IceBase: A proposed suborbital survey to map geothermal heat flux under an ice sheet

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26 June 2013, v. 4.0

Abstract: The IceBase team proposes to map geothermal heat flux and thermal anomalies under the Greenland ice sheet from high (20 km) altitude using a magnetics-focused survey undertaken from NASA's ER-2 and/or Global Hawk platforms. Separation of spatial from temporal field variability will be enabled by the Greenland magnetic observatories, repeat stations, the Swarm satellite constellation, and a potential dropsonde arrangement. The proposed mission would be part of NASA's Earth Venture program. Mapping geothermal heat flux under an ice sheet will reduce the uncertainty in future sea level rise, in turn allowing a more informed assessment of its impact on society. We describe in this paper the theoretical basis for this joint US-Danish-international effort, it's current status based on existing satellite and airborne data, and plans for the analysis of our science data.

Introduction: Magnetic fields provide information about the thermal state of the crust in at least four different ways. First, recent volcanism can often be identified from magnetic surveys because of its characteristic large-amplitude, short-wavelength signal and associated features found in highly magnetic but thin, shallow sources (Finn and Morgan, 2002; Nabighian et al., 2005) Second, magnetic fields induced in crustal rock by the main field provide a measure of the thickness of the magnetic crust, and that thickness provides constraints on the location of isotherms within the crust (Fox Maule et al., 2005). Third, spectral characteristics of the magnetic field can allow for a direct determination of the depth to the magnetic bottom, and this can provide independent constraints on the location of isotherms in the crust (Bouligand et al., 2009). The fourth, and final way of determining thermal state is via an EM survey, whereby the electrical conductivity of layers within the crust is determined (Banks, 2007; Unsworth, 2007). Electrical and thermal properties are often strongly correlated.

Proper planning for the acquisition of magnetic field observations is critical if their full potential for thermal state investigations is to be realized. Magnetic signatures are strongly dependent on the distance from the magnetometer to the magnetic source. This can be quantified by the wavelength sensitivity of the magnetic signature (Fig. 1). There are three caveats important in interpreting this figure. First, all of the wavelengths may not be accessible to interpretation because of overlap with the core field (Purucker and Whaler, 2013). Second, the figure assumes a 2-d source, whereas many of the magnetic anomalies measured in practice can be described as point dipoles. And third, the ability to separate spatial from temporal variation in the magnetic field is independent of the distance factor, but critical to mapping the quasi-static magnetic fields of interest for thermal state determination. In essence, we need to associate the time-varying signals from nearby static and moving magnetometers in order to properly separate temporal from spatial variation. In any case, it can be seen from Fig. 1 that the selection of an altitude, or altitudes, at which to conduct the magnetic survey is critical.

The IceBase investigation has three secondary science goals. Secondary science goal #1 is the remote sensing via motional induction of oceanic circulation in the waters

of the North Atlantic (Vivier et al., 2004). Secondary science goal #2 is the identification of Greenland's oldest ice (Severinghaus et al., 2010). Finally, secondary science goal #3 is the determination of the geologic structure and basin framework of Greenland (Henriksen, 2008).

The IceBase team (Table 1) consists of leading scientists and technologists in the areas of magnetic fields and cryospheric sciences. The team has been involved with the development and interpretation of both airborne and satellite surveys of the magnetic field.

Platform: NASA flies both an unmanned Global Hawk (GH) and a manned ER-2 as part of its high-altitude, suborbital research program (Fig. 2). Both of these jet aircraft fly at 20 km altitude, but the Global Hawk has a much longer useful time aloft (26 hrs vs. 7 hrs.). The Global Hawk has been flying from NASA-Wallops on the U.S. mid-Atlantic coast as part of a program to monitor hurricanes, and it could easily reach Greenland from this location to perform extended missions there. Its base of operations is NASA's Dryden Research Center, located at Edwards Air Force Base in California. NASA acquired its two Global Hawks from the US military, and these two aircraft are some of the first Global Hawks to fly for the US Air Force. As a consequence of its earlier missions from Wallops, the Global Hawk has the necessary airspace clearances to ascend to flight altitude from this location. The Global Hawk has also been outfitted with a dropsonde arrangement in its tail for its hurricane monitoring flights whereby a dropsonde can be dropped from 20 km altitude to monitor pressure, temperature, and wind aloft as it drops to the surface in 30 minutes via parachute, all the while communicating with the Global Hawk. The dropsondes are loaded and dispensed in a 'coke-bottle' type of arrangement, and up to 70 dropsondes can be loaded in the reservoir. To our knowledge, the Global Hawk has never carried a magnetometer before, although a nose stinger was fabricated for the original Global Hawk. Nose stingers, and/or wing tip pods, are the preferred location for housing magnetometers. The Global Hawk does not have wing-tip pods, and for aerodynamic reasons, nothing can be mounted on the wings of the Global Hawk. A nose stinger could house the magnetometers, and the electronics hardware could go in the environmentally controlled forward instrument bay. An effort would need to be undertaken to determine the necessary magnetic characteristics of the GH aircraft before scientific flights could be undertaken.

The ER-2 jet aircraft are NASA modifications of the military U-2 spy plane. The shorter range of the ER-2 dictates that the aircraft would have to fly from Iceland or Greenland for missions over Greenland. The ER-2 has recently completed a month-long campaign flying over Greenland, using Iceland as a base. It could also fly from Greenland as long as the ER-2 managers felt it was safe, and the 15 knot cross-wind speed limit on take off and landing was not exceeded. Because the ER-2 pilot wears a spacesuit, and the engine uses fuels typically reserved for rockets, ER-2 flights evoke the aura of manned space flight, and this makes the ER-2 managers very conservative in their selection of takeoff and landing sites, and in flight planning.

However, the configuration of the ER-2 is more suited to magnetometers, and in fact a Geometrics Cesium magnetometer has flown in five test flights over the US Fresno magnetic observatory in the 1990's (Hildenbrand et al., 1996). So we know that the ER-2 is a suitable platform for magnetometers, and the wing-tip pods are ideal locations for magnetometers.

In summary, the advantages and disadvantages of the two aircraft suggest that it might be best if the Greenland mission begins with the ER-2, and transitions to the Global Hawk as soon as it is properly validated and calibrated for magnetic field measurements.

Instruments: The proposed instruments provide information about the intensity and direction of the geomagnetic field. (Hrvoic and Newitt, 2011), utilizing fluxgate and total field magnetometers. A novel aspect of this effort is the use of a magnetometer-GPS dropsonde arrangement. As noted above, the Global Hawk has been outfitted with a dropsonde arrangement to monitor conditions in the hurricanes it overflies. It may be that the ER-2 can also carry such an instrument deployer too, although this is not considered further here. One of the major difficulties of conducting magnetic surveys over large ice-covered regions such as Greenland and the Antarctic is the logistical difficulty of placing magnetometers on the ground underneath the expected flight path to allow for the proper separation of temporal and spatial variability. A quick inspection of Fig. 2 shows the presence of magnetic observatories only along the Greenland coast where they are more easily accessible. While a certain amount of such temporal-spatial separation can be performed by the polar-orbiting Swarm satellites as they pass overhead, the fact that they are also moving and not constantly overhead (the orbital period is 90 minutes) makes such a separation much more difficult, and often impossible. Dropsondes equipped with calibrated vector, and/or scalar magnetometers, GPS navigation, and onboard commuications (either back to the plane or to satellite) would allow for proper temporal-spatial dealiasing to be performed once the dropsonde lands, and probably even before landing. The arrangement should continue to yield useful data while its batteries are functional, and while a suitable aircraft or satellite is overhead for uploading the information. One of the potential problems with such an arrangement is the cost of the dropsonde and its equipment, although efforts are underway to minimize those costs with new magnetometer designs, and by taking advantage of previous technology developments such as those with dropsondes into hurricanes, such as outlined above. The costs of the dropsonde need to be compared to the costs, and associated risks, of placing base station magnetometers on the ground on the ice sheet in central Greenland. A dropsonde arrangement has the added advantage of providing superior magnetic depths to source as it descends from 20 km altitude to the surface (Blakely, 1995).

Science concept and application using existing data: In this section we will discuss only the second (Fig. 3) of the four concepts introduced in the Introduction because the other concepts have been discussed in more detail elsewhere. Magnetic fields induced in crustal rocks by the main field provide a measure of the thickness

of the magnetic crust, and that thickness provides constraints on the location of isotherms within the crust (Fox Maule et al., 2005) and the basal heat flux. The basal heat flux, in turn, provides a boundary condition for the evolution of the overlying ice sheet (Rutt et al., 2009; Nowicki et al., 2013). The magnetic signal associated with the crustal rock thickness is modeled to be +- 100 nT at 20 km altitude over Greenland. This compares favorably with the sensitivity of the magnetometers to be used, which are in the pT range, and with the range of these instruments, which are optimized for the Earth's field (<60000 nT). Assuming a 12 km line spacing for the magnetic survey and 200 km tie lines, we estimate that 40 flights of the Global Hawk will be required to cover all of Greenland and near offshore regimes.

The reason for preferring a high-altitude measurement of the magnetic field, as opposed to a typical low (1 km) altitude measurement, is that low altitude measurements emphasize isolated magnetic features in the upper crust that are often dominated by magnetic remanence. The magnetic signals from isolated features such as these will decay as 1/r-cubed, in contrast to a 1/r-squared decay for 2-d sources of greater lateral extent. So going to higher altitude will suppress these isolated signals. For our purposes, magnetic remanence is a contaminating signal that needs to be identified, and or removed, prior to our analysis. We want our measurements to be sensitive to the entire magnetic crust because that is our signal, and hence placing the magnetometer at an altitude typical of average continental crustal thickness (20-35 km) appears to offer an optimum signal. In contrast, magnetometers at satellite altitude (350-500 km) are completely insensitive to vertical variations of the magnetic signal within the crust, and have horizontal sensitivities comparable to their altitude. So a magnetometer flying at 400 km will have a full-wavelength horizontal resolution comparable to the altitude. A 400 km horizontal resolution is more than an order of magnitude larger than the crustal thickness, which is the scale at which we expect crustal magnetic thickness, and heat flux, to vary.

The technique for calculating the magnetic crustal thickness, and the associated heat flux, has been discussed in detail in the appendix to Fox Maule et al. (2005) and will not be repeated here. We have updated the satellite magnetic field model to MF-7 (Figs. 4 and 5), which has considerably higher resolution than the version shown in Fox Maule (2005). The full wavelength resolution of the MF-7 model is about 300 km, corresponding to spherical harmonic degree 133. Magnetic fields in the polar region have the largest uncertainties because of unmodeled external fields, and so this number should be considered a conservative guide. In addition to the satellite only model shown in Figure 4, we have implemented a more detailed approach taking into account the poorly determined airborne and marine magnetic fields over Greenland and surrounding areas (Figure 5). This approach uses a local instead of a global data set to dramatically shorten the computation time, and also does not implement a core field filter because the size of the Greenland continental crust (<2600 x 1500 km) is smaller than the spherical harmonic degree 16 cutoff. It currently lacks a model of the oceanic remanence in the oceans surrounding

Greenland, and so the final model should not be interpreted in the oceanic regions. But it is encouraging to see that the two approaches give similar results over Greenland proper. While the combined satellite and aeromagnetic model is much more detailed, it should be kept in mind that there is little reliable magnetic field information with wavelengths between 50 and 200 km.

Validation of science concept: Geothermal measurements at the appropriate scale (Hjartarson and Armannsson, 2010), recent volcanism, ice streams, and supporting geological and geophysical information all offer the opportunity to validate (or invalidate) the science concepts. Validation has been discussed in detail by Rajaram et al. (2009), Fox Maule et al. (2009) and Purucker et al. (2007). We will be discussing the validation of this, and subsequent, models in detail in a further paper, so we will defer any further discussion here.

Plans for analysis of science data: Observations of the magnetic field contain signals from many sources, and these must be characterized prior to their use in mapping the thermal state of the crust (Table 2; Reeves, 2005). The sources can be characterized as natural or man-made. Man-made sources are dominated by the magnetic fields associated with the aircraft. Magnetic compensation is the practice of characterizing and removing the magnetic fields associated with the aircraft from the observations. In a traditional analysis, the magnetic compensation is performed first, followed in a serial fashion by the removal of natural magnetic fields. (Thébault et al., 2013). However, all of the natural and man-made fields can be co-estimated, and this gives a better understanding of the associated errors in the analysis (Sabaka et al. 2013). The tradeoff is generally a lower resolution in the associated crustal field.

Discusion: The risks to the successful completion of this effort are 1) unusually high geomagnetic activity, associated with the location of Greenland under the auroral oval, 2) failure of the ability to separate temporal from spatially-varying magnetic fields, either through problems with the base stations, Swarm, or the novel aircraft-launched dispenser arrangement, 3) magnetic cleanliness of the platform, 4) failure of the primary fluxgate or secondary total field magnetometers , and finally 5) platform (aircraft) failure. These issues can be addressed with a thorough magnetic compensation program, redundancy of instrumentation and approaches, and by acquiring the surveys in magnetically quiet times. Although we are now close to the maximum of the sunspot cycle, this has been the quietest cycle of the space age. Monitoring of solar activity should allow for the suspension of flights in the event of large storms.

Conclusion: The thermal state of the earth's crust is an important variable in understanding the stability of ice sheets. The design of a mission to map the thermal state of the Greenland crust under the ice sheet is an important step towards understanding the vulnerability of the ice sheet to destruction from below.

Acknowledgments: C. Hansen, K. Louzada, and L. Mayo assisted with the development of Fig. 2. We would like to thank Ben Chao, and Weijia Kuang for organizing the Taipei workshop, and for their hospitality. Purucker is supported by NASA's Earth Surface and Interiors Program.

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Tables:

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- T. Sabaka (698). Core, ionospheric, magnetospheric modeling
- G. Le (674). Magnetospheric modeling
- W. Kuang (698). Core, motional induction modeling
- R. Tyler (CREST/698). Motional induction, oceanic modeling
- M. Purucker (SGT/698). PI. Crustal magnetism and thermal modeling
- J. Connerney (695). Induction modeling
- J. Espley(695). Ionospheric and magnetospheric field modeling
- A. Tangborn (UMBC/698). Motional induction modeling
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- Assisted by an instrument and science team from Denmark (J. Matzka, N. Olsen, J. Jorgensen, C. Finlay from DTU and T.M. Rasmussen from GEUS, and C Fox Maule)
- Further assisted by an international team of scientists and engineers (R. Blakely & R. Bracken, USGS; C. Gaina & S. McEnroe, Norway; C. Bouligand and C. Ritz, UnivGrenoble; D. Ravat, UnivKentucky; B. Nelson, Canada; A. Vaughan; E. Thebault, IPGP; V. Lesur, GFZ; and Guðfinna Th Aðalgeirsdóttir, Univ Iceland)
- Advisors: Christie Hansen (IceBridge PM), Lars Toeffner-Clausen (Head of Danish magnetics data center), Coerte Voorhies (698 Emeritus, instrumentation, theory and modeling)

Table 1: Science team members

Plan for analysis of science data

- Remove airplane fields (magnetic compensation)
- remove time-variable core field
- remove time-variable magnetospheric field
- remove tidal oceanic magnetic field
- remove coastal effect
- remove ionospheric currents
- Determine depth to top of magnetic sources
- grid data/level flight lines
- Remove crustal field signatures unrelated to crustal thickness (remanence and magnetic topography, for example)
- Determine depth to Curie isotherm using magnetic crustal thickness and power-spectral approaches.
- determine heat flux using 1-D heat conduction eq. or utilizing the layered model (upper, middle, lower crust) of Fox Maule et al. (2009), with calibration/validation provided by other independent approaches.
- Identify magnetically thin, laterally extensive layers at the surface that may be the signature of recent volcanic activity.
- Model ice sheet evolution using the magnetically determined boundary conditions.

Table 2: Plans for the analysis of science data

Illustrations:

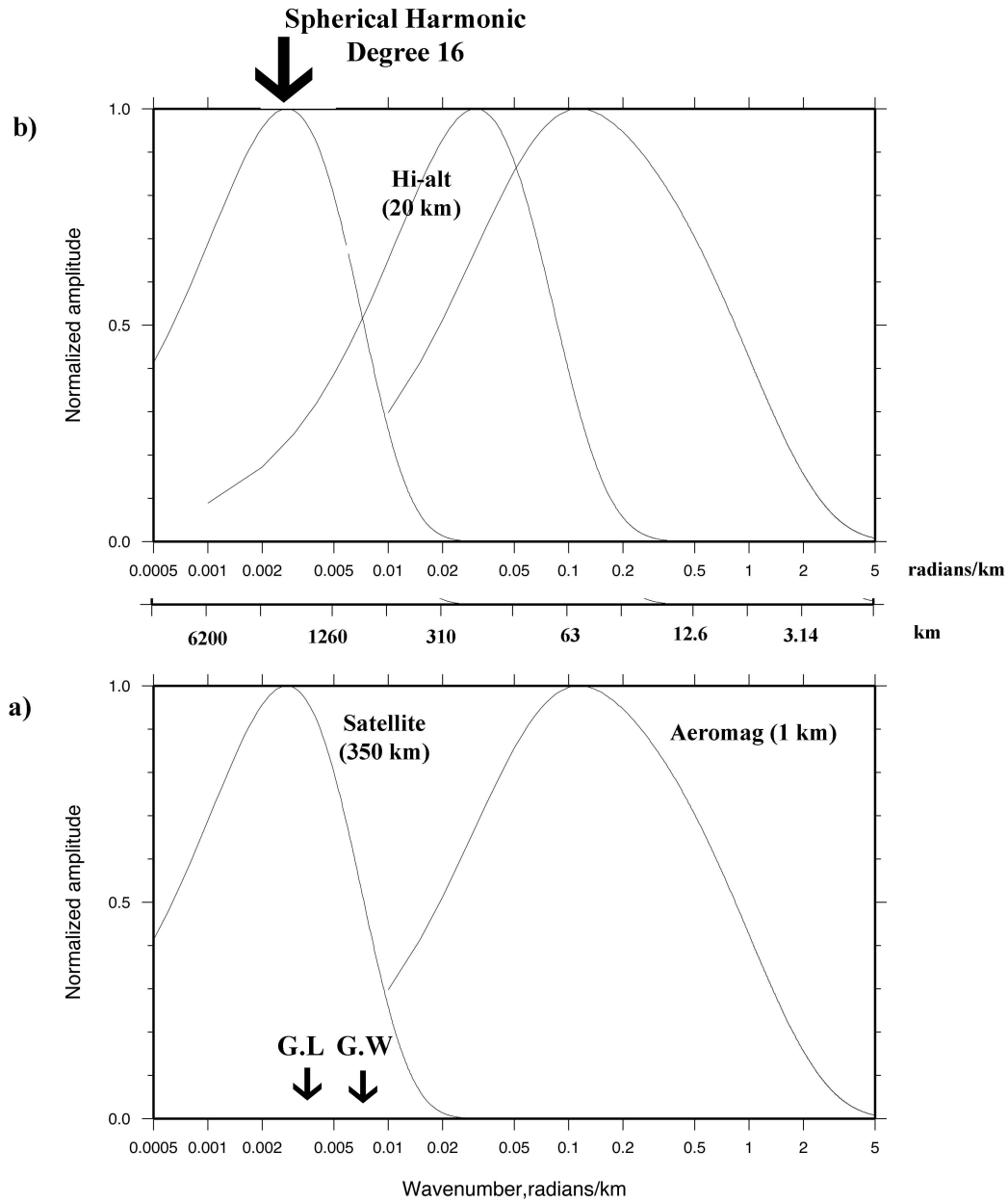

Fig. 1: Wavelength sensitivity of magnetic signature as a function of the measurement-observation distance. The bottom figure (a) shows the wavelength sensitivity of satellite and typical aeromagnetic observations, while in the top figure (b) we add the wavelength sensitivity of the proposed high-altitude survey. The approach is modified from Hildenbrand et al. (1996), and utilizes a 2-D earth filter, based on Eq. 11.35 of Blakely (1995). The top and bottom of the magnetic layer are

assumed to be at the surface (0 km) and 30 km below the surface. G.L.= North-south dimension of Greenland. G.W.=East-west dimension of Greenland. The horizontal axis is labeled in radians/km, km, and spherical harmonic degree (16, the degree at which the power from the crust dominates that from the core). Magnetic fields with spherical harmonic degrees less than 16, corresponding to those to the left of the mark, are not accessible to interpretation.

Fig. 2: IceBase logo with location of Greenland observatories to enable separation of temporal from spatial variability, proposed platforms (NASA's ER-2 and Global Hawk), and participating nations (with flags).

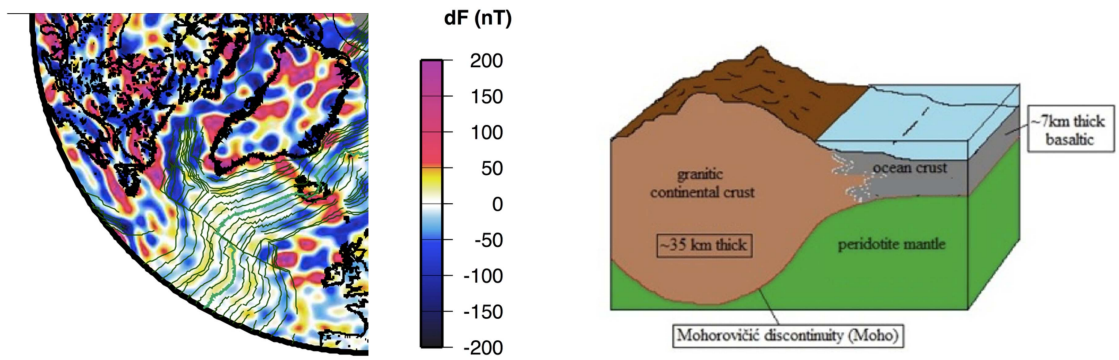

Fig. 3: Science concept illustrating the difference between the magnetic signature of continental and oceanic crust, and the relative magnitude of the signal to be modeled. Crustal magnetic total field (dF) at geoid surface from MF-7 (Maus, 2010) model with superimposed oceanic isochrons (left) and model continental-oceanic cross section (right). In the absence of magnetic remanence, the crustal magnetic total field is proportional to the crustal thickness times the magnetic susceptibility. Heat flux is proportional to the inverse of crustal thickness, assuming steady-state 1-d heat conduction with no lateral variations of material properties or heat production. The Moho is assumed to coincide with the Curie isotherm and to be at 580 C.

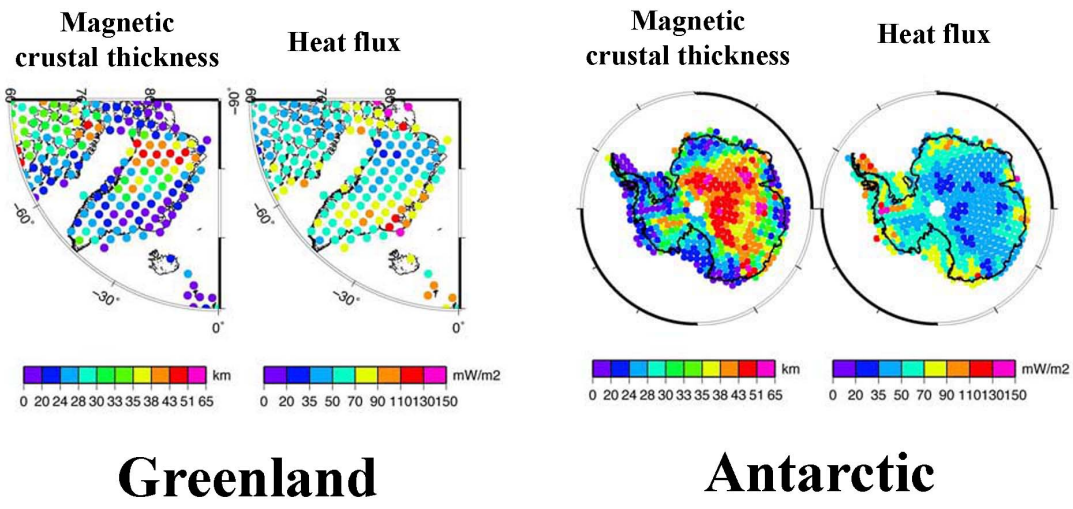

Fig. 4: Modeled magnetic crustal thickness and heat flux over Greenland and the Antarctic using satellite-only model (MF-7) from Maus (2010) and the global approach of Fox-Maule et al. (2005).

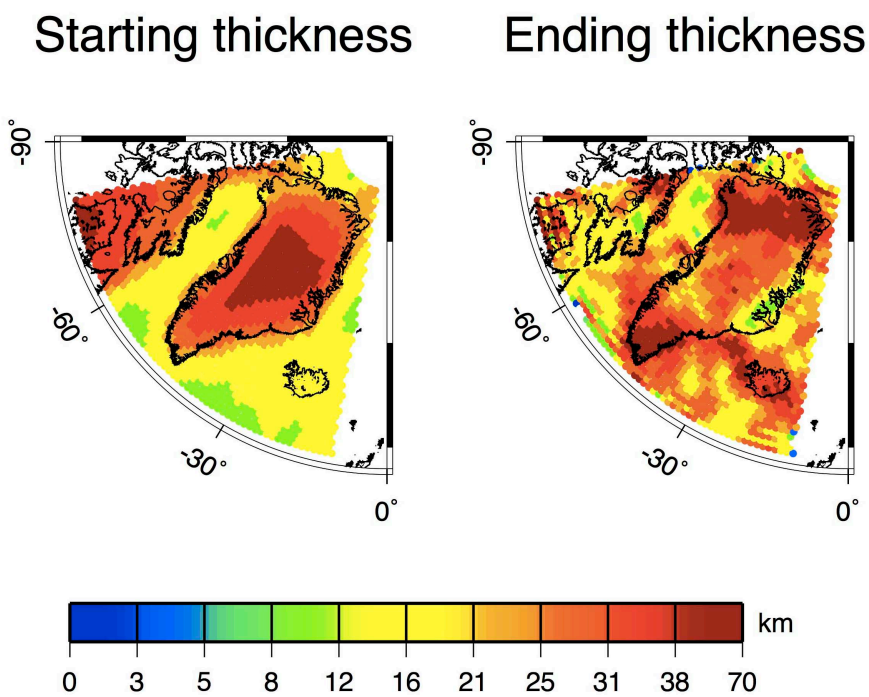

Fig 5. Modeled magnetic crustal thickness over Greenland using a combined satellite-airborne model (NGDC720/EMM2010 degree 720) from Maus (2010) and a local approach, showing the starting (left) and ending (right) crustal thickness values. The starting crustal thickness values are based on the 3SMAC model (Nataf and Ricard, 1996). A value of 0.04 SI was used for the magnetic susceptibility. The

local boundaries are shown on the figure, and values within a few degrees of that boundary should be ignored for the purposes of interpretation. The oceanic values should also be ignored, as the model does not currently take into account the magnetic remanence of the oceanic crust. The shortest wavelength represented is about 60 km.