https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

Repeated ice streaming on the northwest Greenland shelf since the onset of the Middle Pleistocene Transition

Andrew M. W. Newton[1,2], Mads Huuse[1], Paul C. Knutz[3], David R. Cox[1], and Simon H. Brocklehurst[1]

[1]School of Earth and Environmental Sciences, University of Manchester, Oxford Road, UK, M13 9PL.

[2]School of Natural and Built Environment, Queen's University Belfast, University Road, UK, BT7 1NN.

[3]Department of Geophysics, Geological Survey of Denmark and Greenland, Øster Voldgade 10, 1350, Copenhagen, Denmark.

Correspondence to: Andrew M. W. Newton (amwnewton@gmail.com)

Abstract. Ice streams provide a fundamental control on ice sheet discharge and depositional patterns along glaciated margins. This paper investigates ancient ice streams by presenting the first 3D seismic geomorphological analysis of a major glacigenic succession offshore Greenland. In Melville Bugt, northwest Greenland, five sets of buried landforms have been interpreted as mega-scale glacial lineations (MSGL) and this record provides evidence for extensive ice streams on outer palaeo-shelves. A gradual change in mean MSGL orientation and associated depocentres suggests that the palaeo-ice flow and sediment transport pathways migrated in response to the evolving submarine topography. The stratigraphy and available chronology shows that the MSGL are confined to separate stratigraphic units and were most likely formed during several glacial stages since the onset of the Middle Pleistocene Transition at ~1.3 Ma. The ice streams in Melville Bugt were as extensive as elsewhere in Greenland during this transition, but, by the glacial stages of the Middle and Late Pleistocene, the ice streams in Melville Bugt appear to have repeatedly reached the palaeo-shelf edge. This suggests that the ice streams that occupied Melville Bugt during the Middle and Late Pleistocene were more active and extensive than elsewhere in Greenland. High-resolution buried 3D landform records such as these have not been previously observed anywhere on the Greenland shelf margin and provide a crucial benchmark for testing how accurately numerical models are able to recreate past configurations of the Greenland Ice Sheet.

https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

1. Introduction

The northwest sector of the Greenland Ice Sheet (GrIS) is currently experiencing some of the largest mass losses across the ice sheet (Mouginot et al., 2019). During the Pleistocene this sector has also been shown to have responded dynamically to temperature changes across multiple glacial-interglacial cycles (Knutz et al., 2019). To better project future evolution of this region, and the GrIS as a whole, requires the reconstruction of past configurations of the ice sheet (especially its ice streams) and how it responded to past warming – e.g. Marine Isotope Stage 11 (Reyes et al., 2014). Typically, this involves using fragmented geological records to constrain numerical ice sheet models that attempt to map spatiotemporal changes in ice sheet extent and processes as the climate evolves across multiple glacial-interglacial cycles. Improving and building upon that fragmented geological record is, therefore, of considerable importance for helping to improve and calibrate these models.

Much of the past offshore extent of the GrIS and its retreat is poorly resolved (Funder et al., 2011; Vasskog et al., 2015), but there are some areas, such as the Uummannaq and Disko Troughs in west Greenland and the Kangerlussuaq, Westwind, and Norske Troughs in the east and northeast, where studies have documented landforms from the Last Glacial Maximum (LGM) on the continental shelf, deglacial ages, and retreat styles – with retreat often punctuated by Younger Dryas stillstands and an intricate relationship between calving margins and ocean currents (Arndt et al., 2017; Dowdeswell et al., 2010; Hogan et al., 2016; Jennings et al., 2014; Sheldon et al., 2016). Seismic reflection data have been used to explore evidence of older glaciations and show that the GrIS repeatedly advanced and retreated across the continental shelves of west and east Greenland through much of the late Pliocene and Pleistocene (Hofmann et al., 2016; Knutz et al., 2019; Laberg et al., 2007; Pérez et al., 2018). These data show that GrIS extent has varied by 100s km throughout the Pleistocene and offers additional constraining observations to borehole and outcrop data that provide conflicting evidence that Greenland could have been nearly ice-free or persistently ice-covered for parts of the Pleistocene (Bierman et al., 2016; Schaefer et al., 2016).

To help understand these long-term changes, especially those associated with ice streams during glacial maxima, landforms observed on palaeo-seafloor surfaces mapped from 3D seismic data can provide information on past ice sheet geometries and ice streaming locations. Landforms can be observed on surfaces preserved within trough-mouth fans (TMFs), typically deposited on the mid- and upper-slope, or on palaeo-shelves buried on the middle and outer shelf that built out as the TMF prograded (Ó Cofaigh et al., 2003). Here, for the first time offshore

https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

The Cryosphere
Discussions
Open Access

Greenland, buried glacial landforms preserved on palaeo-shelves are documented using 3D seismic reflection data from Melville Bugt (Fig. 1). These landforms have been linked to ice stream activity and show that the outer shelf of Melville Bugt was repeatedly occupied by ice streams since ~1.3 Ma.

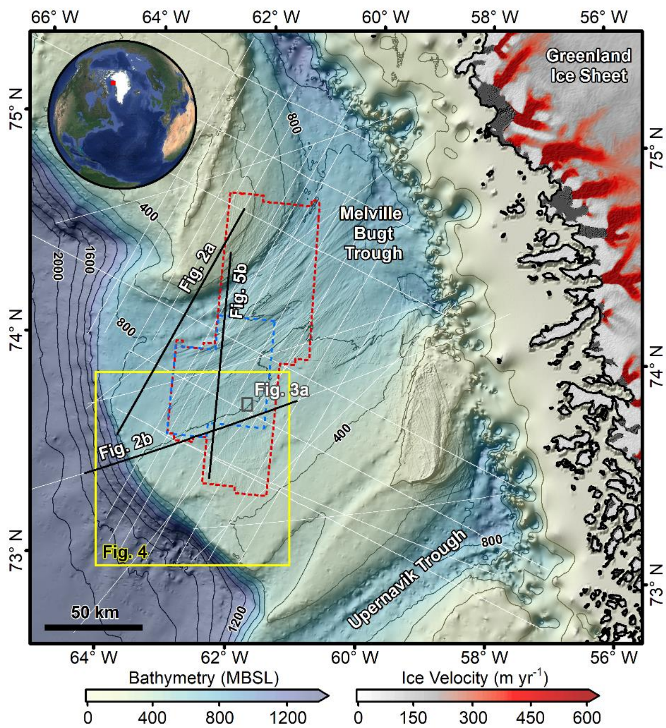

Figure 1: Seabed morphology and ice-flow velocity around the study area. The grey bathymetric contours are every 200 m and the blue/red dashed lines shows the outline of the 3D seismic surveys (blue is a high resolution sub-crop of the original data that was reprocessed by industry to improve resolution). The thin white lines show the locations of 2D seismic data. Mean ice velocity from MEaSURES (cf. Joughin et al., 2010) shows contemporary outlet glaciers flowing into northeastern Baffin Bay. Bathymetry combined from Jakobsson et al. (2012), Newton et al. (2017), and Knutz et al. (2019). Locations of other figures shown. All figures plotted in UTM Zone 21N.

2. Background

Ice streams are corridors (>20 km wide and >100 km long) of fast-flowing (>400-500 m yr^{-1}) ice that are important conduits for ice sheet mass redistribution (Bennett, 2003) and sediment delivery to ice sheet margins (Vorren and

https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

Laberg, 1997). Mega-scale glacial lineations (MSGL) are elongated landforms (typically 1-10 km long) that form by the streamlining (groove-ploughing) (Clark et al., 2003) or accretion of subglacial sediments (Spagnolo et al., 2016) beneath this fast-flowing ice (Clark, 1993). This association is supported by observations of similar features beneath the present-day Rutford Ice Stream in West Antarctica (King et al., 2009). MSGL dated to the LGM have been observed on the present-day seafloor of Melville Bugt (Fig. 1) (Newton et al., 2017; Slabon et al., 2016), but the previous lack of 3D seismic data coverage means they have not been observed for glacials preceding this, meaning that information on past ice flow patterns is broadly inferred from depocentre locations – i.e. areas where large volumes of sediment are associated with the general pathway of ice streams.

The glacial succession in Melville Bugt (Fig. 1) extends across an area of ~50,000 km^2 and measures up to ~2 km thick. The succession records advance and retreat of the northwest GrIS across the shelf multiple times since ~2.7 Ma and is subdivided into 11 major prograding units separated by regional unconformities. The stratigraphy is partly age-constrained by a number of dates extracted from microfossil (~2.7 Ma) and palaeomagnetic data (~1.8 Ma) (Knutz et al., 2019). These dates suggest that whilst accumulation likely varied over orbital and sub-orbital timescales, over timescales longer than this (0.5-1.0 Myr) it did not change substantially and was grossly linear through time since glacigenic deposition began (Knutz et al., 2019). In the northern part of the trough topset preservation is limited due to more recent glacial erosion that has cut into the substrate (Fig. 2a), whereas in the south there is better preservation of aggradational topset strata (Fig. 2b) – i.e. palaeo-shelves where buried landforms might be found.

https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

The Cryosphere Discussions
Open Access
EGU

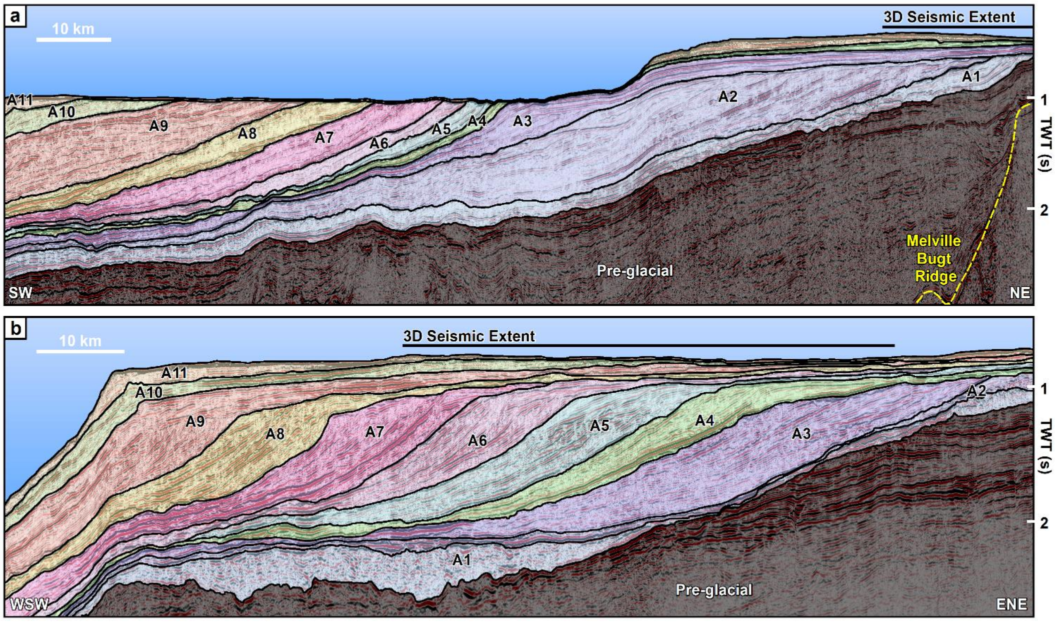

Figure 2: Seismic profiles through the glacigenic succession. The fan comprises 11 seismic stratigraphic units bounded by glacigenic unconformities formed since ~2.7 Ma (Knutz et al., 2019). The tentative chronology from Knutz et al. (2019) suggests that units A8 and A9 likely cover much of the Middle Pleistocene (781-126 ka) and A7 the transition into it from ~1.3 Ma. Location of the profiles are shown on Fig. 1. TWT is two-way-travel time.

3. Methods

This study used industry 3D and 2D seismic reflection data from Melville Bugt, northwest Greenland (Fig. 1). The vertical resolution of the glacial succession is ~10-15 m (frequencies ~30-50 Hz and sound velocity ~2-2.2 km s^{-1}), with a horizontal resolution of ~20-30 m. Horizons were picked from within the 3D seismic data as part of a seismic geomorphological analysis (Posamentier, 2004), and gridded as 25x25 m two-way-time surface maps (i.e. buried palaeo-seafloors maps). Seismic attributes, including variance and Root-Mean Square (RMS) amplitude, were extracted across the surfaces to aid in visualising architectural elements and landforms. This study focused on identifying glacial landforms and used published examples to guide interpretation (e.g. Dowdeswell et al., 2016). Where possible, thickness maps (using the velocity model of Knutz et al. 2019) were created for sub-units derived from deposits that were stratigraphically linked to surfaces containing glacigenic landforms (e.g. correlative slope deposits onlapping the profile of the glacially-influenced clinoform reflection). These depocentre maps show the

https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

predominant area where sediments eroded by the ice sheet were deposited in front of the ice margin, providing insight into how depositional patterns may have changed in response to the evolution of ice streams pathways. In the absence of precise dating for each surface, the linear age model of Knutz et al. (2019) has been used to relatively date the sets of MSGL to the different prograding units.

4. Subglacial landforms

Seismic geomorphological analysis of topset strata showed four sets of buried streamlined features 5-15 km long and 200-300 m wide (Fig. 3 and 4). The landforms are typically 10-15 m high and although they are close to vertical seismic resolution limits (meaning that cross-sectional profiles are subtle) they are best observed in planform using the RMS amplitude or hillshaded surfaces. The streamlined features display a parallel concordance, are confined to individual palaeo-shelf layers within separate stratigraphic units, and their trend cross-cuts acquisition lines obliquely (Fig. 3 and 4). These features are interpreted as MSGL due to their morphology (Spagnolo et al., 2014), and similarity to MSGL observed on the local seafloor (Newton et al., 2017) and buried on other margins (Dowdeswell et al., 2006).

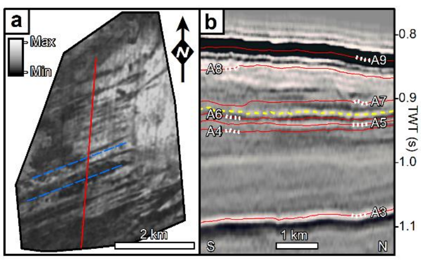

Figure 3: (**a**) The oldest example of mega-scale glacial lineations (blue dashed lines) displayed as an RMS image observed from 3D seismic reflection data and within unit A7 – the yellow dashed line on (b). The colour bar shows the maximum and minimum RMS values. Note that this surface is only partially preserved due to subsequent glacial erosion. For location see Fig. 1. (**b**) Seismic cross-section showing the stratigraphic position of the surface imaged in (a). The location of the profile is shown by the red line on (a).

https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

MSGL set 1 is the oldest and is observed on a partially-preserved surface in the lowest part of a condensed section of unit A7 (~1.3-1.05 Ma) (Fig. 3). It was not possible to confidently determine correlative slope deposits and the associated depocentre due to the limited spatial extent of their preservation. Rising through the stratigraphy, MSGL set 2 is observed in the upper part of unit A8 (~1.05-0.65 Ma) (Fig. 4a) and the associated depocentre is located in the southwestern part of the study area and measures up to 250 m thick. All of the sub-unit depocentres show sediment thicknesses greater than 100 m and have been mapped from the slope deposits that are correlative to the adjacent palaeo-shelves. The slope deposits are typically comprised of onlapping chaotic seismic packages interpreted as stacked glacigenic debrites (Fig. 5a) (Vorren et al., 1989). The MSGL have an average compass bearing of 225° (σ = 5°) that aligns well with the maximum depocentre thickness (Fig. 4a). MSGL sets 3 and 4 are observed in the topset strata of unit A9 (~0.65-0.45 Ma) (Fig. 4b, c, e, f,) and their bearings show a gradual transition to 237° from the 225° observed in unit A8 (Fig. 6).

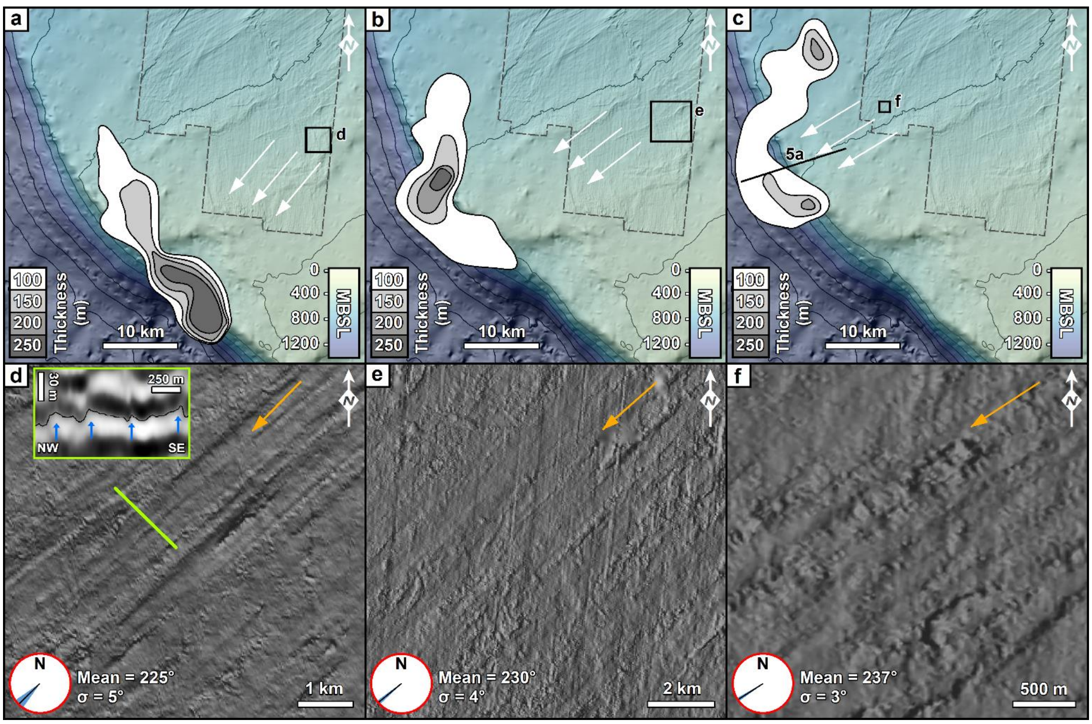

Figure 4: Buried MSGL and associated TMF thickness maps. On panels (**a**) to (**c**) the dashed grey line is the 3D seismic survey outline on the contemporary seafloor and the white arrows show the inferred ice flow direction from

the MSGL displayed as hillshade images in panels (**d**) to (**f**). Orange arrows show the inferred ice flow direction. On panel (d) the green line displays the location of the inset cross-section profile of the MSGL. Blue arrows point to the mounded features visible on the hillshade image. The red circles display average MSGL compass bearings (black line) and the standard deviation (blue fan beneath) for each panel. Location of panels (a) to (c) shown on Fig. 1.

Although the 3D seismic data do not cover the distal part of the succession, by using examples of MSGL that have been observed in 3D (Fig. 3, 4), the 2D seismic data were investigated for similar cross-sectional features. In unit A10 (~0.45-0.35 Ma) a reflection on the outer-shelf shows a similar corrugated morphology (heights of 10-15 m and widths of 200-300 m) to the MSGL pattern observed in the 3D data (Fig. 6b). This interpretation as MSGL (set 5) is less robust due to the lack of 3D data and whilst it is not possible to unequivocally rule out that these features are something else (such as iceberg scours), an interpretation of MSGL is supported by the location of these features in topset strata above the glacial unconformity that marks the top of unit A9, suggesting the presence of grounded and erosive ice on the outer shelf, conditions generally associated with MSGL formation. The final set of MSGL (set 6) is observed in unit A11 (~0.35-0 Ma) on the seafloor and has been interpreted as a grounded ice stream on the outer shelf at the LGM by Newton et al. (2017).

https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

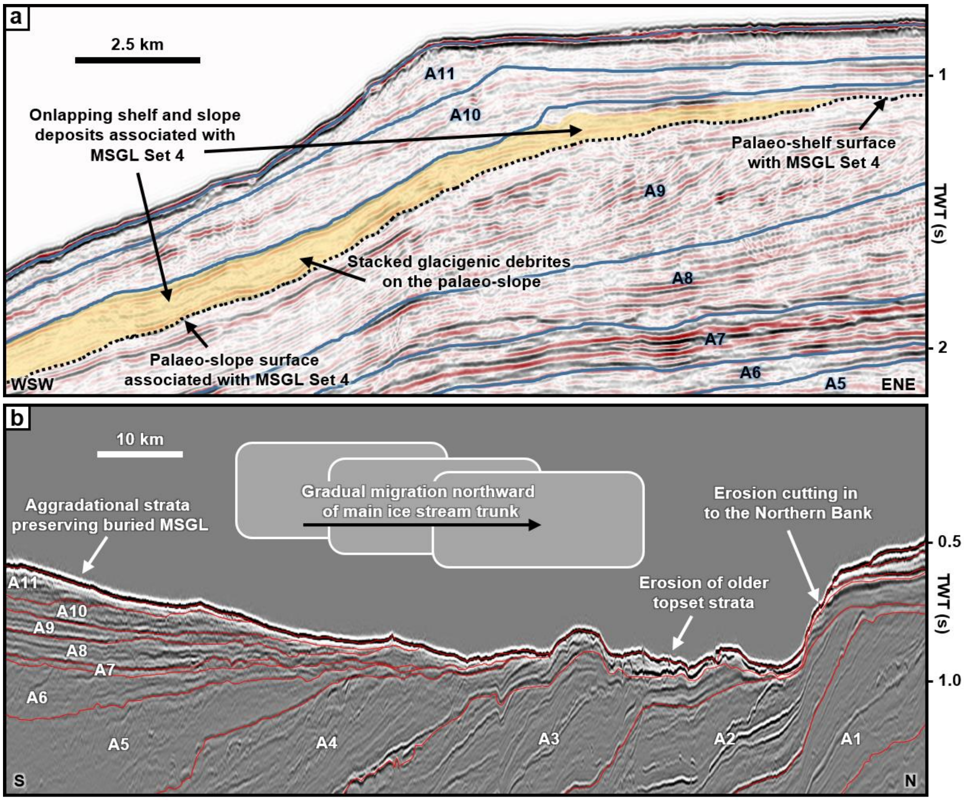

Figure 5: (**a**) Seismic cross-section showing the main glacigenic units and the palaeo-shelf surface (dotted line) where MSGL set 4 is observed. Onlapping and stacked debrite packages are interpreted to be genetically linked to deposition caused by the ice stream that formed this set of MSGL and are used as an indicator of the broad depositional patterns displayed in Fig. 4c. Line location is shown on Fig. 4c. (**b**) Interpreted seismic strike profile across the shelf showing spatially variable preservation of topset deposits associated with the main depositional units. This variable preservation is thought to relate to the gradual migration of the ice stream away from the areas of higher topography that contain the aggradational strata. This northward migration of the ice stream pathways is also reflected by the erosion of the southern flank of the Northern Bank. Location of the line is shown on Fig. 1.

5. Palaeo-ice streams

The observations of six ice streaming events (one on the seafloor, four 3D seismic buried surfaces, and one captured in the 2D seismic) provide repeated evidence for ice streams on the northwest Greenland shelf prior to, and

https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

including, the LGM. Limited chronological constraints are currently available to determine exact timings, but the available chronology suggests these features formed during a number of glacial stages after ~1.3 Ma (Knutz et al., 2019). Although no older MSGL have been imaged on palaeo-shelves captured in the available 3D seismic data, ice streams are inferred to have operated in the area prior to ~1.3 Ma, based on the large volumes of sediment delivered to the margin (Knutz et al., 2019). It is noteworthy that the first observations of MSGL occur at the onset of a major change in the depositional patterns of the Melville Bugt and Upernavik TMFs. Unit A7 was deposited when the Melville Bugt and Upernavik TMFs combined to form an elongate depocentre up to 1 km thick. During the subsequent deposition of unit A8 the TMFs separated into discrete depocentres (up to 700 m thick), signalling a possible reorganisation in ice flow in the region (Knutz et al., 2019). The reasons for this change are unresolved, but changes in depocentre migration and MSGL orientation, such as presented here, may have forced modifications in ice sheet flow on the outer shelf due to changes in accommodation brought about by the evolving submarine topography and glacigenic deposition.

Switches in ice stream pathways on continental shelves between different glacial maxima have been observed on the mid-Norwegian margin, where new cross-shelf troughs were formed through the erosive action of ice (Dowdeswell et al., 2006). In contrast to the mid-Norwegian margin, Melville Bugt does not have buried cross-shelf troughs and the observations show changes in ice stream pathways that appear to have occurred more gradually between each MSGL set but remained focused within the confines of the pre-existing trough. The longevity of the northern bank and the significant overdeepening of the inner trough (cf. Newton et al., 2017) likely provided consistent topographic steering of ice streams on the inner shelf. On the outer shelf, deposition during the preceding glacial stage likely forced gradual ice stream migration northward due to this deposition reducing the available accommodation for subsequent glacial stages. Thickness maps associated with MSGL sets 2-4 demonstrate this gradual, rather than extreme, shift in ice stream drainage pathways that is supported by 5-6° shifts in the mean orientation of each MSGL set from 225° during unit A8 time, to 237° during unit A9 (Fig. 4). This shift continued at the LGM where the majority of MSGL on the outer shelf – except for some cross-cutting related to deglaciation (Newton et al., 2017) – show a mean orientation of ~248°.

The partial preservation of the different palaeo-shelves means ice margin fanning on the outer shelf margin (i.e. a less confined topographic setting) cannot not be definitively ruled out as an explanation for differing MSGL orientations, but the observed metrics and depocentre migration provide complementary evidence that this was in response to a gradual migration of the main ice stream flow pathway – i.e. ice flow pathways gradually moved

https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

northward in a clockwise pattern from unit A8 onwards. This gradual shift northward of the main ice stream pathway and its associated erosion meant that topset deposits in the south, with each passing glacial stage, were increasingly less impacted by the ice stream erosion and therefore the landforms that they contained had a better chance of being preserved through subsequent glacial stages. This suggests that whilst the main palaeo-ice stream trunks associated with each glacial stage were accommodated within the broad confines of the trough, the fast-flowing and erosive ice did not occupy its full width (e.g. there are no MSGL present for the LGM (set 6) in the southern part of the trough). This northward migration of the main ice stream pathway is also reflected by erosion and cutting into the deposits of the northern bank (Fig. 5b). Although ice stream margin fanning or changes in upstream ice sheet controls cannot be ruled out, the gradual depocentre and MSGL migration suggests that deposition during subsequent glacial stages was sufficient to bring about small changes in flow directions and subsequent depositional patterns.

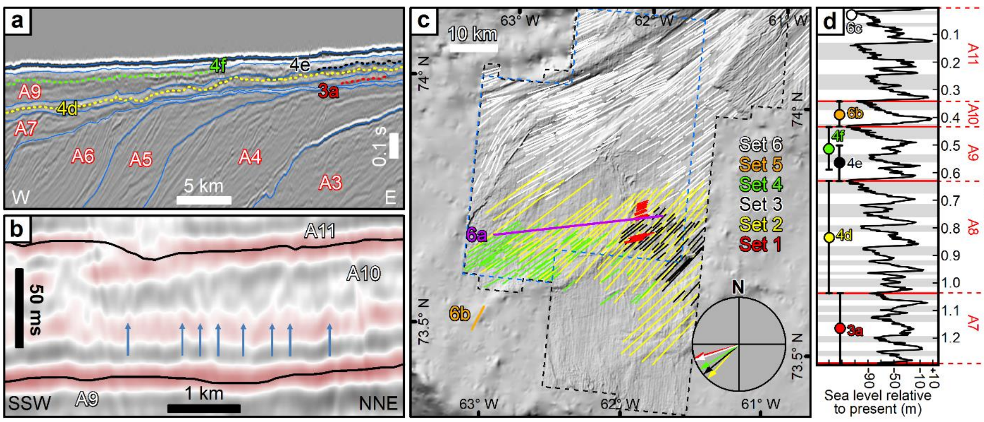

Figure 6: (**a**) Seismic profile showing the stratigraphic location of the surfaces shown in Fig. 3 and 4. The blue lines are the boundaries of the units shown on Fig. 2. The location of the line is shown on Fig. 6c. (**b**) Seismic profile from 2D seismic survey showing evidence for potential MSGL (blue arrows) in unit A10 on the outer shelf. Profile location is shown on Fig. 6c. (**c**) Digitized MSGL record from 3D seismic data. LGM record from Newton et al. (2017). The compass shows mean bearings for each set of MSGL. (**d**) Possible age range for each MSGL surface observed within the glacigenic units of Knutz et al. (2019) and compared against the global sea level record (Miller et al., 2011). Grey bands are glacial stages. Note that in all the panels, the surfaces (a), digitised MSGL (c), mean flow bearings (c), and labels (d) are colour-coded to ease cross-referencing.

In the wider context of the whole GrIS, in east Greenland, sedimentological and geophysical evidence suggest that early in the Middle Pleistocene Transition (MPT - ~1.3 Ma to 0.7 Ma) ice advanced across the shelf (Laberg et al., 2018; Pérez et al., 2019), whilst offshore southern Greenland increased IRD suggests a similar ice advance (St. John and Krissek, 2002). MPT ice sheet expansions have been documented in the Barents Sea (Mattingsdal et al., 2014), on the mid-Norwegian margin (Newton and Huuse, 2017), the North Sea (Rea et al., 2018), and in North America (Balco and Rovey, 2010), highlighting a response of all major Northern Hemisphere ice sheets to a currently unresolved climate forcing. As ice streaming in Melville Bugt continued after the MPT and through to the latest Pleistocene, some studies from lower latitude areas of west and east Greenland show reduced ice stream erosion and deposition at this time (Hofmann et al., 2016; Pérez et al., 2018), perhaps suggesting the high latitude locality of Melville Bugt or the overdeepened and bottlenecked (topographic constraints) topography of the inner trough (Newton et al., 2017) helped promote conditions favourable for ice streaming.

The MSGL record presented here provides some additional insight into the contradictory records on the longevity of the GrIS. Schaefer et al. (2016) showed that cosmogenic signatures require ice-free periods during the Pleistocene and whilst these ice-free periods need not have occurred since 1.1 Ma, ice sheet loss could have occurred during the MPT and after. Ice stream evolution has been shown to have led to rapid ice sheet changes on other ancient ice sheets (Sejrup et al., 2016), and given that ~16% of the GrIS currently drains into Melville Bugt (Rignot and Mouginot, 2012) the ice streams documented here could have contributed to major changes in ice sheet organisation and extent – indeed, the numerical model used by Schaefer et al. (2016) requires the early loss of the northwest GrIS during ice sheet collapse. Fully resolving issues like this requires numerical ice sheet models that are capable of reproducing fragmented geological evidence. For example, recent modelling exploring Pleistocene climate evolution (Willeit et al., 2019) suggests multiple ice sheet reconstructions that do not capture the ice sheet extent that has been inferred from buried landform records on many glaciated margins (e.g. Rea et al., 2018), including Melville Bugt. If these models are not able to recreate ice sheet extent, ice stream locations, and flow pathways that have been extracted from the geological record then those models will require refinement before they can be used as a tool for projecting future GrIS evolution. This underlines how geological records, such as those presented here, provide crucial empirical constraints for modelling the GrIS across multiple glacial-interglacial cycles.

https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

6. Conclusions

This study provides a seismic geomorphological analysis offshore northwest Greenland and documents, for the first time, several sets of buried MSGL anywhere on the Greenland margin. The different sets of MSGL confirm the presence of ancient fast-flowing ice streams a number of times since the onset of the Middle Pleistocene transition at ~1.3 Ma. These landform records show that grounded and fast-flowing ice advanced across the continental shelf to the palaeo-shelf edge of northwest Greenland a number of times, with each subsequent ice stream flow pathway being partly controlled by the deposits left behind by the ice streams that preceded it. This represents a first spatio-temporal insight into sediment deposition and ice flow dynamics of individual ice streams during several glacial maxima since ~1.3 Ma in Melville Bugt. These results help to further emphasise why this area of Greenland would be suitable for future ocean drilling that will help to elucidate ice sheet and climate history of the region.

Data availability

The Geological Survey of Denmark and Greenland or the authors should be contacted to discuss access to the raw seismic reflection data.

Author contribution

AMWN carried out the seismic geomorphological study, drafted the figures, and wrote the initial text. All other authors contributed to interpretation and manuscript preparation.

Competing interests

There are no competing interests to declare.

Acknowledgements

AMWN was supported by the Natural Environment Research Council (NERC - NE/K500859/1) and Cairn Energy. DRC was funded by NERC and the British Geological Survey (NE/M00578X/1). Schlumberger and ESRI are thanked for Petrel and ArcGIS software. All authors thank Cairn Energy and Shell for data and permission to publish. Brice R. Rea is thanked for criticisms that improved the paper.

References

Arndt, J. E., Jokat, W. and Dorschel, B.: The last glaciation and deglaciation of the Northeast Greenland continental shelf revealed by hydro-acoustic data, Quat. Sci. Rev., 160, 45–56, doi:10.1016/j.quascirev.2017.01.018, 2017.

Balco, G. and Rovey, C. W.: Absolute chronology for major Pleistocene advances of the laurentide ice Sheet, Geology, 38, 795–798, doi:10.1130/G30946.1, 2010.

Bennett, M. R.: Ice streams as the arteries of an ice sheet: Their mechanics, stability and significance, Earth-Science Rev., 61, 309–339, doi:10.1016/S0012-8252(02)00130-7, 2003.

Bierman, P. R., Shakun, J. D., Corbett, L. B., Zimmerman, S. R. and Rood, D. H.: A persistent and dynamic East Greenland Ice Sheet over the past 7.5 million years, Nature, 540, 256–260, doi:10.1038/nature20147, 2016.

Clark, C. D.: Mega-scale glacial lineations and cross-cutting ice-flow landforms, Earth Surf. Process. Landforms, 18, 1–29, doi:10.1002/esp.3290180102, 1993.

Clark, C. D., Tulaczyk, S. M., Stokes, C. R. and Canals, M.: A groove-ploughing theory for the production of mega-scale glacial lineations, and implications for ice-stream mechanics, J. Glaciol., 49, 240–256, doi:10.3189/172756503781830719, 2003.

Dowdeswell, J. A., Ottesen, D. and Rise, L.: Flow switching and large-scale deposition by ice streams draining former ice sheets, Geology, 34, 313–316, doi:10.1130/G22253.1, 2006.

Dowdeswell, J. A., Ottesen, D. and Rise, L.: Rates of sediment delivery from the Fennoscandian Ice Sheet through an ice age, Geology, 38, 3–6, doi:10.1130/G25523.1, 2010.

https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

Dowdeswell, J. A., Canals, M., Jakobsson, M., Todd, B. J., Dowdeswell, E. K. and Hogan, K. A.: Atlas of Submarine Glacial landforms: Modern, Quaternary and Ancient, Geological Society of London., 2016.

Funder, S., Kjeldsen, K. K., Kjær, K. H. and O Cofaigh, C.: The Greenland Ice Sheet During the Past 300,000 Years: A Review, in Developments in Quaternary Science, edited by J. Ehlers, P. L. Gibbard, and P. D. Hughes, pp. 699–713, Elsevier, Amsterdam., 2011.

Hofmann, J. C., Knutz, P. C., Nielsen, T. and Kuijpers, A.: Seismic architecture and evolution of the Disko Bay trough-mouth fan, central West Greenland margin, Quat. Sci. Rev., 147, 69–90, doi:10.1016/j.quascirev.2016.05.019, 2016.

Hogan, K. A., Ó Cofaigh, C., Jennings, A. E., Dowdeswell, J. A. and Hiemstra, J. F.: Deglaciation of a major palaeo-ice stream in Disko Trough, West Greenland, Quat. Sci. Rev., 147, 5–26, doi:10.1016/j.quascirev.2016.01.018, 2016.

Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J. A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H. W., Zarayskaya, Y., Accettella, D., Armstrong, A., Anderson, R. M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J. V., Hall, J. K., Hell, B., Hestvik, O., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S. V., Pedrosa, M. T., Travaglini, P. G. and Weatherall, P.: The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0, Geophys. Res. Lett., 39, L12609, doi:10.1029/2012GL052219, 2012.

Jennings, A. E., Walton, M. E., Ó Cofaigh, C., Kilfeather, A., Andrews, J. T., Ortiz, J. D., De Vernal, A. and Dowdeswell, J. A.: Paleoenvironments during Younger Dryas-Early Holocene retreat of the Greenland Ice Sheet from outer Disko Trough, central west Greenland, J. Quat. Sci., 29, 27–40, doi:10.1002/jqs.2652, 2014.

Joughin, I., Smith, B. E., Howat, I. M., Scambos, T. and Moon, T.: Greenland flow variability from ice-sheet-wide velocity mapping, J. Glaciol., 56, 415–430, doi:10.3189/002214310792447734, 2010.

King, E. C., Hindmarsh, R. C. A. and Stokes, C. R.: Formation of mega-scale glacial lineations observed beneath a West Antarctic ice stream, Nat. Geosci., 2(8), 585–588, doi:10.1038/ngeo581, 2009.

Knutz, P. C., Newton, A. M. W., Hopper, J. R., Huuse, M., Gregersen, U., Sheldon, E. and Dybkjær, K.: Eleven phases of Greenland Ice Sheet shelf-edge advance over the past 2.7 million years, Nat. Geosci., 2019.

https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

Laberg, J. S., Guidard, S., Mienert, J., Vorren, T. O., Haflidason, H. and Nygård, A.: Morphology and morphogenesis of a high-latitude canyon; the Andøya Canyon, Norwegian Sea, Mar. Geol., 246, 68–85, doi:10.1016/j.margeo.2007.01.009, 2007.

Laberg, J. S., Rydningen, T. A., Forwick, M. and Husum, K.: Depositional processes on the distal Scoresby Trough Mouth Fan (ODP Site 987): Implications for the Pleistocene evolution of the Scoresby Sund Sector of the Greenland Ice Sheet, Mar. Geol., 402, 51–59, doi:10.1016/j.margeo.2017.11.018, 2018.

Mattingsdal, R., Knies, J., Andreassen, K., Fabian, K., Husum, K., Grøsfjeld, K. and De Schepper, S.: A new 6Myr stratigraphic framework for the Atlantic-Arctic Gateway, Quat. Sci. Rev., 92, 170–178, doi:10.1016/j.quascirev.2013.08.022, 2014.

Mouginot, J., Rignot, E., Bjørk, A. A., van den Broeke, M., Millan, R., Morlighem, M., Noël, B., Scheuchl, B. and Wood, M.: Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018, Proc. Natl. Acad. Sci., doi:10.1073/pnas.1904242116, 2019.

Newton, A. M. W. and Huuse, M.: Late Cenozoic environmental changes along the Norwegian margin, Mar. Geol., 393, 216–244, doi:10.1016/j.margeo.2017.05.004, 2017.

Newton, A. M. W., Knutz, P. C., Huuse, M., Gannon, P., Brocklehurst, S. H., Clausen, O. R. and Gong, Y.: Ice stream reorganization and glacial retreat on the northwest Greenland shelf, Geophys. Res. Lett., 44(15), 7826–7835, doi:10.1002/2017GL073690, 2017.

Ó Cofaigh, C., Taylor, J., Dowdeswell, J. A. and Pudsey, C. J.: Palaeo-ice streams, trough mouth fans and high-latitude continental slope sedimentation, Boreas, 32, 37–55, doi:10.1080/03009480310001858, 2003.

Pérez, L. F., Nielsen, T., Knutz, P. C., Kuijpers, A. and Damm, V.: Large-scale evolution of the central-east Greenland margin: New insights to the North Atlantic glaciation history, Glob. Planet. Change, 163, 141–157, doi:10.1016/j.gloplacha.2017.12.010, 2018.

Pérez, L. F., Nielsen, T., Rasmussen, T. L. and Winsborrow, M.: Quaternary interaction of cryospheric and oceanographic processes along the central-east Greenland margin, Boreas, 48, 72–91, doi:10.1111/bor.12340, 2019.

https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

Posamentier, H. W.: Seismic Geomorphology: Imaging Elements of Depositional Systems from Shelf to Deep Basin Using 3D Seismic Data: Implications for Exploration and Development, in 3D Seismic Technology: Application to the Exploration of Sedimentary Basins, edited by R. J. Davies, J. A. Cartwright, S. A. Stewart, M. Lappin, and J. R. Underhill, pp. 11–24, Geological Society of London., 2004.

Rea, B. R., Newton, A. M. W., Lamb, R. M., Harding, R., Bigg, G. R., Rose, P., Spagnolo, M., Huuse, M., Cater, J. M. L., Archer, S., Buckley, F., Halliyeva, M., Huuse, J., Cornwell, D. G., Brocklehurst, S. H. and Howell, J. A.: Extensive marine-terminating ice sheets in Europe from 2.5 million years ago, Sci. Adv., 4(6), doi:10.1126/sciadv.aar8327, 2018.

Reyes, A. V., Carlson, A. E., Beard, B. L., Hatfield, R. G., Stoner, J. S., Winsor, K., Welke, B. and Ullman, D. J.: South Greenland ice-sheet collapse during Marine Isotope Stage 11, Nature, 510, 525–528, doi:10.1038/nature13456, 2014.

Rignot, E. and Mouginot, J.: Ice flow in Greenland for the International Polar Year 2008-2009, Geophys. Res. Lett., 39, L11501, doi:10.1029/2012GL051634, 2012.

Schaefer, J. M., Finkel, R. C., Balco, G., Alley, R. B., Caffee, M. W., Briner, J. P., Young, N. E., Gow, A. J. and Schwartz, R.: Greenland was nearly ice-free for extended periods during the Pleistocene, Nature, 540, 252–255, doi:10.1038/nature20146, 2016.

Sejrup, H. P., Clark, C. D. and Hjelstuen, B. O.: Rapid ice sheet retreat triggered by ice stream debuttressing: Evidence from the North Sea, Geology, 44, 355–358, doi:10.1130/G37652.1, 2016.

Sheldon, C., Jennings, A., Andrews, J. T., Ó Cofaigh, C., Hogan, K., Dowdeswell, J. A. and Seidenkrantz, M. S.: Ice stream retreat following the LGM and onset of the west Greenland current in Uummannaq Trough, west Greenland, Quat. Sci. Rev., 147, 27–46, doi:10.1016/j.quascirev.2016.01.019, 2016.

Slabon, P., Dorschel, B., Jokat, W., Myklebust, R., Hebbeln, D. and Gebhardt, C.: Greenland ice sheet retreat history in the northeast Baffin Bay based on high-resolution bathymetry, Quat. Sci. Rev., 154, 182–198, doi:10.1016/j.quascirev.2016.10.022, 2016.

Spagnolo, M., Clark, C. D., Ely, J. C., Stokes, C. R., Anderson, J. B., Andreassen, K., Graham, A. G. C. and King, E. C.: Size, shape and spatial arrangement of mega-scale glacial lineations from a large and diverse dataset,

https://doi.org/10.5194/tc-2019-268
Preprint. Discussion started: 28 November 2019

Earth Surf. Process. Landforms, 39(11), 1432–1448, doi:10.1002/esp.3532, 2014.

Spagnolo, M., Phillips, E., Piotrowski, J. A., Rea, B. R., Clark, C. D., Stokes, C. R., Carr, S. J., Ely, J. C., Ribolini, A., Wysota, W. and Szuman, I.: Ice stream motion facilitated by a shallow-deforming and accreting bed, Nat. Commun., 7, 10723, doi:10.1038/ncomms10723, 2016.

St. John, K. E. K. and Krissek, L. A.: The late Miocene to Pleistocene ice-rafting history of Southeast Greenland, Boreas, 31, 28–35, doi:10.1111/j.1502-3885.2002.tb01053.x, 2002.

Vasskog, K., Langebroek, P. M., Andrews, J. T., Nilsen, J. E. Ø. and Nesje, A.: The Greenland Ice Sheet during the last glacial cycle: Current ice loss and contribution to sea-level rise from a palaeoclimatic perspective, Earth-Science Rev., 150, 45–67, doi:10.1016/j.earscirev.2015.07.006, 2015.

Vorren, T. O. and Laberg, J. S.: Trough mouth fans - Palaeoclimate and ice-sheet monitors, Quat. Sci. Rev., 16, 865–881, doi:10.1016/S0277-3791(97)00003-6, 1997.

Vorren, T. O., Lebesbye, E., Andreassen, K. and Larsen, K. B.: Glacigenic sediments on a passive continental margin as exemplified by the Barents Sea, Mar. Geol., 85(2–4), 251–272, doi:10.1016/0025-3227(89)90156-4, 1989.

Willeit, M., Ganopolski, A., Calov, R. and Brovkin, V.: Mid-Pleistocene transition in glacial cycles explained by declining CO_2 and regolith removal, Sci. Adv., 5, eaav7337, doi:10.1126/sciadv.aav7337, 2019.