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# Speaking about Heat Flow, Ice Fusion and Temperature Alterations

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**Abstract.** Heat flow density measurements are difficult to obtain in Antarctica and Greenland due to climate and ice thickness in those regions. The works published about that subject shows that spatial distribution of the heat flux values is highly heterogeneous. Maximum and minimum values of heat flux vary with different authors and method used, but all of them say that East Antarctic is characterized by low heat flux values ( $45\text{--}85\text{ mW m}^{-2}$ ) with the lowest values found especially in the central part. The values obtained in West Antarctic ( $65\text{--}180\text{ mW m}^{-2}$ ) and in the Antarctic Peninsula (maximum of  $170\text{ mW m}^{-2}$ ). In the work whose data is used high values were obtained in the West Antarctic Rift system (maximum value of  $130\text{ mW m}^{-2}$ ). Some local geothermal anomalies have been reported such as Lake Wilhams ( $285\text{ mW m}^{-2}$ ) or Siple Dome ( $69\text{ mW m}^{-2}$ ). Elevated heat flux values are obtained in volcanic regions and in regions with relatively recent tectonic activity, in West Antarctic. The east Antarctic is characterized by low values, however the Coastal part of Queen Mary Land, the Lambert Rift and Victoria Land, show higher values, suggesting Cenozoic processes in the region, including volcanism or extension. Ice fusion occurs near the base of the ice sheet. In order to study these fact relations between heat flux, bed, thickness and ice altitude were studied. In regions with bottom of the ice below sea level ice melting of the ice occurs. The amount of ice obtained is under the measured value. The effect of sea water interacting with ice must be considered. Temperature values alterations at the surface may be found in the ice, including alterations due to last glaciations must they are not the cause of ice melting.

## 1. Introduction

Heat flow density measurements are difficult to obtain in Antarctica and Greenland due to climate and ice thickness in those regions. The heat flow density maps in the region were made using values derived from different data like magnetism and seismology. Data used in this work were obtained from Curie depth values [1] considering a uniform thermal conductivity value of  $2.8\text{ W K}^{-1}\text{ m}^{-1}$  for material under the ice and heat sources of  $2.5 \times 10^{-6}\text{ W m}^{-3}$ , near the surface of rock. The heat flow map used [1] shows values from  $45$  to  $85\text{ mW m}^{-2}$  in East Antarctica and values from  $60$  to  $180\text{ mW m}^{-2}$  in West Antarctica. The highest values are found in the West Antarctic Rift System (maximum value of  $130\text{ mW m}^{-2}$ ) and in the Antarctic Peninsula (maximum values of  $170\text{ mW m}^{-2}$ ). A value of  $59\text{ mW m}^{-2}$  was obtained in the South Pole. The lowest values of heat flow were obtained in the Central Part of Antarctica. Local geothermal anomaly values were not considered in this work.

## 2. Heat flow, ice thickness and topography

Relationships between heat flow, bed topography (bottom of the ice), ice thickness and altitude of ice surface were studied using values from two profiles presented in [1]. The first profile obtained in East



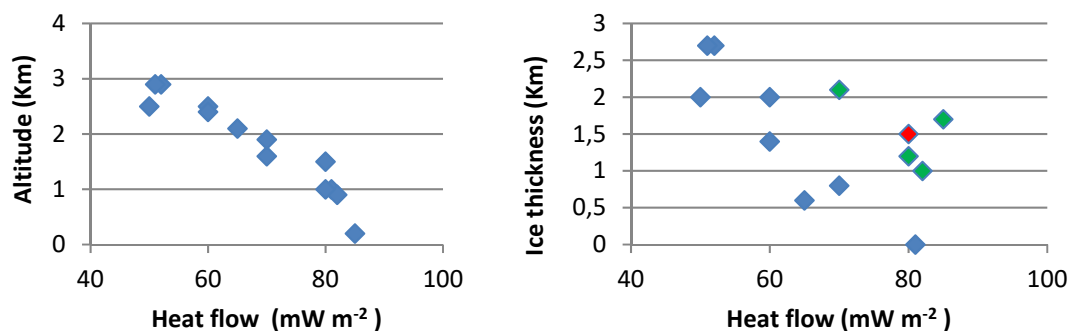
Antarctica is located near the coast and includes Lambert Rift, the second profile obtained in Western Antarctica includes part of the West Antarctic Rift System (WARS). Data of bed topography and ice altitude in the central part of Antarctica, including the South Pole, were obtained in work [2].

### 2.1. Heat flow and bottom of the ice

The highest values of heat flow (from 80 to 140  $\text{mW m}^{-2}$ ) were obtained in regions with the bottom of the ice under the mean sea level. Places with bottom ice above mean sea level are associated to low heat flow values (from 45 to near 89  $\text{mW m}^{-2}$ ). Heat flow values around 80  $\text{mW m}^{-2}$  were found in regions with bottom ice around the mean sea level. Low heat flow values were obtained in the central part of Antarctica with bottom ice above mean sea level. The South Pole is an exception, with bottom of the ice close to mean sea level and a low heat flow value.

### 2.2. Profile including Lambert Rift (East Antarctica)

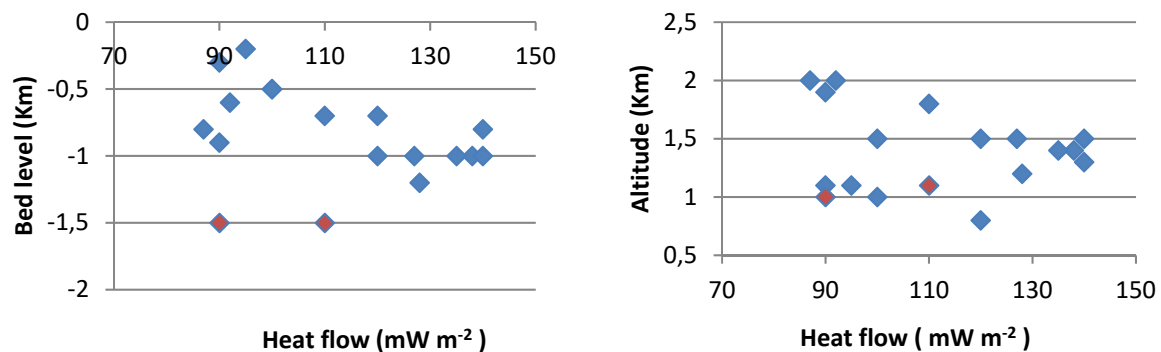
A clear relation was obtained between altitude of the ice surface and heat flow value (Figure 1). Low heat flow values were obtained in regions close to 3 Km high. Ice thickness show a decrease when heat flow increases, in places with bed altitude above mean sea level (blue values in Figure 1). High heat flow values associated with the Lambert Rift also show a similar relation but with a different slope (green values in Figure 1). The red point is the thickness of the ice with the bottom level at mean sea level and a heat flow value of 80  $\text{mW m}^{-2}$ . The maximum bed topographic level is 1 Km, in one side of the Rift, with a heat flow value of 60  $\text{mW m}^{-2}$ , and 1.5 Km, on the other side of the Rift, with a heat flow value of 65  $\text{mW m}^{-2}$ .



**Figure 1.** Heat flow, ice surface altitude and ice thickness in profile including Lambert Rift

### 2.3. Profile in West Antarctica

A clear relation between heat flow, ice thickness and altitude of the ice surface was not found in places with bed of the ice under mean sea level. Figure 2 show values of bottom level versus heat flow and values of altitude versus heat flow. A clear relation is not visible but in the graph on the right it is possible to see a relation between altitude of the ice versus heat flow values. It is important to see that values apparently anomalous in the graph on the left appear with a normal position in the graph of the right. Apparently only heat flow values between 90 and 100  $\text{mW m}^{-2}$  obtained in places with altitude value around 1 or 1.1 km seems to be anomalous. The heat flow values around 140  $\text{mW m}^{-2}$  are obtained in the central part of the rift. The red values were obtained in places with local topographic anomalies but with similar results (increase in ice thickness with increased bed depth).



**Figure 2.** Heat flow, bed level and ice surface altitude in profile of west Antarctica

Heat flow values obtained in places with bed topography above sea level range from 58 to 80  $\text{mW m}^{-2}$ . They are inversely related with ice surface altitude. The maximum altitude value of 2.5 Km is associated to a heat flow value of 58  $\text{mW m}^{-2}$  and the minimum value of 1.5 Km is associated to heat flow values around 80  $\text{mW m}^{-2}$ .

#### 2.4. Other values

Three different places were studied in the Central part of Antarctica. The South Pole with bed topography near zero Km has a thickness of 2.8 km and altitude of 2.8 Km. The heat flow values obtained is 59-60  $\text{mW m}^{-2}$ . Ganburshev mountains with a bed level of 1 Km, a thickness of ice of 2 Km and an altitude of ice of 3 Km is associated to a low heat flow value around 50  $\text{mW m}^{-2}$  and in the East Antarctic Ice Sheet the bed altitude is 0.7 Km, ice thickness of 3.1 Km and an ice altitude of 3.8 Km, the heat flow values are around 43  $\text{mW m}^{-2}$ . Using the three results obtained we can say that low heat flow values are associated to higher ice altitude values.

### 3. Ice melting

Ice melting occurs near the base of the ice sheet. This fact can be tested considering thermal and mechanic equilibrium in the ice system, from the bottom to the surface. The heat flow value in one place is used as the heat flow density entering in the base of the ice. A thermal gradient values is obtained using an average value for the thermal conductivity of the ice considering the temperature at the surface as minimum temperature in the system and  $0^{\circ}\text{C}$  as the maximum temperature of ice. The temperature values at the surface, in regions near the sea, is obtained using altitude values (a decrease of 10 degrees is used per Km of altitude increase). Values of  $-10^{\circ}\text{C}$  at sea level are considered in West Antarctica and  $-20^{\circ}\text{C}$  for the East Antarctica. The values used in the Central Part of Antarctica can be found in the literature. The temperature at the ice bottom can be estimated using the temperature value at the surface and the thermal gradient obtained previously. In some of the places studied the temperature value obtained for the bottom of the ice is a positive value. This result is physically impossible indicating heat loss by another process. A latent heat of fusion value of  $333 \text{ KJ Kg}^{-1}$  was used in the calculus of the amount of ice molten and the thickness of the molten ice per year was obtained using a density value of  $917.5 \text{ Kg m}^{-3}$  for the ice. The results obtained with the described model can be found in Table 1. It is important to note that the word bed means altitude of the bottom of the ice, the altitude presented is the altitude of the surface of ice, considered at a temperature  $T_0$ .  $Q^*$  is the heat used to molten the ice and  $h$  is the thickness of the molten ice per year.

**Table 1.** Heat flow values, thickness, thermal conductivity, temperature at the ice surface and thickness of molten ice per year obtained with the method described in the text

## Central Part

Q (mW m <sup>-2</sup> )	Bed ( Km)	Altitude (Km)	$\lambda_{\text{gelo}}$ (W K <sup>-1</sup> m <sup>-1</sup> )	T <sub>0</sub> (° C )	Q* (mWm <sup>-2</sup> )	h (mm ano <sup>-1</sup> )
43	0.7	3.8	2.62	-65	N/A	N/A
50	1.3	2.7	2.55	-48.8	N/A	N/A
55	1.3	2.7	2.55	-48.8	N/A	N/A
60	0	2.8	2.58	-50	43.8	1.7

## E A –Near the coast

Q (mW m <sup>-2</sup> )	Bed ( Km)	Altitude (Km)	$\lambda_{\text{gelo}}$ (W K <sup>-1</sup> m <sup>-1</sup> )	T <sub>0</sub> (° C )	Q* (mWm <sup>-2</sup> )	h (mm ano <sup>-1</sup> )
50	0.5	2.5	2.47	-45	N/A	N/A
60	0.5	2.5	2.47	-45	5.5	0.6
80	0.0	1.5	2.40	-35	24.2	2.5
80	-0.2	1	2.36	-30	22	2.3
85	-1.5	0.2	2.30	-20	58.6	6.0

## W A –Near the coast

Q (mW m <sup>-2</sup> )	Bed (Km)	Altitude (Km)	$\lambda_{\text{gelo}}$ (W K <sup>-1</sup> m <sup>-1</sup> )	T <sub>0</sub> (° C )	Q* (mWm <sup>-2</sup> )	h (mm ano <sup>-1</sup> )
87	-0.8	2	2.38	-30	62	6.4
90	-0.3	1.9	2.37	-29	59.3	6.1
92	-0.6	2	2.38	-30	65.0	6.7
110	-0.7	1.8	2.37	-28	83.9	9.1
128	-1.0	1.8	2.37	-28	104.7	10.8
135	-1.0	1.4	2.33	-24	112.2	11.6
140	-0.8	1.5	2.33	-25	115.2	11.9

Using the results presented in Table 1, it is possible to say that in the points studied in the Central Part the need of molten ice appeared only in the South Pole. The bottom of the ice is located near the mean sea level and the ice thickness is around 2.8 Km. The thickness of the ice molten layer obtained in places located near the coast seems to increase with heat flow values.

The model used was built considering dry ice but the bottom of the ice is under mean sea level in most places (only in one place the bottom ice level is 0.5 Km). This means that sea water can fill some cracks or micro channels that may exist in the ice or in the contact zone with the adjacent rock. This means that the ice near the depths were molten occurs can be considered as “wet ice”. As a consequence the thermal conductivity of the ice has a different value due to the presence of liquid water with lower thermal conductivities than ice. A lower value of thermal conductivity must be expected for the material at these depths.

Many places in table 1 shows that the bottom of the ice sheet is below sea level. The values found for the thickness of melted ice are under the values presented [3] as average values for thinning at the grounding line between 2010 and 2016 in the West Antarctica. A possible explanation is the effect of sea water (warm water) in melting and thinning the ice at the boundary between the ice sheet grounded to the bed rock and the floating ice [4].

#### 4. Temperature changes near the surface

Time variations of temperature at the Earth's surface affect subsurface temperatures. The perturbations found depend on the temperature change value and the time interval of the occurrence. Thermal physical properties of the ground are also important. A short temperature perturbation of amplitude  $\Delta T$

and duration  $\delta t$  occurred at time  $t$  before present will have its maximum temperature perturbation at a depth  $Z = (2 k t)^{0.5}$  and its amplitude will be [5]

$$\Delta T_{max} = 0.147 \Delta T \frac{\delta t}{t} \quad (1)$$

The parameter  $k$  is the thermal diffusivity of the soil (In our case the  $k$  is the thermal diffusivity of the ice).

Using a surface air temperature anomaly of  $-6^{\circ}\text{C}$  for Last Glacial Maximum [6], during the period 19-23Ka BP, in the South Pole and surrounding region, considering an ice thermal diffusivity value of  $1.44 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ , the maximum temperature occurrence at present will be found at a depth of 1313 m and its maximum value will be  $-0.186^{\circ}\text{C}$ . The ice thickness near the South Pole is 2.8 Km at present. The average rate of ice accumulation near the South Pole is [7]  $\sim 7.5 \text{ cm / year}$ . The record used in the work referred was obtained during a time interval of 2000 years and shows high variability in the accumulation values associated to climate variations in the region. Using this average rate and the present ice thickness, it is possible to predict this temperature perturbation in the region. Another important alteration at surface temperature is the warming after the last glacial retreat 10,000 years ago. Considering an increase of surface temperature of  $4^{\circ}\text{C}$  at that time, the depth of the maximum perturbation at present will be at a depth of 952 m and its maximum value will be  $1.28^{\circ}\text{C}$ , calculated considering a jump of  $4^{\circ}\text{C}$  at 10,000 years before present [5].

$$T(Z) = \Delta T \operatorname{erfc} \left( \frac{Z}{2 \sqrt{kt}} \right) \quad (2)$$

Recent changes in temperature will be present in depths close to the surface. Considering an increase in temperature of  $1^{\circ}\text{C}$ , during 200 years finished at 210 years ago, the maximum temperature perturbation will be  $0.14^{\circ}\text{C}$  at a depth of 138 m.

The values presented were obtained using an ice thermal diffusivity calculated for a temperature of  $-30^{\circ}\text{C}$ . For ice sheet values with higher temperatures (near the coast) the values of this parameter must be changed.

## 5. Discussion

The heat flux map used was obtained using airborne magnetic data considering that magnetite Curie depth coincides with  $580^{\circ}\text{C}$  isotherm. The heat flux values were obtained considering heat conduction under steady state conditions in the vertical directions. No lateral variation of properties was considered. An average thermal conductivity value of  $2.8 \text{ W m}^{-1} \text{ K}^{-1}$  was considered in all the model. In a recent work [8] the geology data from the Antarctic Peninsula is analyzed and the heterogeneity of the region is presented. This fact may hide local flow anomalies and horizontal conduction of heat. Thermal conductivity differences may occur due high temperature values found in /near volcanic active regions. The results obtained in this work can be considered as indicators of possible variations in the different places studied but numerical values obtained must be viewed with some caution.

Depths of temperature anomalies obtained with the simple models used cannot be used directly due to the ice accumulated since the temperature alteration to the present time, but temperature alterations of the past can be detected in the holes. Temperature alterations in sea water may be important specially if current alterations can occur due to temperature of sea water. Average temperature values must be avoided due to different temperature alterations detected [6] in some parts of the Antarctic Coast.

## 6. Conclusions

Analysis of ice thickness, bed and surface altitude of the ice and geothermal heat flow leads to the existence of melting ice to keep the system in balance but the amount of molten ice is less than the

mass loss detected. Bed altitude is above the sea in places with high values of heat loss and the influence of sea water on the system must be considered.

Temperature alterations at ice surface, occurred in a small interval of years, cannot be responsible for the fusion in the bottom of the ice sheet but the influence of a temperature raise at the end of the last glaciations can be detected at present. The effect of temperature alterations of sea water near the base of the ice sheet must be studied from place to place and sea water movement must be known.

The heat flow map used was constructed using an average value for the thermal conductivity. Geology in the region can show heterogeneity and different thermal conductivity values originating alterations in heat flow distribution.

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