Utilizing thermal isostasy to estimate sub-lithospheric heat flow and anomalous crustal radioactivity

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D. Hasterok*, M. Gard

Department of Earth Sciences and South Australian Centre for Geothermal Research (SACGER), University of Adelaide, North Terrace, SA, 5005, Australia

A B S T R A C T

While surface heat flow relates to the heat loss through the lithosphere, it can be difficult to quantify and separate the heat produced internally through radiogenic decay from the heat transferred across the base of the lithosphere by mantle convection. In this study, we apply a thermo-isostatic analysis to Australia and estimate the sub-lithospheric and radiogenic heat flow components by employing a simple 1-D conservation of energy model. We estimate an anomalous radiogenic heat production across much of eastern Australia generally accounting for >50 mW m^{-2}, while western Australia appears to have high crustal compositionally corrected elevation, possibly related to chemical buoyancy of the mantle lithosphere. A moderately high sub-lithospheric heat flow ($\sim$40 mW m^{-2}) along the eastern and southeastern coast, including Tasmania, is coincident with locations of Cenozoic volcanism and supports an edge-driven convection hypothesis. However, the pattern of sub-lithospheric heat flow along the margin does not support the existence of hotspot tracks. Thermo-isostatic models such as these improve our ability to identify and quantify crustal from mantle sources of heat loss and add valuable constraints on tectonic and geodynamic models of the continental lithosphere's physical state and evolution.

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1. Introduction

High surface heat flow within many shields and cratons appears to be dominated by high heat production due to radiogenic decay of heat producing elements (HPEs) (Wopmay orogen, Lewis et al. (2003); Precambrian Australia, Anderson et al. (2013), McLaren et al. (1999, 2005); and Namaqualand, Jones (1987), Andreoli et al. (2006)). Even in low surface heat flow Precambrian environments, the variations are often attributed to variations in heat production (Mareschal and Jaupart, 2004). It is not simply the surface magnitude of the heat production, but also the vertical distribution that determines whether or not the lithosphere is internally warm or resistant to deformation (Sandiford and McLaren, 2006). Predicting the depth distribution of radiogenic heat production has profound consequences for the accurate estimation of lithospheric temperature (Chapman, 1986), its effect on metamorphic and igneous processes (e.g., McLaren et al., 1999; Kramers et al., 2001; Howard et al., 2015), and provides improved constraints for geodynamic and hydrocarbon maturation models.

The most effective HPEs, U and Th, are generally found in trace amounts that, aside from temperature, negligibly influence geo-

physical fields. Our limited ability to predict variations in lithospheric heat production remotely using surface-based geophysical techniques leads to the use of very general heat production models derived from some combination of global geochemical budgets (Rudnick and Gao, 2003, and references therein), exposed crustal cross-sections, seismic models of crustal composition, and/or estimates of P–T-conditions of mantle xenoliths (Rudnick and Nyblade, 1999; Hasterok and Chapman, 2011). However, lateral variations in crustal architecture from one region to another lead to potentially large departures from these general crustal heat production models.

Hasterok and Chapman (2011) suggested a thermo-isostatic analysis shows promise in identifying continental regions with anomalous heat production since elevation responds to the integrated temperature of the lithosphere (Hasterok and Chapman, 2007a). Lithospheric temperatures are affected by vertical heat production distributions, making it possible—and the driving goal of this study—to roughly estimate the integrated vertical distribution of heat production using a thermo-isostatic analysis.

In this paper, we use a 1-D, steady-state thermal model applied to thermo-isostatic analysis to estimate heat production within the Australian lithosphere. We explore the validity of this model for cases where the temperature field is not 1-D or steady-state and its limitations when external contributions to elevation occur, such as compositionally buoyant mantle. A comparative analysis

* Corresponding author.
E-mail addresses: dhasterok@gmail.com (D. Hasterok),
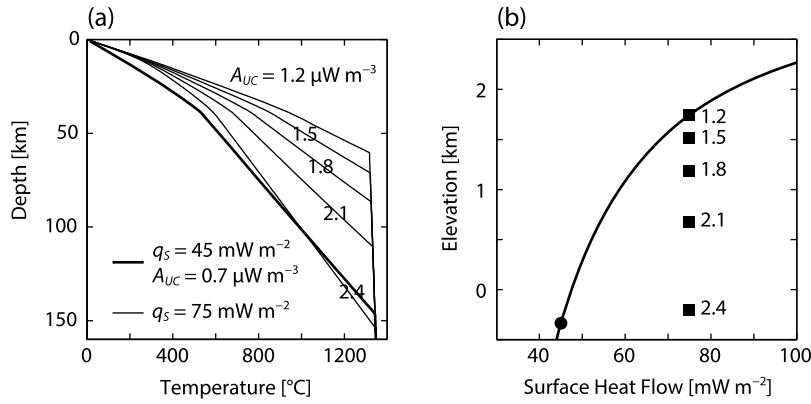matthew.gard@adelaide.edu.au (M. Gard).

Fig. 1. The influence of upper crustal heat production on (a) geotherms and (b) thermo-isostatic anomalies. Five geotherms are shown in (a). Two geotherms have properties consistent with the reference geotherm family (Hasterok and Chapman, 2011): one with surface heat flow of 45 mW m^{-2} (heavy line) and crustal heat production of 0.7 µW m^{-3}; and the second with 75 mW m^{-2} and 1.2 µW m^{-3}. The remaining geotherms (thin lines), all with a surface heat flow of 75 mW m^{-2}, vary only in upper crustal heat production as labeled. (b) Elevations associated with the geotherms in (a) are determined by Equation (1). A region with heat flow and heat production consistent with the reference geotherm family lies on the reference thermo-isostatic curve (solid line) whereas regions inconsistent with the reference are interpreted as anomalous.

is made between thermo-isostatic models of North American and Australian geologic provinces and the relative contributions of internal heat production and sub-lithospheric heat flow to their respective heat loss.

2. Methods

2.1. Thermal isostasy and reference geotherms

Thermal isostasy is the process whereby equilibrium elevation is established as a consequence of differences in lithospheric buoyancy resulting from lateral variations in temperature and the associated thermal expansion/contraction, i.e.,

$$\Delta \varepsilon_T = \int_0^{z_{\max}} [\alpha(z, T_{\text{obs}}) T_{\text{obs}}(z) - \alpha(z, T_{\text{ref}}) T_{\text{ref}}(z)] dz \tag{1}$$

where T_{ref} and T_{obs} are the geotherms for the reference and observed geotherms integrated from the surface, $z = 0$, to the point at which both geotherms reach the mantle adiabat, $z_{\max}$. Expansivity, α, is treated as P–T-dependent (Hasterok and Chapman, 2007a).

To compute geotherms, we use 1-D, steady-state conductive model by Hasterok and Chapman (2011). This model includes a five-layer lithosphere (three crustal + mantle with spinel–garnet transition) to estimate P–T-dependent physical properties. The heat production model is three-layered with a lower crustal heat production of 0.4 µW m^{-3} and mantle heat production of 0.02 µW m^{-3}. The upper/lower crustal boundary is fixed at 16 km throughout this study whereas upper crustal heat production is considered variable. The implications of this choice are discussed in Section 3.1.

To identify regions of anomalous buoyancy, we establish a reference thermo-isostatic model defined from a reference geotherm family. The reference family is parameterized in terms of surface heat flow with upper crustal heat production given as

$$A_{UC} = (1 - P)q_S H_{UC}^{-1}, \tag{2}$$

where P is the partition coefficient, q_S is surface heat flow, and H_{UC} is the thickness of the upper crustal enriched layer (16 km). We use a partition coefficient of $P = 0.74$, which is calibrated to North American surface heat flow and compositionally corrected elevation and xenolith geothermobarometry models from cratons and shields (Hasterok and Chapman, 2011).

Although there is no physical justification for the partition model, it is an empirical model based on a global analysis of reduced heat flow provinces which found a constant ratio of basal to surface heat flow (Pollack and Chapman, 1977). A possible geological explanation for partitioning assumes surface heat flow is increased during tectonomagmatic events by simultaneously raising mantle heat flow and upper crustal radioactivity as magmatism enriches the upper crust in incompatible elements (including HPEs). Following the cessation of tectonic activity, both sub-lithospheric heat flow and radiogenic heat flow decrease as the system cools, elements decay, and erosion thins the enriched upper crust. Previous estimates of the partition coefficient range from 0.74 to 0.60 (Pollack and Chapman, 1977; Artemieva and Mooney, 2001; Hasterok and Chapman, 2007b; Hasterok and Chapman, 2011).

This idealized model provides a useful reference, reasonable for many terranes, from which thermo-isostatic anomalies may be defined. As Hasterok and Chapman (2011) suggest, this approach is similar to that of seismic tomographers who utilize reference Earth models to characterize deviations in seismic velocity from the global average and identify potential anomalies. The global reference may not describe the vertical variations in seismic velocity anywhere on Earth exactly; likewise, our reference thermal model may not describe any particular location but provides a useful point from which to define deviations from the average.

2.2. 1-D conservation of energy model

To model steady-state heat loss, we use a 3-Layered (lithospheric) Radioactivity And Sublithospheric Heat flow (3L-RASH) model throughout this study. To illustrate the thermo-isostatic effect as a function of differences in surface heat flow, consider two regions with surface heat flow of 45 mW m^{-2} and 75 mW m^{-2}, respectively. If both regions have typical values of heat production (Hasterok and Chapman, 2011), the 75 mW m^{-2} geotherm is considerably hotter and the elevations will fall on a line defined by the reference thermo-isostatic curve (Fig. 1).

If upper crustal heat production is greater than the reference (i.e., >1.2 µW m^{-3}) for the 75 mW m^{-2} region, internal temperatures are lower than the reference geotherm, resulting in elevation below the reference curve (Fig. 1). For a 75 mW m^{-2} geotherm with heat production of 2.4 µW m^{-3}, the elevation difference is very similar to the geotherm model computed with 45 mW m^{-2}, 0.7 µW m^{-3}.

Because surface heat flow and elevation differ in sensitivity to upper crustal heat production we can use the combination to improve estimates of upper crustal heat production and/or sub-