11. Heat Flow and Temperature

Heat flow data across Australia are sparse, with around 200 publicly available data points. The heat flow data are unevenly distributed and mainly come from studies undertaken in the 1960s and 1970s by the Bureau of Mineral Resources (BMR) and the Research School of Earth Sciences at The Australian National University. Thus continent-wide studies of heat flow, such as that by Cull (1982), are strongly dependent on the limited data sampling. Nevertheless, three major zones can be identified (see, e.g. McLaren et al., 2003), which are indicated in Figure 11.1.

The dominantly Archean Western Province (W) has an average heat flow of $39 \pm 8 \text{ mWm}^{-2}$, consistent with global averages for this age. In the dominantly Paleozoic Eastern Province (E), the average heat flow is $72 \pm 27 \text{ mWm}^{-2}$, a bit higher than global averages for Phanerozoic terranes. The Central Province (C) has a surface heat flow average of $82 \pm 25 \text{ mWm}^{-2}$, significantly higher than $49–54 \text{ mWm}^{-2}$, the average expected for similar aged terranes around the globe. McLaren et al. (2003) suggest that the additional contribution comes from crustal radiogenic sources.

11.1 Temperature Distribution

Temperature observations are now available from a large number of sites across the continent (Figure 11.1), principally petroleum exploration and production wells, but few have the associated thermal conductivity studies needed to extract heat flow. The distribution of sampling is highly heterogeneous, with strong concentrations in hydrocarbon provinces, both onshore and offshore.

Figure 11.1: Distribution of well data (purple points) used in constructing the OZTemp distribution (Figures 11.2–11.3) superimposed on the surface geology and geological provinces. The main heat flow provinces (W, C, E) are also indicated.
Estimates of the temperature distribution at 5 km depth have been constructed using a simple two-layer model of thermal conduction with a sediment layer over basement with a fixed thermal gradient of 25°C/km. The difference between the mean annual surface temperature and the temperature at the depth of the base of the well provides an estimate of the near-surface gradient. Extrapolation to 5 km is made with the fixed gradient in the basement.

The heterogeneous distribution of temperature estimates across the well sites at 5 km depth is then interpolated to produce a continent-wide distribution employing a kriging procedure following Chopra and Holgate (2005).

The current OZTemp estimate at 5 km depth (Gerner and Holgate, 2010) is illustrated in Figure 11.2, and in Figure 11.3 with the superimposition of geological provinces. The lowest estimated temperatures are associated with regions where basement outcrops, as in the Yilgarn Craton, the Mt Isa Province, the Gawler Craton and parts of the Lachlan Orogen. Although this not unreasonable, these temperatures depend quite strongly on the assumed fixed temperature gradient. Limited deep sampling in such basement areas precludes use of more specific estimates for temperature gradients.

Figure 11.2: OZtemp estimate of the temperature distribution at 5 km depth across the Australian continent.

Figure 11.3: OZtemp temperature distribution at 5 km depth with superimposed geological provinces.
Regions of high temperature are commonly associated with relatively thick sedimentary cover (cf. Figure 2.9) as, e.g. the Canning Basin in Western Australia and the Cooper–Eromanga Basin extending from South Australia into Queensland.

Interpolation artefacts associated with the limitations of data coverage are clearly present in Figures 11.2 and 11.3. A clear example is streaking from observations in the Perth Basin into the Yilgarn Craton. Such features can be quelled if ancillary assumptions are made, such as a direct correlation of the temperature distribution with tectonic units (Chopra and Holgate, 2005). Another region where limited sampling produces complex structure is the North Australian Craton, where a widespread high-temperature anomaly is apparent. Here points with similar temperature are linked without control on whether there is continuity of structure in between.

The large area of high temperature in the Eromanga Basin is generally well constrained with many wells, but the southern extension past Lake Eyre and Lake Torrens depends on far fewer observations. Although the OZTemp results indicate major geothermal potential for energy production, much of the potential resource lies rather far from major population centres.

### 11.2 Use of Geological and Geophysical Information

The rather uneven distribution of temperature observations is unlikely to be significantly modified in the near future. This means that cratonic areas, in particular, will be poorly sampled with little direct control on the temperature distribution. On the other hand, there is substantial geological and geophysical information that can be used to build estimates of the likely temperature distribution in regions without direct observations. This is the approach taken by Haynes et al. (2015), using 3-D modelling with a thermal conduction model (TherMAP) to examine the likely temperature field and its uncertainties.

Thermal conductivity estimates have been made for the major sedimentary basins based on knowledge of the stratigraphy and sediment thickness. Values range from 1.63–3.18 W/mK; a variation of ±0.15 mW/K is allowed. A default value of 3.0 W/mK is used where current information is insufficient with an allowed variation of 0.3 W/mK. For granites the thermal conductivity is taken as 2.79±0.38 W/mK, and for metasedimentary basement 3.54±0.89 W/mK. An allowance is made for the temperature dependence of the thermal conductivity.

The distribution of granite bodies has been identified from the Bouguer gravity distribution (Figure 5.7) with 3-D footprint models. Province-specific heat production rates have then been derived from the OZCHEM geochemical dataset (Champion et al., 2007). A 10 km thickness of basement with elevated heat production rate was included, based on the results for the Central Province of McLaren et al. (2003); the heat production was set at 4±1 mW/m². For sediments, the default heat production rate was set as 3 mW/m².

A fixed base temperature in the range 700±100°C was applied at the Moho. A distribution of Moho depths was allowed, drawing on the probabilistic model of Bodin et al. (2012), based on the earlier analysis of Kennett et al. (2011).
The 3-D model spans the range from 4 km above sea level to 59.8 km below, using voxels with 10 km x 10 km horizontal dimension and 200 m in depth, i.e. approximately 51 million voxels. A constant temperature condition was applied at the top surface and the properties of the atmospheric cells were adjusted to give a good rendering of the mean annual surface temperature distribution at the appropriate elevation.

An ensemble of models were created, with 401 realisations using variations of the input variables within the allowed ranges and a full 3-D solution of the heat equation. The mean of the ensemble values at 4 km depth is displayed in Figures 11.4–11.5, and the standard deviation across the ensemble in Figure 11.6.

The TherMAP results show a large thermal anomaly in Western Australia, with elevated temperature extending from the Pilbara into the Canning Basin. The area of the Pinjarra Orogen shows rather high temperatures. The northwestern Yigarn Craton is also characterised by higher temperatures than the remainder of the craton. Low temperatures are predicted at 4 km in the Mt Isa Province, and the Arunta and Musgrave provinces in central Australia. A band of lower temperatures extends along the Eastern Highlands from the New England Orogen into the Lachlan Orogen, with the coolest conditions in the south.

The variations across the ensemble of models tend to be larger for the hotter zones, though not in the Pilbara Craton. Relatively large variability is seen for the Amadeus and Officer basins where inferred temperatures at 4 km are moderate.
Localised strong variability is found in the Curnamona Province around localised hot spots.

The general pattern of temperature in the TherMAP study links quite well with the OZTemp results in Figures 11.2–11.3, even though these values were not used in the analysis. Nevertheless, there are significant differences in the cratonic areas. Detailed comparison with the OZTemp well database suggests that there is a tendency to underestimate the temperatures in the centre and west of the continent, particularly in the offshore zone. Errors are typically around 50°C in the sedimentary basins, but can reach 100°C on the North West Shelf.

Limitations of the current TherMAP modelling include the assumption of a fixed temperature at the Moho. The results for the base of magnetisation (Figure 4.14) require this depth to penetrate the Moho (Figure 7.17), as discussed further in Section 12.3. Thus if the cessation of magnetisation is controlled by Curie temperature, there must be substantial variability in temperature at Moho depth. Further, the variability in the character of the Moho (Kennett and Saygin, 2015), with many gradient zones at the base of the crust, suggests that a single temperature is an oversimplification. At the elevated temperatures at the base of the crust it is also likely that radiative effects may make a contribution to the apparent thermal conductivity.

Nevertheless, the TherMAP approach provides a useful integration of continental-scale datasets to provide an alternative perspective on the distribution of temperature and heat flow. In particular, the model has predictive power in regions that are otherwise undersampled.