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Eleven phases of Greenland Ice Sheet shelf-edge advance over the past 2.7 million years

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ABSTRACT

Reconstruction of former ice sheets is important for testing Earth-system models that can assess interactions between polar ice sheets and global climate, but information retrieved from contemporary glaciated margins is sparse. In particularly, we need to know when ice sheets began to form marine outlets and by what mechanisms they advance and retreat over timescales from decades to millions of years. Here, we use a dense grid of high-quality 2D seismic data to examine the stratigraphy and evolution of glacial outlets, or palaeo-icestreams, draining the northwest Greenland Ice Sheet into Baffin Bay. Seismic horizons are partly age-constrained by correlation to cores from drill sites. Progradational units separated by on-lap surfaces record eleven major phases of shelf-edge ice advance and subsequent transgression since the first ice sheet expansion 3.3 – 2.6 million years ago. The glacial outlet system appears to have developed in four stages, each potentially caused by tectonic and climatic

changes. We infer that an abrupt change in ice flow conditions occurred during the Mid-Pleistocene transition, about 1 million years ago, when ice movement across the shelf margin changed from widespread to more focused flow (ice streams), forming the present-day glacial troughs.

MAIN TEXT

Melting of polar ice sheets, driven by global warming, have societally critical consequences for Earth's climate, including abrupt changes in global sea level[1,2] and oceanic circulation[3]. The potential for climatological tipping points highlights the need for developing comparative studies of past ice-ocean-climate changes to calibrate model simulations of future climate evolution[4]. A recent study using exposure dating suggested that the northern Greenland Ice Sheet (GrIS) was almost completely absent for an extended period of time during the Pleistocene[5]. This implies that Greenland's glaciers were highly sensitive to past warm climate that, unlike the present, were not exacerbated by human-induced CO_2 emissions. Other studies, however, favour a continuous, albeit fluctuating, presence of the GrIS over the Pleistocene epoch, suggesting that inland ice domes have persisted since the late Miocene[6]. Thus, more research is needed to refine the contradictory and fragmented records on long-term GrIS dynamics.

The GrIS is drained by ice streams that, over millions of years, have advanced repeatedly to the shelf edge, depositing glacially-eroded sediments onto the continental margins. The geological component of these glacial outlets, known as trough-mouth fans (TMFs), are characterized by km-thick sediment accumulations in front of shelf-crossing troughs that mark the main ice stream drainage route[7-9]. The modern distribution of marine-terminating outlet glaciers on glaciated margins is dwarfed by the sizes attained by ice streams during glacial maxima, most recently 22,000 – 18,000 years ago[10]. In this study we use an extensive grid of industry seismic reflection data and borehole stratigraphic information to analyse the anatomy and spatial evolution of two palaeo-ice streams that drained into Baffin Bay on the northwest Greenland margin (Fig. 1 and Supplementary Fig. S1)[11].

Glaciated margin architecture

Covering an area over 50,000 km^2 and with thicknesses exceeding 2 km, the Melville Bugt and Upernavik TMFs form a large sedimentary system resulting from drainage of the northwestern GrIS (Fig. 1). The seabed of the study area is marked by mega-scale glacial lineations (MSGL) formed below fast-flowing ice streams that extended to the shelf break during the last glacial maximum[12,13]. The seismic data reveal a distinct pattern of sequentially organized, prograding depositional units (Fig. 2 and S2). The top of each unit is bounded by planar, laterally continuous reflections that truncate underlying progradational strata with an acoustic response that corresponds to an increase in acoustic velocity. These unconformable relationships are interpreted as the product of repeated advances of the GrIS to the shelf break[7]. They are a distinctive morphological feature that defines the transition from slope clinoforms dipping up to 7°–10° to planar horizons marking abrupt base level rise and transgression (Figs. 2 and 3). The slope segments of the horizons that bound individual units are less distinct than the topset and offlap components, but are often characterized by steep, truncated reflections overlain by packages with hummocky geometries marked by limited lateral continuity (Fig. 3b). These features are interpreted as mass-flow deposits, or glacigenic debrites, that are commonly linked to high sediment fluxes and slope instability at glacial grounding zones[14,15]. Approaching the base-of-slope, the horizons converge into a more condensed bottom-set section and occasionally merge with other horizons. Horizon merging is a complicating factor, but by iteratively tracing the horizons throughout the dense 2D data grid, all the main units can be correlated between the different sectors of the glacial fan system, e.g., a full shelf-to-basin transect. By mapping the major glacial unconformities to their shelf break position and continuing along the corresponding basinward dipping reflections, eleven major prograding units have been defined within the TMF system (Fig. 1). The seismic horizons have been converted to metric depths to produce sediment thickness maps and estimate the gross sediment volumes for each of the unit depocentres (Methods, Table S1).

The TMF system consists of a depositional sequence where each of the seismic units and their associated shelf breaks are covered by top-set strata of the succeeding unit (Figs. 2 and 3a; Supplementary Fig. S2). Exceptions to this trend are seen in areas of the present-day troughs where older top-set strata and associated shelf breaks have been truncated by ice stream erosion (Fig. 3b). Apart from this spatially-limited truncation, the depositional configuration of the shelf margin between the Melville Bugt and Upernavik troughs is remarkably well-preserved. The topset strata are formed by sheeted geometries that expand laterally into asymmetric mounded wedges with internal discontinuous-hummocky or low-angle clinoform reflection patterns (Figs. 3a and S3). These features are interpreted as grounding zone wedges (GZW) formed by rapid accumulation of deforming subglacial tills at the grounding zone of a marine-terminating ice mass[16,17]. Their formation requires sub-glacial accommodation and a high sediment flux. Thus, GZW are commonly associated with deposition below ice shelves or ice that is partly floating[18,19]. These conditions may occur at the shelf edge during the most extensive glacial maxima stages, or at mid-shelf positions during either moderate glacial maxima or intermediate cooling stages during deglaciation. Within the sheeted top-set sections of the seismic units, thin reflections are observed that onlap the glacial erosion surfaces and infill intra-shelf depressions between positive topographic features (Fig. 3a). The reflection geometry and acoustic polarity opposite to the seabed is indicative of hemipelagic marine muds or distal glacial-marine sediments[20]. The widespread presence of onlapping strata above the glacial unconformities may be attributed to relatively brief periods when deposition occurred below floating ice or in open marine conditions, and are thus associated with relative sea level rise following glacial retreat from the shelf edge.

Late Cenozoic context and glaciation chronology

The Neogene – Quaternary succession of the northwest Greenland margin, represented by seismic mega-units (mu) A, B and C, overlies a thick succession of late Mesozoic to early-middle Cenozoic strata associated with the rift and post-rift development of Baffin Bay (Fig. 2)[21]. The onset of progradation at the base of mu-A occurs above a regional unconformity formed by glacial erosion that truncates the late Neogene sedimentary packages (mu-B and C) from a mid-shelf position and toward the fault-bounded Greenland bedrock. Consequently, late Miocene strata with a predominant mudstone character are exposed in the over-deepened inner-shelf troughs (mu-C, Fig. 2). The youngest strata below the prograding units of the TMF system show asymmetric wavy and mounded geometries attributed to sedimentation by contour-parallel bottom currents (mu-B, Fig. 2)[22]. The abrupt transition from marine current-controlled sedimentation to prograding clinoforms provides a clear physical indication for the onset of shelf-based glaciations in northeast Baffin Bay. Using the dense 2D grid, the seismic stratigraphy of the late Cenozoic package has been extended southwards to the Delta-1 exploration well (Fig. 4). The well biostratigraphy indicates a Pliocene age for mu-B and a likely age range of 3.3–2.6 Ma for the onset of glacial deposition above a regional late Pliocene horizon (Methods, Fig. S4). North Atlantic deep drilling records point to a major expansion of the GrIS at 2.7–2.8 Ma[6,23-25] that corresponds with an increase in the amplitude of 41 kyr orbital cycles in the global $\delta^{18}O$ record[26] (Fig. 5a, c-d). By combining the local biostratigraphy with the more detailed North Atlantic chronology, we infer that the northwestern GrIS began to advance beyond the coastline and onto the continental shelf during the latest Pliocene, probably marked by the G6 cooling event at around 2.7 Ma (Fig. 5). The age of the TMF system is further constrained by palaeomagnetic data from cores that were recovered as part of IODP 344S[27] (Methods, Figs. S2 and S5). The chronological evidence favours an age model that assumes a gross linear relationship between time and TMF accumulation (Fig. S6). The model implies that although glacigenic sediment fluxes across the shelf edge likely varied in response to ice sheet advance/retreat cycles (over orbital and sub-orbital time scales), the long-term sediment delivery, i.e. over 0.5-1.0 Myr, did not change substantially. The approach of using depocentre volumes for inferring TMF evolution is supported by seismic mapping across a large catchment area covering two glacial outlets, which means that spatial flux variations associated with relative shifts in ice stream pathways are evened out. We emphasize, however, that whilst the proposed age model provides a time-averaged picture based on currently available data, future scientific drilling is necessary to improve the chronology of the individual prograding units.

Trough-mouth fan development

The progradational build-out of the northwest Greenland margin, represented by mu-A, can be divided into four development stages (DS) (Fig. 6 and S7). The early development stage (DS-I), comprising units 1–2, is characterized by sediment accumulations that partly cover the present-day troughs and the topographic high to the north ("Northern Bank", Fig. 1).

Increased sediment thickness in the basinward section seen for units 1 and 2 is attributed to large mass-transport deposits observed on seismic profiles as truncated reflections and hummocky surfaces that encase chaotic acoustic signatures (Fig. 2). Potential sources for these deposits are related to erosion and mass-wasting associated with early ice sheet advances over a Neogene succession of unconsolidated marine sediments. DS-II (units 3–4) is characterized by convergence of depocentres towards the area located between the contemporary troughs and the abandonment of sedimentation over the "Northern Bank" area. During DS-III (units 5–7) fan depocentres gradually merge, culminating with a complete amalgamation, reflecting near-uniform rates of margin progradation. From unit 7 to 8, the sedimentation pattern shifts to a pronounced build-out in front of the two contemporary troughs. This marked lateral change in depocentre shows no transitional phase and thus points to a rapid reorganization in GrIS flow conditions. DS-IV (units 8–11) is further characterized by the accumulation of a drift-channel system seen as elongate thickness anomalies radiating from the depocentres into the basin (Figs. 2 and 6). Similar sedimentary features have been described from the West Antarctic and the southeast Greenland margins and are thought to have been generated by the interaction of oceanic bottom-currents with downslope-moving fine-grained suspension currents[28,29].

The early TMF depocentres formed over Cretaceous rift basins (Kivioq and Upernavik basins) that are separated by the Melville Bay Ridge[21] (MBR) (Figs. 2, 6, S2 and S7). This ridge has a complex post-rift tectonic history influenced by strike-slip and compressional motion during the late Palaeogene and later. The resulting vertical adjustments triggered regional slope instability and vertical incision of the late Miocene succession[21,22]. The MBR strikes SE-SW and deepens southwards by more than 1200 m over a distance of about 40 km. At its shallowest point, aggradational strata of unit 3 truncate the ridge, while to the south it is deeply buried by late Cenozoic sediment packages. The depocentre distribution and internal progradation patterns of units 1-3 imply that during the early phase of shelf glaciation, ice drained across the present topographic high of the "Northern Bank", which is underpinned by the shallow ridge segment (Fig. 6). It is notable that the convergence and subsequent amalgamation of the glacigenic depocentres (DS II-III) occurs across an area underlain by the distal MBR (Fig. S7). This suggests that the progressive shifts in Early Pleistocene ice stream routes toward the central parts of the TMF system were controlled by relative movements of the ridge. As progradation gradually moved into deeper water, accommodation may have been accentuated by local tectonic adjustments, including flexure and associated fault-reactivation of the underlying crust due to sediment loading. To summarize, we infer that the deposition and the top-set preservation of the TMF system is the result of high glacial sediment fluxes from the northwest GrIS in concert with favourable geological circumstances that include long-term basin subsidence of deep-seated structural elements.

Implications for Greenland Ice Sheet dynamics

The seismic-stratigraphic evidence shows that during the Early Pleistocene, the northwest GrIS was drained by prominent but geographically transient ice streams terminating in Baffin Bay (DS I-II, Fig. 6). The palaeo-ice streams were likely associated with temperate or polythermal basal conditions that, combined with the presence of deformable substrata, determined their ability to form cross-shelf troughs linked with fan depocentres[30-32]. The glacial outlets may have been connected to ice shelves, that would extend the marine ablation zone to a wider area in front of the grounding line[33].

The merging of fan depocentres, culminating in a single, elongate accumulation zone (DS III) signals a gradual change in the mode of sub-glacial transport toward the end of the Early Pleistocene (~1.5–1.0 Ma, Fig. 5). Similar elongate margin progradation of the Early Pleistocene interval has been identified on other glaciated margins[34], but its significance for palaeo-ice sheet dynamics remains elusive. The ice flow conditions associated with a linear ablation zone extending along the shelf margin for over 200 km is incompatible with focussed ice stream glaciation maintained by basal sliding and high meltwater production. Ice streams with similar widths have not been observed in the geological or contemporary record[35] and it seems unlikely that ice sheet volume in northwest Greenland was sufficiently large to sustain a 200 km-wide ice stream. More likely, the even dispersal of sediments reflects a wide glacial front advancing with laterally uniform flow velocities over a deformable bed[30,36]. A possibility is that DS III reflects a long-term equilibrium between warm-based ice and its sedimentary based grounding zones, which was attained after the shelf margin became smoothed by earlier glacial erosion, i.e. limiting the potential for topographic focusing (streaming) of ice flow. This development toward a continuous ablation front could also be influenced by ice sheet dynamics responding to the 41 kyr climate cycles (Fig. 5a).

The shift from even progradation along the entire shelf front (unit 7) to the build-out of crescent-shaped fans (unit 8) (Fig. 6), points to a radical change in glacial flow conditions resulting in focused sediment delivery to the shelf margin. This reorganisation likely occurred at the start of the Mid-Pleistocene transition (MPT: 1.1–0.7 Ma) that demarcates the onset of 100 kyr orbital cycles and a steady increase in the magnitude of sea-level low-stand events from ~70 to 130 m[26,37] (Fig. 5a). A broad correlation between Unit 8 and the MPT is consistent with an erosional deepening of the shelf break grounding line through units 8–9 which may reflect the extreme sea-level lows of MIS (Marine Isotope Stage) 12 and 16 (Figs. 1, 3b and 5a). Furthermore, Unit 8 corresponds to the onset of sedimentary drift accumulation juxtaposed to slope channels, suggesting that the production and downslope transport of fine-grained sediments increased during the MPT. The changes in deposition during DS IV reflects the wide configuration of the Melville Bugt outlet in contrast to the structurally confined Upernavik Trough, flanked to the south by early Cenozoic volcanic terrain (Fig. S7). Explanations for the MPT include (1) ice sheet dynamics controlled by bedrock conditions and the extent of ice-ocean contact zones[38], (2) feedback between ice albedo and CO_2 reservoir exchanges[39], (3) tectonic base-level adjustments[40], and (4) antiphase relationships in interhemispheric ice volume changes[41]. Clark and Pollard (1998)[38] proposed that removal of deformable sediments (regolith) below northern hemisphere ice sheets increased basal friction, thus allowing more ice to remain above the equilibrium line and eventually causing a transition to thicker ice sheets phase-locked to weak eccentricity forcing. The change from a spatially homogenous advance to focused, deeply grounded, and likely fast-flowing, outlet glaciers, as expressed by units 7-8 (Fig. 6), may be a response to changing basal dynamics and/or volumetric expansion of the GrIS associated with the onset of 100 kyr glaciations[6,25,42]. Nevertheless, the question of why the glaciated margin evolved from focused ice streams during the early phase of shelf glaciation to even margin progradation leading up to the MPT, and then followed by a return to focused ice-stream behavior during the Middle–Late Pleistocene remains unanswered. The complexity of this evolution suggests that the GrIS is influenced by factors other than global climate and insolation-driven dynamics.

Since the first shelf edge expansion of the northwestern GrIS, likely about 2.7 Ma, eleven prograding units are identified, each representing multiple cycles of glacial advances across the shelf margin. Comparison of our data with regional palaeoclimate records may provide further insights to the instrumental mechanisms for the observed changes in glacial outlet configuration (Fig. 5). Here we note that for the Early Pleistocene interval, constrained by stratigraphic ties to boreholes, shifts in glacial deposition overlaps with the estimated ages of Kap København Fm A-B and Store Koldewey Fm – deposits indicating boreal tundra conditions in northern parts of Greenland[43,44]. This correlation points to a potential connection between shifts in ice flow pathways and prominent interglacials[45,46] (Fig. 5b) but further verification is precluded by the younger and chronologically unconstrained part of the record. Nevertheless, the parallel reflections onlapping the erosional unconformities in the palaeo-shelf areas (Fig. 3) suggests that major glacial advances were intermittently replaced by floating ice or open marine conditions.

The depositional record of the Melville Bugt – Upernavik TMF system demonstrates repeated reorganization of ice flow patterns that apparently involved relative sea-level rises broadly occurring every 200-400 kyr. Most conspicuous is the fundamental change in shelf margin glaciation style toward the end of the Early Pleistocene, which may suggest a linkage between GrIS dynamics and the increase in glacial intensities through the MPT. These results document large-scale temporal variations in past GrIS flow dynamics that can help to constrain numerical modelling aimed at understanding Pleistocene ice sheet behavior.

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Author contributions.

P.C.K. is the initiator and lead author of the study. As part of his PhD project, A.M.W.N. provided complimentary results and contributed to the discussion. J.R.H. provided data for the depth conversion and contributed to the interpretation and discussion. M.H. contributed to the interpretation and discussion. U.G. provided input to the seismic interpretation. E.S. and K.D. contributed with a biostratigraphic analyses of industry well data.

Competing financial interests.

There are no competing financial interests associated with this submission.

FIGURE CAPTIONS

Figure 1. Map of study area with displayed seismic lines and palaeo-shelf break positions of glacigenic prograding units. Seabed topography, illustrated by grey-scale dipmap, is based on first reflection from 2D and 3D seismic data. Bathymetry in the regional overview (inset, top right) (inset), shown at 300 m contour intervals, is from IBCAOv3[11]. Key drill sites are marked in red. See Fig. S1 for the full seismic data grid. Present shelf-break and palaeo-shelf breaks

(units 1-10, late Pliocene) are marked by coloured curves (mbss: meters below sea surface). MSGL = Mega-scale glacial lineations. IFT = Inter-fan trough.

Figure 2. Seismic profile NE-SW across the Melville Bugt (line position shown in Fig. 1) with key stratigraphic horizons shown in colour. The late Cenozoic succession is partitioned by seismic mega-units (m.u.) A-D. Numbers 1-11 denote glacigenic prograding units within mega-unit A. LPU = Late Pliocene Unconformity, MBR = Melville Bay Ridge, MTD = mass-transport deposits, DCS = drift-channel system. Vertical scale is displayed in two-way travel time (twtt) seconds. Box indicate zoom-in shown in Fig. 3a.

Figure 3. Seismic cross-sections representing the aggradational interfan area (**a**) and the Melville Bugt trough area (**b**). Line positions are shown in Fig. 1. Denotation of stratigraphic horizons and units similar to Fig. 2. White circles indicate intersection with shelf breaks shown in Fig. 1. Triangles point to lenticular strata geometries inferred as grounding zone wedges. Reflections onlapping glacial unconformities are demarcated by green arrows (**a**, inset). Individual clinoform wedges, displaying discontinuous-hummocky reflection patterns, are interpreted as glacigenic debris flows (**b**, examples marked by black arrows).

Figure 4. Seismic profile SE-NW across the drill site of Delta-1 located south of the main study area (Fig. 1 inset). The displayed well logs are resistivity (blue-purple) and gamma-ray (green-orange). Stratigraphic time intervals for the upper and lower boundaries of mega-unit B are based on biostratigraphic information (Methods; Supplementary Fig. S3).

Figure 5. Correlation of the northwest GrIS prograding system (units 1-11, development stages I-IV) with regional and global climate proxies from 3.4 Ma to present. (**a**) Global sea-level curve[37] constructed from the LR4 benthic $\delta^{18}O$ stack[26] with thin, broken lines demarcating trends in sea-level low stands. (**b**) Si/Ti record from Lake El' Gygytgyn, northeast Russia, with high values indicating warmer Arctic climates[45]. (**c**) Flux of coarse fraction (>63 µm) from ODP 646, eastern Labrador Sea[24] with single-point outliers omitted to obtain background signal. (**d**) Natural Gamma-Ray (NGR) variation from site U1308 reflecting flux of glacial weathering products to the central North Atlantic ice-rafting belt[25]. Unit 3, cored at sites U0100/110 (red bar) is correlated to the Olduvai (O) sub-Chron (age model explained in Methods and Supplementary Figures S4-S6). SKF = Store Koldewey Fm. KKF = Kap København Fm. (sections A and B).

Figure 6. Thickness maps for each of the prograding units. Thick white lines demarcate the shelf break position of the top horizon (as in Fig. 1). Red arrows show inferred routes of streaming ice. MTD = mass-transport deposits, GZW = grounding zone wedge, DCS = Drift-Channel System. BFF = Basin-floor fan. Thicknesses < 30 m (white areas) are considered to be below the seismic resolution. Position of coring sites U0100/110 shown in the Unit 3 panel.

METHODS

Data and seismic mapping

The seismic mapping is based on data acquired by TGS from 2007-2010 in the Baffin Bay along the West Greenland margin (Fig. S1). The sedimentary succession was mapped previously and subdivided into genetically related mega-units[21,22] based on seismic stratigraphic principles[47]. The focus in this study is the Melville Bugt – Upernavik Trough-

Mouth Fan (TMF) system forming part of mega-unit A (Fig. 2). The TMF package is comprised of prograding sediment wedges separated by glacial unconformities and corresponding basinward reflections. The glacial unconformities over the shelf areas are interpreted as the product of grounded ice that formed during periods of glacial expansion across the palaeo-shelves and terminating at the shelf-break. In parts where the top-set strata of the TMF are well-preserved, thin, horizontal strata are seen to onlap the glacial unconformities, suggesting phases of marine transgressions that formed after the retreat of grounded ice (Fig. 3a). The base of the TMF system is defined by an unconformity of likely late Pliocene age that caps a Neogene marine sequence (see biostratigraphy below). Seismic interpretation was carried out using Petrel 2016 software. The seismic horizons were gridded using a cell size of 200 × 200 m. Shelf breaks were mapped by tracing the sharp change in gradient on the dip-map attribute extracted from each of the horizons.

Depth conversion and sediment volume calculation

Gridded surfaces representing the top of units 1-11 (top unit 11 is the seabed) were depth converted in Petrel. Because there are no seismic refraction data available in the area, we used plausible velocities based on similar glaciated margins [48,49] and nearby well data. A simple layered model consisting of a water layer over a consolidated sediment layer was assumed, since glaciated margins typically have at most only a thin veneer of unconsolidated sediments. The water velocity assumed is 1460 m s^{-1}. Off Svalbard, the top velocity of the consolidated glacial sediment layer varies from 2100–2300 m s^{-1} and velocity gradients range from 0.3–0.7 m s^{-1} m^{-1}. These velocities and gradients are consistent with velocities observed in the Delta-1 well to the south of the study area (Fig. S1). For the depth conversion, a top velocity of 2100 m s^{-1} and a gradient of 0.5 m s^{-1} m^{-1} in the consolidated sediment layer were assumed.

Isochores were then computed based on the depth converted gridded horizons. Gross sediment volumes were calculated for the shelf margin depocentres of each seismic unit by constructing polygons tracing the 300 m thickness contour that most consistently defines the depocentre geometries (Table S1). Confining the unit volumes to the shelf margin depocentres ensured that gross volumes were comparable and strictly related to glacial sediment transport through the Melville Bugt – Upernavik TMF system, while reducing the influence from other sediment sources, e.g. alongslope transport from nearby glacial outlets. The sediment volumes contained in the depocentres represent gross averages of glacially derived sediments produced primarily by subglacial and englacial transport. In addition to material eroded from the Greenland basement, this includes an unknown component of sediments reworked from the shelf region, e.g. exposed Neogene strata, older tills and interglacial deposits. However, regardless of the ratio between far-travelled and locally eroded material, the marginal depocentres represent the final sink of sediments derived by drainage of a large sector of the north-west Greenland ice sheet, e.g., about 1/7 of its surface area based on current ice flow data[50].

Chronology of trough-mouth fan evolution

The Delta-1 well located on a mid-shelf position south of the main study area drilled through a thick late Cenozoic section (Figs. 1 and 3). The biostratigraphic information[51] from late Neogene marine deposits, corresponding to mega-units B and C, below the glacigenic package was used to obtain a chronology for the likely onset of shelf-based glaciation (Fig. S4). Age estimates were given based on the first and last occurrences of dinocyst species as well as calcareous benthic and agglutinated foraminifera. Interpretation of the dinocyst assemblages were based on earlier studies from the Labrador Sea/Baffin Bay[52-54], north-eastern Atlantic[55], Iceland[56] and the North Sea[57]. The age range of foraminiferal bio-events was based on previous results from North Greenland[58], East Greenland[59], the Norwegian margin[60], and the North Sea[61]. A late Pliocene – Early Pleistocene age for the B1 horizon is supported by an increase in abundance and diversity of calcareous benthic foraminifera[59], including *Elphidium excavatum group*, *Bucella frigida*, *Elphidium albiumbilicatum* and *Elphidium bartletti*, observed between 940-810 m in the Delta-1 well (Fig. S4). The well-tie provides a more robust age range for the onset of shelf-based glaciation than was previously inferred based on long-distance correlation to ODP Site 645 in the southwest Baffin Bay[22].

A late Pliocene onset of shelf margin glaciation in Melville Bay is commensurate with previous results from central West Greenland based on seismic-well correlation[62]. In comparison, glaciation began to influence the central East Greenland margin already in the late Miocene[63] but with major progradation of the Scoresby Sund TMF taking place during the Pleistocene[64]. For the southwest Greenland margin, an onset of glaciation 4.4-4.6 Ma was suggested[65], i.e. 1.1-2.0 Ma earlier than initial glacial advance inferred for central and northern parts of West Greenland. This deviation may partly relate to differences in the definition of the glaciation signatures tied to well biostratigraphy. In the present study and that of Hofmann et al. (2016)[62], the onset of glaciation is inferred directly from the age of marine sediments encountered below glacigenic deposits on the shelf margin. The approach used by Nielsen and Kuijpers (2013) associates the oldest of a series of large mass-transport deposits (MTD), seen at the base of the glacigenic wedge, with the first shelf-edge ice advance in the Davis Strait region. Given that climate modeling results suggest that Pliocene ice was limited to high-elevation areas[4] two plausible scenarios may be considered: either, the oldest MTD was triggered by a brief glacial advance during an early Pliocene cooling stage, or, alternatively, the deposit was formed by slope instability processes unrelated to glacial loading.

A further age constraint on the trough-mouth fan evolution is provided by palaeo-magnetic data obtained from shallow cores recovered at sites U0100 and U0110 in northeast Baffin Bay[27,66]. These sites were drilled over the “Northern Bank” at a position where Unit 3 is clearly defined in the seismic data, above a major unconformity eroding the Melville Bay Ridge (Fig. S2). We therefore consider the age of the recovered sediments to represent the topmost part of Unit 3. The results show a normal polarity for the cored interval, except for an apparent geomagnetic reversal recorded in the upper part of the drilled succession (Fig. S5). The consistency of the inclination for the normal polarity interval, measured on discrete samples from two neighboring sites, covering a stratigraphic section of >50 m, negates the possibility that this could be a geomagnetic excursion within a reversed polarity chron or subchron. Potential age correlations related to the normal palaeomagnetic phase of Unit 3 includes the Brunhes Chron (0-0.8 Ma), Jamarillo sub-Chron (1.0-1.1 Ma) or the Olduvai sub-Chron (1.8-2.0 Ma)[67]. The first two options imply that gross depositional fluxes were very low during the first three glacial advance mega-cycles and then increased to at least threefold values from Unit 4 and onwards (Fig. S6). If the top of Unit 3 corresponds to the Jamarillo sub-Chron then the average shelf-edge sedimentation rates during deposition of units 8-11 would be 1.5-2.0 m kyr^{-1} compared to 0.5-0.7 m kyr^{-1} for units 1-3. To explain such an abrupt change in long-term sediment fluxes, requires that the northern GrIS was dynamically resilient with a low erosional capability throughout the late Pliocene and most of the Early Pleistocene.

However, this scenario is not supported by evidence from deep-sea records indicating that supply of IRD during the Early Pleistocene was similar to that observed for the Late Pleistocene[23,64,68]. Moreover, changes in cosmogenic isotope composition (^{26}Al, ^{10}Be) points to intensified glacial erosion in East Greenland during the Early to Middle Pleistocene[6]. Therefore, the normal palaeo-magnetic phase of Unit 3 is most likely matched with the Olduvai sub-Chron, consistent with a linear relationship between cumulative age and sediment volumes since the onset of progradation (Fig. S6). The preferred age model that befits both previous observations from proxy-based studies (Figs. 5c-d) and the palaeo-magnetic signature of Unit 3 implies that gross sediment fluxes across the shelf margin were on average relatively constant over the long time scale considered here, i.e. several millions of years. We stress, however, that the approach of calculating large volumetric entities involves an averaging process which must be assumed to conceal sediment flux changes over shorter time scales such as orbital periodicities associated with global changes in ice volume. Thus, it is implicit that short hiatuses and spikes in sedimentation rates do not have a significant impact on the longer term averages.

Age model uncertainty

Provided that the seismic unconformities have been interpreted consistently throughout the study area, the absolute sediment volumes determined for each of the depositional units are dependent on the (1) time-to-depth conversion procedure and (2) the thickness threshold for defining the shelf margin depocentres as described above. However, varying the parameters for these procedures affects the units systematically (e.g. in a similar direction) and thus will not significantly influence the relative distribution of the sediment volumes over the time span of TMF deposition. The uncertainty associated with the age model is therefore primarily related to the scarcity of age control within the prograding succession, especially between seismic units 3 to 11. With only one internal age control point, quantification of error margins for the unit ages, e.g. using statistical methods such as Monte Carlo simulation, becomes arbitrary and reliant on a pre-defined confidence level. The lack of well-defined unit ages is illustrated by white gaps between the depositional units shown in Fig. 5. The uncertainty may be in the range of several orbital cycles, e.g. ±50-100 ka, corresponding to ±2-4 % variation in gross sedimentary fluxes, although this needs testing by further sampling and dating of the TMF units.

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Data availability

All seismic data that support the findings are publically released and can be requested from the GEUS data department (www.GEUS.dk)