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Importance of solid earth structure for understanding the evolution of the Greenland ice sheet

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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. 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.

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Meltwater from the Greenland ice sheet (GrIS) has been one of the largest sources of sea-level rise since the early 2000s (e.g. Bamber *et al.* 2018; Fox-Kemper *et al.* 2021; Mankoff *et al.* 2021). Despite the global mean sea-level contribution of up to +0.89 mm a^{-1} (Horwath *et al.* 2022) and a mass loss of more than 247 Gt a^{-1} (2012–16; 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.* 2020*b*; 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 (Fig. 1).

Karlsson *et al.* (2021), for instance, showed that the present GrIS basal melt production amounts to *c.* 21.4 Gt a^{-1} (*c.* 10% of the total mass loss) with an uncertainty ranging from +4.4 to −4.0 Gt a^{-1}.

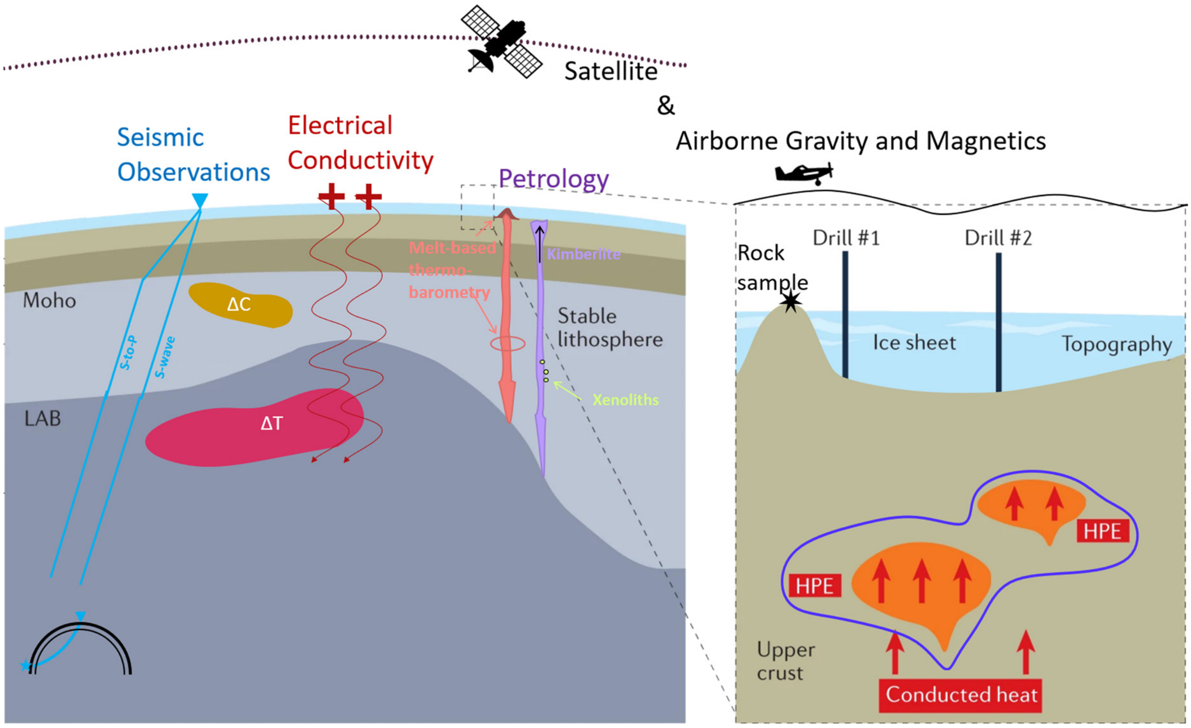

Fig. 1. Main elements of the solid earth structure that can affect cryospheric processes and the related datasets that can constrain upper mantle (left) and crustal (right) structure. HPE, heat-producing elements; ΔT and ΔC indicate temperature and compositional anomalies in the upper mantle; LAB, lithosphere–asthenosphere boundary. Source: modified from Reading *et al.* (2022) mainly by adding geophysical observables.

This *c*. 20% uncertainty is mostly related to the heat flow models used in their calculations. Because 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 those researchers 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.* 2024).

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 (*c*. 98 mW m^{-2}; Grinsted and Dahl-Jensen 2002), and some models require even higher local heat flow to sustain the NE 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 and Conrad 2022). Furthermore, variations in GHF at the ice–bedrock interface are probably 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 1D (spherically symmetric) GIA models tuned to fit palaeo 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.* 2023).

The examples above highlight the need for spatially variable (3D) solid earth models with robust uncertainty estimates that can be utilized when coupling solid earth models to ice-sheet models. Although 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 timescales.

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, not only it is important whether the bed is thawed or frozen, but also 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, is critical. Topography modulates outlet glaciers and controls the state of stress for glaciers, critical for determining the dynamics of the ice-sheets (Catania and Felikson 2022). Even though substantial improvements have been made in recent years in our knowledge of the topography under the ice (e.g. Morlighem *et al.* 2017, 2022), 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 affects basal heat flow (see the 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

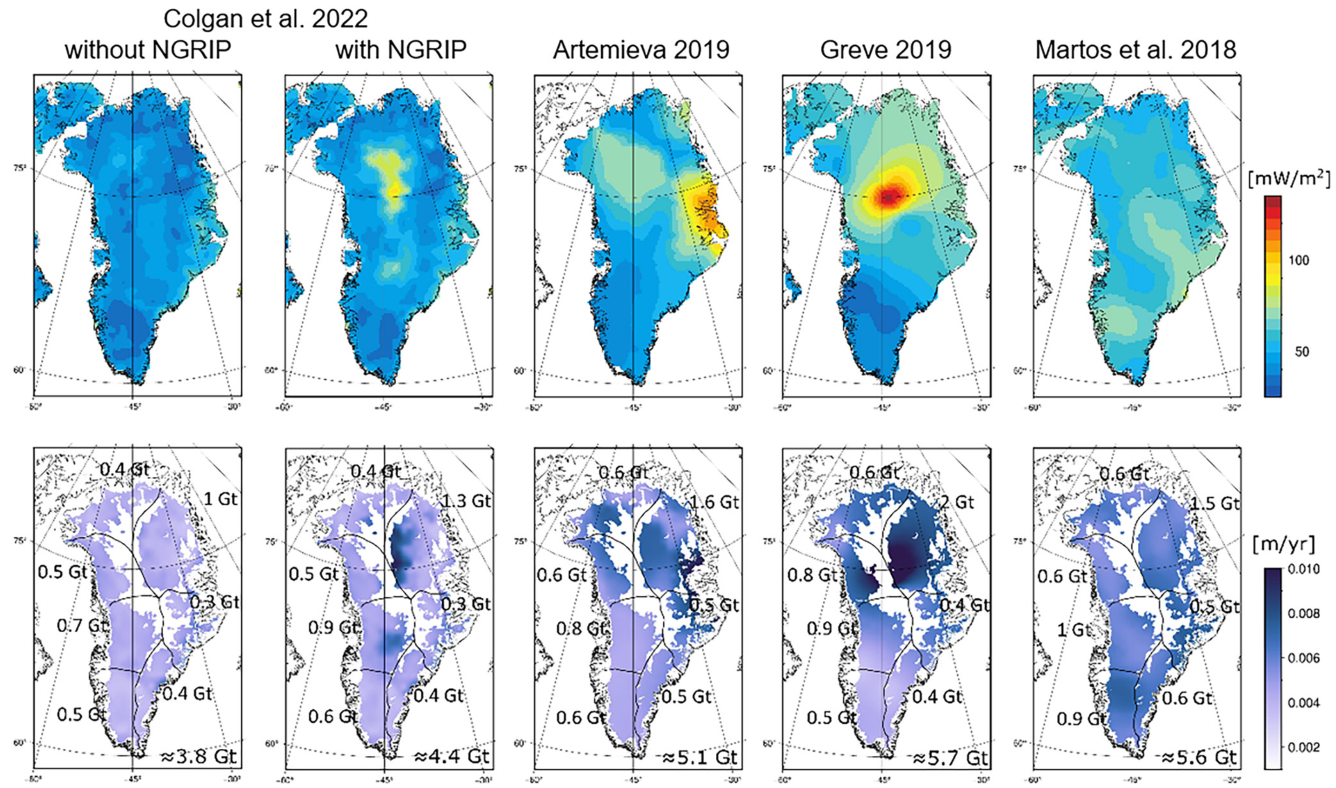

Fig. 2. Estimates of Greenland's GHF (top row) and associated basal melting (bottom row) for a suite of models. Corresponding GHF model sources are listed above each column. Areas considered as being frozen are masked. (Note the wide range of basal melt estimates, from 3.8 to 5.7 Gt a^{-1}.) Source: all basal melting estimates were calculated following the method of Karlsson *et al.* (2021).

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, affect 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) owing to varying geology.

Of the *c.* 21.4 Gt a^{-1} of basal ice melt estimated by Karlsson *et al.* (2021), about half is attributed to basal friction whereas 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 make up 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 Fig. 2). In general, the discrepancies between these models reflect the fact that only about 10 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 NE Greenland Ice Stream. For the ice stream, basalt melt estimates range from 1 to 2 Gt a^{-1}, 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.* (2020*a*) instead argued that very high local heat flow (970 mW m^{-2}), well above the suggested range from observations, is needed in this area, to sustain the NE Greenland Ice Stream. Bons *et al.* (2021) contended 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 as 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 (Fig. 2).

The resulting GHF maps (Fig. 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 remains 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 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

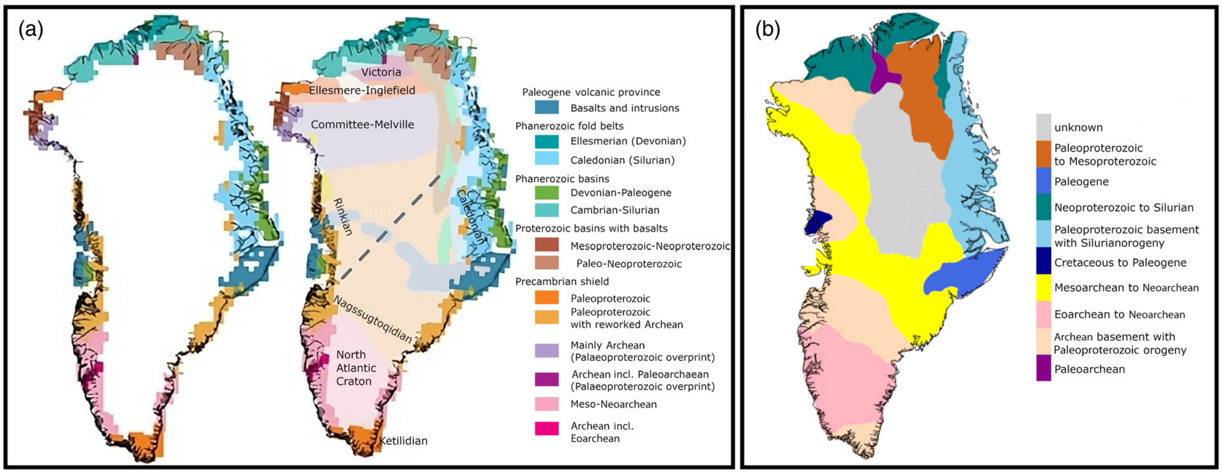

Fig. 3. (**a**) Mapped surface geology and interpretation of sub-ice bedrock in terms of major provinces. Dashed grey line denotes the division of Proterozoic crust. (**b**) Synthesis of apparent subglacial geological provinces from geophysical boundary analysis. Source: (a) major provinces from Dawes (2009); division of Proterozoic crust from Dahl-Jensen *et al.* (2003); (b) MacGregor *et al.* (2024).

sedimentary layer tends 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 geological setting of Greenland was first evaluated by Dawes (2009; Fig. 3a). That 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 geological 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 SW–NE-striking division of Proterozoic crust was identified based on seismic analyses from Dahl-Jensen *et al.* (2003), but no expression of this boundary was indicated in the geology map by Dawes (2009).

Recently, MacGregor *et al.* (2024) provided a new map (Fig. 3b) that describes the geological provinces beneath the GrIS based on a synthesis of geophysical data, where 19 geological and geophysical datasets 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 geological province maps (Fig. 3) are located in North Greenland, where MacGregor *et al.* (2024) inferred 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 Fig. 3b). Hence, although MacGregor *et al.* (2024) presented 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 palaeo-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 (Fig. 4; Darbyshire *et al.* 2018; Toyokuni *et al.* 2020; Jones *et al.* 2021).

The model of Darbyshire *et al.* (2018), which was used by MacGregor *et al.* (2024), focused 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 1D velocity models beneath each station, whereas 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.

Although the available seismic velocity models (Fig. 4) show some similarities, such as the relatively high velocities in western Greenland, there are also some notable differences, such as in northeastern 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 SW–NE-striking division of Proterozoic crust that was identified in the earlier study by Dahl-Jensen *et al.* (2003) (Fig. 3a).

In general, seismic station coverage across Greenland is rather sparse and uneven (Fig. 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; Fig. 3b) has comparatively

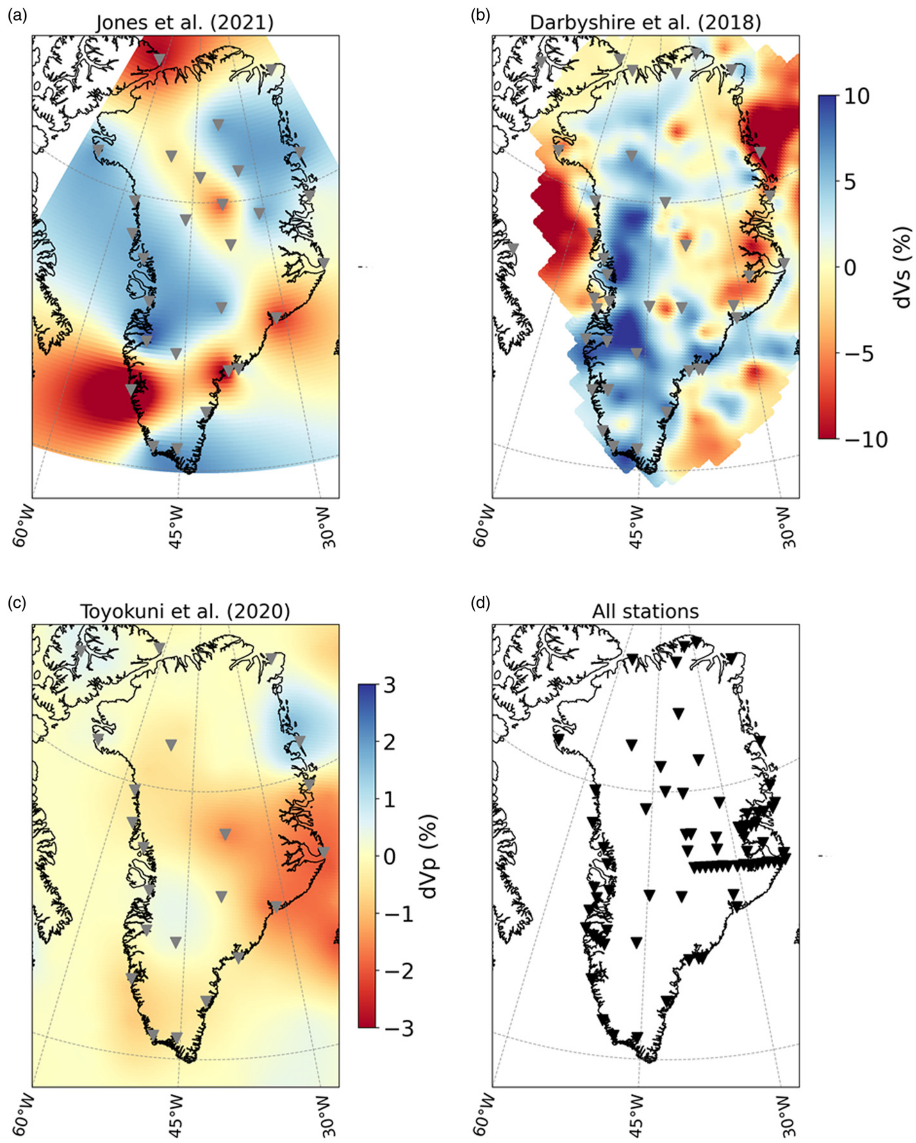

Fig. 4. (**a**) Relative V_s variations at 5 km depth. (**b**) Depth slice at 5 km through the S-wave velocity (V_s) model, as used in the map shown in Figure 3b. It should be noted that the Darbyshire *et al.* (2018) model constrains the V_s from 5 km downwards, whereas the Jones *et al.* (2021) model constrains V_s from 5 km upwards. (**c**) Relative V_p variations at 5 km depth. Each model used different seismic stations (triangles) in their analyses. (**d**) All available broadband stations across Greenland. Source: (a) from the model by Jones *et al.* (2021), which was not directly considered by MacGregor *et al.* (2024); (b) model from Darbyshire *et al.* (2018), as used in the map developed by MacGregor *et al.* (2024) shown in Figure 3b; (c) from the model by Toyokuni *et al.* (2020); (d) T. Dahl-Jensen, pers. comm., 2024.

dense seismic coverage compared with other regions. That said, other data types that were used by 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; Golynsky *et al.* 2018). Despite continuing efforts to reprocess the magnetic datasets for Greenland (Heincke *et al.* 2023) to create a new compilation, the lack of adequate, modern high-resolution data hampers the possibility to trace geological 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.* 2018; 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, as 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 probabely be attributed to ice layer effects on the seismic signal (for further details see Wansing *et al.* 2024).

Models estimating the depth of the lithosphere–asthenosphere boundary (LAB) are even more diverse (Fig. 5), also owing to differences between employed datasets and different methods. Whereas earlier and especially low-resolution global models (e.g. Priestley and McKenzie 2013; Pasyanos *et al.* 2014; Afonso *et al.* 2019) tend to disagree in the estimated lithospheric thickness, most

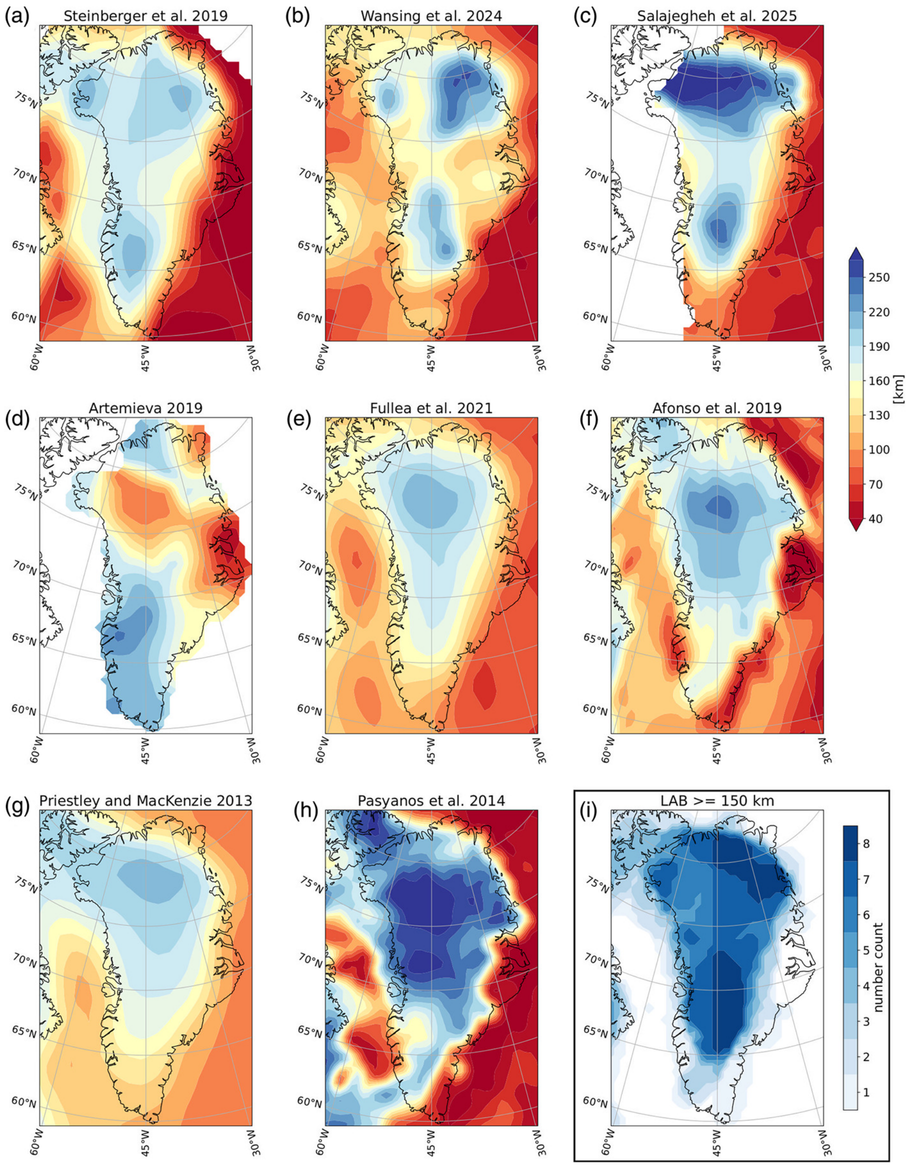

Fig. 5. Lithospheric thickness estimates for Greenland highlighting the thermal structure of the lithosphere. Models (**e**)–(**h**) are global models, models (**a**)–(**d**) are recent Greenland models. Model (a) is based on direct conversion from seismic velocities to lithosphere thickness, while Models (b)–(d) are based on a combination of multiple, yet different, geophysical datasets. Panel (**i**) highlights 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. Source: Corresponding models are listed above the panels.

recent models (e.g. Steinberger *et al.* 2019; Wansing *et al.* 2024; Salajegheh *et al.* 2025) 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 found only 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 myr 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 Fig. 6, and references cited by Martos *et al.* 2018), and although these paths roughly converge at the southeastern Greenland margin, they diverge towards the west or NW (Fig. 6). This partly relates to the unknown subglacial geology (see above), as any direct expression of volcanism is covered by ice and the geophysical signatures are ambiguous. As outlined by Larsen *et al.* (2015), intraplate volcanism in Greenland and the North Atlantic region occurred simultaneously and over a wide area, particularly around 60 myr 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; Horní *et al.* 2017; Steinberger *et al.* 2019).

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 hotspot 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 palaeo-flow along a corridor of thinned lithosphere, seen in central Greenland by most tomographic models (Fig. 5). In contrast, more recent seismic investigations (e.g. Celli *et al.* 2021) suggest the possibility of alternative plume track pathways to the NW (Fig. 6).

Heyn and Conrad (2022) made numerical models of a mantle plume impinging on continental lithosphere and suggested 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 researchers also found that the resulting increase in heat flux depends on the extent of lithospheric thinning, but for Greenland, the heat flux increase is probably 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

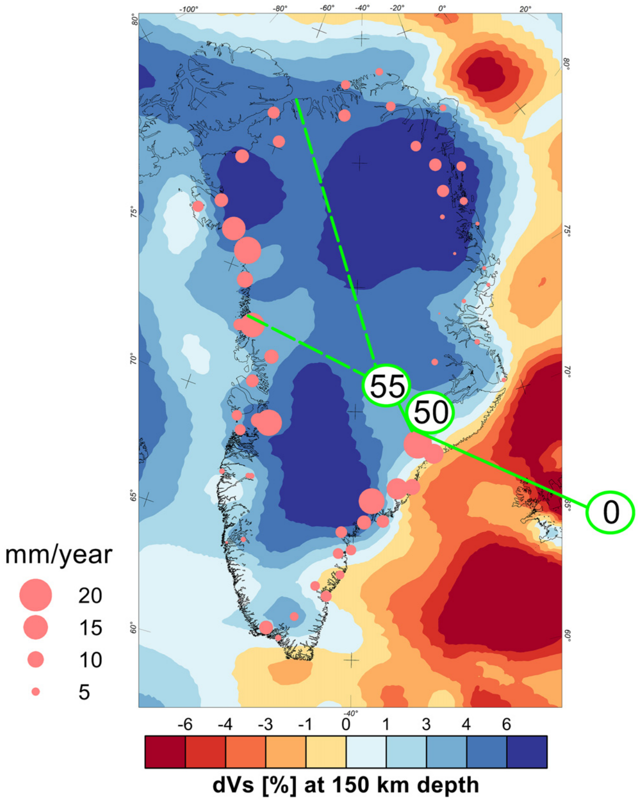

Fig. 6. Upper mantle velocity structure, uplift rates (red points) and possible Iceland plume-track (green lines). Background colours show variations in seismic velocity at 150 km depth. Faster seismic anomalies generally correlate with colder temperatures but also depend on mineral composition. Red circles mark the positions of GNSS stations, with their size proportional to the average crustal uplift rate. Green lines indicate possible paths of the Iceland hotspot beneath Greenland. Source: variations in seismic velocity at 150 km depth from the model by Celli *et al.* (2021); red circles from Berg *et al.* (2024); green lines from summary by Martos *et al.* (2018).

plume should still significantly affect 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 the next section and Weerdesteijn and Conrad 2024).

The importance of Greenland's upper mantle structure for GIA

Greenland GIA is constrained via both geological 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 critical 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 owing 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 researchers have noted that areas of lithospheric thinning near Greenland's SE 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; Fig. 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 SE Greenland. The 3D 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 showed that uplift rates and postglacial sea-level changes are significantly affected by the 3D 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 *c.* 10^{19} Pa s), modern-day deglaciation rates can already induce a rapid viscous uplift of a few centimetres per year (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 SE Greenland.

In addition, recent studies have suggested that the viscosity beneath Greenland may be timescale dependent (e.g. Adhikari *et al.* 2021; Paxman *et al.* 2023). 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 datasets and thus allow 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 2017), which in turn cannot be well understood without the Greenland contribution. They are also probably 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 probably 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 essential to advance our knowledge of

Greenland. Some of the critical parameters cannot be measured directly (e.g. viscosity), whereas 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 with 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.* 2006, 2018) more than two 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 datasets 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. Whereas such maps represent a valuable first-order step, these predictions should be coupled with 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; Afonso *et al.* 2022; Moorkamp 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) showed 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 with 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 owing to continuing 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 term, 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.* 2020*a*), a recent local radar study, which argued for a recent onset of the NE 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 datasets. Petrophysical samples for Greenland can provide constraints on LAB depth (e.g. Fig. 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; Toyokuni *et al.* 2020; Celli *et al.* 2021; Jones *et al.* 2021; Ajourlou *et al.* 2024; Salajegheh *et al*. 2025). The coverage with broadband stations for Greenland is certainly sparse compared with well-covered regions in Europe or the USA, 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 above.

Part of this incongruity between seismic studies is related to differences in the acquisition period between 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 currently being carried out 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 1D 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 southeastern 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. Fig. 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 and 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.* 2013*a*, *b*, 2022; Fullea *et al.* 2021).

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. Whereas the usefulness of MT data has already been demonstrated for Antarctica (e.g. Peacock and Selway 2016; Wannamaker *et al.* 2017), 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 2022). For example, Ramirez *et al.* (2022) and Manassero *et al.* (2024) have recently shown that the combination of MT and seismic data offers 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 SE Greenland, which were most probably affected 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, such as the GIA Model Intercomparison Project (GIAMIP). Thus, discrepancies between 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 datasets. 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 is needed to gain a better understanding and prediction of ice-sheet evolution. As explained above, MacGregor *et al.* (2024) provided 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 research community to acquire key datasets 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 also 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 is 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 (for references, see, for example, Velicogna 2009; Harig and Simons 2012; Velicogna *et al.* 2014), but their results are dependent on GIA models (e.g. Caron *et al.* 2018). Although 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.* (2015) 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.* (2015) that are also relevant for Greenland (it should be noted that we changed the questions by omitting links to the Antarctic ice sheet as these are also valid for the Greenland region).

(1) *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.

(2) *What is the crust and mantle structure, and how does it affect surface motions owing to glacial isostatic adjustment?*
Whereas 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 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, for example, anisotropy (to better understand stress in the crust and mantle flow) and attenuation (to obtain independent information on temperature).

(3) *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 hotspot track beneath Greenland remains unclear before Greenland moved away from above the hotspot around 50 myr ago. The lithospheric architecture appears to show an imprint of the hotspot track, but the thermal effect at a crustal level is still debated.

(4) *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.

(5) *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, for example, from the Iceland plume, will experience rapid bedrock uplift soon after deglaciation, and slower uplift later after deglaciation is

completed (Weerdesteijn and Conrad 2024). Because sub-lithospheric viscosity mostly influences uplift rates at relatively short (hundreds of kilometres) 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).

(6) *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.

Although not all of these questions have been answered even in the case of Antarctica, substantial improvement in our understanding of the processes has 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 a 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 led to a number of multinational efforts that have advanced our knowledge of the continent. Similar coordinated efforts for Antarctica were 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 was at its beginning (e.g. Dowdeswell 2006; Rignot and Kanagaratnam 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 2032–33 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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Data availability The datasets shown can be downloaded from the original publications. Basal melt rates from Figure 2 are available on request from the authors.

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