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Developing Australian Enhanced Geothermal Systems and Hot Sedimentary Aquifer Models For Reducing Risk

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ABSTRACT

Reducing uncertainty at an early stage of resource development is a key necessity to attract project finance. Risk analysis frameworks exist in the petroleum industry for quantifying risk and expected returns (Newendorp 1975; Suslick et al. 2009). For deep Enhanced Geothermal Systems (EGS) and Hot Sedimentary Aquifers (HSA), there is limited knowledge and experience available from in-the-ground projects to make informed estimates of the likelihood of outcomes for incorporation into a risk analysis framework. Modelling incorporating uncertainty analysis based on a library of EGS and HSA geothermal reservoirs, together with proxy data, could be used to develop a Geothermal Play Systems framework for assessing reservoir risk and ranking prospects.

At a basic level, any geothermal system comprises two independent components: heat, and a heat transport mechanism. Practically, these translate to temperature, and a heat transfer fluid (or vapor) with a transport pathway (i.e. permeability). Australia has low heat flow relative to 'traditional' geothermal countries, requiring extensive thermal insulation provided by thick sedimentary accumulations in order to reach temperatures high enough for power generation. Because of the depth at which hot reservoirs occur, matrix permeability in sediments is compromised meaning that permeability enhancement is needed for most projects, and exploration is difficult and expensive. Estimating temperature at depth has so far proven to be robust using heat flow or extrapolation of temperature—where such measurements are available. However, these data are sparse. Approaches such as TherMAP (Haynes et al. 2013) will facilitate exploration in areas with no temperature data by allowing target generation in areas with favorable market conditions. Predicting permeability is a much more difficult task. A range of fracture detection methods exist, or are being further developed, but at the depths of interest (3500–5000 m), these have limited resolution. Therefore, drilling is presently the only way to test predictions of reservoir properties in order to reduce uncertainty to acceptable levels, however drilling is too expensive given the levels of risk for geothermal projects in Australia.

The lack of examples of working deep EGS or HSA reservoirs is an outstanding issue. A study is needed to compile the fracture characteristics of existing projects in Australia and internationally. A complementary conceptual study using discrete fracture network modelling in a stochastic sensitivity analysis may provide constraints on the range of geological environments (lithologies, geodynamic history including uplift, compaction, metamorphism, thermal history, previous deformation, present stress regime) favorable for the development of optimal fracture networks for geothermal exploitation.

This paper proposes how some of the key parameters around permeability may be derived from proxy data sets, and how modelling using statistical methods may be used in predictive exploration and associated risk analysis.

1. INTRODUCTION

The Australian continent has no known active volcanism. Heat is sourced from the underlying mantle and generated within the crust through radiogenic decay, and elevated temperatures are reached only where insulated by thick low thermal conductivity sediments (>3500 m). At these depths, permeability is generally compromised. Four reservoir 'opportunities' have been identified in Australia (Figure 1), and these can be regarded as a continuum between HSA with primary matrix permeability and various levels of EGS. Low to moderate temperatures high enough for direct use or minor power generation can be found in relatively shallow Hot Sedimentary Aquifer systems, as evidenced by the Birdsville power station utilizing artesian bore water of the Great Artesian Basin (example 4 on Figure 1). Where primary permeability in deeper sediments is compromised, faults and fractures may provide suitable circulation pathways with or without permeability stimulation (Example 2 on Figure 1). The sediment-basement interface is often found to be fractured, especially the sedimentary rocks, and readily susceptible to hydraulic stimulation (e.g. the Petratherm Paralana project, example 1 on Figure 1). Finally, fractures in granite or other basement rock can be enhanced by stimulation methods (example 3 in Figure 1).

Without active volcanism and surface manifestations of high heat flow, it is no surprise that Australia is a newcomer to geothermal energy utilization. When the history of geothermal development is considered, it can be viewed that deep EGS is an extension of utilization of progressively deeper geothermal resources. Hot springs at surface have been used for millennia; electricity production has been undertaken at Lardarello, Italy, for over a century (accessing steam at shallow depths); power is produced from wells deeper than 3000 m with temperatures of only 160 °C (e.g. since 2007 at Landau, Germany); and reservoirs have now been created in low permeability rocks at depths of greater than 4500 m. In Australia, exploration for deep EGS and HSA has been conducted for just over one decade. It is in this context that Australia is contributing to the knowledge that will grow the worldwide geothermal resource base. While there is no technology barrier (Meaning that all technologies necessary to conduct EGS projects are available now, that there is no missing piece of technology. Technology developments are necessary to lower costs.) to the utilization of very deep geothermal resources, costs are critical, especially in areas with a competitive power market. The cost/return ratio is dictated by the cost of drilling, completions and plant versus reservoir temperature and well deliverability. Costs for the engineering aspects of geothermal reservoir exploitation and energy conversion are largely market driven but improvements are possible through technology development. Resource temperature is comparatively straightforward to predict at depth. Reservoir productivity is determined by permeability, and therefore permeability is the most unknown factor in deep geothermal exploitation.

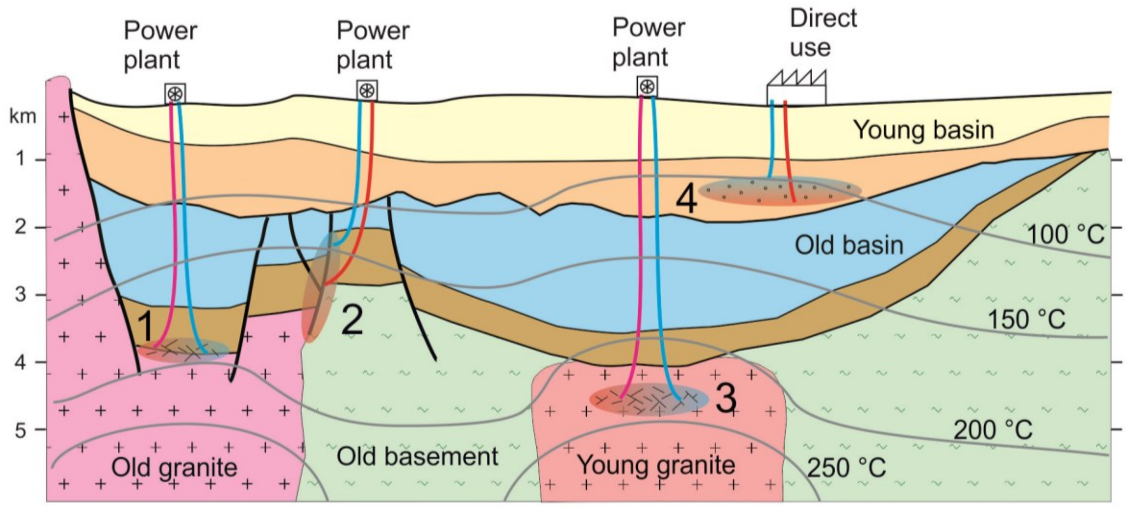

Figure 1. Schematic of unconventional geothermal reservoirs in Australia. Reservoir styles: 1—fractures at basin-basement interface (FABBI) enhanced by hydraulic stimulation; 2—secondary permeability along faults within HSA, with or without permeability enhancement necessary; 3—fractures within granite enhanced by hydraulic stimulation; and 4—primary matrix permeability in HSA.

Worldwide, there are few examples of EGS operations, hence there is little direct evidence available for building a geological understanding of issues related to flowing significant volumes of water deep within the crust. In comparison, the minerals and petroleum industries have a huge library of case studies from which they have established mineral systems and petroleum systems frameworks that underpin exploration and production activities.

These systems frameworks provide a predictive ability for resource location and characterization, underpin engineering approaches, and feed into resource and risk assessments for use by investors and regulators.

In Australia, nine deep wells have been drilled into prospective geothermal resources (Budd and Gerner 2015). In every case, the temperature target was met. However, none met the well delivery targets, i.e. permeability was too low. Each well has contributed to an understanding of reservoir characteristics, information which now needs to be incorporated into a library of Geothermal Play Systems via a catalogue of geological and engineering models.

2. COMPONENTS OF A SYSTEMS FRAMEWORK

The minerals and petroleum sectors have benefited from over two decades of formalized systems frameworks that have boosted success in exploration and production. Magoon and Dow (1991) is the most widely cited reference for the petroleum systems concept, while for mineral systems, Wyborn et al. (1994) is regarded as the benchmark. Both systems utilized a concept of source, migration and accumulation.

The petroleum systems framework initiated by Magoon and Dow (1991) was built by examining the exploration and development of many different oil and gas accumulations. The petroleum systems framework has been credited with increasing the success rate of wildcat drilling, mostly through the ability to use seismic reflection data to target structural or stratigraphic traps. It has also enabled the application of decision and risk analysis tools (e.g. Suslick et al. 2009) because probabilities and their uncertainties around accumulations can be so well defined. Petroleum systems thinking has been combined with risk analysis (e.g. Newendorp 1975, Suslick et al. 2009), and this combined approach underlies resource assessments (e.g. Bradshaw et al. 1998) and future production assessments (e.g. Powell 2004). These methods are used to support decision making for the full range of activities from acreage acquisition, data acquisition, drilling, field development, and government policy and regulation.

Continued development of mineral systems concepts has led to an approach that distinguishes physical processes (gradient in hydraulic potential; porosity; permeability; solubility sensitivity to, and spatial gradient of, pressure, temperature and composition; and time), from geological mapping and interpretation activities (geodynamics; architecture; fluid reservoirs; flow pathways and drivers; and deposition) to derive 'mappable proxies' for physical process applied to various scales (Barnicoat 2008). With thousands of mineral deposits developed, there exists a library of deposits from which to learn (e.g. Cox and Singer 1986), providing a firm basis for conceptual modelling and empirical classification.

These two systems approaches aim to encapsulate all of the aspects involved in forming economic accumulations of commodities of interest. There is, however, a fundamental difference between geothermal and mineral/petroleum resources: geothermal energy is heat and does not have mass—it is a transient material property. Nevertheless, the general approach can be adopted to describe all geological factors necessary to define a geothermal resource.

At a basic level, any geothermal system comprises two independent components: heat, and a heat transport mechanism. Practically, these translate to temperature, and a heat transfer fluid (or vapor) with a transport pathway (i.e. permeability).

Geoscience Australia has focused its work on the development of geothermal systems thinking on temperature mapping, because: (1) temperature is the logical starting point in a geothermal resource evaluation and targeting work flow; (2) of a history of mapping the distribution of temperature throughout Australia including map products such as OZTemp (Gerner and Holgate 2010) and granite-sediment occurrence maps (Budd 2007); (3) of the availability of data inputs and computational tools (leading to the TherMAP work, Haynes et al. 2013); and (4) of a paucity of input data from geothermal reservoirs regarding permeability, permeability susceptibility (to hydraulic fracturing, chemical treatment or thermal cycling), and production history within Australia. Therefore, the discussion below regarding a systems approach to permeability assessment and prediction is based on concepts derived from learnings to date from deep geothermal developments, and will hopefully be pursued in future research.

2.1 Learnings from EGS and HSA developments in Australia

A number of research and development programs, and fewer commercialization projects, have been conducted to investigate hot dry rock or EGS systems. These include: Fenton Hill, USA (EERE 2010); Rosemanowes, UK (MIT 2006); Hijiori, Japan (MIT 2006); Ogachi, Japan (MIT 2006); Soultz-sous-Forêts, France (MIT 2006); Innamincka Deeps (Habanero), Australia (Chen and Wyborn 2009, Hogarth et al. 2013, Geodynamics 2013); and Paralana, Australia (Petratherm 2011). In Australia, two HSA reservoirs have been tested by the Penola project (Panax 2010) and the Innamincka Shallows project in the Cooper Basin (Geodynamics 2011), both in South Australia. These projects provide very valuable information on deep geothermal reservoirs.

2.1.1 Habanero (EGS)

The Innamincka Deeps project by the Geodynamics Ltd (operator) and Origin Energy Pty Ltd Joint Venture drilled several deep (4200 – 4911 m) wells into the Big Lake Suite granodiorite beneath the Cooper Basin. Extensive hydraulic fracturing was undertaken at the Habanero prospect, with the result that the Main Fracture (also known as the Habanero Fault) was well developed (Chen and Wyborn 2009, McMahon and Baisch 2013, Hogarth 2013). A 1 MW pilot plant was successfully operated for 160 days (Geodynamics 2013). Prior to closure of the trial, the plant was producing net power operating on 19 kg/s and 215 °C brine produced at the well-head. The operation of the pilot plant will enable Geodynamics Ltd to complete studies on the financial viability of further development.

One of the main learnings from this development relevant to building exploration models is that hydraulic fracturing activated a single already stressed fault. Earlier concepts for development of an EGS reservoir in granite had an expectation that most volumes of granite would have extensive jointing or other fracturing (e.g. Wyborn 2011). However, Habanero-1 found few fractures within the granite (Chen and Wyborn 2009), and these were overpressured (and therefore not ‘hot dry rocks’) and each fracture had different pressure. The different pressures have made development of more than one fracture per well problematic, restricting flow to a single narrow zone of high permeability (Hogarth et al. 2013).

From an exploration point of view, the experience gained from the Habanero development is that it is desirable to know whether the granite has pre-existing zones of weakness that will be susceptible to stress modification leading to opening or shearing during hydraulic stimulation. The role of granites as a heat source and mapping of buried granites is discussed below. Predicting permeability becomes a matter of understanding stress, pressure and fluid conditions (which have relationships to temperature), and mapping and predicting fractures.

There are no active continental plate boundaries within mainland Australia. Stress orientations within Australia are variable and do not parallel the north-northeast absolute motion of the Indo-Australian plate. Rather, 16 stress provinces have been recognized (Hillis and Reynolds 2003). Despite the absence of parallelism between absolute plate motion and stress orientations, the regional pattern of stress orientation in the Australian continent is consistent with control by plate boundary forces, if the complex nature of the northeastern boundary of the Indo-Australian Plate, and stress focusing by collision segments of the boundary, is recognized (Hillis and Reynolds 2003). At Habanero, it is postulated that compression over the last few million years, along with elevated temperatures above 230 °C and high fluid pressures, have allowed ductile creep to occur at shallow depths of ~4000 m (Schrank et al. 2012, Veveakis et al. 2013, Regenauer-Lieb et al. 2013), creating sub-horizontal features such as the Habanero Fault. This theory may be important in locating additional fractures at Habanero, or in predicting fractures in granite bodies elsewhere.

2.1.2 Paralana (EGS)

The Paralana project by the Petratherm Ltd (operator) and Beach Energy Pty Ltd Joint Venture completed the Paralana-2 well to 4012 m (Petratherm 2010, Petratherm 2011). Petratherm Ltd developed a new type of EGS concept, which they termed ‘Heat Exchanger Within Insulator (HEWI)’ (Petratherm 2007). The following paragraph is based on information from those three Annual Reports. The Paralana project is in the Arrowie Basin adjacent to the northern Flinders Ranges approximately 600 km north of Adelaide. The chosen site is a small but deep graben in Mesoproterozoic basement infilled with Cambrian and younger sediments. The HEWI model postulates that deep sediments above high heat producing granites will be nearly as hot as the deeper granites, but will be easier to create permeable fracture networks within. Being shallower, the trade-off of lower temperature is likely to be offset by cheaper drilling (Sanyal 2009) in addition to higher permeability (permeability is lost with increasing overburden load). The well was fully cased with 7” casing to 3725 m. Excellent results were achieved in this well, with a temperature of 176 °C recorded at 3672 m, slight overpressures with inflows into the well via a number of fractures, and benign brines. An extensive seismic cloud was observed during a relatively small hydraulic stimulation event indicating fracturing extending in all three dimensions, i.e. not planar. Real-time seismic monitoring was employed during the hydraulic stimulation. Repeated magnetotelluric (MT) surveys before and after injection suggest that stimulation occurred in an anisotropic heterogeneous complex fracture network (Peacock et al. 2013), and not a single fault plane. The postulated complex fracture network should provide advantages for efficient fluid-rock heat exchange. The reservoir stimulation results were achieved through a single well perforation interval of six metres between 3679 and 3685 m. It could be expected that additional perforation intervals and stimulations could result in a high reservoir volume for use as a heat exchanger, with a higher fluid-rock surface area than those seen to date in other EGS reservoirs around the world.

Key learnings from the Paralana project are that metasediments may be easier to fracture or shear than granites and, depending on bedding, jointing, folding and (pre-existing) fracturing, may produce a three-dimensional, interconnected and permeable network which should provide an effective heat exchange reservoir. The HEWI model (and variants, e.g. FABBI – see Figure 1) may be more amenable to geothermal development than granite reservoirs because of the more complex pre-existing fractures. It remains to be seen whether a flow rate sufficient to overcome the lower temperature can be achieved at Paralana for commercialization. Further work is needed at Paralana to determine the lithology and paragenesis of the reservoir rocks, and stress regime, as these are key parameters for understanding the behaviour of the reservoir during hydraulic fracturing and water-rock interaction during circulation. This information would be very valuable for determining the applicability of this geological model elsewhere.

2.1.3 Salamander-1, Celsisus-1 (HSA)

The Salamander-1 well was drilled by Panax Geothermal Ltd in 2010, and targeted the Pretty Hill Formation within the Penola Trough of the Otway Basin, South Australia. The well reached a depth of 4025 m and recorded a maximum temperature of 171.4 °C (Panax 2010). However, initial flow rates were far below those prognosed, and actually decreased with further flow testing and efforts to improve flow including removing drilling mud filter cake and acid treatment. Experimental work on rock chips from the Salamander-1 and nearby wells, and flow modelling, indicate that fines migration caused pore throat blocking during flow testing (Badalyan et al. 2014, You et al. 2014).

In May–April 2011 Celsius-1 was drilled to a depth of 2416 m in what has become known as the Innamincka Shallows Joint Venture, operated by Origin Energy Pty Ltd. Celsius-1 was designed to test the potential of using the Hutton Sandstone as a permeable aquifer, in the shallow sedimentary sequence of the Eromanga Basin, above the Habanero granite in far north-eastern South Australia. Temperatures in excess of 145 °C were recorded, but poor flow rates were found (Geodynamics 2011). Elsewhere in the Eromanga Basin, the Hutton Sandstone has previously been found to be a productive oil and gas reservoir. However, Celsius-1 was drilled in a poorly characterized part of the basin, and core analysis from Celsisus-1 and offset wells intersecting the Hutton Sandstone indicate that permeability is significantly lower in Celsius-1 than other wells because of a higher proportion of clays (a depositional feature) and higher temperature diagenesis (Dillinger et al. 2013).

2.2 Temperature component of Geothermal Play Systems

2.2.1. Concept of temperature

Temperature can be measured directly, but in the deep subsurface this is generally impractical. Surface heat flow data, combined with a general understanding of upper crustal structure and composition, allow extrapolation of temperature at depth.

The dominant mode of heat transport in Australia's upper crust is conduction, and is described by the steady state equation:

$$Q_0 = Q_d + \int A(z)\partial z \tag{1}$$

where Q_0 = surface heat flow, Q_d = heat flow at depth d, $\int A(z)\partial z$ = the integral of volumetric heat generation from the surface to d, A = heat production and z = depth (Ayling and Lewis 2010).

The heat flow at depth d can be calculated from the following (Equation 2; Beardsmore and Cull 2001):

$$Q_d = -\lambda_d \left(\frac{\Delta T}{\Delta z} \right)_d \tag{2}$$

where λ_d = thermal conductivity at depth d and T = temperature. The heat flow equation (2) allows the difference in temperature (ΔT) to be predicted between any two points, as long as the thermal conductivity of the medium(s) (λ), the distance between the two points (Δz), and the heat flowing between them (Q) are known.

The key datasets for mapping temperature (the first step of geothermal exploration) are, thus, heat flow, thermal conductivity, depth and heat generation.

2.2.2 Mappable proxies for temperature

Mapping of temperature distribution within the crust can be considered to be a function of heat source and heat flow path. In Australia, advective effects are generally discounted as there is no evidence for large-scale convective transport of magmatic fluid between the deep and upper crust. The dominant heat sources are mantle heat flow and radiogenic decay, with negligible heat from frictional sources. Australia's crust is very old, and magmatic cycles have resulted in chemical differentiation, with the main heat producing elements being fractionated into the upper crust (McLaren et al. 2003), especially into certain types of felsic granites (Budd et al. 2001). Thick rock units containing intervals of low thermal conductivity allow an increased temperature for a given heat flow. The basic model for attaining anomalously high geothermal gradients in conductive crustal regimes (such as Australia's) is elevated heat production (either from granites or metamorphic basement), a component of mantle heat flow, and insulation by thick sediments with some low conductivity layers. Any method of predicting temperature at depth will be cognizant of this basic structure.

In Australia there is very little evidence at surface of anomalous heat flow, presenting difficulties for geothermal exploration. Geoscience Australia and its predecessors have undertaken temperature mapping activities over a period of three decades (Cull 1976, Cull 1978, Cull and Denham 1979, Cull and Conley 1983, Cull and Denham 1978, Nicholas et al. 1980, Somerville et al. 1994). Most of this effort has been in compiling data sets of temperature measurements, culminating in the OZTEMP map of predicted temperature at 5 km depth (Gerner and Holgate 2010). This map has been constructed utilizing measurements of temperature in boreholes, and surface heat flow determinations. This approach uses a simple two-layer model to fit a thermal gradient between surface and measurement point within a well for either bottom-hole-temperatures or heat flow data, then extrapolates temperature to 5 km depth, and interpolates temperature at depth between wells. There are some 5800 wells with temperature or heat flow determinations included within the dataset, but the distribution across the continent is uneven with most areas having sparse data.

To overcome the issue of sparse data, a two-stage development process has recently been undertaken by Geoscience Australia in order to determine what other data sets can be used to provide information about expected temperature at depth. A conceptual approach was taken in the first step, aimed at providing information about geometries and properties of rock volumes needed to reach certain temperature targets. The question posed was "what sized granite of what composition is needed to be buried by a sedimentary pile of what thickness and of what thermal resistivity?" A large number (~150,000) discrete numerical simulations were performed to explore the range of geological conditions present in Australia (Budd et al. 2012, Lescinsky et al. 2012). Variations in intrusive geometry and heat production, sediment thickness and thermal conductivity, basement heat production and basal heat flow were modelled, providing valuable constraints on the range of geologically reasonable scenarios for suitable temperature/depth profiles. The results found that at least one variable (heat production, mantle heat flow, sediment thickness, sediment thermal conductivity) had to be elevated above average values for target conditions to be met, for example in order to reach temperatures of >160 °C at less than 3500 m depth.

The second phase developed a pilot map for predicting temperature using geological and geophysical data sets as proxies for temperature or heat flow measurements. This work, termed Thermal Map from Assessed Proxies (TherMAP, Haynes et al. 2013, Haynes et al. 2015) makes use of a Monte Carlo sensitivity analysis process whereby each of the input variables were allowed to vary within their defined uncertainty distributions.

To predict temperature at depth, the geothermal gradient and surface heat flow terms from Equations 1 and 2 need to be resolved. Thermal conductivity, heat production and heat flow at depth need to be populated, and are done so according to Table 1. Note that this can be performed spatially as a grid of 1D (vertical) heat flow calculations, but the approach taken by Haynes et al. (2013, 2015) is to use 3D mapping software on the National Computational Infrastructure supercomputer at the Australian National University, which has also allowed calculation of error estimates in a stochastic method. In this way, the problem is volumetric rather than purely geometric, requiring spatial extent of geological units to be included in the list of mappable proxies. Average values for each proxy are substituted where no data is available, with a corresponding increase in error.

Beardsmore et al. (2010) proposed a protocol for estimating and mapping global EGS potential. The protocol aimed to produce regional estimates and maps of EGS potential that were directly comparable to one another globally by using a consistent methodology and assumptions. It did not seek to provide a unique answer to the magnitude and distribution of the EGS potential in any particular locality (Beardsmore et al. 2010). The first part of the five-step methodology was to model the temperature, heat flow and available heat in the earth's crust to a depth of 10,000 m. The method used in TherMAP (Haynes et al. 2013, 2015) is analogous in terms of using proxy data to populate the heat flow equation. Table 1 lists the parameters from the heat flow equations and their mappable proxies, listing the suggestions of Beardsmore et al. (2010) and those used specifically for Australia as determined by the available data sets.

Table 1: Examples from Australia of mappable proxy data sets for calculation of predicted temperature at depth. The approach for estimating temperature at depth in the Protocol for Estimating and Mapping Global EGS Potential (Beardsmore et al. 2010) is also summarized where applicable for comparison (distinguished by the header *Protocol*).

Parameter	**Mappable proxy**
Spatial extent	Sediments: 3D grid of sedimentary basins created from a national-scale basin map and properties GIS data set (OZ SEEBase™; FrOGTech 2006). This data set was created using a combination of seismic, drilling, surficial mapping and gravity and magnetic inversion methods. Granites: Mapping the depth extent of granites is very difficult, requiring high-quality geophysical data sets with good drill control (e.g. Meixner et al. 2012). Geophysical inversion of gravity datasets with an automated procedure to pick rounded low-density bodies (interpreted to be granites) from horizontal-gradient 'worms' was performed for all of Australia by Petkovic (2014). There is a general relationship between granite-body radius and thickness established by Petford et al. (2000), providing a means to estimate granite volume (necessary for calculating output from heat production) from gravity data, however, assumptions are required for the depth to top of granite if not otherwise known. Upper crust/lower crust chemical boundary: arbitrary value of 10 km used, based on study by McLaren et al. (2003). Moho surface: taken to represent the basal boundary condition based on study of Bodin et al. (2012).
	Protocol: Grid of 5' x 5' cells for 1D vertical heat flow modelling. Create sediment thickness (depth to basement) map from well and seismic interpretations, potential field inversions etc.
Thermal conductivity	Sedimentary basins populated with a bulk thermal conductivity estimate derived from the harmonic mean of unit thickness and conductivity. Conductivity is either measured (rare) or approximated according to average values for lithological type from drilling or other data available in the literature for each unit. Resistivity is the inverse of conductivity. Total resistivity varies spatially with changing basin depth.

	Granite thermal conductivity varies significantly less than that of sedimentary rocks and is generally higher—a value can be assigned with a distribution estimate. An average value and range were adopted for metasedimentary and metaigneous rocks assumed to be basement (not sediment, not granite, above Moho). Temperature-dependent thermal conductivity can be incorporated into the calculation.
	Protocol: Populate sediment thermal properties (thermal conductivity), include depth variation if known. Use measurements if available, else estimate from lithological mixing and age, else estimate from age and basin setting, else global averages. Populate basement thermal properties (thermal conductivity), from measurements if available, else from lithology, else from global averages.
Heat production	Very few rocks have been measured for heat production in Australia. Therefore, heat production is calculated from whole rock geochemistry. Granites: Australia has an extensive data base of whole rock geochemistry including for felsic igneous units, but is limited (with few exceptions) to samples of outcrop. Known geological province boundaries were used as the basis on which to average outcrop geochemistry to then calculate heat production to assign to buried granites within each province. Basement: A boundary between upper crust and lower crust basement was set at 10 km depth (see 'Spatial extent' above) to account for concentration of highly radiogenic elements into the upper crust through crustal differentiation processes.
	Protocol: Populate sediment thermal properties (heat production), include depth variation if known. Use measurements if available, else estimate from lithological mixing and age, else estimate from age and basin setting, else global averages. Populate basement thermal properties (heat production), from measurements if available, else from lithology and geochemical data, else from global averages.
Heat flow at depth	For any vertical heat flow modelling studies, a basal boundary condition needs to be set. Ideally, knowledge of heat flow provinces (Roy et al. 1968) would be available so that basal (or mantle) heat flow could be assigned for each geological province. This information is not available across Australia, so the depth to Moho discontinuity has been used with an assigned temperature and error range at this depth.
Surface temperature	Mean annualized surface (air) temperature, or soil temperature data sets can be used to provide constraints on the air/water–rock interface (Gerner and Budd 2015). *Protocol*: As above.
Calculate	TherMAP: Calculates temperature and heat flow in 3D using the data sets mentioned above (fully detailed in Haynes et al. 2015). For the whole of Australia, with a voxel size of approximately 10 km by 10 km wide and 200 m depth, extending from 4000 mSL to -58,900 mSL, with resolution of 400x430x295 for the entire continent and surrounds, the models contained some 50.74 million cells each. The GOCAD® voxets were forward modelled using the *Underworld* software package (Moresi et al. 2007). Underworld uses a finite-element method to solve the steady-state thermal solution. Each of the models took approximately 11 minutes to run on 512 CPUs, requiring 1.94 TB of allocated memory, on the National Computational Infrastructure's Raijin supercomputer at the Australian National University. A Monte Carlo sensitivity analysis process was followed, whereby each of the input variables were allowed to vary within their defined uncertainty distributions, and the impact of this on the distribution of output models was examined.
	Protocol: Create surface heat flow map by averaging real data in 5' x 5' cell where available, else for Q_0 use Bottom Hole Temperatures and average conductivity, else assign by tectonic age, else use $Q_0 = Q_M + b \times A_B + S \times A_S$. ($Q_0$ is surface heat flow; Q_M is mantle heat flow and the global average value is 0.032 W/m^2; b is thickness of heat generating basement; A_B is basement heat generation; S is thickness of sediment; A_S is heat generation from the sedimentary pile). The protocol gives ways of estimating these input values. Derive temperature and heat flow at sediment-basement interface. The protocol has different methods depending on the depth of the interface (S < 4000 m, S > 4000 m). Derive temperature at depth of interest between 3000 m and 10,000 m.

2.3 Permeability component of Geothermal Play Systems

Darcy's law at constant elevation is a simple proportional relationship between the instantaneous discharge rate through a porous medium, the viscosity of the fluid and the pressure drop over a given distance:

$$Q = \frac{-kA}{\mu}\frac{(P_b - P_a)}{L} \tag{3}$$

where Q (units of volume per time) is the total discharge, k is the intrinsic permeability of the medium, A (units of area) is the cross-sectional area of flow, (P_b - P_a) is the total pressure drop (Pascals), μ (P_a·s) is the viscosity, and L is the length over which the pressure drop is taking place (L).

Much work has been done elsewhere on advanced fully coupled thermo-hydro-mechanical-chemical (THMC) modelling. This paper is, however, not about such modelling, rather, it is about identifying information from non-specific data sets that can be used as proxies for the key input parameters in numerical models. Also, the emphasis is on risk-based resource evaluation and prediction of key reservoir properties at an early stage in the exploration and development cycle. Some form of modelling incorporating all or some of the elements of THMC will undoubtedly be used in any work flow seeking to predict permeability at depth.

In a geothermal reservoir, several properties controlling permeability can be influenced by engineering. The cross-sectional area is a function of the diameter of the bore hole and its length of intersection within the reservoir. Pressure can be influenced by reservoir management practices such as pumping or draw-down. The length over which pressure drops will be influenced by reservoir pressure management and spacing of drill holes. Permeability can be modified by reservoir stimulation methods such as hydraulic fracturing or shearing, acid treatment, and thermal cycling.

From an EGS or HSA exploration point of view, which of these parameters should be the focus of a targeting and characterization program? Experience from Australia indicates that permeability is the key parameter, as most projects have not delivered high enough flow rates for commercialization. This applies to HSA and EGS projects as outlined below.

2.3.1 Mappable proxies for heat transport via fluid/vapor and permeability

Equations describing flow through porous media (such as the Darcy equation), along with experience in drilling into prospective reservoirs (such as described above for Australian geothermal systems), provide a list of key factors that need to be included in exploration work flows. Specifically, values for permeability can be derived, or assigned, with uncertainty estimates from a variety of spatially located data sets.

Permeability in rocks can be primary (interconnected pore spaces) or secondary in fractures, bedding planes or void spaces. Lithology, diagenesis, tectonic and thermal history and current temperature and stress regime are determinants of permeability, and susceptibility to permeability enhancement methods including hydraulic stimulation, chemical treatment and thermal stimulation.

In an exploration work flow, a set of criteria can be used to assess permeability and to rank prospects, for example: (1) what permeability exists; (2) what controls the permeability; (3) what can, or has, modified the permeability; and (4) how can permeability be predicted? Experience to date from deep geothermal projects in Australia suggests the permeability in geothermal reservoirs will be either: (1) primary; (2) secondary; or (3) enhanced/created. Table 2 summarizes how the criteria can be set as a series of questions for each reservoir type ('play type').

Table 2: Suggested criteria for assessing permeability according to 'play type'

Parameter and Key Questions	**Answers to Questions and Mappable Proxies**
Primary permeability (HSA)	
What is primary permeability?	Interconnected pore space in sedimentary rocks, often restricted to sandstones and limestones and stratigraphically bounded by aquatards. An effective geothermal reservoir must be either devoid of fine particles (e.g. from clays) or have pore throat sizes large enough to avoid bridging and blocking of pore throats.
What controls primary permeability?	Depositional processes – mechanics of formation of individual basins, source of fill and distance of transport.
What modifies primary permeability?	Permeability can be decreased through loss of pore space or reduction in pore throat size. Loss of pore space can occur by compaction during burial or crustal shortening, cementation during diagenesis or metamorphism or hydrothermal alteration. Reduction in pore throat size can occur by cementation or by fines migration during flow. Drilling muds are unlikely to cause reduction in permeability if mud particle size and concentrations are sufficient to allow the formation of a filter cake skin and hence prevent penetration of the drilling fluid into the reservoir. Permeability can be increased—see secondary permeability below.
How can primary permeability be mapped and predicted?	Often, sedimentary basins being considered for HSA geothermal will have previously been explored for oil and gas, so that measurements can be made on drill core or rock chips, or well test data or well logs may be available. Geophysical data may be available, including seismic, magnetic and gravity. Outcrop data may be available for some basins. The above data may be interpreted in a depositional framework (e.g. sequence stratigraphic or paleogeographic) which may map distribution of permeable facies.

Secondary permeability (HSA)	
What is secondary permeability?	Permeability of rocks can be increased by fracturing, or dissolution of one or more minerals. The resulting increase in fluid/rock ratio will depend on the nature and extent of the mechanism.
What controls secondary permeability?	The degree to which a rock unit will fracture during a tectonic event depends on the brittleness of the rock (which may reflect the mineralogy, for example clays can cause a rock unit to deform plasticly; or compaction, for example a deeply buried and dehydrated rock will behave in a brittle manner), the extent of pre-existing weakness (e.g. bedding planes, previous deformation), the orientation of these weaknesses to the stress regime, and confining pressure. Fluid pressure can lower the force required for onset of fracturing. Strain rate is important.
What modifies secondary permeability?	Fracture permeability can itself be modified by deposition (veining) or dissolution of minerals within the fractures, a process which is often episodic during tectonism or metamorphism. Tectonic forces can either hold open or close fractures depending on the relative orientation of the stress field. Mineralogical changes (such as dissolution) occurring at certain P-T-X conditions can be overprinted by a later set of P-T-X conditions (e.g. retrograde metamorphism during uplift).
How can secondary permeability be mapped/predicted?	Data from drilling (drill core, rock chips, well logs) will provide good information about fracturing of intersected rock units. Where fracturing has resulted in the juxtaposition of materials of different physical properties, these contrasts can be seen by geophysical methods that detect those properties (e.g. magnetic susceptibility, density, electrical resistivity). Seismic attribute mapping is being investigated for mapping fracture networks prior to drilling and reservoir development (Abul Khair et al. 2012). Where fracturing has resulted in deposition of mineral phases within the cracks (veining), some of these phases will be detectible by geophysical methods (e.g. magnetite veining detectable by magnetics). The inverse is also possible, for example the destruction of magnetite by fracture-controlled fluids. Interpretations of geological and geophysical data can be used to understand the structural history of a basin. Ideally, the geodynamic history of basin formation and modification can be understood and used to make predictions about the location of volumes of rock that are likely to host secondary permeability.
Enhanced/created permeability (EGS)	
What is enhanced/created permeability?	Permeability that has been modified by an engineering treatment, including hydraulic stimulation (increasing fluid pressure to modify the stress regime), chemical treatment (dissolution of a mineral phase by pH modification), thermal cycling, cutting a notch to initiate a weakness, or explosives.
What controls enhanced/created permeability?	Hydraulic stimulation modifies the stress field to cause either shearing or opening failure. Fluid pressure and pressure change rates have been shown to control the development of fractures, but weakness must be pre-existing in the rock mass. The hydraulic pressure and rate changes that can be applied are limited by well integrity (including well head) and pumping capacity. The effectiveness of chemical treatments (e.g. acidification) is dependent on mineral phases present, and on the ability of the well equipment to deliver the required treatment (e.g. chemical treatment must not cause excessive casing corrosion).
What modifies enhanced/created permeability (how is it done)?	Once circulation within a reservoir for heat extraction commences, thermal and chemical effects may modify the fracture network. Cooling will initially cause contraction of the rock volume which will increase permeability, but settling of the rock mass will eventually cause a reduction in permeability. Propants or continued pumping may be required to maintain fracture openness. Changes in P-T conditions may cause fluid-rock interactions including mineral deposition (scaling) within the reservoir which may decrease permeability. Chemical modification of the fluid may be needed to overcome this, depending on reaction kinetics.
How can enhanced/created permeability susceptibility be mapped/predicted?	Field trials in EGS projects to date indicate that zones of weakness must be present and be optimally oriented to the stress field for hydraulic stimulation to be effective. Therefore, mapping for EGS sites needs to be able make some prediction of the susceptibility of the target rock mass to hydraulic stimulation. Ambient Fracture Imaging (Lacazette et al. 2013),

	and Tomographic Fracturing Imaging (Geiser and Leary 2014) are newly developed seismic survey and interpretation methods that may aid in the detection of transmissive fractures at depth. At a larger scale, geodynamic modelling may assist in assessing whether a site is likely to have been fractured in the past. Geological models that identify previous zones of fracturing can serve a predictive purpose—for example, the Paralana project (previously described) identified that the interface between a granite and overlying basin is likely to be permeable, and the Habanero project (previously described) suggested far-field stresses cause ductile creep fracturing at temperatures over 230 °C. Fracture initiation by explosives, thermal cycling or cutting of a notch is an area of applied research that may reduce the limitations on application of hydraulic stimulation.

3. DISCUSSION

The future success of geothermal for power production from EGS or HSA reservoirs in Australia will be critically dependent on lowering discovery and development costs. Selecting the most productive and amenable reservoir possible for development has a significant impact on subsequent project development. To this end, a Geothermal Play Systems approach is envisioned to operate as follows in Australia.

(1) Temperature will be used as the first selection criteria. The coverage of temperature data is sparse, and so TherMAP has been developed as one approach to overcoming data sparseness.

(2) Economics are important and, in addition to geological factors that affect economics, market and social factors are influential. These factors include distance to market and relevant infrastructure, and whether such a project is allowed at that location (e.g. presence of national parks). Economic (and/or social) factors can refine the area selection.

(3) The likelihood of achieving sufficient well deliverability is the final and most difficult criterion for area selection and project ranking. This paper has identified the key geological factors regarding temperature and permeability.

Predicting temperature at depth utilizing proxy data sets such as those available across Australia is a tractable problem. Predicting or measuring permeability at depth is vastly more difficult because of the expense of drilling, lack of tools available for remote detection (although new seismic and magnetotelluric tools show good promise), and a lack of understanding of the nature of fracturing in potential reservoir rocks (for example, see Leary et al. 2015) including a low number of exemplars. Further work is required in this area, and two lines of investigation are suggested.

A 'play book' of potential reservoirs ('play types') is desirable. This can be based upon examples (such as the Habanero and Paralana projects, above), and conceptualizing a range of geological settings that are likely to give rise to sufficient temperature, and are likely to host primary or secondary permeability or be susceptible to permeability enhancement methods. It is likely that additional data will be forthcoming from the continued development of shale gas reservoirs. Many of these reservoirs are at high enough temperatures to be useful for geothermal energy conversion, and depleted gas reservoirs could potentially be used as geothermal reservoirs. Hydraulic fracturing is the most commonly used permeability stimulation method for shale gas extraction, and this activity will help to refine methods for application to geothermal purposes.

Coupled to the 'play book' could be some form of modelling to constrain the range of permeability values that might be expected for a reservoir. An example of this is provided by Riahi and Damjanac (2013), who present a method for sensitivity analysis for stimulation of EGS reservoirs. Validation of modelling should be done against drilling projects.

The three assessment components together—temperature, economic/social, and permeability—can form a work flow for risk assessment and incorporate uncertainty estimation.

4. CONCLUSION

In old, stable continents like Australia, high temperatures suitable for large-scale geothermal electrical power production can only be obtained at depths of greater than 3500 m, with the implication that permeability will be compromised and exploration will be difficult. Drilling to these depths is costly but is also difficult to target because of the difficulty of observation. Drilling costs and rig availability are determined by demand in the oil and gas industry, and this means that drilling costs are very high and a significant barrier for geothermal projects particularly when the values of the fluids produced (petroleum versus hot water) are compared. Therefore, the economics of deep EGS and HSA projects hinges critically on the ability to effectively target geothermal reservoirs in order to minimize the number of wells drilled and at the same time maximize the productivity of each well.

Exploration for deep EGS and HSA in Australia has demonstrated that temperature at depth can be predicted reliably from a small amount of appropriate data at the prospect (or project) scale. The latest work by Geoscience Australia has been a pilot map for predicting temperature at the continent scale using geological and geophysical data sets as proxies for temperature or heat flow measurements, as these are sparse across Australia. This pilot work, termed Thermal Map from Assessed Proxies (TherMAP, Haynes et al. 2013, Haynes et al. 2015) makes use of a Monte Carlo sensitivity analysis process whereby each of the input variables were allowed to vary within their defined uncertainty distributions.

Predicting permeability at depth with sparse data is much more difficult. In the absence of empirical data, models for permeable geothermal reservoirs can be developed conceptually by using a systematic approach to understanding the formation, modification and preservation of permeability, including susceptibility to permeability enhancement measures. The first step towards such modelling for permeability is to develop a conceptual framework based on best available knowledge, which has been summarized in this contribution. Further work is required to develop a range of synthetic geological reservoir models for numerical simulation which will provide constraints on the key parameters of the models, and further inform the process of developing exploration models for deep geothermal reservoirs in Australia.

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