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~~ [1]Department 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~~six sets of ~~buried~~ landforms (five buried and one on the seafloor) have been interpreted as mega-scale glacial lineations (MSGL) ~~and this record provides~~that provide evidence for extensive ice streams on outer palaeo-shelves. A gradual change in mean MSGL orientation and associated depocentres through time suggests that the palaeo-ice flow and sediment transport pathways migrated in response to the evolving submarine topography~~.~~ through each glacial-interglacial cycle. The stratigraphy and available chronology ~~shows~~show 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~~MSGL record in Melville Bugt ~~were as extensive as elsewhere in Greenland~~ suggests that during ~~this transition, but, by the glacial stages of~~ the Middle and Late Pleistocene, ~~the~~ ice streams ~~in Melville Bugt appear~~continued 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~~be active and extensive ~~than elsewhere in Greenland.~~on the shelf during glacial stages. 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.

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~~, the role and evolution through time of its ice streams~~)~~, and an understanding of how ~~it~~the ice sheet setting as a whole may have responded to ~~past~~ warming during past glacial-interglacial transitions – e.g. Marine Isotope Stage 12 to 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.~~Typically, this involves using fragmented geological records to constrain or test numerical ice sheet models that attempt to map spatiotemporal changes in ice sheet extent and the dominant processes as the climate evolves across multiple glacial-interglacial cycles (Solgaard et al., 2011; Tan et al., 2018). Improving and building upon that fragmented geological record is, therefore, of considerable importance for helping to improve and calibrate these models – i.e. if models can accurately reconstruct the past, then we can have more confidence in what they project for the future.

~~Much~~Although 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 the west ~~Greenland~~ and the Kangerlussuaq, Westwind, and Norske Troughs in the east and northeast~~, where~~ of Greenland, that have been surveyed. Using geophysical data and shallow marine cores these 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 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~~Whilst ice streams are thought to have been present in Melville Bugt since ~2.7 Ma (Knutz et al., 2019), these landforms provide new, direct, and detailed evidence of flow pathways for a number of glacial advances onto the outer shelf of Melville Bugt since ~1.3 Ma.

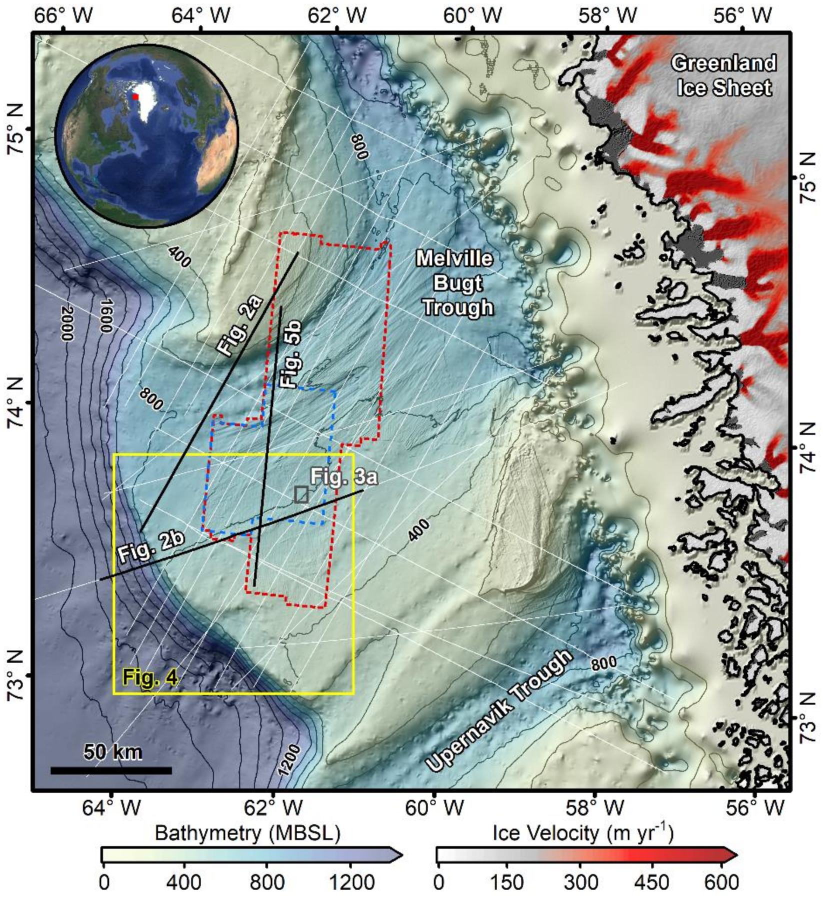

Figure 1: Seabed morphology and ice-flow velocity around the study area. The grey bathymetric contours are every 200 m and the blue/red dashed lines ~~shows~~show the outline of the 3D seismic surveys (blue is a high resolution sub-crop of the original data that was reprocessed~~ by industry to improve 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 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)~~(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~~thought to date to the LGM have been observed on the present-day seafloor of the Melville Bugt study area (Fig. 1) and typically measure 4–6 km long, 100–200 m wide, and 10–20 m high (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. ~~. The MSGL on the outermost shelf show the ice stream reached the shelf edge in Melville Bugt, before retreating and experiencing changes in ice flow pathways, as is indicated by cross-cutting MSGL on the middle shelf (Newton et al., 2017).~~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~~.~~ (Knutz et al., 2019). 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).~~(Christ et al., 2020; Knutz et al., 2019). These dates suggest that whilst accumulation likely varied over orbital and sub-orbital timescales, over ~~timescales~~periods 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.

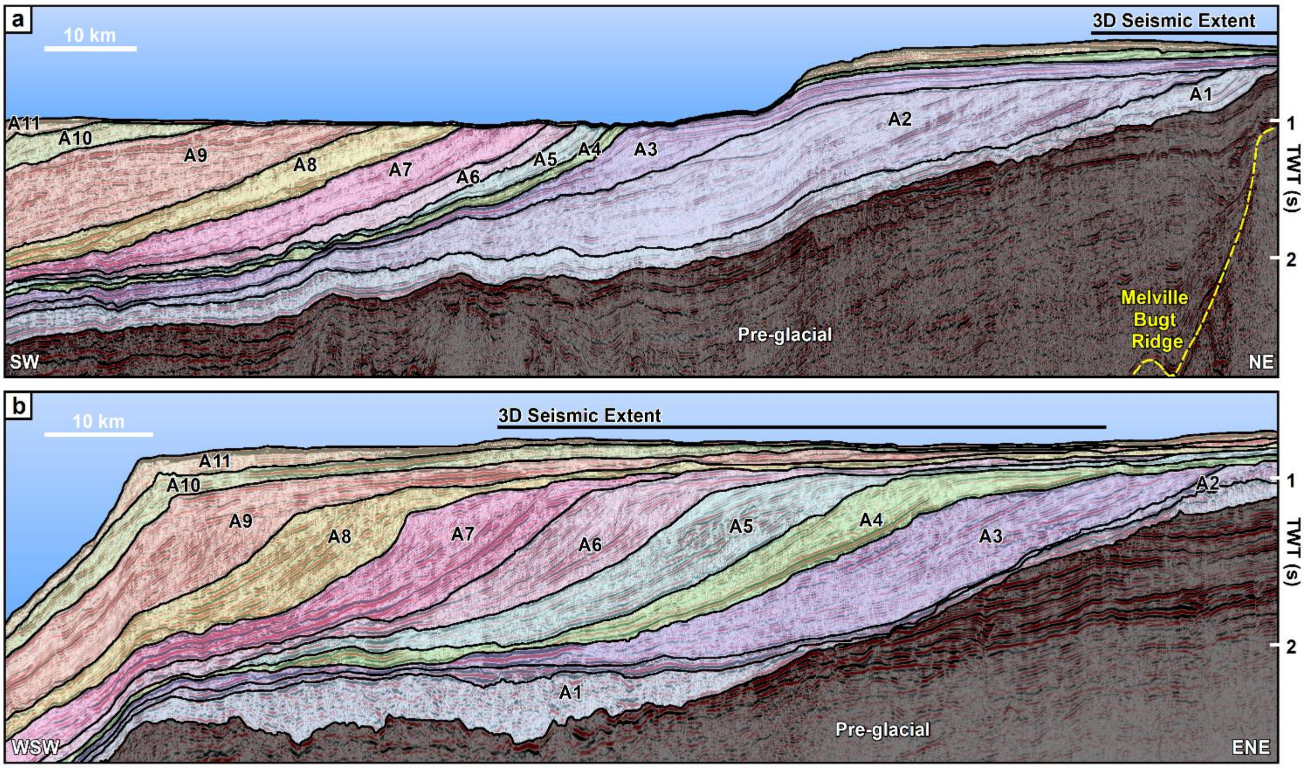

Figure 2: Seismic profiles through the glacigenic succession. The fan comprises 11 seismic stratigraphic units bounded by glacigenic unconformities formed since ~2.7 Ma (Knutz et al., 2019). The tentative chronology from Knutz et al. (2019) suggests that units ~~A8 and~~ A7-A9 likely cover much of the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

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).~~ i.e. buried palaeo-seafloors maps. It is important to note that unlike traditional seafloor studies carried out on bathymetric data, these palaeo-seafloor surfaces will have subsided and compacted since being buried. This means that landform thicknesses likely represent a minimum estimate of their original morphology. 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 predominant area~~can be used to document where sediments have been eroded ~~by the ice sheet were~~and 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 imaged in the 3D data 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 (e.g. Andreassen et al., 2007; Dowdeswell et al., 2006; Montelli et al., 2017; Rea et al., 2018).

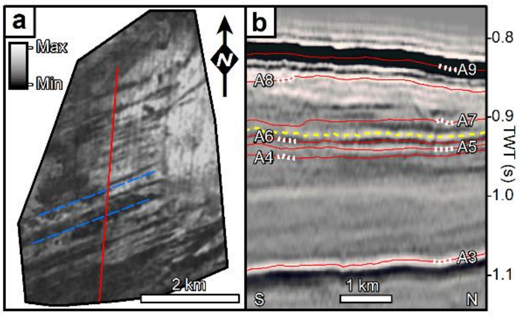

Figure 3: (**a**) The oldest example of mega-scale glacial lineations (blue dashed lines) displayed as an RMS image observed from 3D seismic reflection data and within unit A7 – the yellow dashed line on (b). The colour bar shows the maximum and minimum RMS values. Note that this surface is only partially 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). Interpreted and uninterpreted seismic profiles are provided as supplementary material.

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)~~(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).

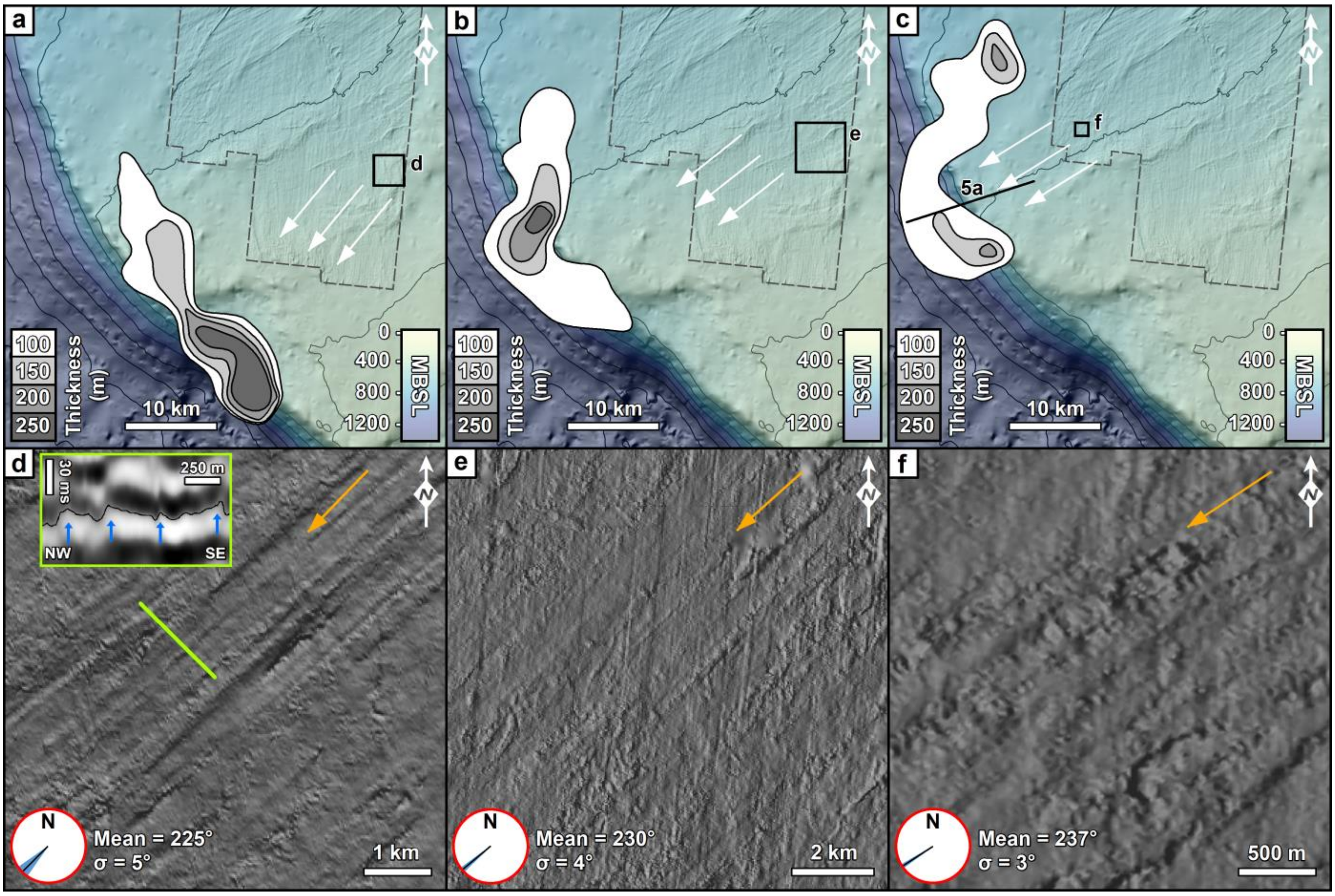

Figure 4: Buried MSGL and associated TMF thickness maps. On panels (**a**) to (**c**) the dashed grey line is the 3D seismic survey outline on the contemporary seafloor and the white arrows show the inferred ice flow direction from the MSGL displayed as hillshade images in panels (**d**) to (**f**). 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).~~(2017). These MSGL show cross-cutting evidence that allow for changes in ice flow patterns to be deduced. The oldest MSGL on the seafloor suggest an ice flow towards the west-southwest that is parallel to the axis of the trough, whilst the younger MSGL (i.e. those which cross-cut the older MSGL) show an ice flow toward the south-southwest, suggesting a change in ice flow during deglaciation (Newton et al., 2017).

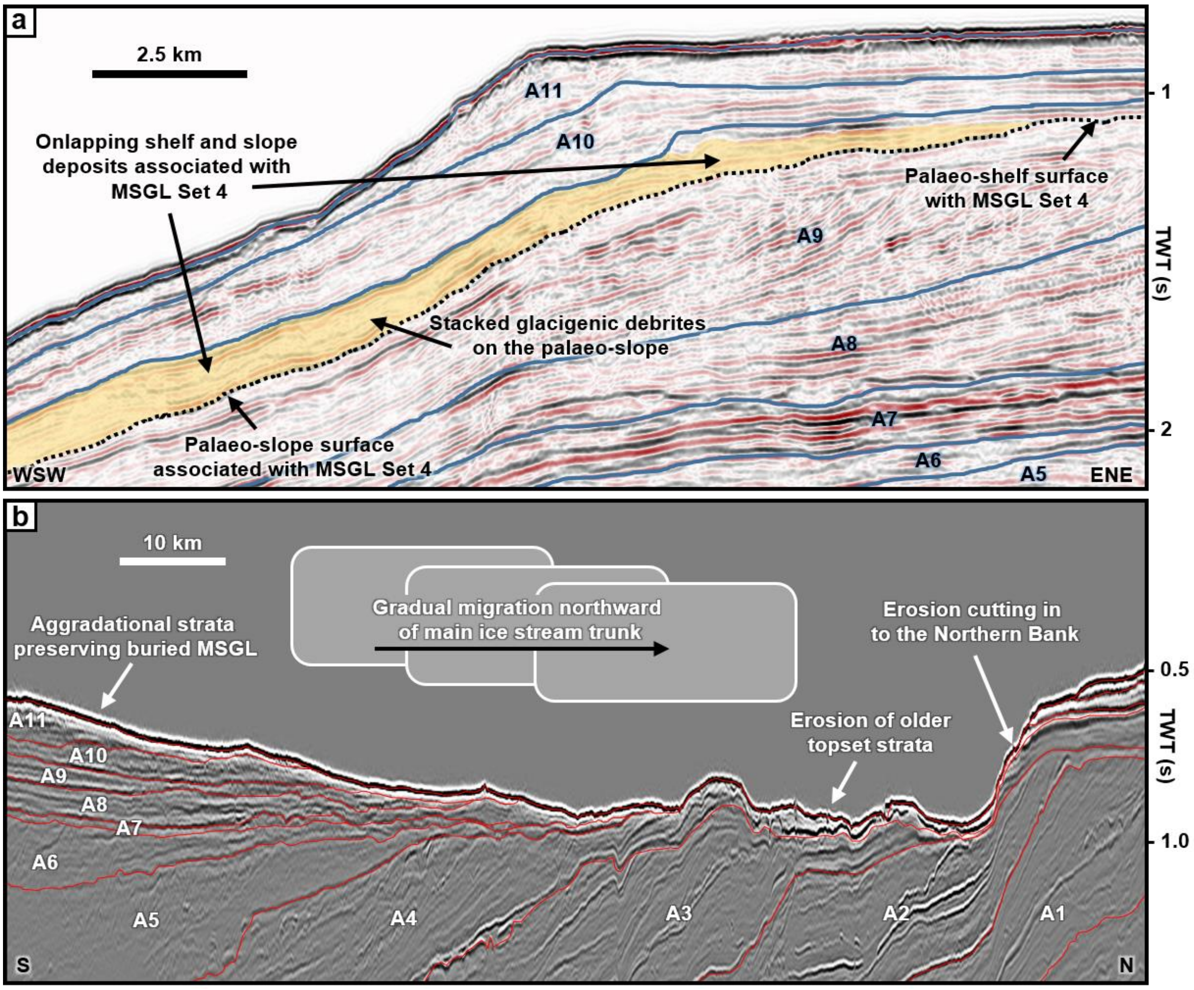

Figure 5: (**a**) Seismic cross-section showing the main glacigenic units and the palaeo-shelf surface (dotted line) where MSGL set 4 is observed. Onlapping and stacked debrite packages are interpreted to be genetically linked to deposition caused by the ice stream that formed this set of MSGL and are 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. Interpreted and uninterpreted seismic profiles are provided as supplementary material.

5. Palaeo-ice streams

The ~~observations~~previous lack of 3D seismic data coverage means that ice stream landforms have not been observed for glacials preceding the LGM, meaning that information on past ice flow patterns has relied upon broad inferences from depocentre locations – i.e. areas where large volumes of sediment are associated with the general pathway of ice streams. ~~six ice streaming events~~ Using these new data to document six sets of ice stream landforms (one on the seafloor, four 3D seismic buried surfaces, and one captured in the 2D seismic~~)~~), they provide ~~repeated~~ evidence for multiple ice ~~streams~~streaming events on the northwest Greenland shelf prior to, and 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, the available data in Melville Bugt does not ~~have~~show evidence of buried cross-shelf troughs~~ and the~~. 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~~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 northward in a clockwise pattern from unit A8 onwards~~. This~~ (~1 Ma). The 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~~The Melville Bugt Trough is the widest in Greenland (Newton et al., 2017) and it is possible that the preservation of these topsets is a consequence of this. The preservation 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 most 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~~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.~~ may have been sufficient to bring about small changes in flow directions and subsequent depositional patterns. Future ice sheet modelling can contribute to this discussion by exploring whether ice volume over northern Greenland would have been sufficient to maintain ice flux if the ice streams occupied the full width of the Melville Bugt Trough. To a lesser extent, it is possible that the Melville Bugt Ridge, an underlying tectonic structure which has previously generated accommodation in the southern part of the basin through differential subsidence (Cox et al., 2020; Knutz et al., 2019), could have contributed to reducing potential erosion of aggradational topsets by increasing palaeo-water depths.

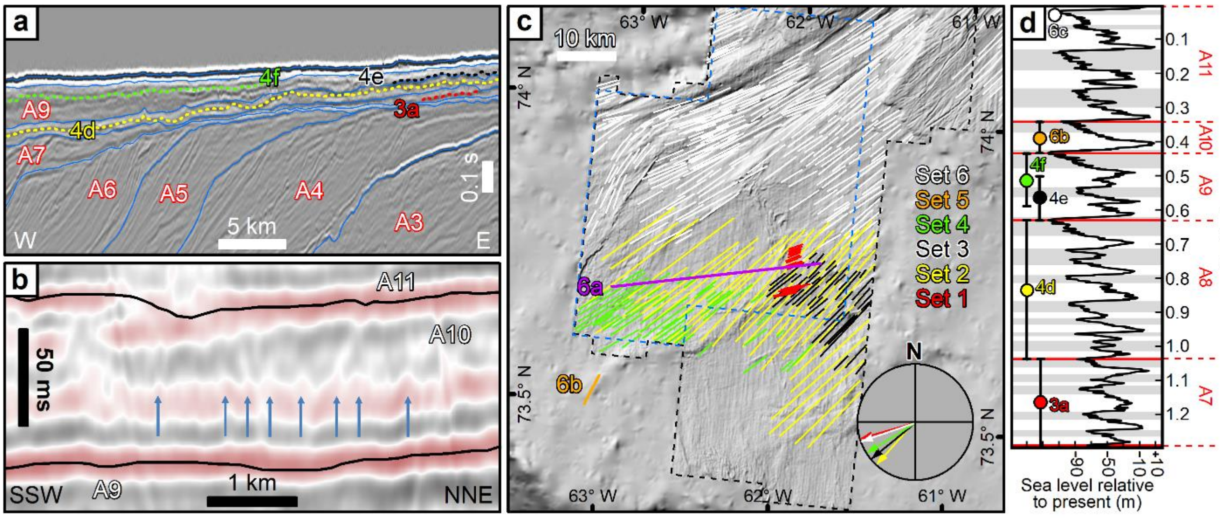

Figure 6: (**a**) Seismic profile showing the stratigraphic location of the surfaces shown in Fig. 3 and 4. The blue lines are the boundaries of the units shown on Fig. 2. The location of the line is shown on Fig. 6c. (**b**) Seismic profile from 2D seismic survey showing evidence for potential MSGL (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 the mean bearings for each set of MSGL. (**d**) Possible age range for each MSGL ~~surfaces~~surfaces 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. Interpreted and uninterpreted seismic profiles are provided as supplementary material.

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~~geometry 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~~These potential discrepancies underline how geological records, such as those presented here, provide crucial empirical constraints for modelling the GrIS across multiple glacial-interglacial cycles.

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~~Rea, Lara F. Perez, an anonymous reviewer, and the editor are thanked for helpful comments and handling of the manuscript.

References

Andreassen, K., Ødegaard, C. M. and Rafaelsen, B.: Imprints of former ice streams, imaged and interpreted using industry three-dimensional seismic data from the south-western Barents Sea, in Seismic geomorphology: applications to hydrocarbon exploration and production, edited by R. J. Davies, H. W. Posamentier, L. W. Wood, and J. A. Cartwright, pp. 151–169, Geological Society Special Publication., 2007.

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.

Christ, A. J., Bierman, P. R., Knutz, P. C., Corbett, L. B., Fosdick, J. C., Thomas, E. K., Cowling, O. C., Hidy, A. J. and Caffee, M. W.: The Northwestern Greenland Ice Sheet During The Early Pleistocene Was Similar To Today, Geophys. Res. Lett., 47(1), doi:10.1029/2019GL085176, 2020.

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.

Cox, D. R., Huuse, M., Newton, A. M. W., Gannon, P. and Clayburn, J. A. P.: Slip Sliding Away: Enigma of Large Sandy Blocks within a Gas Bearing Mass Transport Deposit, Offshore NW Greenland, Am. Assoc. Pet.

Geol. Bull., 104(5), 1011–1044, doi:10.1306/10031919011, 2020.

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.

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.

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.

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.

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.

Montelli, A., Dowdeswell, J. A., Ottesen, D. and Johansen, S. E.: Ice-sheet dynamics through the Quaternary on the mid-Norwegian continental margin inferred from 3D seismic data, Mar. Pet. Geol., 80, 228–242, doi:10.1016/j.marpetgeo.2016.12.002, 2017.

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.

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.

Solgaard, A. M., Reeh, N., Japsen, P. and Nielsen, T.: Snapshots of the Greenland ice sheet configuration in the Pliocene to early Pleistocene, J. Glaciol., 57(205), 871–880, doi:10.3189/002214311798043816, 2011.

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, 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.

Tan, N., Ladant, J. B., Ramstein, G., Dumas, C., Bachem, P. and Jansen, E.: Dynamic Greenland ice sheet driven by pCO2 variations across the Pliocene Pleistocene transition, Nat. Commun., 9, 4755, doi:10.1038/s41467-018-07206-w, 2018.

~~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.

Response to reviewers

The authors are grateful to the editor and reviewers for their helpful comments. All comments have been acted upon and the changes made as suggested.

Editor – Dr. Pippa Whitehouse

I would like to thank both reviewers for their constructive comments on this manuscript and also the authors for posting their response to the reviewers' comments.

In their response, the authors outline the steps that they propose to take to address all the main points raised by the reviewers. I request that the authors consider two additional points as they prepare a revised version of their manuscript (the first is taken from my original access review):

- The authors partly motivate their study by referring to ongoing discussions about the timing and extent of ice sheet minima during the Pleistocene. However, given that this study presents evidence relating to ice sheet maxima, the link is a little weak. The desire to provide more-complete geological evidence to test ice-sheet model reconstructions is well posed, but you may want to consider whether being able to reproduce ice sheet behaviour during a glacial period automatically qualifies an ice sheet model as being suitable for projecting future Greenland Ice Sheet change.

  Response: The editor has raised a fair point about this linkage and we have modified the text to make the link clearer. Our thinking behind this justification is that these snapshots provide a test for how accurately numerical ice sheet models recreate the past. If they are able to reproduce the observations for glacial maxima (such as ours), then we can, perhaps, have more confidence that the underlying physics contained within these models is a good representation of reality. Therefore, when these models are used to explore glacial minima we can have more faith in their outputs. An additional point, which is in the discussion section, relates to how ice streams at glacial maxima can have a significant bearing on how ice sheets retreat during the transition to minima (the role of ice streams in the North Sea being a good example). So we believe the link is justifiable and have made the text in the opening paragraph clearer to reflect this.

- Please ensure that, where necessary, statements are suitably supported by references.

  Response: All locations suggested by the reviewers that would benefit from additional references have had them added.

In general, both reviews are positive, and I therefore encourage you to submit a revised manuscript that addresses the points mentioned above and in the individual reviews.

Kind regards,

Pippa Whitehouse

Reviewer #1 – Dr. Lara Perez

Dear Editor and Authors, It has been a pleasure review your manuscript ‘Repeated ice streaming on the northwest Greenland shelf since the onset of the Middle Pleistocene Transition’. I find the manuscript in a very good shape and ready for publication after minor revisions. This manuscript constitutes an important contribution to our understanding of glacial-related systems. In addition, future ice sheet models can take advantage of the insights provided here.

Response: The authors would like to thank Dr. Lara Perez for her insights and helpful comments that will improve the readability of our manuscript and its robustness. We also thankful to Dr. Perez for the quick turnaround of the review.

My main concern is regarding the consideration of the seismic horizon gridded maps as palaeo-seafloor maps. Even though, we make this extrapolation often, it should be mentioned in the manuscript that the maps of the palaeo-surfaces presented have not been backstripped or decompacted. Therefore, variations with respect the original morphology of the palaeo-seafloor are expected.

Response: Important point and we have added this narrative in as suggested.

In addition to this, I would appreciate to see the seismic profiles and maps without the overlapped interpretation (e.g. Fig. 2, 3, 5 and 6). Perhaps the same sections of the profiles can be included as supplementary material that the reader can check if needed.

Response: Very happy to include supplementary material with the revised version showing the un-interpreted and interpreted seismic profiles.

Finally, I have a few minor suggestions that can perhaps contribute to the improvement of the manuscript.

Line 12: They are actually 6 sets of landforms considering the ones of the seafloor previously described. I suggest to rephrase this sentence to include them all.

Response: Changed as suggested.

Line 30: Here and elsewhere you include important information in brackets. I suggest to limit the brackets and include these statements within the main text.

Response: Changed as suggested.

Line 33: I know there are many examples, but could you give a couple of main references in case the reader wants to check other works?

Response: A couple of references referring to the issues of piecemeal geological/glacial reconstruction have been added.

Lines 35 to 41: This sentence is long and difficult. Could you split the information here?

Response: Agreed. Changed as suggested.

Line55: How this fit with Knutz et al., 2019 and the ice advance at aprox. 2.3 Ma?

Response: Important point. These new results do not suggest ice advance from Knutz et al. (2019) is wrong, but instead build upon that by adding confidence to some of the interpretations by providing direct and definitive evidence of ice stream landforms. Text has been clarified to make sure this is clear.

Lines 71 to 73: Perhaps this part fits better in the Introduction section feeding the discussion regarding the lack of previous evidences. Here you can develop further (2-3 sentences) the description of the seafloor MSGL which can become more important in the discussion regarding the change in time of the MSGL patterns.

Response: Good suggestion. Implemented as suggested with some extra description of the seafloor MSGL.

Line 77: Knutz et al., 2019. There are any previous references on this?

Response: Reference to key study added in as suggested.

Line 96: Please clarify that the surface maps have not been backstripped or decompacted and these processes can have an important impact in the original morphology, particularly on the deepest sections.

Response: Clarified as suggested.

Lines 102 to 103: This is close to interpretation.

Response: Edited to make this clearer.

Line 105: It would be very interesting to have a more accurate age model. Perhaps, the future drilling proposals help on this.

Response: Agreed that the age model is a key issue and is something we explored refining in a number of ways by trying to sync the landform records with other proximal ODP/IODP records with good dating chronologies. However, whilst this is potentially insightful it is not robust enough to refine the age model confidently so we elected not to include this (also based on comments at AGU from colleagues that raised similar discussions). Not sure if a text edit was required or if this was just a general comment.

Lines 113 to 114: This is also interpretation. Can be somehow moved to the discussion, so you keep here plain description?

Response: Fair point. Though we have written this section as a Description-Interpretation section as that helps prevent repetition of how descriptions inform the interpretation, which we thought was preferable for a short paper like this. We would prefer to keep it as is, but if the reviewer would like that changed then we will be happy to discuss.

Line 115: e.g. There are more works focus on MSGL.

Response: Other example references as suggested.

Line 165: Newton et al. A short description of the seafloor MSGL should be included in this work too.

Response: Agreed. Added as suggested.

Line 193: cannot not?

Response: Typo and corrected.

Line 196: (1 Ma) onwards. Add the age information.

Response: Agreed. Edited as suggested.

Reviewer #2 – anonymous

It has been a pleasure to read this very well written manuscript. I am not a geophysicist, but I find the presentation of the geophysical data and the interpretations of the data to be very logical and understandable. The authors do a good job of outlining why this unusual record of multiple periods of ice streaming to the palaeo shelf edge is important and what its implications are.

Response: We are grateful to the reviewer for their comments and have made all the required edits. We also thank them for their quick turnaround of the review.

I have only one complaint. Given how unusual it is to have preservation of aggradational topset strata and given the paucity of 3-D seismic data around Greenland (I presume it is not abundant), how do we know how extensive ice streams were elsewhere? In the abstract, but not in the conclusions, you state: 'This suggests that the ice streams that occupied Melville 21 Bugt during the Middle and Late Pleistocene were more active and extensive than elsewhere in Greenland.' I think it is less presumptive and likely more correct to state that these have not been observed elsewhere around Greenland. If other areas of the palaeo shelf had 3-D seismics and aggradational topset strata, then perhaps one would find that Melville Bugt is not the only area where ice advanced multiple times to the palaeo shelf edge. As you state, the record of past glacier ice extent is fragmentary. You have found a very informative fragment and even better, you can correlate your unusual preserved shelf strata to slope deposits (Knutz. Etal.,2019). I think it is more likely than not that many parts of the Greenland shelf had extensive ice at the same times as shown by the Melville Bugt record. Modeling might actually show what type of configuration of the ice sheet is likely and where/when more of these deposits might be found, guided by your observations. I think the conclusions are well written and would be a good model for revising the abstract. The unusual preservation of topset beds is interesting. Why is there is accommodation space in Melville Bugt. You say it is because the ice streams are not occupying the whole trough and so not eroding previous sediments. Did I understand that correctly. Is Melville Bugt unusually wide compared to other troughs? It looks like it is wider than most.

Response: Fair point. This interpretation had been based on longer geological core records that have been published from elsewhere on the margin, but our writing clearly needs a little refinement to make sure it is clear what we mean. Abstract text has been modified as suggested and we have left this component of comparisons for just the discussion section, as with the stated limitation on data availability it is an observation that carries important caveats that is a discussion point, rather than something for the abstract. Regarding the second point about the available accommodation, this is a good point about its width. The reviewer's explanation is correct and we have added a short narrative that helps to make the thinking clearer on this point as to the potential reasons why aggradational topsets have been preserved. This edit should clarify our current understanding of why we think the aggradational topsets have been preserved.

A couple of minor comments:

P9 line 166...delete repeated ... and say multiple steaming events. 193...cannot not. Double negative or needs editing?

Response: Rogue "not". Edits made as suggested.

199 and another example Line 241 and other places in the manuscript. Unattended this. Try to add what ‘this’ is each time, just as you did in line 196, where you say ‘this gradual shift’. It will make the writing even more clear.

Response: Great point on writing style, edited as suggested to improve clarity.