Heat flow variations in the Antarctic Continent

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Abstract

The present work provides a reappraisal of terrestrial heat flow variations in the Antarctic continent, based on recent advances in data analysis and regional assessments. The data considered include those reported at the website of IHFC and 78 additional sites where measurements have been made using a variety of techniques. These include values based on the Method of Magmatic Heat Budget (MHB) for 41 localities in areas of recent volcanic activity and estimates that rely on basal temperatures of glaciers in 372 localities that are known to host subglacial lakes. The total number of data assembled is 491, which has been useful in deriving a 10°x10° grid system of homogenized heat flow values and in deriving a new heat flow map of the Antarctic continent. The results reveal that the Antarctic Peninsula and western segment of the Antarctic continent has distinctly high heat flow relative to the eastern regions. The general pattern of differences in heat flow between eastern and western of Antarctic continent is in striking agreement with results based on seismic velocities.

1. Introduction

It is widely recognized that heat flux from the Earth’s interior is a significant source of thermal energy in Polar Regions. Detailed understanding subglacial geothermal field beneath Antarctic ice sheet is important not only for outlining crustal geothermal conditions but also for understanding deep tectonic processes. Results of early geophysical studies reveal that much of the Antarctic region is below sea level, a consequence of isostatic adjustment of local crust in response to the weight of ice cap. It is bounded by extensional mid-ocean ridge systems. The present adjoining lithospheric segments are Nazca, South America, Africa, Somalia, Australia and Pacific. Figure 1 illustrates the current locations of these plates relative to the Antarctic continent. Note that the upper plate segment of Antarctic Peninsula is in contact with southwestern segment of the South American plate.

The current understanding of rocks and geological structures in Antarctic region beneath the ice have been inferred from the limited areas exposed at the surface as well as from remote sensing technologies that include satellite imagery, ground penetrating radar, use of seismic waves, and study of gravity anomalies. Very little is known of regional heat flow variations within the Antarctic plate segment and its interactions with the geothermal fields of neighbouring tectonic units. A number of geothermal studies have been carried out in the Antarctic region. We mention here a selected list of works by Rink and Hochstein (1974), Engelhardt (2004), Morin et al. (2010), Carson et al. (2014), Schroeder et al. (2014), Fischer et al. (2015), Begelman et al. (2017), Dziadek et al. (2017). One of the convenient ways of minimizing such limitations is to make use of results of suitable geophysical surveys that can provide proxy information useful for assessment of subsurface thermal conditions. In particular, appropriate geophysical survey data on thickness and basal temperatures of glaciers in areas of subglacial lakes may be employed as proxy for estimating regional scale variations in heat flow across Antarctica. This is the approach adopted in the present work.
2. Geologic Context of the Study Area

The Antarctic region may be divided into two distinct geological provinces, separated by the Transantarctic Mountains (see for example Harley et al, 2013). The eastern segment is dominated by cratonic igneous and metamorphic rocks of Precambrian age. Exposures have been mapped along the coast and inland localities, as described in studies of Fedorov et al, (1982), Lisker et al (2003), and Phillips and Laufer (2009). The Transantarctic Mountains is located along the Neoproterozoic passive margin on the edge of the East Antarctic Craton. According to Stump (1995) and Goode (2002) it had transformed into an active convergent margin by the Cambro–Ordovician period. Prominent features of East Antarctica include the Transantarctic Mountains, Gamburtsev mountains, Vostok Highlands, Dronning Maud Land, Prince Charles Mountains, Lambert Graben, Amery Shelf, Pyrydz and Lutzow–Holm bays, Lake Vostok as well as Aurora and Wilkes basins.

On the other hand, West Antarctica comprises several Palaeozoic–Mesozoic terranes dominated by magmatic arc systems. According to Dalziel and Elliot (1982) and Vaughan et al, (2005) these have been subject to active tectonic processes during the Palaeozoic and Mesozoic. Principal blocks of West Antarctica include the Antarctic Peninsula, the Ellsworth–Whitmore Block, Haag Nunataks, Marie Byrd Land, and the Thurston Block.

3. Geothermal data sets

In the present work, we consider heat flow data sets available as parts of global compilations of IHFC, inferred values based on present knowledge of the magmatic heat budget of volcanic settings and estimates that rely on basal temperatures of glaciers in localities which are known to host subglacial lakes. Notable in this context are large data sets derived from basal temperatures and thicknesses of frozen layers that allowed estimates of heat flow in areas of approximately 400 subglacial lakes, distributed mainly in the eastern parts of Antarctica (See for example: Robin et al, 1970; Siegert et al., 2005; Wright and Siegert, 2012).

3.1. Heat Flow Data Reported in Previous Works

As per the website maintained by the International Heat Flow Commission (IHFC, 2009) heat flow values have been reported for 8 localities of the Antarctic continent. The earlier IHFC website is currently inactive. In a more recent work, Martos et al. (2017) reported heat flow values for additional 29 sites. A summary of data reported in these compilations is presented in Table 1. Both compilations have been edited for completing some of the missing details and in eliminating duplicate data. In the case of IHFC data, heat flow in excess of 100 mW/m² has been reported for North Fork basin and Lake Leon. The remaining sites have moderate to low heat flow. In the case of data set reported by Martos et al (2017) values in excess of 150 mW/m² has been reported for Lake Whillans, West Antarctic ice sheet and Hut Point Peninsula (Ross Island). Intermediate heat flow in the range of 80 to 120 mW/m² have been reported for 11 sites. Heat flow in excess of global mean value of 65mW/m² (Vieira and Hamza, 2018) has been found for 6 localities in IHFC compilation and 19 localities in the data set of Martos et al. (2017). Most of high heat flow values (>65mW/m²) are found to occur in west Antarctic region. Relatively low values are found in localities of the east Antarctic region.

| Locality            | Longitude (degree) | Latitude (degree) | q   |
|---------------------|-------------------|------------------|-----|
| DVDP-14/North Fork  | 161.41            | -77.54           | 142 |
| DVDP-12/Lake Leon   | 162.85            | -77.63           | 100 |
| DVDP-3/Ross Island  | 166.67            | -77.85           | 92  |
| DVDP-6/Lake Vida    | 161.81            | -77.38           | 88  |
| DVDP-3/Ross Island  | 166.67            | -77.85           | 84  |
| Nagursk-1           | 47.71             | -80.78           | 57  |
| Nagursk-1.2         | -168.62           | -88.37           | 54  |
| Lake Whillans       | 206.31            | -84.24           | 285 |
| WA Ice Sheet        | -112.09           | -79.49           | 240 |
| Hut Point (Ross Isl.)| 166.67          | -77.82           | 164 |
| McMurdo             | 162.28            | -77.76           | 115 |
| Thwaites Glacier WA | 106.80            | -75.50           | 114 |
| Lake Whillans       | 206.310           | -84.24           | 105 |
| Concordia Subglacial| 125.050           | -74.05           | 100 |
| Dolleman Island     | -60.930           | -70.58           | 100 |
| Dyer Plateau        | -65.000           | -70.50           | 100 |
| Thwaites Glacier WA | 106.80            | -75.50           | 97  |
| Siple Coast         | -155.00           | -82.00           | 90  |
| Bruce Plateau       | -64.07            | -66.03           | 87  |
| Lake Vida           | 161.81            | -77.82           | 85  |
| McMurdo Ice Shelf   | 162.28            | -77.76           | 82  |
| Byrd Station        | -119.52           | -80.01           | 75  |
| Law Dome            | 112.80            | -66.76           | 75  |
| Siple Dome          | -148.81           | -81.65           | 69  |
| EPICA Dome C        | 123.40            | -75.10           | 67  |
| Southern Prydz Bay  | 76.00             | -69.50           | 65  |
| Upper Vincennes     | 122.00            | -73.50           | 65  |
| South Pole          | 0.00              | -90.00           | 61  |
| Dome F              | 39.70             | -75.10           | 59  |
| Vostok              | 106.87            | -78.45           | 53  |
| EPICA Dome C        | 123.40            | -75.10           | 45  |
| Conc. Trench Dome C | 125.05            | -74.05           | 40  |
| Dome C area         | 123.83            | -75.12           | 40  |
| Lower Vincennes     | 122.00            | -73.50           | 40  |
| Rauer Islands       | 77.83             | -68.85           | 40  |
| Vestfold Hills Block| 78.25             | -68.68           | 31  |

3.2. Estimates of Heat Flow for Volcanic Regions

In west Antarctic, there are two major volcanic environments, namely West Antarctic rift system and its associated alkaline provinces, and the volcanic field of northern Antarctic Peninsula. In nearby oceanic regions and in basins surrounding Antarctica there are several intraplate island volcanoes, as for example the active South Sandwich island arc. During post-Cretaceous times, there has been uplift and rifting between West and East Antarctica. The rift system in western segment is still active and hosts much of current volcanic activity in Antarctica. There are also inactive volcanoes in the Transantarctic Mountains. Figure 2 indicates locations of main volcanic systems in the Antarctic region (LeMasurier, et al. 1990).
A list of regions of volcanic activity where residual heat is important may be considered is given in Table 2. Note that most of the volcanic systems are located in west Antarctic region, to the southwest of the Transantarctic Mountains. Areas of recent volcanism are absent in east Antarctica, located to the northeast of this mountain system.

Table 2 – Regions of recent volcanism in Antarctic Peninsula. Alt. – Altitude (m); $E_r$–Estimate of time elapsed since latest magma activity.

| Locality          | Alt. | Longitude (degree) | Latitude (degree) | $E_r$ (Yrs) |
|-------------------|------|--------------------|-------------------|-------------|
| Mount Berlin      | 3478 | -134.13            | -76.05            | <100        |
| Mount Erebus      | 3794 | -167.15            | -77.52            | <100        |
| Brown Peak        | 1167 | 164.58             | -67.42            | <100        |
| Deception Is.     | 602  | -59.37             | -62.95            | <100        |
| Penguin Island    | 180  | -56.10             | -62.10            | <100        |
| Mt. Melbourne     | 2732 | 164.70             | -74.35            | <100        |
| L. Christiansen   | 1640 | -89.48             | -68.77            | <200        |
| Paulet Island     | 353  | -54.22             | -63.58            | 1000        |
| Hudson Mount.     | 749  | -98.50             | -74.42            | 2230        |
| The Pleiades      | 3040 | 165.53             | -72.70            | 3070        |
| Mt. Haddington    | 1630 | -56.37             | -64.22            | 5000        |
| Mt. Takahe        | 3460 | -111.92            | -76.28            | 7570        |
| Mt. Waesche       | 3292 | -125.10            | -77.17            | 8000        |
| Melville Peak     | 549  | 57.68              | -62.02            | 11700       |
| Mount Siple       | 3110 | -125.90            | -73.25            | 19500       |
| R. Soc. Range     | 3000 | 162.67             | -78.17            | 80000       |
| Mount Andrus      | 2978 | -131.77            | -75.80            | 100000      |
| Seal Nunatak      | 368  | -59.70             | -65.05            | 200000      |
| Mt. Morning       | 2723 | 163.58             | -78.52            | 200000      |
| Mount Bursey      | 2787 | -131.37            | -76.02            | 490000      |
| Mount Moulton     | 3070 | -134.87            | -76.05            | 480000      |
| Toney Mt.         | 3595 | -114.20            | -75.80            | 500000      |
| Mt. Terra Nova    | 2130 | -166.05            | -77.52            | 800000      |
| Mount Terror      | 3262 | 168.53             | -77.52            | 820000      |
| Mount Murphy      | 2703 | -109.27            | -75.33            | 900000      |
| Argo Point        | 360  | -59.08             | -66.25            | 900000      |
| Beaufort Island   | 740  | 166.93             | -76.93            | $1.3 \times 10^4$ |
| Bridge Is.        | 240  | -55.27             | -62.07            | $1.3 \times 10^4$ |
| Black Island      | 1041 | 166.42             | -78.20            | $1.7 \times 10^4$ |
| Mount Frakes      | 3654 | -116.30            | -76.80            | $1.7 \times 10^4$ |
| Mt. Discovery     | 2578 | 165.02             | -78.17            | $1.9 \times 10^4$ |
| Franklin Island   | 247  | 168.32             | -76.08            | $2.6 \times 10^4$ |
| Adare Penin.      | 1023 | 170.50             | -71.67            | $2.6 \times 10^4$ |
| Gausberg          | 370  | 89.18              | -66.25            | $2.6 \times 10^4$ |
| Mount Bird        | 1765 | 166.73             | -77.27            | $3.8 \times 10^4$ |
| Mount Sidley      | 3285 | -125.90            | -77.03            | $4.7 \times 10^4$ |
| Mount Harcourt    | 1570 | 169.92             | -72.53            | $5.5 \times 10^4$ |
| Mount Overlord    | 3395 | 164.60             | -73.17            | $7.0 \times 10^4$ |
| Coulman Island    | 1998 | 169.75             | -73.47            | $7.2 \times 10^4$ |
| Mount Steere      | 3500 | -116.18            | -76.73            | $8.0 \times 10^4$ |
| Mt. Hampton       | 3325 | -124.20            | -76.48            | $11 \times 10^4$ |

According to available information (see for example, Harley et al., 2013) most of the recent volcanic activities in western parts of Antarctica have age values less than a few thousand years while the volumes of magma chambers emplaced are in the range of $10^2$ to $10^3$ km$^3$.

Our interest in the present context is in estimating heat flux for volcanic regions in the Antarctic. The starting point is the relation between magma volume (in cubic kilometers) and time elapsed (in years) proposed by Smith and Shaw (1978). It is approximately linear, when both are expressed on log scale.

An example of this line of reasoning is illustrated in Figure 3 where the domain limited by dashed lines may be considered as representing the extent of regions where residual heat is important. It includes west Antarctic Peninsula and regions of transantarctic rift system. In other words, sites falling in the region below the belt of dotted lines may be considered as having potential for retaining residual magmatic heat in subsurface layers. For the same reason, sites falling above the belt of dotted lines may be considered as those with little residual magmatic heat.

According to available information, it is known that the emplacement temperature ofandesitic magma at mid crustal levels is approximately 1200°C while the depth of emplacement falls mostly in the range of 10 to 15 km. For the purposes of the present work, a mean depth value of 12.5 ± 2.5 km has been assumed for all areas of recent volcanism. This is obviously a first order simplification, which can be improved with availability of more reliable data. Noguchi (1970) argued that magma temperatures drop to about 900°C in about 60000 years after emplacement. This argument allows intra-crustal magma chamber emplacement temperature ($T_e$) to be estimated from the elapsed time of emplacement ($t_e$). For the age range of $0$ to $60000$ years, the relation is:

$$T_{em} = 1200 - (300/60000) t_e \quad (1)$$

In this case, $t_e$ is equivalent of $E_r$ in table 2. For times greater than 60000 years, the magma temperature is assumed to drop to about 500°C. The arguments of Noguchi (1970), Annen et al. (2006) and Suarez (2017) are based on petrological considerations and is equivalent to the simplified assumption that temperature gradient in the crust, above regions of magma emplacement, falls from the initial value of about 95°C/km to about 75°C/km in 60000 years. These are
obviously first order estimates but considered sufficient for describing main heat flow variations in regions of deep-seated magma intrusions.

The next step is determination of heat flow corresponding to the emplacement temperature (Te). For a crust with temperature dependent thermal conductivity (λ), the relevant relation for magmatic heat flow (q_v) corresponding to residual temperature (Te) as a function of depth (z) is (Carslaw and Jaeger, 1959; Iyer and Hamza, 2019):

\[ q_v(z) = \frac{\alpha}{\lambda} \ln \left( \frac{0.0011}{\alpha T_0} \right) \]  

(2)

where \( \alpha = 1 + \alpha \delta z \), and \( \alpha = 1 + \alpha T_0 \). \( \alpha \) is the temperature coefficient of thermal conductivity and \( T_0 \) the surface temperature. This approach of estimating heat flow for volcanic regions has been designated as the method of magmatic heat budget – MHB by Vieira and Hamza (2019).

The values of parameter adopted in the MHB method for selected areas of recent volcanism in the Antarctic Peninsula are given in Table 3 for 41 sites.

Table 3 – Values adopted in applying MHB method for estimating heat flow in areas of recent volcanism in the Antarctic Peninsula.

| Volcanic Structure   | \( T_0 \) (Yrs) | \( T_e \) (°C) | \( q_v \) (mW/m²) |
|----------------------|-----------------|----------------|------------------|
| Mount Berlin         | <100            | 1200           | 180 - 220        |
| Mount Erebos         | <100            | 1200           | 180 - 220        |
| Brown Peak           | <100            | 1200           | 180 - 220        |
| Deception Is.        | <100            | 1200           | 180 - 220        |
| Penguin Island       | <100            | 1200           | 180 - 220        |
| Mt. Melbourne        | <100            | 1200           | 180 - 220        |
| L. Christiansen      | <200            | 1199           | 170 - 210        |
| Paulet Island        | 1000            | 1195           | 170 - 210        |
| Hudson Mount.        | 2230            | 1189           | 170 - 210        |
| The Pleiades         | 3070            | 1185           | 170 - 210        |
| Mt. Haddington       | 5000            | 1175           | 160 - 200        |
| Mount Takahe         | 7570            | 1162           | 160 - 200        |
| Mt. Waesche          | 8000            | 1160           | 160 - 200        |
| Melville Peak        | 11700           | 1142           | 160 - 200        |
| Mount Siple          | 19500           | 1103           | 160 - 200        |
| R. Soc. Range        | 80000           | 800            | 120 - 160        |
| Mount Andrus         | 100000          | 700            | 120 - 160        |
| Seal Nunatak         | 200000          | 500            | 80 - 100         |
| Mt. Morning          | 200000          | 500            | 80 - 100         |
| Mount Bursey         | 400000          | 500            | 80 - 100         |
| Mount Moulton        | 480000          | 500            | 80 - 100         |
| Toney Mt.            | 500000          | 500            | 80 - 100         |
| Mt. Terra Nova       | 800000          | 500            | 80 - 100         |
| Mount Terror         | 820000          | 500            | 80 - 100         |
| Mount Murphy         | 900000          | 500            | 80 - 100         |
| Argo Point           | 900000          | 500            | 80 - 100         |
| Beaufort Island      | \( 1.3 \times 10^5 \) | 500            | 60 - 80         |
| Bridgeham Is.        | \( 1.3 \times 10^5 \) | 500            | 60 - 80         |
| Black Island         | \( 1.7 \times 10^5 \) | 500            | 60 - 80         |
| Mount Krekes         | \( 1.7 \times 10^5 \) | 500            | 60 - 80         |
| Mt. Discovery        | \( 1.9 \times 10^5 \) | 500            | 60 - 80         |
| Franklin Island      | \( 2.6 \times 10^5 \) | 500            | 60 - 80         |
| Adare Penin.         | \( 2.6 \times 10^5 \) | 500            | 60 - 80         |
| Gaussberg            | \( 2.6 \times 10^5 \) | 500            | 60 - 80         |
| Mount Bird           | \( 3.8 \times 10^5 \) | 500            | 60 - 80         |
| Mount Sidley         | \( 4.7 \times 10^5 \) | 500            | 60 - 80         |
| Mount Harcourt       | \( 5.5 \times 10^5 \) | 500            | 60 - 80         |
| Mount Overlord       | \( 7.0 \times 10^5 \) | 500            | 60 - 80         |
| Coulman Island       | \( 7.2 \times 10^5 \) | 500            | 60 - 80         |
| Mount Steere         | \( 8.0 \times 10^5 \) | 500            | 60 - 80         |
| Mt. Hampton          | \( 1.1 \times 10^6 \) | 500            | 60 - 80         |

The subscript zero in equation (2) indicate values of parameters evaluated at the surface (\( z = 0; T_0 = 0 \)). These calculations assume a mean value of 0.0011 for temperature coefficient of thermal conductivity (\( \alpha \)) and a mean thermal conductivity (\( \lambda_0 \)) of 2 W/m/K for basic magmatic rocks.

The limitations in the arguments of Noguchi (1970) and Smith and Shaw (1978) impose constraints on the validity of Eq. (2). Thus, heat flow values obtained using this approach should only be considered as first order approximations, useful for initial estimates of heat flow in areas of recent magmatic activity. On the other hand, such limitations are considered to be of minor importance in the present context of heat flow variations for the Antarctic continent.

Note that we have ignored the contribution of radiogenic heat, as it is only of secondary importance in the present context. For values of time elapsed larger than 60000 years it is assumed that the emplacement temperature of magma drops to about 500°C at depths of 12.5km, which imply a heat flow of 80mW/m².

3.3. Heat Flow estimates for Subglacial Lakes

One of the striking features of the Antarctic region is the presence of a large number of lakes beneath the glaciers (See for example: Robin et al., 1970; Siegert et al., 2005; Wright and Siegert, 2012). Subglacial lakes are bodies of liquid water that lie beneath the ice sheet, at the interface between the ice and the bedrocks. With ice acting as an insulator, typical levels of geothermal heat flux are sufficient to warm the ice base to the pressure melting point, even though surface temperatures are tens of centigrade below freezing. Subglacial water accumulations are under the combined forces of gravity and pressure of the ice above and can promote formations of ponds in subglacial hollows and troughs, forming lakes.

About 372 subglacial lakes has been mapped beneath the Antarctic ice sheets. These range from giant stable lakes to small pockets of water connected with fast-flowing ice streams (Wright and Siegert, 2012). The map of Figure 4 illustrates its spatial distribution.

In the present work, the focus is on exploring thermal consequences of melting in isolated localities and its application for determining heat flux beneath ice sheets in Antarctic. A number of parameters control basal ice-sheet temperatures. These include ice thickness, surface
temperature, ice accumulation rate and heat transported by horizontal advection. The basal heat gradient is related to the geothermal heat flux, heat produced from basal sliding and heat derived from internal ice deformation.

In models of basal thermal regimes of glaciers, it is customary to take into account the roles of geothermal heat flux, generation of frictional or strain heat near the base of the ice and the temperature changes arising from the height changes of the ice in the surface layer. The basal heating provides the boundary condition for conventional steady-state conditions in which the temperature does not vary with time at a given level in a vertical column through the ice sheet.

The basal thermal gradient is dependent on flow at the ice-sheet base, and its magnitude will therefore increase with distance from the ice divide as glacier velocity increases. However, at the ice divide, the sole supply of basal heat will be from geothermal processes. Numerical models of the ice-sheet thermal regime in such regions have been employed in estimating thermal energy required to allow basal melting to take place.

An analytical model that can be used for such a purpose was developed by Robin (1955) according to which the ratio of basal temperature of the glacier (\(T_b\)) and the mean annual surface temperature (\(T_s\)) may be written as:

\[
\frac{T_b}{T_s} = 1 - \sqrt{\frac{\pi \alpha}{2 \lambda}} \left(\frac{dr}{dz}\right)_b \text{ erf} \left(\frac{h}{\sqrt{\alpha}}\right)
\]  

(3)

In equation (3) \(z\) is the vertical coordinate (positive upwards and zero at the ice-sheet base), \(h\) is the ice thickness above the subglacial lake, \(b\) the mean annual surface accumulation of ice-sheet above the lake. The parameter \(L\) in Eq. (3) is given by the relation:

\[
L = \frac{2 \lambda h}{\sqrt{\alpha}} \left(\frac{dr}{dz}\right)_b \text{ erf} \left(\frac{h}{\sqrt{\alpha}}\right)
\]  

(4)

where \(\alpha\) is thermal diffusivity of ice, \(\lambda\) its thermal conductivity and \(q\) basal geothermal heat flux and erf the error function (for tabulated values see Carslaw and Jaeger, 1959). The relation for heat flow may be derived from (3) and (4):

\[
q = \lambda \frac{2 \lambda (T_b - T_s) \sqrt{P/2}}{h \sqrt{\alpha} \text{ erf} (P/2)}
\]  

(5)

The parameter \(P\) in Eq. (5) is the ratio of advection to conduction (known as the Peclet number). It may be expressed as:

\[
P = \frac{bh}{\alpha}
\]  

(6)

where \(b\) is the accumulation rate of ice. Equation (5) was used in calculating heat flow values making use of estimates of basal temperatures for 372 subglacial lakes. Heat flow higher than 100 mW/m² has been found for 11 of the lakes.

In most of the sites in East Antarctic region heat flow values are less than the global mean of 65 mW/m² (Vieira and Hamza, 2018). However, there are several localities, mainly in West Antarctic where the heat flow is higher than the global mean. A list of such relatively high heat flow values for 66 sites is presented in Table 4.

Such high values have been considered as arising from hidden geothermal manifestations in subglacial lakes. Detailed list of heat flow values for the remaining 306 sites is presented in the Appendix.
4. New Heat Flow Map of Antarctic Continent

Heat flow data sets discussed in items (2.1), (2.2) and (2.3) were employed in deriving a new heat flow map of the Antarctic continent. Standard mapping procedures adopted for this purpose included calculation of mean heat flow values for a regular grid system of 10 x 10 degrees. However, the fact that not all grid elements have observational data creates a problem in interpolation schemes employed for deriving maps. Thus, representative heat flow values derived from the work of Goodge (2018) were assigned for grid elements that did not have observational data.

Note that the work of Goodge (2018) is based on a model of Van Liefferinge and Pattyn (2013), which averages heat flow values derived from various geophysical data sets such as seismic and satellite magnetic data. The overall geographic disposition of data sets compiled in the present work is illustrated in the map of Figure 5. In this map black circles indicate locations of heat flow values based on basal temperatures of subglacial lakes while the red circles indicate those based on the MHB method.

The new heat flow map for the Antarctic region is illustrated in Figure 6. Note that the region of Antarctic peninsula is characterized by heat flow values in excess of 80mW/m². It appears to be continuation of high heat flow belt in the southwestern parts of the Andean magmatic belt (Vieira and Hamza, 2019). The belt of moderately high heat flow continues to the south of Antarctic peninsula in areas of subglacial lakes. This is a consequence of the fact that thermal regime above the subglacial lakes require heat fluxes of more than 60 mW/m² to maintain basal ice at the pressure-melting point.

The practice of inserting representative theoretical values to fill gaps in observational data sets is similar to that adopted in deriving global heat flow maps (Hamza et al, 2008; Davies and Davies, 2010; Vieira and Hamza, 2018). On the other hand, large parts of the eastern Antarctic region are characterized by heat flow values lower than the global mean. This observation is in general agreement with those observed for Precambrian cratonic regions. In the interior parts of eastern Antarctica areas with heat flow less than 50mW/m² seem to occur along a north south trending belt. The separation between low and high heat flow belts occur along the position of Transantarctic Mountains.

5. Conclusions

The present work provides a new look into the nature and distribution of terrestrial heat flow in the Antarctic continent, based on recent advances in data analysis and regional assessments. The datasets considered include that compiled by the global data base of IHFC, inferences based on volcanic settings and estimates that rely on basal temperatures of glaciers in localities that are known to host subglacial lakes. Most heat flow values reported in the present work are in reasonable agreement with results discussed in several previous studies (e.g. Begelman et al., 2017; Carson et al., 2014; Dziadek et al., 2017; Engelhardt, 2004; Fisher et al., 2015; Risk and Hochstein, 1974; Salamatin et al., 1998; Schröeder et al., 2014).

The high heat flux in areas of subglacial lakes appears to be a consequence of active hydrological systems believed to be operating beneath the glaciers. The eastern region is characterized by relatively low heat flow values in the range of 30–60 mW/m², as expected for dominantly cratonic regions. This observation appears to be in general agreement with the Curie depth values derived from spectral analysis magnetic survey data. The major features in the new heat flow map of the present work reveal striking agreement with conclusions of An et al. (2015), based on seismic velocities.

The new heat flow map is believed to have potential implications not only in studies of regional tectonics, but also in a better understanding of geothermal systems operating beneath subglacial lakes.

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### Appendix

**Heat flow data for 306 localities based on basal temperatures of glaciers in the Antarctic region, with values higher than the global mean of 65 mW/m² (Vieira and Hamza, 2018).** (GT – Glacier thickness; q – Heat Flow)

| Location          | Long | Lat  | GT (m) | q (mW/m²)          |
|-------------------|------|------|--------|-------------------|
| MacAyeal        | 135.69 | -70.25 | 1260.87 | 34270             |
| Academyley2     | 135.69 | -70.25 | 1260.87 | 34270             |
| Bindschadler2   | 135.69 | -70.25 | 1260.87 | 34270             |
| Recovery5       | 135.69 | -70.25 | 1260.87 | 34270             |
| Recovery6       | 135.69 | -70.25 | 1260.87 | 34270             |
| Lake Ventok     | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-2             | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-3             | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-4             | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-5             | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-6             | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-7             | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-8             | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-9/16/20      | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-10            | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-11/11/16     | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-12            | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-13/14/14/16/10| 135.69 | -70.25 | 1260.87 | 34270             |
| SI-15            | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-16            | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-17            | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-18            | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-19            | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-20            | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-21            | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-22            | 135.69 | -70.25 | 1260.87 | 34270             |
| SI-23            | 135.69 | -70.25 | 1260.87 | 34270             |

International Journal of Terrestrial Heat Flow and Applied Geothermics, VOL. 3, NO. 1 (2020); P. 1-10.
| Location | No. 1 | No. 2 | No. 3 | No. 4 | No. 5 | No. 6 | No. 7 | No. 8 | No. 9 | No. 10 | No. 11 | No. 12 | No. 13 | No. 14 | No. 15 | No. 16 | No. 17 | No. 18 | No. 19 | No. 20 | No. 21 | No. 22 | No. 23 | No. 24 | No. 25 | No. 26 | No. 27 | No. 28 | No. 29 | No. 30 | No. 31 | No. 32 | No. 33 | No. 34 | No. 35 | No. 36 | No. 37 | No. 38 | No. 39 | No. 40 | No. 41 | No. 42 | No. 43 | No. 44 | No. 45 | No. 46 | No. 47 | No. 48 |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|----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| Location     | Latitude | Longitude | Heat Flow (°C/m) | Reference |
|--------------|----------|-----------|------------------|-----------|
| EAP8         | 109.85   | -75.19    | 3612             | 49        |
| EAP9         | 135.56   | -75.81    | 3584             | 49        |
| Kamb11       | 239.86   | -81.25    | 2489             | 59        |
| Kamb12       | 242.92   | -80.85    | 2847             | 55        |
| Mulock1      | 149.11   | -76.09    | 2766             | 56        |
| Nimrod1      | 184.27   | -70.89    | 3169             | 52        |
| Nimrod2      | 141.00   | -84.32    | 3300             | 51        |
| Recovery7    | 354.02   | -81.64    | 2141             | 64        |
| Recovery8    | 355.88   | -81.80    | 2250             | 62        |
| Recovery9    | 3.33     | -82.91    | 2375             | 61        |
| Recovery10   | 5.94     | -83.50    | 2455             | 60        |
| Recovery11   | 8.42     | -81.72    | 2651             | 57        |
| Totten1      | 107.50   | -70.10    | 2455             | 60        |
| Totten2      | 110.51   | -70.83    | 3942             | 47        |
| Vostok1      | 106.83   | -77.17    | 3739             | 48        |
| Whillans8    | 246.40   | -83.50    | 2794             | 56        |
| Wilkes1      | 106.71   | -68.81    | 3245             | 52        |
| Wilkes2      | 121.57   | -68.70    | 2132             | 64        |
| R03Wa_1      | 130.40   | -70.43    | 3910             | 47        |
| R04Wa_9      | 135.00   | -71.62    | 2790             | 56        |
| R05Wa_4      | 128.12   | -71.67    | 3284             | 51        |
| R05Wa_5      | 129.05   | -71.84    | 3750             | 48        |
| R06Wa_4      | 127.04   | -72.88    | 3869             | 47        |
| R07Wa_9      | 126.02   | -73.44    | 3707             | 48        |
| R07Ta_1      | 125.65   | -73.91    | 3644             | 49        |
| R08Wa_0.1    | 122.50   | -74.29    | 3745             | 48        |
| R08Wa_0.2    | 122.50   | -74.30    | 3709             | 48        |
| R13Wa_8      | 106.04   | -75.98    | 3521             | 50        |
| R15Wa_4      | 100.82   | -74.08    | 3523             | 50        |
| Byrd2        | 146.89   | -80.68    | 2161             | 64        |