EP12D-02: Improving thermal properties estimates of the Antarctic crust and their uncertainties

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Introduction

Heat flux and temperature at the **base of an ice sheet** are **important boundary conditions** necessary for accurately modeling ice dynamics (Pittard et al., Annals Glaciology, 2016)

Geothermal heat flux (heat loss from the solid Earth) is a significant contributor to the energy balance in slow moving ice, but is **poorly constrained** (Lösing et al., Front. Earth Sci., 2020; Shen et al., GRL, 2020)

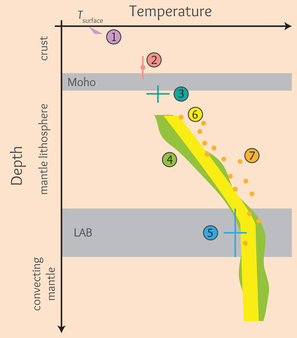
Few observations of geothermal heat flux has **lead to estimates using geophysical proxies** (e.g., An et al., 2014; Martos et al, 2017)

Proxy estimates of heat flux are highly dependent upon assumptions about **thermal conductivity and heat production** (Gard et al., in prep.)

Small-scale **refractive effects are significant**, but **cannot be identified from geophysical proxies**

Lithospheric Temperature Proxies

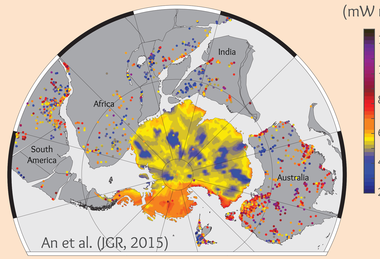
Several methods can be used to estimate geothermal heat flux and subglacial temperatures. Each have been shown to work well in some instances, but can suffer from non-uniqueness of competing physical influences. All the methods have limited zones of resolution, generally within the mantle requiring extrapolation to estimate geothermal (surface) heat flux, which **requires accurate estimates of heat production and thermal conductivity**.



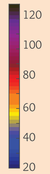
1. **Geothermal heat flux**
   sparse to non-existent, subject to surface effects including fluid flow
2. **Magnetics (Curie depth)**
   high uncertainty, dependent on starting model
3. **Sub-Moho Pn velocity**
   uncertainties from compositional variations
4. **Seismic tomography**
   uncertainties from compositional variations
5. **Receiver functions**
   is the seismic LAB a thermal boundary?
6. **Electrical conductivity**
   difficult to separate temperature from hydration and melt effects and very little data
7. **Xenolith thermobarometry**
   a paleogeotherm, relevant to present? few exposed localities
8. **Thermal isostasy**
   good integrated measure of thermal state; poor spatial resolution

Existing proxy estimates are not well correlated and do not fit data on conjugate margins

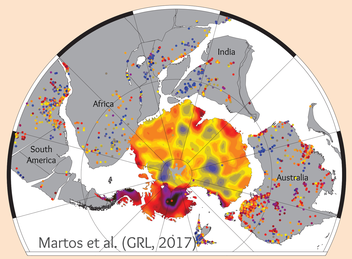
Seismic Estimated Geothermal Heat Flux



Heat Flux (mW m^{-2})



Curie Depth Estimated Geothermal Heat Flux



Modern heat flow data (Pollett et al., G^3 2019; updated from Hasterok & Chapman, EPSL 2011) positions reconstructed to 200 Ma.

Both magnetic and seismic proxy methods are sensitive to temperatures in the lower crust and mantle, but only moderately to geothermal heat flux. To constrain geothermal heat flux using these methods, assumptions must be made about the thermal conductivity and heat production profiles through the crust (equations below), but are poorly constrained leading to some of the differences above.

heat production

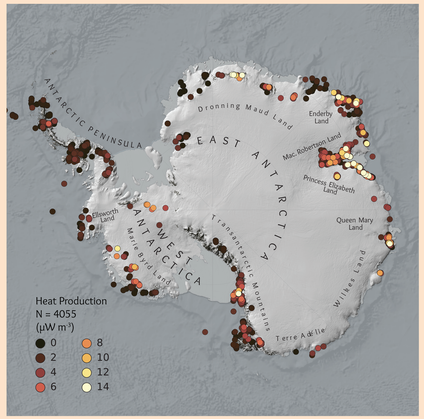
$$k(z)\nabla^2 T(z) = -A(z)$$

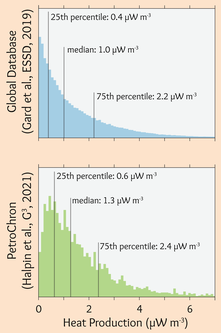
thermal conductivity — temperature

$$q(z) = k(z)\nabla T(z)$$

heat flux

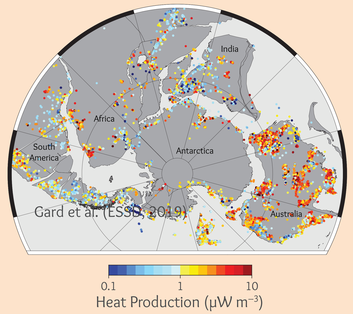
Estimating Heat Production





Heat production measurements from Antarctica are constrained by limited rock exposures (far left).

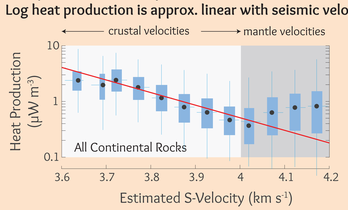
Additional constraints can be added from conjugate margins (below).



Radiogenic heat production is generally considered to be difficult to estimate, but there are several predictors for heat production. A large global geochemical database is used to estimate heat production and determine how it varies as a function of rock type, age, and tectonic setting.

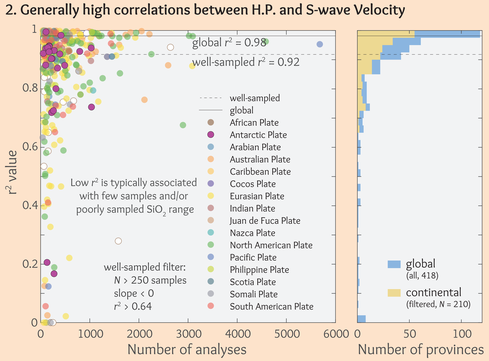
Only crustal thickness and seismic velocity can be remotely sensed.

1. Heat production can be predicted from seismic velocities, Log heat production is approx. linear with seismic velocity

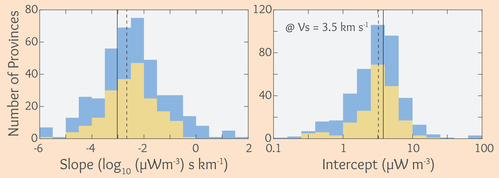


$$\log_{10} A(\mu W\ m^{-3}) = 0.560 \pm 0.004 - 2.84 \pm 0.02\ (Vs(km\ s^{-1}) - 3.5)$$

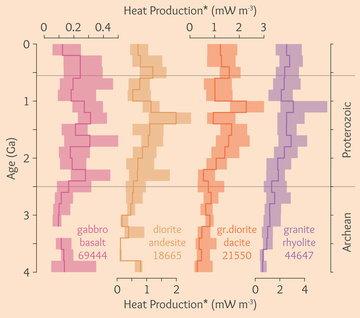
2. Generally high correlations between H.P. and S-wave Velocity



3. Wide range of linear models...key point, province dependent



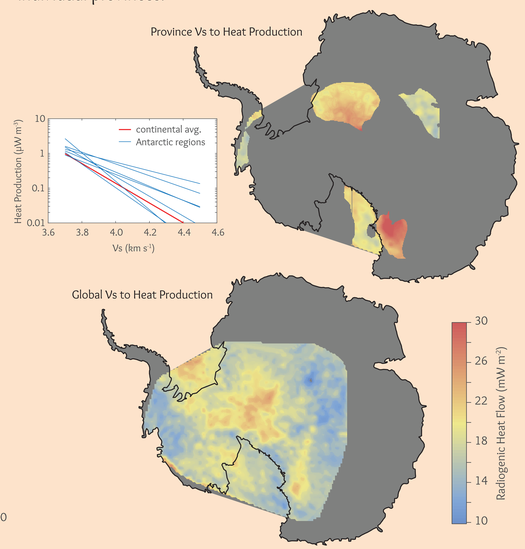
Proxies for heat production, include age (below), rock type (below), crustal thickness (not shown) and seismic velocity (right).



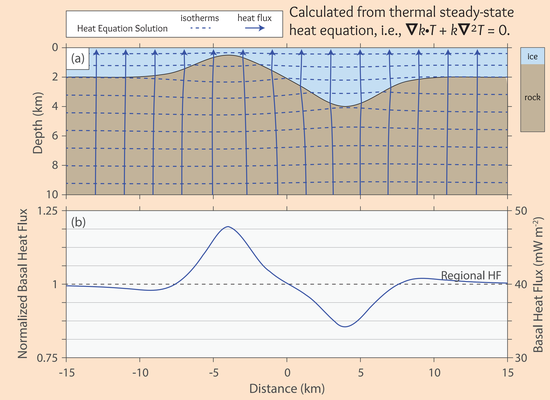
*Australian data are excluded because of anomalous radioactivity that skews global averages

Gard et al. (Lithos, 2019) and Hasterok et al. (Precambrian Res., 2019)

Heat production models below estimated from shear-wave (Vs) velocities (Shen et al., JGR, 2010). There are significant difference between calibrations using the global estimates and those using individual provinces.

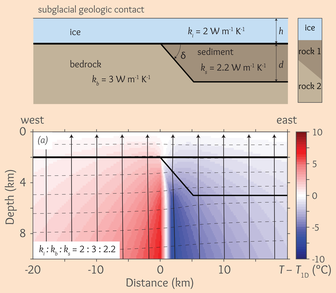


Thermal Conductivity

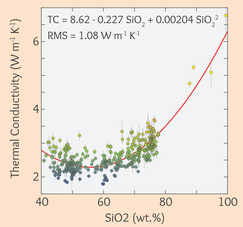


Calculated from thermal steady-state heat equation, i.e., $\nabla k \cdot T + k\nabla^2 T = 0$.

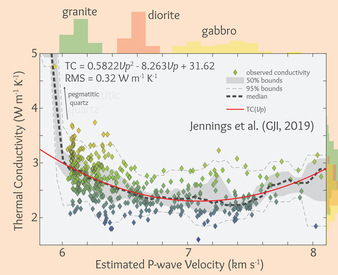
Thermal conductivity has the potential to distort isotherms and bend (refract) the heat flow field. This refraction effect occurs whether or not there is subglacial topography when there are lateral differences in crustal thermal conductivity.

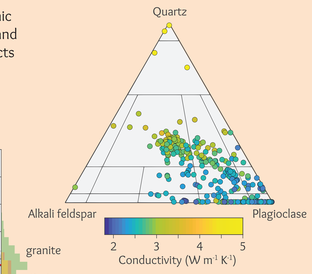


Thermal conductivity is compositionally dependent and can be predicted from mineralogy and major elements...at least for igneous rocks.



Thermal conductivity is weakly correlated with seismic velocity. These estimates are at surface conditions and must be adjusted for temperature and pressure effects (e.g., Ray et al. 2021).





Summary

Estimates of geothermal heat flux from geophysical proxies requires accurate estimates of thermal conductivity and heat production.

Both properties can be reasonably estimated from sesimic velocity but heat production ideally should be calibrated to measurements in each province or there will be large uncertainties.

Thermal conductivity can also cause refractive effects that produce temperature anomalies at the base of ice sheets.

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