The 3D Basement and Thermal Structure of the Gunnedah Basin

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With the development of geothermal resources by in the Cooper Basin, South Australia, interest in sedimentary basins for potential resources has intensified. In Eastern Australia sedimentary basins not only host large deposits of coal, they are closer to large population centres with established infrastructure. The 3D architecture and geothermal potential of such sedimentary basins has so far not been assessed in great detail, however the assessment of temperature at 5km and heat flow in these Basin systems by Budd (2007) indicates some potential in the Sydney-Gunnedah-Bowen Basin System. This paper focuses on the Gunnedah Basin and aims to better constrain the 3D structure and thermal evolution of the Basin and presents a 3D depth to basement model, derived from regional gravity modelling, density measurements, borehole and seismic information, and basement temperatures from thermal modelling.

Keywords: Gunnedah Basin, 3D depth to basement, thermal modelling.

Geological Background

The Gunnedah Basin, part of the Sydney-Gunnedah-Bowen Basin (SGBB), began as an extensional rift basin in the Late Carboniferous to Early Permian towards the end of the Hunter-Bowen Super Cycle (Glen, 2005). The extensional tectonic regime initiated half-graben like structures and produced large quantities of rift volcanics (Tadroz, 1993) which overly the basement rocks of the Lachlan Fold Belt. Basin fill, including coal bearing deposits, localised in rapidly subsiding troughs separated by highlands and ridges consisting of silicic and mafic volcanics with the northerly orientated Boggabri Ridge effectively acting as a principle sediment source and dviding the Gunnedah Basin into two sub basins, Maules Creek and Mullaley. At the end of the Hunter-Bowen Super Cycle in the Late Permian, the SGBB developed into a foreland basin followed by a period of convergence, uplift and erosion. Final filling of the Gunnedah Basin (235 to 230Ma) was dominated by detritus shed from the New England Orogen (Glen, 2005). Vitrinite reflectance data suggest the removal of up to 2km of Triassic and Permian sediments between 227Ma and 235Ma. Compressional movement of the Hunter-Mooki Fault resulted in the development of a number of high relief anticline (Glen, 2005). During the Jurassic-Cretaceous the epicontinental Surat Basin developed over the northern and western parts of the Gunnedah Basin.

The geology, stratigraphy and structural history are well documented by Tadroz (1993) and drilling in the basin has reached top of basal rift volcanics in many areas and defines the stratigraphy thickness over an extensive area. This provides good geological controls for gravity modelling of the Gunnedah Basin, with the only main variable the top of the Lachlan Fold Belt.

Methodology

Gravity modelling of the Gunnedah Basin used eight profiles derived from the Gravity Anomaly Grid of the Australian Region 2008 (Fig. 1), available for download from Geoscience Australia. These profiles were modelled using the interactive potential-field modelling package ModelVision Pro v8.0 supplied by Pitney Bowes ®. Model profiles were constructed similarly to Guo *et al*., (2007) for density values, body extent and total model depth. The upper 5km of the models are constrained by over 60 boreholes for key stratigraphic layers such as the base of Jurassic, top of rift volcanics and were available top of the Lachlan Fold Belt. Increasing density with depth is accounted for with a change in density for sediments >300m deep, as determined by the measure borehole densities of Guo *et al*. 2007 and density measurement of 185 core samples drilled from hand samples of representative key geological units using:

$$D = [(A \text{ x } \partial_L)/(A - B)] + C$$

where D is density (g/cm^3), A is dry weight (g), B is wet weight (g), ∂_L is liquid density and C is the air buoyancy constant of 0.0012. All depths to stratigraphy derived from the gravity modelling were converted to metres Australian Height Datum (mAHD) and gridded in Surfer v8.0 supplied by Golden Software ® producing surfaces for the 3D model at a 0.05 degree interval.

Thermal models for the basin were developed using an existing, extensively benchmarked research finite element code *Ellipsis* (Moresi *et al*., 2003). Distinct layers from the gravity models were imported as different materials into the code, which solved the time-dependent energy equation with constant temperature top and bottom boundary conditions. The thermal properties for each material layer is outlined in Table 1, and are aggregates of measurements on each unit/rock type. The main free parameter in these models was the bottom temperature condition at 5km, which was estimated from the National temperature at 5km map (eg. Budd *et al*. 2007) to be ~180°C, and fine tuned to match existing temperature data for the Gunnedah Basin.

Table 1. Thermal Properties

Rock Type	Density (kg/m³)	Conductivity (W/m-K)	Heat Production (W/m³)
Basement	2700	3	2
Mafics	2900	3	0.5
Sediments	2500	2	1.25
Coal Measures	1500	0.3	1.25

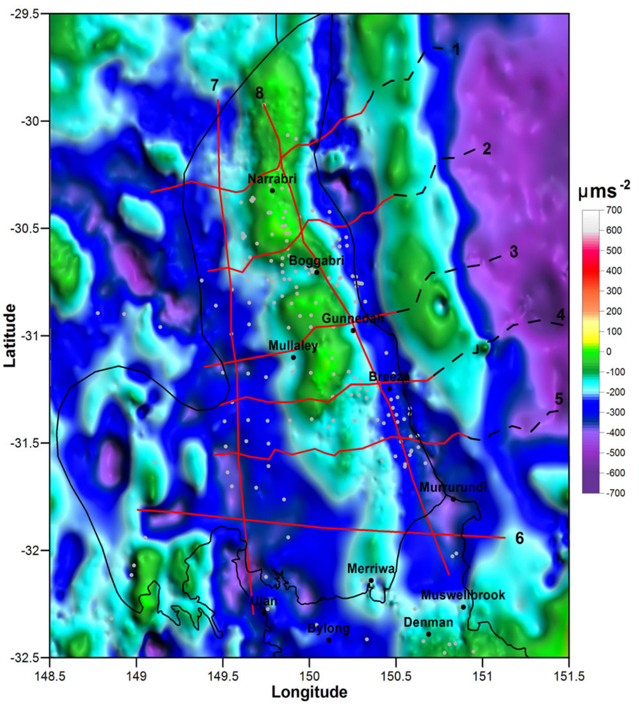

Figure 1: Gravity anomaly map for the Gunnedah Basin (outlined in black) with NE relief using a 0.01 degree grid spacing in Surfer ®. Gravity profile locations shown by red lines, extension of profiles black dashed lines and boreholes grey circles. Grid data available for download from Geoscience Australia.

Gravity Modelling

The geometry of the Gunnedah Basin during modelling was initially based on the work of Guo *et al*. (2007), however borehole and seismic constraints required a review of this. The final model geometry derived for the profiles correlates well with the recently published work of Krassay *et al*. (2009). Presented in Figure 2 are the six east-west profiles. The densities of the key structural units are Jurassic 2.31t/m³, Tertiary Volcanics 2.88t/m³, Gunnedah Sediments <300m depth 2.38t/m³, >300m 2.54t/m³, Granite 2.59t/m³, Lachlan Fold Belt 2.60t/m³ and 2.70t/m³ and basal rift volcanics 2.95t/m³.

From the gravity modelling a 2.5-3km deep channel runs through the central part of the basement of the Gunnedah Basin. The overlying basal rift volcanics fill the basement channel and in some areas reach a thickness of up to 3km thick. The Rocky Glen Ridge forms a clean structural high to control the western extent of the rift volcanics whilst the Hunter-Mooki Fault truncates them at depth in the east. To the north

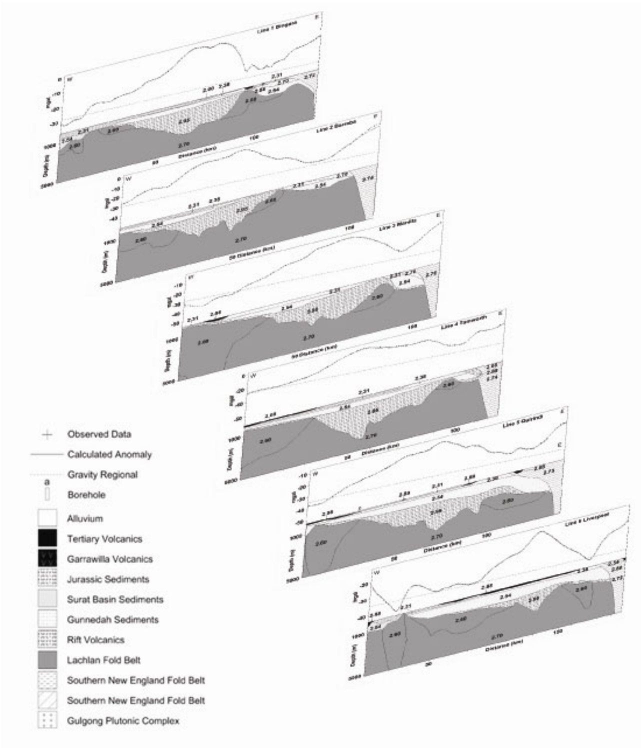

Figure 2: 2.5D E-W Gravity model profiles through the Gunnedah Basin. Model depth shown is 5km, profiles stacked to view NE.

and south the basal volcanics appear continuous into the Bowen and Sydney Basins.

3D Depth to Basement Model

The basement of the Gunnedah Basin is defined here as the metamorphic rocks of the Lachlan Fold Belt, which includes metasediments, granites and volcanics. Using borehole information, and the gravity model profiles a 3D basement structure of the Gunnedah Basin is interpolated in Figure 3. In addition to interpolating the top of the Lachlan Fold belt the Permian Coal Measures interval is also interpolated from borehole information. As the coal measures act as a thermal blanket in basin geometry it is necessary to determine their extent and thickness for the thermal modelling of temperature at depth.

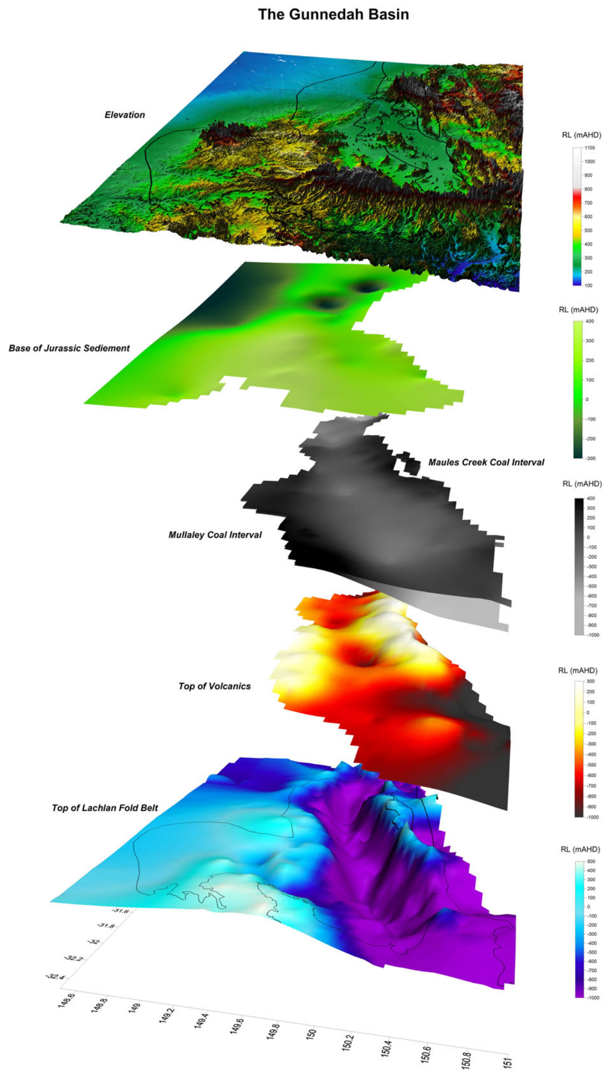

Figure 3: 3D basement structure of the Gunnedah Basin, showing the top of the Lachlan Fold Belt, Top of Volcanics, top and base of Permian coal interval, base of Jurassic and surface elevation from 90m SRTM satellite data.

Thermal Modelling

Thermal models were constructed for six lines (Gravity Lines 1-6), using the thermal properties listed in Table 1, which are derived from published values for each lithology or composite lithology, and the boundary conditions listed in the methodology. The heat production in the basement is taken from representative Lachlan fold belt granites immediately adjacent to the Gunnedah Basin (OZCHEM database). The initial thermal profile is linear between the top and bottom temperatures, and is allowed to evolve in response to the conductivity and heat production structure of the crustal units until equilibrium is reached. We use the finite element code Ellipsis (Moresi et al., 2003) to solve the non-steady state heat equation with internal heat sources in two dimensions.

The model's boundary conditions were refined using limited available temperature data from the Gunnedah Basin. The two data points within the Gunnedah region from the only available continent-scale compilation (Cull, 1982) suggest heat flows in the range 50-80mW/m^2 are appropriate for the Gunnedah Basin - within the range of our models (~70 +/- 10 mW/m^2). Many publicly available down-hole temperature measurements were made in non-equilibrium conditions shortly after drilling, and so are of limited value in constraining the steady-state thermal structure of the crust. Our recent measurements in the southern Gunnedah area suggest temperatures of around 60^{o}C at 1km, or a geothermal gradient of around 0.048 ^{o}C/m.

Figure 4a illustrates the temperature field and material configurations of two of the thermal models, from Lines 2 and 6. Surface heat flux is shown at top of Figure 4a. The critical difference between the two Lines is the thickness of the coal sequences in Line 6. These economic coal measures, whilst interbedded with the sedimentary sequence, have, on bulk, a significantly lower thermal conductivity than the surrounding basins sediments. This results in a blanketing effect and a thermal refraction of heat flow around the insulating coal measures. As a result, despite the highest basement temperatures occurring beneath the thick coal and mafic volcanic units, the highest surface heat flow and near surface temperatures are exhibited around the periphery of the coal. This demonstrates the danger of extrapolating near-surface heat flow measurements to depth without considering 2 and 3-D thermal effects.

We have also stacked and gridded the 2D cross-sections to obtain a 2.5D model of the basement temperatures across the entire Gunnedah basin, shown in Figure 4b. The temperatures at the top of the basement were obtained for each individual profile, this data was then gridded, and draped across our model for the basement architecture. The highest basement temperatures occur in the deeper portions of the basin, particularly under the thickest coal and mafic units. The basement temperatures range from ~105-165^{o}C, with the highest temperatures occurring at the northern and southernmost extents of the basin. Higher temperatures again extend deeper within the crystalline basement.

The model presented here considers thermal conduction only, it does not take into account advective effects, or the effects of varying surface temperature conditions. It does include variable near surface topography, though the effects of this are negligible here given the relief and extent of the Gunnedah Basin. The most critical part of this modelling is establishing a lowermost thermal boundary condition for the model. This boundary condition can, potentially, take the form of a temperature or heat flux constraint. In either case the uncertainty and variability of this parameter are very large. Here we have combined available deep borehole temperature constraints and heat flux measurements, including some of our own measurements, to converge on a lower boundary condition (ie. T-180°C at 5km) which is most consistent with the regional thermal constraints. This value, and perhaps the model, may be refined as improved steady-state deep borehole temperature measurements of this region become available.

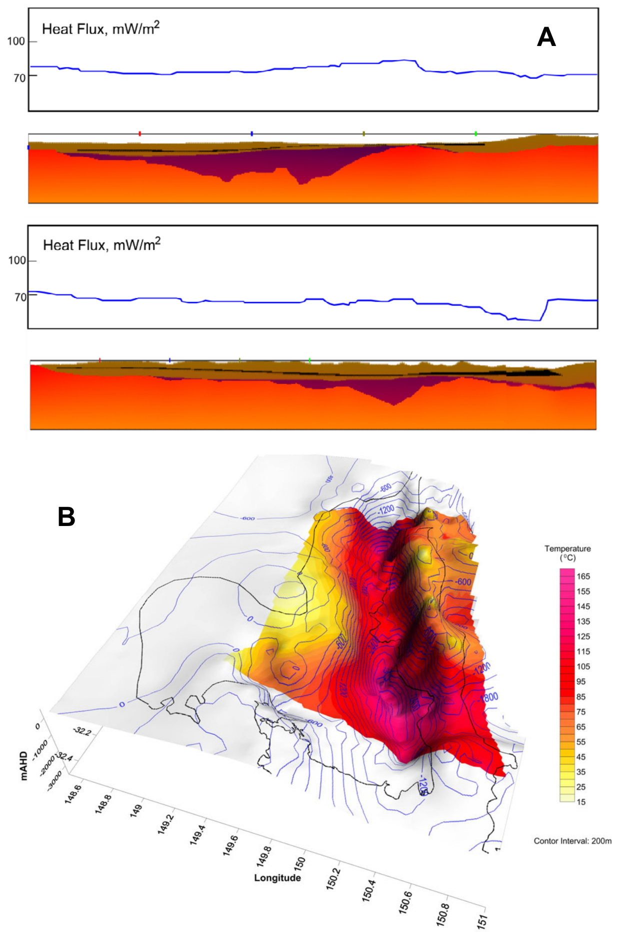

Figure 4: a) 2D cross sections of the modelled temperature field of Lines 2 and 6. Different colours represent different materials, which from top to bottom are basin sediments, interbedded coal measures, mafic volcanics, and Lachlan fold belt basement. Colour gradients represent temperatures. Surface heat flux is also plotted.

b) Temperatures at the top of the Lachlan Fold Belt basement, interpolated from 2D profiles, draped over the basement architecture. Basement contour interval is 200m AHD.

Summary and Discussion

The 3D structure of the Gunnedah Basin is characteristic of a typical rift basin. This provides a deep central channel in the basin where up to 3km of sediments and volcanics have accumulated over basement with temperatures of 105-165°C.

Our modelling demonstrates the importance of 2/3D effects - particularly the distribution of low conductivity sediment cover - in determining basement temperatures. Temperatures may be elevated beneath blanketing sediments, but this may not be evident in shallow borehole temperature measurements. Instead heat may be refracted around such insulators, giving heat flux anomalies at the edge of thick low-conductivity sediment cover. This highlights a potential complication in extrapolating shallower borehole temperatures to depth as per the Austherm07 database. While a good starting point for regional temperatures at depth, it is essential to compare modelled temperature results, using accurate basin geometries, with regional borehole data to ascertain the validity of the model's boundary conditions, and the reproducibility of the subsurface temperature field.

The potential for geothermal resources in the Gunnedah Basin based on this initial work is strongest in the northern and southern most parts of the basin where the coal/sediment blanket provides thermal insulation. In these areas temperatures deeper within crystalline basement are expected to be hotter.

References

Budd, A.R., 2007, Australian radiogenic granite and sedimentary basin geothermal hot rock potential map (preliminary edition), 1:5 000 000 scale. Geoscience Australia, Canberra.

Cull, J.P., 1982, An appraisal of Australian heat flow data. BMR Journal of Australian Geology & Geophysics v.7, p. 11-21.

Glen, R.A., 2005, The Tasmanides of eastern Australia in Vaughan, A.P.M., Leat, P.T., and Pankhurst, R.J., ed., Terrane Processes at the Margins of Gondwana: Geological Society, London, Special Publications 246, p. 23-96.

Guo, B., Lackie, M.A., and Flood, R.H., 2007, Upper crustal structure of the Tamworth Belt, New South Wales: constraints from new gravity data. Australian Journal of Earth Sciences v.54, p.1073-1087.

Krassay, A.A., Korsch, R.J., and Drummond, B.J., 2009, Meandarra Gravity Ridge: symmetry elements of the gravity anomaly and its relationship to the Bowen-Gunnedah-Sydney basin System. Australian Journal of Earth Sciences v.56, p. 355-379.

Moresi, L., Dufour, F., Muhlhaus, H.-B., 2003, A Langrangian integration point finite element method for large deformation modeling of viscoelastic geomaterials. J. Comput. Phys. v.184, p. 476–497.

Tadroz, N.Z., 1993, The Gunnedah Basin, New South Wales: Geological Survey of New South Wales, Memoir Geology 12, 649.