3D thermal modelling VS down-hole temperature extrapolation and the implications for targeting potential geothermal anomalies: a Sydney Basin case study

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Geothermal exploration programs require accurate subsurface temperature information and currently this information primarily comes from temperature maps created from the extrapolation of shallow down-hole temperature measurements. These extrapolations are often taken from measurements made in non-equilibrated boreholes and do not account for variations in geological structure or thermal conductivity. Here we present a case study for the Sydney basin where we explore temperature maps at 5km created from extrapolated equilibrated and non-equilibrated borehole measurements and from modelled basin temperatures and the implications for targeting potential geothermal anomalies. The modelled temperatures are derived from finite element models using 3D basin geology and defined thermal properties.

Keywords: Sydney Basin, 3D thermal modelling, temperature extrapolation, geothermal exploration

Case Study – Sydney Basin

The Sydney Basin, part of the Sydney-Gunnedah-Bowen Basin system, is a major sedimentary basin in the east coast of Australia and an important economic resource. Much attention is given to the coal and coal seam gas prospects but recently the focus has shifted to the basins thermal structure and geothermal potential. Previous work in the Gunnedah Basin (Danis et al., 2010) has shown that basin architecture and insulating sediments have a profound impact on the thermal structure. Heat refracts around insulating coal and sediment layers, into adjacent zones of lower thermal resistance, resulting in large lateral variations in the subsurface temperature.

In order to determine areas for potential geothermal resource exploration an assessment of the temperature at depth is required. Short of drilling deep and expensive boreholes, current methods extrapolate down-hole temperatures from shallow boreholes to 5km using shallow geothermal gradients. This method relies on non-equilibrated temperature information and geothermal gradients, which fails to account for lateral variations in geology and thermal conductivity. Such extrapolations may differ significantly to actual temperatures at depth and my result in false target anomalies. 3D thermal modelling provides a more representative analysis of the thermal structure, with the ability to set model parameters for lateral geological variation and define thermal characteristics.

The work presented here compares the results of extrapolated equilibrated and non equilibrated temperature information from shallow boreholes to 5km depth and thermal modelling using geological models for target anomaly location. There is a significant difference in temperature structure at depth between equilibrated and non-equilibrated extrapolated temperatures as well as thermal modelled temperatures. These differences have significant implications for targeting resource areas for geothermal exploration.

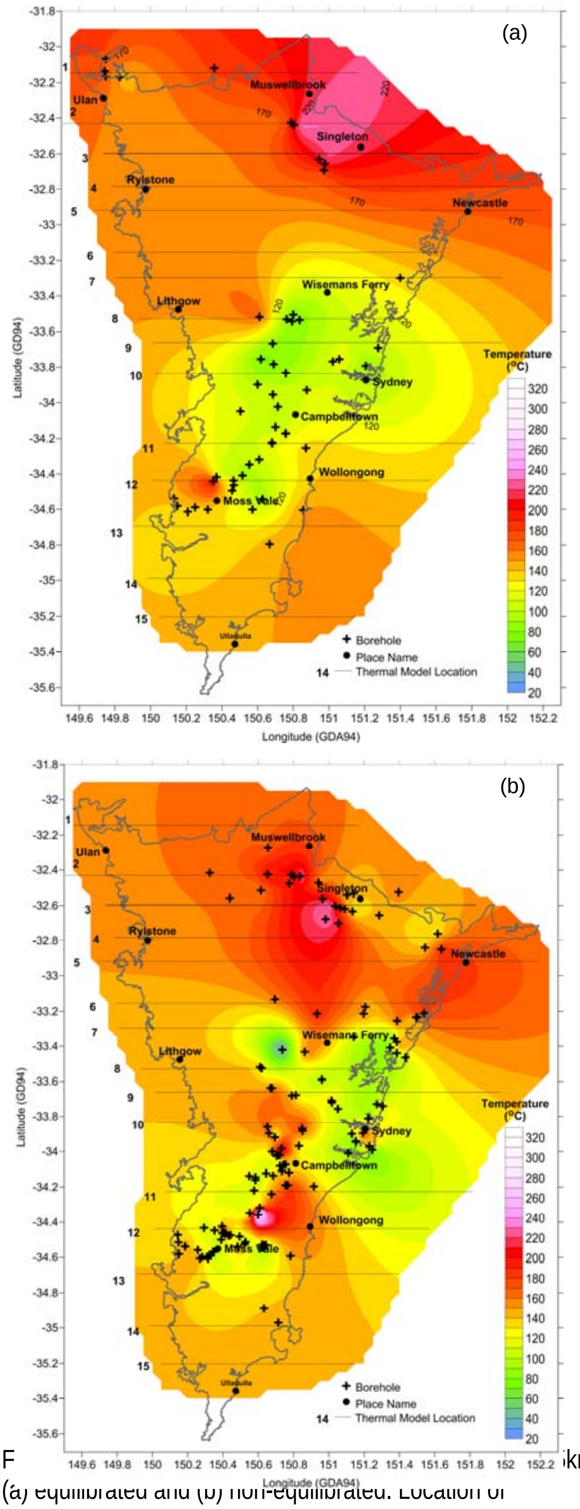
Methods and Results

Down-hole Temperature Measurements: Equilibrated and Non-equilibrated

Routinely temperature measurements in boreholes are not conducted for the purpose of geothermal exploration, instead they often are designed to assess groundwater aquifer locations and cement setting during construction of groundwater bores. In exploration drillholes temperatures are recorded at the bottom of the hole during airlift tests or geophysical surveys (other than temperature). These results are taken immediately following drilling, generally within 24hrs, and are therefore considered non-equilibrated. On rare occasions temperature information is collected several months or even years after drilling, this is considered equilibrated.

To assess the impact of non-equilibrated and equilibrated temperature maps we collected a large amount of temperature results from both non-equilibrated and equilibrated boreholes. Most equilibrated data is collected in the field using methodology outlined in detail in Danis et al. (2010). As Beardsmore & Cull (2001) recommend equilibrated measurements can be recorded after waiting 3 times the drilling time length, our temperature results were divided accordingly. In general any measurements taken one month or greater after drilling were considered as equilibrated results.

Geothermal gradients were determined for each equilibrated and non-equilibrated borehole using the 1D two layer extrapolation method (outlined by Chopra & Holgate, 2006) and temperature at 5km depth below surface contour map produced (Figure 1). All temperatures were corrected for climatic variations based on Cull (1979). Where only a bottom hole temperature measurement was recorded a surface temperature average of 15°C was used to calculate the geothermal gradient. Where possible only temperatures from below 100m ground surface were used, to try and avoid diurnal/seasonal temperature influences.



F[illegible]km (a) equilibrated and (b) non-equilibrated. Location of boreholes used shown as crosses.

The first layer (sediments) is defined from our Sydney Basin geological model and used the calculated geothermal gradient. The second layer (basement) is also defined from our geological model and uses the uniform geothermal gradient of 25°C/km so as to be comparable to the current temperature at 5km map.

Figure 1 shows a distinctive difference between the extrapolated equilibrated and non-equilibrated measurements for temperature observed at 5km. The equilibrated boreholes (Figure 1a) show low temperatures (60-120°C) in the central part of the Sydney Basin, where sediment thickness is greatest, whilst near the edges of the basin (i.e Ulan and Singleton) temperatures are approaching 200 - 250°C. The non-equilibrated bores also show a similar trend, however on a slightly different scale, with several elevated anomalies in the generally colder parts of the central and southern Sydney Basin.

The position of temperature highs (or in some cases lows) will shift depending on whether equilibrated or non-equilibrated temperatures are used. Three highs appear around the Sydney-Campbelltown-Wollongong region in the non-equilibrated data which are not prominent in the equilibrated map. The high near Singleton is also more localised with the non-equilibrated measurements.

The pattern in temperature distribution of lows over the centre and highs on the edge of the Sydney Basin, were an expected feature. They tie in with the fact that the coal measures provide a thermal insulator, thus temperatures measured above coal measures would be expected to be cooler than those measure in or below coal measures. On the edge of the basin heat refracting around the coal measures produces the elevated temperatures.

Previous thermal modelling of the Gunnedah Basin (Danis et al., 2010) showed basin architecture and the refraction of heat around the coal interval to be major controlling factors in the thermal profile. Therefore to better understand the impact of extrapolating shallow thermal measurements to depth we created 15 thermal model profiles along the lines shown in Figure 1.

Thermal Modelling: Underworld

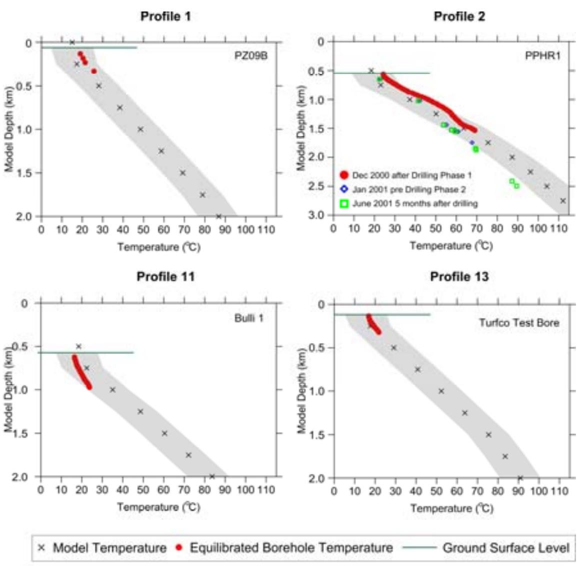
Thermal models were developed using the finite element code *Underworld*. The code solves the non-steady state heat equation with internal heat sources in two dimensions. Distinct layers from our 3D geological model are imported as different materials into the code, with constant temperature top and bottom boundary conditions. The thermal properties for each material layer are outlined in Table 1, and are aggregates of measurements on each unit/rock type. In addition there is one quasimaterial called 'air'. This top air layer has a large conductivity and its purpose is to allow direct thermal coupling of the varying topographic surface with the top boundary condition. The side boundary conditions are reflecting, and an extra 10km has been added to either side of the model profile to avoid any reflecting edge effects.

Table 1

Rock Type	Density (kg/m³)	Conductivity (W/m-K)	Heat Production (µW/m³)
Basement	2700	3	2
Mafics	2950	3	0.5
Sediments	2460	2	1.25
Coal Interval	1900	0.3	1.25

The main free parameter is the bottom temperature condition at 12km, which was extrapolated from the National Temperature at 5km map (e.g Budd, 2007) to be ~350°C. Heat production in the basement is taken from representative Lachlan Fold Belt granites in the OZCHEM database. The model considers thermal conduction only, it doesn't take into account advective effects or the effects of varying surface temperature conditions.

The model boundary conditions were calibrated using limited available equilibrated temperature from shallow boreholes (Figure 2).



equilibrated borehole temperatures for four selected profiles. Ground surface (green line) varies from model depth zero depending on topography. Gray shaded area represents ±10°C of the model geotherm.

The equilibrated borehole temperatures (Figure 2) compare well with the model geotherms and are from boreholes in the Permian sequence. Equilibrated temperatures in profile 1 are from field measurements using Hobo logging equipment, whilst profiles 2, 11 and 13 have been geophysical logged. The precision of the Hobo logging equipment is 0.37°C at 20°C and the general precision of geophysical temperature logging equipment is 0.1°C (from AUSLOG). The uncertainty of the climate correction applied to the equilibrated measurements is approximately ± 5°C at the surface, ±3°C at 500m and ± 1°C at 1km. We therefore allow an uncertainty buffer of ± 10°C in our measured temperatures when comparing them to the modelled geotherms. It is important to note in profile 2 the green measurements are the equilibrated results and are lower than expected due to cleaning of the borehole before logging. The red and blue measurements represent non-equilibrated temperatures.

In order to compare the results of extrapolated temperature measurements with thermal modelling, a series of temperature profiles were taken along a selected thermal model line. Here the equilibrated and non-equilibrated temperature measurements were extracted at 500m and 5km depth and compared to those of the thermal model profile at the same depths, as shown in Figure 3.

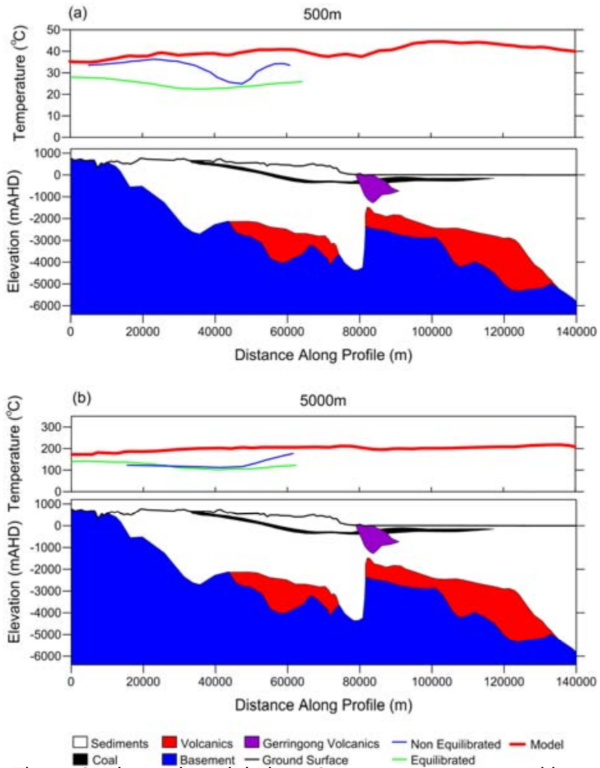


Figure 3: Thermal model Line 12 temperature output with extrapolated temperatures (green = equilibrated, blue = non-equilibrated) at (a) 500m and (b) 5000m below ground surface and showing model geology.

From Figure 3 a distinctive difference in anomaly structure can be seen between the 500m and 5km depths. In both cases the extrapolated equilibrated and non-equilibrated measurements underestimate the modelled temperatures. Even at 500m, above the influence of the coal measures the extrapolated temperatures are still lower than the modelled temperatures.

At 5km the model temperature also shows very little variation as they are predominately in the Lachlan Fold Belt basement. At 500m shallow surface variations in the modelled temperatures are observed and are most likely related to the geology and/or influences of shallow groundwater aquifers.

In both profiles (Figure 3) the effects of the insulating coal interval on extrapolated equilibrated or non-equilibrated versus modelled temperatures can be seen. It appears that the extrapolation of shallow measurements, without any consideration of the geology and/or thermal conductivity, to depth propagates shallow surface features and produces false anomalies.

To further illustrate the difference between the extrapolated and modelled temperatures Figure 4 is a contour map of modelled temperatures at 5km below ground surface for the Sydney Basin.

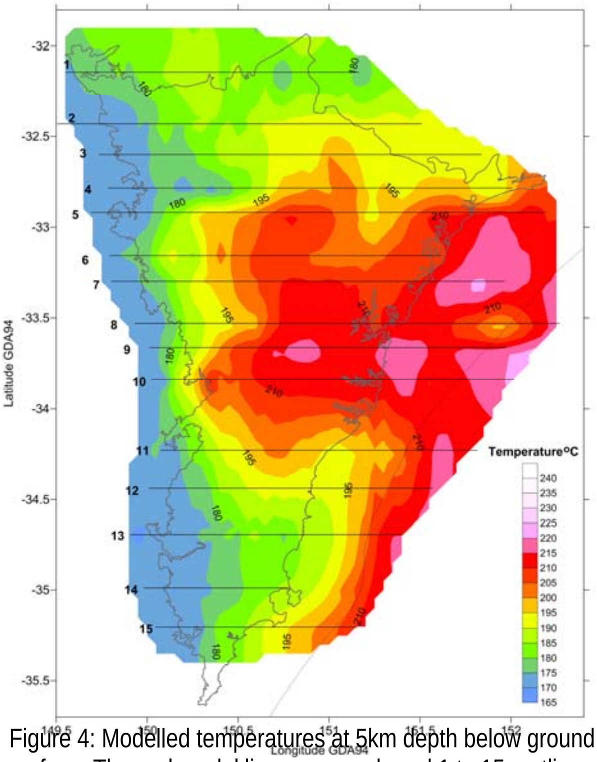


Figure 4: Modelled temperatures at 5km depth below ground surface. Thermal model lines are numbered 1 to 15, outline of the Sydney Basin shown in grey and edge of continental shelf is the offshore black line.

Modelled temperatures (Figure 4) in the Sydney Basin at 5km are hottest where the thickest layers of sediment and coal intervals are. This is most prominent around Sydney and north towards the Hunter/Newcastle Coalfields, where sediment thickness ranges from 3 to 4km, and a thick layer of basal volcanics are also present. The temperature anomaly observed wast of Singleton in the equilibrated extrapolation map appears in a similar location with the modelled temperatures, but is less pronounced. The high on Line 12 north of Mossvale in the equilibrated extrapolation map is not apparent in Figure 4. High basement temperatures offshore of Newcastle in the Newcastle Syncline are a new feature observed with the modelled temperatures. Where basement is shallow, i.e. the southern parts of the Sydney Basin, modelled temperatures at 5km are lower than those further north with greater sediment cover, predominately because the coal interval is generally absent, removing the insulating effect, and sediment thickness is less than 1km.

Modelled temperatures show high (210+°C) temperatures under areas of thick sediment cover, whilst shallow extrapolated temperature measurements often reflect the insulating effect of the coal interval (if above the coal interval) with temperatures ranging from 60°C to 230°C.

Summary

These results show that the temperature variations observed in maps created from extrapolated shallow borehole measurements are likely to be inaccurate. The simple linear extrapolations shown here of both equilibrated and non-equilibrated show shallow temperature measurements propagate near surface features to depth which, when compared to modelled temperatures, are not true anomalies. Therefore given most of the measurements used in the creation of temperature at 5km maps are taken from non-equilibrated boreholes extreme caution should be exercised when considering the temperatures.

However thermal modelling did show that equilibrated measurements are an excellent calibration tool. The modelled geotherms fit well with the shallow equilibrated measurements. A well calibrated thermal model will better account for basin structure and changes in thermal conductivity than extrapolated temperature maps.

Extrapolation doesn't take into account the thermal effects of basin architectural structure and should be avoided as a geothermal exploration tool. Not only is there a risk of the target anomalies being false positives, possible positive targets may be incorrectly located as a result of refracted heat from the basin structure.

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