Establishing Geothermal Play Systems for 'Hot Rock' Exploration in Australia

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ABSTRACT

Hot Rock exploration and development has progressed rapidly in Australia in the last decade. A wealth of pre-competitive geological data acquired by government surveys and mineral and petroleum explorers is available in Australia, but heat flow data specific to geothermal exploration is sparse. A methodology is presented that sets out the key parameters required in Hot Rock exploration. Mappable practical proxies corresponding to these parameters can utilize existing geological datasets. Australia has an enviable amount of geological data that is publicly available, and this can be used to show that many parts of the continent are attractive Hot Rock exploration areas.

Introduction

Mineral Systems Analysis or Petroleum Play Systems are well established in their respective industries. Exploration methods for conventional geothermal systems are likewise well established. To date, most EGS or Hot Rock projects (in Australia at least) have used compilations of bottom-hole temperatures to identify prospective geothermal systems. These data are mostly restricted to petroleum exploration areas. As a result, with few exceptions only areas of historical petroleum potential in Australia have been identified as having geothermal potential, whether Hot Rock or hydrothermal. The other obvious data type for temperature prediction (heat flow) is poorly constrained in Australia with only ~150 publicly-available measurements.

Hot Rock systems are not restricted to the geological settings favorable for oil and gas accumulation and preservation. Therefore, it is to be expected that there are areas of Australia with untested Hot Rock geothermal potential. Geoscience Australia is deriving a Geothermal Plays System approach, modelled on the '5 Questions' evolution (Barnicoat 2008) of the Mineral Systems Analysis, to formulate a framework for Hot Rock exploration. This approach links the key parameters of the geological system under consideration, with mappable 'practical proxies' to define exploration criteria. It is a scalar approach that works for terrain selection, area selection and drill target selection.

To derive the key components necessary to form an accumulation of heat in a Hot Rock geothermal play, a systematic approach is desirable. From these key components, the geological, geophysical and geochemical data necessary for exploration should be identifiable. Importantly, 'practical proxies' should be able to be developed, which utilize existing datasets to make informed assumptions regarding missing data. This would enable Hot Rock exploration in Australia to progress.

Method

Hot Rock systems comprise a heat source, an insulating layer, and sufficient permeability – either natural or enhanced - to enable sufficient flow of fluid through the heat reservoir.

An argument may be made that temperature is the first fundamental property in Hot Rock exploration. This applies whether an explorer is searching for the highest possible temperature accessible, or for a certain temperature threshold for a given depth.

The steady-state equation for temperature (1) shows that the important determinants of temperature are: thermal conductivity λ, depth-integrated heat generation A, mantle or basal heat flow Q_m and the crustal thickness under consideration Z.

$$T = \int \frac{A_z + Q_m}{\lambda} d_z \quad (1)$$

In most areas of Australia, this temperature equation cannot be solved by input of direct measurements. Estimates must be used based on inference from other datasets. These estimates may be derived from other geoscience datasets that were acquired for other purposes, and as such are practical, proxy measurements. Further, some of these proxies translate readily to mappable features that have concerned petroleum and mineral exploration geologists for many years. Increasingly in Australia, 3D geological maps are being made at various scales that already contain many of the mapped proxy data necessary for Hot Rock exploration, and these may be practically utilized for predicting the thermal structure of the upper crust.

Thermal Conductivity

The thermal conductivity of rocks varies according to grainsize, composition, porosity, temperature and pressure. Basic geological mapping and logging of drill core or chips will record lithology, and this information can be used to estimate grainsize, porosity and composition. Porosity may be determined from density measurements and well data. Pressure is mostly depth dependent, while temperature is usually the unknown of interest. In a simplistic first-pass assessment, the effect of temperature may be ignored as its influence is smaller than effects from grainsize, porosity or composition. In more advanced problem-solving models, it may be solved-for iteratively.

Heat Generation

Heat generation is a property that is dependent on composition. Uranium, thorium and potassium are the main radiogenic elements that contribute to heat generation. The density of a rock is also an important variable. The heat generation of a rock is given by the equation of Ryback (1988):

$$A = 10^{-5}\,\rho(9.52_{U} + 2.56_{Th} + 3.48_{K}) \qquad (2)$$

where ρ = density in kg m^{-3} and U, Th and K are the concentration of uranium and thorium in parts per million and potassium in weight percent.

Geochemical analyses of whole-rock samples plus determination of density will fully solve the equation. In Australia, geochemical data is often analyzed for a sample although density is generally not. In such case, density must be estimated based on lithology, the determination of which will be aided by geochemistry. In detail, the heat production of a rock also depends on its age.

In Australia, where recent active volcanism is lacking, high-heat-producing granites are generally the only rocks capable of creating a sufficient additional heat flow in the upper crust to cause significantly elevated temperature necessary for viable Hot Rock geothermal systems. Further, such granites occur as deeply (>3 km) buried plutons and are not directly sampled. Granite plutons, suites and supersuites share a genetic lineage that potentially enables some constraints to be placed on unsampled plutons.

Mappable practical proxies for heat production (from granites) can therefore be utilized from mapping geochemistry, geochronology and geophysics (gravity, magnetic, radiometrics, seismic surveys) by: (1) mapping trends of granites from outcrop to beneath insulating materials using geophysical interpretations; (2) using the chemistry (either measured or inferred from radiometrics) of outcropping granites to calculate heat production; and (3) estimating the depth and area (and therefore volume) of buried granites using constraints supplied by seismic surveys and interpretation of gravity and magnetic potential field data (see Meixner *et al*. this volume).

In Australia, the general nature of granites in geological provinces is quite well known and continues to be refined. For example, it is known that late Archean granites in the Yilgarn Craton are high-heat producing (Cassidy *et al*. 2002), as are the more felsic members of numerous supersuites of the Paleozoic of eastern Australia (eg Chappell *et al*. 2000). Proterozoic granites in Australia generally have high U, Th and K compared to granites of older and younger periods, and many Proterozoic supersuites are high heat producing (Budd *et al*. 2001, McLaren *et al*. 2003).

At a national scale, the newly released Radiometric Map of Australia (http://www.ga.gov.au/minerals/research/national/radiometric/index.jsp) shows the surface distribution of K, U and Th for over 80 per cent of the continent (Figure 1). This new radiometric map has been produced by combining more than 450 individual surveys collected over the past 40 years into a single seamless compilation. This dataset readily shows areas of high U, Th and K, some of which may correlate to high-heat-producing granites.

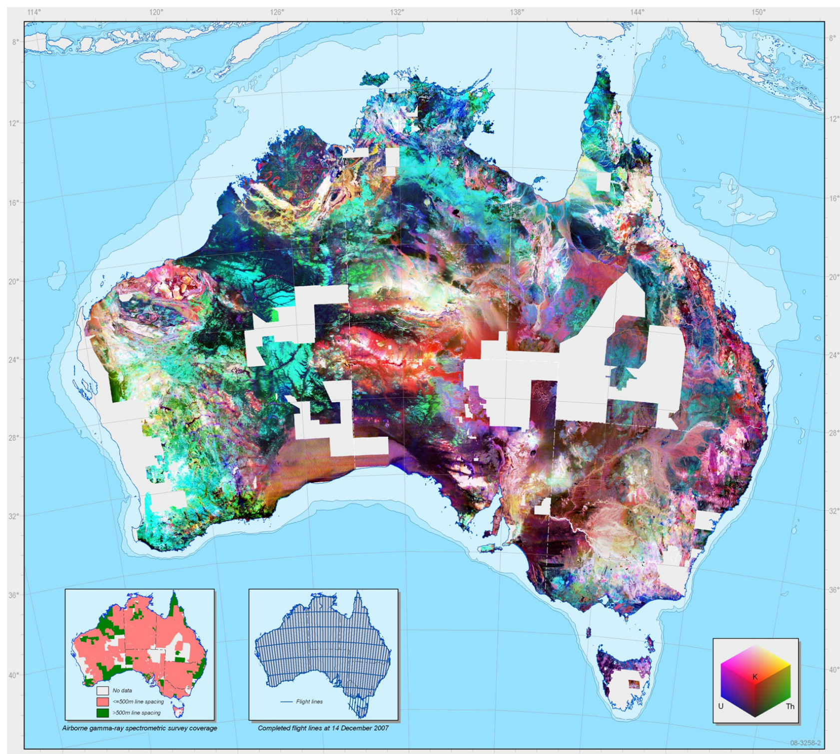

Figure 1. A clip-out of the Radiometric Map of Australia, First Edition (Minty et al. 2008). The ternary radiometric image shows the concentrations of the radioelements potassium (K), uranium (U) and thorium (Th) at the Earth's surface as measured using the airborne gamma-ray spectrometric method. The image is a false color composite using the colors red, blue and green to represent K, U and Th respectively.

Heat production may also be estimated from gamma logs or from seismic velocity.

These various mappable proxies for heat production are supported by extensive publicly-available datasets, and are readily incorporated into both 2D GIS and 3D maps.

Mantle/Basal Heat Flow and Section Depth

In comparison to some other parts of the world, the broad thermal structure of the Australian crust is understood in great detail in only small areas. Sass and Lachenbruch (1979) and Cull (1982, 1991) examined information on heat flow in Australia, but with less than 150 heat flow measurements across the entire continent, the data available are insufficient to be definitive. From this work, it was recognized that several areas of Proterozoic crust have anomalously high heat flow (and include abundant high-heat-producing granites). Several studies have examined the occurrence of this high heat flow, heat production and implications for tectonic evolution, including (but not limited to): McLaren *et al*. (2006) in the Mount Painter Province, South Australia; Neumann *et al*. (2000) in the area of the South Australian Heat Flow Anomaly; and Sandiford et al (2001) in central Australia. Even with these studies, considerable further work is required to be done throughout Australia to better understand the application of *heat flow province* understanding as outlined by Roy *et al*. (1968).

Information on crustal structure is key to understanding the overall thermal structure of the crust and for deriving mantle heat flow. Seismic reflection surveys directly map crustal structure, and provide information on the potential range of lithologies and hence heat generation and thermal conductivity. Seismic velocities derived from the data also have implications for thermal structure including temperature and heat generation. Seismic velocity is a proxy for density, which may assist in the mapping of granite volumes and therefore potential heat production. Australia has a good database of seismic reflection surveys, and surveys are being continually acquired.

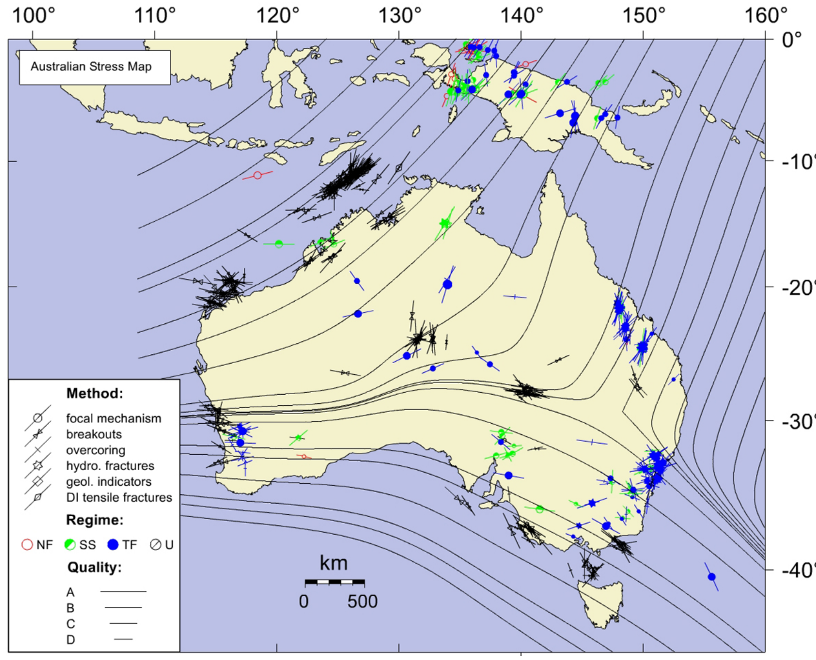

Figure 2. Stress trajectories calculated from the Australian Stress Map (Hillis and Reynolds, 2000). The stress trajectories indicate the orientation of the maximum horizontal stress at each point along the trajectory, but they do not imply information about magnitudes.

Other Parameters

Once the temperature of a potential geothermal Hot Rock reservoir is constrained, the next concern is whether a fluid can pass through the reservoir at the necessary velocity and volume (flow rate) to extract the required energy from the reservoir and transport it to the surface. Darcy's law describes the flow of a fluid through a porous medium:

$$q = \frac{-\kappa A}{\mu} \frac{(P_b - P_a)}{L} \qquad (3)$$

where q is the total discharge (units of volume per time, e.g., m^3/s) and is equal to the product of the permeability (κ units of area, e.g. m^2) of the medium, the cross-sectional area (A) to flow, and the pressure drop ($P_b - P_a$), all divided by the dynamic viscosity μ (in SI units e.g. kg/(m·s) or Pa·s), and the length L the pressure drop is taking place over.

Of most interest during a resource evaluation phase is the permeability of the target reservoir or formation. Other than direct measurement, mappable practical proxies for this include predicted lithology and seismic velocity.

As Hot Rock developments usually include reservoir engineering to enhance reservoir permeability, mapping the stress regime at that crustal level is of interest. This is mapped either directly through borehole measurement, medium- to long-term passive seismic monitoring using an Australia-wide seismic monitoring network, short-term passive seismic monitoring using temporary array deployments, or indirectly through surface neotectonic kinematic indicators. The Australian Stress Map (Hillis and Reynolds, 2000) showing the crustal stress regime is available at http://www.asprg.adelaide.edu.au/asm/ (Figure 2) and has provided useful information for geothermal explorers in the early stages of their developments.

Conclusion

In Hot Rock exploration in Australia, it is possible to link the fundamental geothermal parameters to the exploration process by means of the geological expression of the fundamental processes and the application of a scale-dependent mapping of these into exploration decision making.

The most important step in the process is translating the understanding of the process and the key parameters controlling the process into factors that can be determined spatially. Hot Rock geothermal exploration in Australia is in its infancy and with some exceptions has been based on the database of bottom-hole temperatures from petroleum drilling. By incorporating national-scale datasets into a Geographical Information System, a relatively rapid assessment of Hot Rock geothermal plays can be done at a regional scale. This will inform both exploration programs (and therefore lower risk) and pre-competitive data acquisition programs.

A companion paper (Meixner *et al*. this volume, *Establishing Hot Rock Exploration Models for Australia*) describes the use of thermal modelling of 3D geological datasets as a more detailed way of assessing geothermal prospectivity at a regional scale. Australia has extensive publicly-available geological datasets, and with the understanding of how to practically apply these to geothermal exploration in combination with the tools to perform

3D thermal modelling, the assessment of Hot Rock geothermal play assessments will highlight Australia as an attractive candidate for geothermal investment.

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