

Asynchronous ice-sheet development along the central East Greenland margin: a GLANAM project contribution

Lara F. Pérez and Tove Nielsen

The sedimentary record of the glaciated margins of the North Atlantic holds evidence of past ice-sheet activity, and reflects spatial and temporal variations in the ice–ocean–climate interaction as well as the influence of tectonic processes. Furthermore, the record of cross-shelf ice sheets provides a direct link between the continental ice cover and the deep ocean, a relevant issue in the context of climate research.

With a four-year funding period, a Marie Curie Initial Training Network on the Glaciated North Atlantic Margins (GLANAM) was started in the spring 2013. The network involved international partners from both academia and industry and enrolled 15 young scientists working in different areas of the North Atlantic margins.

The Geological Survey of Denmark and Greenland was partner in the network, leading the Greenland margin research and hosting three fellows. One of the main topics of the GLANAM project was to investigate the impact of the ice sheets on the large-scale evolution of the East Greenland margin. The present work summarises some new insights into the glacial history of the central East Greenland margin gained through a study within this project (Fig. 1).

The glaciated East Greenland margin

The dynamic evolution of the Greenland ice sheet is related to the glacial history of the Northern Hemisphere (e.g. Thiede *et al.* 2010). Despite evidence of glaciated hinterland and tidewater glaciers in Greenland during the Eocene and Miocene (e.g. Thiede *et al.* 2010), the onset of large-scale glaciations in the Northern Hemisphere, where ice expanded onto the continental shelf, has been suggested to date between 5 and 2.5 Ma based on a marked decrease in global benthic $\delta^{18}\text{O}$ values and the presence of ice-rafted debris deposits (e.g. Bailey *et al.* 2013). Since the Mid-Pliocene the oscillation of the ice sheets of the Northern Hemisphere, and thus of the East Greenland margin, is considered to have followed the glacial–interglacial cycles (e.g. Sarnthein *et al.* 2009).

Major tectonic events related to the Miocene–Pliocene uplift of the East Greenland margin have been pointed to

as instigators of the eastwards glacial advance across the shelf (Døssing *et al.* 2016). Furthermore, the build-up of the North Atlantic ice sheets has also been influenced by the oceanographic circulation which, along East Greenland, is mainly controlled by the East Greenland Current (EGC; Fig. 1; Sarnthein *et al.* 2009). The EGC is a southward-flowing current formed by a complex system of branches and different water masses (Våge *et al.* 2013).

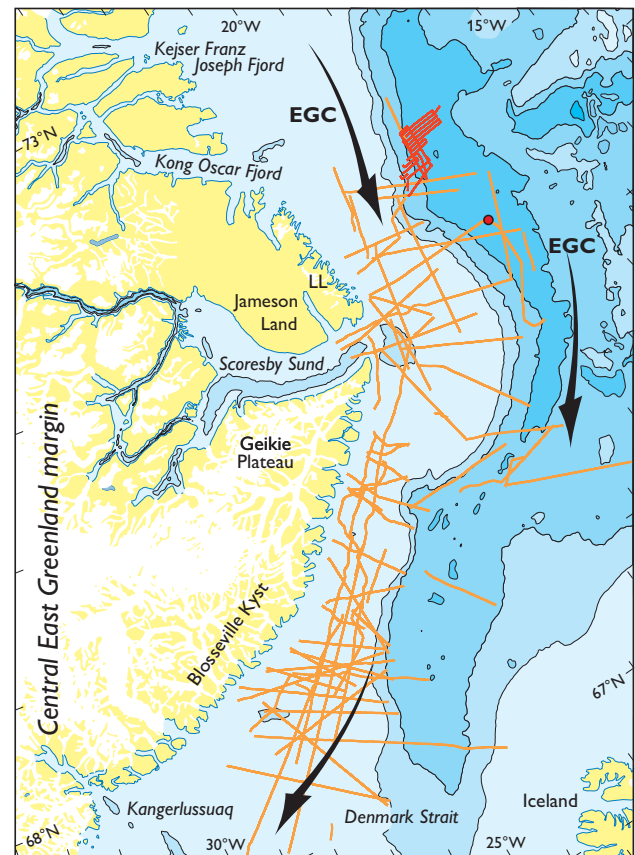


Fig. 1. Bathymetric map of the study area based on the International Bathymetric Chart of the Arctic Ocean (IBCAO; Jacobsson *et al.* 2012). Contour interval: 500 m. Orange lines: reflection seismic profiles. Red lines: sub-bottom and multibeam data. Red dot: ODP site 987. Black arrows: general circulation of the East Greenland Current (EGC). LL: Liverpool Land. Note the outwards bulging of the shelf edge off the major fjords.

It is an important component of the Atlantic Meridional Overturning Circulation (AMOC) and therefore has implications for the global climate system (De Schepper *et al.* 2015). The contribution of the EGC to the AMOC has been partly controlled by tectonic pulses of the Denmark Strait (Parnell-Turner *et al.* 2015), a 600 m deep threshold located around 67°N (Fig. 1). The Denmark Strait is part of the Greenland–Scotland Ridge and constitutes a natural boundary that divides the East Greenland margin into a northern and southern part, which have experienced different ice-sheet dynamics. Our study focuses on the glacial history of the margin section that lies just north of the Denmark Strait, i.e. the central East Greenland margin (Fig. 1).

Database and interpretation procedure

Based on a large database of 2D seismic reflection profiles (Fig. 1), we have divided the sedimentary record into major seismic sequences, which show evidence of various sedimentary processes (Pérez *et al.* unpublished data). A local dataset of high-resolution reflection seismic, sub-bottom profiles and swath bathymetry allowed for a detailed breakdown of the recent stratigraphic and morphological features (Pérez *et al.* unpublished data). The ages of the major seismic sequences have been assessed by a direct tie to site 987 of the Ocean Drilling Program off Scoresby Sund (Fig. 1; Pérez *et al.* unpublished data). Seismic-stratigraphic analyses of these datasets made a large-scale reconstruction of key stratigraphic events possible, revealing several stages of the Greenland ice sheet dynamics along the central East Greenland margin from late Miocene to Present.

Evidence for cross-shelf ice sheets and ice streams

Central East Greenland is characterised by large fjords, many of which are connected with cross-shelf troughs that are up to 300 m deep and 35 km wide (Fig. 1). These troughs were formed by erosion of ice streams that passed from the fjords across the shelf, delivering a concentrated accumulation of sediments to the shelf edge (e.g. Batchelor & Dowdeswell 2014). From there the sediments were transported down the slope as glacial debris flows that build up to form large prograding wedges called trough-mouth fans. The presence of a trough-mouth fan is often revealed in the seabed morphology as an outwards bulging of the shelf edge (Fig. 1), and the youngest debris flows are often observed on the present-day seabed. Ice streams are recognised as one of the most important controls on ice-sheet configuration and stability (e.g. Stokes *et al.*

2016). Therefore the study of palaeo-ice stream behaviour and dynamics by mapping buried cross-shelf troughs and trough-mouth fans is a useful tool in reconstructing former ice-extent and palaeoclimate variability (e.g. Batchelor & Dowdeswell 2014). In addition, submarine glacial forms outside the cross-shelf troughs hold clues of the existence of more steady, grounded ice. Notable features are grounding-zone wedges up to 160 m high identified along the central East Greenland shelf. These ridge-like sedimentary features mark a temporary position of the ice margin on the shelf (Dowdeswell & Fugelli 2012).

Discussion

Prograding deposits off Blosseville Kyst dating back to the late Miocene constitute the first evidence of cross-shelf glaciations on the central East Greenland margin (Fig. 2). The oceanward glacial advance continued during the early Pliocene, where cross-shelf troughs and trough-mouth fans off Blosseville Kyst and Scoresby Sund denote ice-sheet growth with ice streams occasionally reaching the palaeo-shelf edge (Fig. 2). This glacial intensification coincided with the first large-scale glaciation reaching to the palaeo-shelf edge along the south-western Greenland margin (Nielsen & Kuijpers 2013).

During the middle Pliocene (3.65–2.90 Ma), the seismic-stratigraphic analysis denotes a period of glacial retreat along the central East Greenland margin. As the ice retreated, the oceanic current took over the control of the depositional environment, indicated by a predominance of current-generated wavy facies. The observed glacial retreat is coeval with the global Mid-Pliocene Warmth (3.3–3.0 Ma; e.g. Robinson 2009) and a supposed enhancement of the EGC along the East Greenland Margin (e.g. Raymo *et al.* 1996).

Thick trough-mouth fan deposits led to a major oceanward advance of the shelf edge off Scoresby Sund, providing evidence of multiple cross-shelf glaciations during the Quaternary (Fig. 2). The ice-sheet extension was largest during latest Pliocene – earliest Pleistocene (2.90–2.33 Ma), revealing a slightly older age for the onset of margin progradation off central East Greenland than observed farther north off North-East Greenland (*c.* 76°N), where the first margin progradation began *c.* 2.5 Ma (Berger & Jokat 2009). The large progradation of the central East Greenland margin coincided with the proposed onset of major Northern Hemisphere cooling at 2.7 Ma (e.g. Bailey *et al.* 2013) and the suggested full-scale glaciation of Greenland at 2.9 Ma (Sarnthein *et al.* 2009).

In addition to the cross-shelf troughs off Blossville Kyst and Scoresby Sund, grounding-zone wedges are identified on the shelf off Liverpool Land within the Quaternary sequences, providing evidence of steady, grounded ice. Thus, repeated glacial advances over the shelf, occasionally reaching the shelf edge, are inferred along the entire central East Greenland margin during the Quaternary (Fig. 2).

However, the study of glacialigenic debris-flow deposits observed on the high-resolution dataset of the Liverpool Land margin (Fig. 1) indicates that the Quaternary glacial advances to the shelf edge were not synchronous along the margin. The glacialigenic debris-flow deposits identified within the early Pleistocene sequences in the southern part of the Liverpool Land dataset suggest a distal downslope input from the Scoresby Sund ice stream, in agreement with higher sediment supply to the north of the Scoresby Sund trough-mouth fan between 1.77 and 0.78 Ma (La-berg *et al.* 2013).

An upward increase of glacialigenic debris-flow deposits within the upper seismic section indicates an intensification of glacial control on the sedimentation during the middle Pleistocene. This scenario matches the increase in global ice volume that accompanied the Mid-Pleistocene

transition *c.* 0.9–0.8 Ma (Head & Gibbard 2005) and gave rise to the growth of larger ice sheets in the Northern Hemisphere (e.g. Dowdeswell *et al.* 1997; Stokes *et al.* 2016). The internal distribution of the middle Pleistocene glacialigenic debris-flow deposits points to a changing sediment source through time. Whereas the oldest glacialigenic debris-flow deposits are most abundant in the southern part of the Liverpool Land area, pointing to an ice-stream source in Scoresby Sund, the youngest glacialigenic debris-flow deposits are more abundant in the northern part of the study area and thus are likely fed by an ice stream from Kong Oscar Fjord (Fig. 2). This northern-sourced pattern continued during the latest Pleistocene and Holocene, in agreement with the presence of ice-rafted debris trapped inside Scoresby Sund during the last 10 ka (Stein *et al.* 1993) and the southward-pointing, cross-shelf trough off this fjord observed in the present-day seafloor (Dowdeswell *et al.* 1997). Farther north, moraines related to the maximum extent of the Greenland ice sheet during the Last Glacial Maximum have been identified off Kejser Franz Joseph Fjord (Evans *et al.* 2002).

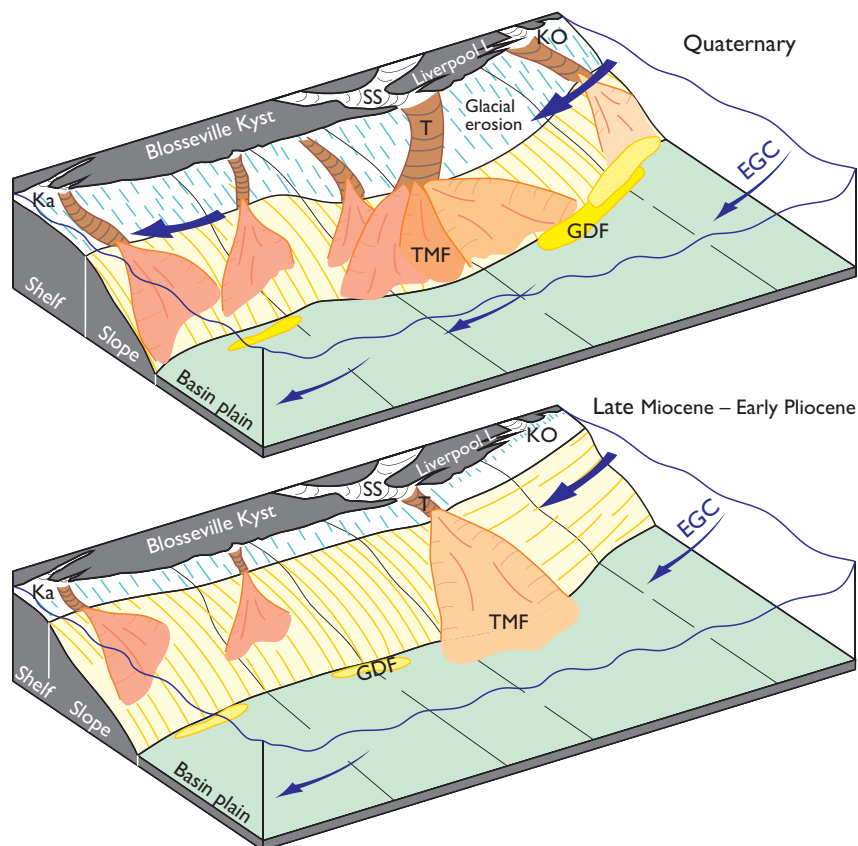


Fig. 2. 3D sketch of the central East Greenland Margin development during the late Miocene – early Pliocene and the Quaternary showing the main morphological features and key depositional processes. Within the same age range, darker colours represent older processes or deposits. **T**: trough. **TMF**: trough-mouth fan. **GDF**: glacialigenic debris-flow deposit. Blue lines on shelf: predominantly glacial erosion. Orange lines on slope: predominantly progradation. Blue arrows: **EGC**: East Greenland Current. **Ka**: Kangerlussuaq. **SS**: Scoresby Sund. **KO**: Kong Oscar Fjord.

Concluding remarks

Our data indicate an early cross-shelf glaciation off Blossville Kyst during the late Miocene and early Pliocene followed by major cross-shelf glaciations off Scoresby Sund during the early Quaternary and off Liverpool Land in the late Quaternary. Higher resolution of the Quaternary data off Liverpool Land indicates that the activity of the Scoresby Sund ice-stream system was gradually taken over by the Kong Oscar Fjord ice-stream system during the Pleistocene. Overall, our study reveals an asynchronous growth of the ice sheet across the shelf, with a marked northward progradation of ice-stream activity from the late Miocene to the Present along the central East Greenland margin.

Acknowledgements

The research leading to these results received funding from the People Programme (Marie Curie Actions) of the EU FP7 programme FP7/2007-2013/ under REA grant agreement no. 317217. The research forms part of the GLANAM (GLAciated North Atlantic Margins) Initial Training Network. For further information on the GLANAM project visit www.glanam.org.

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Authors' address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark; E-mail: lfp@geus.dk