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The key role of global solid-Earth processes in preconditioning Greenland's glaciation since the Pliocene

Bernhard Steinberger,[1,2] Wim Spakman,[2,3] Peter Japsen[4] and Trond H. Torsvik[2,5,6]

[1]*GFZ German Research Centre for Geosciences, Telegrafenberg, Potsdam 14473, Germany;* [2]*Centre for Earth Evolution and Dynamics (CEED), University of Oslo, P.O. Box 1028, Blindern, Oslo 0315, Norway;* [3]*Faculty of Geosciences, Utrecht University, Budapestlaan 4, Utrecht 3584CD, The Netherlands;* [4]*Geological Survey of Denmark and Greenland (GEUS), Øster Voldgade 10, Copenhagen 1350, Denmark;* [5]*Geological Survey of Norway (NGU), Trondheim 4791, Norway;* [6]*School of Geosciences, University of Witwatersrand, WITS 2050, Johannesburg South Africa*

ABSTRACT

After >500 Ma of absence, major Northern Hemisphere glaciations appeared during the Plio-Pleistocene, with Greenland leading other northern areas. Here, we propose that three major solid-Earth processes underpinned build-up of the Greenland ice-sheet. First, a mantle-plume pulse, responsible for the North Atlantic Igneous Province at ~60 Ma, regionally thinned the lithosphere. Younger plume pulses led to uplift, which accelerated at ~5 Ma, lifting the parts of the East Greenland margin closest to Iceland to elevations of more than 3 km above sea level. Second, plate-tectonic reconstruction shows a ~6° northward component of Greenland motion relative to the mantle since ~60 Ma. Third, a concurrent northward rotation of the entire mantle and crust towards the pole, dubbed True Polar Wander (TPW), contributed an additional ~12° change in latitude. These global geodynamic processes preconditioned Greenland to sustain long-term glaciation, emphasizing the role of solid-Earth processes in driving long-term global climatic transitions.

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Introduction

No large-scale Northern Hemisphere glaciations (NHG) have been documented for the entire Phanerozoic (past ~540 Ma) prior to ~2.6 Ma. What caused these glaciations to commence in Greenland (Jansen *et al.*, 2000; Thiede *et al.*, 2011) remains uncertain. Our understanding of the Pliocene history of NHG (Bailey *et al.*, 2013; De Schepper *et al.*, 2014), and the Greenland Ice Sheet (e.g. Nielsen and Kuijpers, 2013; Bierman *et al.*, 2014; Rohling *et al.*, 2014) in particular, has improved significantly in recent times, but significant gaps in our knowledge still exist. Orbital forcing (Maslin *et al.*, 1998), tectonic causes, including uplift and erosion of mountain ranges (Molnar and England, 1990) and plateaus (Ruddiman and Kutzbach, 1989), and closing of the Panama isthmus (Haug and Tiedemann, 1998) may all have contributed to the origin of extensive NHG during the Quaternary. The Iceland plume caused changes in bathymetry of the North Atlantic, and hence variations in overflow of North Atlantic Deep Water, which may be another controlling factor in the onset of glaciation (Wright and Miller, 1996; Poore *et al.*, 2006; Robinson *et al.*, 2011). The possibility that tectonic uplift in Greenland itself (Japsen *et al.*, 2012) was an important preconditioning factor has only just been reconsidered: the models of Solgaard *et al.* (2013) show that, under climatic conditions colder than present, high topography leads to increased stability of the Greenland Ice Sheet. DeConto *et al.* (2008) found that, with current Greenland topography, the threshold of atmospheric CO_2 for NHG is ~280 p.p.m. and was reached around 25 Ma. But, it drops below 180 p.p.m. for lower topography and thus may never have been reached until Greenland's topography was sufficiently high – this implicitly assumes that Greenland was at sufficient northern latitudes.

Recent studies show that there was no significant topography in East Greenland at 10 Ma and that much of the uplift has occurred since ~5 Ma (Bonow *et al.*, 2014; Japsen *et al.*, 2014). Glacial erosion can cause uplift of the remaining mountains, but this mechanism cannot explain the overall high topography (Medvedev *et al.*, 2013). Significant parts of Greenland's uplift appear to pre-date large-scale glaciations, but not by more than a few millions of years, so that a causal link appears viable (Japsen *et al.*, 2014). Here, we suggest how three geodynamic processes were fundamental in preconditioning the extensive ice-sheet build-up during the Pliocene: the Iceland plume affecting uplift in East Greenland, the plate-tectonic movement of Greenland since ~60 Ma and a rotation of the Earth's crust and mantle, called true polar wander (TPW).

Correspondence: Bernhard Steinberger, GFZ German Research Centre for Geosciences, Telegrafenberg, Potsdam 14473, Germany. Tel.: +49 331 288 1881; fax: +49-331-288-1938; e-mail: bstein@gfz-potsdam.de

East Greenland uplift affected by a pulsating Iceland plume

A mantle plume beneath Iceland has been clearly imaged in the upper mantle (Wolfe *et al.*, 1997). A lower mantle origin is indicated by transition zone thinning (Shen *et al.*, 1998) and whole-mantle P-wave tomography (Bijwaard and Spakman, 1999). An upgrade (Amaru, 2007) of Bijwaard and Spakman (1999) also indicates a tilted plume conduit (Fig. 1A). These anomalies can be followed to the lowermost mantle. A similar structure (Fig. 1B) appears in

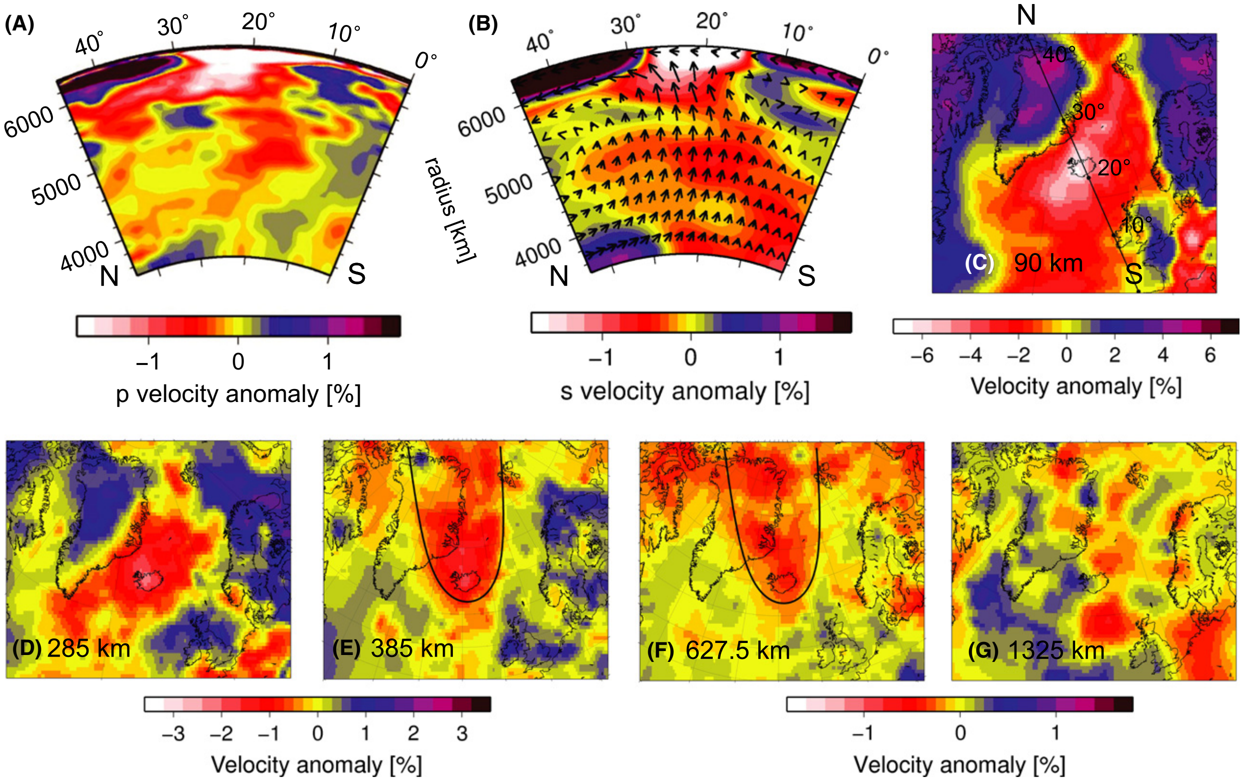

Fig. 1 Tomographic images and inferred flow of the mantle beneath the North Atlantic, Iceland and Greenland. (A) Cross-section through P-wave velocity anomaly model P06_CSloc (Amaru, 2007; http://igitur-archive.library.uu.nl/dissertations/2007-0202-201924/index.htm) along the line shown in (C). (B) Cross-section through SMEAN S-wave model (Becker and Boschi, 2002*)* and inferred mantle flow (arrow length 3 degrees at surface = 3 cm a^{-1}) along the same line. The negative anomaly in the bottom right corner, which is less clear in the P-wave model, is at the northern tip of the African Large Low Shear-wave Velocity Province (LLSVP). (C–G) P-wave anomalies (Amaru, 2007) at depths 90 km, 285 km, 385 km, 630 km and 1325 km. (E) and (F) also show the boundary of material flowing out of the plume computed with eq. 1 derived in Data S1.

S-wave anomalies (Becker and Boschi, 2002; Rickers *et al.*, 2013). The Iceland plume may find its root in the northern edge of the African Large Low Shear Velocity Province (LLSVP) in the deep mantle (Fig. 2A; Lekic *et al.*, 2012; Torsvik *et al.*, 2006; Steinberger and Torsvik, 2012). It appears to be pulsating (Vogt, 1971; White *et al.*, 1995; Ito, 2001; Jones *et al.*, 2002) – i.e. the flow of hot material up the plume conduit and in the asthenosphere away from the plume appears to vary with time, causing uplift and subsidence of the overlying lithosphere (Rudge *et al.*, 2008) and variations in volcanism (O'Connor *et al.*, 2000) and crust production with time. Short-time-scale pulsation, causing V-shaped ridges south of Iceland, with about a 5 Ma time-scale, appears to be superposed by long-time-scale pulsation showing larger

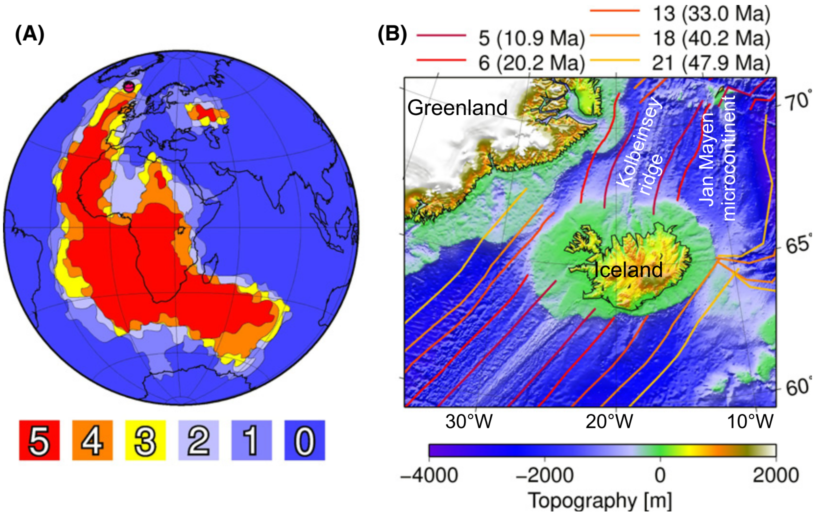

Fig. 2 (A) Location of Iceland (purple dot) relative to the African LLSVP. Colours indicate counts in a cluster analysis of tomography models (Lekic *et al.*, 2012). The African LLSVP is the large region with high counts. (B) Topography and magnetic isochrons around Iceland. Isochrons near the western edge of the Iceland Plateau indicate that its formation began at ~25 Ma.

fluctuations in the plume activity (Abelson *et al.*, 2008). The *c.* 60 Ma North Atlantic LIP may have been caused by the initial plume head or a large pulse in a pre-existing plume. A more recent long-term pulsation may have reached the surface beneath Iceland ~25 Ma ago (Abelson *et al.*, 2008; Mjelde and Faleide, 2009) concurrent with the emergence of the Iceland plateau (Fig. 2B). The blob-like structure centred at depth ~1325 km several hundred km south of Iceland (Fig. 1A, B, G), seen in both P- and S-wave anomalies, may represent the next pulse rising through the mantle, similar to that seen in numerical modelling results (Lin and van Keken, 2006).

Slow anomalies extending mainly northward from Iceland (Fig. 1E) can be explained by hot material flowing out of the Iceland plume into a low-viscosity upper mantle and flowing ~northward (Fig. 1B) beneath the lithosphere (Data S1) as part of a global pattern of up-wellings above the two LLSVPs and flow away from them in the upper mantle.

Although plume pulses may travel at speeds of about 20 cm a^{-1} in the low-viscosity asthenosphere beneath the spreading ridge (Vogt, 1971), asthenospheric flow beneath Greenland is likely slower. Our computations indicate flow speeds of ~3 cm a^{-1} (Fig. 1B); a pulse that arrived beneath Iceland at 25 Ma moving laterally at that speed would have reached East Greenland ~600 km away from the Iceland plume ~5 Ma ago and could hence be the cause of recent uplift (Bonow *et al.*, 2014; Japsen *et al.*, 2014) that facilitated ice-sheet build-up and increased the stability of the ice sheet (Solgaard *et al.*, 2013). After the Jan Mayen microcontinent started breaking away from Greenland *c.* 30 Ma ago (Gaina *et al.*, 2009), thin lithosphere of the nascent ocean could have acted as an upside-down drainage pattern for the buoyant plume material (Sleep, 2007).

To investigate these qualitative predictions, we created numerical models of dynamic topography due to density anomalies inferred from seismic tomography models (Grand, 2002; 2010 model update; Becker and Boschi, 2002; Amaru, 2007) and flow in the mantle. A detailed description of these computations is given, and their reliability and uncertainties are discussed in Data S1.

The predicted uplift pattern (Fig. 3) is due to hot and less dense material upwelling beneath the North Atlantic, and most strongly beneath Iceland, and flowing outward and predominantly northward (Fig. 1B). The predicted uplift since 5 Ma in easternmost Greenland due to plume impact reaches 200–800 m according to the models shown in Fig. 3. This is a significant fraction of the uplift found by Japsen *et al.* (2014): they found that uplift since 5 Ma in this region exceeded that of other areas in East Greenland as well as of West Greenland by ~1 km. This provides a first-order assessment of uplift, as our model of plume-related lithosphere uplift is rather simplified.

Thin lithosphere in East Greenland facilitating uplift

While fast seismic velocities indicate that the thickness of Archaean lithosphere can reach ~200–300 km in large parts of Greenland (Fig. 1D), the lithosphere in East Greenland (Fig. 1C and Data S1) is much thinner – perhaps less than 100 km – and hence can be more effectively uplifted by hot material in the upper mantle beneath. A reconstruction of tectonic plates relative to the mantle (Doubrovine *et al.*, 2012) offers a possible explanation for thin lithosphere in that region: it shows that regions in southern Norway and eastern Greenland where topography (computed after isostatically unloading ice) is high are mostly reconstructed within a circle of ~650 km radius around the computed 60 Ma location of the Iceland plume (Fig. 4). These are also regions for which seismic tomography models of both P- and S-wave velocity variations (Amaru, 2007; Simmons *et al.*, 2012; Rickers *et al.*, 2013; Schaeffer and Lebedev, 2013) as well as a seismology-based lithosphere thickness model (Priestley and McKenzie, 2013) indicate <100 km thin lithosphere (Figs 1C and 4). It is thus credible that the lithosphere has been thinned by both thermal and mechanical erosion from underneath due to the plume head (Brune *et al.*, 2013) or pulses since ~60 Ma, in addition to thinning during rifting since the late Palaeozoic. Subsequently, hot plume material has been flowing to these regions and maintained a thin lithosphere, particularly in parts of easternmost Greenland, which are still only ~600 km away from the Iceland plume. Such a mechanism may explain why elevations are higher (>3 km) and areas of high elevations extend over a larger area than in West Greenland (<2 km above sea level).

Global geodynamic causes for Greenland's northward motion

Our modelling experiments demonstrate that the Iceland mantle plume combined with mantle flow can contribute to episodic uplift since ~60 Ma which eventually led to the high altitudes favourable for glaciation to commence after 5 Ma. However, it does not explain why major glaciations only started much more recently (e.g. 4.5 Ma; Nielsen and Kuijpers, 2013). Prior to ~60 Ma, Greenland was located at lower latitudes, only gradually increasing to Pliocene–Present latitudes, and this may have prevented earlier large-scale glaciations in Greenland; e.g. during the Caledonian orogeny (430–420 Ma) when Greenland was located at the equator. To quantify the effect of Greenland's latitude, we reconstruct the plate-tectonic path of Greenland in the latest global moving hotspot reference frame (GMHRF; Doubrovine *et al.*, 2012), i.e. absolute plate motions are computed to optimally fit geometry and age progressions of hotspot tracks thought to be generated as plates move over mantle plumes (Data S1). The resulting Iceland hotspot track, and in particular its computed 60 Ma position relative to Greenland, hence depends on both the computed motion of the Iceland hotspot and the plate motion reference frame. This reconstruction implies that Greenland has moved ~800 km towards the NW (~6° northward component) over the mantle since 60 Ma (Fig. 5, blue circles and blue line).

Another, so far unrecognized contribution to Greenland's northward

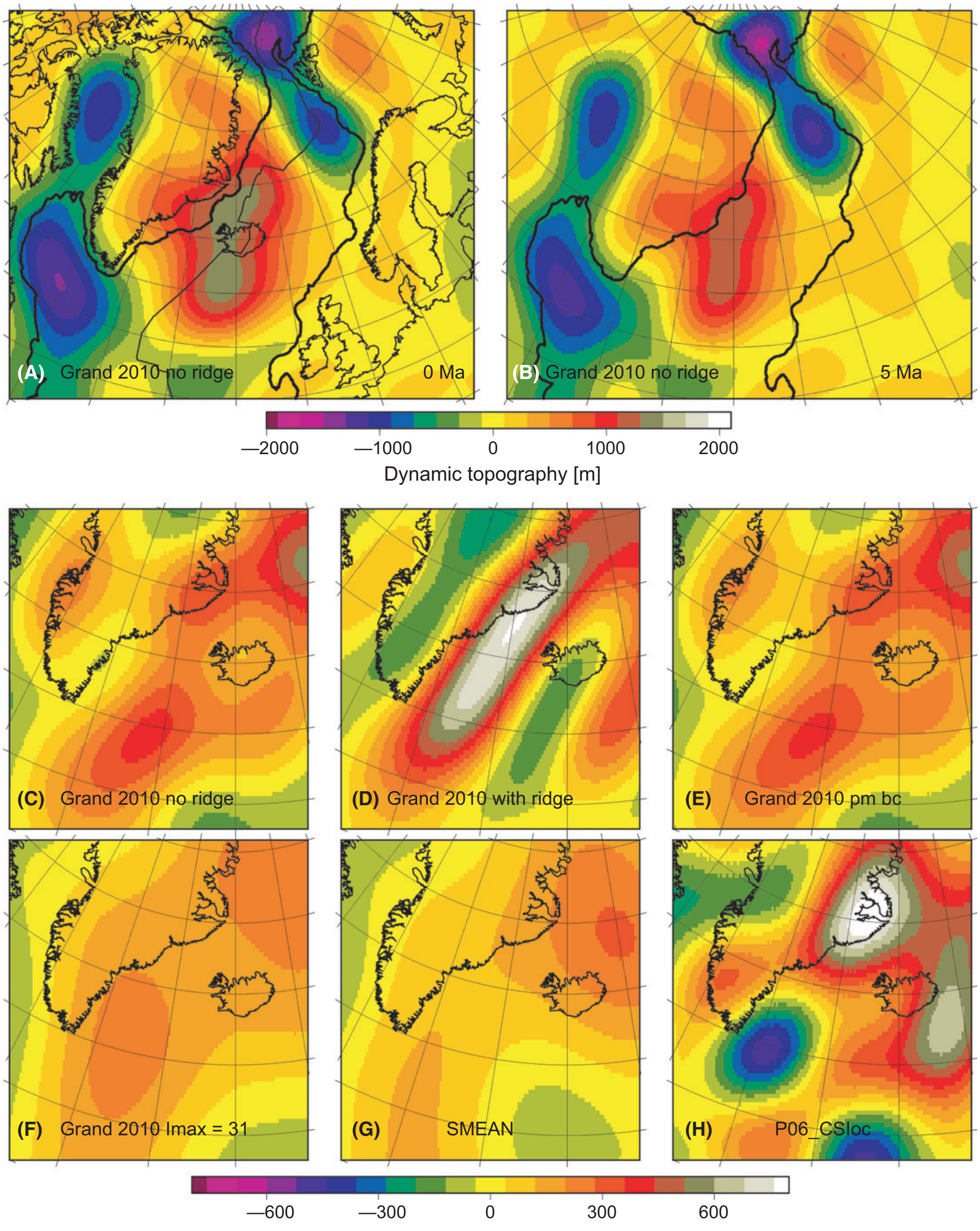

Fig. 3 (A) Present-day dynamic topography computed from density and viscosity model derived from Grand (2002; 2010 model update) tomography model. Density anomalies related to sea-floor spreading are subtracted, based on the age grid version 3.6 of Müller *et al.* (2008), assuming half-space cooling and corresponding to isostatic topography 3 km × (1− (age/100 Ma)$^{0.5}$) if age is given. Expansion to degree 63; topography with zero mean and cosine taper applied between degrees 31 and 63. Thick black lines are the 800 m isobath along continental margins. Also shown are continental outlines. (B) Computed dynamic topography at 5 Ma for the same case as in Fig. 3A. Black lines are the 800 m isobath, rotated according to the plate reconstruction of Doubrovine *et al.* (2012), indicating the motion of the continents. (C) Dynamic topography change since 5 Ma, obtained by subtracting topography in Fig. 3A from that in Fig. 3B. (D) As (C), but without subtracting density anomalies related to sea-floor spreading. (E) As C, but with prescribed surface plate motions instead of free-slip as surface boundary condition. (F) As C, but with expansion to degree 31. (G) As F, but for SMEAN (Becker and Boschi, 2002) tomography model. (H) As C, but for model P06_CSloc (Amaru, 2007).

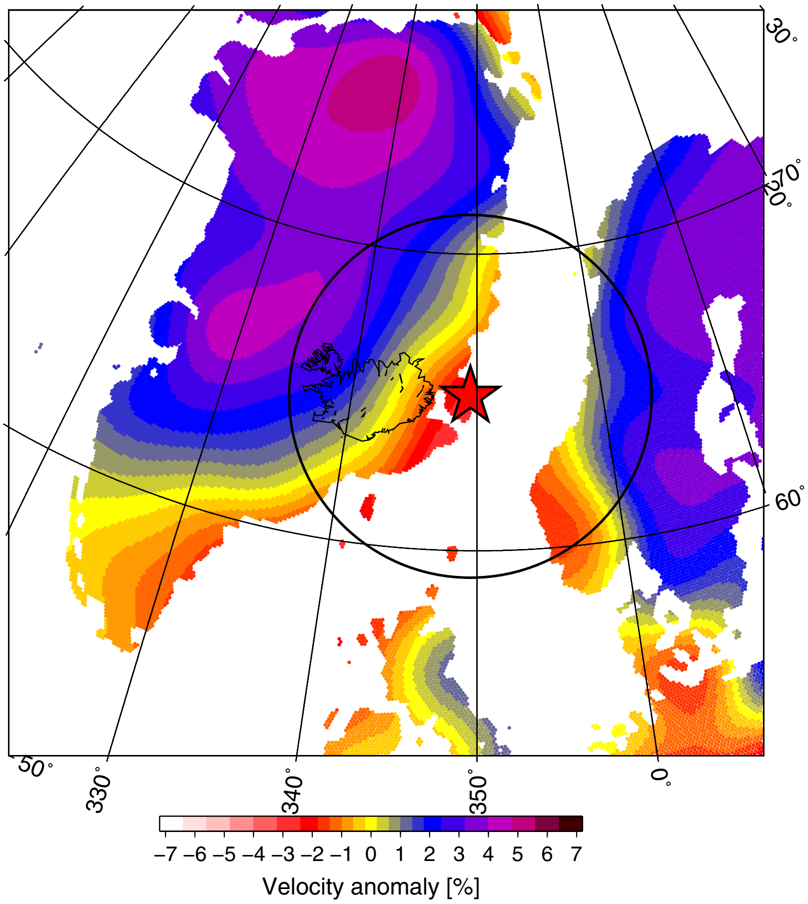

Fig. 4 P-wave anomalies (Amaru, 2007) 90 km beneath land areas, indicating regions of thick (blue – violet) and thin (red – orange) lithosphere, rotated according to a 60 Ma plate reconstruction in a moving hotspot mantle reference frame (Doubrovine *et al*., 2012). Present-day coastline of Iceland is shown for orientation. The red star is the computed 60 Ma location of the Iceland hotspot, which, according to that model (Doubrovine *et al*., 2012), has moved ~300 km due to slow westward flow in the upper part of the lower mantle.

motion relative to the pole is TPW: this is rotation of the entire crust–mantle relative to the pole. TPW motion on a geological time-scale is caused by changes in the Earth's internal mass distribution, which is primarily due to mantle flow. In response, the Earth will re-orient itself relative to its spin axis such as to maximize its moment of inertia, while Earth's total angular momentum is conserved. This gives about 12° additional northward motion (Fig. 5, green circles and green line) since 60 Ma, with ~400 km formal uncertainty, and is further supported by numerical models of how the moment of inertia and hence the polar axis would have changed due to the motion of density anomalies in the Earth's mantle (Steinberger and O'Connell, 1997; Steinberger and Torsvik, 2010) (Fig. 5, magenta and orange circles). In Data S1 more details on the computation of plate motions, hotspot motion and true polar wander are given, and their uncertainties are discussed.

With these two contributions combined, we infer that at ~60 Ma Greenland was located at latitudes of present-day Great Britain and has since been moving northward at an average rate of ~0.3° ± 0.1° Ma^{-1}. We therefore hypothesize that Greenland has only recently been sufficiently far north for high topography to have led to glaciations. Even if earlier plume pulses or orogenies had caused high topography, the regions of high topography were too far south to become glaciated on a large scale.

Conclusions and outlook

Our work was motivated by the question of why extensive glaciations of Greenland started only during the past few million years after more than 500 Ma of absence of NHG. We propose that the combined effect since ~60 Ma of uplift driven by mantle flow combined with the Iceland plume, a northward component of plate-tectonic motion of ~6°, and a true polar wander contribution of ~12°, played a central role in preconditioning Greenland for widespread glaciation following the late Pliocene decline in $p\mathrm{CO}_2$. We note that TPW may be an important mechanism, influencing climate throughout Earth history on temporal scales of tens of millions of years, and our proposed scenario shows how this influence may have come into play in the recent North Atlantic.

Comprehensive models of climate and ice-sheet evolution (Abe-Ouchi *et al*., 2013) have now reached a level of great detail and realism, accounting for vertical motions of the lithosphere due to glacial isostatic adjustment, as well as vertical motions unrelated to glaciations (Solgaard *et al*., 2013). We have shown that global mantle processes have significantly increased Greenland's northerly position – a polar journey thus far unaccounted for in climate–ice-sheet modelling – and its topography. We hypothesize that, in combination, these geodynamic processes were fundamentally preparatory for NHG to culminate since the middle Pliocene, and advocate that future sensitivity experiments of fully coupled climate–ice-sheet models incorporate these effects for Greenland as well as for other land masses. Incorporation of these effects will allow our proposed mechanism linking ice-age initiation on Greenland to mantle dynamics to be tested and will improve our understanding of the concerted impact of solid-Earth, oceanic and atmospheric processes on long-term climate change and geologically recent glaciations. In particular, during the past few million years, the impact of solid-Earth processes has caused the strong global environmental changes under which mankind arose.

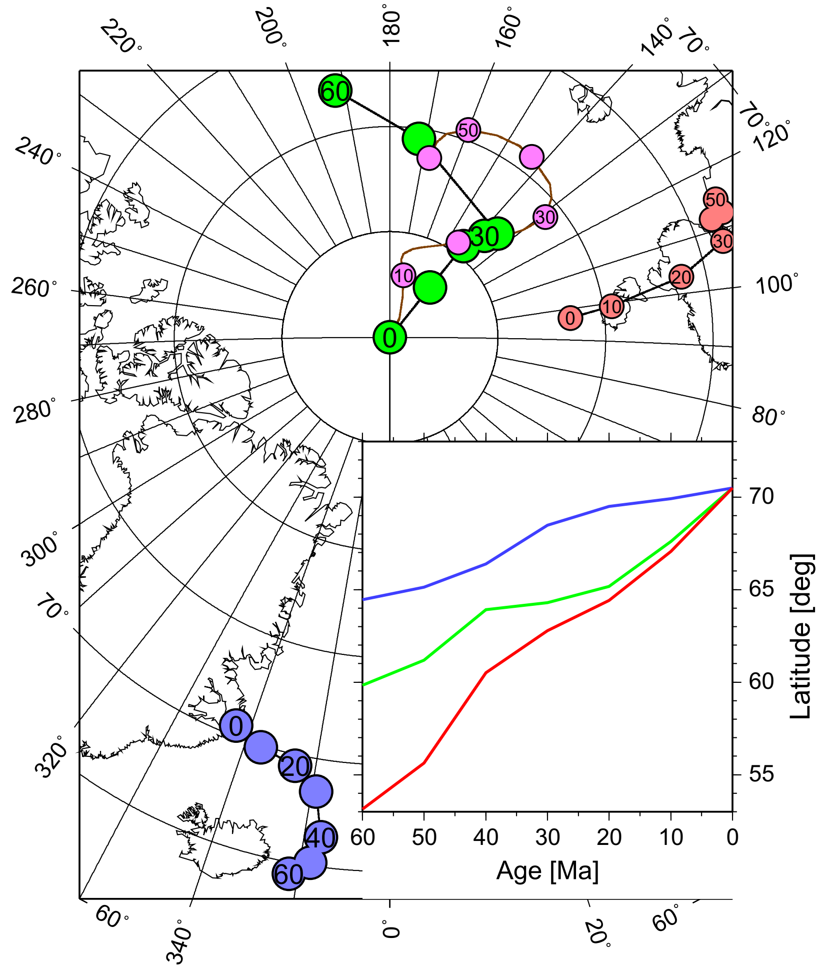

Fig. 5 Changes in Greenland's latitude since 60 Ma due to plate motions (continental drift) and true polar wander (TPW). Blue circles/blue line: plate motion and change in latitude of Ittoqqortoormiit (70.5°N, 22 W) in a mantle reference frame (Doubrovine *et al.*, 2012). Green circles/green line: TPW and corresponding latitude change inferred from palaeomagnetic data in the same reference frame. Red line: Latitude change from plate motions and TPW combined. For comparison, magenta circles show changes in the maximum moment of inertia (MMI) axis computed from backward-advecting mantle density anomalies (Steinberger and O'Connell, 1997) inferred from tomography; pink circles show the MMI axis for density anomalies (Steinberger and Torsvik, 2010) inferred from the history of subduction. If this axis changes sufficiently slowly, the rotation pole will closely follow (Steinberger and O'Connell, 1997).

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. contains further evidence for thin lithosphere beneath East Greenland and southern Norway and for northward upper mantle flow of Iceland plume material, a simple analytical model of a plume feeding into a low-viscosity upper mantle layer, more details on the computation of dynamic topography and its change with time, plate motions, hotspot motion and true polar wander, and an assessment of the reliabilty and uncertainties of these computations.