ISAES Geothermal Heat Flux (GHF) Side Meeting

Report

Friday 26th July 2019, 13:00-15:00, Songdo Convensia, Incheon, Republic of Korea

Attendees (abbreviations used in the text in parentheses):

Alex Burton-Johnson (ABJ – Side Meeting Chair)
Ricarda Dziadek (RD – Session Chair)
Weisen Shen (WS – Session Chair)

Audrey Huerta (AH)
Andreas Laufer (ALa)
Andrew Lloyd (ALl)
Adam Martin (AdM)
Alessandro Maritati (AlM)
Anya Reading (AR)
Catherine Ritz (CR)
Erica Emry (EE)
Fausto Feraccioli (FF)
Folker Pappa (FP)
Guy Paxman (GP)
Jorg Ebbing (JE)
John Smellie (JS)
John Goodge (JG)
Kenichi Matsuoka (KM)
Kirsty Tinto (KT)
Laura Crispini (LC)
Mareen Losing (ML)
Naresh Pant (NP)
Paul Winberry (PWi)
Pippa Whitehouse (PWh)
Stewart Jamieson (SJ)
Tobias Staal (TS)
Yasmina Martos (YM)

Absent, but involved in instigating the meeting and advising on the report

Jacqueline Halpin (JH)

Introduction

The geothermal heat flux to the base of the Antarctic ice sheet is inherently difficult to measure, yet accurate estimates are necessary to better understand cryosphere dynamics. This is crucial to improve models of ice flow, mass loss and sea level change, and optimise site selection for ice core paleoclimate studies. At the POLAR18 meeting in Davos a proposal was put forward to form a sub-group of SERCE focusing on better understanding geothermal heat flux across Antarctica. This ISAES Side Meeting facilitated a meeting of this sub-group and any other interested delegates to build on discussions that took place at POLAR18 and also the SERCE-funded workshop, "TACtical" held in Hobart in March 2018 (see report https://www.scar.org/scar-news/serce-news/report-tact-2018/).

1. Existing regional and continental models

- To open discussions, the basic methodology and broad limitations of the seismic and magnetically-derived GHF models were presented (e.g. An et al., 2015; Fox Maule et al., 2005; Martos et al., 2017; Shapiro and Ritzwoller, 2004).

1a. Considerations for seismically-derived GHF models

- Velocity in seismic models doesn't account for variability of mantle compositions, mineralogy, grain size, and water content of the mantle or crust; although it may be possible to constrain this empirically by comparing with other settings.
    - To address the uncertainties regarding the Antarctic mantle, a Geological Society of London Memoir is currently being compiled summarising data gained from mantle xenoliths, including a database of xenoliths, and a compilation of their grain size and water content. This information can be shared despite the future publication date. These xenoliths are from shallow sources, as their occurrence is biased towards areas of crustal rifting where the lithosphere is thinner. Some information comes from deeper parts (e.g. Amery Rift and Ferrar Dolerite).
- Uncertainty in seismic models is large (>50 %) and has a skewed distribution.
- The velocity variations utilised by seismic models of GHF are affected by both temperature and composition. For example, slow mantle velocities at subduction zones can be caused by water or hydrous fluids. By inverting seismic velocity to temperature only a few % are related to temperature and vary spatially across the continent. It's not known how much of the velocity anomaly is related to temperature.
    - Whilst constraining these variables individually (temperature, composition, water content) is tricky, it may be possible by empirical methods. For instance if you take the seismic mantle velocity in the US and compare it to Antarctica. If the mantle velocity is similar, then perhaps the mantle temperature is similar as well. Combined with plotting the local GHF distribution gives some information how the reality differs from the models and their assumptions.

1b. Considerations for magnetically-derived GHF models

- Satellite-derived magnetic GHF models (e.g. Fox Maule et al. 2005) are obsolete and no longer require equal presentation or discussion with models from airborne data. Regions where only satellite data is available should be blanked out in continental GHF models.
- Variable window sizes are necessary for spectral magnetic analysis of curie depth (e.g. between East and West Antarctica, or where different tectonic terranes are assumed). Analysis is based on the assumption that the window size has to be 10x larger than the bottom of the magnetic source. Results are unrealistic if invariable window sizes are used, due to the different depths of the magnetic source (particularly between East and West Antarctica). Geological and tectonic maps and boundaries, plus crust and lithosphere thickness, would help inform on appropriate window sizes and wave numbers.
- Care must be taken when considering the absolute values of curie depths. We can be more confident in the patterns of anomalies rather than absolute values. Curie depths deeper than 25-30 km have problems, as windows become too broad and details are not captured (as shown at the Norwegian margin; Ebbing et al., 2009).
- Sensitivity tests of magnetic analysis in areas with a shallow geotherm (where the Curie depth is well above the Moho depth) show that the patterns are reliable even if depths themselves are less constrained (e.g. Audet and Gosselin, 2019; Bouligand et al., 2009; Ebbing et al., 2009).
- An uncertainty study on curie depth methods would be helpful to determine the effect of data spacing (flight line or profile spacing) on our interpretations. Processes that create artificial

long-wavelength anomalies, for instance, are the flight-line geometry. Magnetic-derived GHF models need to consider the implications of long-wavelength anomalies.

1c. Crustal heat production

- In seismic models, GHF is derived from the upper mantle velocity and an assumption of crustal heat production. Understanding crustal heat production is important to estimate more accurate GHF from seismology.
- Whilst crustal heat production is intrinsic to magnetic models of GHF via its effect on the crustal geotherm and Curie depth, a better understanding of the heat production of the column will make models more robust.
- Either the use of Gamma Ray Spectroscopy (GRS) or Heat Producing Element (HPE) chemistry can be used successfully to determine crustal heat production are fine. HPE data allows utilisation of a larger archive of existing data.
- Rather than using GRS equipment in the field, utilise the existing sample archives and database, or analyse samples in the lab. Anne Grunow (Byrd Polar Rock Repository) is keen to help. However, note that rock samples are collected for various reasons.
- Geoscience Australia and the University of Tasmania are compiling geochemical data for locations in East Antarctica, inc. the Amery Ice shelf, Vestfold Hills and Prydz Bay (Carson et al., 2016; Carson and Pittard, 2012). UTAS is compiling Antarctic geochemistry including HP. V1 is available as part of a global dataset (Gard et al., In review) and the next version (due first half 2020) will be enhanced for Antarctica (both East and West).
- Burton-Johnson et al. (2017) attributed a geology map with HPE data and integrated this with existing seismic models to understand spatial variability of GHF in areas with poor constraints. This was limited by lateral and vertical constraints; important as spatial variability may change between basin scales to pluton scales.
- Heat production in the upper crust has been shown to decrease exponentially with depth, with most radiogenic heat sourced from the upper 10 km. It is not clear if seismology could help at this resolution. This relationship has been observed elsewhere, but only in shield/cratonic settings. It has also not observed in detailed field studies of exhumed crustal profiles (Alessio et al., 2018), indicating need for further understanding of crustal HPE distribution.

1d. Other methods and considerations

- Beyond geophysical models, geotherms can be investigated petrologically from exposed crustal sections in Victoria Land (Berg et al., 1989; Martin et al., 2014).
- Regarding whether one methodology is applicable to the whole continent, or different approaches should be applied in different geographic regions, it is interesting to see where different approaches/models converge. Regional/sub-continental studies, where rock is exposed and undertaking a similar effort (e.g. Burton-Johnson et al., 2017) give a better sense of spatial variability of crustal contributions. Useful to have multiple regions with more insight to compare to. There might be areas where magnetic or seismic models make more sense.
- Not only the background GHF is important to know but also the spatial scale. GHF can vary by 100mW/m^2 over just a few metres, and for finding oldest ice, small scale variations are really important (+-5 mW/m^2). Flight lines from radar/interface conditions allow initial estimation.
- Topographic correction can increase GHF by 100% (paper in review). Topographic correction at 500m spatial resolution; will help to understand/quantify the details of spatial variations in GHF. Recent work (in review) used BedMachine (Morlighem et al., 2017) rather than BedMap (Fretwell et al., 2013) as there is no gap across the grounding line.

- Groundwater effects on GHF require consideration. For example, Fisher et al. (2015) measured a value of 285 ±80 mW/m^2 at a WISSARD site into the Whillans Ice Stream; this value is higher than on some mid-ocean ridges and likely a result of advective heat transport by subglacial fluids. However, the gradient here was calculated from two numbers. A different attempt to measure heat flow with a higher penetration depth 100 km from Fisher et al. (2015) on the WIS got a value of 88 ±8 mW/m^2 (Begeman et al., 2017); still high but more similar to the predicted values for West Antarctica
- Given the differences between models, independent low-resolution models are useful for quality control of higher resolution methods. Papers on low-resolution heat flux inferred from L-band satellite data (CryoSMOS), which detects a 1 km integrated temperature signal from electro-magnetic waves (Macelloni et al., 2016; Passalacqua et al., 2018, plus an unpublished but available technical report). This approach only works in cold-base settings.
    - Satellite measurements can give how microwaves are attenuated near the surface of the ice sheet. Microwave penetrates only max 100 m or so, thus this absorption rates give thermal information in this depth range, say the shallowest 3-5% of the ice sheet. Retrieving geothermal flux from such shallow temperature information is challenging, though it might be useful to be an independent check of large-scale regional values.
- Erosion histories influence current GHF by reinforcing the signal between erosion and heat flux (since heat flux will influence basal melt, and hence ice dynamics, and hence erosion)
- The alternative approach of TS for identifying potentially distinct regions looks promising for differentiating crustal blocks; including how to compare Antarctica with the conjugate margins.

2. Direct and indirect measurements and model validation

- GHF can vary by 100mW/m^2 over just a few metres, so caution is advised when utilising borehole measurements for validation. Be wary of using point measurements to ground truth models. GHF values derived from ice cores (borehole temperatures) also rely on models and assumptions. Even point measurements taken close to one another are known to give very different measurements of GHF in response to the high spatial variability of the system; a local value may not be regionally representative. There are geophysical/geological reasons why adjacent point values may differ.
- Some validation is provided where lakes have been cored. A few locations where temperature profiles have been measured along ice core boreholes (sometimes to the bed) were documented in the talk by Rob Mulvaney.
- The presence of subglacial lakes can provide a *minimum* GHF at that location through ice sheet modelling using the heat equation (the papers of Brice van Liefferinge are highlighted; Liefferinge et al., 2018; Liefferinge and Pattyn, 2013). However, constraining the lakes based on their cold-wet transition may give both minimum and maximum values.
    - Utilising lakes to calculate GHF only works in certain locations, and lakes only provide point GHF values. The inventory of subglacial lakes can be used to identify GHF in some areas, but this method only works where there is no horizontal advection of ice, i.e. interior of the EAIS. Whether lakes are in a depression or not must be considered as this affects whether a lake can form. But perhaps can use distribution of lakes to place bounds. Categorising different types of lakes may help when inferring GHF.
    - The presence of a lake also depends on bed conditions and whether water can drain away. No lake/water does not imply that the bed is frozen, and proving conclusively that ice is frozen to the bed is challenging
- GHF can also be inferred from ice draw down.

- Ice borehole temperature inversions to determine GHF still require modelling. The preferable method is to measure in the bedrock and sediments, perhaps even using repeat measurements. RAID will drill 20-50m in to the bedrock and leave the borehole open after drilling using drill fluid of the same density as the ice. A thermistor will be left in the borehole, allowing repeat measurements.
- Marine measurements of GHF are dependent on seafloor temperature variations. It is easier to measure temperatures if there is sediment coverage, but considerations of the water temperature are required. Similar to base of ice sheets, where processes act on different time scales. You need to measure temperature over at least 3-4m down a borehole. ~160 mW/m^2 was measured ~20km offshore JRI, while onshore measurements show only 50 mW/m^2. You have to account for sediment type, and can only do this in small valleys where there is enough sediment, which limits sampling locations. Also possible are: temperature sensors on the gravity corer, which allows 3in1 observation: sediment type, and measurements of the water column and sediment temperature.
- Fox Maule (in review) have some HF measurements from Australia that they extrapolate to Antarctica. Pollett et al. (In review) will also offer a Gondwana interpolation of heat flow to assess spatial variability in East Antarctica.
- Remote sensing could provide a broad differentiation of felsic and mafic rocks. Seismology can also be used to determine how felsic the crust is; perhaps currently just crustal average, but could potentially get at depth variations with more sophisticated methods. However, felsic/mafic differentiation is useful to a first order only. For example, shales are high in K, but have low thermal conductivities.

3. Future directions

- Need for a database of glacial evidence (subglacial lakes, ice draw-down), GHF measurements, and the data and uncertainties from geology and geophysics. A statistical framework is required, and information must be useful at different levels.
- With the end of the current SCAR scientific research programs (e.g. SERCE, PAIS) in 2020, now would be an opportune time to write a white paper to influence the future SCAR initiatives. SCAR wants to reduce the number of scientific research programs post-2020. Consequently, a white paper would need to be submitted before the end of 2020. Such a report should present clear aims or a “product”. In addition, there will be a call for side meetings at the August 2020 SCAR Open Science Meeting in Hobart.
  - Initial volunteers from this meeting for contribution to the white paper, and preliminary subject areas are: ABJ, RD, JH, CR (glaciological discussion), YM (magnetic discussion), WS (seismic discussion), AR (data compilation discussion), AM (mantle compositions), JE (discussion of satellite data), JG (discussion of RAID). Other recommended contacts were also proposed (Brice van Liefferinge, Frank Pattyn).
- Request a Side Meeting at the 2020 Scar Open Science Meeting.
- A proposal is being developed regarding a post-2020 scientific research program that will bring together many of the interests currently covered by SERCE, PAIS and AntClim21. The overall aim will be to improve our understanding of Antarctica’s contribution to future sea level. Folded into this is the need to understand all the processes controlling ice dynamics, which is where GHF comes in. The proposal is being framed around a series of 15-20 key questions. One of these relates to better understanding GHF across the continent. Tim Naish is co-ordinating the proposal; he is currently revising the structure. PWh to liaise with Tim about the timing of when input is next needed. Will need to provide a short paragraph on the key questions that need to be addressed regarding GHF, likely by early December.

- Provide geotiffs of the different heat flux models, along with point data of heat flux measurements and other evidence to KM for presentation and dissemination via Quantarctica.
- A short “bibliography” of selected papers will be hosted on the SCAR/SERCE webpage to aid background reading and orientation in this subject. This is particularly important for GHF research as it requires specialists from diverse fields. Researchers are invited to submit to ABJ their favourite papers and a short paragraph summarising the paper and explaining its merits.
- Rather than developing a new GHF mailing list, it was agreed to utilise the existing PAIS and SERCE mailing lists to build and support the broader interest in this topic.

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