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Taking the Temperature of the Antarctic Continent

Abstract Book

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Inferring geothermal heat flux from englacial temperatures in East Antarctica

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Geothermal heat flux (GHF) supplied to the base of the Antarctic ice sheet strongly controls its internal temperature distribution. GHF is, therefore, a critical thermal boundary condition in ice sheet modeling directly influencing the deformability of ice and ice-flow velocities. Accurate and high-resolution GHF measurements are necessary to reliably predict ice sheet evolution and future climate change. But, GHF datasets used in ice sheet models are poorly constrained by actual measurements. Here, we use englacial temperature measurements to estimate GHF for key regions in East Antarctica. The attenuation rate of radar reflections is greatly affected by the temperature within the ice sheet and its chemical properties. Spectral analysis of the radar reflectors through the ice sheet will be employed to constrain radar attenuation, which will then be used as a proxy for ice temperature. The GHF can be inferred from the gradient of englacial temperatures and thickness of the ice. Here we will describe the different methods used to extract the attenuation of reflections from radar datasets, which will enable us to map englacial temperature distributions and produce high-resolution GHF estimates.

Evaluating the difference between geothermal flux and basal heat flux in the context of ice divide stability, Little Dome C, East Antarctica

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Basal heat flux is the thermal energy that crosses the ice/bed interface and is geothermal flux modified by processes such as vertical advection of groundwater and local variability in geology. The basal conditions of Little Dome C are of particular interest due to the potential for the existence of 1.5 Myr old ice that is interpretable as a paleoclimate proxy. The stability of Dome C is a function of the basal interface character including basal heat flux and water distribution and each can be modified by groundwater, water flow in the subglacial sediment and bedrock. Here we test the rate of heat flux from groundwater flow and its sensitivity to assumed subglacial geology and associated hydrological parameters. Multiple probable geological models are constructed for the Dome C region from radar derived geometry and interpretation of co-located gravity and magnetic field observations. The impact of groundwater on basal heat flux is sensitive to the chosen background geothermal gradient, but more so to the degree of assumed hydrological permeability. In certain configurations groundwater flow can modify local basal heat flux but a factor greater than 2. Our interpretation is that the position of Dome C is above a region of lower hydrological permeability that decreases exposure of basal ice to heat and may play a stabilizing role, and therefore increase the likelihood of 1.5 Myr old ice survival. These result suggest the hypothesis that ice divide stability and old ice survivability are, in part, a function of the underlaying geology.

Spatial variability in geothermal heat flux in Antarctica: new measurements and ice dynamical implications

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The difficulty of measuring geothermal heat flux (GHF) below ice sheets has directly hindered progress in understanding their role in ice sheet dynamics. We present a new GHF measurement from below the West Antarctic Ice Sheet, made in subglacial sediment near the grounding zone of the Whillans Ice Stream. The measured GHF is 88 ± 7 mW/m², a relatively high value compared to other continental settings and to other GHF measurements along the eastern Ross Sea of 55 mW/m² and 69 ± 21 mW/m², but within the range of regional values indicated by geophysical estimates. The new GHF measurement was made ~100 km from the only other direct GHF measurement below the ice sheet, which was considerably higher at 285 ± 80 mW/m², suggesting spatial variability that could be explained by shallow magmatic intrusions or the advection of heat by crustal fluids. Analytical calculations suggest that spatial variability in GHF exceeds spatial variability in the conductive heat flux through ice along the Siple Coast. Accurate GHF measurements and high-resolution GHF models may be necessary to reliably predict ice sheet evolution, including responses to ongoing and future climate change.

Partitioning the geothermal component of basal melting beneath ice-sheets: lessons from Greenland

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Geothermal heat flux impacts meltwater production and ice motion at the base of ice sheets. However, additional to geothermal heating, frictional and deformational heat sources also contribute to melt the ice base. Recent studies in Greenland Ice Sheet implicate that geothermal heating related to ancient hotspot activities influences the distribution of present-day subglacial hydrology. However, these studies mostly rely on qualitative comparisons between basal water and heat flux models. Presently, it is unclear how much of the observed basal water is produced by geothermal heating and how much is strain or friction related. Here we combine ice-sheet modeling, basal water predictions from radar sounding analysis, and the most advance geothermal heat flux distribution to provide a quantitative assessment of the role of geothermal heat flux on basal water production. We examine the sensitivity of basal melting to variations in geothermal heat flux using a thermal enthalpy scheme in the NASA Ice Sheet System Model (ISSM). By coupling the thermal and stress balance modeling components, we partition the relative contribution of geothermal, frictional, and deformational heating on basal melting for different regions across Greenland. We also use an ice-sheet-wide constraint for basal water derived from variability in radar bed reflectivity as an independent constraint to examine the model capabilities to produce basal melting. Together, our results reveal that the spatial distribution of elevated geothermal heat flux can explain the observed meltwater underneath vast regions of the Northern and Eastern ice-sheet interior. We discuss the implications of the presence of a stable melt production related to geothermal heating to the long-term dynamics and mass balance of the Greenland ice sheet. We also discuss how the approaches developed in Greenland could be adapted to further characterize the geothermal heat flux of the Antarctic Ice Sheet.

GHF inferred from in-situ temperature measurements in the Amundsen Sea, West Antarctica

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Due to a complex tectonic and magmatic history of West Antarctica, the region is suspected to exhibit strong heterogeneous geothermal heat flux variations. Although the maximum ice extent has retreated from the shelf since the last glacial maximum, the trends of offshore GHF patterns and the overall order of magnitude are hypothetically related to those areas onshore where the West Antarctic Ice Sheet (WAIS) rests on geologically related structures. High-resolution GHF will aid the understanding of the paleo-retreat of the ice sheet in the Amundsen Sea Sector. This presentation builds on our previous studies in which we discussed geothermal heat flux based on 26 in-situ temperature measurements that were conducted in 2010 in the Amundsen Sea Embayment (ASE) in West Antarctica. We found, that the shallow (3 m) in-situ temperature measurements were likely influenced by inter-annual bottom-water temperature variability, leading to GHF estimates biased towards lower values (mean = 33 mWm^{-2}). During RV Polarstern expedition PS104 in early 2017 we collected additional 28 in-situ temperature measurements in marine sediments (11 m) for deriving geothermal heat flux in the ASE, which will overall improve the spatial coverage of this region. Furthermore, we monitored the vertical temperature profile of the water column at these stations, which allows to map Circumpolar Deep Water (CDW) distributions across the inner Pine Island Shelf with greater detail.

Linking GHF to crustal structures and DBMS Estimates in the Amundsen Sea Sector

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The West Antarctic Rift System is one of the least understood rift systems on earth, but displays a unique coupled relationship between tectonic processes and ice sheet dynamics. Geothermal heat flux (GHF) is a poorly constrained parameter in Antarctica and suspected to affect basal conditions of ice sheets, i.e., basal melting and subglacial hydrology. Thermomechanical models demonstrate the influential boundary condition of geothermal heat flux for (paleo) ice sheet stability. Young, continental rift systems are regions with significantly elevated geothermal heat flux (GHF), because the transient thermal perturbation to the lithosphere caused by rifting requires ~100 Ma to reach long-term thermal equilibrium. We discuss airborne, high-resolution magnetic anomaly data from the Amundsen Sea Sector, to provide additional insight into deeper crustal structures related to the West Antarctic Rift System in the Amundsen/Bellingshausen sector. With the depth-to-the-bottom of the magnetic source (DBMS) estimates we reveal spatial changes at the bottom of the igneous crust and the thickness of the magnetic layer, which can be further incorporated into tectonic interpretations.

Taking the temperature of Antarctica with satellites

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Different methods have been applied in recent years to quantify the thermal structure of Antarctica. Estimates are often derived from modelling of satellite data or seismological models, or based on a combination of these. Here, we present results from the ESA Support to Science Elements GOCE+Antarctica and CryoSMOS.

An interesting, novel and complimentary observation to the estimates mainly derived on geophysical data reflecting the Solid Earth, is the geothermal heat flux as established by analysis of data from the SMOS (Soil Moisture and Ocean Salinity) satellite mission. In the CryoSMOS study, it was shown that the L-band brightness temperature (TB) observations over Antarctica could mainly be attributed to the ice-sheet temperature profile variability. Error assessment showed that the geothermal heat flux, as resulting from the inversion against the ice temperature profiles from SMOS, is in the range of ±20 mW/m2. The difference is huge with respect to its implications on ice-sheet conditions.

We compare these results to a 3D lithospheric model based on the integration of satellite gradient gravity data and seismological models as established in the GOCE+Antarctica study. Differences of more than 10 km in crustal thickness estimates are observed. Such huge differences have strong implications for the characteristics of the crust itself and the underlying mantle in terms of density, temperature and composition. To isostatically compensate the differences in Moho depth, the composition and thermal thickness of the lithospheric mantle is adjusted. In both cases, the observables are equally well explained, but the models significantly differ in the heat flow for the coastal region (differences >20 mW/m2).

The different satellite derived estimates differ significantly from heat-flow estimates based on magnetic satellite data and we discuss how to reconcile the different observations by modelling the crustal thermal properties.

Devil in the detail: enhanced imaging of Antarctic crustal and lithospheric provinces to aid future geothermal heat flux estimation

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Geothermal heat flux is a key and yet poorly understood boundary condition that can affect past, present and future ice sheet dynamics via e.g. its influence on subglacial hydrology, and sediment and basal ice deformation, and it also important to determine in the quest for retrieving the oldest ice via new deep ice core drilling. In addition to its relevance for glaciology and paleo ice sheet studies GHF is important also as both a tracer and an influence on the tectonic and magmatic evolution of the Antarctic continent.
Studies to date of Antarctic geothermal heat flux comprise e.g. estimates derived from seismology, satellite and airborne magnetics, radar-derived estimates of basal reflectivity and basal water, direct measurements via drilling and rock samples, erratics and modelling approaches. The results of these studies vary significantly both in terms of spatial distribution, spatial resolution, magnitudes and uncertainties.
The recent availability of continental scale compilations of airborne gravity, new satellite gravity gradient data and notably a new magnetic anomaly compilation (ADMAP 2.0) that includes almost 3.5 Ml line km of data provide the means to start tackling the issues surrounding GHF estimation in additional ways too. As part of a new European Space Agency initiative ADMAP 2.0+, an extension to the 3D Earth project of ESA, which will be launched in Feb. 2018 we plan to image and model the variability in crustal and lithospheric architecture of Antarctica in unprecedented detail and also assess its implications for the spatial variability of GHF. Here we will present the approaches that the project intends to develop further. A new basement province map for a large part of East Antarctica will be compared and contrasted with the currently available estimates of GHF and several key areas where new thermal models are required will be discussed.

Improved models of Antarctic geothermal temperatures and crustal heat flux: constraints from geochemistry and Curie depth analysis

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In this study, we develop a new model for heat flux and crustal temperatures for the Antarctic continent utilising new geophysical and geochemical constraints. Crustal heat flux directly influences ice sheet stability, glacial dynamics and basal melting. However, the geothermal input into the base of the ice sheets is poorly constrained due to the logistical difficulty and high expense of obtaining direct measurements through the ice sheets. Thus we require robust indirect estimates by utilising proxies. Past studies focus on seismic velocity estimates of temperature, but this method is limited to mantle temperatures, which constrain mantle contributions to crustal heat loss. However, seismic models have poor sensitivity to the crustal radiogenic contribution to the crustal heat loss. Radiogenic heat generation can contribute anywhere from 30-80% of the total crustal heat loss, and therefore must be considered as part of any geothermal model. In this study, we improve estimates of crustal heat generation by employing empirical estimators applied to geophysical datasets. The empirical estimators are calibrated to geochemical estimates of heat production made on Antarctic rock samples and from formerly adjacent continental terranes determined by tectonic reconstructions. We combine this radiogenic model with crustal temperatures constrained though Curie depth analysis. Curie depth estimates computed from the equivalent dipole method are achieved by utilising a new lithospheric magnetic model derived from SWARM and CHAMP satellites. This improved lithospheric magnetic model is much higher resolution than previous Curie depth studies. Our estimates of temperature and crustal heat flux into the base of the Antarctic ice sheet represent an improvement over previous models, allowing for more realistic models of ice sheet dynamics.

Warm, warmer, hot! Antarctic crustal radiogenic heat production.

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The geothermal heat flux (GHF) to the base of the Antarctic ice sheet is inherently difficult to measure, yet accurate estimates are necessary to better understand cryosphere dynamics. GHF includes heat supplied to the lithosphere from the convective mantle and radiogenic heat generated within the lithosphere from the decay of heat producing elements (HPEs), mainly Thorium (Th), Uranium (U) and Potassium (K). Through differentiation processes, HPEs are preferentially concentrated into the dominantly felsic rocks of the upper continental crust. The distribution of HPEs is therefore heterogeneous at a range of scales, and fundamentally tied to the geological evolution of the crust in space and time.

Current GHF models of the Antarctic continent based on geophysical properties use idealised crustal parameters that do not reflect the inherent geological heterogeneity. For example, recent studies have shown that radiogenic heat production values for Antarctic granites and gneisses can be significantly enriched (>10-15, and up to 65 micro watts per metre cubed) compared to average crustal values that are used across the entire continent in existing Antarctic GHF models (~ 1-2 micro watts per metre cubed). Regional ice sheet models have shown that localised regions of such high HPE-enriched crust can impact the organisation of ice flow, particularly in slow-flowing regions, underscoring the need for improved knowledge of both the magnitude and spatial variability of radiogenic heat production in Antarctic crust.

Here we assess the range in heat production values from diverse lithologies across outcrops and moraines in Antarctica using a compilation of previously published and new geochemical analyses. We explore variations with lithology, age and between geological terranes. Our analysis demonstrates significant spatial variability in heat production that will need to be integrated with deeper lithospheric structure and heat flow constraints to improve GHF models of the Antarctic continent.

The GeoMAP dataset of Antarctic rock exposures

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The SCAR GeoMap action group has been building a detailed digital geological dataset of Antarctica. We have been capturing existing geological map data, refining its spatial reliability, improving representation of glacial sequences and geomorphology. The initiative is aimed towards continent-wide perspectives and for cross-discipline use, our international team is collaboratively classifying and describing around 72,000 distinct areas that cover 51,000 km2. The dataset will describe ‘known geology’ of rock exposures rather than ‘interpreted’ sub-ice features. Glacial deposits are an important focus for their potential to contain records of ice fluctuations of relevance to climate change. Here we present background on: (1) Degree of completion toward the first version of a continent-wide dataset. All rock outcrops will have geological attributes assigned to them in GeoSciML suitable for use at 1:250,000 (or more-regional) scale. (2) The large number of hard-copy geological maps and data sources, which range in scale and quality. (3) Development of local legends, which highlight geological variation across the region. (4) Progress towards a unified classification scheme. (5) Bibliographic links referencing authors of key original work. (6) Potential for the dataset to provide fresh perspectives, for example, through combined geological legends and interrogation of continent-wide time-space plots. It is our expectation that the dataset will be ideal to constrain and develop models of heat flow in the Antarctic continent.

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

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We present findings recently published in GRL (Burton-Johnson et al., 2017) on the variability of Antarctic sub-glacial heat flux and the impact from upper crustal geology.
A new method reveals 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 mWm-2) where silicic rocks predominate, than on the west and north (mean 67 mWm-2) where volcanic arc and quartzose sediments are dominant. Whilst the data supports the contribution of heat producing element-enriched granitic rocks to high heat flux values, sedimentary rocks can be comparable 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 dataset facilitate improved numerical model simulations of ice sheet dynamics.
The most significant challenge faced remains accurate determination of crustal structure, particularly the depths of the heat producing element-enriched sedimentary basins and the sub-glacial geology away from exposed outcrops. Continuing research (particularly detailed geophysical interpretation) will better constrain these unknowns and the effect of upper crustal geology on the Antarctic ice sheet.

Deriving Antarctic crustal heat production using gamma ray spectrometry

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Current Antarctic geothermal heat flux (GHF) models employ simple representations of lithospheric composition that do not yet capture the significant heterogeneity known from geological studies. Radiogenic heating within the crust from decay of naturally occurring radioactive elements, which varies as a function of the geological evolution of a terrane, is particularly poorly resolved, and yet this component can dominate the total surface GHF.

Heat production estimates are derived from the main heat producing element (HPE) content (i.e. U-Th-K) of a rock. Generally these HPE concentrations are determined using geochemical methods, and while fairly routine, these techniques are both expensive (~AUD $200/sample) and destructive.

We aim to augment the current Antarctic heat production inventory based on compiled geochemical analyses, with a new dataset of heat production estimates using a novel non-destructive method. The U-Th-K content of samples will be determined using a calibrated gamma ray spectrometer containing a high-density bismuth germanate detector in a lead-lined analytical cavity. This system is already in operation at the universities of Adelaide and South Australia and we are establishing a further facility at the University of Tasmania. Using this technique, we will analyse the heat production of legacy rock samples that reside in collections across Australia, encompassing a very high proportion of the entire basement evolution of East Antarctica, at a fraction of the cost of conventional geochemical methods.

Using this technique we expect to generate an unprecedented volume of heat production data, which will represent a major advance in characterising the natural variability of radiogenic heat production in Antarctic crust for use in future GHF models.

Thermal isostatic contributions to elevation: implications for the thermal state of Antarctica

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Fifty years ago isostatic subsidence was proposed as a method to investigate the thermal state of the oceanic lithosphere. But it has always been more difficult to use isostatic methods on the continents due to significantly larger variations in composition, crustal thickness, and thermal properties (i.e., thermal conductivity and heat production). The development of continent-wide seismic models of velocities and crustal thickness in recent years combined with laboratory-constrained models of physical properties as a function of composition allow for sufficiently accurate estimates of compositional buoyancy to reveal the thermal contribution to elevation. As a result isostatic methods applied to North America and Australia have shown great potential for improving estimates of the thermal state, particularly if heat production and/or sublithospheric heat flux can be constrained independently. In this study, we will discuss the potential—and pitfalls—for applying thermal isostatic methods to predict the thermal state beneath the Antarctica ice sheet. We will review previous constraints on the thermal state of the Antarctic lithosphere, and how these can be used with new estimates of crustal heat production and thermal conductivity to conduct thermal isostatic analysis.

Heat production estimates from a global geochemical dataset: A priori constraints on Antarctic heat production

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Radiogenic heat production is one of the greatest uncertainties in thermal models of the lithosphere. The difficulty in sensing radiogenic heat production using remote sensing techniques has been an impediment to developing accurate thermal models of the continental lithosphere. Most studies simply assume heat production values based on an average continental lithospheric composition, but heat production varies considerably from region to region. In this study, we present heat production estimates from >200,000 whole-rock analyses distributed globally. We find that patterns of heat production fundamentally differ between igneous and sedimentary rocks as a function of major element chemistry and physical properties. For igneous samples, heat production can be correlated to seismic velocity and density, which can be used as a proxy for estimating heat production with depth. Systematic variations in heat production also exist in space and with crystallization age that must also be accounted for when developing crustal models. We demonstrate how this method can be used to estimate the heat production of the Australian lithosphere, which produces results similar to independent estimates of heat production derived from thermal isostatic methods. From this dataset, it is possible to develop a set of predictors for heat production of Antarctic terranes both laterally and vertically.

Constraints on Heat Flow in Antarctica based on Thermomechanical Models of the Tectonic Evolution

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Results from thermomechanical models of tectonic systems can be used to constrain the magnitude and spatial variability of geothermal heat flux across continents. In the case of the Antarctic Continent, the unique geologic evolution provides stringent constraints on the past and current thermal structures of East and West Antarctica. For example, previous results of models simulating the Mesozoic to Cenozoic tectonic evolution of the West Antarctic Rift System show that the geometry and evolution of rifting is a direct consequence of the initial and evolving thermal structure of the lithosphere. Thus, this suite of successful simulations can be used to constraint the spatially and temporally varying contributions of mantle and crustal heat sources to the surface geothermal heat flux.

Changes in Greenland ice bed conditions inferred from seismology

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Basal conditions of the Greenland Ice Sheet (GrIS) are a key research topic in climate change studies. The recent construction of a seismic network has provided a new opportunity for direct, real-time, and continuous monitoring of the GrIS. Here we use ambient noise surface wave data from seismic stations all over Greenland for a 4.5-year period to detect changes in Rayleigh-wave phase velocity between seismic station pairs. We observe clear seasonal and long-term velocity changes for many pairs, and propose a plausible mechanism for these changes. Dominant factors driving the velocity changes might be seasonal and long-term pressurization/depressurization of the GrIS and shallow bedrock by air and ice mass loading/unloading. However, heterogeneity of the GrIS basal conditions might impose strong regionalities on the results. An interesting feature is that, even at adjacent two station pairs in the inland GrIS, one pair shows velocity decrease while another shows velocity increase as a response to the high air and snow pressure. The former pair might be located on a thawed bed that decreases velocity by increased meltwater due to pressure melting, whereas the latter pair might be located on a frozen bed that increases velocity by compaction of ice and shallow bedrock. The results suggest that surface waves are very sensitive to the GrIS basal conditions, and further observations will contribute to a more direct and quantitative estimation of water balance in the Arctic region.

Temporal–spatial variations in infrasound sources related to cryosphere dynamics in Lützow–Holm Bay Region, Antarctica

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Characteristic features of infrasound waves observed in the Antarctic reflect the physical interaction between the surface environment along the continental margin and the surrounding Southern Ocean. The temporal–spatial variability of the source locations for infrasound excitation during 2015 was investigated using recordings made by two infrasound arrays deployed along a section of the coast of Lützow–Holm Bay (LHB), Antarctica. The infrasound arrays clearly detected temporal variations in frequency content and propagation direction during this period. A number of infrasound sources were identified, many located north of the arrays. Many of the events had a predominant frequency content of a few Hz, higher than microbaroms from the ocean. A comparison of the results with MODIS satellite images revealed that these infrasound sources were ice-quakes associated with the calving of glaciers, the breaking off of sea ice, and collisions between this sea ice and icebergs around the LHB. Continuous measurements of infrasound in the Antarctic may serve as a proxy for monitoring the regional surface environment in terms of climate change at high southern latitudes.

Heat and groundwater transport between the Antarctic Ice Sheet and subglacial sedimentary basins from electromagnetic geophysical measurements

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Numerical models of contemporary as well as palaeo ice sheets suggest that groundwater and heat exchanges between subglacial sedimentary basins and the ice sheet above can be substantial and influence the ice flow. A strategy for the measurement and assessment of such fluxes beneath contemporary ice sheet has not so far been available, however. Here we summarise, first, existing evidence for groundwater and heat exchanges between contemporary and palaeo ice sheets and the substrate below. Second we explain the utility of electromagnetic (EM) geophysical measurements in elucidating such exchanges, and present magnetotelluric (MT) forward models of the deep sedimentary basin beneath the Institute Ice Stream in West Antarctica by way of illustration. Third we propose a simple empirical model by which heat exchanges between subglacial sedimentary basins and the overlying ice sheet can be estimated to first-order from electromagnetic data. We then apply this model to existing Antarctic magnetotelluric data and discuss upcoming field electromagnetic projects on the Whillans and Institute Ice Streams in West Antarctica.

New geological insights fingerprint high heat producing crust in the remote interior of Wilkes Land, East Antarctica

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Heat produced by radioactive decay within East Antarctic crust provides a significant contribution to the total heat flow balance that is supplied at the base of the East Antarctic Ice Sheet. However, the distribution of heat-producing crustal rocks in ice-covered regions remains poorly constrained. Wilkes Land, East Antarctica hosts the Totten Glacier catchment area, one of the largest ice drainage basins in East Antarctica, and is one region where an improved knowledge of sub-glacial geology is of fundamental importance to understanding solid Earth-cryosphere interactions.

We examined the provenance of three low-grade quartzite erratic samples from the Windmill Islands region to provide evidence of the age and composition of the ice-covered bedrock. We suggest these quartzite erratic samples were sourced from a previously-unknown intra-continental sedimentary basin in the interior of Wilkes Land. U–Pb ages of detrital zircons include dominant age peaks at c. 1200 Ma and c. 1490 Ma, which fingerprint the provenance of this sedimentary basin.

Based on the detrital zircon record in these quartzite erratic samples, and using recent Australia-Antarctica plate reconstructions, we suggest there are heat-producing granitic source rocks in Wilkes Land equivalent in age and composition to those present in the Coompana Province of southwestern Australia. We further suggest that the significant heat production variability that characterises the Coompana granitic basement (2.52–6.39 µW/m3) can therefore also be expected in the interior of Wilkes Land. These new geological insights indicate that a higher and more variable regional sub-glacial heat flow might be expected in this region than currently resolved in available models.

Revealing the geothermal heat flux of the Antarctic continent

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Antarctica is the largest reservoir of ice on Earth and it contains around 70% of the world's fresh water. Understanding its ice sheet dynamics is crucial to unraveling past global climate change and making robust climatic and sea level predictions. Of the basic parameters that shape and control ice flow, the most poorly known is geothermal heat flux. Direct observations of heat flux are difficult to obtain in Antarctica, and until now continent-wide heat flux maps have only been derived from low-resolution satellite magnetic and seismological data. We present the most advanced geothermal heat flux model and associated uncertainty derived from spectral analysis of the latest continental compilation of airborne magnetic data. Small-scale spatial variability and features consistent with known geology are better reproduced than in previous models, between 36% and 50%. Our results have the potential to contribute to more realistic and precise studies of subglacial hydrology distribution, improved ice-core site selection, and enhance ice-sheet and sea-level modeling to better reconstruct past and predict future changes.

Uncertainty reduction of geothermal heat flux from assimilating seismic tomography and depth to Curie temperature

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Surface heat flux is highly sensitive to small temperature fluctuations at varying timescales. The magnitude of these variations depend on the duration of climatic fluctuations and add significant uncertainty to present-day surface heat flow estimates. We assimilate heat flow data with multiple geophysical observations that resolve the crust in its present-day state to improve the constraints on subsurface thermal models and quantify the uncertainty in surface heat flux. The Curie depth isotherm is computed from magnetic data to constrain temperatures in the middle-lower crust, while P and S-wave velocities that we extract from tomographic models are sensitive to temperature to varying degrees throughout the lithosphere. We integrate these within an adjoint inversion framework that we apply to Southeastern Australia to invert the structure of thermal conductivity and heat sources within the crust. Based on previous inversions solely constrained by surface heat flow points and seismic velocity, we found that relatively high rates of heat production in Proterozoic crust control the variation of heat flux at the surface. This Proterozoic crust shares tectonic provenance with Antarctica and may have significant implications for its heat flow regime. Here, we will quantify the uncertainty reduction of thermal structure from assimilating Curie depth in addition to seismic velocity and heat flow observations. Our inversion framework can be easily adapted to integrate additional data types available for Antarctica to improve the precision of geothermal heat flux estimates.

Heat production and heat flow variations in Australian continental terranes, lessons for geological based estimates of sub-glacial heat flow in Antarctica

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Prior to the breakup of Gondwana (beginning around the late Cretaceous) cratonic rocks of southern Australia, including the Gawler and Curnamona cratons, are thought to have been contiguous with similar aged rocks in East Antarctica. In Australia, excellent outcrop exposure means that these rocks are reasonably well understood. One of the key characteristics of these Australian Proterozoic-aged cratonic blocks is unusually high measured surface heat flow, averaging 2-3 times that of similarly-aged cratonic blocks elsewhere globally. This high heat flow arises from anomalously high concentrations of the heat producing elements, U, Th and K, which have been demonstrated to profoundly impact a range of temperature-dependent geological processes, such as metamorphism and magmatism. But the spatial distribution of these rocks is highly variable. Moreover, the vertical distribution of the heat producing elements is also important.

Geochemical analysis of rocks from the George V Land-Terre Adelie and eastern Prydz Bay regions suggest heat flow is highly heterogenous in East Antarctica, with the presence and variable distribution of U, Th and K enriched crustal rocks providing a first-order control on sub-glacial heat flow variations. Our data show that variations in abundance and distribution of heat producing elements within the Antarctic continental crust results in greater and much more variable regional sub-glacial heat flows than currently assumed in ice modelling studies. Such elevated heat flows may have significant effect on ice sheet behavior and highlights the importance of assessing the geological controls on heat flow for predictions of ice mass balance and sea-level change.

Promising Oldest Ice sites in East Antarctica based on thermodynamical modelling

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To resolve the mechanisms behind the major climate reorganisation which occurred between 0.9 and 1.2 Ma, the recovery of a suitable 1.5 million-year-old ice core is fundamental. The quest for such an Oldest Ice core requires a number of key boundary conditions, of which the poorly known basal geothermal heat flux (GHF) is lacking. We use a transient thermodynamical 1D vertical model that solves for the rate of change of temperature in the vertical, with surface temperature and modelled GHF as boundary conditions. For each point on the ice sheet, the model is forced with variations in atmospheric conditions over the last 2 Ma, and modelled ice-thickness variations. The process is repeated for a range of GHF values to determine the value of GHF that marks the limit between frozen and melting conditions over the whole ice sheet, taking into account 2 Ma of climate history. These threshold values of GHF are statistically compared to existing GHF data sets (Shapiro and Ritzwoller, 2004; Fox-Maule et al., 2005; Puruker, 2013; An et al., 2015). The new probabilistic GHF fields obtained for the ice sheet thus provide the missing boundary conditions in the search for Oldest Ice. High spatial resolution radar data are examined locally in the Dome Fuji and Dome C regions (Karlson et al., in prep; Young et al., 2017), as these represent the ice core community's primary drilling sites. GHF, bedrock variability, ice thickness and other essential criteria combined highlight a dozen major potential Oldest Ice sites in the vicinity of Dome Fuji and Dome C.

The importance of geothermal heat flux in modelling of the Antarctic Ice Sheet

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Ice sheet models are the only physically-based tools that allow us to simulate the future evolution of the Antarctic Ice Sheet, including its contribution towards changes in global sea level. However, due to limitations in our understanding of ice sheet dynamics, modelling is an inherently uncertain exercise. A typical approach towards optimising ice sheet models is to “tune” key physical parameters by finding the values that give the most realistic simulations of the present-day ice sheet, based on criteria such as ice sheet geometry or ice velocity. However, this approach assumes that there are no errors in the boundary conditions being used to drive the models.

Here, we use the Parallel Ice Sheet Model to explore the sensitivity of the simulated Antarctic Ice Sheet to the available geothermal heat flux (GHF) datasets. We find that the choice of GHF is a significant source of uncertainty, leading to basin-wide differences in excess of 1000m in the simulated ice thickness. Using different GHF datasets to drive the model, we then “tune” it by determining the optimal values of key physical parameters. We show that the parameter combinations obtained are sensitive to the choice of GHF.

Our results highlight the importance of GHF in ice sheet modelling. Reliable GHF estimates are critical to optimising numerical models of the Antarctic Ice Sheet and, therefore, to reducing uncertainty in projections of future global sea level rise.

Sensitivity of ice flow to local and regional variations in geothermal heat flux

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Geothermal heat flux is one of the key thermal boundary conditions for simulations of ice flow. We assess the sensitivity of the Lambert-Amery glacial system within the East Antarctic Ice Sheet to both local and regional variations in geothermal heat flux using the Parallel Ice Sheet Model. Geothermal heat flux can vary locally through elevated radiogenic heat production, with heat flow modelling within the Lambert-Amery glacial system estimating localised elevated geothermal heat flux of at least 120 mWm-2. To assess the influence of these local high heat flux regions on ice flow, we insert a geothermal heat flux anomaly into the dataset beneath five different types of ice flow. Geothermal heat flux can also vary more broadly, with different techniques of estimating geothermal heat flux producing different spatial patterns of heat flux. Using four different geothermal datasets scaled to the same median heat flux we assess the importance of the spatial variation on regional ice flow.

The simulations show that localised high heat flow regions can significantly enhance flow in slow-moving ice, with the influence extending both upstream and downstream of the anomaly. The scaled regional simulations demonstrate this further, with the ice divides being the most sensitive to regional variations in ice flow. Additionally, the position of the onset of basal sliding, in addition to the width of the region experiencing basal sliding was dependent on the underlying geothermal heat flux. Our results suggest that localized regions of elevated geothermal heat flux may play an important role in the organisation of ice sheet flow.

Constraining basal heat flux in eastern Antarctica using new heat flow data from the Coompana Province, Nullarbor Plain, southern Australia

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A critical parameter in accurately modelling Antarctic ice sheet behaviour is basal heat flux, which has a significant impact on ice viscosity and melt generation. Currently, this input is poorly constrained due to the logistical and financial challenges of obtaining boreholes that intersect basement rocks blanketed by thick ice cover. Consequently, we have pursued an alternative approach that employs heat flow measurements from analogous rock units in the Coompana Province of southern Australia, representing the geological counterparts of those beneath the Totten Glacier in eastern Antarctica. The Coompana Province is underlain largely by Mesoproterozoic granitic and gneissic rocks characteristic of the Musgrave orogenic system, observed to project into Wilkes and Queen Mary Land. Facilitated by mineral exploration drilling as part of the PACE Program undertaken by the Geological Survey of South Australia and Geoscience Australia, we have compiled 10 new continuous temperature logs from this previously uncharacterised region. Drill core samples have also enabled an accompanying dataset of thermal conductivity values to be obtained. Preliminary calculations indicate heat flow estimates in the range 52–62 mWm^{-2}, equivalent to global continental averages. All values are slightly lower than the single heat flow measurement of 72 mWm^{-2} obtained from Law Dome located on the conjugate margin of eastern Antarctica, and appreciably lower than the average of ~80 mWm^{-2} for Proterozoic terranes of the central Australian heat flow province. Combined with existing data from adjacent parts of southern Australia, this provides the first regional heat flow characterisation of geological provinces previously contiguous with eastern Antarctica, allowing a more robust evaluation of the contribution of anomalous basal heat flux to ice sheet instability.

Combining interpolated and locally observed contributions to heat flow models

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The spatial variation of heat supplied to ice sheets is an important input model parameter in ice sheet models. Continental models of heat flow (usually referred to in the cryosphere research community as heat flux density, abbreviated to heat flux) may be calculated using seismic wavespeed tomography maps or by inference from other geophysical observables. These broadscale maps are interpolated, smoothed representations. Upper crustal models, in contrast, are generated directly from measuring the heat production of dominant or particularly radiogenic lithologies.

In this contribution, we combine interpolated and locally observed contributions to heat flow models with a focus on East Antarctica, including the continental interior which is covered by ice of several kilometres thickness. We review alternative approaches to combining low resolution information on the deeper lithosphere with broad spatial coverage, and high resolution information with very limited spatial coverage relating to the present day upper crust. Providing effective estimates of the heat supplied by the upper crust is an important research goal due to the significance of small pockets of elevated heat flow on ice sheet models. Alternative approaches inform future probabilistic solid Earth constraints for ice sheet models.

Observationally Constraining Geothermal Heat Flux Using Ice Penetrating Radar

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Geothermal heat flux exerts a fundamental control on the behavior, stability, and evolution of ice sheets. However, this basal boundary is also exceedingly difficult and costly to measure directly. Geophysical remote sensing technique provides a cheap and effective way to constrain the distribution of geothermal heat that is critical for the initialization and spin-ups of predictive ice sheet models. Airborne ice penetrating radar sounding can provide observations of englacial and subglacial conditions at the catchment- to continent-scale. Specifically, the character and strength of radar bed echoes encode information about the thermal and hydrologic state of the ice sheet and its bed. While on an echo-by-echo basis, this information is highly non-unique, on a regional basis advanced radar processing approaches can disambiguate englacial- and subglacial-genic signals. However, even high-fidelity basal condition mapping does not directly map geothermal heat flux . This requires careful and creative application of hydrological, geologic, and glaciological assumptions and information to the parameter estimation problem. However, despite these considerable challenges, we will demonstrate how to combine radar sounding data with subglacial hydrologic and thermo-mechanical models to place meaningful observational constraints geothermal heat flux in a range of glaciological settings. We present a range of promising applications and problems for these approaches as well as their underlying assumptions, enabling conditions, and inherent limitations.

Ice flow modeling and geothermal heat flux

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Conditions at the base of ice sheets are critical to understand ice motion and the future evolution of the ice sheets but remain largely unknown due to the lack of direct measurements. These conditions are influenced by the underlying crust and mantle, including the presence of mantle plumes, which translate into high geothermal heat flux at the interface between ice and the underlying bedrock.

In this presentation, we will discuss the impact of geothermal heat flux on ice sheet dynamics, and how uncertainties in such measurements affect ice flow simulations and ice sheet future contribution to sea level rise. Ice flow models are also limited by uncertainties in many other model inputs, including geometry, boundary conditions and ice properties, so we examine how uncertainties in other model inputs compare to uncertainties in geothermal heat flux. Finally, we will consider the possibilities of using ice flow models to infer poorly known ice sheet basal properties, including sliding and geothermal heat flux, and the observations required to better constrain such parameters.

This work was performed at the California Institute of Technology's Jet Propulsion Laboratory under a contract with the National Aeronautics and Space Administration, Cryospheric Sciences and Sea Level Science Team Programs.

Thermal structure and heat flow of central and West Antarctica estimated from seismic data

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Investigating the thermal state of the Antarctic lithosphere plays an important role for understanding the history and future of the West Antarctic Ice Sheet (WAIS), at least from two perspectives: 1) Surface heat flow imposes a key boundary condition for ice sheet dynamics modeling; 2) Mantle viscosity and lithospheric thickness are important parameters for glacial isostatic adjustment calculation. However, because of its remoteness and lack of direct measurements, the lithosphere's thermal state is not completely understood. Here we discuss a most recent effort that produces a thermal model for the Antarctic lithosphere using the seismic data collected in the past two decades.
By processing over 15-year seismic data recorded across Antarctica, we obtain a seismic velocity model for the crust and uppermost mantle from a Bayesian Monte Carlo inversion of Rayleigh waves from earthquakes, ambient noise, and receiver functions. After fixing crustal thickness, we further invert the seismic data for thermal structure employing experimental results relating mantle shear velocity variations to temperature, with a range of acceptable crustal heat generation values as prior constraints. We solve for the best fitting conductive geotherm through a thermodynamic inversion, thus providing estimates of surface heat flow and the thermal lithospheric thickness. The resulting seismic and thermal models reveal a highly heterogeneous mantle lithospheric thermal structure. In particular, thinner lithosphere and higher estimated geothermal heat flow (70-100 mW/m2) are found beneath the West Antarctic Rift system, Marie Byrd Land, Ellsworth-Whitmore Mountains, and southern Transantarctic Mountains, while the East Antarctica has lower heat flow (40-60mW/m2). Notably, an anomalously thin lithosphere with high surface heat flow is identified in the vicinity of the Thwaites Glacier, indicating a mantle source that may facilitate the future instability of the WAIS in that area.

Towards a multi-domain lithospheric model of East Antarctica.

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The knowledge of the lithospheric structure of East Antarctica is very limited and as a consequence we cannot produce accurate and precise maps of the subglacial geothermal heat flux density. Seismic tomography studies and potential field data can be used to derive lithosphere structure, but the resolution is relatively low, and the smoothed models don't reflect the amalgamation of lithospheric terranes that formed the continent.

We combine geophysical constraints with geological knowledge from the sparse outcrops and known geology from Gondwanan neighbours in a plate reconstruction framework to attempt a regionalization of East Antarctica. We use Bayesian inference to suggest the most probable boundaries by using a multivariate prior constrained by available geophysical datasets. The boundaries form a segmentation of the Antarctic lithosphere and can be weighted with probabilistic significance and location. Our implementation allows sequential improvement as updated and refined seismic tomography and potential field data compilations. Likewise, a more consistent approach to adding mapped geological information adds further robust constraints.

The result is presented as a first draft of a multi-domain tessellated terrane map of the East Antarctic lithosphere. We believe that this approach will be useful in estimating both basal lithosphere and crustal contributions to heat flux. The approach provides a stepping stone towards more refined models in an evolving framework.

Temperature gradients and geothermal fluxes in deep boreholes drilled through the Antarctic Ice Sheet: a review

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The temperature of the Antarctic ice sheet and the temperature gradient at its base have been directly measured only a few times, although extensive thermodynamic modeling has been used to interpolate among measurements. During the last five decades, deep drilling projects at seven sites – Byrd, Dome C, South Pole, Kohnen, Dome F, Vostok, WAIS Divide – have succeeded in reaching to, or nearly to, the bedrock in inland locations in Antarctica. The Byrd and Kohnen holes encountered water at the base of the ice sheet and water welled up into the holes. The borehole at Vostok penetrated to subglacial Lake Vostok at 3769.3 m, and here water rose from the lake to a height of more than 340 m. Measured temperature profiles in five of the boreholes (Vostok, Dome C, Kohnen, Dome F, South Pole) increase nearly linearly with depth as expected in locations with minimal accumulation and hence small vertical velocities. Vertical advection is much greater at the locations of the Byrd and WAIS Divide boreholes in West Antarctica and there the upper part of the ice sheet is nearly isothermal, but at depth the temperature gradient is nearly the same as at the other sites. Temperature gradients at the bed are 2.2-2.5 C/100 m at Dome C, Dome F and Vostok, and significantly higher – 3.04 C/100 m – at Kohnen. Measured temperature gradients at Dome C, Kohnen, and Dome F correspond to conductive heat fluxes between 51.1–62.7 mW m-2, while at Vostok, at the boundary between the ice and the lake water, the flux is only 46.1 mW m-2. To estimate the geothermal flux from the sub-ice temperature gradients, however, one also needs to account energy used to melt ice at the base.

The high temperature creep deformation of ice: new laboratory measurements

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The dynamic behaviour of the Antarctic ice sheet is controlled by both creep deformation and the occurrence of sliding at the base of the ice sheet. The activity of these processes is highly temperature dependent and as such they are influenced by the geothermal heat flux at the ice-solid Earth interface.

The constitutive relation describing the rate of ice deformation in numerical ice sheet models is typically a power-law relationship between the stresses driving the flow and the corresponding strain rates, with a separate term describing the temperature dependence. Many models use a simplified prescription of the temperature dependence which does not adequately describe the sensitivity of deformation rates to temperature within ~5°C of the melting point. This leads to an underestimation of strain rates in the warmest ice.

While the increased sensitivity of deformation rates to temperature near the melting point is clearly demonstrated by laboratory experiments, it is constrained by a relatively small number of observations due to the inherent difficulties in conducting experiments at high temperatures. Here we present preliminary results from an experimental program designed to improve the constraint on deformation rates at temperatures close to the melting point. Simple shear deformation experiments were conducted at temperatures between -2°C and -0.3°C at 0.1 MPa (octahedral shear stress). Unlike previous studies investigating temperatures close to the melting point, these experiments were continued through to high shear strains (>10%) to ensure that samples had developed the mechanical anisotropy and corresponding enhanced flow rates that are associated with the microstructural evolution that is typical of polar ice sheets.

These data contribute to the continued development of a constitutive relation for polycrystalline ice that will improve the accuracy of ice sheet models, and are relevant to model studies utilizing inverse methods to infer the spatial extent of basal sliding.

Elevated sub-ice thermal flux mapping using magnetotellurics considering the U.S. Great Basin as an analog

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Bedrock heat flux of Marie Byrd Land and much of the West Antarctic Ice Sheet has been conjectured to significantly exceed the global average of ~85 mWm-2, e.g. 100-200 mWm-2 or more, with implications for ice sheet stability. Advective affects may complicate shallow heat flow measurements and so deeper-seeking geophysical techniques may have a greater role in estimating crustal thermal state. The actively extensional U.S. Great Basin province has been considered a partial tectonic analog to West Antarctica although extension rates in the latter are generally much less. The magnetotelluric (MT) geophysical method has been widely applied in the Great Basin to understand province-scale down to geothermal prospect-scale thermal structure using electrical resistivity as a proxy. There, widespread zones of crustal magmatic underplating and fluid release over broad areas correlate with surface heat flow and volcanic occurrences, with depth to top of low resistivity approximating an isotherm. Spatially concentrated low-resistivity upwellings imply local upward convection and commonly connect into known high-temperature geothermal resource areas exhibiting magmatic-origin fluid fluxes. This has been the basis of significant recent research into greenfield reconnaissance for blind, high-enthalpy geothermal systems. Similar low-resistivity structures correlating with analogous magmatic and convective processes in West Antarctica have been revealed in recently published MT field campaigning there. Appropriately designed surveys have potential to constrain the magnitude and spatial variation of crustal geotherms including local hotter zones that could provide particularly high thermal input to the overlying ice sheets.

Constraints on the geothermal heat flow of Antarctica and surrounding oceans from new seismic structure models

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Geothermal heat flow has a major effect on ice sheet dynamics, but there are few direct measurements of Antarctic heat flow. Previous studies have estimated the geothermal heat flow of Antarctica from seismic structure models, but these efforts have had very limited resolution due to poor seismic station coverage. We have recently constructed two new seismic structure models of Antarctica using complementary methodologies that incorporate data collected from more than 200 temporary broadband seismic stations deployed across Antarctica over the last 15 years. One model seeks to obtain the highest possible resolution within the upper 200 km depth in the well-instrumented region of central and West Antarctica using a joint inversion of Rayleigh wave velocities and receiver functions (Shen et al., submitted). We obtain an estimate of the geothermal heat flux via a Bayesian inversion of Rayleigh wave observations for thermal structure using relationships between seismic velocity and temperature (see Weisen Shen presentation). The second seismic structure model is an adjoint full-waveform inversion for mantle structure beneath the entire continent and surrounding oceans, extending down to mantle transition zone depths (Lloyd et al., in prep). This model allows for lithospheric thickness to be mapped across the entire Antarctic plate, and for corresponding implications for geothermal heat flow to be made. Very thin or absent lithosphere along the Ross Sea Coast from Northern Victoria Land to the Southern Transantarctic Mountains, along the Amundsen coast and continental shelf, and beneath the Antarctic Peninsula suggest the likelihood of higher geothermal heat flow in these locations. Although most of East Antarctica shows thick, cold lithosphere, we also find younger or tectonically modified thinner lithosphere beneath portions of Dronning Maude Land and the Lambert Graben, suggesting the possibility of somewhat higher mantle contributions to heat flux in these areas.

Reconciling geological and radioglaciological context for heat flow in West Antarctica

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West Antarctica hosts the large West Antarctic Rift System (WARS), a region of continental extension which has formed during several stages of rift reactivation from the Cretaceous through the Cenozoic.

Subglacial volcanic activity has been documented along the Executive Committee Range in Marie Byrd Land, where a swarm of deep long-period earthquakes was registered in 2010 and 2011 by the POLENET seismic network. Recent modeling has also evaluated the sensitivity of the West Antarctic Ice Sheet to hotspots; however, these results have not been evaluated in the context of basal conditions and crustal geology.

Here we analyze magnetic anomalies collected during recent aerogeophysical expeditions over Thwaites Glacier (THW), Pine Island Glacier (PI), and eastern Marie Byrd Land (MBL), in order to evaluate the distribution of potential hotspots in the region. We identify three different regions with distinct magnetic character and correlate each one of them to specific stages of tectonic and magmatic activity in WARS. Our interpretation supports both the hypothesis that MBL was tectonically and magmatically reactivated multiple times during the Cretaceous and that a hotspot was emplaced there later in the Cenozoic, therefore pointing to a hotter MBL compared to THW and PI.

We also evaluate the basal conditions in the interior flank of Marie Byrd Land, in the context of basal reflectivity, specularity, and subglacial water routing. We find a region of high specularity (indicative of elevated subglacial water) along the flank of Marie Byrd Land. We evaluate whether this water formed in place, or routed out of the Marie Byrd Land dome.

We place these observations in the context of the now well surveyed larger scale structure of the West Antarctic Rift System, and the crustal gradients observed by POLENET.