

Stochastic Temperature, Heat Flow and Geothermal Gradient Modelling Direct from a 3D Map of the Cooper Basin Region, Central Australia

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ABSTRACT

Significant volumes of Big Lake Suite granodiorite intrude basement in the Cooper Basin region of central Australia. Thick sedimentary sequences in the Cooper and overlying Eromanga Basins provide a thermal blanketing effect resulting in elevated temperatures at depth. 3D geological maps over the region have been produced from geologically constrained 3D inversions of gravity data. The inverted density models delineate regions of low density within the basement that are interpreted to be granitic bodies. The 3D maps include potential heat sources and thermally insulating cover, the key elements in generating an Enhanced Geothermal System (EGS) play.

A region was extracted from the 3D geological map and used as a test-bed for modelling the temperature, heat flow and geothermal gradients. The test region was populated with thermal properties and boundary conditions were approximated. Temperatures were generated on a discretised version of the model within GeoModeller and were solved by explicit finite difference approximation using a Gauss-Seidel iterative scheme. The thermal properties that matched existing bottom hole temperatures and heat flows measurements were applied to the larger 3D map region.

An enhancement of the GeoModeller software is to allow the input thermal properties to be specified as distribution functions. Multiple thermal simulations are carried out from the supplied distributions. Statistical methods are used to yield the probability estimates of the temperature and heat flow, reducing the risk of exploring for heat.

1. INTRODUCTION

The Cooper Basin region of central Australia straddles the Queensland and South Australian borders (Figure 1). The region is intruded by significant volumes of Big Lake Suite Granodiorite (BLS). 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 (Figure 2). These areas are coincident with thermal anomalies described by Cull and Denham (1979) and Cull and Conley (1983). 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). A summary of the geology of the Cooper Basin region is provided in Meixner and Holgate (2009a,b).

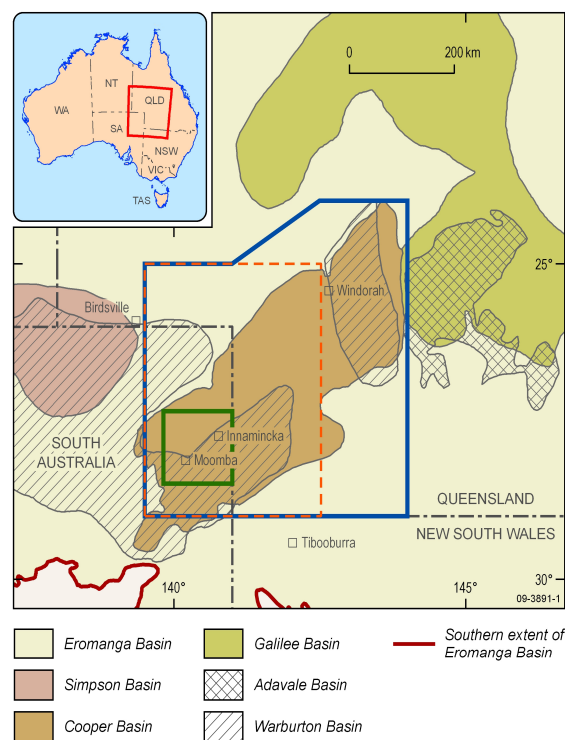


Figure 1: Location of the Cooper Basin region, showing the spatial extents of the stacked Warburton, Cooper and Eromanga Basins. The red dashed box indicates the extent of the 3D map produced as part of this study. The blue outline indicates the extent of the proposed extension to the 3D map and the green box indicates the extent of the test-bed thermal and stochastic models.

2. THE COOPER BASIN REGION 3D MAP

As part of this study, a 3D geological map of a portion of the Cooper Basin region has been produced for an area of 300 by 450 km to a depth of 20 km (Meixner and Holgate, 2009a,b) (Figure 1). The map was based in part on 3D property inversions of Bouguer gravity data using the method of Li and Oldenburg (1998). Geological data, such as well intersections and seismic surveys, 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 and Eromanga Basins that are inferred to be granitic bodies. Figure 3 shows a density section through the inversion model. The densities of the Eromanga and Cooper Basin sediments and the granitic bodies were constrained to narrow ranges, while the density of the basement was left unconstrained. This interpretation is supported by spatial correlations between the modelled bodies and known granite intersections from wells in the area. A perspective view of the interpreted sub-

sediment granitic bodies in the 3D map is shown in Figure 4. The 3D map includes potential heat sources (granitic bodies) and thermally insulating cover (Cooper and Eromanga Basins), the key elements in generating an EGS play.

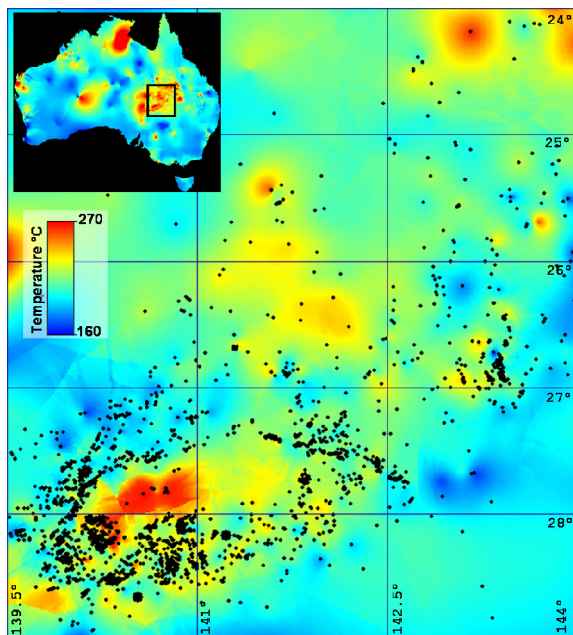


Figure 2: Predicted temperature at 5 km map Chopra and Holgate (2005) of the Cooper Basin region. Well locations are shown.

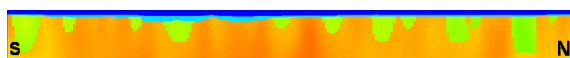


Figure 3: North-south density section through the constrained gravity inversion model. Eromanga Basin sediments - dark blue ($2.3 \pm 0.2 \text{ g cm}^{-3}$), Cooper Basin sediments - light blue ($2.5 \pm 0.2 \text{ g cm}^{-3}$), interpreted granitic bodies - green ($2.6 \pm 0.2 \text{ g cm}^{-3}$) and basement - yellow-red ($>2.65 \text{ g cm}^{-3}$). The section is 450 km long with a depth extent of 20 km.

It is intended that a future study will extend the 3D map 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. 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 conductivity properties 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 as 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 future 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.

3. 3D THERMAL FORWARD MODELLING

To test our thermal understanding of the region, a 188 by 144 km by 16 km volume was extracted from the Cooper Basin 3D map and used as a test-bed for modelling the temperature, heat flow and geothermal gradients (Figure 1). The test-bed was populated with thermal properties for each lithology (heat production rates and thermal conductivities) and boundary conditions were approximated (surface temperature) or assumed (Neuman-type side boundaries, constant basal heat flow). Initial heat production rates for the granites and sediments and the thermal conductivity of the sediments were sourced from published literature (Beardsmore, 2004; Middleton, 1979). Temperature predictions were generated on a discretised version (voxel) of the model within GeoModeller 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 achieved – whichever occurs first. The thermal quantities computed were temperature, vertical heat flow, vertical temperature gradient and total horizontal temperature gradient.

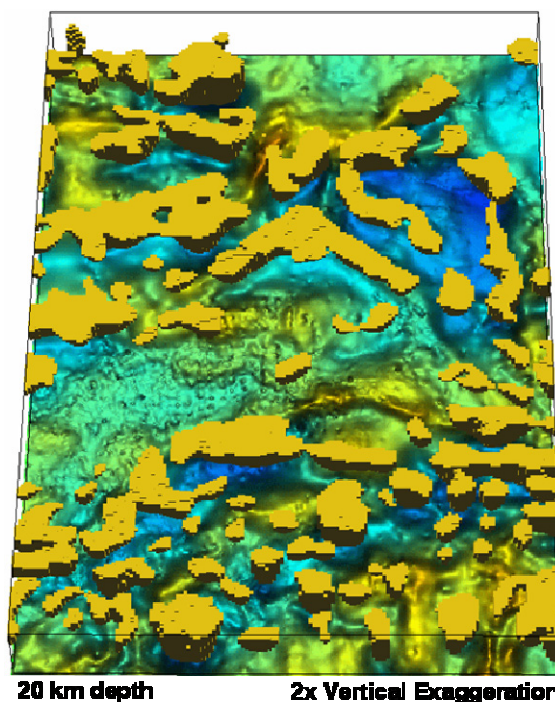


Figure 4: 3D model viewed obliquely from the south of inferred sub-sediment granitic bodies overlying an image of the gravity data. The image covers the same aerial extent as the red dashed box of Figure 1.

Results of the test-bed thermal modelling were compared to 21 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 with varying property inputs that were chosen to minimise the temperature differences between the BHT and the modelled temperatures, as well as minimising the difference between the measured and modelled heat flow measurements.

The test-bed thermal modelling process has provided constraints on the thermal conductivity and heat production properties of the basement, granites and sediments as well

as a predicted value of heat flow into the base of the model. These values were applied to the entire 3D map area and a thermal model computed. Figure 5 shows a horizontal temperature slice at 3 km depth from this thermal model.

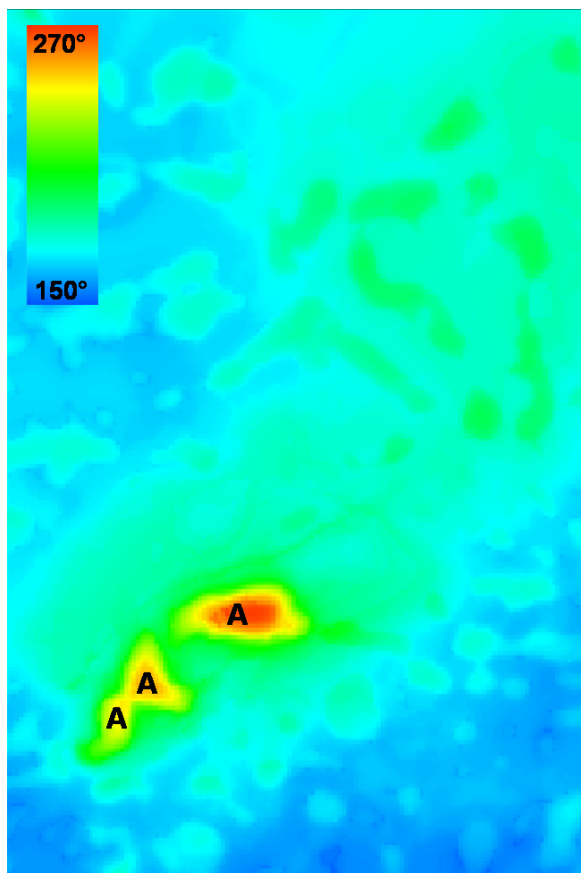


Figure 5: A 3 km depth slice through the thermal model of the study area. The elevated temperatures due to the high heat producing BLS (A) are clearly visible. The broad north-east trending temperature anomaly is due to the insulating effects of the Cooper and Eromanga Basin sediments.

4. STOCHASTIC TEMPERATURE, HEAT FLOW AND GEOTHERMAL GRADIENT MODELLING

In order to explore the uncertainty of estimates of heat resources within the Cooper Basin region, we have used an approach based on the generation of multiple models. These models reflect the full population of viable alternatives, due to the uncertainty in the input model thermal properties. An initial voxet model of preferred geology is generated in GeoModeller. From this initial model, multiple models are generated containing the plausible ranges of varying thermal properties, based on a normalized probability distribution. Following forward 3D temperature calculations, the family of voxet-model outcomes (3D results for temperature, heat flow and geothermal gradient) are then interrogated by statistical methods to yield the mean values and standard deviations of the temperature, heat flow and temperature gradient. This will allow for calculation of probability estimates of the in-situ heat resource of a region.

Stochastic thermal modeling was applied to the test-bed region. Normalized property distributions (mean value and first standard deviation) were specified for the thermal conductivity of the Cooper and Eromanga Basin sediments

and the heat flow into the base of the model. The granite bodies were divided into two suites, the BLS and all other interpreted granites. The two suites were assigned separate heat production distributions. The mean values for the five properties to be varied in the stochastic simulation were based on the thermal properties derived from the test-bed forward thermal models. The remaining properties were given a mean value only and, therefore, not vary in the stochastic simulation. An example of the stochastic thermal modelling is shown in figure 6.

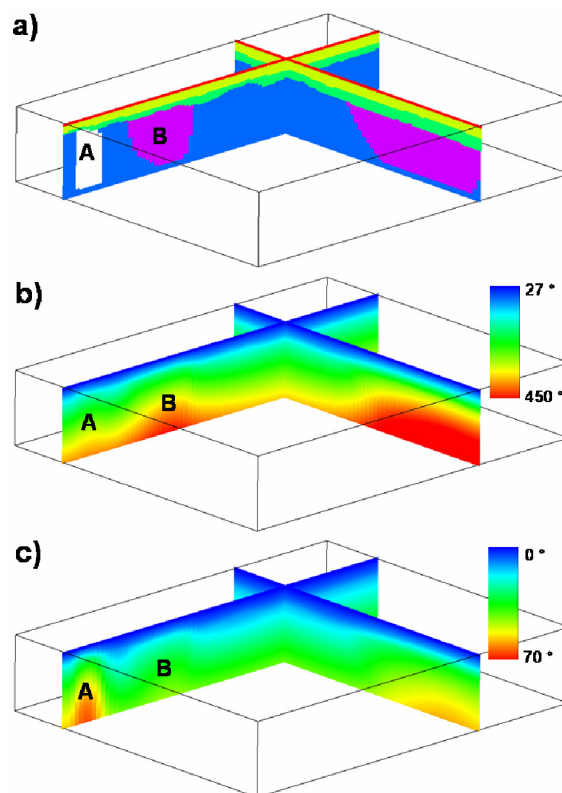


Figure 6: a) Vertical slices, viewed from the south-east, through the test-bed region of the 3D map showing the input lithologies used in the stochastic modelling (red – above topography; yellow – Eromanga Basin sediments; green – Cooper Basin sediments; blue – basement; purple – BLS; white – other interpreted granites). b) Results of the stochastic thermal model showing the mean temperature. The large temperature anomaly due to the high heat producing BLS (B) is evident, as is the lesser temperature anomaly due to the other granites (A) which were assigned a lesser heat production. c). 1st standard deviation of the temperature uncertainty. The large temperature uncertainty (A) is due to the higher uncertainty assigned to the input heat production value for the other granites compared to the lower heat production uncertainty for the BLS (B).

A limitation of this new method is that the process is computationally expensive. This is due to the total number of forward models that are produced equals the number of lithologies to be varied, raised to the power of three. For the test-bed stochastic model, which contained five variables (two variable heat production, two variable thermal conductivities and the heat flow into the base of the model), a total of 243 thermal forward models were computed. A new solver strategy is being developed for the steady-state

heat equation that is much faster than the commonly used finite difference and finite element methods. The solver uses Fourier domain techniques to solve for the inhomogeneous heat equation in free space, following the time evolution of the solution. This simulation work will build on the work of Li and Greengard, (2007) and Osterholt et al. (2009) to achieve the aims. The new method typically increases the speed of computation by a factor of 1000 when compared with the conventional solvers.

5. CONCLUSION

The 3D map includes potential heat sources and thermally insulating cover, the two key elements in generating an EGS play. By assigning thermal properties and applying thermal modelling techniques, a better understanding of heat flow and temperature distribution is achieved, and hence the generation of 3D models is a useful predictive tool to locate potential EGS plays. We expect that the proposed extended 3D geological map employing detailed basin stratigraphy will provide enhanced control on the density values derived through inversion of gravity data, and consequently expect to derive an improved 3D map of sub-sediment granitic bodies.

The test-bed thermal modelling indicates that suitable estimates of thermal properties can be assigned to the geological units in the 3D map to reproduce existing temperature and heat flow data in the region. It is expected that a more detailed 3D map of the Cooper and Eromanga sediments and the use of additional thermal conductivity measurements will produce a thermal model that will more closely match the existing temperature and heat flow data.

The stochastic thermal modeling allows scenarios to be tested in early phases of geothermal exploration. For example, what are the envelopes of uncertainty in 3D temperature calculation, given specified variability of the bulk thermal conductivity property for shale in the project area, combined with end-member possibilities of the heat production rate of the granite? The ability to generate 3D temperature and heat flow probability maps (and thus quantify the uncertainty) will significantly reduce the risk of EGS exploration, not only in the Cooper Basin, but elsewhere. We envisage that this modelling method will be a useful predictive tool that will reduce the risk of exploring for heat prior to committing to costly deep drilling.

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