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A Re-evaluation of the Geothermal Potential in Western Queensland, with Stochastic Thermal Modelling

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ABSTRACT

A large subsurface elevated temperature anomaly is well documented in Central Australia. High Heat Producing Granites (HHPGs) intersected by drilling at Innamincka are often assumed to be the dominant cause of the elevated temperatures, although their presence in other parts of the temperature anomaly has not been confirmed. Geological controls on the temperature anomaly remain poorly understood. Additionally, methods previously used to predict temperature at 5 km depth in this area are simplistic and possibly do not give an accurate representation of the true distribution and magnitude of the temperature anomaly. We propose a new temperature map at 5 km depth for the Queensland part of the temperature anomaly and re-evaluate the geological controls on the geothermal potential using a stochastic thermal model. Estimated temperature and heat flow at 5 km depth are most sensitive to the thermal conductivity of the strata. Nevertheless, the lack of correlation between the predicted geothermal gradient and the inverse of mean thermal conductivity of the sedimentary cover thickness suggests that thermal blanketing is not the sole cause of high geothermal gradients. In addition, the small mean temperature errors between modelled and observed temperature profiles indicate that the assumption of steady-state, purely conductive heat transfer may be valid and that effects of advective, convective or transient heat transfer are likely to be minor on the regional scale. Estimations of the relative contributions of mantle versus crustal heat input from below 5 km depth suggest that the observed high geothermal gradients are unlikely to be generated by elevated mantle heat flow alone. Consequently, we conclude that the crust between 5 and 40 km depth is relatively high heat producing in the region of anomalously high crustal temperatures. Our study supports evidence for a felsic continental lower crust enriched in heat producing elements. A SW-NE trend of lower heat flow and inferred average heat production through the study area correlates with structural trends and may relate to zones of thinned continental crust and therefore lower total crustal heat production.

1. INTRODUCTION

High geothermal gradients have long been recognised in the Great Artesian Basin (GAB) of central-eastern Australia (Polak and Horsfall, 1979). A recent map of estimated temperature at 5 km depth in Australia has been generated to evaluate the geothermal energy potential (Somerville et al., 1994; Chopra and Holgate, 2005; Gerner and Holgate, 2010). This map indicates the presence of a large subsurface temperature anomaly, which extent approximates 800,000km^2, and temperatures exceed 235°C at 5 km depth. The intersection of High Heat Producing Granites (HHPGs) at Innamincka, South Australia, have led several authors (e.g., Chopra and Holgate, 2005; Draper and D'Arcy, 2006) to suggest that elevated geothermal gradients in Central Australia result from subsurface HHPGs. Nevertheless, available heat production values of intersected granitic rocks (Champion et al., 2007) in the SW Queensland part of the temperature anomaly are well below values estimated for the granites at Innamincka (1.6-4.2 μWm^{-3} versus 9.7 μWm^{-3} for the Big Lake Suite; Middleton, 1979).

Give the apparent lack of intersected HHPGs beneath large tracts of the temperature anomaly, an important issue for geothermal energy evaluation across this area is a critical appraisal of the quality of data upon which the temperature map is based. Several issues related to the current temperature map are: 1) the linear extrapolation of borehole temperature measurements; 2) unreliable, shallow (e.g., <500m) temperature measurements extrapolated to 5 km depth; 3) temperature extrapolations without considering material properties (e.g., thermal conductivity and heat production) of the intersected lithological formations.

This study provides a new temperature and heat flow map at 5 km depth for the SW Queensland part of the temperature anomaly which will serve as a guide for more focused geothermal exploration studies. In total, 163 new heat flow and temperature estimates are generated using a stochastic thermal model.

2. INVERSION AND STOCHASTIC MODELLING

Our approach is a modified version of Chapman (1986), with different boundary conditions. We assume a thermal steady-state heat transfer and treat each well as a 1D multi-layer diffusion problem. Each layer corresponds to a lithological formation for which thermal conductivity and radiogenic heat production were considered constant. Deeper temperature measurements (e.g., >1km) are considered more reliable than shallow or surface temperature measurements and therefore we modeled the temperature profiles from bottom to top using the following equation:

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$$T(z) = -\frac{A}{2K}\left(z^2 + z_B^2\right) + z\frac{Q_B + Az_B}{K} + T_B - \frac{z_B Q_B}{K} \text{ [1]},$$

Where T(z) is the temperature at a specific depth z, A and K are the radiogenic heat production and thermal conductivity of the layer and z_B, Q_B and T_B are the vertical position, heat flow and temperature of the bottom layer respectively.

The temperature profile is calculated layer by layer, by upward propagation of equation [1] with updated material properties and bottom temperature and heat flow. This procedure requires that the bottom temperature and heat flow are known. Here we estimate temperature T_T and heat flow Q_T at 5 km depth, a depth that has not been intersected in the study area.

Assuming that the material between the deepest observation in the well and z_T remains identical, T_T and Q_T can be inverted by minimising the mean squared temperature error of the calculated temperature profile :

$$\Delta\varepsilon = \sum_{i=1}^{N} \frac{(Ti - ti)^2}{N} \text{ [2]},$$

where N denotes the number of actual temperature observations in the well, *Ti* is the measured temperature at a given depth, and *ti* is the predicted temperature at that depth. For a given Q_T, it is straightforward to calculate the best-fit T_T.

Equation 1 indicates that the selection of the initial T_B controls the position of the temperature profile and thermal conductivity controls its shape. A change of T_T would hence shift the temperature profile by its magnitude along the temperature axis. Thus, T_T can be calculated by minimising the mean squared temperature error :

$$\Delta\varepsilon = \sum_{i=1}^{N} \frac{(Ti - (ti + X))^2}{N} \text{ [3]},$$

and with ΔTi = (Ti – ti):

$$\Delta\varepsilon = X^2 - \frac{2}{N}X\sum_{i=1}^{N}\Delta Ti + \frac{1}{N}\sum_{i=1}^{N}\Delta Ti^2 \text{ [4]}.$$

Eq. 4 has the minimum:

$$\Delta\varepsilon' = 2X - \frac{2}{N}\sum_{i=1}^{N}\Delta Ti = 0 \text{ [5]}.$$

Therefore, the following solution for T_T is obtained:

$$X = \sum_{i=1}^{N}\frac{\Delta Ti}{N} \text{ [6]}.$$

The minimised square temperature error can therefore be expressed using Eq. 4 and 6:

$$\Delta\varepsilon = \sum_{i=1}^{N}\frac{\left(Ti - \left(ti + \sum_{i=1}^{N}\frac{\Delta Ti}{N}\right)\right)^2}{N} \text{ [7]}.$$

This procedure requires that Q_T is known, which is not the case. Eq. 7 shows that Δε is a quadratic function of Q_T:

$$f(Q_T) = \Delta\varepsilon = aQ_T^2 + bQ_T + c \text{ [8]}.$$

Given three points, $P_j(Q_{Tj}/\Delta\varepsilon_j)$, the coefficients a, b and c of this quadratic function can be calculated empirically and the best fit Q_T determined by minimisation. Thus, both the best-fit temperature profile and the respective temperature and heat flow at 5 km depth are determined in a three step process for any given well: first, three arbitrary Q_T are assumed (0, 50, and 100 μWm^{-3}). For each one, the corresponding best-fit T_T and its mean squared temperature error are calculated analytically with Eqs. 6 and 7. This yields the desired three pairs of Q_T and Δε data needed to calculate the coefficients of Eq. 8. The best-fit Q_T is simply the minimum of Eq. 8: $-b(2a)^{-1}$. In the third step, the corresponding T_T is computed for the best-fit Q_T with Eq. 6.

We applied this method for 163 wells within and outside the recognised temperature anomaly in Queensland. Wells were selected according to their geographical location (to provide sufficient spatial coverage data interpolation maps) and to the quantity and quality of available information (e.g., lithological descriptions, reliable temperature measurements (Horner and/or DST)).

Thermal conductivity measurements for sedimentary formations were estimated using average thermal conductivity for a particular lithology with the approach of Beardsmore (2004), correcting for porosity and saturation when information is available (Gallagher, 1987) and correcting for temperature (Birch and Clark, 1940).

The radiogenic heat production of sedimentary formations was considered constant with a value of 1.87 μWm^{-3}, based on average U, Th and K concentrations from Kamber et al. (2005). Where available, we applied measured values for granite heat production (Champion et al., 2007). Otherwise a heat production value of 2.5 μWm^{-3} was used, estimated by Meixner et al. (2012) using available whole-rock chemistry of Australian granites (Champion et al., 2007). Heat production for other type of basement rocks was considered to be 1.7 μWm^{-3}(Meixner et al., 2012), using global upper crustal averages of U, Th and K concentrations (Rudnick and Gao, 2003).

Only the most reliable borehole temperature measurements were selected, i.e., drill stem tests and Horner corrected temperatures.

3. RESULTS AND DISCUSSION

Our results indicate that the mean temperature error is low (≤ 10°C, and in > 50% of the map it is < 5°C). In other words, the model error is of the order of the uncertainty imposed by poorly constrained material properties and that of the actual down-hole temperature measurements. Higher mean errors (10 to 23°C) occur only locally and may indicate areas for which thermal transport is advective or convective. We therefore conclude that 1D steady state conduction generally predicts the temperature data well on the regional scale.

The new predicted temperature map for 5 km depth (Fig.1) has significant differences compared to the predicted Oztemp temperature map of Gerner and Holgate (2010). The regional extent of the Oztemp anomaly is much smaller with a prominent SW-NE trend of elevated (200-250°C) temperatures (Fig. 1). Only scattered anomalous temperatures are now predicted north of the Roma Shelf and in the Georgina Basin.

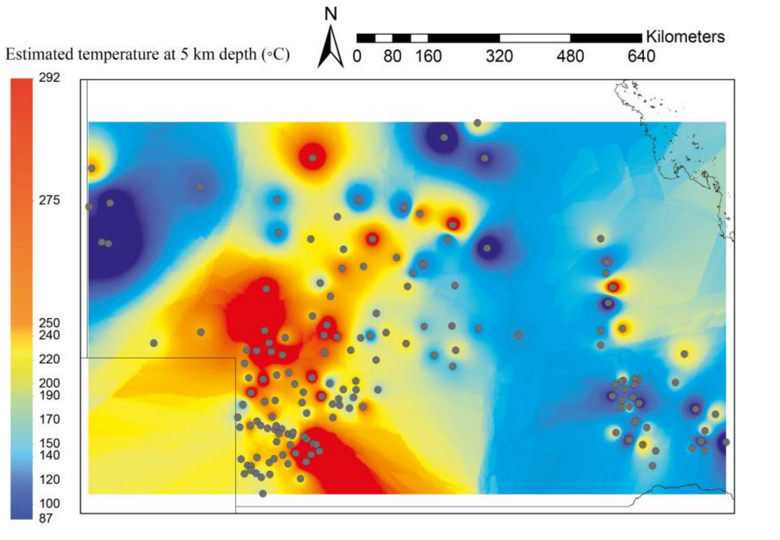

Figure 1: Median estimated temperature map at 5 km depth

A lower heat flow zone (Fig. 2) with values ranging from 80 to 100 mWm^{-2} is observed in between zones with elevated heat flow (> 100 mWm^{-2}). This lower heat flow zone is oriented along a SW-NE trend, parallels and adjacent to the high temperature trend described above.

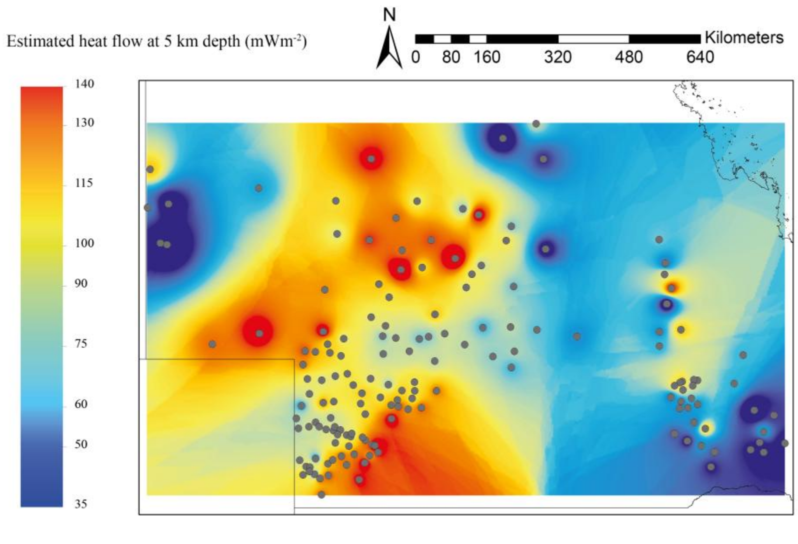

Figure 2: Median estimated heat flow map at 5 km depth

High temperature areas at 5 km depth are not always associated with high heat flow areas at 5 km depth, particularly towards the Galilee Basin where heat flow is high (ca. 100 mWm^{-2}) and temperatures generally lower (three temperature below 170°C). Such differences may result from changes in thermal conductivity of the sedimentary cover. Indeed, higher thermal conductivities are observed (e.g., average sedimentary pile conductivity > 2.75 $Wm^{-1}K^{-1}$) towards the Galilee Basin.

4. CONCLUSION

This study provides a re-evaluation of the geothermal potential in SW Queensland. A new temperature map at 5 km depth reveals a dominant SW-NE trend with temperatures reaching 200-250ºC. Additionally, a lower heat flow zone has been recognized and is adjacent to the high temperature SW-NE trend. Differences in elevated heat flow and temperature estimates result from variations of thermal conductivity of the sedimentary cover.

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