

# Rapid ice sheet retreat triggered by ice stream debuttressing: Evidence from the North Sea

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## ABSTRACT

Using high-resolution bathymetric and shallow seismic data from the North Sea, we have mapped hitherto unknown glacial landforms that connect and resolve longstanding gaps in the Quaternary geological history of the basin. We use these data combined with published information and dates from sediment cores to reconstruct the extent of the Fennoscandian and British Ice Sheets (FIS and BIS) in the North Sea during the last phases of the last glacial stage. It is concluded that the BIS occupied a much larger part of the North Sea than previously suggested and that North Sea ice underwent a dramatic disintegration ~18,500 yr ago. This was triggered by grounding-line retreat of the Norwegian Channel Ice Stream, which debuttressed adjacent ice masses, and led to an unzipping of the BIS and FIS accompanied by drainage of a large ice-dammed lake. Our reconstruction of events provides an opportunity to improve understanding and modeling of the disintegration of marine-based ice sheets, and the complex interplay between ocean circulation and the cryosphere.

## INTRODUCTION

Understanding the processes and rates of disintegration of large ice sheets as a consequence of climate forcing is now a major endeavor, because they are relevant for predictions of ice sheet recession in Antarctica and Greenland and the resulting sea-level rise. Of particular concern are processes occurring when ice sheets have marine margins, because nonlinear behavior in response to steady climate forcing is known to exist; the marine instability hypothesis forecasts abrupt and irreversible collapses of ice sheets (Joughin et al., 2014). Have such rapid retreats occurred in the past, from which we can learn?

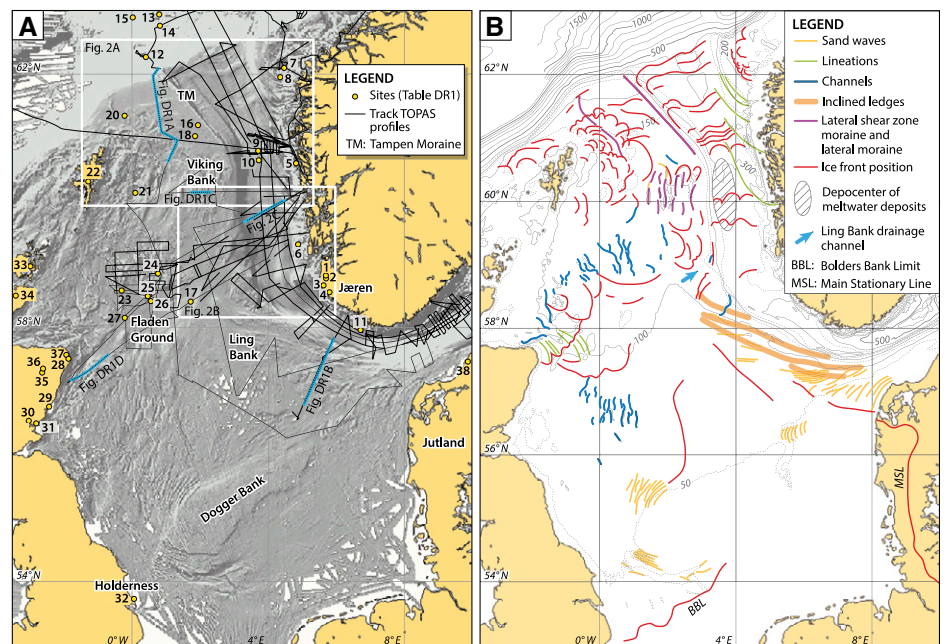
Investigation of glacial landforms and sediments over the past 150 yr has yielded enough evidence to reconstruct the extent and configuration of the British Ice Sheet (BIS) and the much larger Fennoscandian Ice Sheet (FIS) on land (Clark et al., 2012; Kleman et al., 1997). The marine areas have, however, been less investigated. Early reconstructions depicted ice expanding from Britain and Norway into the North Sea (Geikie, 1894). Identification of glacial sediments in shallow drillings and seismic surveying suggested cojoined ice sheets across the North Sea during some glacial stages (Ottesen et al., 2005; Sejrup et al., 2005), and ice sheet modeling experiments indicate that once the two ice sheets meet, their thicknesses increase to form an ice divide straddling the North Sea (Boulton and Hagdorn, 2006). Seafloor images have made possible the mapping of landforms in the North Sea associated with the last glacial phases off Shetland, in the Fladen Ground, and along the Norwegian margin (Bradwell et al., 2008;

Ottesen et al., 2005; Sejrup et al., 2015) (Fig. 1A). A more complete understanding of the spatial extent of ice in North Sea, and its retreat geometry during the last glacial stage, has been limited and controversial. Here we report new mapping and interpretation of ice marginal landforms in the northern and central North Sea that, combined with previous results, require substantial revision of earlier reconstructions with important findings for how deglaciation was triggered.

## DATA AND METHODS

Seabed imagery and bathymetric information were obtained from the Olex database (Olex AS, www.olex.no), representing the seafloor as a series of 5 × 5 m cells with a vertical accuracy of <1 m (Fig. 1A). Approximately 12,800 km of subbottom profiles, acquired between 2005 and 2014 by the University of Bergen (Norway) with R/V *G.O. Sars* using a Kongsberg TOPAS (parametric subbottom profiler) system, with a penetration of typically 25–50 m and a vertical resolution of as much as 0.3 m, have been analyzed. We emphasize that the TOPAS coverage, and locally the Olex coverage, is poor in the southern part of the North Sea. The method for classifying and mapping of glacial landforms (Fig. 1B) is provided in the GSA Data Repository<sup>1</sup>.

<sup>1</sup>GSA Data Repository item 2016112, methods for mapping, dates discussed in text, and TOPAS seismic data examples, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.



**Figure 1. A: Relief-shaded elevation model from the OLEX database (Olex AS; www.olex.no) with seismic profiles and sites in the North Sea (TOPAS is a parametric subbottom profiler; www.km.kongsberg.com). B: Mapped landforms.**

Information on sediment composition and chronological control was obtained from published data from shallow drillings and piston and gravity cores (Fig. 1A; Table DR1 in the Data Repository). For calibration procedures for radiocarbon dates, see the Data Repository.

## MAPPING OF ICE MARGINAL FEATURES

Using the topographic expression and knowledge of ice sheet configurations over Britain and Fennoscandia, we first separate out the main elements to identify the extent of grounded glacial ice in the North Sea and the boundary between the BIS and FIS. For the northern ice margin, we mainly follow earlier reconstructions (Bradwell et al., 2008; Sejrup et al., 2005) with ice extending to the shelf edge, but find new landforms and associations that are revealing. A ridge of as much as 15 m in relief to the northeast of Shetland (Figs. 1B and 2A) and trending parallel to the western edge of the Norwegian Channel is interpreted as the lateral margin of the FIS flowing northward. This interpretation is supported by the finding of ice marginal landforms that can be traced from the floor of the Norwegian Channel, climbing up onto the channel flank and extending westward and abutting this lateral ridge. This landform system is overprinted in places by smaller, more sharply defined and strongly curved ridges interpreted as moraines related to ice from a Shetland ice mass (Fig. 2A; Fig. DR1A).

Further south, on the shallower parts of the Viking Bank (Fig. 1A), the westward limit

of the FIS can be traced by a series of ridges approximately parallel to the edge of the Norwegian Channel interpreted as lateral shear zone moraines (Fig. 1B; Fig. DR1C). These line up with series of inclined ledges extending up and out of the Norwegian Channel at its southernmost part (Fig. 1B; Fig. DR1B) that are interpreted as erosional benches cut by the lateral edge of the Norwegian Channel Ice Stream (NCIS). These sets of landforms extending from the shelf edge, toward Denmark, indicate that the NCIS was not always restricted to its channel, but overtopped it and extended as much as 100 km farther west than previously thought.

The southern limit of North Sea ice remains poorly known, with reconstructions usually connecting a line between known positions in England and Denmark but with positions varying from north of, on, or south of Dogger Bank (e.g., Fitch et al., 2005; Holmes, 1977; Gibbard and Clark, 2011). Here we follow Cameron et al. (1992) in defining the ice limit as the southernmost extent of the Bolders Bank Formation, the offshore equivalent of the Skipsea Till in eastern England, which is dated to the last glacial (Fig. 1B). This places the ice limit to the south of Dogger Bank, and we extend this line to meet up with the Main Stationary Line in Denmark (Houmark-Nielsen and Kjær, 2003).

We have identified an ice marginal position north of Dogger Bank (Fig. 1B) that requires eastward flow from Britain. Combined with the sequence of ice margins that record retreat to the northwest across the Fladen Ground (Fig. 1B;

Fig. DR1D) and the well-known northward retreat of ice up the English east coast, these elements indicate the presence and then withdrawal of British ice from the central North Sea. The last phase of backstepping retreating ice flow across the seafloor surrounding the Fladen Ground must have been orthogonal to the moraine sequence and therefore toward the southeast. This is consistent with northwest-southeast-oriented megascale glacial lineations reported by Graham et al. (2010) in the area, but contradicts their interpretation of the flow direction; they presumed that flow was to the northwest, nourished by the FIS.

## CHRONOLOGY

In the following, numbers in parentheses refer to locations in Figure 1A and dates with references in Table DR1. In the northeast, the North Sea Fan was primarily formed during periods of shelf-edge glaciations by deposition of glaciogenic debris flows (GDFs) from a fast-flowing ice stream in the Norwegian Channel (Sejrup et al., 2005). Basal radiocarbon dates from marine sediments on top of the youngest stack of GDFs (13, 14, and 15) indicate that the grounding line of the NCIS started to retreat ca. 19 ka. Norwegian Channel cores that penetrate deglacial sediments above till have basal dates compatible with a retreat of the NCIS from the shelf edge at 19 ka, and deglaciation at Troll (9, 10) close to 18.5 ka and south of southern Norway close to 17.8 ka (11). These dates on deglaciation align with those from northern Jutland (42) and from coastal areas of southern Norway (3, 4). Exposure dates (6) from the island of Utsira have yielded ages between 25 and 20.2 ka for the last deglaciation (Svendsen et al., 2015), somewhat older than the chronology of the last disintegration of the NCIS suggested from the radiocarbon dates discussed here.

An important region for the reconstruction of the last glacial phases in the northern North Sea is the Fladen Ground area (Fig. 1A). Based on interpretation of sediment cores with radiocarbon dates (23–27) and more recently on high-resolution seismic profiling and bathymetric data (Graham et al., 2010; Sejrup et al., 2015), it was concluded that this part of the North Sea deglaciated and remained ice free as early as ca. 26 ka. This conclusion was based on the dating of a marine sequence above a till unit in borehole 77/2 (25). A problem with this scenario has been the suggestion of an ice-free central North Sea at the same time ice of the last glacial stage reached its southern maxima, according to numerous dates in Denmark and eastern England (Bateman et al., 2011; Houmark-Nielsen and Kjær, 2003). With our new mapping recording an ice margin moving toward the northwest from the maximum position (Fig. 1B), this ice-free central North Sea during the Last Glacial Maximum (ca. 21 ka) becomes

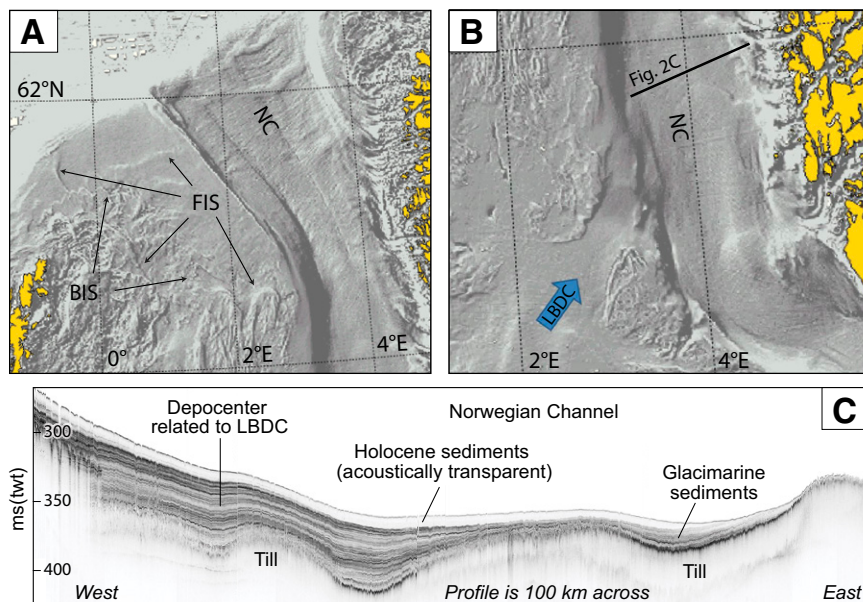


Figure 2. Sejrup et al.

**Figure 2. A, B: North Sea locations in Figure 1A. A: A series of ice marginal landforms of the British Ice Sheet (BIS) overprint landforms from the Fennoscandian Ice Sheet (FIS). NC—Norwegian Channel. B: A smooth surface, bounded by arcuate ridges, is interpreted as the Ling Bank drainage channel (LBDC). C: TOPAS (parametric subbottom profiler; www.km.kongsberg.com) profile showing a distinct depocenter, which likely represents sediments transported through the LBDC (tw—two-way traveltime).**

implausible. We therefore suggest that there must be an ~6 k.y. hiatus in the marine sequence below the GDF in borehole 77/2, and that the lower part represents an ice-free period before the last glacial phase lasting from ca. 26 to 23 ka. The upper part of this unit represents marine sedimentation immediately after deglaciation, between 18.0 and 17.0 ka.

## DISCUSSION

The distribution of landforms is used to build a reconstruction of the configuration of North Sea ice and its subsequent retreat. The least-contrived compatibility between the new landform patterns, notably the west and northward withdrawal of British ice from the central North Sea, and the ice-free dates in the Fladen Ground yield a reconstruction of maximum ice extent (Fig. 3A) between 23 ka and 19 ka. Consistent with numerical modeling experiments (Boulton and Hagdorn, 2006), a major trans-North Sea ice divide is reconstructed with ice nourished over Britain dominating the area, and an ice stream occupying just the distal end of the Norwegian Channel. A consequence of a thick grounded ice sheet must have been the development of a large ice-dammed lake south of the ice margin (Fig. 3A). Such ice-dammed lakes and related overspill systems have been hypothesized, and some evidence was reported, but mostly for earlier glaciations (Belt, 1874; Valentin, 1957; Cohen et al., 2014; Hijma et al., 2012; Murton and Murton, 2012).

We interpret that ice sheet collapse was initiated by growth in width and length of the NCIS (Figs. 3A and 3B). Well-dated records of GDFs

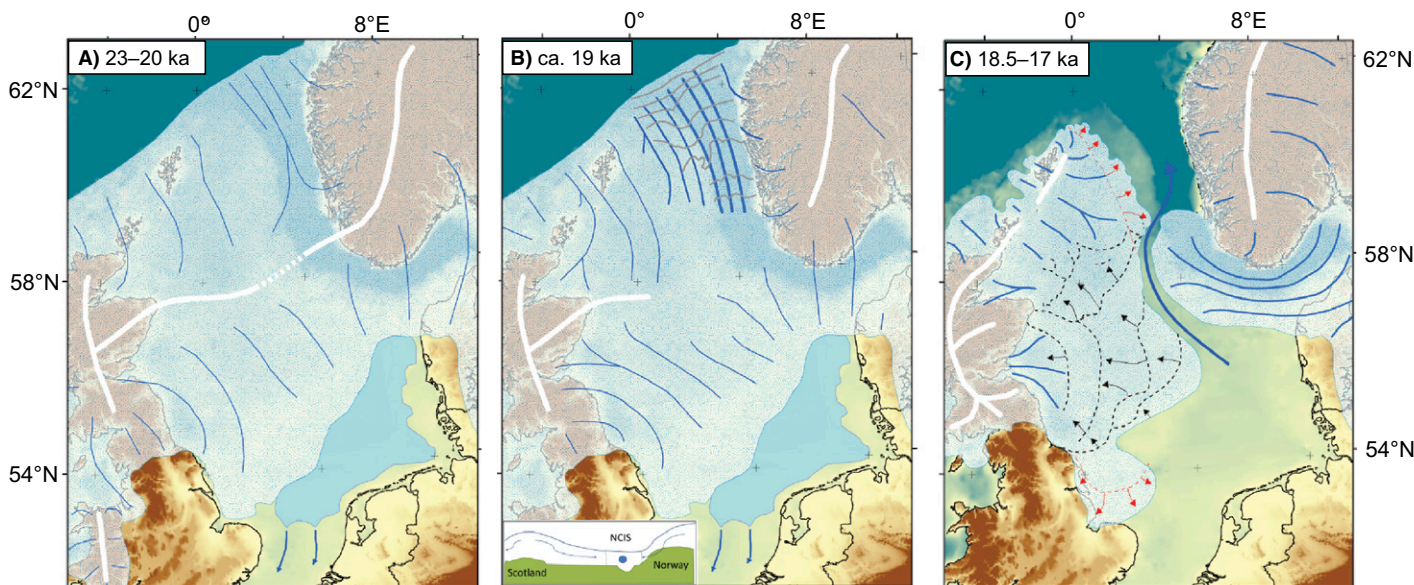
at the ice stream terminus demonstrate a pulse of extremely high sediment flux (Nygård et al., 2007) between 20 and 19 ka. We suggest that this is the geologic signal of increased velocity of the ice stream that preceded and promoted the retreat. Increased ice flux is interpreted to have drawn down and then eradicated the cross-channel ice divide, permitting the ice stream to time-transgressively translate southward. By relating the backstepping grounding zone wedges in and adjacent to the Norwegian Channel to the series of parallel northwest-southeast-trending ridges, we reconstruct that the ice stream retreated up the channel, narrowing and eventually becoming confined to the relief of the channel (Figs. 3B and 3C). As the ice stream withdrew, ice from the Shetland region expanded eastward as a consequence of reduced buttressing and maintained an ice seal in the northern North Sea (the stage between Figs. 3B and 3C). This interpretation satisfies the overprinting of ice marginal features emanating from Shetland on the ice stream lateral shear zone moraines (Fig. 1B). By 18.5 ka, the NCIS grounding line rapidly retreated nearly 200 km (at a rate of ~400 m yr<sup>-1</sup>), accompanied by the lowering of its surface profile, and the ice sheets unzipped along a line from the Viking Bank to the southern margin of the ice sheet (Fig. 3C). Drainage from ice-dammed lakes southeast of Dogger Bank through the Ling Bank drainage channel (Figs. 1B and 2B) likely facilitated the final stage of separation. Downstream of the Ling Bank drainage channel is an ~35-m-thick depocenter of acoustically laminated sediments in the Norwegian Channel (Figs. 1B and 2C),

interpreted as meltwater deposits from this event and subsequent fluvial drainage.

Withdrawal and thinning of the NCIS removed lateral support of the ice sheets on either side (Fig. 3C) and led to a reorganization in ice flow, with ice lobes spreading and thinning as a consequence of this debuttressing, expressed as margin readvances. Some readvances are documented (Evans and Thomson, 2010; red arrows in Fig. 3C). This resulted in reduced ice elevations at a time of climate warming, promoting increased surface ablation and rapid margin retreat ca. 17 ka (Fig. 3C). Relative to what is known about the rate of decay of terrestrial parts of ice sheets, the disintegration of the BIS from its southern margin to Fladen Ground must have happened rapidly and within the accuracy of the dating methods applied (hundreds of years). Our reconstruction shows the last remnants of the BIS in the North Sea as an ice cap extending from Scotland to Shetland and with a lobe rapidly withdrawing along the eastern English coast and back into the Moray Firth. Dates from Jæren (Fig. 1A) and northern Denmark suggest that the Norwegian Channel was completely ice free ca. 17 ka (Houmark-Nielsen and Kjær, 2003; Sejrup et al., 2009).

## CONCLUSIONS

The reconstruction presented here is the first effort to combine high-resolution acoustic data with information from dated offshore sediment cores and onshore dates to reveal the last glacial phases for the entire North Sea. We find that the reconstruction represents a much better agreement between dates of ice extent from



**Figure 3. Reconstructions of maximum ice extent. A: Maximum configuration with ice divides meeting in a saddle and an ice-dammed lake. B: Initiation of collapse. Norwegian Channel Ice Stream (NCIS) grew (dark blue lines), increasing the drawdown of ice and destroying the ice divide. Grounding line retreat (gray) up the Norwegian Channel debuttressed ice on either side as it thinned and withdrew (inset). C: Unzipping and collapse. NCIS narrows down and separates from British ice and the ice-dammed lake discharges through the Ling Bank drainage channel (blue arrow). Known readvances are in red.**

Denmark (Houmark-Nielsen and Kjær, 2003) and the eastern UK (Hughes et al., 2011), and with ice-free dates from the North Sea (Sejrup et al., 2009) that had previously been troublesome to combine (cf. Clark et al., 2012). Further support for our reconstruction of collapse and its timing is found in evidence from adjacent deep-sea cores. Proxies for freshwater inputs at 21–18 ka in cores from the Celtic margin and the northern Bay of Biscay have been used as indicators for a phase of overflow drainage from a North Sea ice-dammed lake (Menot et al., 2006; Toucanne et al., 2010). Continued routing of rivers through the Straits of Dover is consistent with our reconstruction if, as suggested in Toucanne et al. (2010), glacioisostatic warping of topography helped maintain such a flow direction. From the southern Norwegian Sea, rapidly deposited plume sediments with light oxygen isotope peaks indicative of freshwater input, emanating from the mouth of the Norwegian Channel (Hjelstuen et al., 2004), have been dated to 18.6 ka (Lekens et al., 2005). These findings likely reflect our reconstructed lake drainage event, consistent with the final unzipping of the BIS and FIS close to 18.5 ka.

Our results demonstrate a rapid retreat of a marine ice sheet sector driven by grounding line retreat of the major ice stream, likely to be pivotal in furthering our understanding of such processes, their tipping points and rates of change, and their interactions with ocean circulation. With greater dating control this reconstruction could be a data-rich environment for improving numerical ice sheet modeling, by providing time scales more relevant to collapse events (hundreds to thousands of years) than can be provided by modern observations in polar regions.

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