

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

Tony Meixner^{1*}, Stephen Johnston¹, Alison Kirkby¹, Helen Gibson², Ray Seikel², Kurt Stüwe³, Des FitzGerald², Nick Horspool¹, Richard Lane¹ and Anthony Budd¹

¹ Geoscience Australia, GPO Box 378, Canberra, ACT, 2601

²Intrepid Geophysics, Unit 2, 1 Male St, Brighton VIC 3186

³Universitaet Graz, Heinrichstr. 26 A-8010, Austria

* corresponding author Tony.Meixner@ga.gov.au

A large number of exploration models for Hot Rock geothermal energy plays in Australia are based 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 its thermal properties and the thickness and thermal properties 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, and the Millungerra Basin region east of the Mt Isa Inlier, have been constructed from gravity inversions 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 using GeoModeller software by assigning measured and estimated thermal properties to the mapped lithologies.

An enhancement of the GeoModeller software allows input of thermal properties to be specified as distribution functions. Multiple thermal simulations were used to estimate the in-situ heat resource, thus reducing the exploration risk. 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 region 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 bodies.

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.

There are two fundamental unknowns surrounding the minimum requirements to produce an Australian style Hot Rock geothermal play. The first unknown is the amount of heat production required, which is linked to the concentration of radiogenic elements, and the volume and geometry of HHPGs. The second unknown is the thermal insulation required from the overlying basin sediments, which is a function of the thickness and thermal conductivity of the overlying sediments 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 (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).

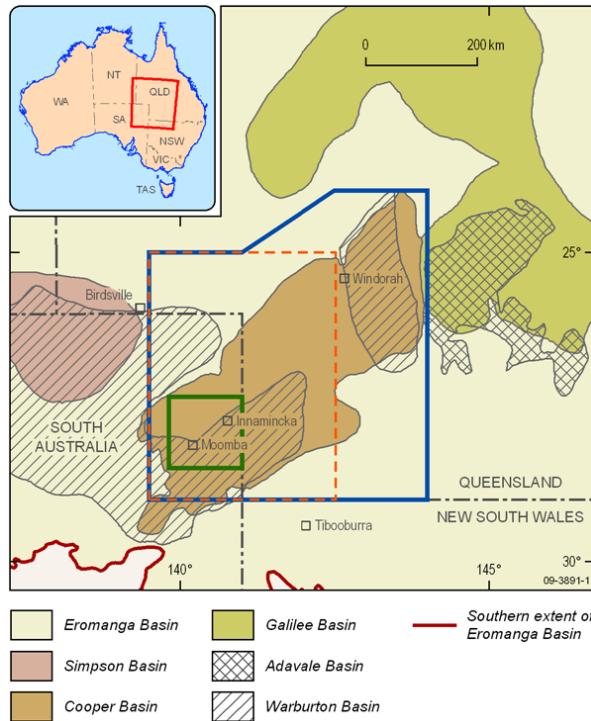


Figure 1. Location of the Cooper Basin region, showing the spatial extents of the stacked Warburton, Cooper and Eromanga Basins. The red dashed box indicates the extent of the original 3D map, the blue outline indicates the extent of the extended 3D map, and the green box indicates the extent of the 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 using the method of Li and Oldenburg (1998). The geometries and densities of the Eromanga and Cooper Basin, derived from well and seismic 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 based on measured and inferred values, 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.

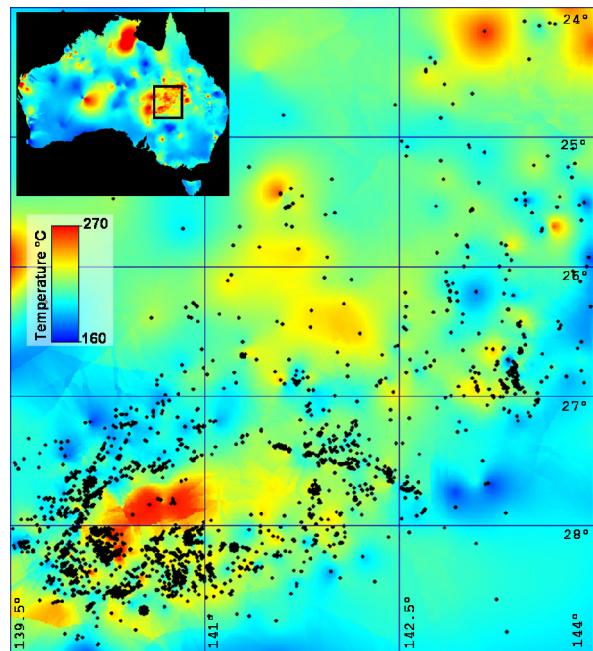


Figure 2: Predicted temperature map at 5 km for the Cooper Basin region, based on bottom hole temperatures, after Chopra and Holgate (2005). Well locations are shown.

For the present study, the 3D map was 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 includes 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 allowed 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, was 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 used an averaged density value for each individual stratigraphic unit derived from well density logs. The use of enhanced density constraints for the sedimentary section enhances the credibility of the density variations derived for the basement unit, and therefore provides a more accurate delineation of interpreted granitic bodies.

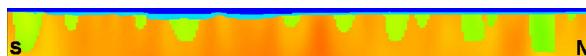


Figure 3: North-south density section through the litho-constrained gravity inversion model. Eromanga Basin sediments (dark blue: $2.3 \pm 0.2 \text{ g cm}^{-3}$), Cooper Basin sediments (light blue: $2.5 \pm 0.2 \text{ g cm}^{-3}$) and the granitic bodies (green: $2.6 \pm 0.2 \text{ g cm}^{-3}$) were constrained to a narrow density range, while the basement (yellow-red: $2.65\text{--}2.75 \text{ g cm}^{-3}$) was left unconstrained. The section is 450 km long and 20 km deep.

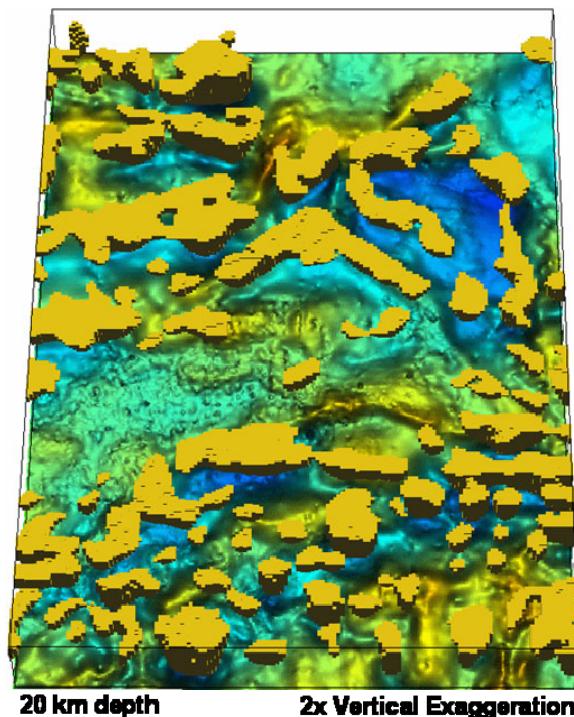


Figure 4: Cooper Basin region 3D map viewed obliquely from the south showing the inferred sub-sediment granitic bodies, overlying an image of gravity data.

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 (heat production rates and thermal conductivities) for each lithology and boundary conditions were approximated (mean surface temperature) or assumed (Neuman-type side boundaries, constant basal heat flow). Initial heat production rates for the granites and sediments and thermal conductivities for the sediments were sourced from published literature (Beardmore, 2004; Middleton, 1979).

Temperature predictions were generated on a discretised version of the model within GeoModeller¹ 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 fall below

a specified threshold; or b) a specified maximum number of iterations were reached – whichever occurred 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 (Beardmore, 2004) from wells in the test area. A number of thermal models were generated by minimising 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 sections show a clear rise in temperature at shallow depth in the north of the model that is coincident with a HPG intersected by wells.

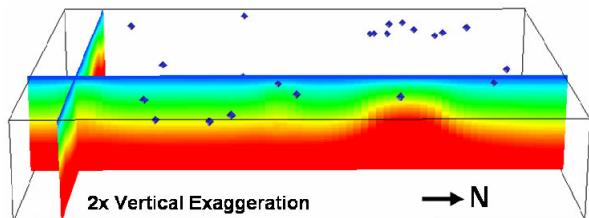


Figure 5: Vertical sections through the 3D temperature model showing the locations of the BHT data (dark blue). Modelled temperatures range from 27° (blue) to 390° (red).

The 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, were then used in a thermal model of the extended 3D map to predict the temperature, thermal gradient and heat flow in regions where little or no temperature data exists.

Cooper Basin stochastic thermal 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 will reflect the full population of viable alternatives, consistent with the expected thermal property probability distribution functions (for thermal conductivity and heat production rate) – but with fixed geological geometries.

The initial voxel model of preferred geology (discretised from the continuous geology model) was generated in GeoModeller. From this initial voxel model, multiple models containing the plausible ranges of varying thermal properties

were produced. Following forward 3D temperature calculations, the family of voxel-model outcomes (3D results for temperature, heat flow and geothermal gradient) were then interrogated by statistical methods to yield the probability estimates of the in-situ heat resource for the Cooper Basin.

To implement this approach we are developing a new solver strategy for the steady-state heat equation that can be scaled to the larger volumes of rock in this study. A fast solver for the inhomogeneous heat equation in free space, following the time evolution of the solution is being developed using Fourier domain techniques. The method we are developing is up to 1000 times faster than the commonly used finite difference and finite element methods. It can also solve much larger problems. This simulation work builds on the work of Li and Greengard, (2007) and Osterholt et al. (2009).

The Millungera Basin 3D geological map

The previously unknown Millungera Basin (Korsch and Huston, 2009), to the east of the Mt Isa Inlier was identified in the 2006 Mt Isa (Hutton, et al., 2009) and 2007 North Queensland seismic surveys (Korsch et al., 2009). Geological relationships suggest that the age of the basin, which underlies the Carpentaria-Eromanga basins, lies between the Mesoproterozoic and Early Mesozoic. Non-reflective zones below the base of the Millungera Basin that are interpreted as granite, also coincide with gravity lows. Based on this interpretation, the region may host potential Hot Rock geothermal plays given the high-heat producing nature of nearby granites of the Williams Batholith (Hutton, et al., 2009) and the thick sequences, up to approximately 3900 m, of potentially insulating Millungera sediments.

A 3D geological map (192 by 315 km, 20 km depth extent) is currently being constructed over the Millungera Basin using similar methodologies to the Cooper Basin study. This 3D map will form the basis for thermal modelling in order to gain a better understanding of the thermal properties of a region that contains no heat flow measurements and few down-hole temperature measurements.

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 (5 km, 10 km, 20 km, 30 km, 50 km and 70 km), with different depth extents (2, 4, 6, 8, 10 and 12 km) embedded in basement. These models also

include different depths of burial of the granite/basement beneath sediments (varying from 1000 m to 6000 m, in 1000 m increments) as well as three different density contrasts between the granites and basement (Figure 6).

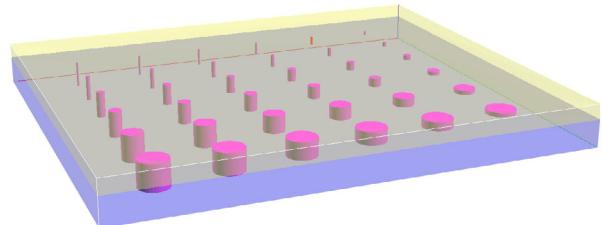


Figure 6: Synthetic model showing a series of granites embedded in basement and overlain by 6 km of sediments. Granite diameters range from 5 to 70 km. Granite thicknesses range from 2 to 12 km.

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

Due to the non-uniqueness of interpretations of gravity data, the explorer may not be able to pinpoint 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 potential granite geometries have been identified, the 3D thermal models can be used to predict surface heat flow and vertical temperature gradient. For a selected granite geometry the explorer can then choose from a range of inputs (five different heat production rates for the granites and five different thermal conductivities for the overlying sediments) to predict the likely heat flow and thermal gradient over the granite body. In all, a total of 5400 unique geothermal scenarios were produced from 216 unique granite/sediment geometries. The gravity and thermal anomaly are 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 and Millungera Basin studies, 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.

References

¹GeoModeller is a commercially available software package and has been produced by Intrepid Geophysics and Bureau de Recherches Géologiques et Minières (BRGM). www.geomodeller.com.

Archibald, N., Gow, P., and Boschetti, F., 1999, Multiscale edge analysis of potential field data: *Explor. Geophys.*, 30, p. 38-44.

Beardmore, G.R., 2004, Thermal modelling of the Hot Dry Rock geothermal resource beneath GEL99 in the Cooper Basin, South Australia: Sydney: 17th Aust. Soc. Explor. Geophys. Conference. Extended Abstracts.

Chopra, P., and Holgate, F., 2005, A GIS Analysis of Temperature in the Australian Crust: World Geothermal Congress, Turkey, 24-29 April 2005, Abstracts.

Collins, C.D.N., and Lock, J., 1990, Velocity variations within the upper crustal basement of the central Eromanga Basin: Bureau of Mineral Resources, Geology and Geophysics, Canberra. Bulletin, 232, p. 177-188.

Cull, J.P., and Denham, D., 1979, Regional variations in Australian heat flow: Bureau of Mineral Resources, *Journal of Australian Geology and Geophysics* 4, p. 1-13.

Cull, J.P., and Conley, D., 1983, Geothermal gradients and heat flow in Australian sedimentary basins: Bureau of Mineral Resources, *Journal of Australian Geology and Geophysics* 8, p. 329-337.

Hutton, L.J., Gibson, G.M., Korsch, R.J., Withnall, I.W., Henson, P.A., Costelloe, R.D., Holzshuh, J., Huston, D.L., Jones, L.E.A., Maher, J.L., Nakamura, A., Nicoll, M.G., Roy, I., Saygin, I., Murphys, F.B., and Jupp, B., 2009 Geological interpretation of the 2006 Mt Isa Seismic Survey: In: Camuti, K., and Young, D. eds., Northern Queensland Exploration & Mining 2009 and North Queensland Seismic and MT Workshop: Extended Abstracts. Australian Institute of Geoscientists Bulletin No. 49, p. 137-142.

Korsch, R.J., and Huston, D.L., 2009. Geodynamics and Metallogeny of North Queensland: insights from new deep crustal seismic data: In: Camuti, K., and Young, D. eds., Northern Queensland Exploration & Mining 2009 and North Queensland Seismic and MT Workshop: Extended Abstracts. Australian Institute of Geoscientists Bulletin No. 49, p. 57-63.

Korsch, R.J., Withnall, I.W. Hutton, L.J., Henson, P.A., Blewett, D.L., Huston, D.L., Champion, D., Meixner, A.J., Nicoll, M.G., and Nakamura, A., 2009, Geological interpretation of deep seismic reflection line 07GA-IG1 the Cloncurry to Croydon transect: In: Camuti, K., and Young, D. eds., Northern Queensland Exploration & Mining 2009 and North Queensland Seismic and MT Workshop: Extended Abstracts. Australian Institute of Geoscientists Bulletin No. 49, p. 153-158.

Li, J-R., and Greengard, L., 2007, On the numerical solution of the heat equation I: Fast solvers in free space: *Journal of Computational Physics* 226, p. 1891-1901.

Li, Y., and Oldenburg, D.W., 1998, 3-D inversion of gravity data: *Geophysics*, 63, p. 109-119.

McLaren, S., Sandiford, M., Hand, M., Neumann, N., Wyborn, L., and Bastrakova, I., 2003, The hot southern continent; heat flow and heat production in Australian Proterozoic terranes: In: Hills, R.R., and Mueller, D.R. eds., Evolution and dynamics of the Australian Plate. *Geol. Soc. of America Special Paper* 372, p. 157-167.

Meixner, A.J. and Holgate, F., 2009a, In search of hot buried granites: a 3D map of sub-sediment granitic bodies in the Cooper Basin region of Australia, generated from inversions of gravity data: Adelaide: 20th Aust. Soc. Explor. Geophys. Conference. Extended Abstracts.

Meixner, A.J., and Holgate, F., 2009b, The Cooper Basin Region 3D Map Version 1: A Search for Hot Buried Granites: Geoscience Australia, Record, 2009/15.

Middleton, M.F., 1979, Heat flow in the Moomba, Big Lake and Toolachee gas fields of the Cooper Basin and implications for hydrocarbon maturation: *Bulletin – Aust. Soc. of Exploration Geophysics* 10(2), p. 149-155.

Murray, A.S., Morse, M.P., Milligan, P.R. and, Mackey, T.E., 1997, Gravity anomaly map of the Australian region (second ed.), scale 1:5 000 000. Australian Geological Survey Organisation, Canberra.

Osterholt, V., Herod, O., and Arvidson, H., 2009, Regional Three-Dimensional Modelling of Iron Ore Exploration Targets, *Proceedings: Orebody*

Modelling and Strategic Mine Planning Conference, Perth.

Sass, J.H., and Lachenbruch, A.H., 1979, Thermal regime of the Australian Continental Crust, in McElhinny, M.W., ed., *The Earth: its origin, structure and evolution*. Academic Press, London, p. 301-351.

Seikel, R., Stüwe, K., Gibson, H., Bendall, B., McAllister, L., Reid, P., and Budd, A., 2009, Forward prediction of spatial temperature variation from 3D geology models: Adelaide: 20th Aust. Soc. Explor. Geophys Conference. Extended Abstracts.

Somerville, M., Wyborn, D., Chopra, P., Rahman, S., Estrella, D., and Van der Meulen, T., 1994, Hot dry rock feasibility study: Energy Research and Development Corporation, Report 94/243. 133pp.

Van der Wielen, S.E., Kirkby, A., Britt, A., Schofield, A., Skirrow, R., Bastrakov, E., Cross, A., Nicoll, N., Mernagh, T., and Barnicoat, A., 2009, Large-Scale Exploration Targeting for Uranium Mineral Systems within the Eromanga Basin. Townsville 10th Soc. Geol. App. Min. Dep Conference. Extended abstracts. in prep.