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**Key Points:**

- As a direct result of lithological heterogeneities in the upper crust, subglacial heat flux is much more variable than can be resolved by geophysical methods
- Upper crustal heat production on the Antarctic Peninsula contributes 6–70% of the total subglacial heat flux
- Sedimentary basins can produce comparably high heat fluxes to granitic intrusions; coupled with their erodible nature, these basins may impart a greater control on ice sheet dynamics than previously recognized

**Supporting Information:**

- Supporting Information S1
- Data Set S1
- Data Set S2
- Data Set S3

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# A new heat flux model for the Antarctic Peninsula incorporating spatially variable upper crustal radiogenic heat production

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**Abstract** A new method for modeling heat flux shows that the upper crust contributes up to 70% of the Antarctic Peninsula's subglacial heat flux and that heat flux values are more variable at smaller spatial resolutions than geophysical methods can resolve. Results indicate a higher heat flux on the east and south of the Peninsula (mean 81 mW m$^{-2}$) where silicic rocks predominate, than on the west and north (mean 67 mW m$^{-2}$) where volcanic arc and quartzose sediments are dominant. While the data supports the contribution of heat-producing element-enriched granitic rocks to high heat flux values, sedimentary rocks can be of comparative importance dependent on their provenance and petrography. Models of subglacial heat flux must utilize a heterogeneous upper crust with variable radioactive heat production if they are to accurately predict basal conditions of the ice sheet. Our new methodology and data set facilitate improved numerical model simulations of ice sheet dynamics.

**Plain Language Summary** As the climate changes, the Antarctic ice sheet represents the single largest potential source of sea level rise. However, one key parameter controlling how the ice sheet flows remains poorly constrained: the effect of heat derived from the Earth's geology on the base of the ice sheet (known as subglacial heat flux). Although this may not seem like a lot of heat, under slow-flowing ice, this "heat flux" can control how well the ice sheet can flow over the rocks and even lead to melting of the ice at its base. Current models for Antarctica's heat flux use geophysics to determine how thin the crust is and consequently how easily heat from the Earth's mantle can warm the surface. We show here that heat produced by radioactive decay within the Earth's crust can have an even greater and much more variable contribution to the subglacial heat flux than estimated by these previous models. We present a new methodology allowing this crustal heat production to be calculated and combined with the geophysical models, producing a new map of heat flux on the Antarctic Peninsula highlighting the variations in heat flux caused by different rock types.

## 1. Introduction

Following the identification of anthropogenic global climate change and the risks posed by a consequent rise in global sea level, increased attention has been drawn to understanding the dynamics of the world's largest potential driver of sea level rise: the Antarctic ice sheet [*Fox*, 2010].

Modeling ice sheet dynamics requires understanding the ice-bed interface, but measuring these basal conditions is inherently difficult. Subglacial geothermal heat flux is one of the least constrained basal parameters [*Llubes et al.*, 2006; *Larour et al.*, 2012] but affects (1) ice temperature and rheology, (2) basal melting and consequent mechanical decoupling at the ice-bed interface, and (3) the development of unconsolidated water-saturated sediments, all of which can promote ice flow [*Greve and Hutter*, 1995; *Siegert*, 2000; *Winsborrow et al.*, 2010; *Larour et al.*, 2012].

### 1.1. Existing Methods

Subglacial heat flux is the sum of mantle-generated heat conducted through the lithosphere and radiogenic heat from the lithosphere conducted to the surface of the crust. Heat flux is typically measured directly from boreholes drilled directly into bedrock [*Pollack et al.*, 1993], but this is logistically challenging in Antarctica due to the remoteness and inaccessibility of exposed bedrock and by the ice sheet covering 99.8% of the surface [*Burton-Johnson et al.*, 2016]. Only very sparse heat flux measurements have been measured in boreholes into subglacial lake sediments [e.g., *Fisher et al.*, 2015] and seafloor sedimentary strata [e.g., *Schröder et al.*, 2011] or derived from basal temperature gradients in deep ice boreholes [e.g., *Engelhardt*, 2004].

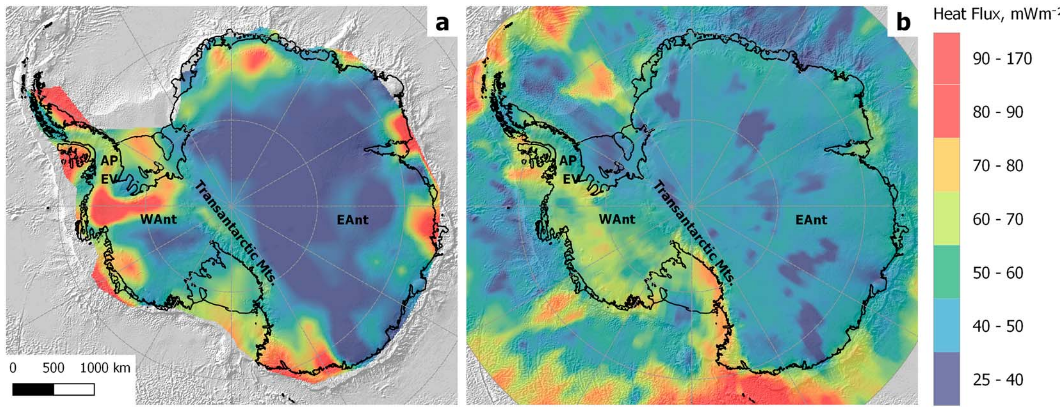


**Figure 1.** (a) Magnetically derived [*Fox Maule et al.*, 2005] and (b) seismically derived [*An et al.*, 2015] maps of subglacial heat flux. AP, Antarctic Peninsula; EAnt, East Antarctica; EV, Evans Ice Stream; and WAnt, West Antarctica. ETOPO1 surface relief [*Amante and Eakins*, 2009].

Because of this paucity of direct measurements, heat flux has instead been estimated using magnetic and seismic geophysical data. *Fox Maule et al.* [2005] estimated the subglacial heat flux (Figure 1a) from satellite-derived geomagnetic data by determining the depth of the Curie isotherm. The Curie isotherm is a temperature surface of ~580°C at which rocks switch from higher ferrimagnetic or ferromagnetic susceptibility to much lower paramagnetic susceptibility [*Blakely*, 1988]. Increasing the geothermal gradient, either through increasing radiogenic heat production or thinning the lithosphere, reduces the Curie isotherm depth.

However, the magnetically derived map of subglacial heat flux is limited by resolution of a few hundred kilometers (resulting from the satellite altitude), methodological uncertainties with combined errors, and the use of a laterally constant crustal heat production. Additionally, in regions where mantle rocks are shallower than 580°C, the calculated Curie isotherm will appear shallower due to a lack of magnetic rocks [*Frost and Shive*, 1986; *Wasilewski and Mayhew*, 1992].

Alternatively, heat flux has been determined from seismic data [*Shapiro and Ritzwoller*, 2004; *An et al.*, 2015]. Mantle heat flux can be determined from seismic data as temperature is the dominant control on seismic velocity in the upper mantle. Seismic data also identify the density discontinuity marking the base of the crust and allow the determination of the isotherm (1330°C) marking the base of the lithosphere. The calculated mantle heat flux can be combined with an estimate of lithospheric heat production to produce a map of subglacial heat flux (Figure 1b). However, this model is also limited to a lateral resolution of >120 km and is insensitive to the lithospheric geotherm.

Both models treat the lithosphere as internally laterally uniform in its structure (only varying in thickness) and possessing low and constant radiogenic heat production (maximum of 2.5 $\mu$W m$^{-3}$ exponentially decreasing with depth for the magnetic method and 1.0, 0.4, and 0.1 $\mu$W m$^{-3}$ in the seismic method for the upper, middle, and lower crust, respectively). Consequently, subglacial heat flux inversely correlates with crustal thickness with highest values overlying the thinnest lithosphere. As we will show here, heterogeneity in upper crustal heat production renders this an oversimplification.

### 1.2. Radiogenic Lithospheric Heat Production

The lithosphere produces heat from the radiogenic decay of heat-producing elements (HPEs). Although numerous radioactive isotopes exist, U, Th, and K are responsible for ~98% of lithospheric heat production [*Beardsmore and Cull*, 2001]. These elements are incompatible with mineral structures in the mantle and lower crust, so concentrate in the upper crust during planetary differentiation with decreasing abundance with depth [*Roy et al.*, 1968; *Rudnick and Fountain*, 1995].

The upper crust itself is highly heterogeneous in composition. The distribution of minerals in the crust is primarily determined by magma differentiation and HPE distribution by their compatibility in different mineralogies, concentrating them in Si-rich silicic rocks (e.g., granite or rhyolite) relative to Fe-rich mafic rocks

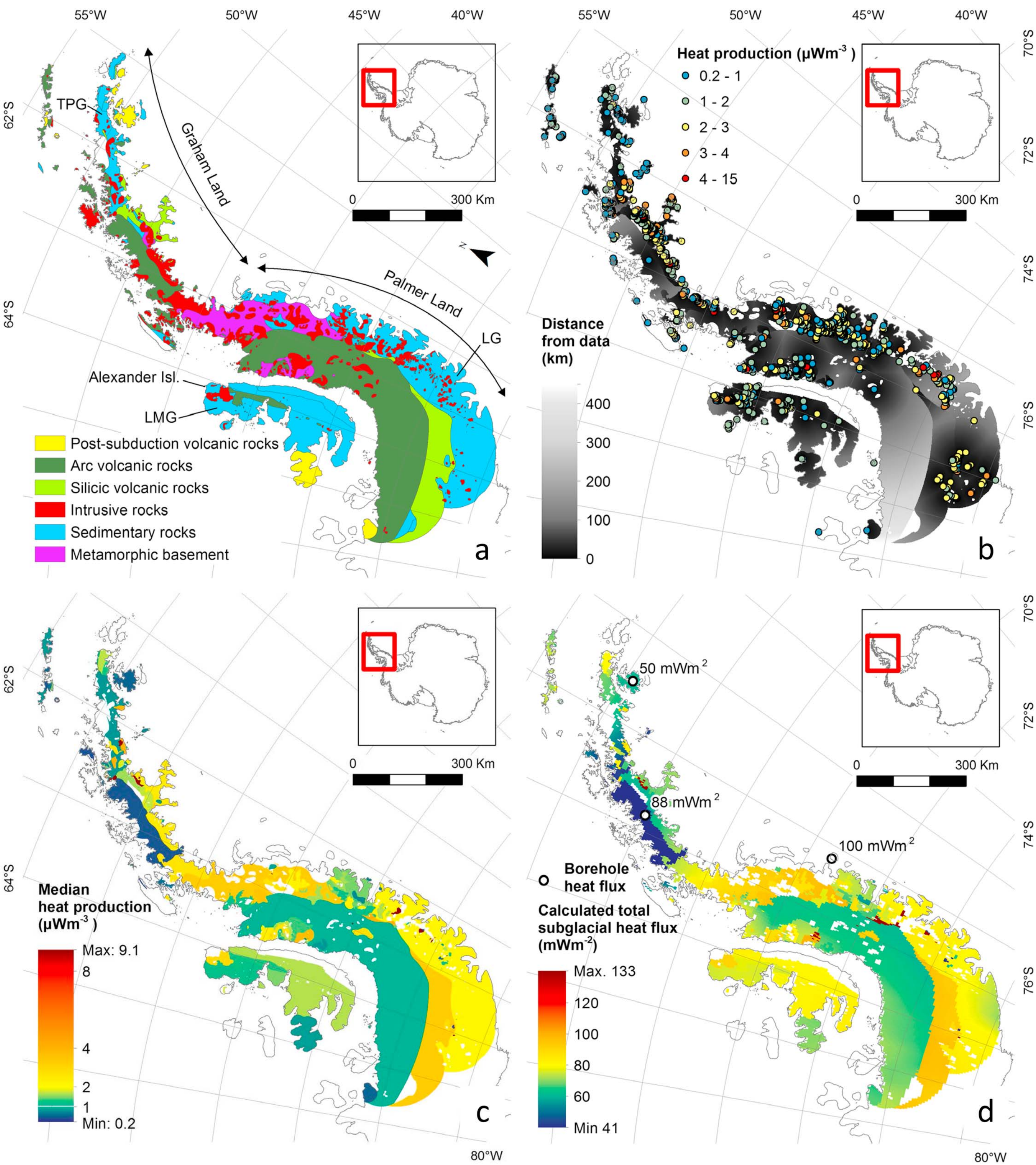


**Figure 2.** (a) Geological map of the Antarctic Peninsula [*Burton-Johnson and Riley*, 2015, and references therein]. TPG—Trinity Peninsula Group; LMG—LeMay Group; and LG—Latady Group. (b) Geochemical data locations and the distance of calculated data from a data point. (c) Calculated median heat production values. (d) Calculated total subglacial heat flux utilizing our heat production values (Figure 2c) and the data of *An et al*. [2015].

(e.g., gabbro or basalt). Sediments largely inherit the HPE abundance of their eroded source rocks. Consequently, crustal heat production is heterogeneous and the most significant control of HPE abundance and consequent heat production in the crust is the distribution of its composite lithologies [*Lachenbruch*, 1968; *McLennan et al.*, 2006; *Sandiford and McLaren*, 2002].

### 1.3. Geology of the Antarctic Peninsula

This study will investigate the influence of crustal heterogeneity in the Antarctic Peninsula on crustal heat flux, for which an understanding of the region's geology is fundamental. For a detailed description refer to *Burton-Johnson and Riley* [2015].

The Antarctic Peninsula developed as a continental volcanic arc similar to the Andes and Patagonia. The oldest units are metamorphosed 487–175 Ma sedimentary and igneous rocks forming the metamorphic basement [*Gledhill et al.*, 1982; *Riley et al.*, 2012] exposed in Graham Land and northern Palmer Land (Figure 2a). These units developed on the margin of the Gondwanan supercontinent. Thick turbidite sequences developed along the edge of this continental margin [*Bradshaw et al.*, 2012], depositing thick sequences of sedimentary rocks in Graham Land (Figure 2a). In the Early Jurassic, Gondwana began to separate. The Weddell Sea opened, separating South Africa from the Antarctic Peninsula. Rifting triggered voluminous silicic volcanism along the Peninsula between 188 and 172 Ma [*Pankhurst et al.*, 2000], and deep sedimentary basins developed along the east coast of Palmer Land (Figure 2a). Following breakup (at ~162 Ma [*Pankhurst et al.*, 2000]), the Peninsula returned to a continental volcanic arc setting [*Leat and Scarrow*, 1994] with distinct periods of extensive intrusive magmatism [*Pankhurst and Rowley*, 1991] and thick fore-arc and turbidite sedimentation forming Alexander Island (Figure 2a) [*Tranter*, 1986; *Doubleday et al.*, 1993]. Pacific subduction ceased progressively northward between ~60 and 6.5 Ma [*Larter et al.*, 1997; *McCarron and Larter*, 1998], and magmatism waned until the production of postsubduction alkaline intraplate volcanism between 6.5 and 0.1 Ma [*Rex*, 1976; *Ringe*, 1991] (Figure 2a).

## 2. Methodology

### 2.1. Input Data

To predict upper crustal heat production, two data sets were used: (1) the geological map of *Burton-Johnson and Riley* [2015] (Figure 2a), with subglacial geology interpreted from surrounding outcrops, surface and subglacial topography, and aeromagnetism, and (2) a georeferenced HPE database (Figure 2b) compiled from published geochemical analyses and unpublished data from the British Antarctic Survey's archives, filtered to include only bedrock geology and exclude minor outcrops (e.g., clasts, enclaves, and dykes).

### 2.2. Heat Production

Radiogenic heat production for each sample ($H$, μW m$^{-3}$) for the present day ($t$ = 0) was determined from equation (1) [*Turcotte and Schubert*, 2014]:

$$H = \left(0.9928C_0^{\mathrm{U}}H^{U238} + 0.0071C_0^{\mathrm{U}}H^{U235} + C_0^{\mathrm{Th}}H^{\mathrm{Th}232} + 0.000119C_0^{\mathrm{K}}H^{\mathrm{K}40}\right)D \tag{1}$$

where $C_0^{\mathrm{U}}$, $C_0^{\mathrm{Th}}$, and $C_0^{\mathrm{K}}$ are the measured concentrations (ppm) of U, Th, and K, respectively, and $H^{\mathrm{U}238}$, $H^{\mathrm{U}235}$, $H^{\mathrm{Th}232}$, and $H^{\mathrm{K}40}$ are the heat productivities of the respective isotopes $^{238}$U (9.37 × 10$^{-5}$ W kg$^{-1}$), $^{235}$U (5.69 × 10$^{-4}$ W kg$^{-1}$), $^{232}$Th (2.69 × 10$^{-5}$ W kg$^{-1}$), and $^{40}$K (2.79 × 10$^{-5}$ W kg$^{-1}$). $D$ is the assumed density of the rock (2700 kg m$^{-3}$). Problematically, most bedrock geochemical analyses in the British Antarctic Survey database occurred prior to the development of methods to accurately quantify U contents (e.g., high-resolution XRF or inductively coupled plasma-mass spectrometry), leaving only 319 samples with complete U, Th, and K data. However, using samples with data for all three HPE, we derive an empirical relationship (correlation coefficient, $R^2$ = 0.9; Figure S1 in the supporting information) to calculate $H$ from K and Th heat production ($H_{\mathrm{K,Th}}$):

$$H = 1.4H_{\mathrm{K,Th}} + 0.3 \tag{2}$$

Equation (2) increased the heat production data set to 3070 georeferenced samples and applies for each broad lithology with $R^2$ values of 0.9 for sedimentary rocks, 0.9 for volcanic rocks, 0.9 for intrusive rocks, and 0.7 for metamorphic rocks.

To attribute heat production values to the geology, we experimented with interpolated variable surfaces between the data points. However, although most locations are <100 km from a data point, the sample distribution is biased toward accessible outcrop (Figure 2b) creating false anomalies beneath the ice sheet and misrepresenting the data. Instead, the spatial extent of each lithology (i.e., each geological polygon) was assigned the median *H* value of the samples within it.

### 2.3. Heat Flux Calculation

To calculate a total subglacial heat flux, our heat production values were incorporated into the heat flux model of *An et al*. [2015]. Their calculations combined a layered crust (upper, middle, and lower crustal layers of equal thickness and constant heat productivities) with the lithospheric and asthenospheric mantle heat flux determined by seismic analysis. By deriving the *An et al*. [2015] crustal model and replacing it with a two-layer model (upper and lower crust) using our upper crustal heat production values, a new subglacial heat flux model of the Antarctic Peninsula was calculated. By this method, only the heat flux of *An et al*. [2015] is required for calculation and not the absolute temperatures.

A major limitation of any crustal heat production model is our understanding of deep crustal structure, principally the relative thicknesses of the HPE-enriched upper crust and the HPE-depleted lower crust. HPE abundance is often modeled as decreasing exponentially with depth, reflecting the decrease in HPE abundance with increasing metamorphic grade [*Lachenbruch*, 1968; *Sandiford and McLaren*, 2002; *Fox Maule et al*., 2005]. However, the lithological change from the largely silicic upper crust to the mafic lower crust has a larger influence on HPE abundance [*Bea and Montero*, 1999; *Bea*, 2012]. Consequently, we adopt the layered crustal approach of *An et al*. [2015] but with limited knowledge of the deep crustal structure employ a simple two-layer crustal model. Total crustal thickness (equally divided between the upper and lower crust), upper and lower crustal conductivities, and lower crustal heat production are those used in *An et al*. [2015].

## 3. Results

Heat production (Figure 2c) and resultant heat flux (Figure 2d) were calculated for almost all of the Antarctic Peninsula with most locations being <70 km from a data point (Figure 2b). The number of samples used to assign each polygon and the standard deviation of heat production values are shown in Figures S2 and S3.

### 3.1. Heat Productivity

The median calculated heat productivities are highly variable (0.2–9.1 $\mu$W m$^{-3}$, Figure 2c). They are higher on the east coast and far south of the Peninsula (mean 2.2 $\mu$W m$^{-3}$), where silicic rocks predominate (clastic sedimentary rocks, gneissose metamorphic basement, silicic volcanic rocks, and granitic intrusions), while the west and northernmost coasts' lower values (mean 1.1 $\mu$W m$^{-3}$) are associated with mafic and intermediate volcanic rocks and quartzose sedimentary rocks.

The highest calculated median heat production values are associated with intrusive rocks (mean 1.7, maximum 9.1 $\mu$W m$^{-3}$), similar to localized regions of East Antarctica [*Carson and Pittard*, 2012; *Carson et al*., 2014], but these intrusions on the Antarctic Peninsula are scattered and limited in their extent. More extensive areas of high heat production are the metamorphic basement (mean 2.5 $\mu$W m$^{-3}$) and silicic volcanic rocks (mean 2.5 $\mu$W m$^{-3}$; Figure 2). The sedimentary rocks of Palmer Land and Alexander Island show elevated heat production (mean 2.0 and 1.5 $\mu$W m$^{-3}$, respectively) relative to the constant upper crustal value employed by *An et al*. [2015] (1.0 $\mu$W m$^{-3}$). The lowest heat productivity values are from the mafic-intermediate subduction and postsubduction-related volcanic rocks (mean 0.9 $\mu$W m$^{-3}$).

### 3.2. Heat Flux

Calculated upper crustal heat flux contributes 6–70% of the total subglacial heat flux, resulting in the similar spatial distributions of upper crustal heat production and subglacial heat flux variation (Figures 2c and 2d). In central Graham Land and southeast Palmer Land, the superposition of low mantle heat flux anomalies (Figure 1b) lowers the subglacial expression of high crustal heat production relative to other regions of the Peninsula (compare the heat production and heat flux values for central Graham Land and eastern Palmer Land, Figures 2c and 2d).

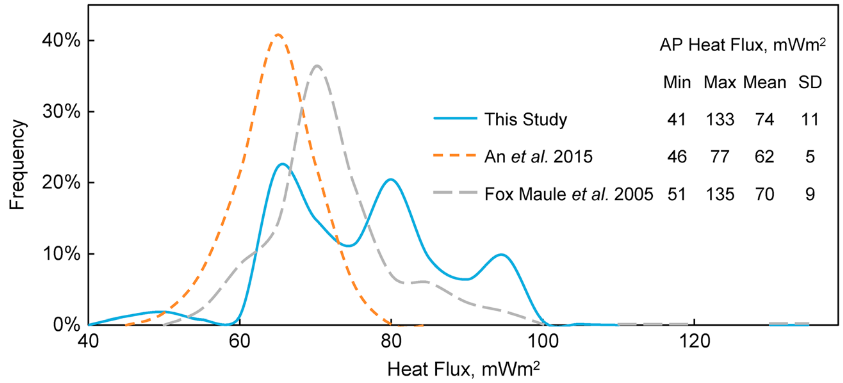


**Figure 3.** Heat flux distributions for the three models discussed. Bins are 5 mW m$^2$.

## 4. Discussion

### 4.1. Influence of Upper Crustal Lithologies on Subglacial Heat Flux

Our analysis demonstrates that lithological controls on subglacial heat flux are imparted by the relative HPE abundance of different lithologies.

#### 4.1.1. Intrusive Rocks and the Metamorphic Basement

Granitic rocks are HPE enriched, and previous studies have highlighted their influence on heat flux [*Roy et al.*, 1968; *Carson et al.*, 2014]. Our results associate the highest subglacial heat flux values with granitic intrusions (Figure 2), but their extent is limited. Additionally, granitic intrusions are more laterally than vertically extensive (i.e., disc shaped [*McCaffrey and Petford*, 1997]), so their thickness and contribution to total heat flux may be overestimated in layered crustal models.

In older crust where intrusions have accumulated, the vertical and horizontal extent of intrusive rocks increases. Felsic igneous rocks form the protoliths to the granitic gneisses dominating the Peninsula's metamorphic basement, associating this basement with high heat flux (Figure 2). Similar regions of older felsic metamorphosed continental crust, abundant in East Antarctica [*Aitken et al.*, 2014], likely have larger effects on subglacial heat flux than isolated HPE-enriched intrusions.

#### 4.1.2. Volcanic Rocks

A range of volcanic lithologies occur on the Antarctic Peninsula. Silicic volcanic rocks chemically resemble granitic rocks, producing regions of high heat flux in eastern Graham Land and southern Palmer Land (Figure 2). In contrast, HPE-poor mafic volcanic rocks in Graham Land and western Palmer Land (Figure 2) are produce areas of low heat flux. They are also associated with a high magnetic anomaly (the Pacific Margin Anomaly [*Ferraccioli et al.*, 2006]) indicating similar mafic rocks at depth.

Volcanic rocks are abundant in West Antarctica and the Transantarctic Mountains, although extensive silicic volcanic rocks are restricted to the Peninsula [*Bradshaw et al.*, 1985; *LeMasurier and Thomson*, 1990; *Riley and Knight*, 2001]. Thus, on a continental scale, volcanic rocks will be associated with regions of lower heat flux.

#### 4.1.3. Sedimentary Rocks

Three extensive sedimentary sequences occur on the Antarctic Peninsula (Figure 2a): the Trinity Peninsula Group (TPG), the Latady Group (LG), and the LeMay Group (LMG). While low heat production is predicted for the TPG (calculated median value of 0.8 μW m$^{-3}$), higher heat production is predicted for the LMG (1.6 μW m$^{-3}$) and LG (2.0 μW m$^{-3}$), higher than many LG-hosted intrusions (Figure 2c).

The in-heat productivity differences resemble observations from basin analysis [*Rybach*, 1986] and relate to each sediment's maturity and provenance. The LG's relatively low maturity and consequently high lithic content results in a high HPE content inherited from their silicic volcanic source rocks [*Willan*, 2003]. In contrast, the LMG is dominantly sourced from metasedimentary and more mafic volcanic rocks [*Willan*, 2003], producing sedimentary detritus with a lower HPE content. The relatively low HPE content of the TPG results from its higher maturity and quartz content.

All three sedimentary units form basins many kilometers thick, and similar basins are prevalent across Antarctica [e.g., *Barrett et al.*, 1986; *Aitken et al.*, 2014; *Frederick et al.*, 2016; *Maritati et al.*, 2016].

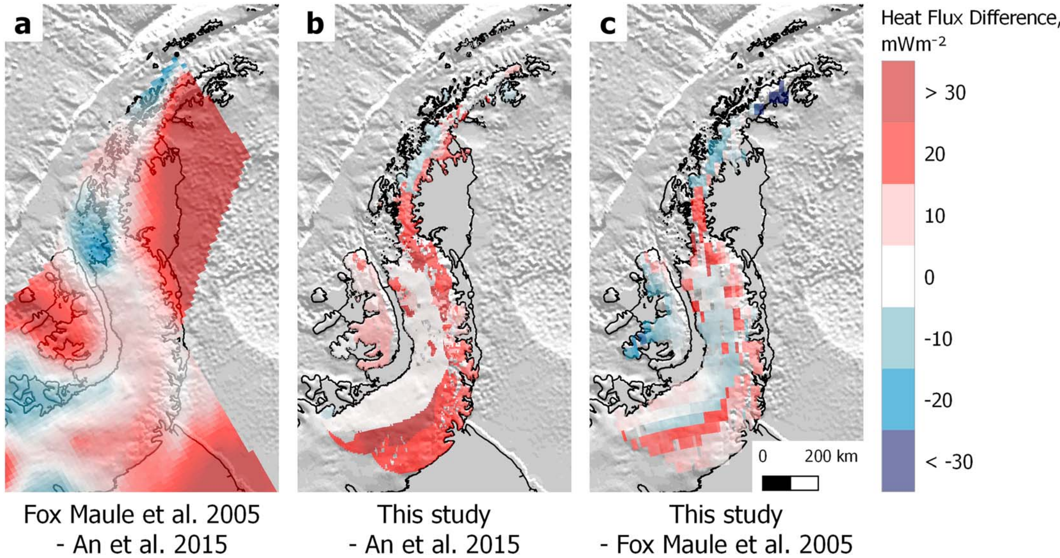


**Figure 4.** Differences in the heat flux values between the models of *Fox Maule et al.* [2005], *An et al.* [2015], and this study. ETOPO1 surface relief [*Amante and Eakins*, 2009].

Understanding their individual petrography and provenance is important in determining their contribution to subglacial heat flux.

### 4.2. Comparison With Existing Models

The variable HPE content of rock outcrops across the Antarctic Peninsula controls upper crustal radiogenic heat production, imparting significant influence on the subglacial heat flux. Consequently, upper crustal lithological heterogeneity contributes to higher variability in subglacial heat flux than geophysical models predict. Comparing the distribution of this study's heat flux values with the seismic and magnetic models (Figures 3 and 4) highlights this increased variability. Our range and average heat flux values (Figure 3) more closely resemble the distribution of the magnetically derived model [*Fox Maule et al.*, 2005] than the more homogenous values of the seismic model [*An et al.*, 2015].

Subglacial heat flux in the seismic-based model [*An et al.*, 2015] is inversely related to crustal thickness. As their calculated crustal thickness is relatively uniform beneath the Antarctic Peninsula (33 km with a standard deviation of 6 km), so too is their predicted heat flux (Figure 3). The magnetically derived model [*Fox Maule et al.*, 2005] is only slightly less uniform than the seismic model, reflecting its low resolution (~200 km), but shows a broader range of values, similar to that predicted by our model (Figure 3).

Our model predicts higher heat flux on the east and south of the Peninsula than the west and north (Figure 2d), at odds with both previous models (Figure 4). The seismic model [*An et al.*, 2015] predicts thinner crust and consequently higher heat flux on the west of the Peninsula than the east (particularly under Alexander Island), with low heat flux in southeast Palmer Land due to thicker crust. The magnetic model [*Fox Maule et al.*, 2005] also predicts higher heat flux in Alexander Island than Palmer Land but indicates a higher heat flux in central Palmer Land than western Palmer Land or Graham Land (Figure 1), similar to our calculations. This may reflect an increase in the upper crustal geotherm and consequent reduction of the Curie depth, indicating that the magnetic model is better able to resolve the effect of upper crustal heat production. However, their resolution is too low for detailed interpretations.

### 4.3. Model Validation

Thorough validation of the subglacial heat flux models is not feasible due to the lack of direct borehole measurements. Subglacial heat flux has been calculated from the temperature profiles of three glacial boreholes (Figure 2d). A value of 50 mW m$^{-2}$ from James Ross Island [*Mulvaney et al.*, 2012] is lower than the model of *An et al.* [2015] (65 mW m$^{-2}$) and much lower than *Fox Maule et al.* [2005] (112 mW m$^{-2}$), but is similar to our model (60 mW m$^{-2}$), reflecting the island's HPE-poor volcanic rocks.

The 88 mW m$^{-2}$ was calculated in western Graham Land, much higher than the calculated values of this study, *An et al*. [2015], or *Fox Maule et al*. [2005] (42, 47, and 53 mW m$^{-2}$, respectively) as it is in an area of low HPE volcanic rocks. The value compares to nearby intrusions in our model (81–103 mW m$^{-2}$) potentially indicating the presence of additional subglacial intrusions and highlighting the impact of local geology, unresolvable by geophysical methods.

Our model's extent does not cover a borehole from Dolleman Island in Palmer Land [*Nicholls and Paren*, 1993] due to a lack of outcrop. The heat flux calculated (100 mW m$^{-2}$) is higher than *An et al*. [2015] (66 mW m$^{-2}$) but comparable to *Fox Maule et al*. [2005] (91 mW m$^{-2}$) and our value for the nearby metamorphic basement (92 mW m$^{-2}$).

### 4.4. Implications for Glaciological Research

Geothermal heat flux is an important control on ice sheet dynamic processes predominantly through the modulation of basal ice temperatures, determining regions of basal ice at pressure melting point where meltwater is produced.

Previous studies have investigated the sensitivity of simulated ice sheet dynamics to subglacial heat flux. The largest impacts occur in slow-flowing areas of the ice sheet [*Larour et al*., 2012], where basal meltwater production has the potential to substantially alter flow properties both upstream and downstream of localized heat flux hot spots [*Pittard et al*., 2016a, 2016b]. Basal meltwater produced in regions of elevated geothermal heat flux has also been linked to glacier surging [*MacAyeal*, 1992; *Bell et al*., 2007], impacting overall ice sheet mass balance estimates [*Rignot et al*., 2011], and the development of subglacial hydrological systems, including the evolution of subglacial lakes [*Dowdeswell and Siegert*, 2003; *Siegert*, 2005]. Where high heat flux values are combined with a deformable till, the production of meltwater will lead to faster basal motion, modifying the flow properties of the ice sheet [*Rippin et al*., 2003].

This study highlights the potential for high heat fluxes in Antarctic sedimentary basins. Being more easily eroded than crystalline rocks and conducive to subglacial till production (decoupling the ice and bedrock), sedimentary rocks can preferentially focus ice streams [*Tulaczyk et al*., 1998; *Winsborrow et al*., 2010]. Permeable sedimentary strata are vulnerable to advected heat via circulating groundwater [*Gooch et al*., 2016]. High heat flux has the greatest effect on slow-flowing ice. Consequently, the elevated heat flux of some sedimentary rocks (coupled with their erodible nature) may have encouraged the development of upper tributaries to paleo-ice streams. For example, the high heat flux predicted for southeast Palmer Land may have aided development of the upper tributaries of the Evans Ice Stream (Figure 1), increasing ice flow through these tributaries despite the reduced direct impact of heat flux on ice flow downstream.

Our results encourage investigation into upper crustal heat production in basins elsewhere in Antarctica and their impact on ice sheet dynamics. This is of particular relevance in regions undergoing rapid retreat, such as the Totten Glacier in the Sabrina Subglacial Basin [*Li et al*., 2015; *Aitken et al*., 2016], where improved heat flux models will help constrain future mass balance changes. Additionally, elevated heat flux encourages basal melting in areas of thick ice, rendering the current search for Antarctica's oldest ice sensitive to the effect of subglacial heat flux and requiring accurate high-resolution determination of this parameter to successfully retrieve these key climate records [*Fischer et al*., 2013].

### 4.5. Limitations and Future Directions

The principal limitations of our methodology are the accuracy and coverage of its input data: surface geological mapping, distribution of HPE abundance data, and constraints on 3-D crustal structure. Crustal structure introduces the greatest uncertainty as extrapolation of surface outcrops to half crustal thickness will overrepresent thin sedimentary basins and isolated plutons. Crustal structure may be resolvable through geophysical interpretation, as it has been in determining sedimentary thicknesses in the Weddell Sea region [*Golynsky and Aleshkova*, 2000; *Jordan et al*., 2017].

To develop the technique further and to apply it across the Antarctic continent, the following key parameters must be constrained: (1) improved continent-wide mapping of Antarctica's subglacial geology [e.g., *Cox*, 2015]; (2) collation of a continent-wide geochemical database; (3) determination of the surficial geology thickness and the structure of the deep crust though geophysical modeling; (4) glaciological modeling using the alternative heat flux models, to investigate the sensitivities and implications for ice sheet dynamics; and (5) direct heat flux measurements for validation.

## 5. Conclusions

1. Existing models for Antarctic subglacial heat flux underestimate its scale and variability due to their use of constant values for upper crustal heat production [*Shapiro and Ritzwoller*, 2004; *Fox Maule et al*., 2005; *An et al*., 2015].
2. Subglacial heat flux on the Antarctic Peninsula varies from 43 to 133 mW $m^{-2}$, with upper crustal heat production contributing 6–70% of the total. Variability is higher and occurs at a wider range of spatial resolutions than is currently resolved by geophysical techniques.
3. Subglacial heat flux on the Antarctic Peninsula is higher on the eastern and southern coasts (mean 81 mW $m^{-2}$) than the western and northern coasts (mean 67 mW $m^{-2}$) due to the predominance of silicic intrusive and volcanic rocks and more lithic-rich sedimentary rocks to the east compared to the more mafic volcanic rocks and quartzose sedimentary rocks to the west.
4. Sedimentary rocks can produce comparatively high radiogenic heat depending on their provenance and maturity and thus may impart a greater control on ice sheet dynamics than previously recognized. To understand the influence of Antarctica's extensive sedimentary basins on subglacial heat flux, their provenance, petrography, and chemistry must be constrained.

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## References

Aitken, A. R. A., D. A. Young, F. Ferraccioli, P. G. Betts, J. S. Greenbaum, T. G. Richter, J. L. Roberts, D. D. Blankenship, and M. J. Siegert (2014), The subglacial geology of Wilkes Land, East Antarctica, *Geophys. Res. Lett.*, *41*, 2390–2400, doi:10.1002/2014GL059405.

Aitken, A. R. A., J. L. Roberts, T. D. Van Ommen, D. A. Young, N. R. Golledge, J. S. Greenbaum, D. D. Blankenship, and M. J. Siegert (2016), Repeated large-scale retreat and advance of Totten Glacier indicated by inland bed erosion, *Nature*, *533*(7603), 385–389.

Amante, C., and B. W. Eakins (2009), ETOPO1 arc-minute global relief model: Procedures, data sources and analysis, National Oceanic and Atmospheric Administration Technical Memorandum NESDIS NGDC-24.

An, M., D. A. Wiens, Y. Zhao, M. Feng, A. Nyblade, M. Kanao, Y. Li, A. Maggi, and J.-J. Lévêque (2015), Temperature, lithosphere-asthenosphere boundary, and heat flux beneath the Antarctic Plate inferred from seismic velocities, *J. Geophys. Res. Solid Earth*, *120*, 8720–8742, doi:10.1002/2015JB011917.

Barrett, P. J., D. H. Elliot, and J. F. Lindsay (1986), The Beacon Supergroup (Devonian-Triassic) and Ferrar Group (Jurrasic) in the Beardmore Glacier Area, Antarctica, *Geol. Cent. Transantarctic Mt.*, 339–428.

Bea, F. (2012), The sources of energy for crustal melting and the geochemistry of heat-producing elements, *Lithos*, *153*, 278–291, doi:10.1016/j.lithos.2012.01.017.

Bea, F., and P. Montero (1999), Behavior of accessory phases and redistribution of Zr, REE, Y, Th, and U during metamorphism and partial melting of metapelites in the lower crust: An example from the Kinzigite Formation of Ivrea-Verbano, NW Italy, *Geochim. Cosmochim. Acta*, *63*(7), 1133–1153.

Beardsmore, G. R., and J. P. Cull (2001), *Crustal Heat Flow: A Guide to Measurement and Modelling*, p. 24, Cambridge Univ. Press, Cambridge.

Bell, R. E., M. Studinger, C. A. Shuman, M. A. Fahnestock, and I. Joughin (2007), Large subglacial lakes in East Antarctica at the onset of fast-flowing ice streams, *Nature*, *445*(7130), 904–907.

Blakely, R. J. (1988), Curie temperature isotherm analysis and tectonic implications of aeromagnetic data from Nevada, *J. Geophys. Res.*, *93*(B10), 11,817–11,832, doi:10.1029/JB093iB10p11817.

Bradshaw, J. D., S. D. Weaver, and M. G. Laird (1985), Suspect terranes and Cambrian tectonics in northern Victoria Land, Antarctica, in *Circum-Pacific Terrane Conference*, edited by D. C. Howeel et al., pp. 36–39, Standford Univ. Press, Standford, Calif.

Bradshaw, J. D., A. P. M. Vaughan, I. L. Millar, M. J. Flowerdew, R. A. Trouw, C. Fanning, and M. J. Whitehouse (2012), Permo-Carboniferous conglomerates in the Trinity Peninsula Group at View Point, Antarctic Peninsula: Sedimentology, geochronology and isotope evidence for provenance and tectonic setting in Gondwana, *Geol. Mag.*, *149*(4), 626–644.

Burton-Johnson, A., and T. R. Riley (2015), Autochthonous v. accreted terrane development of continental margins: A revised in situ tectonic history of the Antarctic Peninsula, *J. Geol. Soc.*, *2014–110*.

Burton-Johnson, A., M. Black, P. T. Fretwell, and J. Kaluza-Gilbert (2016), An automated methodology for differentiating rock from snow, clouds and sea in Antarctica from Landsat 8 imagery: A new rock outcrop map and area estimation for the entire Antarctic continent, *The Cryosphere*, *10*(4), 1665–1677.

Carson, C. J., and M. Pittard (2012), *A Reconaissance Crustal Heat Production Assessment of the Australian Antarctic Territory (AAT)*, pp. 1–57, Geoscience Australia, Canberra, Australia.

Carson, C. J., S. McLaren, J. L. Roberts, S. D. Boger, and D. D. Blankenship (2014), Hot rocks in a cold place: High sub-glacial heat flow in East Antarctica, *J. Geol. Soc.*, *171*(1), 9–12.

Cox, S. (2015), Towards improved geological maps of Antarctic rocks and surficial deposits, in ISAES XII Pre-Symposium Workshop, Goa, India.

Doubleday, P. A., D. I. M. Macdonald, and P. A. R. Nell (1993), Sedimentology and structure of the trench-slope to forearc basin transition in the Mesozoic of Alexander Island, Antarctica, *Geol. Mag.*, *130*(06), 737–754.

Dowdeswell, J. A., and M. J. Siegert (2003), The physiography of modern Antarctic subglacial lakes, *Global Planet. Change*, *35*(3), 221–236.

Engelhardt, H. (2004), Ice temperature and high geothermal flux at Siple Dome, West Antarctica, from borehole measurements, *J. Glaciol.*, *50*(169), 251–256.

Ferraccioli, F., P. C. Jones, A. P. M. Vaughan, and P. T. Leat (2006), New aerogeophysical view of the Antarctic Peninsula: More pieces, less puzzle, *Geophys. Res. Lett.*, *33*, L05310, doi:10.1029/2005GL024636.

Fischer, H., et al. (2013), Where to find 1.5 million yr old ice for the IPICS "Oldest-Ice" ice core, *Clim. Past*, *9*(6), 2489–2505.
Fisher, A. T., et al. (2015), High geothermal heat flux measured below the West Antarctic Ice Sheet, *Sci. Adv.*, *1*(6), e1500093.
Fox, D. (2010), Could East Antarctica be headed for big melt?, *Science*, *328*(5986), 1630–1631.
Fox Maule, C., M. E. Purucker, N. Olsen, and K. Mosegaard (2005), Heat flux anomalies in Antarctica revealed by satellite magnetic data, *Science*, *309*(5733), 464–467.
Frederick, B. C., D. A. Young, D. D. Blankenship, T. G. Richter, S. D. Kempf, F. Ferraccioli, and M. J. Siegert (2016), Distribution of subglacial sediments across the Wilkes Subglacial Basin, East Antarctica, *J. Geophys. Res. Earth Surf.*, *121*, 790–813, doi:10.1002/2015JF003760.
Frost, B. R., and P. N. Shive (1986), Magnetic mineralogy of the lower continental crust, *J. Geophys. Res.*, *91*(B6), 6513–6521, doi:10.1029/JB091iB06p06513.
Gledhill, A., D. C. Rex, and P. W. G. Tanner (1982), Rb-Sr and K-Ar geochronology of rocks from the Antarctic Peninsula between Anvers Island and Marguerite Bay, in *Antarctic Geoscience*, edited by C. Craddock, pp. 315–323, Univ. of Wisconsin Press, Madison, Wisconsin.
Golynsky, A. V., and N. D. Aleshkova (2000), Regional magnetic anomalies of the Weddell Sea region and their geological significance, *Polarforschung*, *67*(3), 101–117.
Gooch, B. T., D. A. Young, and D. D. Blankenship (2016), Potential groundwater and heterogeneous heat source contributions to ice sheet dynamics in critical submarine basins of East Antarctica, *Geochem. Geophys. Geosyst.*, *17*, 395–409, doi:10.1002/2015GC006117.
Greve, R., and K. Hutter (1995), Polythermal three-dimensional modelling of the Greenland ice sheet with varied geothermal heat flux, *Ann. Glaciol.*, *21*(1), 8–12.
Jordan, T. A., F. Ferraccioli, and P. T. Leat (2017), New geophysical compilations link crustal block motion to Jurassic extension and strike-slip faulting in the Weddell Sea Rift System of West Antarctica, *Gondwana Res.*, *42*, 29–48.
Lachenbruch, A. H. (1968), Preliminary geothermal model of the Sierra Nevada, *J. Geophys. Res.*, *73*(22), 6977–6989, doi:10.1029/JB073i022p06977.
Larour, E., M. Morlighem, H. Seroussi, J. Schiermeier, and E. Rignot (2012), Ice flow sensitivity to geothermal heat flux of Pine Island Glacier, Antarctica, *J. Geophys. Res.*, *117*, F04023, doi:10.1029/2012JF002371.
Larter, R. D., M. Rebesco, L. E. Vanneste, L. A. P. Gamboa, and P. F. Barker (1997), Cenozoic tectonic, sedimentary and glacial history of the continental shelf west of Graham Land, Antarctic Peninsula, in *Geology and Seismic Stratigraphy of the Antarctic Margin*, vol. 2, edited by P. F. Barker and A. K. Cooper, pp. 1–27, AGU, Washington, D. C.
Leat, P. T., and J. H. Scarrow (1994), Central volcanoes as sources for the Antarctic Peninsula Volcanic Group, *Antarct. Sci.*, *6*(03), 365–374.
LeMasurier, W. E., and J. W. Thomson (1990), *Volcanoes of the Antarctic Plate and Southern Oceans*, *Antarctic Res. Ser.*, pp. 1–481, AGU, Washington, D. C.
Li, X., E. Rignot, M. Morlighem, J. Mouginot, and B. Scheuchl (2015), Grounding line retreat of Totten Glacier, East Antarctica, 1996 to 2013, *Geophys. Res. Lett.*, *42*, 8049–8056, doi:10.1002/2015GL065701.
Llubes, M., C. Lanseau, and F. Rémy (2006), Relations between basal condition, subglacial hydrological networks and geothermal flux in Antarctica, *Earth Planet. Sci. Lett.*, *241*(3), 655–662.
MacAyeal, D. R. (1992), Irregular oscillations of the West Antarctic ice sheet, *Nature*, *359*(6390), 29–32.
Maritati, A., A. R. A. Aitken, D. A. Young, J. L. Roberts, D. D. Blankenship, and M. J. Siegert (2016), The tectonic development and erosion of the Knox Subglacial Sedimentary Basin, East Antarctica, *Geophys. Res. Lett.*, *43*, 10,728–10,737, doi:10.1002/2016GL071063.
McCaffrey, K. J. W., and N. Petford (1997), Are granitic intrusions scale invariant?, *J. Geol. Soc.*, *154*(1), 1–4, doi:10.1144/gsjgs.154.1.0001.
McCarron, J. J., and R. D. Larter (1998), Late Cretaceous to early Tertiary subduction history of the Antarctic Peninsula, *J. Geol. Soc.*, *155*(2), 255–268.
McLennan, S. M., S. R. Taylor, and S. R. Hemming (2006), Composition, differentiation, and evolution of continental crust: constraints from sedimentary rocks and heat flow, in *Evolution and Differentiation of the Continental Crust*, edited by M. Brown and T. Rushmer, pp. 92–134, Cambridge Univ. Press, Cambridge, U. K.
Mulvaney, R., N. J. Abram, R. C. Hindmarsh, C. Arrowsmith, L. Fleet, J. Triest, L. C. Sime, O. Alemany, and S. Foord (2012), Recent Antarctic Peninsula warming relative to Holocene climate and ice-shelf history, *Nature*, *489*(7414), 141–144.
Nicholls, K. W., and J. G. Paren (1993), Extending the Antarctic meteorological record using ice-sheet temperature profiles, *J. Clim.*, *6*(1), 141–150.
Pankhurst, R. J., and P. D. Rowley (1991), Rb-Sr study of Cretaceous plutons from southern Antarctic Peninsula and eastern Ellsworth Land, Antarctica, in *Geological Evolution of Antarctica*, edited by M. R. A. Thomson, J. A. Crame, and J. W. Thomson, pp. 387–394, Cambridge Univ. Press, Cambridge, U. K.
Pankhurst, R. J., T. R. Riley, C. M. Fanning, and S. P. Kelley (2000), Episodic silicic volcanism in Patagonia and the Antarctic Peninsula: Chronology of magmatism associated with the break-up of Gondwana, *J. Petrol.*, *41*(5), 605–625.
Pittard, M. L., B. K. Galton-Fenzi, J. L. Roberts, and C. S. Watson (2016a), Organization of ice flow by localized regions of elevated geothermal heat flux, *Geophys. Res. Lett.*, *43*, 3342–3350, doi:10.1002/2016GL068436.
Pittard, M. L., J. L. Roberts, B. K. Galton-Fenzi, and C. S. Watson (2016b), Sensitivity of the Lambert-Amery glacial system to geothermal heat flux, *Ann. Glaciol.*, *57*(73), 56–68.
Pollack, H. N., S. J. Hurter, and J. R. Johnson (1993), Heat flow from the Earth's interior: Analysis of the global data set, *Rev. Geophys.*, *31*(3), 267–280.
Rex, D. C. (1976), Geochronology in relation to the stratigraphy of the Antarctic Peninsula, *Br. Antarct. Surv. Bull.*, *43*, 49–58.
Rignot, E., J. Mouginot, and B. Scheuchl (2011), Ice flow of the Antarctic ice sheet, *Science*, *333*(6048), 1427–1430.
Riley, T. R., and K. Knight (2001), Age of pre-break-up Gondwana magmatism, *Antarct. Sci.*, *13*(2), 99–110.
Riley, T. R., M. J. Flowerdew, and M. J. Whitehouse (2012), U-Pb ion-microprobe zircon geochronology from the basement inliers of eastern Graham Land, Antarctic Peninsula, *J. Geol. Soc.*, *169*(4), 381–393, doi:10.1144/0016-76492011-142.
Ringe, M. J. (1991), Volcanism on Brabant Island, Antarctica, in *Geological Evolution of Antarctica*, edited by M. R. A. Thomson, J. A. Crame, and J. W. Thomson, pp. 515–519, Cambridge Univ. Press, Cambridge, U. K.
Rippin, D. M., J. L. Bamber, M. J. Siegert, D. G. Vaughan, and H. F. J. Corr (2003), Basal topography and ice flow in the Bailey/Slessor region of East Antarctica, *J. Geophys. Res.*, *108*(F1), 6008, doi:10.1029/2003JF000039.
Roy, R. F., D. D. Blackwell, and F. Birch (1968), Heat generation of plutonic rocks and continental heat flow provinces, *Earth Planet. Sci. Lett.*, *5*, 1–12.
Rudnick, R., and D. Fountain (1995), Nature and composition of the continental crust: A lower crustal perspective, *Rev. Geophys.*, *95*, 267–309, doi:10.1029/95RG01302.
Rybach, L. (1986), Amount and significance of radioactive heat sources in sediments, *Collect. Colloq. Semin.*, *44*, 311–322.
Sandiford, M., and S. McLaren (2002), Tectonic feedback and the ordering of heat producing elements within the continental lithosphere, *Earth Planet. Sci. Lett.*, *204*(1), 133–150.

Schröder, H., T. Paulsen, and T. Wonik (2011), Thermal properties of the AND-2A borehole in the southern Victoria Land Basin, McMurdo Sound, Antarctica, *Geosphere*, *7*(6), 1324–1330.

Shapiro, N. M., and M. H. Ritzwoller (2004), Inferring surface heat flux distributions guided by a global seismic model: Particular application to Antarctica, *Earth Planet. Sci. Lett.*, *223*(1), 213–224.

Siegert, M. J. (2000), Antarctic subglacial lakes, *Earth Sci. Rev.*, *50*(1), 29–50.

Siegert, M. J. (2005), Lakes beneath the ice sheet: The occurrence, analysis, and future exploration of Lake Vostok and other Antarctic subglacial lakes, *Annu. Rev. Earth Planet. Sci.*, *33*, 215–245.

Tranter, T. H. (1986), The LeMay Group of central Alexander Island, *Br. Antarct. Surv. Bull.*, *71*, 57–67.

Tulaczyk, S., B. Kamb, R. P. Scherer, and H. F. Engelhardt (1998), Sedimentary processes at the base of a West Antarctic ice stream: Constraints from textural and compositional properties of subglacial debris, *J. Sediment. Res.*, *68*(3).

Turcotte, D. L., and G. Schubert (2014), *Geodynamics*, p. 166, Cambridge Univ. Press, Cambridge.

Wasilewski, P. J., and M. A. Mayhew (1992), The Moho as a magnetic boundary revisited, *Geophys. Res. Lett.*, *19*(22), 2259–2262, doi:10.1029/92GL01997.

Willan, R. C. R. (2003), Provenance of Triassic-Cretaceous sandstones in the Antarctic Peninsula: Implications for terrane models during Gondwana breakup, *J. Sediment. Res.*, *73*(6), 1062–1077.

Winsborrow, M. C., C. D. Clark, and C. R. Stokes (2010), What controls the location of ice streams?, *Earth-Sci. Rev.*, *103*(1), 45–59.