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COMMENTARY

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Key Points:

- Antarctic ice sheet stability is highly dependent on the crustal contribution of radiogenic heat production to geothermal heat flow
- Contrasts in crustal density may indicate upper crustal radiogenic heat production distributions
- Robust geothermal models need to factor in heterogeneity at the scales of intrusions, metamorphic facies, and sedimentary units

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Geology Matters for Antarctic Geothermal Heat

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Abstract Geothermal heat plays a vital role in Antarctic ice sheet stability. The continental geothermal heat flow distribution depends on lithospheric composition and ongoing tectonism. Heat-producing elements are unevenly enriched in the crust over deep time by various geological processes. The contribution of crustal heat production to geothermal heat flow is widely recognized; however, in Antarctica, crustal geology is largely hidden, and its complexity has frequently been excluded in thermal studies due to limited observations and oversimplified assumptions. Li and Aitken (2024), https://doi.org/10.1029/2023GL106201 take a significant step forward, focusing on Antarctic crustal radiogenic heat. Utilizing gravity inversion and rock composition data, they show that the crustal heterogeneity introduces considerable variability to heat flow. However, modeling crustal heat production proves challenging because it lacks distinct associations with geophysical observables and has a narrow spatial association. Robust quantification of geothermal heat production and heat flow must incorporate explicit aspects of geology.

Plain Language Summary Even moderate amounts of geothermal heat, or the natural warmth from the Earth's interior, can cause the base of Antarctica's ice sheets to melt or change how the ice behaves as it flows slowly toward the coast. Geothermal heat is not evenly spread within continents. Instead, it's influenced by how plate tectonics has affected the types of rocks present. While scientists agree that the Earth's crust is a major contributor to geothermal heat generation, studies in Antarctica have often left out how rock type differences might affect heat distribution. The study by Li and Aitken (2024), https://doi.org/10.1029/2023gl106201 looks more closely at how the Earth's crust beneath Antarctica varies and how that affects the heat impacting its ice sheets from below. In this commentary, we highlight that although heat production is difficult to model, their findings are important for understanding the natural influences on ice sheets as we observe and predict the impact of ongoing climate change. However, to provide robust estimates, a detailed geological understanding is required.

1. Urgency and Controversy of Antarctic Geothermal Heat

Climate change is impacting Earth with profound consequences for the future of humanity and habitats around the globe. One of the most significant ramifications is the projected decreasing mass of the Antarctic ice sheets and glaciers. The mass loss rate, regional patterns, state of tipping points, and feedback mechanisms are not yet fully understood (Noble et al., 2020). One of the essential boundary conditions for predicting ice sheet stability is the basal temperature derived from friction and naturally occurring geothermal heat (Burton-Johnson et al., 2020; Reading et al., 2022; Whitehouse et al., 2019). From ice sheet modeling studies, we know that geothermal heat impairs the ice sheet's mass balance in complex ways. In some regions, small-scale heat flow anomalies can have a significant impact (Jordan et al., 2018; Pittard et al., 2016); however, in other regions, the influence of the geothermal heat component can be practically neglected (McCormack et al., 2022; Pattyn, 2010).

Geothermal heat flow includes deep primordial heat and radiogenic heat produced from the isotopic decay of thorium, uranium and potassium, which are concentrated in the crust through differentiation processes over geological time. The mantle contribution is typically relatively low and uniform across stable continental interiors (Jaupart et al., 2016). Therefore, a significant and varying proportion of continental geothermal heat flow originates from the radiogenic heat production in the upper and lower crust, which introduces variations on a geological scale (Hasterok & Chapman, 2011; Hazzard & Richards, 2024; Jaupart et al., 2016; Willcocks et al., 2021). Geochemical analysis of rock samples has shown that heat production in Antarctica can vary significantly even over short distances (Burton-Johnson et al., 2017; Carson et al., 2014; Goodge, 2018; Sanchez et al., 2021).

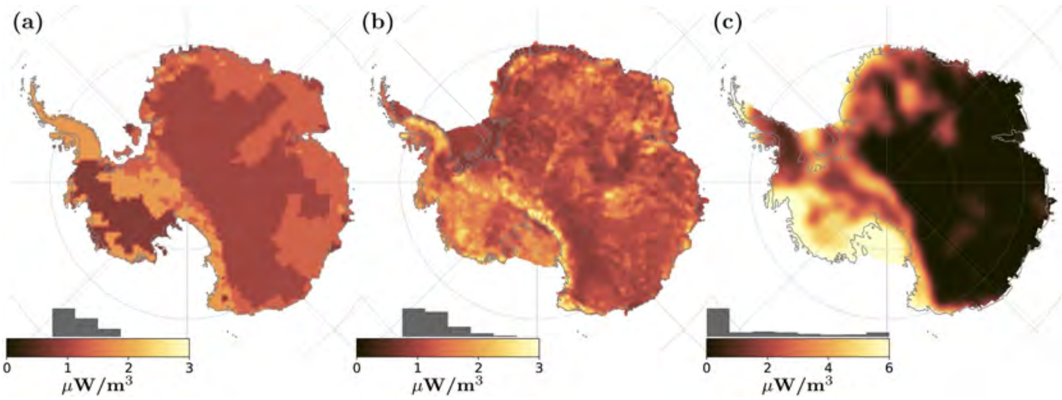

Figure 1. Three recent efforts to map continental crustal heat production in Antarctica. (a) Mean heat production based on energy balance and assumptions regarding crustal type and age from seismic tomography and geological extrapolations (Stål et al., 2020). To align with the content of (b and c), the values have been recomputed from the original publication to reflect the upper crust instead of the entire crust. (b) Upper crustal heat production using gravity inversion, with median density-heat production relationship (Li & Aitken, 2024). (c) Mean heat production based on calculations of steady-state geotherms, temperatures and properties derived from seismic tomography (Hazzard & Richards, 2024). The figures are not comparable; for example, the definition of upper crust varies, but they highlight the overall variability depending on the methods and data used. Due to its larger range of values, subfigure (c) has a distinct color range compared to subfigures (a and b). Links to data and code are listed in the Data Availability Statement.

Most of Antarctica (>99%) is concealed beneath ice and snow, and there are very few direct estimates of heat transfer from ice sheet boreholes (Burton-Johnson et al., 2020; Stål et al., 2022). Extrapolation of Antarctic geology from sparse marginal outcrops (e.g., Cox et al., 2023; Sanchez et al., 2021) into the subglacial regions is largely based on geophysical interpretations, linked where possible with geological observations of ice-transported moraines and marine sediment (Aitken et al., 2014; Aitken & Urosevic, 2021; Goodge, 2018; Goodge et al., 2017; Kodama et al., 2024; Mulder et al., 2019; Stål et al., 2020). Entirely cryptic terranes, not constrained by direct geological observations, are likely in the subglacial interior (e.g., Aitken et al., 2014; Ferraccioli et al., 2011; Fitzsimons, 2000; Goodge & Finn, 2010; Hasterok et al., 2022; Stål et al., 2019). Hence, we only have observations of Antarctic crustal heat production from coastal regions with at least some outcrops (Burton-Johnson et al., 2017; Carson et al., 2014), but unfortunately not in areas where the geothermal heat has the largest impact on the ice sheet stability (McCormack et al., 2022; Pattyn, 2010). The variations in heat production estimates can explain some of the substantial variations in maps of geothermal heat flow (Burton-Johnson et al., 2020; Hazzard & Richards, 2024; Reading et al., 2022), but with limited direct observations of the geology, heat production estimates of the crust can only be derived from models (Figure 1).

The distribution of geothermal heat flow in Antarctica has been debated during the past decades, and different studies have presented often incompatible results (discussed by Burton-Johnson et al., 2020; Lösing et al., 2020; Stål et al., 2021; Stål et al., 2020; Reading et al., 2022). In some regard, the controversy can be explained by how each study has considered and incorporated the composition and scale of the crustal geology in the analysis. Geophysical models of the lithosphere can use observable data to compute temperature or heat transfer directly from, for example, temperature relationships with seismic wave speed or magnetic anomalies. However, models based solely on the temperature differences between the Earth's surface and an isotherm in the lower crust or upper mantle, without considering the crust's composition and properties, fall short in accounting for the variations in continental geothermal heat.

A more convoluted approach yielding more robust model outputs is to utilize geophysics to indicate, map and evaluate geological properties and then apply those derived insights to the thermal model. Inferential methods using indirect observables are common in empirical studies, which may project values from in-situ measurements to map heat flow based on the association of the geological setting (e.g., Al-Aghbary et al., 2022; Davies & Davies, 2010; Goutorbe et al., 2011; Shen et al., 2020; Stål et al., 2021). Empirical multivariate thermal studies can provide robust results for interdisciplinary applications; although they do not attempt to fully explain underlying geology, they can capture certain crustal properties. Nevertheless, forward modeling studies offer valuable insights by allowing us to examine the parameters involved (Haeger et al., 2019, 2022; Hazzard &

Richards, 2024; Lowe et al., 2023; Stål et al., 2020). Comparing the results from forward models with empirical computations further reveals new insights into the lithospheric structure (Li & Aitken, 2024; Reading et al., 2022).

Herein lies one of the biggest challenges in modeling geothermal heat across the Antarctic continent—crustal heat production controls variability in geothermal heat flow but does not directly correlate to any crustal property that can be sensed through the ice (Hasterok et al., 2018; Hasterok & Webb, 2017). Li and Aitken (2024) (Figure 1b) present one of the first attempts to infer the variability in heat production by linking upper crustal density and geometry to the compositions of the rocks as computed in a petrological compilation.

The disagreement between geothermal models has caused confusion in interdisciplinary studies that use geothermal heat as an input. For example, model limitations well understood in solid Earth geophysics and geology might not be validly applied when geothermal heat is incorporated into ice sheet models (Reading et al., 2022).

2. Frustrations in Inferring Heat Production

Several studies have correlated heat production in rocks with geophysical observables such as density and seismic *P*-wave velocity (discussed by Hasterok and Gard (2016); Hasterok and Webb (2017); Jaupart et al. (2016)). While these petrophysical approaches are informative and valuable in many regards, no single geophysical observable can provide a robust estimate of heat production when the geological setting and history are unknown.

Li and Aitken (2024) use gravity inversion, coupled with seismic observations and interpolations of crustal thickness, to derive density variations in the lithosphere. Their analysis incorporates predictions of subglacial sedimentary basins (Aitken et al., 2023; Li et al., 2022) to yield a geologically coherent model of crustal structure. They then apply an empirical relation to link upper crustal density to map the distribution of crustal heat production with a resolution of 40 km. Low density is related to elevated heat production because heat-producing elements correlate with higher SiO_2 content in igneous and metaigneous rocks. The processes that occur during partial melting and fractional crystallisation enrich heat-producing elements in felsic, less dense rocks such as granites (Gard et al., 2019; Hasterok et al., 2018; Wollenberg & Smith, 1987).

Challenges emerge in analyzing and drawing conclusions from large, global databases in Earth science, foremost being the notable occurrence of sampling bias (Gard et al., 2019; Stål et al., 2022). Always limited by costs and logistical difficulties, rocks collected by field geologists are typically selected due to their regional or economic significance. Rock samples are collected from the present-day Earth surface, typically the upper crust, and only in deeply exhumed regions can we sample the mid and lower crust. Therefore, it is not certain whether the records of these databases represent the bulk compositions, particularly in the undersampled Antarctica. Antarctic rock compilations (e.g., PetroChron Antarctica; Sanchez et al., 2021) have the additional bias that outcrops resistant to glacial erosion are over-represented, and most samples are collected near existing coastal infrastructure.

To suggest a single value to represent heat production for an entire terrane or a grid cell in a model is problematic. When making bulk estimates, it is essential to consider the distribution of heat-producing elements within each geological unit (Burton-Johnson et al., 2017; Davies & Davies, 2010). Additionally, one must determine how this distribution scaling would apply to the resolution and extent required for input into ice sheet models (McCormack et al., 2022). Some studies apply the median value of heat production for samples within a defined unit; however, the median does not scale arithmetically when we want to calculate the bulk heat production for a larger volume. By using the median value as the measure of central tendency, we have already accepted that the distribution we sampled is not representative of the crust. The density variation recovered by Li and Aitken (2024) is limited to indicate the bulk chemistry of the crust averaged over large volumes and cannot capture the variety of rock types that make up the volume.

Further assumptions are often made regarding the change in heat production with depth, which remains speculative unless other evidence of the tectonic history, structure, and composition is known. It can generally be assumed that crustal heat production decreases with depth (Jaupart et al., 2016), due to extraction and redistribution of melts rich in heat-producing elements that pond and crystallize in the upper crust. Another possibility is that the poorly sampled lower crust is more mafic and dense in composition, which could yield lower heat production in the deep crust (Bea, 2012). However, a decrease in heat production with depth does not always prevail along exposed crustal depth profiles (Alessio et al., 2018) or in global compilations that examine heat production with metamorphic grade (Hasterok et al., 2018).

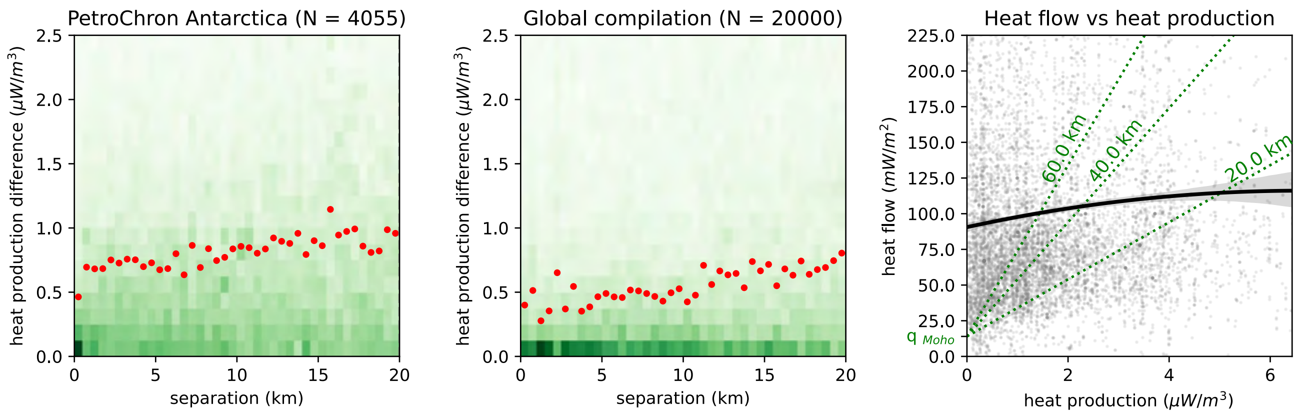

Figure 2. The heat production values found in rock databases do not support the premise that the spatial proximity between samples is a reliable predictor for heat production within a grid cell or polygon. In Figure (a–b), the *x*-axis represents the distance between any two samples in the catalog, while the *y*-axis shows the difference in heat production between those same two samples. The distribution of correlated pairs is shown as a 2D histogram (green), which has been normalized to compensate for the number of samples in each separation distance bin. The red markers show the median heat production for each such distance bin. (a) Data from PetroChron Antarctica includes all 4,055 samples with determined heat production values (Sanchez et al., 2021). (b) Data from a global whole rock compilation, in which 20,000 randomly sampled records are analyzed (Gard et al., 2019a). For clarity, the figures show cropped data ranges (additional figures displaying distance-difference plots are available Stål et al., 2024). (c) Heat production versus heat flow, using values of heat production from Gard et al. (2019a) and heat flow in the Global Heat Flow Database (Fuchs et al., 2023). Gray dots (N = 9,364) indicate records in the GHFD below the 95th percentile, associated with corresponding heat production value within 20 km (Gard et al., 2019a). A second-order polynomial regression (black) shows the lack of correlation. For comparison, the green dotted lines show hypothetical relations for constant heat production throughout a crust of thicknesses 20, 40 and 60 km. A steady state mantle heat flow component (q_{Moho}) of 14 mW m^2 is assumed (Jaupart et al., 2016). Links to data, code, and further details are provided by Stål et al. (2024).

To get an appreciation of the spatial variance of heat production values, we plot the difference in calculated heat production versus distance between samples in Figures 2a and 2b. We observe no spatial correlation using either PetroChron Antarctica (Sanchez et al., 2021) or the global compilation (Gard et al., 2019a), used by Li and Aitken (2024). The disagreement between samples remains largely consistent regardless of the separation distance, demonstrating the lack of reliable predictability of heat production on almost any scale. Within a few hundred meters, there might be some association that leads to a slightly better prediction, but from just a few kilometers separation, there appears to be no strong correlation with heat production for rock samples presumed to have formed in the same geological setting (also shown in Supplementary Material for Stål et al. (2021)). We also observe that the disagreement in the Antarctic PetroChron database (Sanchez et al., 2021) is generally more prominent than the global compilation; this may be explained by the low proportion of sedimentary samples in PetroChron or different selection criteria when samples were collected in the field.

Given these challenges, it is striking that some similarities do prevail in some crustal heat production models (Figures 1a and 1b) using different data and methods (Li & Aitken, 2024; Stål et al., 2020), whereas another approach (c) suggests a different distribution (Hazzard & Richards, 2024). It is encouraging that fundamental properties of the crust can be derived from different sources. The residual differences are informative as they provide independent views on the structure of the Antarctic lithosphere.

3. Spatial Variability, and Why Geology Matters

Based on the understanding that crustal heat production significantly contributes to continental geothermal heat flow (Jaupart et al., 2016; Li & Aitken, 2024; McLaren et al., 2003), we might expect the two data sets to be spatially associated. Figure 2c shows the correlation between heat flow values on the *y*-axis (Fuchs et al., 2023) and calculated heat production in rocks from the international compilation on the *x*-axis (Gard et al., 2019a). We only consider data pairs where the independent estimate of heat production is located within 20 km of the heat flow measurement (the exact maximum distance of correlation appears not to have a significant impact). Records identified as marine, exceptionally high heat production or heat flow above the upper 2σ range are omitted from the analysis. Such excluded data points may come from anomalous oversampled geologic settings, such as volcanoes and uranium ore deposits. Apparently, heat production in rock samples and heat flow values are not simply correlated in the continental crust.

Figure 2c illustrates pitfalls when utilizing sample databases without considering the detailed geology. This lack of correlation between heat flow and heat production databases can be understood when one appreciates that heat flow estimates measured near the Earth's surface integrate the total radiogenic heat generated throughout the crust and heat conducted vertically from the mantle, whereas crustal heat production values are generated from rocks that may not represent the total crustal column (Gard et al., 2019; Reading et al., 2022). This underscores the need to understand specific regions' tectonic history and crustal-scale architecture so that crustal heat production values from rock samples can be assessed and carefully integrated. The scale of the thermal model is crucial. At a fine scale (m-to-km-scale), shallow thermal conductivity variations and hydrology may largely determine the distribution of geothermal heat (e.g., Willcocks et al., 2021). A fuller understanding of the geological setting, topography, groundwater and paleoclimate history is required to realistically model the heat flow with the resolution required for ice sheet models (McCormack et al., 2022), even if the heat production distribution was known in detail.

To enhance our understanding and quantification of subglacial geothermal heat in Antarctica, refinement in the characterization of crustal geology and its complexity is crucial. This can be achieved through in-depth research into tectonic history and many aspects of geology, facilitated by: (a) more comprehensive rock sampling and studies on glacially derived materials; (b) accessing subglacial sediment and bedrock; (c) improved statistical and computational methods to incorporate and analyze multivariate data to differentiate crustal properties; (d) promoting interdisciplinary studies linking glaciology (observations and modeling) and subglacial geology.

4. Conclusion

Understanding geothermal heat flow, a critical boundary condition affecting the Antarctic ice sheets, is a matter of utmost urgency. The work of Li and Aitken (2024) makes a significant contribution by focusing on one of the most variable and significant factors—crustal heat production. A lack of direct geological sampling in much of Antarctica and the significant challenge of extrapolating from samples cautions us from inferring a uniform bulk heat production value across a crustal volume at any scale. The detailed geology, including igneous intrusion history, crustal reworking and sedimentary rock provenance, is crucial for valid heat production estimates. Importantly, Li and Aitken's (2024) contribution encourages further study of Antarctica's lithospheric structure and the geological character of subglacial terranes and landforms.

Data Availability Statement

Additional figures and code to perform the analysis are provided by Stål et al. (2024). The repository also contains the recalculated heat production output from Stål et al. (2020). PetroChron Antarctica is available from Sanchez et al. (2021b). Global whole-rock geochemical database compilation is available from Gard et al. (2019b). The Global Heat Flow Database is the compilation of the world heat flow data maintained by the International Heat Flow Commission (IHFC) of the IASPEI, and is available from Fuchs et al. (2023). The model outputs from Li and Aitken (2024) are available from Li and Aitken (2023). The model outputs from Hazzard and Richards (2024) are available at (Hazzard & Richards, 2024b). All data used are accessible from public repositories. Maps are plotted using the Python package *agrid* (Stål & Reading, 2020).

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