Establishing Hot Rock Exploration Models: From Synthetic Thermal Modelling to the Cooper Basin 3D Geological Map

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Abstract

Exploration models for Rot Rock geothermal energy plays in Australia are based primarily on high-heat producing granites (HHPG) in combination with overlying low-conductivity sedimentary rocks providing the insulator necessary to accumulate elevated temperatures at unusually shallow (therefore accessible) depths. Unknowns in this style of geothermal play include the composition and geometry of the HHPG and thermal properties, and the thickness of the overlying sediments. A series of 3D geological models have been constructed to investigate the range of geometries and compositions that may give rise to prospective Hot Rock geothermal energy plays.

A 3D geological map of the Cooper Basin region which contains known HHPG beneath thick sedimentary sequences, has been constructed from gravity inversions and constrained by geological data. The inversion models delineate regions of low density within the basement that are inferred to be granitic bodies. Thermal forward modelling was carried out by incorporating measured and estimated thermal properties to the mapped lithologies. An enhancement of the GeoModeller software is to allow the input thermal properties to be specified as distribution functions. Multiple thermal simulations using Monte-Carlo methods would be carried out from the supplied distributions. Statistical methods will be used to yield the probability estimates of the in-situ heat resource, reducing the risk of exploring for heat. The two thermal modelling techniques can be used as a predictive tool in regions where little or no temperature and geological data are available.

A series of synthetic 3D maps were constructed using different granite geometries beneath varying thicknesses of cover sediments. The gravity, heat flow and vertical temperature gradients were forward modelled using typical density contrasts, heat production rates and thermal conductivities. Geothermal explorers in the Cooper Basin can now use the results of the density modelling to identify the geometries and depth of burial of potential HHPG bodies, and also use the results of the thermal modelling to predict heat flows and temperature gradients associated with the body.

Keywords: 3D map, thermal modelling, stochastic, Cooper Basin, high-heat producing granites, inversion modelling

Introduction

Hot Rock geothermal exploration methods used in Australia are significantly different to those used for conventional geothermal plays elsewhere in the world. Hot Rock geothermal energy plays essentially comprise a heat source and an insulating layer. In Australia, high-heat producing granites (HHPG) are often the presumed heat source, while low-conductivity sedimentary rocks provide the insulator necessary to create an accumulation of heat and elevated temperatures. Other elements of a hot rock geothermal play such as porosity, permeability and fracture-networking are also crucial, though these can sometimes be artificially enhanced by hydrofracturing or chemical treatment to achieve the required permeability, or the injection of circulation water.

Several unknowns surround the requirements of Hot Rock geothermal plays in Australia. These include the following: a) How much heat production is required? (linked to the concentration of radiogenic elements, and the volume and geometry of HHPGs); b) What is the thermal insulation requirement from the overlying basin sediments? (a function of thickness and thermal conductivity); and c) What is the required geometry and extent for the insulating package above a given granite?

To investigate the range of geometries and compositions that may give rise to Hot Rock geothermal systems, two linked processes have been undertaken in this study. Firstly, thermal modelling has been conducted using a 3D geological map from a well-constrained area. Secondly, a series of synthetic models have been constructed for 3D temperature and heat flow modelling.

Cooper Basin 3D geological map

A summary of the geology of the Cooper Basin region is provided in Meixner and Holgate (2009a;b).

In brief, significant volumes of Big Lake Suite (BLS) granodiorite intrude basement in the

Cooper Basin region of central Australia (Figure 1). Thick sedimentary sequences in the Cooper and overlying Eromanga Basins provide a thermal blanketing effect for these anomalously high heat producing BLS intrusions, resulting in temperatures up to 270° C at depths less than 5 km. The region, which straddles the Queensland/South Australia border, is coincident with a prominent geothermal anomaly (Cull and Denham, 1979; Cull and Conley, 1983; Somerville et al., 1994) (Figure 2). The region also forms part of a broad area of anomalously high heat flow which is attributed to Proterozoic basement enriched in radiogenic elements (Sass and Lachenbruch, 1979; McLaren et al., 2003). Australia's first commercial Enhanced Geothermal System (EGS) is under development at Habanero-1 and Habanero-3 near Innamincka (Figure 1).

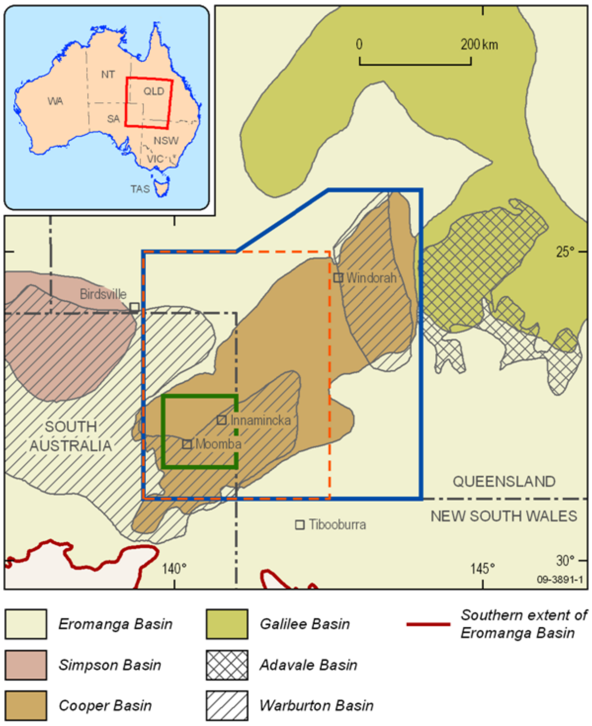

Figure 1. Location of the Cooper Basin region, showing the spatial extents of the stacked Warburton, Cooper and Eromanga Basins. The red dashed box indicates extent of the original 3D map, the blue outline indicates the extent of the extended 3D map and the green box indicates the extent of the test-bed thermal model.

A 3D geological map for the Cooper Basin region was constructed as part of a previous study (Meixner and Holgate, 2009a;b). The map, which covered an area of 300 by 450 km (Figure 1), was based in part on 3D inversions of Bouguer gravity data (Li and Oldenburg, 1998). Geological data as well as gravity 'worms' (Archibald et al., 1999) were used to constrain the inversions. The 3D map delineates regions of low density within the basement of the Cooper/Eromanga Basins that are inferred to be granitic bodies. This interpretation is supported by spatial correlations between the modelled bodies and known granite occurrences from drill holes in the area. Figure 3 shows a density section through the inversion model. The densities of the Eromanga/Cooper Basin sediments and the granitic bodies were constrained to narrow ranges, while the density of the basement was left unconstrained. A perspective view of the interpreted sub-sediment granitic bodies in the 3D map is shown in Figure 4.

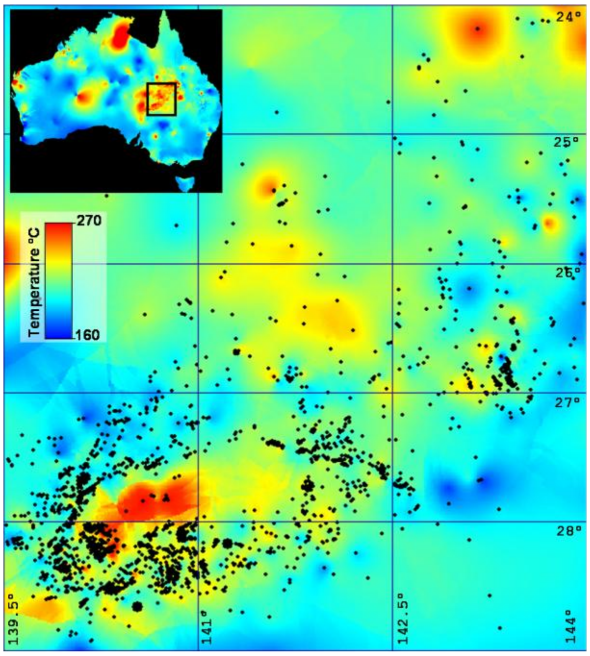

Figure 2: Predicted temperature map at 5 km for the Cooper Basin region after Chopra and Holgate (2005). Well locations are shown.

During the present study, the 3D map will be extended 150 km to the east and 100 km to the north in order to cover the entire Cooper Basin region (Figure 1). In addition, the map will include more detailed subdivisions for the Eromanga (Van Der Wielen, in prep) and Cooper Basin stratigraphies, based on data from ~1000 wells. The greater stratigraphic detail will allow for enhanced geological constraint during the gravity inversion modelling, as well as significantly better control on the assignment of thermal conductivities to individual geology units during the thermal modelling process. Delineation of the sub-sediment granitic bodies for this extended version of the 3D map will be carried out using the methodology described in Meixner and Holgate (2009a;b). The original 3D inversions used single density values for the Eromanga and Cooper basins that were derived from a refraction seismic survey in the study area (Collins and Lock, 1990). The present study will use an averaged density value for each individual stratigraphic unit derived from well density logs. The use of enhanced density constraints for the sedimentary section should enhance the credibility of the density variations derived for the basement unit, and therefore provide a more accurate delineation of interpreted granitic bodies.

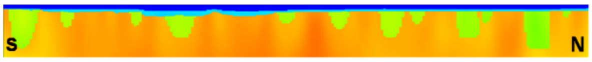

Figure 3: North-south density section through the litho-constrained gravity inversion model. Eromanga Basin sediments (dark blue: 2.3 +/- 0.2 g cm-3), Cooper Basin sediments (light blue: 2.5 +/- 0.2 g cm-3) and the granitic bodies (green: 2.6 +/- 0.2 g cm-3) were constrained to a narrow density range, while the basement (yellow-red: 2.65-2.75 g cm-3) was left unconstrained.

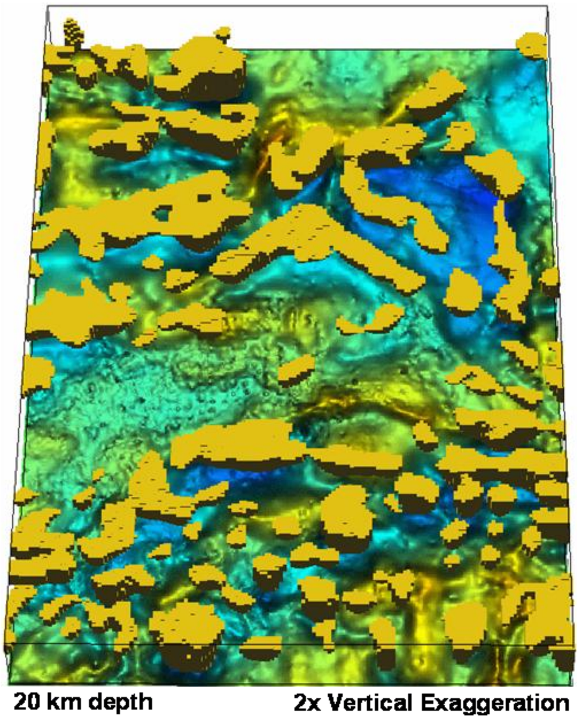

Figure 4: Cooper Basin region 3D map viewed obliquely from the south showing the inferred sub-sediment granitic bodies, overlying an image of gravity data.

Cooper Basin thermal forward modelling

A region 188 by 144 km, by 16 km in depth was extracted from the initial Cooper Basin 3D map and used as a test region (Figure 1) for modelling the temperature, heat flow and geothermal gradients. The test region was populated with thermal properties for each lithology (heat production rates and thermal conductivities) and boundary conditions were approximated (mean surface temperature) or assumed (Neuman-type side boundaries, constant basal heat flow). Initial heat production rates (granites and sediments) and thermal conductivities (sediments) were sourced from published literature (Beardsmore, 2004; Middleton, 1979).

Temperature predictions were generated on a discretised version of the model within GeoModeller[1] using the method described by Seikel et al. (2009). Temperatures were solved by explicit finite difference approximation using a Gauss-Seidel iterative scheme implemented until either: a) the sum of the residual errors fell below a specified threshold; or b) a specified maximum number of iterations were reached – whichever occurs first. The thermal quantities computed were: temperature, vertical heat flow, vertical temperature gradient and total horizontal temperature gradient.

Results of the test-bed thermal modelling were compared to 21 corrected bottom hole temperature (BHT) measurements (Chopra and Holgate, 2005), as well as 30 modelled 1D heat flow measurements (Beardsmore, 2004) from wells in the test area. A number of thermal models were generated commencing with varying rock property inputs that were chosen to minimise the temperature differences between the BHTs and the modelled temperatures, as well as minimising the difference between the measured and modelled heat flow measurements. Vertical temperature sections through the final test-bed thermal model are shown in Figure 5. The section shows a clear rise in temperature at shallow depth in the north of the model that is coincident in location with a high heat producing granite.

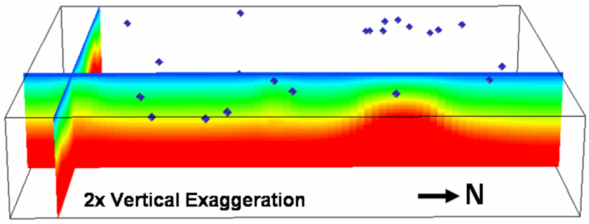

Figure 5: Vertical sections through the 3D temperature model showing the locations of the BHT data (dark blue). Modelled temperatures range from 27° (blue) to 390° (red).

By an iterative process aiming to match measured thermal values, test-bed thermal modelling has provided constraints on the possible thermal conductivity and heat production properties of the basement, as well as a predicted value of mean heat flow into the base of the model. This information, together with additional thermal conductivity measurements from drill core, will be fed into a thermal model of the extended 3D map to predict the temperature, thermal gradient and heat flow in regions where little to no temperature data exists.

Cooper Basin stochastic thermal modelling

The need to explore the uncertainty of estimates of heat resources within the Cooper Basin region, has led us to consider an approach by which we will generate multiple models. These models will reflect the full population of viable alternatives, consistent with the expected rock heat property probability distribution functions (for thermal conductivity and heat production rate) – but fixed in terms of geology geometry.

Generation of the initial voxet model of preferred geology (discretised from the continuous geology model) is already easily accommodated in

GeoModeller. From this initial voxet model, Monte-Carlo methods will be used to simulate multiple models containing the plausible ranges of varying rock heat properties. Following forward 3D temperature calculations, the family of voxet-model outcomes (3D results for temperature, heat flow and geothermal gradient) will then be interrogated by statistical methods to yield the probability estimates of the in-situ heat resource for the Cooper Basin.

One problem that arises in our approach is that a new solver strategy needs to be developed for the steady-state heat equation that can be scaled to the larger volumes of rock - one that is much faster than the commonly used finite difference and finite element methods. A fast solver for the inhomogeneous heat equation in free space, following the time evolution of the solution has been developed using Fourier domain techniques. This solver can solve much larger problems in a much shorted time than the traditional methods. This simulation work will build on the work of Li and Greengard, (2007) and Osterholt et al. (2009) to achieve the aims. Typical speed-ups for this strategy over the conventional solvers are better than 1000 to 1.

Synthetic modelling

A key dataset for geothermal energy exploration in Australia is the gravity anomaly map of Australia (Murray et al., 1997). Buried granites typically exhibit a negative gravity anomaly in relation to the crystalline basement they intrude, due to their lower relative density. A total of 648 unique granite models have been produced, based on differing diameter circular granites (5km, 10km, 20km, 30km, 50km and 70km), with different depth extents (2, 4, 6, 8, 10 and 12 km) imbedded in basement. These models also include different depths of burial of the granite/basement beneath sediments (varying from 1000m to 6000m, in 1000m increments) as well as three different density contrasts between the granites and basement (Figure 6).

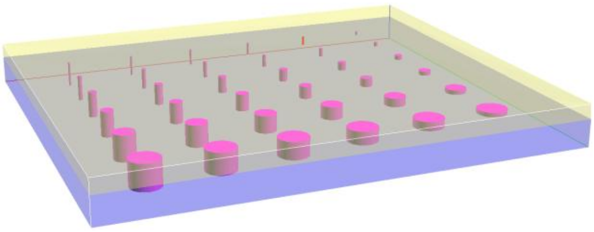

Figure 6: Synthetic model showing a series of granites imbedded in basement and overlain by 6 km of sediments. Granite diameters range from 5 to 70 km. Granite thicknesses range from 2 to 12 km.

Forward modelling the gravity signatures from this wide range of starting models will produce a comprehensive range of gravity anomalies. A geothermal explorer, interested in identifying unknown potential HHPG beneath a sedimentary basin, will be able use the reference gravity anomaly maps to identify gravity lows and then match their observed anomaly with a likely style of modelled anomaly (and associated, known geometry, depth and rock properties).

Due to the non-uniqueness of interpretations of gravity data, the explorer may not be able to pin-point a single model because a number of differing geometries and density contrasts could produce a similar gravity anomaly. The explorer will however, have a range of potential granite geometries for use in predicting temperature and heat flow. As more geological knowledge is gained about a particular region, such as the thickness of sediments and/or density contrast between the granite and basement, the number of modelled granite geometries that match the observed data will become restricted.

Once one or more potential granite geometries have been identified, the 3D thermal models can be used to predict surface heat flow and vertical temperature gradient. For each of the selected model geometries, forward models of heat flow and thermal gradients can be computed. The explorer can then choose from a range of thermal inputs consisting of five different heat production rates for the granites and five different thermal conductivities for the overlying sediments. In all, a total of 5400 unique geothermal scenarios are in the process of being produced from 216 unique granite/sediment geometries. The gravity and thermal anomaly arrays will be displayed in graph form in order to condense the results so they are easier to interpret and use.

Summary

Case study 3D maps and thermal models, such as the Cooper Basin study, incorporate all available geological knowledge into a 3D map. Often little or no information is known about the basement composition beneath sedimentary basins. Inversion of gravity data is, therefore, a valuable tool for identifying regions of low density within the basement that are potentially due to granitic bodies, which in turn may be acting as a viable heat source for a hot rock geothermal energy play.

Thermal forward modelling and stochastic thermal modelling of 3D maps, which contain both potential heat sources and thermally insulating cover, can be used as a predictive tool to identify the locations of potential geothermal plays. Where case study models do not exist, synthetic modelling provides a systematic approach to the interpretation of exploration datasets.

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