Supporting online material

Heat flux anomalies in Antarctica revealed from satellite magnetic data

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The supporting online material includes supporting text on the formulation of the model approach, validation of our method, and error discussion.

Formulation of the model approach

An outline of the approach of deriving the magnetic crustal thickness from magnetic satellite data is given in the flow diagram of Fig. S1 and explained briefly in the figure caption; a more detailed description can be found in (*1*).

To determine the heat flux from the magnetic crustal thickness we start with the 1D heat conduction equation, which under the given assumptions (steady state, no lateral variations of material properties and heat production) is

$$\frac{\partial^2 T(z)}{\partial z^2} = -\frac{H(z)}{k} = -\frac{H_0}{k}\exp\left(-\frac{z}{\delta}\right) \qquad (1)$$

where T is temperature, z is depth below surface, k is thermal conductivity of the crustal rocks, $H(z)$ is the heat production, taken to decrease exponentially with depth with scale depth δ, and H_0 the heat production at the surface. The boundary conditions to the problem are that the temperature is T_{sur} at bedrock surface (z = 0) and equal to the Curie temperature, T_c, at the Curie depth, z_c. The solution for the crustal temperature-depth profile is

$$T(z) = T_{sur} + \frac{H_0\delta^2}{k}\left(1 - \exp\left(-\frac{z}{\delta}\right)\right) + \frac{z}{z_c}\left(T_c - T_{sur} - \frac{H_0\delta^2}{k}\left(1 - \exp\left(-\frac{z_c}{\delta}\right)\right)\right) \tag{2}$$

Heat flux is related to the temperature profile through

$$q(z) = -k\frac{\partial T}{\partial z} \tag{3}$$

Thus, the surface heat flux (underneath the ice sheet) is

$$q(z=0) = -\frac{k(T_c - T_{sur})}{z_c} - H_0\delta + \frac{H_0\delta^2}{z_c}\left(1 - \exp\left(-\frac{z_c}{\delta}\right)\right) \tag{4}$$

From this equation we calculate the geothermal heat flux underneath the ice sheet ($z = 0$) using the derived magnetic crustal thickness, z_c, and the numerical values for the thermal parameters as given in the paper (k = 2.8 mW/m^2, T_c-T_{sur} = 580 K, H_0 = 2.5·10^{-6} W/m^3, δ = 8 km).

Validation of our method

Validation of the hypothesis that magnetic anomalies are a robust proxy for geothermal heat flux requires comparison of our results with direct measurements of surface heat flux.

We have done this for Australia, where a large amount of high quality direct measurements are available, and Australia has the further advantage of having been part of the same supercontinent as East Antarctica. Fig. S2B shows the three major Australian heat flow provinces, as defined by (*2*) on the basis of linear relationships between heat flow and surface heat production. The highest heat flow values are found in the youngest, Eastern province, intermediate heat flow values are found in the central province, and the lowest heat flow values are found in the old Western shield. Seismic velocities also vary with temperature, and provide a whole crust view of temperature. Fig. S2A shows travel time residuals (*3*) for Australia, with early arrivals (shown as blue -) in the relatively cold Precambrian crust and later arrivals (shown as red +) along the warmer southeast coast, consistent with the heat flow domains. Finally, Fig. S2C shows the derived magnetic crustal thickness and (unscaled) heat flux in Australia determined with the same technique, and satellite data, as used in this manuscript. All three tell a similar story, and the close correspondence of the travel time residual and magnetically determined heat flux is especially striking, as both sample the entire Australian crust.

Error discussion

The two primary sources of uncertainty in the heat flux estimate are

1) uncertainties in the magnetic field model, including contamination by the external (ionospheric and magnetospheric) contributions, and
2) hard remanent magnetization in the Antarctic continental crust.

Secondary sources of uncertainty include

a) the starting seismic and thermal model,

b) lateral variations in magnetic susceptibility,

c) uncertainties associated with the temperature boundary conditions, and

d) lateral variations in the thermal conductivity.

The uncertainty in the magnetic field model (topic 1 of the above list) is the dominating error source. The largest signals in the data, that high degree magnetic field models are unable to model, are external fields in the polar regions. This uncertainty can be quantified by comparing magnetic crustal field models produced using different approaches to external field parameterization. MF-3 (*4*), the model used in this study, removes large-scale external fields on a pass-by-pass basis. CM4 (*5*), the only other high-degree magnetic field model, co-estimates the internal and external fields, and corresponding induced fields. The difference of the heat flux predicted by these two models is typically ± 20 mW/m^2 in tectonic areas, and ±10 mW/m^2 in cratonic areas. Summarizing, we find that these differences comprise the major source of error in our heat flux estimate.

The uncertainty due to unconsidered remanent magnetization may be important in some regions of the Antarctic, but our seismic starting model predicts the location and approximate magnitude of 8 of the 10 major regional magnetic anomalies associated with crustal thickness changes, and it predicts all of the major features in the vicinity of the thermal anomalies. This means that induced magnetization can explain at least 80% of the anomalies. Thus the error from remnant magnetization is at most 13 mW/m^2. Furthermore our method does not give unrealistic (either too high, or negative) magnetic crustal thickness values, hence a removal of remanent magnetization is not required to explain our results, thus we conclude that the Antarctic does not have any 'super' anomalies that require hard remanent magnetization to be explained.

It is not possible to quantify the uncertainty of the starting crustal model until we have multiple models of the Antarctic crust. 3SMAC (*6*) is currently the only self-consistent thermal and material property model that exists. However, as the starting model predicts 8 of the 10 major regional anomalies associated with crustal thickness changes as previously discussed, we consider this a minor error, and estimate that the error from this source is less than 5 mW/m^2.

It is not possible to quantify the error from lateral variations of the magnetic susceptibility. However, the crustal field is in general stronger over the continents than over the ocean, and the crustal thickness difference is larger than the susceptibility difference. Thus the susceptibility variation is considered to be minor as compared to other uncertainty factors. We expect this error to be less than 5 mW/m^2.

The temperature at bedrock surface varies from about 0°C to about -30°C in certain locations underneath the ice (*7*). This variation introduces an error in our results as we assume 0°C everywhere, the 30 K difference corresponds to an error of about 5% (since Curie temperature is about 580°C). The lowest basal temperatures are found beneath the Transantarctic Mountains, in areas where our model predicts the highest heat flux. A basal temperature lower than the assumed would increase the resulting heat flux in these areas. There are comparable uncertainties associated with the lower temperature boundary as the Curie temperature varies (550-580°C) (*8* and references therein), depending on the Ti-content of the magnetites. Summarizing, we find the uncertainty due to the two assumed boundary temperatures, which are independent, to be 7% or 5 mW/m^2.

Thermal conductivity depends largely on the quartz content, porosity, and fluid content of the rocks. At depth, for temperatures above 300°C and pressures above 20 MPa (typically below 10 km depth), thermal conductivity, and its variability, decrease significantly. Significant lateral changes in thermal conductivity might be expected if there are significant lateral changes in the quartz content of the entire crust. However, quartz is preferentially found in sedimentary sections in the uppermost crust, and secondarily, as quartzite in metamorphic rocks. Lower and mid-crustal rocks are typically mafic in composition, with relatively minor amounts of free quartz. If we use an amphibolite from the KTB drill hole (*9*) as representative of rocks of this type, 84 measurements of thermal conductivity showed a standard deviation of 15%. Using this standard deviation as representative of the lateral variation of thermal conductivity suggests that variations at the 15% level (10 mW/m^2) in the heat flux might be expected as a consequence.

The combined error on the geothermal heat flux estimate from these independent, uncorrelated error sources is 21 mW/m^2 in cratonic areas and 27 mW/m^2 in tectonic areas.

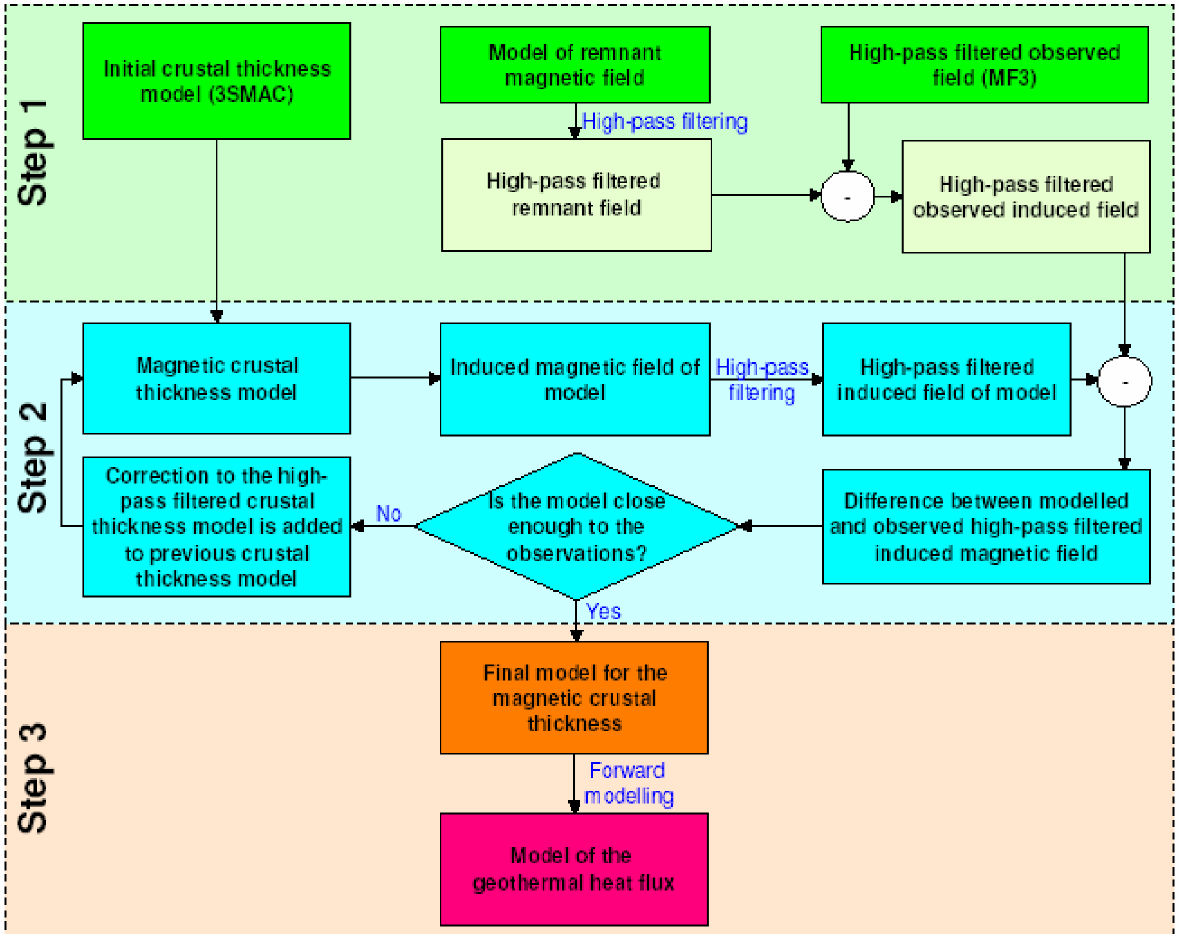

Fig. S1. The magnetic data consist of the high-pass filtered observed field as given by the geomagnetic field model MF-3 (*4*). To obtain the induced part of the field we subtract a model of the remanent field (also high-pass filtered). The high-pass filtered observed induced field is our data. We take an iterative forward modelling approach to estimate the magnetic crustal thickness. We start with an initial model for the magnetic crustal thickness, the 3SMAC model (*6*). From this we calculate the induced magnetic field that this crust would produce. The induced field of the model is then high-pass filtered in order to compare it with the observed induced field. The difference between the modelled and the observed high-pass filtered induced field is taken and tested as to whether the difference between the model and the data is less than the uncertainty of the data. If not, a correction to the crustal thickness model is made by conjugate gradient inversion of the residual. The correction is only on short wavelengths due to the high-pass filtering. The correction is then added to the previous magnetic crustal thickness model, and the iteration repeated until the difference between the model and the observations are sufficiently small. Finally, the magnetic crustal thickness is obtained, and heat flux is determined.

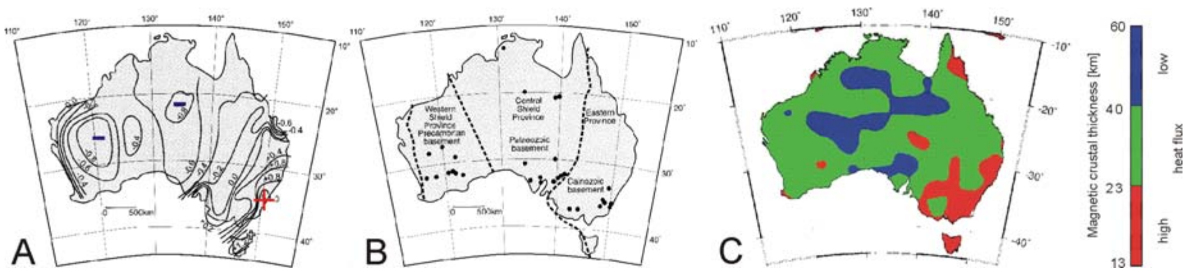

Fig. S2. (A) Teleseismic travel time residuals over Australia. (B) Heat flow provinces and locations of measurements. Circles indicate the measurement locations. (C) Magnetic crustal thickness and derived heat flux. Modified after (*10*).

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