# Importance of Solid Earth Structure for Understanding the Evolution of the Greenland Ice Sheet

Jörg Ebbing, John R. Hopper, Clinton P. Conrad, Glenn Milne, Rebekka Steffen, Juan Carlos Afonso, Valentina R. Barletta, Ana M. G. Ferreira, Judith Freienstein, Samantha E. Hansen, Björn H. Heincke, Glenn Jones, Sergei Lebedev, Max Moorkamp, Derek L. Schutt & Agnes Wansing

**Title: Importance of Solid Earth Structure for Understanding the Evolution of the Greenland Ice Sheet**

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Authors:

Jörg Ebbing[1,*], John R. Hopper[2,3], Clinton P. Conrad[4], Glenn Milne[5], Rebekka Steffen[6], Juan Carlos Afonso[7], Valentina R. Barletta[8], Ana M. G. Ferreira[9], Judith Freienstein[1], Samantha E. Hansen[10], Björn H. Heincke[2], Glenn Jones[9,11], Sergei Lebedev[12], Max Moorkamp[13], Derek L. Schutt[14], Agnes Wansing[1]

1. Kiel University, Institute of Geosciences, Otto-Hahn-Platz 1, 24118 Kiel, Germany
2. Geological Survey of Denmark and Greenland, (GEUS), Øster Voldgade 10, 1350 Copenhagen, Denmark
3. Department of Geosciences and Natural Resources, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen, Denmark
4. Centre for Planetary Habitability, University of Oslo, Oslo, Norway
5. Department of Earth and Environmental Sciences, University of Ottawa, Ottawa, ON, K1N 6N5, Canada
6. Lantmäteriet (The Swedish Mapping, Cadastral and Land Registration Authority) , Sweden
7. University of Twente, Langezijds Bld., Hallenweg 8, Enschede 7522 NH, the Netherlands
8. Department of Geodesy and Earth Observations, DTU Space, Lyngby, Denmark
9. University College London, Department of Earth Sciences, UK
10. Department of Geological Sciences, The University of Alabama, Tuscaloosa, AL, USA
11. University of Cardiff, School of Earth and Environmental Sciences, UK
12. University of Cambridge, Department of Earth Sciences, UK
13. Institute for Applied Geosciences, Technical University of Berlin, Ernst Reuter Platz 1, 10587 Berlin, Germany
14. Department of Geosciences, Colorado State University, Fort Collins, CO, USA

*Correspondence: Joerg.ebbing@ifg.uni-kiel.de

## Abstract

The solid earth structure beneath Greenland, meaning the rocky part of Earth from the ice-bed interface to depth, has gained increased interest in recent years as it provides a critical boundary condition for the dynamic evolution of the Greenland ice sheet (GrIS), one of the largest sources of sea-level rise contributions since the early 2000s. However, no consensus has been reached regarding the key internal or surface earth properties influencing this boundary condition and thus GrIS behaviour. One important surface property is the subglacial heat flow, which affects sliding conditions of the ice sheet including the onset of major ice streams and is related to subglacial geology. Lithospheric architecture and mantle viscosity structure are internal properties that influence ice sheet evolution through changes in the height and slope of the ice-bed interface caused by glacial isostatic adjustment (GIA). Because there is no general agreement regarding crustal and lithospheric structures, some glaciological studies use an ensemble of solid earth models to incorporate uncertainties into their GrIS predictions, but it is unclear how these variations ultimately affect estimates of future sea-level rise. Here we describe the main solid earth properties that are important for GrIS evolution (heat flow, temperature, viscosity), from the base of the ice sheet to the upper mantle, and we provide some perspectives on how future collaborative efforts and integrated studies could lead to better agreement regarding these key characteristics.

Meltwater from the Greenland ice sheet (GrIS) has been one of the largest sources of sea-level rise since the early 2000s (e.g., Mankoff et al. 2021, Bamber et al. 2018, Fox-Kemper et al. 2021). Despite the global mean sea level contribution of up to +0.89 mm/yr (Horwat et al. 2022) and a mass loss of more than 247 Gt/a (2012-2016; Bamber et al., 2018), the driving components behind ice mass loss and their corresponding feedback mechanisms are still not completely understood. Thus, future ice mass loss remains one of the largest uncertainties for future sea-level projections (e.g., Bamber et al., 2019, Fox-Kemper et al. 2021). It has been demonstrated that subglacial conditions can play an important role in ice-sheet behaviour (e.g. Bell 2008, Smith-Johnsen et al., 2020a, McCormack et al. 2022). Sub-ice geology, geothermal heat flow (GHF), topography, and topographic changes resulting from glacial isostatic adjustment (GIA), can all influence GrIS evolution. These factors may be especially important for marine-terminating glaciers, where ice interaction with seawater has been shown to accelerate deglaciation in Greenland (Wood et al. 2021). However, rapid GIA-induced bedrock uplift (Whitehouse et al. 2019) or fjord topography resulting from geological structures may block inflow of warm water by ocean currents (Jakobsson et al. 2020) and can exert a stabilizing influence. Such interactions have been demonstrated as important for Antarctica (e.g., Book et al. 2022), but are poorly constrained for Greenland. Therefore, it is essential to enhance our knowledge of solid earth and cryosphere interactions (e.g., Bell 2008, Whitehouse et al. 2019) and to better constrain the solid earth properties that control them.

Karlsson et al. (2021), for instance, showed that the present GrIS basal melt production amounts to ~21.4 Gt/a (~10% of the total mass loss) with an uncertainty ranging from +4.4 to −4.0 Gt/a. This ~20% uncertainty is mostly related to the heat flow models used in their calculations. Since the uncertainty of individual models is difficult to assess, Karlsson et al. (2021) used an ensemble of models to determine an average heat flow estimate. Rogozhina et al. (2012) performed sensitivity tests to determine how different input GHF distributions affected simulations of the present state of the GrIS. Their results indicate a high sensitivity of the GrIS to the input GHF, demonstrating the importance of reducing uncertainty in this quantity. Ultimately, Rogozhina et al. (2012) questioned whether or how geophysical models should be used, given their large uncertainties. The conclusions of the authors are supported by a more recent study that quantified the impact of using seven different GHF models to spin up a GrIS model to an equilibrium state (Zhang et al. 2023).

Additional uncertainties stem from the thermal interactions between the Iceland hotspot track and Greenland's lithosphere. Individual observations suggest high heat flow in central Greenland (~98 mW/m²; Grinsted and Dahl-Jensen 2002), and some models require even higher

local heat flow to sustain the Northeast Greenland Ice Stream (e.g., Greve 2019). However, reconstructed hotspot tracks and lithospheric-scale models continue to exhibit significant variability and uncertainty regarding the location of potential heat flow anomalies, leaving the expected magnitude of GHF unresolved (e.g., Heyn et al. 2022). Furthermore, variations in GHF at the ice-bedrock interface are likely accompanied by thermal heterogeneities in the underlying mantle. Such an anomalous mantle structure may contribute to the rapid uplift rates, which are observed by global navigation satellite system (GNSS) data (e.g., Khan et al. 2016, Berg et al. 2024). These uplift rates are considerably faster than those predicted by 1-D (spherically-symmetric) GIA models tuned to fit paleo sea-level data that reflect the response of the solid earth to GrIS deglaciation since the Last Glacial Maximum (e.g., Lecavalier et al. 2014; Khan et al. 2016). This has led to the suggestion of a significant transient component in the deformational response (Adhikari et al. 2021, Paxman et al. 2024).

The examples above highlight the need for spatially variable (3-D) solid earth models with robust uncertainty estimates that can be utilized when coupling solid earth models to ice-sheet models. While significant effort has been made to develop such constraints for Antarctica, especially in terms of incorporating geothermal heat flow (Reading et al. 2022) as well as isostatic and erosional changes (Whitehouse et al. 2019), similar initiatives for Greenland are still missing. The upcoming 5th International Polar Year in 2032/33 should provide an opportunity for coordinated international research to tackle the biggest challenges of polar research, including the development of improved solid earth models to more accurately evaluate past and future GrIS evolution on century to millennial time-scales.

## The role of solid earth structures for the evolution of the Greenland ice sheet

From a solid earth perspective, the conditions along the base of the ice sheet are the most critical for GrIS evolution. Bell (2008) and Whitehouse et al. (2019) described some of the main components. These include the role of subglacial water or basal melt, which may result from elevated GHF, as well as local bedrock conditions. Therefore, it is not only important whether the bed is thawed or frozen, but knowledge about the rugosity, which relates small-scale changes in topography and the geology at the ice-bed interface and the presence of sediments at the ice-bed interface, are also critical. Topography modulates outlet glaciers and controls the state of stress for glaciers, critical for determining the dynamics of the ice-sheets (Catania & Felikson 2023). Even though substantial improvements have been made in recent years in our knowledge of the topography under the ice (e.g. Morlighem 2017, 2021), data coverage is still

sparse in some critical regions. For example, knowledge of local bedrock composition, the crustal thickness, and tectonic history are needed to understand the distribution of radioactive elements, which impacts basal heat flow (see next section). In addition, variations in lithosphere thickness also allow for large mantle contributions to GHF, although on a different scale. Additionally, the thermal structure of the upper mantle plays a critical role in determining the viscosity distribution and lithospheric thickness (e.g., Paxman et al. 2023, Weerdesteijn and Conrad 2024), which influence the rate and amplitude of isostatic responses, affecting the bed topography. These factors, in turn, impact ice-sheet elevation and surface mass balance (e.g. van den Berg et al. 2008, Zeitz et al. 2022). We provide further details on these characteristics, and the geophysical datasets available to constrain them, in the following sections.

## *Basal melt and heat flow*

Conditions at the base of an ice sheet play a key role in governing subglacial water and basal melt. Radar imaging is the most effective tool to determine basal water distribution and to assess whether the ice sheet is thawed or frozen at the base (e.g., MacGregor et al. 2016, Jordan et al. 2018). These data, however, do not necessarily account for changes in bedrock reflectivity (i.e., the reflection amplitude) due to varying geology.

Of the ~21.4 Gt/a of basal ice melt estimated by Karlsson et al. (2021), about half is attributed to basal friction while viscous heat dissipation from surface melt water and GHF each contribute about one quarter. For individual drainage basins, the relative contributions vary, reflecting the different basal conditions but also the uncertainties. These uncertainties comprise about 20% of the total basal melt estimate and reflect how poorly GHF models agree. The significant differences in GHF amplitude and spatial distribution are apparent when models that have been published over the last decade are compared (e.g. Colgan et al. 2022). This comparison translates into highly variable basal melt rate estimates from GHF (see Figure 2). In general, the discrepancies between these models reflect the fact that only about ten observation points from boreholes or ice measurements are available from Greenland's interior and that estimates for one of those observation points are highly debated.

That particular point of contention is the heat flow at the onset of the Northeast Greenland Ice Stream. For the ice stream, basalt melt estimates range from 1 to 2 Gt/a, with variations mainly depending on the treatment of the North Greenland Ice core Project (NGRIP) GHF determination. For example, Dahl-Jensen et al. (2003) provided upper and lower bound GHF estimates of 160 and 90 mW/m$^2$, respectively, for the NGRIP data, based on models of the age

of ice layers determined from radar echograms. Smith-Johnsen et al. (2020b) instead argued that very high local heat flow (970 mW/m²), well above the suggested range from observations, is needed in this area, to sustain the Northeast Greenland Ice Stream. Bons et al. (2021) contend that such extreme heat flow is unrealistic, as there is no plausible geological origin for it and Freienstein et al. (2024) provided a statistical analysis of all available observation points and concluded that the NGRIP data point should be considered with caution since it is statistically an outlier, at least on a regional scale. Questions surrounding the NGRIP observation also provided the motivation for the GHF prediction by Colgan et al. (2022), where all observation points have been compiled and (re-)analysed, to present two alternative heat flow maps, one including and the other excluding the NGRIP value (Figure 2).

The resulting GHF maps (Figure 2) show, that except in the immediate vicinity of NGRIP, one might be able to provide a reasonable regional baseline heat flow estimate. However, local variations, which are needed to describe the coupling conditions for ice-sheet models, might still be obscured (e.g. McCormack et al. 2022). Therefore, the prediction of local GHF variations remain a challenge for accurate assessment of GrIS changes. It is worth noting that similar challenges are faced in Antarctica. Reading et al. (2022), for instance, discussed how small-scale heat flow variations are difficult to constrain, and Stål et al. (2024) stressed the importance of gaining a better understanding of subglacial geology to link point-wise observations with regional heat flow models.

## Sub-ice geology

Sub-ice geology affects the ice sheet in different ways. Rugosity at the ice-bed interface affects basal sliding conditions for example a sedimentary layer tend to be less dense and less erosion resistant, and hence smoother, facilitating enhanced basal sliding. Geology affects the transfer of heat from the crystalline crust to the ice, reflecting variations in radiogenic heat production. In sedimentary layers and shallow bedrock, porosity and pore fluid compositions affect the thermal conductivities. Variations of either subglacial topography where the thermal conductivity of glacial ice and the solid Earth differ, or in thermal conductivity, can lead to thermal refraction at the ice-bed interface (e.g. Willcocks et al. 2021). Further, neighbouring tectonic units are often associated with different thermal properties (radiogenic heat production and thermal conductivity), which can influence heat flow on a local scale. Hence, detailed knowledge of the sub-ice geology is a prerequisite for describing the basal conditions of the system accurately.

The subglacial geologic setting of Greenland was first evaluated by Dawes (2009, Figure 3A). This study examined exposed geology in the ice-free coastal regions as well as glacial erratics from GrIS outflow streams. Similar and synchronous formations along the coast and plausible tectonic scenarios were often used to propose boundaries between major geologic provinces, but these were typically unconstrained across several hundreds of kilometres. It was also recognized that some features identified by geophysical data were inconsistent with some surface-based inferences (Dawes 2009). For example, a southwest-northeast striking division of Proterozoic crust was identified based on seismic analyses from Dahl-Jensen et al. (2003), but no expression of this boundary is indicated in the geology map by Dawes (2009).

Recently, MacGregor et al. (2024) provided a new map (Figure 3Figure 3.B) that describes the geological provinces beneath the GrIS based on a synthesis of geophysical data, where 19 geologic and geophysical data sets were used to delineate major geological provinces. For example, subglacial topography was considered as a potential constraint on subglacial geology. Most of the differences between the two geologic province maps (Figure 3) are located in North Greenland, where MacGregor et al. (2024) infer a less extensive Ellesmere-Inglefield terrane and the Committee-Melville terrane has been eliminated, despite its onshore exposure. In addition, inferred basins, from which exotic glacial erratics could have originated, have also been eliminated. The erratics could plausibly have come from the extensive 'unknown' area on the MacGregor et al. (2024) map (see grey area in Figure 3B). Hence, while MacGregor et al. (2024) presents an alternative view of the sub-ice geology, a key shortcoming is that it is inconsistent with the exposed geology in several areas. For example, the East Greenland rift basins are assigned Devonian–Permian ages, despite the fact that significant and thick deposits of Mesozoic sections are well exposed in these areas (e.g. Stoker et al. 2017, Fyhn et al. 2021 and references therein). Such considerations have important implications for understanding basal paleo-heat flow during past deglaciations.

A second issue with the MacGregor et al. (2024) map is that it relies on the interpretation of geophysical data that are highly heterogeneous in terms of quality as acknowledged by the authors. For example, the choice of a seismic velocity model is subjective as competing and contradicting models exist (Figure 4, Jones et al.2021, Darbyshire et al. 2018, Toyokuni et al. 2020).

Darbyshire et al. (2018), the model used in MacGregor et al. 2024, focussed on the overall crustal structure using group velocity measurements from regional earthquakes. In contrast, Jones et al. (2021) targeted near surface anomalies using Rayleigh wave ellipticity

measurements to describe the subglacial properties. Further, the Jones et al. (2021) model is based on a single-station approach that generates 1-D velocity models beneath each station, while the Darbyshire et al. (2018) model was developed using relatively long path-averaged structures. In contrast to these studies, Toyokuni et al. (2020) presented a model based on the analysis of P-wave arrival time data that shows a clear seismic anomaly extending from Iceland to eastern Greenland in the crust and upper mantle, but the model is in general focused on the overall lithospheric architecture.

While the available seismic velocity models (Figure 4) show some similarities, such as the relatively high velocities in western Greenland, there are also some notable differences, such as in north-eastern Greenland, reflecting the differences in methods and data. Given the relatively large inter-station distances in Greenland, the differences between these models are not surprising. Additionally, each study selected different stations for their analyses to make use of the best-quality data for the specific method applied. Interestingly, neither the map by MacGregor et al. (2024), nor the tomographic models, show an indication of the southwest-northeast striking division of Proterozoic crust that was identified in the earlier study by Dahl-Jensen et al. (2003) (Figure 3A).

In general, seismic station coverage across Greenland is rather sparse and uneven (Figure 4D), and any seismic model would benefit from additional data. It is interesting to note that the unresolved area indicated by MacGregor et al. (2024; Figure 3B) has comparatively dense seismic coverage compared to other regions. That said, other data types that are used in MacGregor et al. (2024), such as the magnetic field anomalies acquired from the Earth Magnetic Anomaly Grid (Meyer et al., 2017), have relatively crude coverage in this region. Magnetic data are arguably the most sensitive to upper crustal structure and are thus helpful in interpreting sub-ice geology (e.g., Aitken et al., 2014, Brethes et al. 2018, Golysnky et al. 2018). Despite ongoing efforts to reprocess the magnetic data sets for Greenland (Heincke et al. 2023) to create a new compilation, the lack of adequate, modern high-resolution data hampers the possibility to trace geologic structures from the coast and beneath the ice, thereby limiting our ability to use magnetic data for an accurate prediction of variations in subglacial geology.

## Crustal and lithospheric architecture

Improved constraints on the crustal and overall lithospheric architecture beneath Greenland are critical for us to gain a better understanding of the solid earth-ice interaction because the lithospheric structure is controlled by both rheological and thermal properties. A number of studies have evaluated lithospheric variability beneath Greenland (e.g., Steffen et al. 2017,

Artemieva 2019, Wansing et al. 2024), using a range of data types and approaches. Most models are based on gravity measurements, seismic velocities and/or petrophysical data. Considerable differences exist between resulting models that relate to both station (data) coverage and methodological differences.

As an example, seismic estimates of crust–mantle boundary (Moho) depth display large disagreements, even between models based on the same dataset. For instance, Dahl-Jensen et al. (2003) analysed P-wave receiver functions for 20 broadband seismic stations to estimate the crustal structure beneath central Greenland and found Moho depths ranging from 23 to 50 km, which were interpreted to reflect different tectonic blocks. Kumar et al. (2007) reinterpreted the same P-wave receiver function data and added S-wave receiver functions, since they are less affected by multiples in the ice layer. They found significantly shallower Moho depths beneath central Greenland, which deviate by up to 11 km. The largest discrepancies were found for stations deployed on ice and can likely be attributed to ice layer effects on the seismic signal (see Wansing et al. 2024 for further details).

Models estimating the depth of the lithosphere-asthenosphere boundary (LAB) are even more diverse (Figure 5), also due to differences between employed data sets and different methodologies. While earlier and especially low-resolution global models (e.g. Priestley & McKenzie 2013, Pasyanos et al. 2014) tend to disagree in the estimated lithospheric thickness, most recent models (e.g. Steinberger et al. 2019, Wansing et al. 2024, Salajegheh et al. 2024) show similar variation patterns and image the cratonic cores in North and South Greenland in similar locations. In general, the thermal base of the lithosphere appears to be deeper than 150 km for most of Greenland's interior, and significantly thinner lithosphere (<120 km) is only found beneath the south-eastern Greenland coast (see Figs. 5 and 6).

## Role of the Icelandic hotspot track and its link to lithospheric architecture

Greenland is thought to have passed over the Iceland plume between about 80-65 and 50 million years ago, forming a hotspot track that crosses the island (e.g., Martos et al., 2018; Steinberger et al., 2019). Several possible tracks have been identified based on geological observations, heat flow constraints, and tectonic reconstructions (see Figure 6, and references within Martos et al., 2018), and while these paths roughly converge at the south-eastern Greenland margin, they diverge towards the west or north-west (Figure 6). This partly relates to the unknown subglacial geology (see above), since any direct expression of volcanism is covered by ice and the geophysical signatures are ambiguous. As outlined by Larsen et al. (2015), intraplate

volanism in Greenland and the North Atlantic region occurred simultaneously and over a wide area, particularly around 60 million years ago, but this volcanism shows no resemblance to a hotspot track, suggesting instead that plume material (head or tail) injected beneath Greenland was channelled into lithospheric thin spots from Mesozoic rift basins along both West and East Greenland (Nielsen et al. 2002; Steinberger et al., 2019; Horní et al. 2017).

However, heat from the Iceland plume may also have thinned and weakened parts of Greenland's lithosphere. For example, Steinberger et al. (2019) based their interpretation of the hot-spot track on the tomographic model from Lebedev et al. (2018), in combination with plate reconstructions and numerical models of mantle flow. These predict east–west paleo-flow along a corridor of thinned lithosphere, seen in central Greenland by most tomographic models (Figure 5). In contrast, more recent seismic investigations (e.g., Celli et al., 2021) suggest the possibility of alternative plume track pathways to the northwest (Figure 6).

Heyn and Conrad (2022) made numerical models of a mantle plume impacting continental lithosphere and suggest that the interaction tends to thin the lithosphere along the plume track. The amount of thinning significantly depends on the characteristics of the plume, the lithosphere, and the underlying asthenosphere, with stronger plumes and weaker rheologies generating more thinning. The authors also found that the resulting increase in heat flux depends on the extent of lithospheric thinning, but for Greenland, the heat flux increase is likely limited to at most about 20% of the pre-thinning heat flux. This finding agrees with evidence for only moderately increased heat flow in the interior of the island (e.g., Martos et al. 2018). However, the plume should still significantly impact the thermal structure of the lower lithosphere, especially if the heat is transported by melt (Heyn et al. 2024), and this added heat may have left a low-viscosity zone in the upper mantle. If so, the plume may significantly accelerate rates of uplift following periods of deglaciation (see next section and Weerdesteijn & Conrad 2024).

## The importance of Greenland's upper mantle structure for GIA

Greenland GIA is constrained via both geologic and geodetic observations. Through modelling these observations, inferences have been made on GrIS evolution and earth viscosity structure (e.g. Tarasov and Peltier 2002, Fleming and Lambeck 2004, Lecavalier et al. 2014, Khan et al. 2016). This section focuses on the application of geodetic data, and how our knowledge of upper mantle structure is key to inferring GrIS changes via GIA modelling of these data.

Uplift rates in Greenland reflect the isostatic (GIA) response to both contemporary (during the GNSS monitoring period) and past ice mass changes. The latter includes signals associated with regional-scale deglaciation since the Last Glacial Maximum (e.g., Simpson et al. 2011, Khan et al. 2016) as well as signals due to more recent, lower amplitude changes, such as the Little Ice Age (Kjeldsen et al. 2015, Adhikari et al. 2021).

Contemporary ice-mass loss across Greenland can be estimated using satellite altimetry (Simonsen et al. 2021, Khan et al. 2022) and from satellite observations of temporal changes in the gravity field (e.g., from the GRACE-FO twin satellites). These estimates require a correction for GIA-related earth deformation, which is about 5-10% of the total signal (e.g. Wake et al. 2016, Barletta et al. 2024). Thus, an accurate estimate of the GIA signal is necessary to produce an accurate determination of contemporary ice mass changes, which are required for sea-level budget calculations and are an important initial condition for projecting future changes in the GrIS.

Several authors have noted that areas of lithospheric thinning near the Greenland's southeast coast coincide with areas of rapid uplift rates observed from GNSS networks (e.g. Bevis et al. 2012, Khan et al. 2016, Adhikari et al. 2021, Paxman et al. 2023, Berg et al. 2024, Weerdesteijn and Conrad 2024; Figure 6). This highlights the emerging consensus that GIA uplift rates are sensitive to variations in lithospheric thickness and mantle viscosity, which in turn are a result of temperature and compositional variations within the Earth. Lithospheric thickness and mantle viscosity may be reduced in areas that have been heated, as, for example, the Iceland plume may have done for southeast Greenland. The three-dimensional rheological viscosity structure beneath Greenland may thus control the rates of coastal uplift following deglaciation. Including 3D viscosity models in GIA calculations is computationally expensive and so relatively few cases have been explored to date. One study shows that uplift rates and postglacial sea-level changes are significantly affected by the 3-D viscosity structure (e.g., Milne et al., 2018). If viscosities are reduced beneath the lithosphere (e.g., 100-200 km wide regions with viscosity of $\sim 10^{19}$ Pa s), modern-day deglaciation rates can already induce a rapid viscous uplift of a few cm/yr (Weerdesteijn et al., 2022). Furthermore, Weerdesteijn and Conrad (2024) showed that recent deglaciation of Greenland drives unusually rapid uplift when positioned above a low-viscosity plume track beneath southeast Greenland.

In addition, recent studies suggest that the viscosity beneath Greenland may be timescale dependent (e.g. Adhikari et al., 2021, Paxman et al. 2024). That is, there may be a significant transient component to the deformational response such that the (apparent) viscosity is lower

for shorter timescale ice sheet changes. The existence of a transient signal has been proposed to explain why GIA models tuned to fit postglacial sea-level observations produce a poor fit to GNSS-determined uplift rates (Adhikari et al., 2021). Including a transient component increases the contribution of ice mass changes during and following the Little Ice Age (Kjeldsen et al., 2015) to match contemporary uplift rates. On the other hand, Pan et al. (2024) noted that including a thin and weak asthenospheric layer can alternatively explain rapid modern uplift rates, without timescale-dependent rheology. Clearly, improved constraints on the thermal and compositional structure of the earth from non-GIA approaches (e.g., Wansing et al. 2024) are necessary to reduce the ambiguity in the interpretation of GIA data sets and thus enable more robust constraints on GrIS evolution.

Future sea level predictions are sensitive not only to our understanding of the GrIS evolution (e.g. Höning et al. 2023) but also to global GIA patterns (e.g. Spada et al. 2017), which in turn cannot be well understood without the Greenland contribution. They are also likely dependent on feedbacks between GIA and ice-sheet evolution (e.g., Whitehouse et al. 2019). Such feedbacks have been proposed for Antarctica (Adhikari et al. 2014, Kingslake et al. 2018, Albrecht et al. 2024) and are likely also important for Greenland, but have not been adequately explored.

## The way forward

We have outlined some of the key elements from a solid earth perspective that influence the evolution of the GrIS. The question is where to proceed from here? First of all, better data coverage and improved data processing are key to advance our knowledge of Greenland. Some of the critical parameters cannot be measured directly (e.g. viscosity), while others (e.g. heat flow) are difficult to acquire beyond measurements in selected spots (boreholes).

However, geophysical data from seismic, magnetotelluric, gravity, and magnetic methods are, compared to a large number of boreholes, relatively cheap and feasible to acquire. For example, between the first and second generations of the Antarctic magnetic anomaly map (Golynsky et al. 2001, 2018) more than 2 million line kilometres of airborne data have been acquired, despite the more challenging logistics in Antarctica. If the same amount of data is acquired over Greenland with a regular spacing, the entirety of Greenland would be covered with 1 km profile distance.

With improved spatial coverage of geophysical measurements and their integrated interpretation, the key parameters for the coupling of the solid earth and ice sheet models could

be estimated with lower uncertainty, when considered in an integrated manner (e.g. Wansing et al. 2024).

## *Subglacial conditions*

The recent map by MacGregor et al. (2024) has demonstrated the potential of synthesizing boundaries of different data sets in order to image the subglacial setting for Greenland. A similar approach has mapped sedimentary basins (Aitken et al., 2023) and lithospheric architecture (Stål et al., 2019) for Antarctica. While such maps represent a valuable first-order step, these predictions should be coupled and tested by a physical earth model grounded in geological and tectonic knowledge. Modern approaches that consistently combine different physical models in joint inversions and employ thermodynamic models for the crustal and overall lithospheric architecture hold the potential to enhance our knowledge of the critical parameters beneath the GrIS (e.g. Fullea et al. 2021, Moorkamp 2022, Afonso et al. 2022, Lebedev et al. 2024).

Of course, the accuracy of any model depends on data quality and coverage. Magnetic data are one of the datasets most sensitive to the near-surface geology, but large areas of Greenland are still not well covered. For example, Wansing et al. (2024) shows a stepwise inversion for the lithospheric and crustal architecture, and the resulting density and magnetic susceptibility distribution in general agrees with petrophysical data. However, the structure of the model can be described as patchy at best and is not an adequate representation of the complexities of subglacial geology. This is especially true compared to detailed studies in Antarctica (e.g. Aitken et al. 2014, Lowe et al. 2024), where for large regions the data coverage and quality is far better due to ongoing efforts both in acquisition and coordination (e.g. SCAR Expert Group ADMAP or SCAR RINGS Action Group).

As mentioned above, complete coverage of Greenland would require a dedicated coordinated multi-national effort, but in the short run, a more localized airborne campaign near the onset of the NE Greenland Ice Stream (in the vicinity of the NGRIP stations) might be achievable. This area seems to be critical for deciphering the role of the subglacial geology for geothermal heat flow, but also for understanding the evolution of the ice sheet. Beyond the ice sheet modelling mentioned above (e.g., Smith-Johnsen et al., 2020b), a recent local radar study, which argues for a recent onset of the Northeast Greenland ice stream (Jansen et al. 2024), would rule out a massive heat flow influence, but still would allow sub-ice geology to exert a controlling influence.

Any dedicated gravity and magnetic airborne mission should be accompanied by further work on petrophysical, seismic and electromagnetic data sets. Petrophysical samples for Greenland

can provide constraints on LAB depth (e.g., Figure 1; Lee et al. 2009) and are available mostly from the coastal, ice-free areas. Yet, despite massive collections of rock samples from decades of (geological) mapping or from drilling projects (e.g. Christiansen et al. 2024), no tailored petrophysical database for Greenland is yet available. However, magnetic susceptibility, rock density, seismic velocity, thermal conductivity and heat production are important parameters to benchmark crustal models based on potential field airborne data and to predict thermal parameters that are important for heat flow under the GrIS.

## The solid earth architecture and its link to viscosity

In addition to the conditions at the ice-bed interface, an improved knowledge of the lithospheric architecture is also needed. Seismic data provide one of the main constraints on the crustal and lithospheric architecture of Greenland (e.g. Dahl-Jensen et al. 2003, Darbyshire et al. 2018, Lebedev et al. 2018, Mordret 2018, Tokoyuni et al. 2020, Celli et al. 2021, Jones et al. 2021, Ajourlou et al., 2024, Salajeghegh et al., 2024). The coverage with broadband stations for Greenland is certainly sparse compared to well covered regions in Europe or the US, but not all differences between models can be explained by this. A major difference is that often only a subset of available stations is used, and this selection varies from study to study as seen in the examples before.

Part of this incongruity among seismic studies is related to differences in the acquisition period among stations, as well as where and how the data are available. Here, a common reprocessing format and the establishment of a reference database would be useful, where metadata are properly described and tailored, based on which different processing methods can be easily compared. Such an initiative is ongoing but should be complemented by data acquisition in some of the key areas, especially near the coast. In addition, individual seismological studies often use specific types of methods, such as single station techniques, to build 1-D models beneath stations (e.g., receiver functions, Rayleigh wave ellipticity) versus multiple station approaches that constrain inter-station averaged seismic structures (e.g., earthquake and ambient noise tomography). In regions with large inter-station distances such as in Greenland, it is unsurprising that using these different approaches leads to conflicting results, as discussed above. Future work should focus on joint inversions of the seismic observables used with these complementary techniques (e.g., dispersion measurements, ellipticity, receiver functions, amplification) to tighten the constraints on subsurface structures. Further, to explore whether the high-uplift rates along the south-eastern coast of Greenland are related to the Iceland hotspot, a tighter coupling of offshore and onshore studies is also needed.

Methodological improvements may also be helpful, both for seismological methods (e.g. Lebedev et al. 2024) as well as for integrated approaches. For example, seismic tomography maps velocity variations in the mantle (e.g. Figure 6), which depend strongly on temperature, but the conversion factor between velocity and temperature is nonunique (e.g. Lu et al., 2020, Lebedev et al. 2024). Thermodynamic inversion methods that use computational petrology and thermodynamic databases can avert much of the non-uniqueness and resolve the thermal structure and thickness of the lithosphere based on the Rayleigh and Love surface-wave data, as well as Pn data (e.g., Schutt et al., 2018, Porter & Reid 2021, Lebedev et al. 2024). The methods are also effective for implementing the joint inversion of seismic and other data for both temperature and composition (e.g., Afonso et al. 2013a,b, Fullea et al. 2021, Afonso et al. 2022).

Other geophysical observables, such as magnetotelluric (MT) data, may become increasingly important for constraining Greenland's upper mantle structures. MT data, which are collected locally in temporary (days-long) deployments, provide constraints on electrical conductivity down to upper mantle depths. While the usefulness of MT data has already been demonstrated for Antarctica (e.g., Peacock and Selway, 2016; Wannamaker et al., 2018) so far, only a few measurement points over Greenland are available. Yet, MT data present the possibility, especially in combination with the data discussed above, to provide a more detailed image of the crustal architecture (e.g., Liu and Hasterok 2016, Moorkamp et al. 2023). For example, Ramirez et al. (2022) and Manassero et al. (2024) have recently shown that the combination of MT and seismic data offer useful constraints to both the temperature and water content of upper mantle rocks. Because these two factors represent the most important controls on rock viscosity, imaging of the subsurface using both MT and seismic methods can provide a new constraint on the viscosity structure of the upper mantle. Initial tests of the joint use of MT and seismic data for Scandinavia, where observations of surface uplift provide independent constraints on viscosity, are promising (Ramirez et al. 2024). Thus, a combination of seismic and MT data may complement, or even provide critical input to, numerical studies of GIA. Here, Central and Southeast Greenland, which were most likely impacted by the Iceland plume, represent key areas of interest.

Improvements in the imaging of the Earth structure will improve GIA models. Milne et al. (2018) showed the importance of using 3D GIA models for Greenland, but with more recent estimates of seismic velocity variations as well as better constraints on lithospheric thicknesses and improved GIA modelling capabilities (e.g., Weerdesteijn et al. 2023) these models can be enhanced. In addition, the determination of certain structures in the lithosphere and mantle

based on various geophysical datasets would give GIA modellers a unique set of boundary conditions, in line with upcoming initiatives, like the GIA Model Intercomparison Project (GIAMIP). Thus, discrepancies among GIA models could be reduced, which in turn affects mass balance as well as sea-level rise estimates.

## Modelling and measurement perspectives

The main challenge limiting our understanding of the solid earth beneath the GrIS is data coverage and lack of accurate descriptions of vintage data sets. Still, on the regional scale models converge towards similar results, as shown here for lithospheric thickness, but also for heat flow estimates, despite the unusual NGRIP measurements. In contrast, much remains unknown with respect to the local structure beneath the ice, which are needed to gain a better understanding and prediction of ice-sheet evolution. As explained above, MacGregor et al. (2024) provide a first approach of mapping subglacial geology, which should be extended by more advanced statistical methods (e.g. based on machine learning methods, e.g. Li et al. 2022), but also coupled with 3D Earth models (e.g. Lowe et al. 2024).

In addition, dedicated efforts should be made by the community to acquire key data sets in some of the most vulnerable and least understood regions of Greenland. Ideally, a combination of airborne data with ground based seismic and MT installations should be acquired to fill some of the gaps in Central Greenland, which appears to be the least understood region. This links to efforts in southeastern Greenland, where an improved understanding of ground-based observations (e.g., GNSS) and regional data requires an improved understanding of the lithospheric structure from Iceland towards Greenland. Recent discussion on an AtlanticArray (e.g., Ferreira 2024) spanning this region can only be supported from a Greenland perspective.

In addition to such campaigns, there are as well possibilities from upcoming (e.g. Next Generation Gravity Mission) or candidate (e.g., CryoRad) satellite missions. The advantage of satellite missions is the monitoring of the ice sheets in terms of mass, temperature and height changes, which allows us to decipher short-term and long-term effects, providing important information for testing structural models in dynamic modelling. However, such data and models also require detailed information from the solid earth. An example are the ice temperature models based on the SMOS (Soil Moisture and Ocean Salinity) satellite mission (e.g. Macelloni et al. 2019), which rely on geothermal heat flow as constraint, but so far on models with low confidence. The gravity field missions (GRACE and GRACE-FO) provided a unique method to estimate the ice-mass changes for Greenland (references, e.g. Velicogna 2009, Harig and Simons 2012, Velicogna et al. 2014), but their results are dependent on GIA models (e.g. Caron

et al., 2018). While these missions can complement studies of the GrIS as well as Greenland's lithospheric architecture and dynamic processes, they cannot replace stations on the ground.

# Conclusions and recommendations

In 2014, Kennicutt et al. (2014) defined a roadmap with key questions for Antarctic science for the next two decades, which raised awareness and motivated a number of studies dedicated to Antarctica. Without attempting to reproduce such a detailed analysis, we will highlight some of the key questions identified by Kennicutt et al. (2014) that are also relevant for Greenland (Please note that, we changed the questions by omitting links to the Antarctic ice sheet as these are also valid for the Greenland region):

- *Do variations in geothermal heat flux provide a diagnostic signature of sub-ice geology?*
  Yes, they do, but the absence of heat flow measurements means that sub-ice geology is taken as a proxy to derive geothermal heat flow.

- *What is the crust and mantle structure, and how do they affect surface motions due to glacial isostatic adjustment?*
  While recent models of LAB-depth show convergence on the regional scale, there is still a disconnect between geophysical and GIA models of the lithosphere and mantle, which has to be addressed in order to more accurately interpret observations of postglacial sea level changes and present-day land motion. In addition, future imaging of the crust and mantle should focus not only on elastic, isotropic structures, but also on other properties, such as, e.g., anisotropy (to better understand stress in the crust and mantle flow) and attenuation (to obtain independent information on temperature).

- *How does volcanism affect the evolution of the lithosphere, ice sheet dynamics, and global climate?*
  If we refer here to the Iceland hotspot and its interaction with Greenland, the location of the hot-spot track beneath Greenland remains unclear before Greenland moved away from above the hot-spot around 50 My ago. The lithospheric architecture appears to show an imprint of the hot-spot track, but the thermal effect at a crustal level is still debated.

- *How do the characteristics of the ice sheet bed, such as geothermal heat flux and sediment distribution, affect ice flow and ice sheet stability?*

Here, we are still at an infancy stage for Greenland as detailed models of the ice sheet bed are missing. For Antarctica, this has been addressed for example by McCormack et al. (2022) showing the importance of local variations on subglacial conditions.

- *How do tectonics, dynamic topography, ice loading and isostatic adjustment affect the spatial pattern of sea level change on all timescales?*

Changes to Greenland's ice load drive glacial isostatic adjustment (GIA), which proceeds more rapidly in areas with thinner lithosphere or reduced sub-lithospheric viscosity (e.g., Milne et al. 2018, Weerdesteijn et al. 2022). Thus, regions subjected to mantle heating, e.g., from the Iceland plume, will experience rapid bedrock uplift soon after deglaciation, and slower uplift later on after deglaciation is completed (Weerdesteijn and Conrad 2024). Because sub-lithospheric viscosity mostly influences uplift rates at relatively short (100s of km) wavelengths (Pan et al. 2024), these variations in uplift rate are likely to be regionally important for uplift and sea level change along Greenland's coastline. For coastlines distant from Greenland, Greenlandic deglaciation drives sea level change through its net mass loss and via spatial variations associated with the "sea level fingerprint", which accounts for Earth's gravitational and rotational changes in addition to solid earth deformation (e.g., Mitrovica et al. 2011). The sea level fingerprint has already been detected for modern deglaciation in Greenland (Coulson et al. 2022) and drove significant sea level variability following the last glacial maximum (e.g., Lin et al. 2021).

*How will the sedimentary record beneath the ice sheet inform our knowledge of the presence or absence of continental ice?*

Mapping the subglacial conditions in Greenland is a prime target to understand the feedback between the solid earth and cryosphere, but requires dedicated campaigns to fill some of the most critical (e.g. seismic and magnetic) data gaps to verify the location and thickness of sedimentary basins.

While not all of these questions have been answered even in case of Antarctica, substantial improvement in our understanding of the processes have been made and many of the lessons learned for the Antarctic ice sheet hold for the GrIS. In Antarctica, a number of dedicated international initiatives have been running for long time or have been initiated in recent years (e.g. Frémand et al. 2022, Colleoni et al. 2024).

Some of the initiatives almost date back to IPY-3 (1957-58), which is an especially good example for coordinated research activities. IPY-3 was part of the International Geophysical Year and led to the first geophysical traverse from the coast of East Antarctica to the interior of the continent and can be considered as the start of geophysical surveying of Antarctica (Dodds et al. 2010), which later on led to a number of multinational efforts that have advanced our knowledge of the continent. Similar coordinated efforts for Antarctica, where running under the umbrella of IPY-4 which ran from 2007 to 2009. IPY-4 involved over 200 projects examining a wide range of physical, biological and social research topics for both poles. However, research in the Arctic was largely dedicated to processes related to the Arctic ocean, but none of the projects was dedicated to Greenland or its structure beneath the ice sheets (see list at https://www.ipy.org/projects). This omission was at the time certainly related to the fact that the melting of the GrIS was just becoming apparent in satellite data and the discussion of its implication for sea-level rise at the beginning (e.g. Rignot & Kanagaratnam 2006, Dowdeswell 2006). As we now are aware of the drastic changes in Greenland mass balance in recent years and with the 5th International Polar Year in 2032-2033 on the horizon, we emphasize the urgent need for coordinated international research to advance our understanding of the solid earth structure beneath, and its interaction with, the Greenland ice sheet.

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# Figure Captions

Figure 1. Main elements of the solid earth structure that can affect cryospheric processes and the related datasets that can constrain upper mantle (left) and crustal (right) structure (modified from Reading et al. 2022 mainly by adding observables). HPE: Heat producing elements, $\Delta T$ and $\Delta C$ indicate temperature and compositional anomalies in the upper mantle.

Figure 2. Estimates of Greenland's GHF (top row) and associated basal melting (bottom row) for a suite of models. Corresponding GHF model sources are listed above each column, and all basal melting estimates were calculated following the method of Karlsson et al. (2021). Areas considered as being frozen are masked. Note the wide range of basal melt estimates, from 3.8 to 5.7 Gt/a.

Figure 3. (A) Mapped surface geology and interpretation of sub-ice bedrock in terms of major provinces from Dawes (2009). Dashed, grey line denotes the division of Proterozoic crust from Dahl-Jensen et al. (2003). (B) Synthesis of apparent subglacial geologic provinces from MacGregor et al. (2024).

Figure 4. (A) Relative Vs variations at 5 km depth from the model by Jones et al. (2021), which was not directly considered by MacGregor et al. (2024). (B) Depth slice at 5 km through the S-wave velocity (Vs) model from Darbyshire et al. (2018), as used in the map developed by MacGregor et al. (2024) shown in Figure 3b. Note that the Darbyshire et al. (2018) model constrains the Vs from 5 km downwards, while the Jones et al. (2021) model constrains Vs from 5 km upwards. (C) Relative Vp variations at 5 km depth from the model by Toyokuni et al. (2020). Each model used different seismic stations (triangles) in their analyses. (D) All available broadband stations across Greenland (Trine Dahl-Jensen, pers. comm.).

Figure 5. Lithospheric thickness estimates for Greenland highlighting the thermal structure of the lithosphere. Models (E) to (H) are global models, models (A) to (D) are recent Greenland models. From the local models, Steinberger et al. (2019) is based on direct conversion from seismic velocities to lithosphere thickness, all other models (B) to (D) are based on a combination of multiple, yet different, geophysical datasets. Panel (I) is highlighting the agreement between these models in terms of their predicted depths to the thermal lithosphere-asthenosphere boundary (LAB) by showing the number of models predicting LAB > 150 km depth.

Figure 6. Upper mantle velocity structure, uplift rates (red points) and possible Iceland plume-track (green lines). Background colours show variations in seismic velocity at 150 km depth

from the model by Celli et al. (2021). Faster seismic anomalies generally correlate with colder temperatures but also depend on mineral composition. Red circles mark the positions of GNSS stations, with their size proportional to the average crustal uplift rate (Berg et al. 2024). Green lines indicate possible paths of the Iceland hot-spot beneath Greenland based on the summary in Martos et al. (2018).
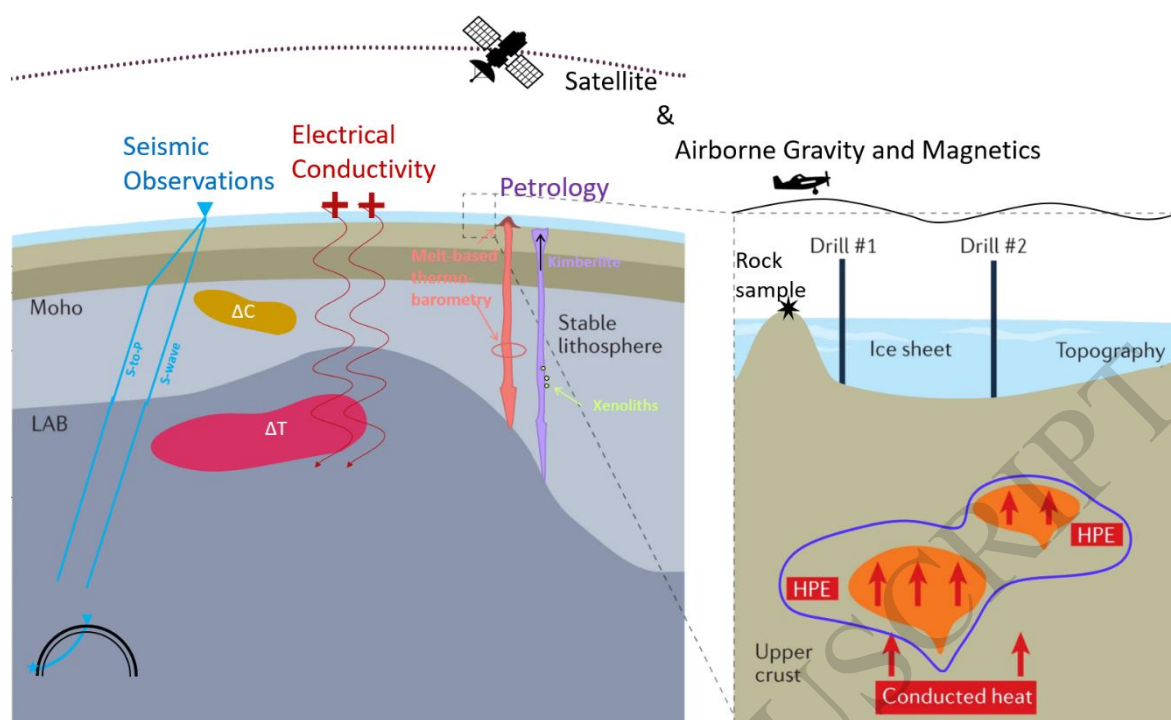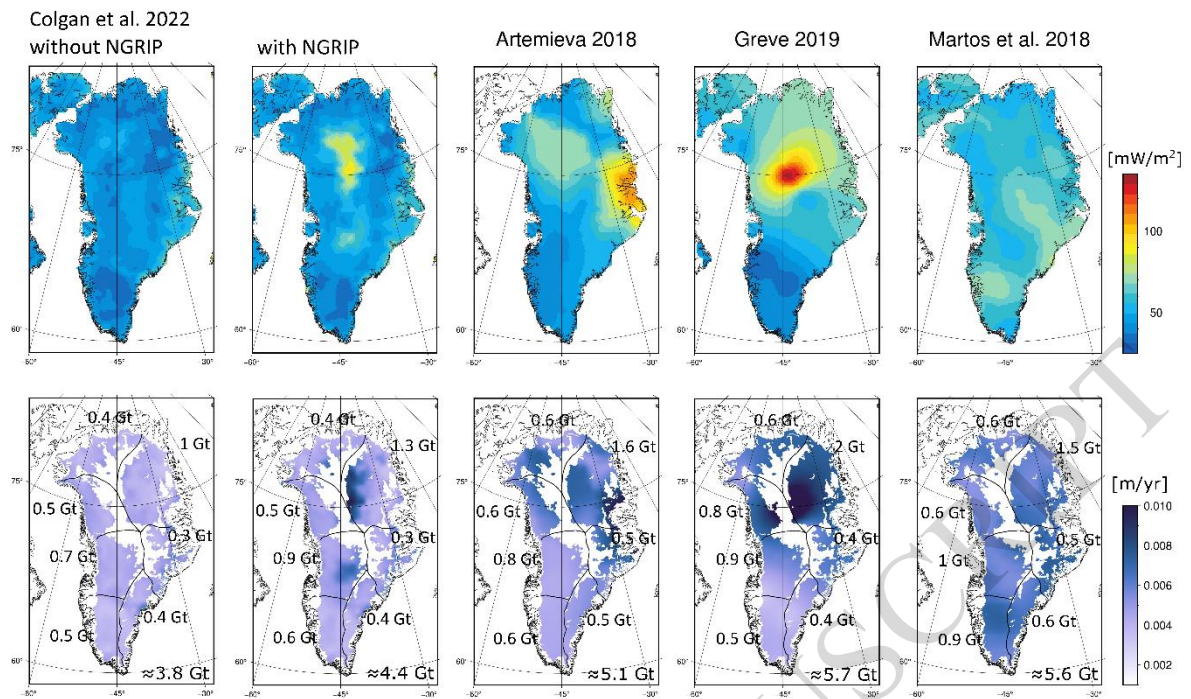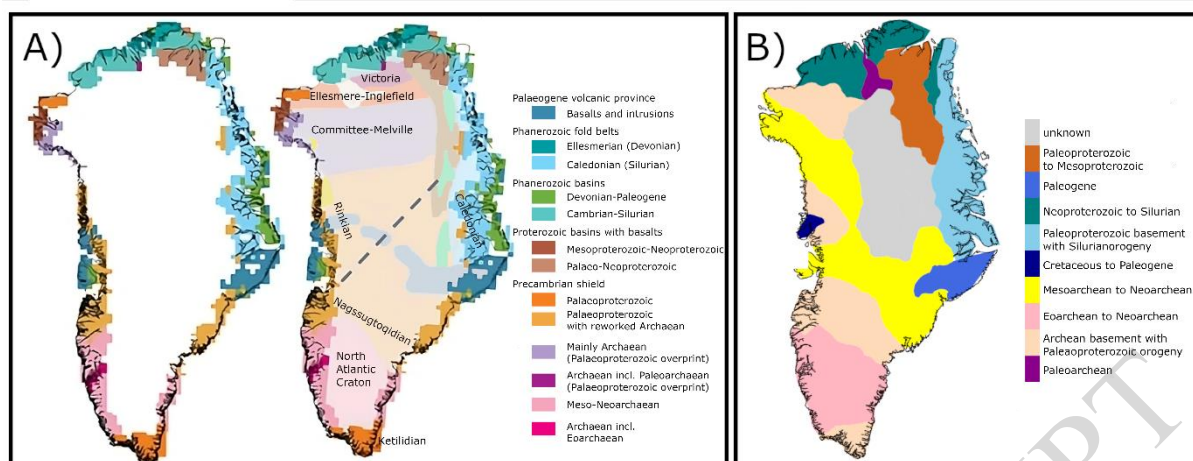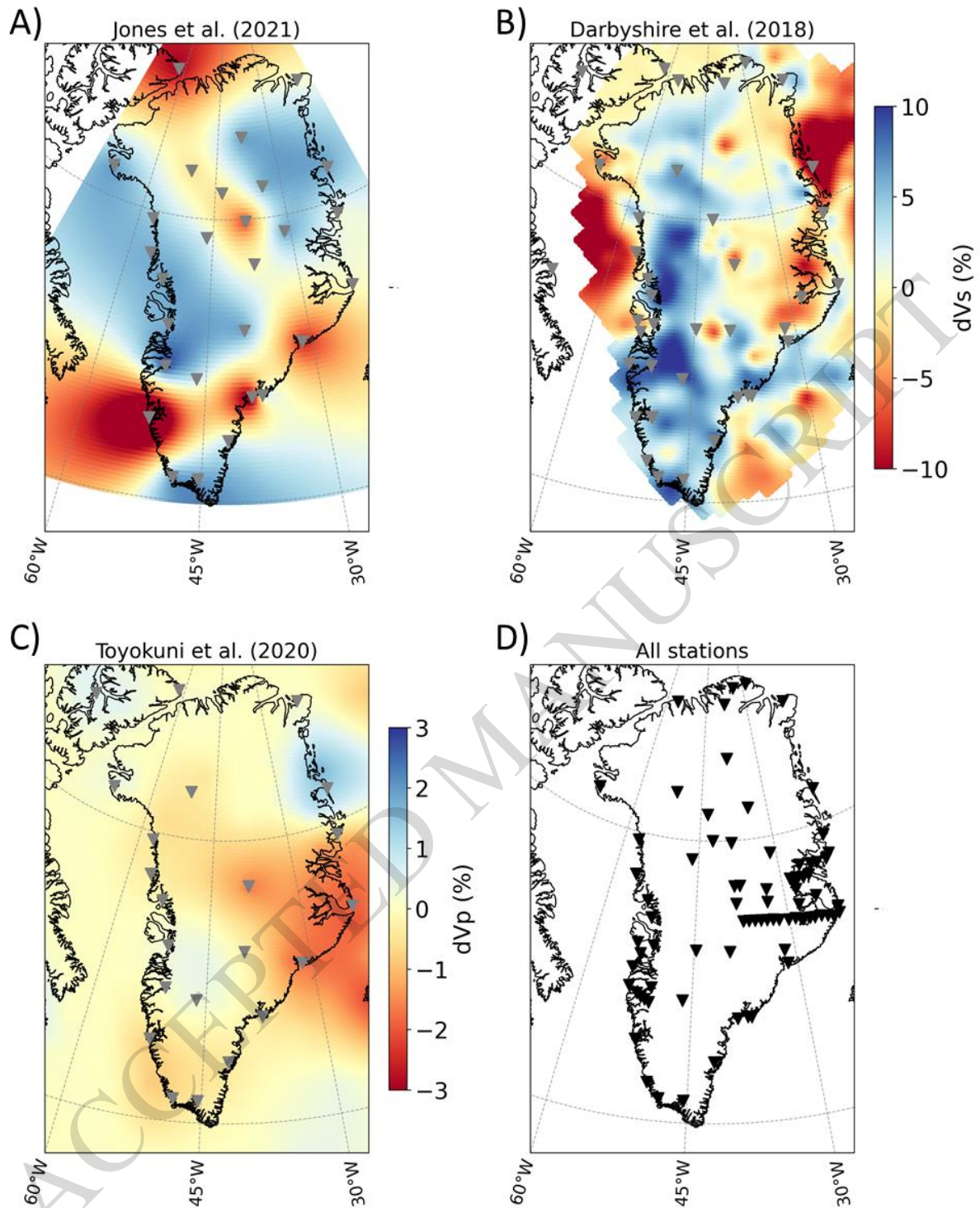
Figure 1

Figure 2

Figure 3

A) Jones et al. (2021)

B) Darbyshire et al. (2018)

C) Toyokuni et al. (2020)

D) All stations

Figure 4

Figure 5

mm/year

Figure 6