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Short communication

The geomorphic record of marine-based ice dome decay: Final collapse of the Barents Sea ice sheet

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ABSTRACT

New high-resolution geophysical data acquired from eastern Storbanken in the central Barents Sea allow reconstruction of the flow of marine-based ice dome during the final stages of ice-sheet decay. Ice-marginal and subglacial landforms show diverging and quasi-radial grounding-line retreat patterns, implying that an isolated, dynamic, shrinking ice dome was centred at ~77° N 40° E on eastern Storbanken prior to final marine-based ice-sheet collapse. This geomorphological reconstruction contrasts with previous numerical and observational models that infer a northward-migrating ice dome or crest that extended longitudinally from Svalbard to Franz-Josef Land prior to its eventual demise. Our results provide an important past analogue for late-stage decay of marine ice domes, as well as robust empirical constraints that can be used to calibrate numerical models simulating the behaviour of marine-based ice sheets in a warming environment.

1. Introduction

Marine-based ice sheets (i.e., those grounded predominately below sea level) are particularly vulnerable to ocean forcing and non-linear mass loss. However, the lack of observations relating to the millennial-scale grounding-line dynamics of present-day marine-based ice masses, such as that in West Antarctica, limit our understanding of long-term marine ice-sheet evolution and associated sea-level change (e.g., Joughin and Alley, 2011; Patton et al., 2015). The Barents Sea Ice Sheet (BSIS), that covered over ~1,500,000 km^2 of the continental shelf of the northern Eurasian Arctic during the late Weichselian glaciation, provides a direct palaeo—analogue for the long-term growth and decay of a marine-based ice sheet.

Previous investigations of seafloor sedimentary records in the western Barents Sea have documented a range of past grounding-line reorganisations and a palimpsest of complex ice-flow sets (e.g., Dowdeswell et al., 2010; Winsborrow et al., 2010; Bjarnadóttir et al., 2014; Hughes et al., 2016). Recent work by Sejrup et al. (2022) compiled vast multibeam and acoustic profiling datasets with available dated sediment cores, showing that disintegration of the western sector of the BSIS began between 17 and 15 ka (Fig. 1), when major fast-flowing corridors of ice, such as Bjørnøyrenna ice stream, collapsed leaving an ice saddle occupying the relatively shallow areas of the central and northern Barents Sea (e.g., Bjarnadóttir et al., 2014; Hughes et al., 2016). Both numerical models and chronologically controlled empirical reconstructions suggest that, between the warming Bølling transition ~14 ka and the onset of the colder Younger Dryas ~13 ka, the remnants of the BSIS had become confined to islands and shallow banks between eastern Svalbard and Franz Josef Land (e.g., Patton et al., 2017; Brendryen et al., 2020). However, these reconstructions are based largely on data collected from the Norwegian sector of the Barents Sea (e.g., Bjarnadóttir et al., 2014; Sejrup et al., 2022), whereas huge

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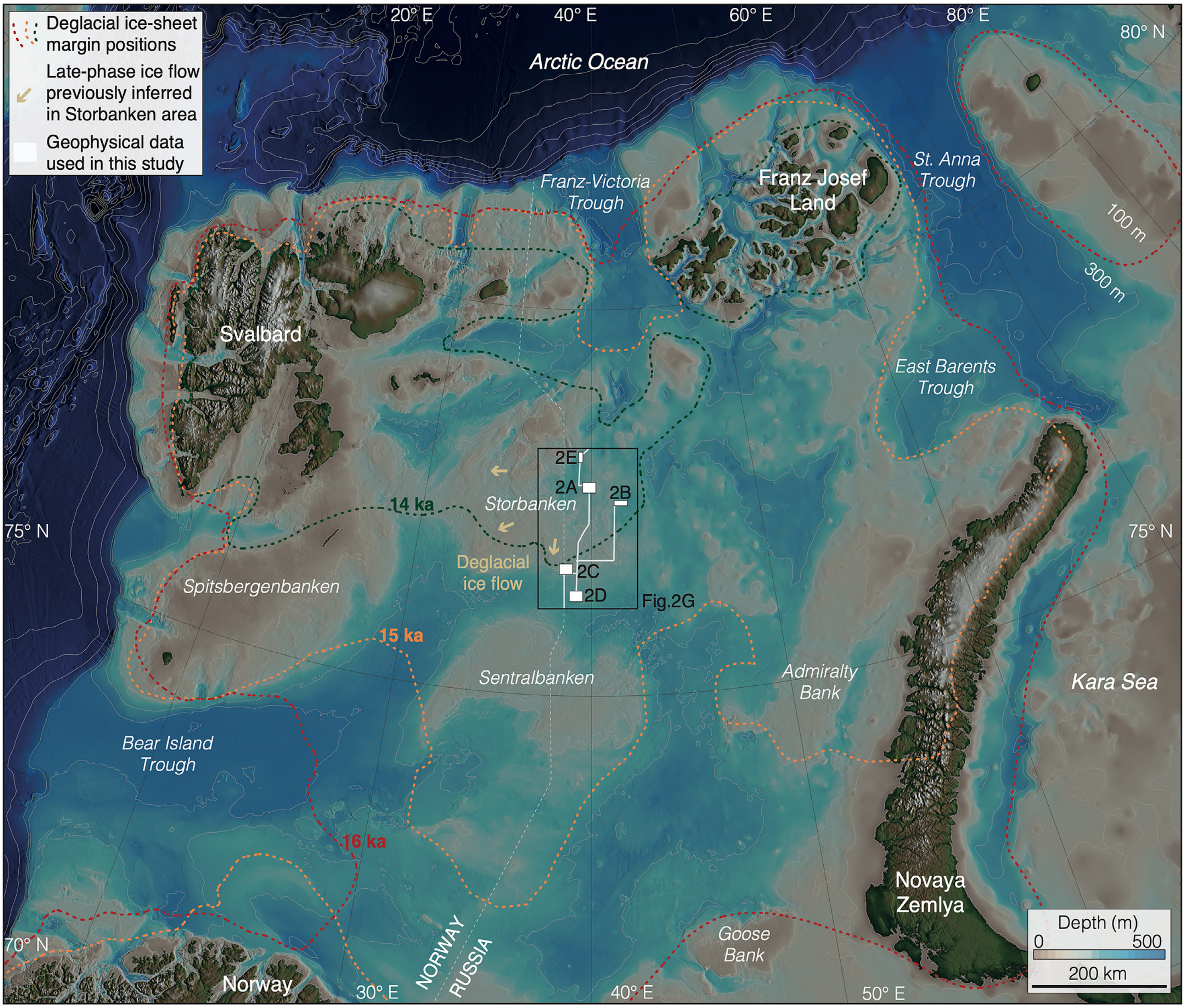

Fig. 1. Barents Sea regional bathymetry from International Bathymetric Chart of the Arctic Ocean (IBCAO), v. 4.0 (Jakobsson et al., 2020). White boxes and lines show locations of high-resolution multibeam echo-sounding data and shallow acoustic sub-bottom profiles (Fig. 2). Yellow arrows indicate direction of ice retreat during deglaciation, inferred from distribution of ice marginal features reported in existing geomorphological reconstructions in Storbanken area (Bjarnadóttir et al., 2014; Jakobsson et al., 2014; Patton et al., 2015; Newton and Huuse, 2017; Sejrup et al., 2022).

parts of the seafloor to the east, where some of the major ice domes were located prior to collapse, remain very poorly known (Fig. 1).

The notable lack of observations from the eastern Barents Sea preclude accurate inferences about the configuration of major ice domes and divides during late Weichselian deglaciation - information critical for testing and tuning ice-sheet numerical models of marine-based ice-sheet decay. In September 2021, the international TTR (“Training-through-Research”) expedition to the central eastern Barents Sea was able to access and collect new geophysical datasets at 150–280 m water depths across hitherto data-sparse eastern Storbanken area of 3500 km^2, allowing the first observation-based reconstruction of the form and flow of the BSIS in the central eastern Barents Sea prior to its final decay ~14 ka ago.

2. Methods

Multibeam bathymetry and sub-bottom profiler data were collected during TTR-20 cruise on *R/V Akademik Nikolaj Strakhov* in a study area located to the west of the TTR-19 expedition site (Dowdeswell et al., 2021). The on-board multibeam echo-sounder was a Reson SeaBat 7150 (12 kHz, 256 beams, 1.5° by 1.5° configuration). A Reson SVP70 velocity probe was used for calibration of sound velocity in seawater. A hull-mounted EdgeTech 3300 4.2 kHz penetration echo-sounder was used to collect sub-bottom acoustic data along a series of profiles, over 1000 km long in total, across the study area (Fig. 1). In this paper, we illustrate five large blocks of multibeam data connected by continuous acoustic profiles and bathymetric surveys along the acquisition tracks (Fig. 2). Data were

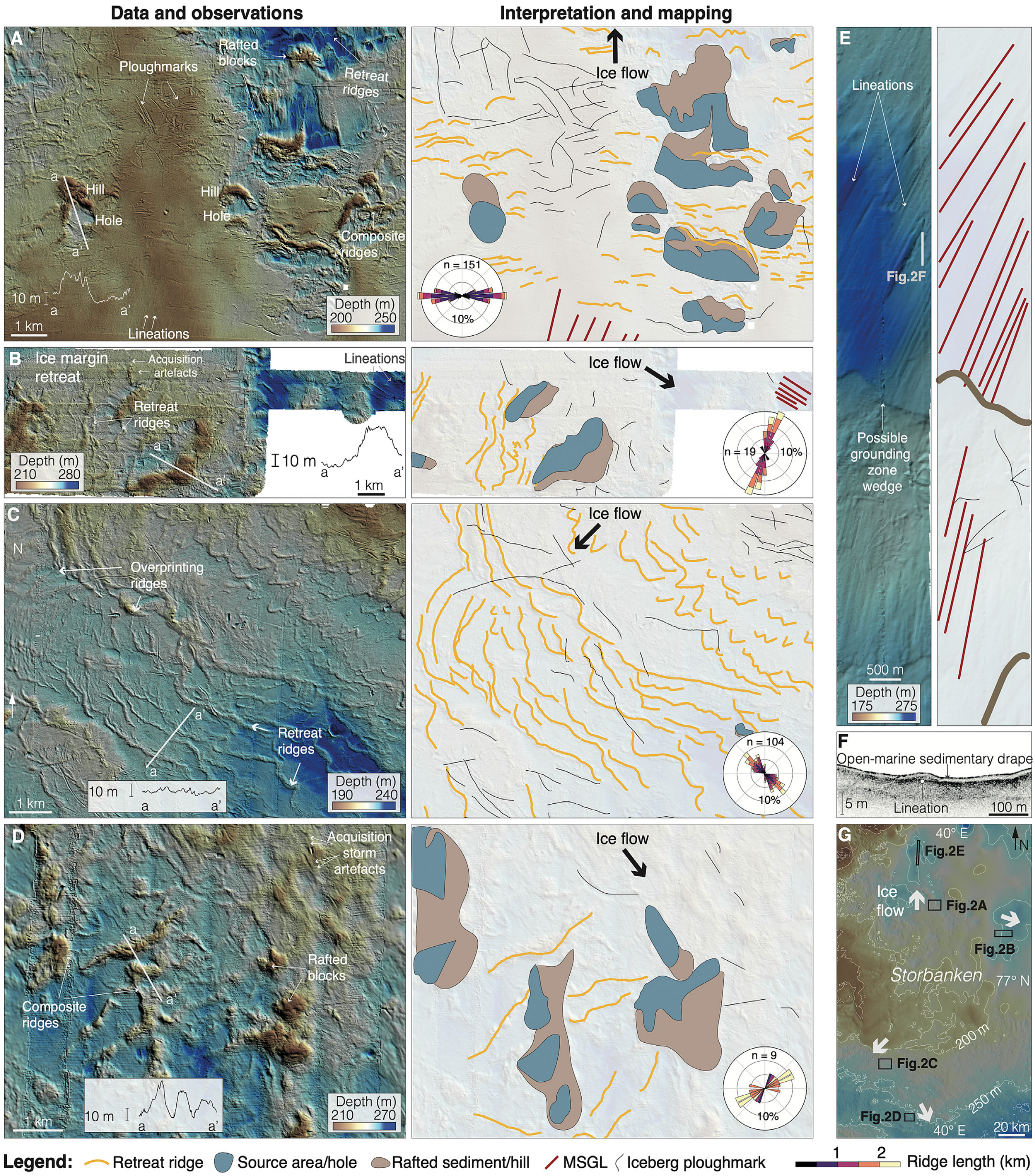

Fig. 2. Examples of submarine glacial landforms mapped on eastern Storbanken from multibeam data (Fig. 1). A–E: High-resolution bathymetry data (left panel) and geomorphic maps of the same area (right panel). A: Seafloor morphology in the north of the study area, showing submarine glacial landforms diagnostic of past ice-flow direction, including retreat ridges and a series of glacitectonic hill-hole pairs (pointing to a generally northern direction of ice flow). B: Multibeam bathymetry of the seafloor ~40 km to the southeast of the area shown in Fig. 2A, with retreat and composite ridges, as well as glacitectonic hill-hole pairs, indicating an east/southeast direction of ice flow. C: Seafloor ~95 km south of the block of multibeam data in Fig. 2A, with overprinting retreat and composite ridges showing ice flowing west/southwest. D: Seafloor ~40 km to the southeast of Fig. 2C, with retreat and composite ridges pointing in a southeastern direction. E: Seafloor morphology in the north of the study area, showing fragments of elongated features interpreted as MSGLs. F: Sub-bottom acoustic profile through a MSGL (Fig. 2E). Distribution of interpreted landforms with their depth on Storbanken seafloor. G: Map of the study area showing main directions of late-phase (i.e., deglacial) ice flow in respective locations.

collected from the shallow eastern Storbanken, acquired at 150–280 m water depths and covering a total area of over 550 km^2 of the seafloor (Fig. 1). PDS2000 software was used for digital data processing, producing images of 15 m grid-cell size.

3. Observations: diagnostic glacial landforms and open-marine sediment thickness

Three main flow-diagnostic types of landform are distinguished on the new high-resolution imagery of the seafloor of Storbanken. First, sets of small ridges and ridge fragments are found in all blocks of multibeam data (Fig. 2). In plan view, the ridges are laterally continuous (traced for up to 5 km horizontally), densely but irregularly spaced (75 m–1 km), and sometimes have a slightly arcuate configuration (Fig. 2C). In cross-section, they range between 3 and 15 m in height and 50–250 m in width. In addition, large (up to 40 m high), irregular, often arcuate positive-relief features with a series of multiple adjacent ridges and rafted blocks of sediment are also found in the study area (Fig. 2B). Mapping of all ridges (~300 in total) shows their crests spreading in a quasi-radial pattern around eastern Storbanken area. The second type of landform comprises paired sets of irregular erosional depressions and adjacent sedimentary depocentres. These features (~30 in total) are up to a few tens of meters in amplitude, and range between 0.05 and 2 km^2 in area (Fig. 2). Across the study area, mapped depression-depocentre complexes demonstrate a diverging configuration, with depocentres pointing outwards from the adjacent depressions relative to the central part of the eastern Storbanken. Third, patches of over 50 individual parallel ridge-groove features, highly elongate in plan-form and up to 5 m high (Fig. 2B,E) are present in the northern part of the study area. Identified landforms were better preserved in areas of less intensive iceberg ploughing (i.e., at water depths of over 200 m).

Based on their configuration, asymmetrical morphology and lateral continuity, we interpret the small ridges as moraines formed at the grounding lines of retreating ice-sheet margins (e.g., Ottesen et al., 2005; Bjarnadóttir et al., 2014; Newton and Huuse, 2017). The relatively dense spacing of the small ridges is typically linked to regular re-advances and/or relatively short term still-stands during overall regional deglaciation. The paired depocentres and depressions (Fig. 2) are interpreted as hill-hole pairs formed by glacitectonic processes at the ice-bed interface close to the thinning and retreating ice-sheet margin. The hills are always located down-flow of the holes and are produced from sediment excavated from the adjacent depressions (e.g., Aber and Ber, 2007). Similar features have been reported widely from high-latitude margins in both hemispheres (e.g., Ottesen et al., 2005; Klages et al., 2013; Kurjanski et al., 2019). More irregular larger ridges and rafted sediment blocks (Fig. 2) resemble ice-marginal composite ridges, with their large-scale displacement, compression and stacking of proglacial sediment marking the position of readvances or still-stands (e.g., Lovell and Boston, 2017); such composite features may represent a morphological continuum between retreat moraine ridges and hill-hole pairs. The depositional orientation of both morainal and composite ridges is orthogonal to ice-flow direction. Finally, highly elongate features found in the northern part of Storbanken are interpreted as Mega-Scale Glacial Lineations (MSGLs), parallel-to-flow features that have been widely reported from high-latitude continental margins, as well as observed underneath the modern fast-flowing Antarctic ice streams (e.g., Ottesen et al., 2005; King et al., 2009; Andreassen et al., 2014).

Sub-bottom profiles allow regional mapping of a distinctive semi-transparent, conformable acoustic facies that drapes the seafloor topography (Fig. 2F). On Storbanken, between Sentralbanken and Franz Victoria Trough (Fig. 1), these uppermost stratigraphic units are up to 2 m thick; they usually thin or are absent on very steep slopes. Covering glacially-produced landforms, this facies is interpreted as glacimarine and/or open-marine sediment sourced from the rain-out of fine-grained suspended material that is contained within the water column (e.g., Ó Cofaigh et al., 2005). In the Barents Sea, radiocarbon-dated open-marine sediment and underlying glacial landforms were attributed to the Holocene and the late Weichselian deglaciation, respectively (Hughes et al., 2016; Sejrup et al., 2022).

4. Discussion: past ice flow on Storbanken

The mapping of landform assemblages diagnostic of past ice flow on Storbanken allows reconstruction of the BSIS configuration in this important but poorly surveyed part of the central Barents Sea during the late Weichselian deglaciation (Fig. 3). Complementing the previous reconstructions from the western Storbanken (Bjarnadóttir et al., 2014; Newton and Huuse, 2017; Sejrup et al., 2022), our mapping shows the moraines stepping back onto central Storbanken from all directions, together with hill-hole pairs pointing outwards (Figs. 2 and 3), indicate that an independent and retreating ice dome was present on Storbanken. Ice-marginal glacial landforms, such as morainal retreat ridges, likely reflect the patterns of late-phase ice flow during regional deglaciation from the Weichselian maximum (e.g., Bjarnadóttir et al., 2014; Dowdeswell et al., 2021). Overprinting morainal ridges on southern Storbanken (Fig. 2C) are probably linked to the behaviour of ice flowing within the trough between Storbanken and Sentralbanken (Fig. 1). They likely represent ice-sheet unzipping and eastward ice retreat from this trough, followed by separation of the ice dome on Storbanken and minor grounding-line readvance with further northward decay of the remnant ice dome.

The types of landforms left by retreating ice domes provide insights into the subglacial thermal regime during the terminal stages of ice dome decay. In particular, glacitectonic hill-hole pairs and hummocky ridges containing blocks of rafted sediment have been attributed to basal freeze-on caused by oscillations of basal temperatures around the pressure melting point (e.g., Sættem, 1990). In the Barents Sea, such features have also been found in relation to the localised zones of high basal traction caused by subglacial formation of methane gas hydrates (Winsborrow et al., 2016). However, in the absence of diagnostic seafloor landforms such as pockmarks, or other geophysical and geochemical evidence for active fluid migration, the glacitectonic features we identify on eastern Storbanken are more likely to indicate frozen bed patches within overall warm-based conditions in that area during deglaciation. In the central and western Barents Sea, warm-based conditions during the initial phase of late Weichselian deglaciation are also supported by a number of meltwater channels and channel segments mapped at a range of depths on the modern seafloor both west and east of the present study area (Bjarnadóttir et al., 2017; Dowdeswell et al., 2021).

The newly mapped landforms from the eastern sector of Storbanken provide valuable new information on the glacial ice flow and retreat patterns Storbanken, increasing our knowledge of possible ice divide and ice marginal positions within the data-poor central Barents Sea. The quasi-concentric pattern of retreat inferred from the mapped morainal ridges and hill-hole pairs (Figs. 1–3) indicates that an isolated ice dome was centred on eastern Storbanken at about 77° N, 40° E (Fig. 3B) immediately preceding the final collapse of the marine-based ice sheet in the Barents Sea. Previous mapping of eastward-stepping morainal ridges on western Storbanbken (Figs. 1 and 3) suggested the gradual retreat of the westernmost ice margin, whereas the largely uncertain deglacial configuration of the remainder of the bank has been hypothesised

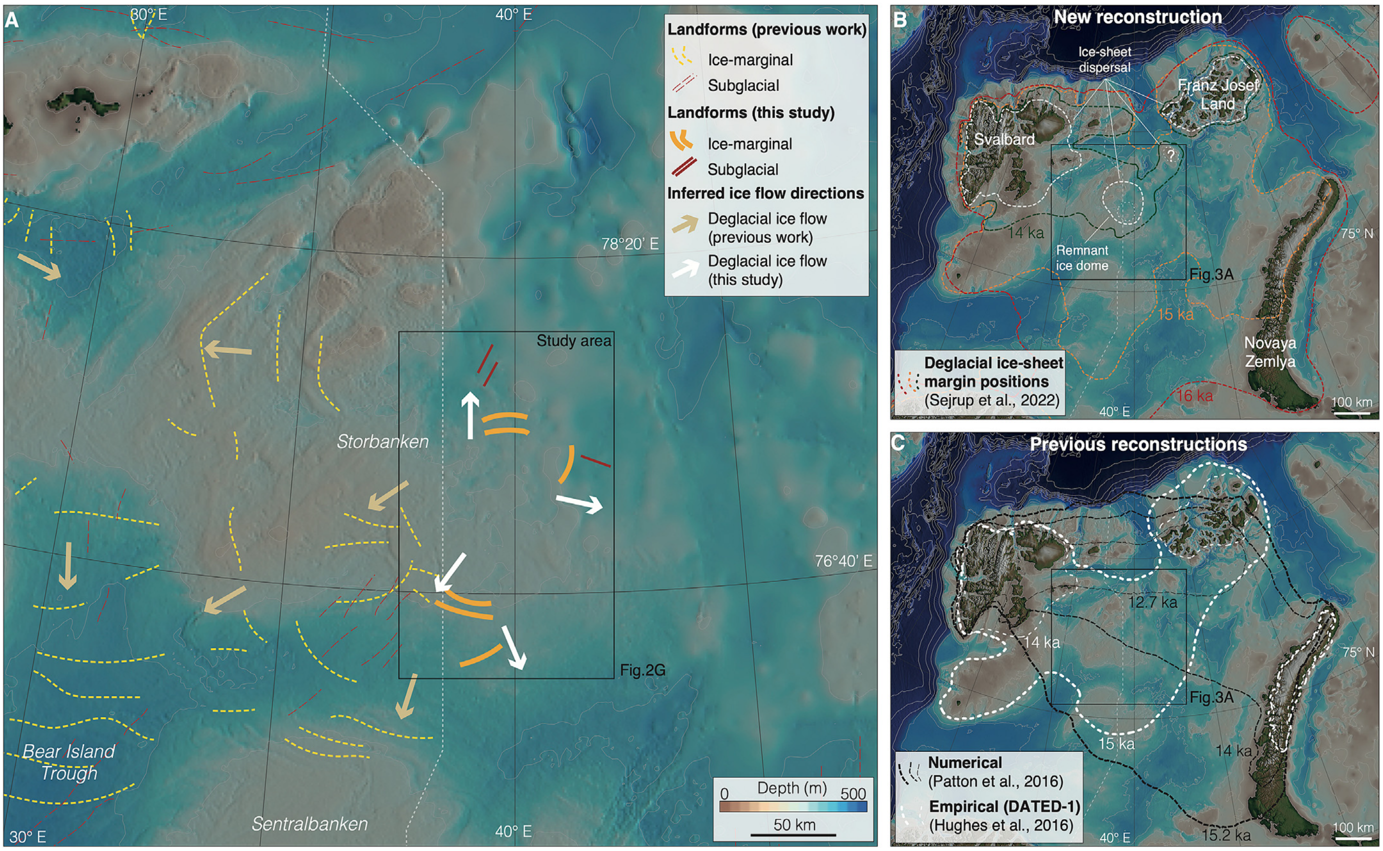

Fig. 3. Late-deglacial marine-based ice reconstructions for the Barents Sea. A: Our new, geomorphologically derived reconstruction of late-deglacial ice flow on Storbanken prior to the final decay of marine-based BSIS. Yellow arrows show deglacial ice flow directions derived from the previous studies (Sejrup et al., 2022). White arrows indicate deglacial ice flow new mapping of diagnostic ice-marginal landforms (Fig. 2). B: New reconstruction of late-stage ice-sheet dispersal and locations of remnant ice domes in the Barents Sea, based on regional deglaciation framework presented in reconstruction by Sejrup et al. (2022). C: Previous reconstructions of deglaciation in the Barents Sea, showing northward ice-divide migration across Storbanken (at 15 and 14 ka) from the empirical DATED-1 reconstruction (Hughes et al., 2016); and numerical model outputs from Patton et al. (2015) showing northward ice-divide migration across Storbanaken during deglaciation between 15 ka and 12.7 ka.

previously only on the basis of broad-scale morphology (Bjarnadóttir et al., 2014; Patton et al., 2015).

Existing ice-sheet reconstructions provide varying views on the presence (or absence) of isolated marine-based ice domes in the Barents Sea during the late Weichselian glaciation. Extensive, chronologically constrained grounding-line positions from the DATED-1 reconstruction (Hughes et al., 2016) suggested that, between 15 and 14 ka, the ice margin migrated rapidly northwards across shallow Sentralbanken and Storbanken to leave these areas ice free, despite large uncertainties of up to 400 km in likely ice-margin positions. The DATED-1 reconstruction suggested the remnant BSIS covering the Svalbard and Franz Josef Land archipelagos by 14 ka (Fig. 3C). Brendryen et al. (2020) recalibrated the available marine radiocarbon dates linked to BSIS retreat. They further integrated revised deglacial chronologies with ice-sheet geometries interpolated from the DATED-1 reconstruction to suggest a potential marine-based ice dome occupying Storbanken shortly after 13.9 ka. However, the absence of geomorphological data from eastern Storbanken emphasised the tentative nature of inferred ice dome in that area (Brendryen et al., 2020). Beyond geologically derived reconstructions, a three-dimensional thermo-mechanical numerical model of the BSIS suggested that no remnant isolated ice dome was present on Storbanken, and predicted the northward migration of the ice-sheet margin across both Sentralbanken and Storbanken between 15.2 and 12.7 ka (Patton et al., 2017) (Fig. 3C). The possibility of a much reduced individual ice dome remaining over Storbanken has been hypothesised previously (Patton et al., 2015), but the new seafloor-morphological data presented here show clearly that late-deglacial marine-based ice domes can persist on shallow banks until the very end of marine-based ice-sheet collapse (Figs. 2 and 3B).

The evidence for a separate ice dome on Storbanken implies that a large, full-glacial saddle-shaped ice divide disintegrated to leave possibly a few smaller remnant ice domes during the latest stages of regional deglaciation (Fig. 3B). Given that the regional morphology of the Barents Sea is characterised by shallow banks dissected and surrounded by deeper seafloor areas (Fig. 1), this disintegration was likely to be topographically controlled, with initial deglaciation taking place first in the major overdeepened troughs (Bjarnadóttir et al., 2014). A similar picture has recently been shown by multibeam observations from marine-based sectors of the past Antarctic Ice Sheet in the Ross Sea (Greenwood et al., 2018). There, ice-marginal glacial landforms indicated retreat from deeper troughs onto Crary Bank from all sides, suggesting the formation of an isolated ice rise (an ice dome surrounded by floating ice shelves) that was independent of the main ice sheet.

Our reconstruction of the late BSIS deglaciation strengthens the empirical framework against which future modelling investigations of marine-based ice sheets can be developed and calibrated (Patton et al., 2017; Sejrup et al., 2022). Even so, several questions remain about the history of the final BSIS collapse. First, it is unclear whether, following the initial ice-sheet disintegration, the remaining ice also occupied the shallow areas in Sentralbanken, and also between Franz-Josef Land and Storbanken (Fig. 3B), during at least part of the interval through which an ice dome existed over Storbanken. Northeastward-stepping moraine ridges overprinted by northward-retreating ice (Fig. 2C) suggest that grounded ice could exist at the same time on both Sentralbanken and Storbanken as the overdeepened area between these two shallow banks deglaciated, thus splitting a larger ice centre into two separate ice domes. However, largely southward ice flow is indicated by landforms in the southernmost seafloor sector of our study area (Fig. 2D), as well as by orientation of ice-marginal landforms in the Sentralbanken (Newton and Huuse, 2017). Together, this evidence implies that Sentralbanken may have been free of grounded ice by the time a local ice dome was present in the Storbanken, as predicted in many existing ice-sheet reconstructions (Fig. 3B and C). Acquisition of more multibeam data in the eastern Barents Sea to the south of eastern Storbanken would likely clarify the pattern of ice decay in the central Barents Sea in greater detail.

Apart from the lack of marine-geophysical datasets across the adjacent sectors of the eastern Barents Sea, an important gap in our understanding of the late BSIS is the absence of a precise chronology for ice-dome decay on its shallow banks. Although somewhat conflicting configurations of the deglacial BSIS have been produced by different observational and numerical models (Fig. 3C), available radiocarbon dates from sediment cores in the Barents Sea imply that ice had retreated completely from Storbanken by ~13 ka (Hughes et al., 2016; Patton et al., 2017; Brendryen et al., 2020). The calibrated BSIS model of Brendryen et al. (2020) also suggests that an ice dome persisted across Storbanken immediately after rapid BSIS collapse during the Bølling warming event ~14.6–14.3 ka that could contribute as much as half of Meltwater Pulse 1 A. However, recent study by Sejrup et al. (2022) used an updated marine radiocarbon age calibration curve to infer that rapid deglaciation across the central Barents Sea may have occurred ~0.5 ka earlier compared to the previous reconstructions (Brendryen et al., 2020). Together with previous work by Bjarnadóttir et al. (2014), Newton and Huuse (2017) and Sejrup et al. (2022), the high-resolution seafloor imagery presented here will assist in planning a series of coring sites which could establish the timing of these major deglaciation events of the marine-based ice-sheet in the Barents Sea.

5. Conclusion

New high-resolution multibeam imagery of seafloor from the shallow Storbanken in the eastern Barents Sea allows the reconstruction of the form and flow of a marine-based ice-sheet prior to its final collapse. Glacitectonic complexes and retreat moraines found in five closely spaced blocks of the imaged seafloor show quasi-concentric grounding-line retreat patterns, implying that an isolated, shrinking ice dome, ~100 km in diameter, was centred at 77° N 40° E in the central Barents Sea prior to final marine-based ice-sheet collapse. This geomorphic reconstruction provides a new empirical framework against which future numerical models of marine-based ice sheets in the Barents Sea and elsewhere can be tested.

Credit author statement

Aleksandr Montelli and Julian A. Dowdeswell wrote the manuscript. Aleksandr Montelli, Marina Solovyeva and Grigorii Akhmanov planned the TTR-20 surveys. Grigorii Akhmanov, Marina Solovyeva, Adriano Mazzini, and Elena Bakay led the TTR-20 research cruise, including acquisition and processing of geophysical datasets.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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