The Curie depth of Australia, and its uncertainty

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SUMMARY

The Curie depth is the depth at which the crust or upper mantle ceases being magnetic due to temperature effects. Although there are several methods available to map this depth, magnetic methods are most often used. These methods, however, introduce uncertainty into the depth estimates and this uncertainty has not been adequately addressed in previous studies.

In this study, we have used magnetic data, at multiple scales, in combination with Monte Carlo techniques to evaluate both the Curie depth and its uncertainty for the Australian continent. Variations in the Curie depth for Australia are related to differences in mineralogy and thermal regimes across differing provinces of Australia, and may also be used to further our knowledge of crustal geothermal gradients. Increasing our knowledge in these areas will advance our understanding of uranium, geothermal and hydrocarbon systems in Australia.

Key words: Curie depth, magnetics, inversion

INTRODUCTION

The Curie depth is the depth at which the crust and/or uppermost mantle cease being magnetic due to temperatures in a region exceed the Curie or Néel temperatures of the minerals of a region. The Curie (for ferromagnetic minerals) or Néel (for ferrimagnetic or antiferromagnetic minerals) temperatures are different for individual minerals (Figure 1). Within this abstract, we will use the term Curie temperature, and its corresponding depth equivalent, even for ferrimagnetic or antiferromagnetic minerals.

The key magnetic minerals within the lower crust are inferred to be magnetite or titanomagnetite (Hunt et al, 1995). Substitution of titanium for iron results in a lower Curie temperature, as well as a lower magnetic susceptibility. Generally for the deepest magnetic sources, which would require the greatest magnetic susceptibility to be imaged, magnetite is the key mineral and thus the Curie depth is inferred to relate to a temperature between ~580-590ºC (Telford et al., 1990). There is the possibility that changes in mineralogy could result in a lower Curie temperature for a region; this would result in a shallower Curie depth. Nevertheless, the Curie depth is most often interpreted as only reflecting the thermal structure of the lower crust and upper mantle.

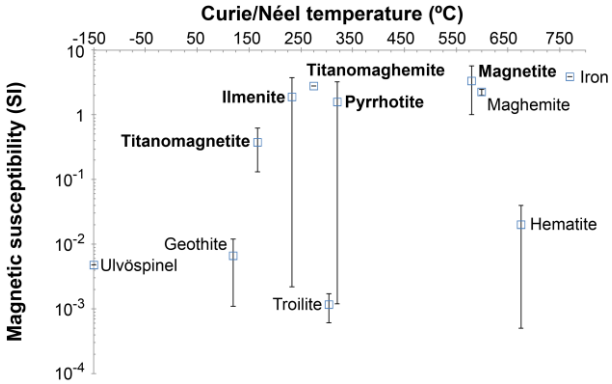

Figure 1: Magnetic susceptibility versus Curie or Néel temperatures for key magnetic minerals (Hunt et al., 1995). Within the lower crust, magnetite and titanomagnetite are the two key magnetic minerals.

Many methods have been developed to map the Curie depth of regions of the Earth, from a local to a global scale. These studies have general used these approaches:

1. Inferring temperature, and hence potentially Curie depth, from seismic tomography models (e.g. Artemieva, 2006);
2. Modelling temperature from heat flow and other thermal data (e.g. Tselentis, 1991); and
3. Magnetic modelling to derive the base of magnetisation within the crust or uppermost mantle (e.g. Spector and Grant, 1970; Okubo, et al., 1985; Maus et al., 1997; Bouligand et al., 2009; Fox Maule et al., 2009).

Of these approaches, magnetic modelling has been the primary method used to calculate the Curie depth. In general, the modelling takes the form of either a frequency-domain (spectral, often with a fractal model of source magnetisation e.g. Bouligand et al., 2009) analysis of magnetic data or utilising an optimisation for a spatial domain of magnetisation (such as the equivalent source method of Fox Maule et al., 2009). No matter the approach taken, there is a high degree of uncertainty in these approaches as the base of a magnetised body is the most difficult parameter to derive (Telford et al., 1990).

We illustrate some of the uncertainty in Curie Depth estimates using the fractal approach of Bouligand et al. (2009) for a region of North Queensland, Australia (locality map: Figure 2). This fractal technique can be applied at a variety of scales; for simplicity, only a single scale of analysis is shown here but the technique is applicable at larger scales and for larger regions of the continent.

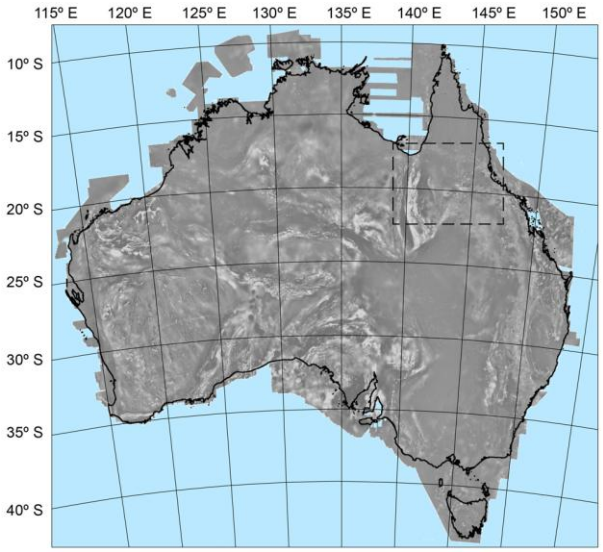

Figure 2: Location of the study area discussed in this abstract. Study area was chosen to allow for brief discussion of our technique to derive the Curie depth from magnetic intensity data. Base data is the magnetic anomaly map for Australia (Milligan et al., 2010), variably reduced to the pole as used for this study. Data are projected to an Albers equal area projection, standard parallels 18º and 36º S, central meridian 134º E.

METHOD AND RESULTS

The method of Bouligand et al. (2009) utilises a fractal distribution of magnetic sources. The analysis begins by taking the Fourier transform of the magnetic intensity data and then taking the 2D power spectrum of these frequency-domain data. Then, the radial average of the logarithm of the 2D power spectrum is taken, which is the observable for the inversion for a given region. Assuming a fractal distribution of magnetic sources, with self-similarity parameter β, depth to the top of the sources z_t and depth to the base of magnetic sources Δz, an analytical expression for the 1D power spectrum is given by equation 4 of Bouligand et al., (2009):

$$\textit{Radial average ln(1D power spectra)} = C - 2k_H z_t - (\beta - 1)\ln(k_H) + \left[-k_H \Delta z + \ln\left(\frac{\sqrt{\pi}}{\Gamma(1+\frac{\beta}{2})}\left(\frac{\cosh(k_H \Delta z)}{2}\Gamma\left(\frac{1+\beta}{2}\right) - K_{\frac{1+\beta}{2}}(k_H \Delta z)\left(\frac{k_H \Delta z}{2}\right)^{\frac{1+\beta}{2}}\right)\right)\right] \quad (1)$$

where Γ is the gamma function and K_α is the modified Bessel function of the second kind.

We have used this analytical expression to calculate theoretical power spectra, and compare them to observed spectra. These spectra have been computed from moving 150 x 150 km windows of the magnetic data from the Australian magnetic anomaly map, 5th edition (Milligan et al., 2010) that has been reduced to the pole using a variable RTP method. The data were also projected to an Albers equal area projection to preserve area but provide distances in kilometres for the calculation of the Curie depth. Solutions that fit within a standard deviation of the observed 1D power spectra, derived through the averaging process, are allowed through a parallel direct search inversion, implemented in Python on the *vayu* supercomputer at the National Computational Infrastructure National Facility. This approach allows for the definition of the uncertainty in the estimates of Curie depth and other associated parameters. As each tile is processed independently, the limiting factor in processing speed is simply the number of available processors.

The modal results for the Curie depth for North Queensland highlight two major features: a relatively deep Curie depth beneath Mt Isa and a relatively shallow Curie depth in the central southern portion of the study area, located beneath the Eromanga basin (Figure 3).

These results also compare favourably with estimates of temperature at 5 km depth from heat flow and temperature measurements (Gerner and Holgate, 2011); the shallowest Curie depths observed, in the central southern portion of the study area, correspond to a wide zone of elevated temperatures at 5 km depth (Figure 4). Nevertheless, there are some differences between the estimated temperature at 5 km and the Curie depth image that must be tested against other independent data.

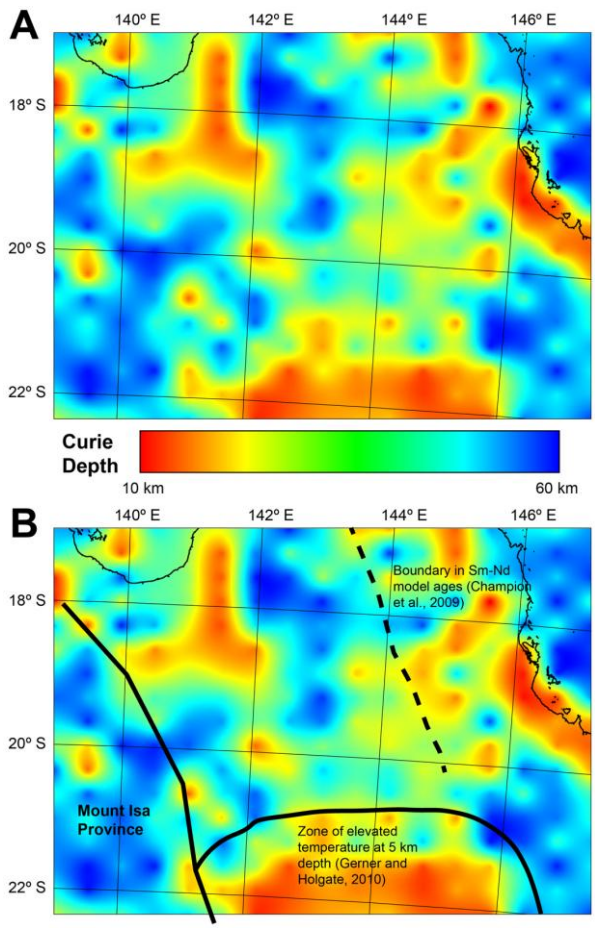

Figure 3: A) Results for the study of the Curie depth of North Queensland. Deeper Curie depths are highlighted in blues (indicating lower geothermal gradients), shallower in red (indicating higher geothermal gradients). Major colour breaks, such as red to yellow, are indicative of uncertainty in depth estimates. B) Highlighted features: the eastern boundary of the Mount Isa Province is apparent in these data, as is a northwest-southest trending boundary noted in the Sm-Nd model age data (Champion et al., 2009). The elevated temperate beneath the thickening Eromanga Basin

in the central southern portion of the image is noted as a relatively shallow Curie depth of 10 – 15 km.

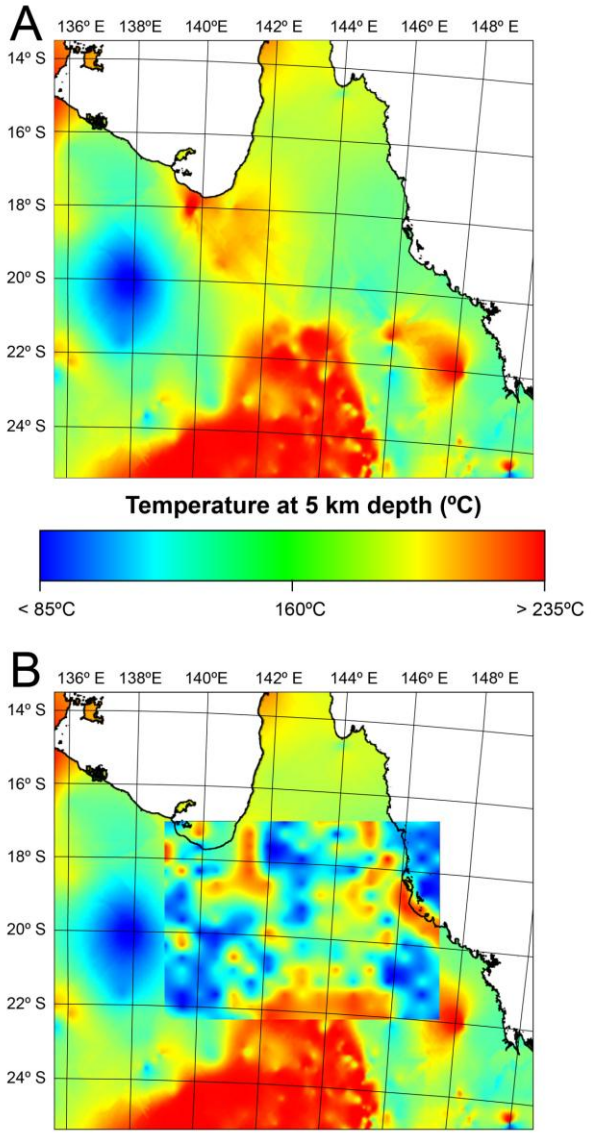

Figure 4: Comparison between the temperature predicted at 5 km depth (OzTemp: Gerner and Holgate, 2010) and the Curie depth estimates produced in this study. A) is a portion of the OzTemp thermal estimate image, predominantly derived from temperature data from deep drillholes and B) is our Curie depth estimate for North Queensland overlying OzTemp.

CONCLUSIONS

The results for North Queensland indicate the application of nonlinear inverse techniques to the estimation of Curie depth from magnetic data can provide robust results while defining the uncertainties. These Curie depth estimates compare favourably both with known independent geological evidence for the thermal state of the Australian crust in the North Queensland region and previous studies of Curie depth, and also with previous studies of the Curie depth in the region. Through the use of high-performance computing, the methodology can be applied up to the national scale to define the Curie depth for the entire Australian continent.

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