temperature data has a ranking of 1 or 2 (Table 3) have been left blank.

Temperature Projection

<u>Depth-to Isotherms</u>

Heat flow modelling allows the estimation of depth-to-isotherm targets by applying Equation 1, and is demonstrated by Figure 7; the gridded 150°C isothermal surface. Most of the basin has the 150°C isotherm modelled at <5,000 m depth implying potential EGS prospectivity, depending on the suitability of target lithologies for fracture stimulation. Parts of the basin centred on the Broome Platform, Wallal Sub-basin, Jurgurra Terrace, Mowla Terrace and Barbwire Terrace have the 150°C isotherm

modelled at <4,000 m, becoming increasingly shallow (<3,000 m) on the Broome Platform. In many central and northern areas the 150°C isotherm is coincident with Palaeozoic sedimentary units. If a lithology in this area preserves natural permeability, it may be possible that HSA systems can be developed.

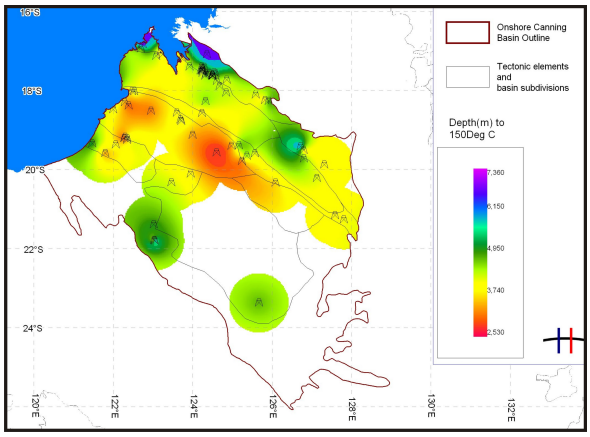

Figure 7: Estimated depth to the 150°C isotherm for the onshore Canning Basin. Each well was assumed to represent an area encompassing a radius of 75 km from the well. Those parts of the basin in which there are no wells, or where the reliability of temperature data has a ranking of 1 or 2 (Table 3) have been left blank.

Temperature at 5,000 m

The temperature at basement can be estimated from 1D heat flow modelling. As the Canning Basin is exceptionally deep (sediment exceeding 18 km thickness), Driscoll *et al.* (2009) restricted this mapping to areas where basement is <5,000 m deep, an assumed economic drilling limit.

Figure 8 shows the modelled temperature at 5,000 m depth for the Canning Basin. In general, the basement is cooler in the northern areas, centred on the Lennard Shelf, and the northern portion of the Gregory Sub-basin where estimated temperatures are <140°C. The highest estimated temperatures (>200°C) are found on the Broome Platform and Crossland Platform.

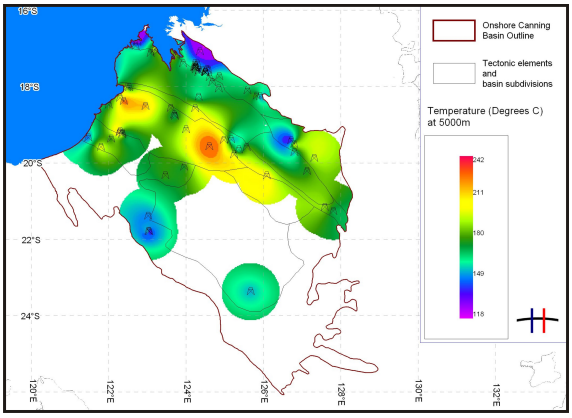

Figure 8: Estimated temperature at 5,000 m depth for the onshore Canning Basin. Each well was assumed to represent an area encompassing a radius of 75 km from the well. Those parts of the basin in which there are no wells, or where the reliability of temperature data has a ranking of 1 or 2 (Table 3) have been left blank.

THERMAL RESISTANCE RISK

For both EGS and HSA systems, a thick, low thermal conductivity sequence such as coals, carbonaceous shales or fine-grained siltstones is optimal to ensure that the ambient heat flow translates into maximum thermal gradients. The required thickness of the sedimentary package is dependent on the thermal resistance of lithological units, but it is generally in the order of a few kilometres. It is unlikely that a lithological unit will be homogeneous over its entire thickness, and so techniques must be deployed to give an idea of the degree of heterogeneity. Whilst seismic can give a broad idea of what lithologies are present within a sequence, a drilling program incorporating wireline testing and regular core sample collection will give the best indication of thermal resistance.

Recent investigations by HDRPL indicate that anisotropy can have a profound effect on the thermal conductivity of a sediment package. Strongly anisotropic strata can have thermal conductivity values several times greater than a corresponding homogeneous package of the same sediment, as cleavage and fractures can act as conduits for vertical heat conduction.

Low conductivity sediments are common within the stratigraphic succession and widely distributed throughout the Canning Basin.

RESERVOIR RISK

Reservoir risk has many guises, and depends on whether the geothermal target is a HSA or an EGS.

Porosity and permeability of sedimentary rocks is, amongst other parameters, a function of depth of burial. Whilst it is true that producing oil and gas fields are often found within sedimentary rocks at burial depths of 3-4 km, it should be noted that high flow rates are required from HSA reservoirs for the system to be economically viable. Thus, when looking at a HSA, it is entirely possible that the reservoir will require hydraulic stimulation in order to enhance interconnectivity of pores, thus increasing permeability (but not necessarily porosity).

The successful development of an EGS is dependent upon several factors, but one of the most critical factors is the response of the fractured rock mass to the *in situ* stress field. Historically, crystalline basement, and in particular granitic basement, has been the preferred medium because of the notion that fluid losses from a circulation system can be constrained if the host rock mass has negligible *in situ* porosity and permeability.

Granites have an internal fabric of joints and fractures. These need to be artificially widened in order to act as conduits for substantial flow of water or any other heat transport medium. This is achieved by increasing the pore pressure through the injection of fluid, usually water, into the base of a deep injection well, leading to the slight opening of pre-existing fractures. Natural internal stresses that operate at depth within the granite cause the separated rock faces to slip in a process referred to as ‘micro-sliding’. When the pore pressure is returned to normal, the fractures close again but do not fit neatly due to the slipping; a network of voids that are all in communication is thus produced. The resulting zone of enhanced permeability represents an artificially engineered reservoir.

Stress-dependant permeability of deep-seated, fractured rocks is well documented in studies relating to both hydrocarbon and geothermal reservoirs as well as nuclear

repositories (e.g. Gentier *et al*., 2000; Hillis *et al*., 1997; Hudson *et al*., 2005). In particular, *in situ* stress fields are known to exert a significant control on fluid flow patterns in fractured rocks with a low matrix permeability. For example, in a key study of deep (>1.7 km) boreholes, Barton *et al*. (1995) found that permeability manifests itself as fluid flow focussed along fractures favourably aligned within the *in situ* stress field, and that if fractures are critically stressed this can impart a significant anisotropy to the permeability of a fractured rock mass. Preferential flow occurs along fractures that are oriented orthogonal to the minimum principal stress direction (due to low normal stress), or inclined ~30° to the maximum principal stress direction (due to dilation).

Knowledge of both the local- and regional-scale stress regime is important for EGS projects in order to understand and predict potential reservoir growth and flooding directions. In general, stress fields are anisotropic and inhomogeneous. They are defined in simplified terms by three mutually orthogonal principal axes of stress, being the vertical (SV), maximum horizontal (SH) and minimum horizontal (Sh) (Anderson, 1951).

Canning Basin Stress Measurement Data

A compilation of all currently available *in situ* stress field data for the Canning Basin contains only twelve recorded measurements (Figure 9). These stress data, sourced from the World Stress Map (WSM), are mainly derived from borehole breakouts and earthquake focal mechanisms, with one shallow hydraulic fracturing measurement (Heidbach *et al*., 2008). The stress data range in WSM quality ranking from A–E (i.e. high–low), however, for the purposes of this study, data assigned a quality ranking of E was deemed too low quality and thus not used. Borehole breakouts and earthquake focal mechanisms are generally considered better quality indicators of the *in situ* stress field (Heidbach *et al*., 2008). However, as there are so few data points spread across the entire basin and they are of variable quality rankings this information can only be used to describe the far-field, regional-scale stress field orientations and style (no magnitudes). The single hydraulic fracturing measurement is probably too shallow to be truly representative of the far-field, tectonic regime and is considered irrelevant to this discussion.

Relevance of the Regional Stress Field Data

In the absence of more substantial stress field data, Driscoll *et al*. (2009) were unable to make definitive statements regarding the influence of the *in situ* stress field on the geothermal prospectivity of the Canning Basin. However, the existing data indicate that the contemporary, far-field stress regime currently affecting the onshore Canning Basin is most likely strike-slip, where SH > SV > Sh. Under a strike-slip stress regime, EGS reservoir growth and permeability orientation is predicted to favour steep to vertical dipping fractures that strike <45° (commonly 30°) to the direction of SH. The mean SH orientation for all onshore data of quality ranking A–C is approximately 54°, with a standard deviation of 12° (n=10). This implies that maximum fracture permeability will occur in steep to near vertical fractures that strike in an approximately NE–SW direction. This is roughly orthogonal to the apparent north-westerly structural grain of the onshore portion of the basin.

WORKING FLUID RISK

There is growing awareness within the geothermal community that access to a working fluid should be addressed during the initial exploration stage of a geothermal project rather than just be considered during the developmental and production phase. This is due to both public concerns about water security, and also to water-use being subject to increasingly stringent regulatory frameworks.

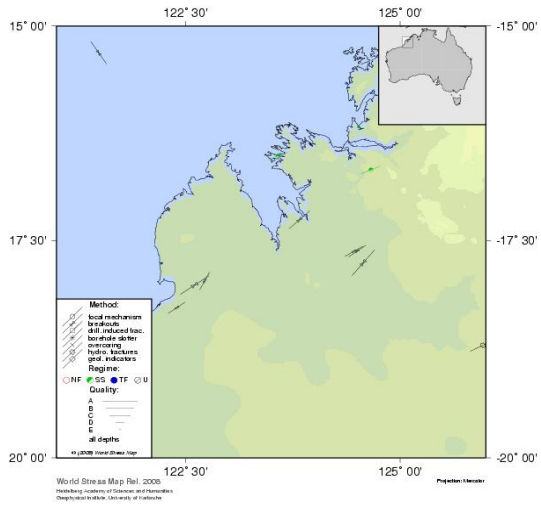

Figure 9: *In situ* stress field measurements in the Canning Basin, including the method, quality ranking, stress regime and orientations of the principle horizontal stress axis (SH) (from Heidbach *et al*., 2008).

The working fluid is classed as the medium through which heat can be extracted from the sub-surface realm and brought to surface, otherwise referred to as a heat transmission fluid. Whilst most geothermal operators consider water to be the optimal working fluid, there is ongoing research into other fluids such as super-critical CO_2 (Brown, 2000; Pruess, 2006). Whilst CO_2 has many benefits including being a non-polar fluid, low viscosity at temperatures and pressures within the reservoir, and a large buoyancy effect; there are several drawbacks such as a lower heat capacity and large frictional losses (due to gas-phase flows in the production well-bore) which leads to lower thermodynamic performance within the system (Atrens *et al*., 2009).

Cordon and Driscoll (2008) quantified the volumes, rates and quality of water required at successive stages of exploration, development and production of geothermal resources in a South Australian context, and these data are transferrable to geothermal projects elsewhere.

In order to commercially exploit a HSA geothermal resource, detailed knowledge of the aquifer and water-flow characteristics needs to be ascertained. With EGS, the water requirements tend to be focused on the volume required to initially charge the system, and volumes required to sustain the system once water losses are accounted for.

Flow characteristics are especially important in order to ensure extraction does not cool the system and exhaust the heat resource too quickly. It is therefore essential that an investigation into the water required by geothermal energy projects be carried out.

As there are very few operational EGS in the world, hydrothermal projects are generally used in comparison to provide an estimate water usage for the production phase of geothermal energy projects. In a typical, successful hydrothermal reservoir, wells can produce a minimum of

5 MW of net electric power through a combination of high temperatures and high flow. For instance, a well in a shallow hydrothermal reservoir producing water at 150°C needs to flow at about 125 kg/s (~125 l/s) to generate 4.7 MW (Tester *et al*., 2006) of net electric power to the grid.

The Canning Basin has a strong degree of anisotropy in its rainfall distribution pattern with large swathes of the inland southern described as arid (annual rainfall <250 mm) or semi-arid (annual rainfall 250-500 mm). Annual rainfall increases in a northerly direction with the isohyets roughly coincident with lines of latitude. The northern coastal areas of the basin record rainfall >800 mm.

There are several high-yielding aquifers, most notably the Grant Group sandstones which extend throughout much of the basin and are several kilometres thick in places. The basin has been divided into a series of groundwater management units administered by the Western Australia State Government. The vast majority of the basin is covered by just two units, the Desert and Wallal groundwater management units, both of which have very low to minor development of the Grant Aquifer with high sustainable yields (218 and 296 Gl/yr respectively). Assuming the geothermal system requires flow rates of 100 l/s, the water is reinjected back into the same aquifer, and there is 2% water loss, then water requirements would be ~64 Ml/yr for production. The Grant Aquifer can therefore be regarded as having excellent development potential.

Changes in rainfall distribution and intensity have been well documented in Australia. Geothermal operators will need to offer creative solutions to acquire and source their water supply over the lifetime of the project.

SUMMARY

The principle aim of geothermal exploration is to locate anomalously high temperatures at an economically and technically viable drilling depth. Whilst the application of GSAs to geothermal exploration reduces risk by quantifying key parameters, it should be noted that it is impossible to reduce risk to zero. Uncertainties will always be an inherent part of any project.

The 101 wells modelled in the Driscoll *et al*. (2009) study suggest that the Canning Basin has a median heat flow only marginally higher than the Australian median of 64.5 mW/m^2. However, there are portions of the basin where the heat flow is considerably higher. In addition, the 150°C isotherm is modelled to lie shallower than 5,000 m across many parts of the Canning Basin, and as such, may be prospective for EGS development. The increasing heat flow towards the central parts of the basin results in the modelled 150°C isotherm becoming increasingly shallower (<3,000 m) on the Broome Platform, which may indicate the possibility of developing HSA geothermal systems if suitably permeable sedimentary rocks are present.

In order to mitigate the risks further, a comprehensive work program in the Canning Basin was suggested by Driscoll *et al*. (2009) which included the following recommendations:

- Increase the spatial distribution of heat flow values by incorporating all remaining wells in the Canning Basin within a similar conductivity-heat flow study, and then incorporate these data into a 3D heat flow model to better understand possible isotherm surfaces away from control points.
- As there is a lack of suitable temperature data for many wells, new data can be obtained via Precision Temperature Logging (PTL) of existing petroleum wells or water bores. Water bores in areas where no petroleum wells exist may provide crucial data to delineate heat flow in parts of the Canning Basin that are presently unexplored.
- In order to make any reliable stress field prediction and models, a substantial amount of additional stress field measurements are required across the entire Canning Basin. This may be facilitated by a field program, which involves obtaining stress field estimates via hydraulic fracturing or borehole imaging of existing wells across the region. With robust stress field data, 2D or 3D numerical hydro-mechanical modelling could be undertaken to constrain expected geothermal reservoir growth and flooding directions. This numerical modelling exercise would also require: (1) estimates of pore fluid pressures from either well drill stem tests or leak off tests; (2) laboratory estimates of the hydraulic and bulk moduli properties of key rock types as collected from selected core samples; and (3) detailed structural interpretations at both the regional and prospect scale.
- Improve the reliability of heat flow estimates and temperature projections by expanding the database of thermal conductivity measurements.

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