How Hot is Antarctica? Constraining Crustal Heat Production

Thesis submitted in accordance with the requirements of the University of Adelaide for an Honours Degree in Geology/Geophysics

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HOW HOT IS ANTARCTICA?

ABSTRACT

Antarctica is more influential to sea level rise, and has a lower level of outcrop than any other continent on the planet. The main factor in Antarctica's influence to sea level is its reaction to the warming oceans surrounding it, which is influenced by basement heat flux and crustal heat production. In this study, a new Gamma Ray spectrometry method was developed and calibrated which allows the fast, accurate calculation of a rock's heat production through the analysis of the smallest of hand samples, without destroying the samples themselves. This method is applied to a large collection of hand samples collected throughout Antarctica and the resulting data is compiled into a dataset of Antarctic bedrock geochemistry and is compared to ice flow velocity of similar areas, in an attempt to give insight into the influence of crustal heat production in ice flow velocity and Antarctica's reaction to global warming. Although the dataset is subject to bias based on a lack of objectivity during collection, it can be argued that a basic correlation can be seen between heat production and ice flow velocity. Comparing heat production values to geological ages also shows that younger rock types generally have higher heat production values than those of the Proterozoic or Archaean eras.

KEYWORDS

Antarctica, geochemistry, geophysics, heat production, radiogenic, gamma ray spectrometry

TABLE OF CONTENTS

Appendix A: Geochemical Dataset https://www.dropbox.com/s/m8pwcdo8dapxmgs/Appendix%20A%20-%20Geochemical%20Dataset.xlsx?dl=0

Appendix B: Method Calibration Data https://www.dropbox.com/s/6kacpjh7yhsc1zw/Appendix%20B%20-%20Method%20Calibration%20Data.xlsx?dl=0

Appendix C: Method Test Data https://www.dropbox.com/s/qvbopzng8p2ph71/Appendix%20C%20-%20Method%20Test%20Data.xlsx?dl=0

LIST OF FIGURES AND TABLES

1. INTRODUCTION

Antarctica has the least known geology of any continent in the world, yet is the most influential continent to Sea level as its overlying ice sheets react to the warming of the surrounding oceans. Thus, understanding the behaviour and stability of these ice sheets is paramount in assessing the risk involved with global warming.

Antarctica is home to a number of geological provinces, with varying ages, rock types and geochemical compositions. This high variance results in a similarly varying crustal heat production, and a variable heat flux into the base of the overlying ice sheets. These provinces are rarely seen inland as rock outcrop covers only 0.18% of Antarctica's total land area, but their extent inland, along with their relationship to the Australian and Indian geology, has been modelled by (White, Gibson, Lister, 2013) in their reconstruction of the Gondwanan plate and the Antarctic-Australian break up (see Figure 1).

The heat flux into the Antarctic ice sheets plays an important role in the stability and flow rate of the ice, and the response of the ice sheets to warming oceans. A high heat flux leads to decoupling of the ice sheets from the underlying bedrock through melting of the ice sheet base and may allow ice sheet flow over the bedrock, resulting in a greatly increased flow rate than through internal deformation (Lubes, Lanseau, Rémy, 2006).

A total of nine boreholes have been used to determine the heat flux over the continent (see Figure 1), with results varying from 60-285mWm^{-2} in the West Antarctic ice sheet (Fisher, Mankoff, Tulaczyk, Tyler, Foley, 2015; Schroeder, Blackenship, Young, Quartini, 2004.) and 46-73 mWm^{-2} in the East Antarctic ice sheet (Zhang, Talalay, Markov, 2015).

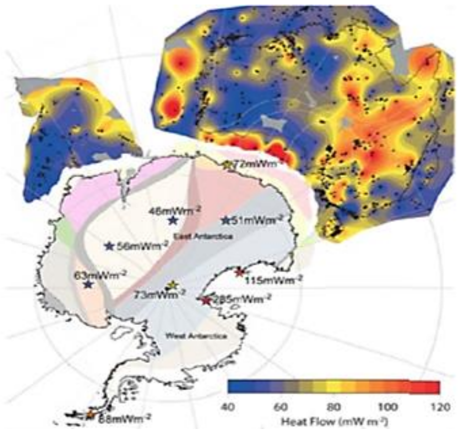


Figure 1: Model showing Antarctic geological provinces (White et al. 2013) and borehole locations with accompanying heat flux measurements (Fisher et al. 2015, Schroeder et al. 2004) and current heat flux measurements in Australia and India (Hasterok, 2010 (www.heatflow.org)).

These values are especially important when combined with models from (Lubes et. al. 2006) and (Budd, Jacka, 1989.) that show that ice sheet viscosity decreases dramatically as basal ice sheet temperature rises from ca. -10°C to melting point (See Figure 3), and that an increase in heat flux from 40mWm^{-2} to 60mWm^{-2} would result in a 450% increase in the region approaching or exceeding melting point (See Figure 2).

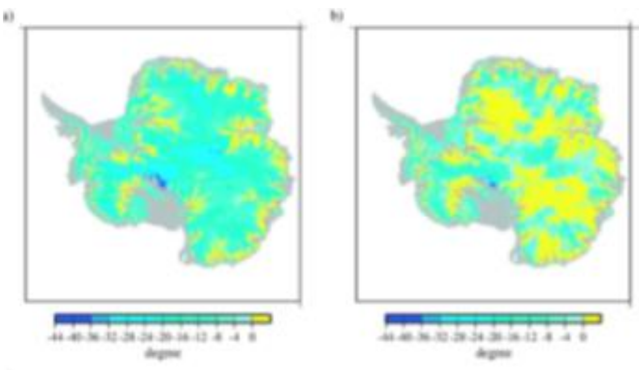


Figure 2: Model showing difference in basal ice temperature with a heat flux of 40mWm^{-2} (Left) and 60mWm^{-2} (Right) (Llubes et al. 2006).

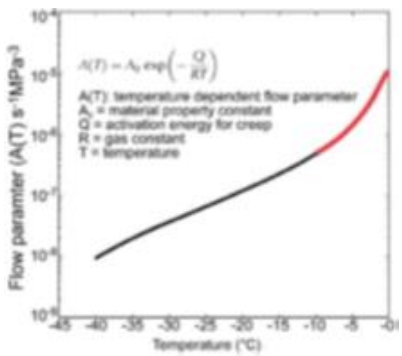


Figure 3: Relationship between ice temperature and viscosity, showing a rapid increase in flow rate as ice approaches melting point.

Unfortunately, borehole data over Antarctica is scarce, and with such varying heat flux values and bedrock geology, it would be necessary to have a more spatially dense survey of the continent, which is impractical due to the logistical problems of using this method in such difficult locations.

In a study by (Pittard, Galtin-Fenzi, Roberts, Watson, 2016), a number of large granites with high heat flow were inserted beneath the ice sheets of the Lambert-Amery region to examine the change in ice velocity. The study showed that ice sheet velocity increased in each experiment, and that the amount of increase in ice sheet velocity was much higher for areas of low initial velocity. This showed that bedrock heat production can have a significant influence on ice flow velocity, especially in areas of low geothermal heat flow.

The heat production of Antarctic bedrock samples can be calculated from their concentration of heat producing elements, Potassium, Uranium and Thorium, which can be obtained through gamma ray spectrometry of XRF. But Gamma ray spectrometry can only be applied in the field, which poses logistical problems when considering remote areas with limited access, and XRF requires samples to be crushed, which can prove expensive and time consuming when applied to a large set of samples.

The aim of this project is to develop and apply an unconventional, non-destructive method to determine the concentrations of K, U and Th to a number of samples of

Antarctic bedrock held by the University of Adelaide from Adelie Land and Wilkes Land, and combine the results with geochemical data on Antarctic bedrock samples used in various other studies to compile a large dataset of geochemical concentrations, which will be used to calculate bedrock heat production and relate it to areas of differing ice flow rates. Although this ice flow comparison will have no statistical significance, it may give a good overview of the heat production of the Antarctic bedrock and the influence of that heat production on ice flow.

2. METHODS

2.1 Geochemical Dataset Gathering

For a large, detailed dataset of Antarctic rock sample geochemistry, the geochemical composition of samples analysed in various studies, as published in various theses, were gathered and added to geochemical data from samples analysed through unconventional gamma ray spectrometry.

2.2 Unconventional Method Calibration

In the development of an unconventional method, a number of crushed samples with known Potassium, Uranium and Thorium concentrations were analysed using a portable gamma ray spectrometer. Due to their small size, the gamma ray spectrometer only calculates a small percentage of the true concentration of the samples, as it only reads a small percentage of the radiation it would otherwise read when used in the field.

To calibrate the experimental spectrometry method, a set of calibration curves similar to (Chiozzi, De Felice, Fazio, Pasquale, Verdoya, 2000) were used, where the recorded radiation of known samples of a particular size was plotted against their true geochemical composition. This calibration method is unique in that it uses a number of calibration curves that represent different sample sizes, as a difference in sample size will result in differences in the total radiation recorded. The unknown samples can then be matched to a calibration curve based on size. This method should allow samples ranging in mass from 1000 grams and above to be accurately analysed. This method should also allow large sets of samples to be analysed quickly, cheaply and without damaging the samples themselves. This way the samples can also be used for other analytical methods, such as geochronology or apatite fission tracks.

2.3 Method Setup

The selection of samples used in this method consisted of the East Antarctic rock samples currently held by the University of Adelaide above a minimum size limit of 1000 grams. The samples were placed, along with a gamma ray spectrometer using a high density Bismuth Germanate detector, inside a large, stainless steel plated, lead chamber with thick walls to shield the system from background radiation (see Figure 4). The samples were then analysed for a period of 300 seconds, and the geochemical composition of the samples were determined using the produced calibration curves.

Figure 4: Image showing the method calibration setup, with the portable gamma ray spectrometer in front of a mixture of rock powder and fragments, inside a thick-walled lead chamber.

2.4 Method Test

In order to test the accuracy of the method, it was applied to a number of samples collected from the Windmill Islands, where a number of geochemical readings were conducted in the field, and the calculated heat production histogram for the entire area was plotted against a test histogram produced from the field derived values. The comparison of the position of the mean and the spread of the data would then determine the overall accuracy of the method.

2.5 Heat Production Calculation

The geochemical data of the analysed samples and those gathered from other studies was then used to calculate heat production (in mWm^{-3}) using the equation $\mathbf{H=10^{-8}\rho(3.48c_K + 9.52c_U + 2.56c_{Th})}$ where ρ is the rock density, and c_K, c_U and c_{Th} are the concentrations of Potassium (wt%), Uranium (ppm) and Thorium (ppm) respectively. Due to the lack of Density data in the gathered samples, and the time restrictions for the study, rock density was estimated based on rock material, with an estimated density of 2700 kg/m^3 for Felsic, 2850 kg/m^3 for Intermediate and 3000 kg/m^3 for mafic material.

2.6 Ice Flow Comparison

The heat production values calculated from the analysed samples, along with the data collected from other studies, were plotted on a map of Antarctica and compared to an ice flow map produced by NASA (See Figure 5) in an attempt to distinguish any kind of correlation or relationship between basement rock heat production and overlying ice flow.

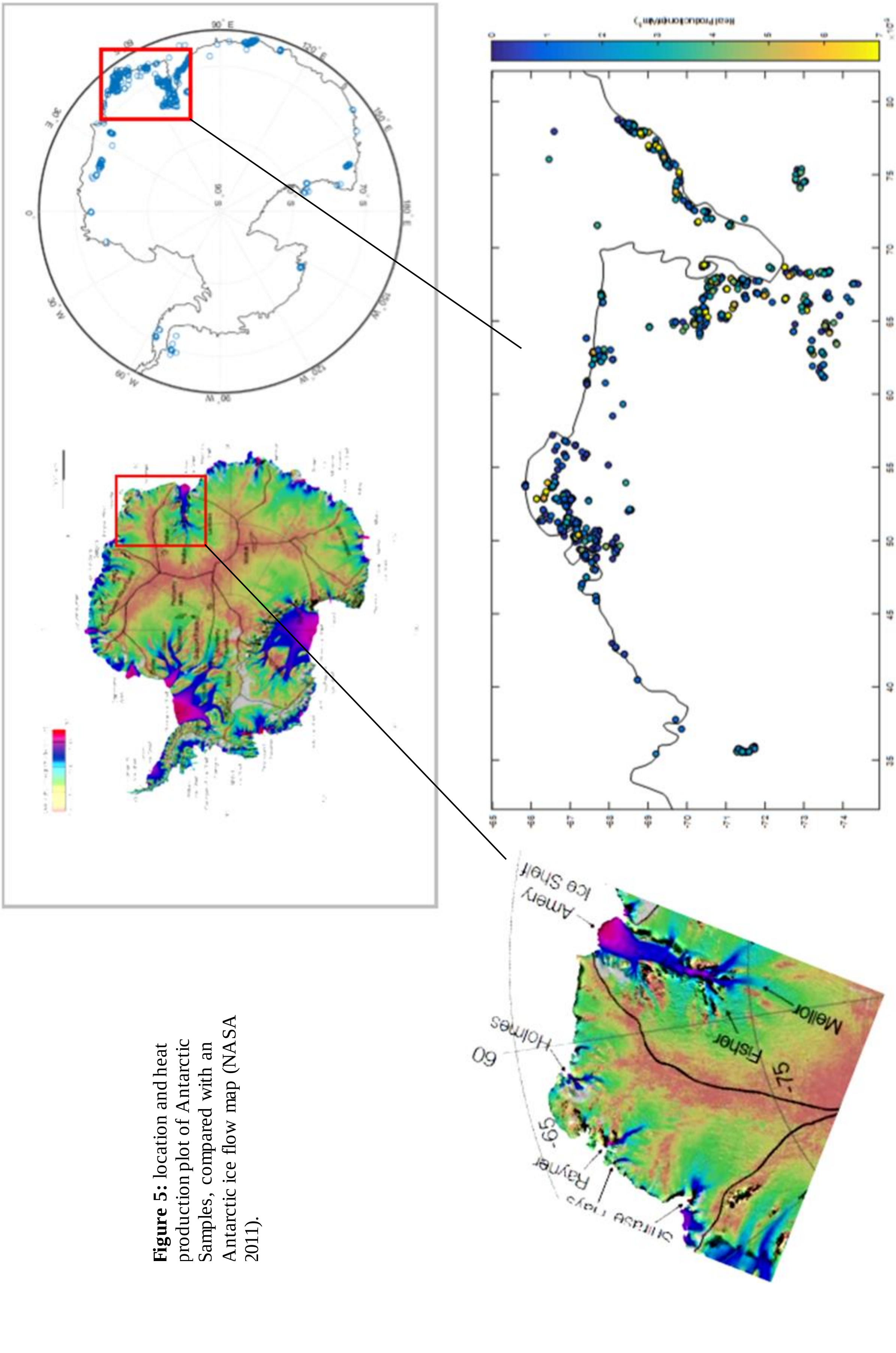


Figure 5: location and heat production plot of Antarctic Samples, compared with an Antarctic ice flow map (NASA 2011).

3. RESULTS

3.1 Geochemical Dataset Gathering

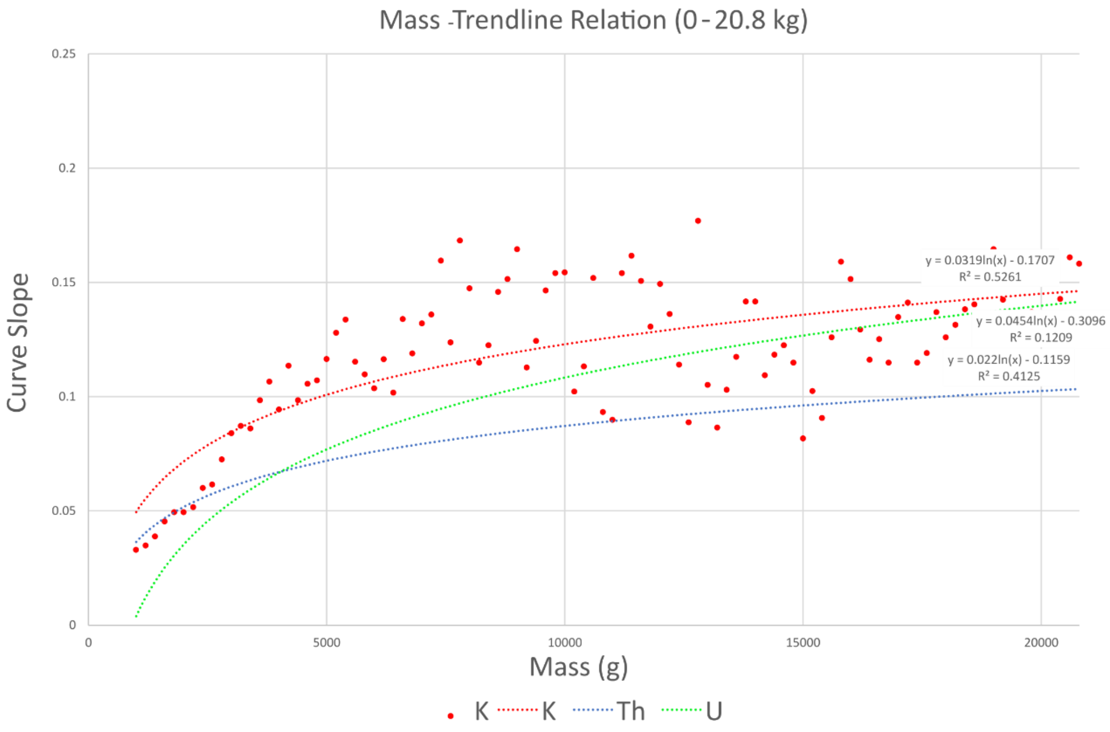
The final dataset consists of geochemical U-Th-K of over 2200 samples throughout East and West Antarctica (Appendix A). Due to time constraints, not all of the samples held by the University of Adelaide were able to be analysed, although a number of samples from the Windmill Islands, along with many of those collected by Sir Douglas Mawson in his expedition Through King George V Land, were successfully analysed and their heat production values calculated (see Table 1). The metamorphic samples in the dataset are mostly limited to the Proterozoic and Archaean samples. Although approximately 90% of samples in the dataset were of this age range. Mafic Igneous samples are the most common in the dataset, having the highest percentage of each age, except for the Archaean samples, in which metamorphic rocks with felsic composition were the most common.

Rock Classification	Percentage of Samples	Heat Production Average
Cenozoic	4.19%	2.15E-03
Mafic Igneous	2.65%	1.95E-03
Intermediate Igneous	1.24%	2.62E-03
Felsic Igneous	0.29%	2.03E-03
Mesozoic	2.65%	1.61E-03
Mafic Igneous	1.30%	1.36E-03
Intermediate Igneous	1.06%	1.70E-03
Felsic Igneous	0.12%	2.30E-03
Felsic Sedimentary	0.18%	2.52E-03
Paleozoic	1.12%	2.08E-03
Mafic Igneous	0.47%	1.85E-03
Intermediate Igneous	0.24%	2.61E-03
Felsic Igneous	0.35%	1.77E-03
Felsic Metamorphic	0.06%	3.61E-03
Proterozoic	70.75%	1.63E-03
Mafic Igneous	17.39%	8.54E-04
Mafic Metamorphic	9.55%	1.08E-03
Intermediate Igneous	8.96%	1.05E-03
Intermediate Metamorphic	5.84%	1.70E-03
Felsic Igneous	9.96%	3.04E-03
Felsic Metamorphic	19.04%	2.12E-03
Archaean	20.17%	1.52E-03
Mafic Igneous	0.12%	6.14E-04
Mafic Metamorphic	3.01%	1.11E-03
Intermediate Igneous	0.18%	6.99E-04
Intermediate Metamorphic	3.24%	8.41E-04
Felsic Igneous	2.00%	4.58E-03
Felsic Metamorphic	11.62%	1.31E-03

Table 1: Dataset overview from Appendix B

3.2 Unconventional Method Calibration

The gamma ray spectrometer appears to calculate a certain percentage of the geochemical concentrations of potassium, uranium and thorium for each fixed sample mass, and the percentage recorded generally increases for increasing sample mass (defined by the slopes of the linear calibration curves in Appendix B). However, as the calibration required masses in excess of that which the powdered samples could accommodate, and a mixture of powder and rock fragments was used, the inhomogeneity of the fragments became apparent as the position of the calibration curves did not reflect the increase of sample masses. This effect was magnified greatly as the percentage of fragments in the mixture rose above 50%. At this point the slope of the calibration curves became significantly more sporadic (see Figure 6). Despite this, the curve slopes for varying masses followed a generally logarithmic pattern. Although the lead chamber shielded the system from a great deal of background radiation, it did not completely remove the background levels, and the results incorporated a small level of fluctuating radiation. As such, upon compensating for the average background radiation recorded, some values, particularly those involving very low levels of uranium and thorium, were calculated as negative.



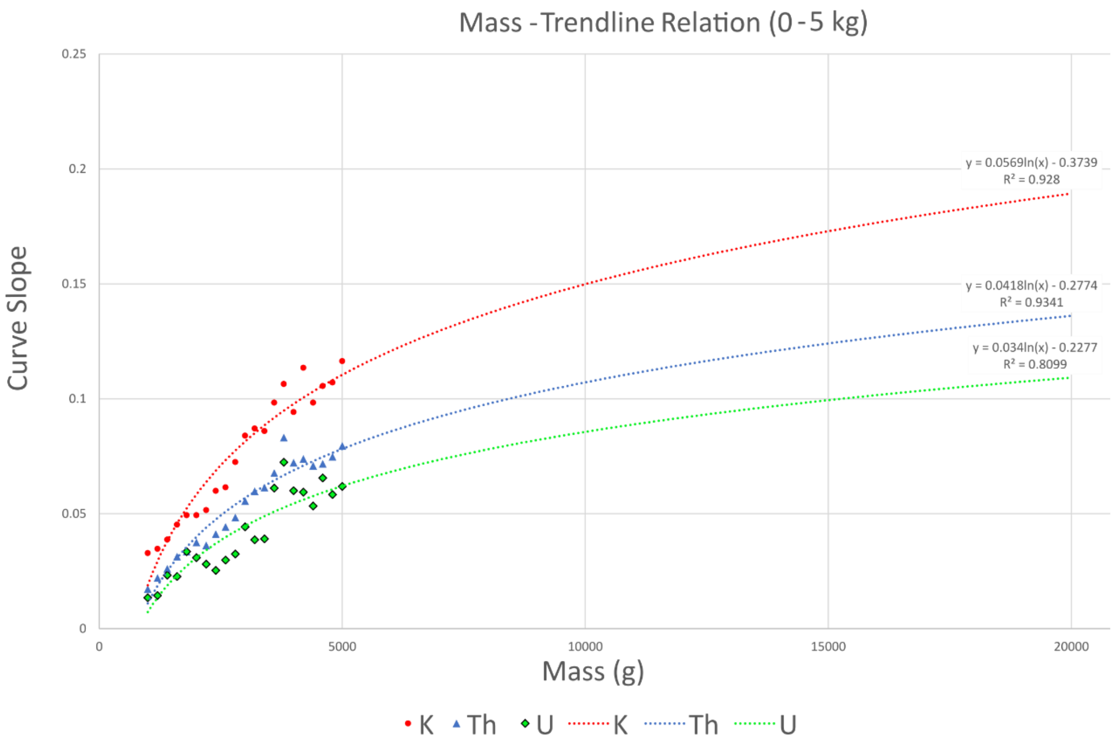


Figure 6: Plot showing sporadic behaviour in high mass samples, and the difference when highly variable data is removed.

3.3 Method Test

The method test produced a number of histograms which proved to be remarkably similar in both shape and position to that of the recorded geochemistry of the Windmill Islands area (See Figure 7). The test histogram shows a double peak for potassium concentration at 0-0.25 and 2-2.75 wt% with approximately 10% of the data falling within the first and 12% falling within the second peak. Both thorium and uranium histograms shows peaks at 0 with gradual decreases in intensity as concentration rose, with the majority of the data falling below 15ppm for thorium and 3 ppm in uranium. The heat production histogram shows a peak from $5x10^{-7}$-$6x10^{-7}$ mW/kg, constituting approximately 21%, and another for values below $1x10^{-7}$, containing 13% of the data. Although the data for all methods were overall similar in shape to the test histograms, the heat production histogram for the ‘Linear’ method shows a small secondary peak between 1 and $1.5x10^{-7}$ mW/kg, though this peak contains approximately 12% of the data in a range more than double that of the primary peaks (a group of 4 binomials each containing approximately 4% of the data). The potassium histogram for the ’Long Log’ method also shows an inaccuracy in which the data is more concentrated between the two main peaks than the test histogram. Although their positions are similar, the peaks for thorium in the method histograms had an overall higher intensity, with 20% of the data falling within this range, than those of the test histogram, which only contain 15% of the data. As can be seen in table 2, the ‘Long Log’ method has a much larger total difference (variance from test mean + variance from test standard deviation) in heat production than the other methods, whereas the other two methods are much closer to the test. This large difference is mostly due to the difference in standard deviation.

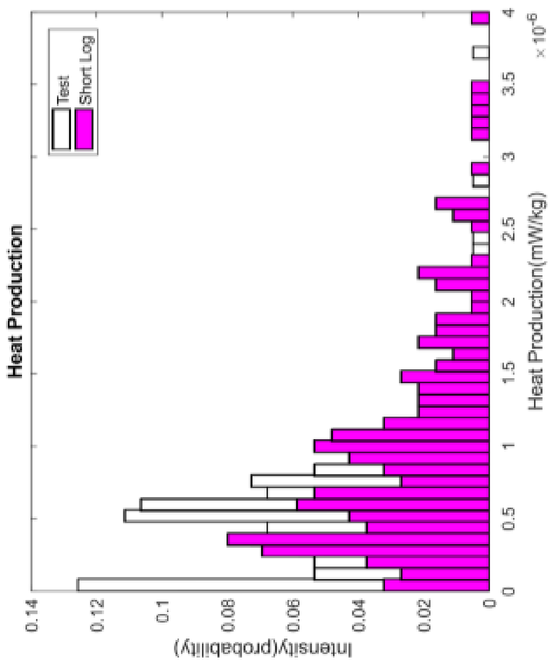
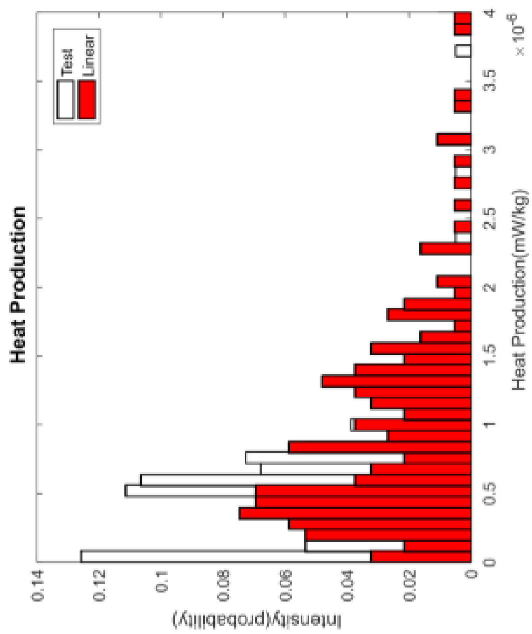
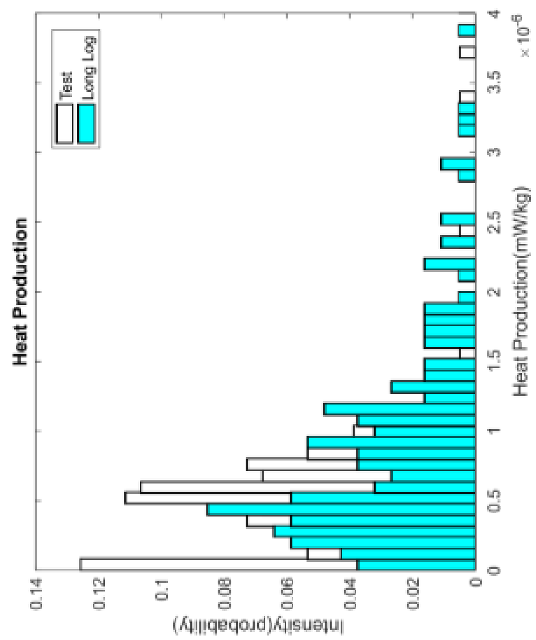


Figure 7: Data histograms comparing the results of each method with the test.





Method	Mean (mW/kg)	Standard Deviation (mW/kg)	Total difference
Test	7.19E-07	1.01E-06	
Linear	1.14E-06	1.35E-06	7.60E-07
Short Log	1.23E-06	1.45E-06	9.49E-07
Long Log	4.28E-07	8.16E-06	7.44E-06

Table 2: Overview of the three methods compared to the test.

3.4 Sample Analysis

The samples analysed consisted of those collected by Sir Douglas Mawson from King George V Land. Due to time constraints, only 55 of these samples could be analysed. These samples, along with those analysed from the Windmill Islands, were added to the dataset (see Appendix A). The samples show an average of 4×10^{-3} mW/m^3, with approximately 13% of the samples falling between 1.3×10^{-3} and 1.6×10^{-3} mW/m^3. Of the samples analysed 42% are mafic, 25% are intermediate and 33% are felsic in composition.

4. DISCUSSION

The studies from Carson et al. 2014 and Pittard et al. 2016 show the importance of this method. Firstly, the study from Carson et al. 2014 shows that the heat flow of Antarctica is highly variable, and greatly influenced by crustal rocks with high uranium, thorium and potassium concentrations, and that the crustal heat flow in Antarctica can vary by quite large amounts in relatively short horizontal distances, and that current models for crustal heat flow are not accurate, as they assume a more thermally homogeneous crust. Pittard et al. 2016 expanded on this by proving that a localised high heat production would not only have a significant influence on ice sheet flow, but also that this effect can be observed up to 100km upstream and 300km downstream, further illustrating the importance of being able to accurately distinguish these locally high and low heat producing areas in order to accurately model overall heat flow, ice sheet stability and response to global warming.

4.1 Geochemical Dataset

The percentage of each different rock type and composition of the dataset relates to the samples gathered, and therefore are not representative of the basement lithology of Antarctica. This issue arises due to the standpoint from which the samples were chosen. Due to the difficulty of access to the target area, it becomes difficult to retain a certain level of objectivity when selecting rock types as samples, as samples can often exceed the maximum weight for transportation, and so samples less important to the current study must be removed, creating a bias in the samples gathered. One method to incorporate the representativeness of the samples and form a more reasonable heat production average is to gather a number of geological maps of Antarctica and determine the percentage of area of each geological province. This would allow samples to be weighted based on their representative rock types, and would therefore act to remove the bias involved in sample gathering.

4.2 Method Calibration

The limitations of the calibration method used are based on the fact that rock samples are inhomogeneous in terms of geochemistry, and therefore individual rock fragments may have concentrations much higher or lower than average. The best way to avoid this uncertainty in concentration is to crush the rock samples and have the resulting rock powder homogenized. This process is extremely time consuming, however, and therefore a mixture of powder and rock fragments was used in an attempt to lessen the effect of this issue.

Two different methods were used to correlate the GRS measurements to respective geochemical concentrations, and were then applied to the samples from the Windmill Islands and tested against the K, U, Th concentrations measured in the field to determine which method was most accurate. These methods involved a ‘Linear’ calibration, where the sample masses were matched to the closest linear trend line and used to calculate the geochemical values, and a ‘Long Log’ calibration, where the slope of the linear calibration curves were plotted against sample mass and the trend of the resulting data was used to calculate the geochemical values. Production of the ‘Long Log’ method showed the extent of the sporadic behaviour when sample sized exceeded 5kg, when the samples exceeded 50% rock fragments. This inspired the production of a third method, the ‘Short Log’ method, which removed data beyond the 5kg sample size in an attempt to give a more accurate calibration (see Figure 8).

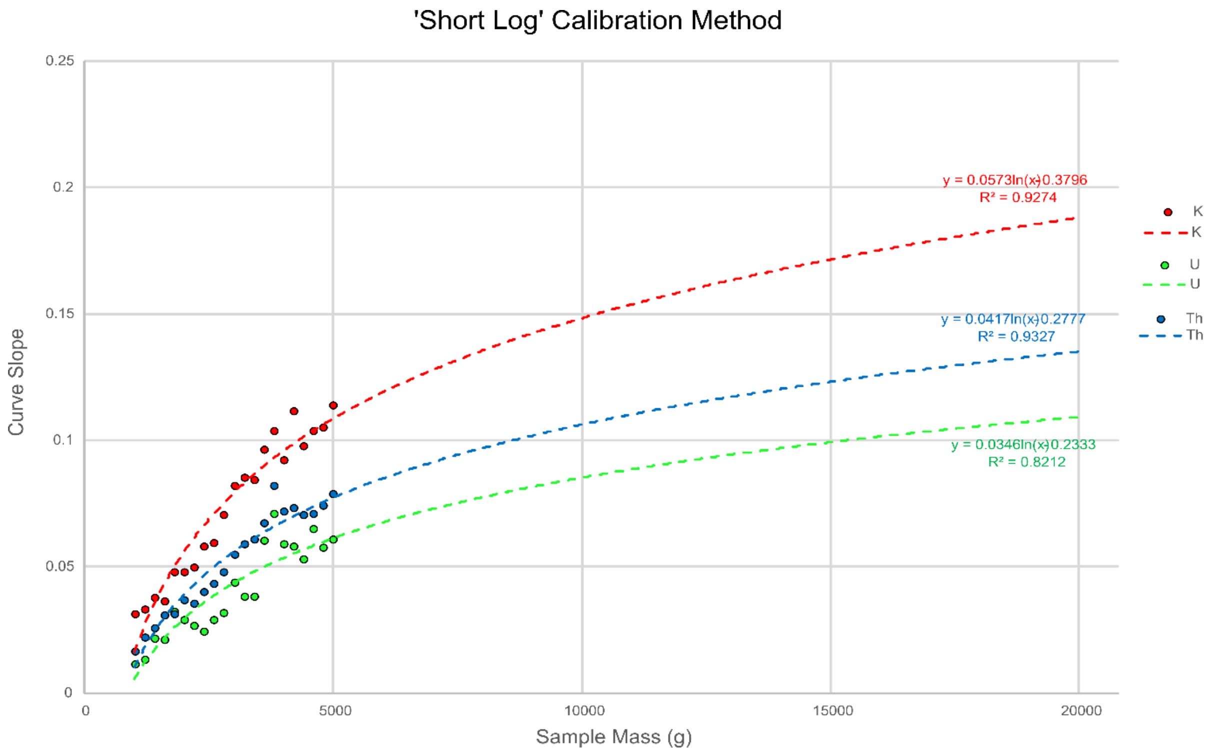


Figure 8: plot showing calibration curves and equations of the 'Short Log' method.

As the fluctuating radiation background could not be controlled to give a steady background, a short term average was developed by taking frequent background readings before and after each sample analysis. These averages were then subtracted from the readings, and any values that still resulted in negative measurements were labelled as "below detection" and removed from the heat production equation.
Many of these issues, including the fluctuating background and the inhomogeneous rock fragments, were allowed to influence the method due to time constraints on the project. Another factor influencing the results of this method was the resolution of the gamma ray spectrometer. As the spectrometer analysed the concentrations of potassium, thorium and uranium, it displayed these values with an accuracy of 0.1% for Potassium, and 0.1ppm for Uranium and Thorium, and all recorded values are rounded to these intervals. This gave the analyses an initial error of ±0.05, which, although is of little influence for large samples, is much more influential when dealing with smaller samples that may only show values of 0.03 wt% potassium but, due to its small size, may return a value of 2-3wt% when run through the appropriate calibration curve. The effects of this error were slightly reduced, by taking a three point average, to approximately 0.03, yet still have a somewhat significant effect on the final results.

4.3 Method Test

Although no individual method showed any significant differences to the test data, and none of the methods varied greatly from one another, the 'Short Log' method seemed to have the best fitting model through the exclusion of the sporadic results drawn from the rock fragment dominated mixtures. This method allowed for a much faster application than the 'Linear' method by using one universal formula rather than having to manually choose between a large set of formulae depending on sample size, and also removed the 'Uranium Error' resulting in the higher sample size limit involved in the 'Long Log' sample. For these reasons, the 'Short Log' method was seen as the best calibration method of the three, and was used as the main method of calibration for the unknown samples collected in the University of Adelaide.

The test also showed that, although calibrations for each element concentration and their resulting heat production were remarkably similar to those recorded in the field, those for Potassium seemed to be the least accurate of the three. A possible explanation for this could be that, as the samples were collected from a metamorphic geology standpoint, a slight bias may have existed in the sample selection, effectively removing data from areas of higher Potassium concentration which would have been analysed in the in-situ GRS recording. This small bias could also account for the difference in peak intensity involved in the Thorium histogram, where samples of higher Thorium concentration may have been collected, and the areas of low Thorium concentration, which would have been analysed by the in-field GRS, would have been ignored.

4.4 Heat Production

The most accurate heat production calculations were in units of mW/kg. Upon conversion to mW/m^3, as some assumptions had to be made about the density of the rock samples based on composition, some error was ensued. Without information on the thickness of Antarctic bedrock layers, it is impossible to accurately convert this data to mW/m^2 in order to form a complete comparison to the heat flux information stated earlier. With such little outcrop, the only way to obtain any detailed information about rock layer thickness is through drill hole exploration.

A comparison between the heat production data of samples in the dataset and their geological ages shows an overall higher heat production in younger samples than that of the Proterozoic or Archaean eras (See Figure 9). This could be due to the fact that, based on the samples, the older rock types have experienced much more metamorphism than those that formed more recently. This metamorphism may have removed the more unstable elements within its minerals, including uranium and thorium, hence decreasing the radiogenic concentration and overall heat production of the rocks.

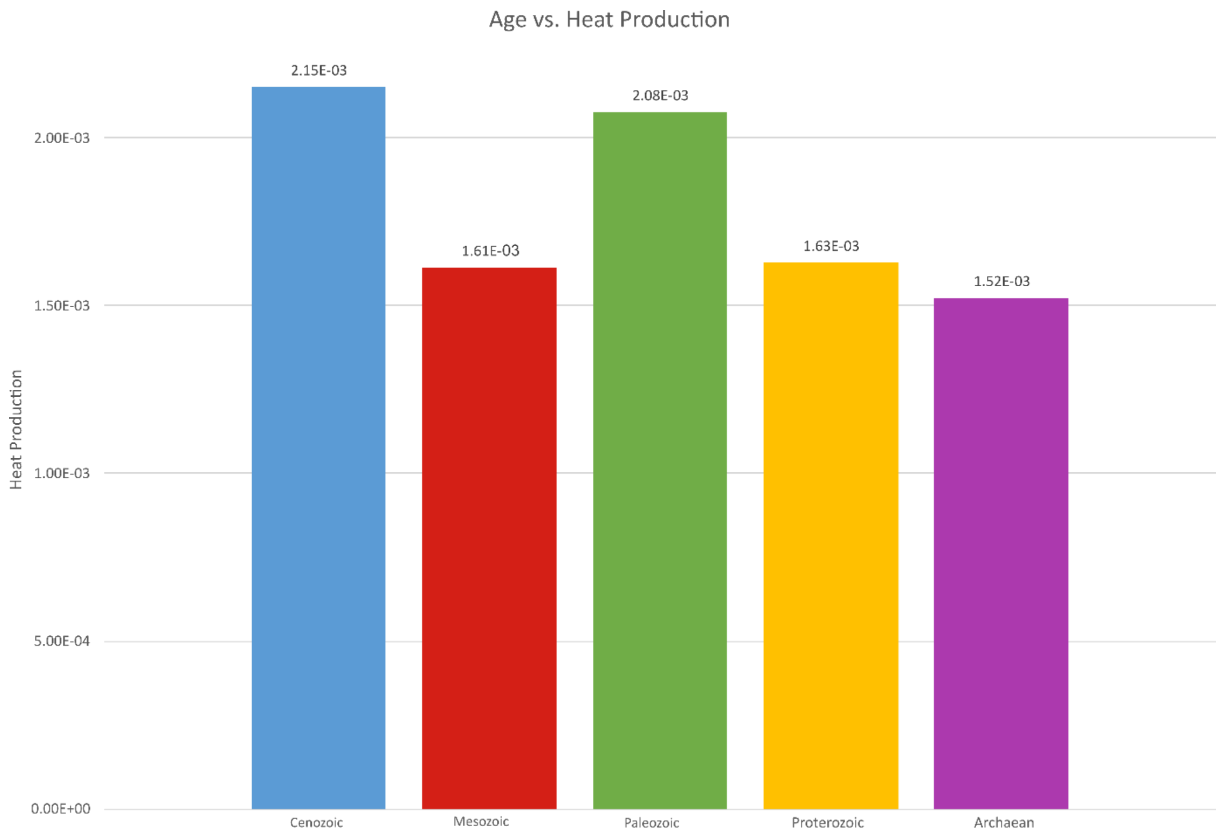


Figure 9: Comparison of average heat production and geological age

4.5 Ice Flow Comparison

Although a correlation between ice flow and heat production could arguably exist by the comparison (See Figure), the error involved and the nature of the project could not allow any conclusions about the influence of basement heat production on ice flow rates in Antarctica at this point. The aim of the project is merely to give an initial insight into the heat production of the Antarctic bedrock.

5. CONCLUSION

The method calibration successfully produced an accurate, background independent GRS method that allows rapid, inexpensive geochemical analysis of large sample sets without the need to destroy the samples themselves. This method would be ideal for samples collected from areas where access for in-field analysis is limited or costly, and small samples that were collected in expeditions, that are too valuable to destroy.
Although this method involved errors of approximately 10-20%, the errors involved are predominantly due to the time frame in which the method had to be calibrated. Due to time constraints, errors generated from issues such as inhomogeneous rock fragments and uncontrollable background variability could not be corrected, and as such the errors were allowed to progress and influence the final results of the method.

In order to amend the inaccuracies of the developed method, the calibration procedure should be undertaken in a chamber that completely shields the system from background radiation. The samples used should also be crushed and homogenised, in order to remove the error of high and low concentrations in rock fragments. The heat production values could also be improved by undertaking density calculations on the samples after analysis, and the values could be converted to units more comparable to the heat flux data if the Antarctic bedrock could be successfully extrapolated from contiguous areas in southern Australia and India. Although these improvements could not be made in this study due to time and budget constraints, they are possible improvements for any future studies that may not have these limitations.

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