The last deglaciation of the Norwegian Channel – geomorphology, stratigraphy and radiocarbon dating

BJÖRN M. MORÉN, HANS PETTER SEJRUP, BERIT O. HJELSTUEN, MARIANNE V. BORGE AND CATHRINA SCHÄUBLE

Ice streams are important vectors of mass within ice sheets (e.g. Bentley 1987; Bamber et al. 2000; Anderson et al. 2002; Bennett 2003; Evans et al. 2005), with Pine Island and Thwaites ice streams accounting for almost 30% of ice loss from the present West Antarctic Ice Sheet (Thomas et al. 2004; Rignot et al. 2008) and Jakobshavn Isbrae draining 6.5% of the Greenland Ice Sheet (Joughin et al. 2004). Furthermore, ice streams are considered to be crucial for the dynamics of ice sheets and their stability (e.g. Alley et al. 1986; Stokes & Clark 2001; Dowdeswell et al. 2008; Pritchard et al. 2009). Marine-based ice streams, which, compared with terrestrial ice streams, are sensitive to sea-level changes and changes in ocean temperature are potentially significant contributors to ice-sheet destabilization and rapid mass loss, and therefore also to rapid sea-level rise (Alley et al. 2005; Pritchard et al. 2009, 2012). Because ice streams are such an essential feature of ice sheets, it is important to understand ice streams to be able to fully understand the behaviour and dynamics of ice sheets both in the past and in the present. As the observation time of present ice streams is relatively short, studies of palaeo-ice streams are uniquely helpful in this research.

Locations of palaeo-ice streams have been inferred from the presence of glacially eroded troughs and the identification of mega-scale glacial lineations (MSGLs; Stokes & Clark 2001; Livingstone et al. 2012). Onshore palaeo-ice streams are commonly mapped by detailed DTMs and from satellite imagery (e.g. Clark 1993; Stokes & Clark 2003; De Angelis & Kleman 2008), whilst the palaeo-ice stream beds offshore have been mapped from marine geophysical data, such as swath bathymetry and seismic data (e.g. Canals et al. 2000; Ó Cofaigh et al. 2002; Ottesen et al. 2005; Graham et al. 2007).

In the last few decades, several palaeo-ice stream beds have been mapped on the continental shelf of northwestern Europe within both the Fennoscandian Ice Sheet (FIS; Sejrup et al. 1998, 2003; Nygård et al. 2005; Ottesen et al. 2005) and the British–Irish Ice Sheet (BIIS; Van Landeghem et al. 2009; Howe et al. 2012; Bradwell & Stoker 2015). This study addresses the last phase of the Norwegian Channel Ice Stream (NCIS), the largest palaeo-ice stream of the eastern North Atlantic margin next to the Bear Island Ice Stream, and the last deglaciation of the Norwegian Channel. To elucidate the deglaciation dynamics of the FIS, the NCIS must be considered in terms of dynamic behaviour, such as slowdowns, stillstands or re-advances of the grounding line. To improve understanding of the last deglaciation of the NCIS, we present lithological data and radiocarbon dates from sediment cores, a shallow seismo-stratigraphical framework and the result of glacial-geomorphic mapping based on seabed imagery data of the Norwegian Channel. The new dates are compiled with published dates from the Norwegian Channel and the surrounding areas to constrain the last deglaciation of the region. Finally, retreat rates of the NCIS are compared with palaeo-ice streams in Antarctica, Greenland and northwestern Europe.

Background and setting

The Norwegian Channel is located in the easternmost part of the North Sea and is ~850 km long, stretching

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from the inner parts in the Skagerrak to the shelf edge west of Western Norway. The width of the channel varies between ~70 and ~150 km, with the widest part located at the shelf edge (Fig. 1). The deepest part is found in the Skagerrak, where the water depth is ~700 m. From the Skagerrak, the channel shoals and reaches its shallowest point outside Stavanger, with a water depth of about 280 m (Ottesen et al. 2000; Rise et al. 2008). This shallow zone acts as a topographical threshold in the Norwegian Channel. North of the threshold, the channel deepens towards the shelf edge, where it is ~400 m deep.

During the last deglaciation, the Norwegian Channel was a fjord-like embayment of the North Sea, until approximately 10.2 ka, when the North Sea opened up again (Thiede 1987).

During the Pleistocene, northern Europe experienced a number of glaciations (Lee et al. 2012). The first recorded extensive ice advance in the North Sea, with ice reaching the shelf edge, has been estimated to 1.1 Ma (Sejrup et al. 1995). Nygard et al. (2005) suggested that the NCIS advanced to the shelf edge during Marine Isotope Stages (MIS) 2, 6, 8, 10 and
12. Furthermore, it has been estimated that close to 50% of the sediments derived from the catchment area of the NCIS through the Quaternary were deposited in the North Sea Fan, located on the continental slope north of the channel (Hjelstuen et al. 2012). As such, the Norwegian Channel is the product of multiple glaciations and not merely a Late Weichselian feature.

It is generally accepted that during the LGM, the ice sheet reached the shelf edge from Ireland to Svalbard and that the BIIS and FIS merged in the central parts of the North Sea (Sejrup et al. 2005). The geomorphic imprint of the last NCIS has been described in studies by Longva & Thorsnes (1997) and Longva et al. (2008), who found glacial lineations in the Skagerrak. In addition, Sejrup et al. (2003) and Nygård et al. (2004) mapped the geomorphology of the Maløy Plateau, where they found evidence of local glacial advances in the form of drumlinized ridges and end moraines. Recently, Sejrup et al. (2016) described a number of features, such as grounding-zone wedges (GZW), in the North Sea tied to the NCIS, providing evidence that the NCIS spilled over the western edge of the Norwegian Channel during some phases of the last glaciation.

A number of radiocarbon dates have been related to the timing of the last deglaciation, both from the channel itself and from the areas adjacent to the channel (Lehman et al. 1991; Sejrup et al. 1994, 2009; Haflidason et al. 1995; King et al. 1998; Table 1). Generally, these radiocarbon ages show a consistent internal chronology with a deglaciation of the Norwegian Channel off western Norway between 18.5–19 ka. However, a recent study by Svendsen et al. (2015) presented cosmogenic exposure ages from the island of Utsira (Fig. 1) that seem to indicate a somewhat earlier deglaciation at 20 ka. Nygård et al. (2005, 2007) investigated the North Sea Fan and the glaciogenic debrisflows deposited during what is assumed to represent periods of shelf-edge glaciations and estimated the sediment volumes deposited on the trough-mouth fan by the NCIS. Marine sediments immediately above the youngest debrisflows have been dated to 19.7–19.1 ka (King et al. 1998). The terrestrial deglaciation of the areas surrounding the Norwegian Channel has been investigated by numerous workers (e.g. Mangerud 1977; Sejrup et al. 1998; Houmark-Nielsen & Kjer 2003; Raumholm et al. 2003; Knudsen et al. 2006; Mangerud et al. 2013; Anjar et al. 2014) and can be considered to be well constrained with the oldest radiocarbon dates close to 17 ka.

Data and methods

Bathymetric data were used to map surface features, such as MSGLs, lateral moraines and ice-terminal landforms. Olex bathymetric data that cover the investigated area (Fig. 1) were provided by Olex AS (www.olex.no). A bathymetric data set from the Norwegian Hydrographic Survey, with a horizontal resolution of 500 m, was used for additional verification for the outer two thirds of the Norwegian Channel. The Olex data and the 500-m bathymetric data set were imported into ArcMap 10.3, which was used for the mapping. In addition, a high-resolution data set (3–10 m) from the Norwegian Mapping and Cadastre Agency and processed using Fledermaus 7.3 was used for a smaller part of the Norwegian Channel (Fig. 1).

Three calypso cores, two gravity cores and acoustic data collected during University of Bergen cruises with R/V G.O. Sars between 2006 and 2014 were used in this study (Fig. 1). The acoustic data were collected using a Kongsberg Topographic Parametric Sonar (TOPAS) PS 18 system with a frequency range of 0.5–6 kHz and comprise some 8600 km of sub-bottom profiler data with a vertical resolution of ~30 cm. The penetration was generally 25–50 m. For conversion of sediment thicknesses and depths in metres, we used a velocity of 1500 m s⁻¹.

The sediment core locations were chosen with the aim of penetrating the postglacial marine sediments down into the till below, in order to obtain dateable material as close as possible to the contact. Magnetic susceptibility and gamma density were measured on all cores with a GEOTEK Multi-Sensor Core Logger with a resolution of 0.5 mm. The cores were described visually and subsampled for AMS ¹⁴C dating and grain-size analyses. The subsamples were wet-sieved using 63, 150 and 1000 μm sieves for four of the five cores. The subsamples from GS12-172-04PC were wet-sieved using 63, 125 and 1000 μm sieves. The focus of the core studies was to study the time close to the last deglaciation. Therefore, the sampling frequency was higher in those parts where substantial lithological changes occurred that were assumed to reflect the last deglaciation from the interpretation of the TOPAS data. Undrained shear strength was measured along the cores by fall-cone tests (Hansbo 1957).

AMS ¹⁴C dating was performed on samples of benthic foraminifera and some molluscs at Beta Analytical Inc. in Florida, USA, and at the Laboratory for Ion Beam Physics, ETH Zurich (Table 1). The AMS radiocarbon ages were calibrated using the standard reservoir effect (ΔR = 0) on the Marine13 curve (Reimer et al. 2013) and converted to calibrated ages with Calib 7.0.4 (Stuiver & Reimer 1993, 2013). Existing radiocarbon dates from the region were also recalibrated to make them comparable with the present study (Table 2).

Results

Glacial landforms

We mapped three main types of glacial landforms in the acoustic data: ice-terminal landforms (including GZW's
Table 1. Available radiocarbon and cosmogenic exposure dates from the Norwegian Channel and its surroundings. The radiocarbon dates have been calibrated using Marine13, except for the sample from Stemmavatn (Lab ID Poz-5419), which has been calibrated using IntCal13 (Stuiver & Reimer 1993, 2013; Reimer et al. 2013).

| Core no./location | Lab. ID    | Depth in core (m) | Uncorr. 
\(^{14}\text{C} \) age (a) | SD | Cal. age (a BP) | SD | \(^{10}\text{Be} \) age (a) | SD | Geological context | Reference |
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Table 2. Radiocarbon dates presented in this study. The radiocarbon dates have been calibrated using Marine13 (Stuiver & Reimer 1993, 2013; Reimer et al. 2013).

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<th>Longitude</th>
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<th>Core length (m)</th>
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and end moraines), lateral moraines and glacial lineations (Figs 2, 3).

**Ice-terminal landforms.** – GZWs are common features of marine-based palaeo-ice stream beds (Batchelor & Dowdeswell 2015), partly characterized by a wedge-like profile with a steep distal sea-floor ramp and a shallow proximal side (Livingstone et al. 2012), but mostly by their larger size compared to end moraines. Within the Norwegian Channel, such features are only identified off western Norway, where they are between 10 and 80 km in length and 10–25 m high (Figs 2, 3, 4A, 5A). In contrast to GZWs, end moraines are generally smaller ridges (Livingstone et al. 2012). The identified end moraines in the outer part of the Norwegian Channel are generally 10–45 km long, with heights of about 5–15 m (Figs 2, 3, 4A, 5A). End moraines are also found on the Måløy Plateau to the northeast of the Norwegian Channel (Fig. 2). These end moraines are smaller than the ones found in the outer part of the Norwegian Channel and have been described in detail by Nygård et al. (2004). Off the west coast of Sweden, in the eastern part of Skagerrak, the observed end moraines have lengths of 5–15 km.

In the outer parts of the Norwegian Channel, large ice-marginal landforms have been formed laterally in the centre of the glacial trough (Fig. 2; Sejrup et al. 2016). The ice-marginal features off the western coast of Norway are generally larger and more arcuate in shape compared with the ones found close to the continental shelf edge, which are straighter.

**Glacial lineations.** – MSGLs are elongated features that have been subglacially streamlined. They are orientated according to the ice-flow direction at the time of their formation (Clark 1993; Spagnolo et al. 2014) and are confined to regions of soft till (Ó Cofaigh et al. 2007). The MSGLs on the seabed in the Norwegian Channel vary between 10 and 100 km in length, with an elongation ratio of more than 10:1 and with amplitudes of about

![Fig. 2. Distribution of mapped glacial landforms in the Norwegian Channel. Ice-marginal features (end moraines and grounding-zone wedges) are red, glacial lineations are green and lateral moraines are purple.](image-url)
2–10 m. In addition to the lineations in the outer and middle parts of the Norwegian Channel, there are sets of glacial lineations in the NE part of the channel, where the western Norwegian fjords enter the Norwegian Channel (Fig. 2). These lineations have lengths of 5 to 20 km. In the southern part of the trough, from the area outside Stavanger to the Skagerrak, there are also lineations (Fig. 2). MSGLs are most easily identified from multi-beam bathymetry when the ridges are seen at the sea floor because the overlying sediments mimic the morphology of the till surface. However, buried MSGLs have been identified in the TOPAS seismic profiles, of which some are superimposed on the identified GZWs (Fig. 4A), especially where parallel TOPAS profiles cutting across the ridges allow tracing of the individual MSGLs. These superimposed MSGLs indicate a re-advance of the ice margin over the GZWs. Furthermore, Nygård et al. (2007) identified probable MSGLs in the Norwegian Channel from TOPAS data.

Lateral moraines. – Lateral moraines are found at the western outer edge of the Norwegian Channel (Fig. 2). Such features are formed in various ways, for example along the sides of a glacier or an ice sheet and in shear zones between ice masses. This could result in lateral moraines occurring in the centre of a trough. The identified lateral moraines in this study vary in length, between 15 km and almost 140 km. These features are generally between 10 and 25 m high. The longest lateral moraines are found in the north, with the shorter moraines in the south.

In addition to the landforms described above, iceberg ploughmarks have been identified (Figs 4B, 5C, 6). In the central part of the Norwegian Channel, the iceberg ploughmarks are expressed at the seabed, with a thin sediment cover and ploughing depths of up to 10 m (Figs 5C, 6). Buried iceberg ploughmarks are identified in the outer part of the Skagerrak within the lower parts of the studied sediment package (Fig. 4B).

Seismic stratigraphy

Based on the TOPAS seismic data, the upper ~50 m of the sediments in the Norwegian Channel have been
A

Hemipelagic (U3)

Glaciomarine (U2)

Till (U1)

Flat internal reflector (FIR)

B

Hemipelagic (U3)

Glaciomarine (U2)

Till (U1)

Iceberg perturbation

C

Hemipelagic (U3)

Till (U1)

Flat internal reflector (FIR)

Glaciomarine (U2)
The last deglaciation of the Norwegian Channel

subdivided into three acoustic units, following the subdivision of Nygård et al. (2007). The mapped units represent an upper acoustically transparent unit (U3), an acoustically laminated unit (U2) and a lower acoustically homogeneous unit (U1) (Figs 4, 5). These units are separated by distinct reflectors R1, R2 and R3. Unit U1 is distinguished by a featureless acoustic seismic facies, commonly with no or faint internal acoustic structures. Flat internal reflectors (FIRs) are however, locally, mapped about 5–10 m below the upper distinct reflector (R1; Figs 4A, B, 5B, C), similar to the Antarctic findings of Ó Cofaigh et al. (2007). The FIRs are mostly found in the outer part of the Norwegian Channel (Fig. 5B), but they are also identified in the Skagerrak (Fig. 4C). Distinct reflector R1 is commonly irregular, but fairly well defined. The distinct reflector is less well defined in areas where iceberg turbation has occurred (Fig. 4B). This unit does not have a defined lower boundary for most of the study area due to the low penetration of the TOPAS data, but from other investigations, we know that it can reach considerable thickness (Rise et al. 1984), especially in the channel off Bergen where Sejrup et al. (1995) reported thicknesses of up to 60 m. However, in the Skagerrak, this unit is generally thinner (up to 30 m in the Skagerrak, but very thin or completely absent on the channel sides) and deposited directly on the underlying Mesozoic bedrock (Bøe et al. 1998).

Unit U2 is up to 100 m thick, but more commonly 5–20 m thick in the outer parts of the Norwegian Channel and 15–40 m thick in the Skagerrak. Unit U2 is characterized by an acoustic laminated facies with a medium to high amplitude. The bottom of this unit shares the boundary reflector (R1) with unit U1. The upper limit of the unit is characterized by a reflector (R2) of lower amplitude than R1. In areas where U1 and U2 are thick, it is possible that the base of U2 was not detected.

Unit U3 is an up to 50-m-thick sediment package (more commonly 5–10 in the outer parts of the channel and 5–20 m in the Skagerrak) that is characterized by an acoustic transparency, with a slight tendency towards weak laminations in its lower parts in some parts of the study area, most notably the Skagerrak. However, it should be noted that the strength of these laminations varies within the Skagerrak, with some parts hardly experiencing any lamination. The upper limit of this seismic unit is the sea floor (R3).

In general, the sediment thickness of units U2 and U3 is greater in the Skagerrak compared to the outer parts of the Norwegian Channel. Close to the shelf edge units U2 and U3 are about 7 m or less. In the inner parts of the Skagerrak, U2 and U3 are in total about 30 m in thickness. However, as can be seen in the along-channel profile (Fig. 5A), the sediments are thickest inside the mid-channel threshold, whereas in the area just north of this area, U2 and U3 are almost non-existent (Fig. 5B). In addition, the sediment thickness is greater in the western part of the channel, especially along its central parts (Fig. 4A) and in the southern part of the Skagerrak compared with the northern part (Fig. 4C). Furthermore, there are differences in sediment thickness and distribution over rather short distances, for example between the profiles in Fig. 4B, where unit U2 is significantly thicker than U3 in Fig. 4C.

**Sediment cores**

The sediment cores collected (Fig. 1) penetrate through units U3 and U2 and into U1 (Fig. 7). In the cores, the transition from U1 to U2 is reflected by a decrease in material coarser than 63 μm, shear strength, gamma density and magnetic susceptibility. Deeper in unit U1, the shear strength generally decreases, whereas the other parameters are more variable (Fig. 7B, D), with the caveat that the penetration in till is poor. Unit U1 consists of dark-grey, fine-grained sediments, with occasional sand and/or silt lenses, laminae and clasts (Fig. 7). Deformational structures, such as shear planes and shear zones, are also observed in the unit. Units U2 and U3 consist of fine-grained sediments with occasional shell fragments. The boundary between U2 and U3 (R2) is generally reflected in the grain-size distributions, where, based on the cores available, unit U3 contains much less coarse material in the Skagerrak, whereas U2 contains less coarse material in the outer parts of the Norwegian Channel (Fig. 7).

In the outer parts of the Norwegian Channel, the basal date in GS12-172-12GC shows an age of c. 17.8 cal. ka BP, whilst the dates higher up in seismic unit U2 show ages of c. 17.4 cal. ka BP and c. 16.9 cal. BP (Fig. 7A; Table 2). In GS12-172-13GC and GS12-172-11PC, the base of the seismic unit U2 has been dated to c. 18.8 cal. ka BP and 17.2 cal. ka BP, respectively (Fig. 7B, C; Table 2). The high shear-strength values in the lower part of unit U2 in core GS12-172-11PC do not correspond to any pronounced increase in either the magnetic susceptibility or the gamma density. However, the grain-size log shows a slightly higher content of coarser material, but not as high as in the upper part of the same unit, where the coarser material does not correspond to an increase in shear strength.

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**Fig. 4.** TOPAS sub-bottom profiler records. The locations of the lines are shown in Fig. 1. Note vertical exaggeration. Distinct reflectors R1–R3 are located between U1 and U2 (R1), U2 and U3 (R2) and above U3 (R3). A. Profile from the central part of the Norwegian Channel, showing MSGLs, GZWs and the identified three sedimentary units, in addition to the flat internal reflector denoting the boundary between soft and stiff tills. Note the lack of surface expression of the MSGLs and the thicker overlying sediments in the western end of the line. B. Profile from outside Lista, showing seismic character of units U1–U3. C. Profile from inner part of the Norwegian Channel, showing the character of units U1–U3. Note the thinner sediment cover on the northern part of the line.
The sediment core outside Lista, GS12-172-04PC, has 11 dates, mostly in stratigraphical order, with the lowermost two dates being reversed, ranging from 17.7 cal. ka BP to 11.9 cal. ka BP (Fig. 7D, Table 2). For the sediment core in the Skagerrak, GS14-191-01CC, the basal date shows an age of c. 17.6 cal. ka BP, noting that all dates within seismic unit U2 at this location also are in stratigraphical order (Fig. 7E, Table 2). At about 1100 cm in core GS12-172-04PC, there is a marked boundary in the gamma density, with higher values below that depth. This increase corresponds with higher upper values in the magnetic susceptibility, but not in the shear strength.

Discussion

In the following, we will discuss depositional environments and processes acting during the last retreat of the NCIS, and the style of retreat of the NCIS. Furthermore, we will establish a deglacial chronology of the Norwegian Channel and a mean retreat rate, which we compare with available retreat rates from the Antarctic.

Depositional environments and processes under, during and after NCIS retreat

Based on the shear strength measurements, grain-size data, structures, radiocarbon dates and biostratigraphy, sediments included in our seismic unit U1 has previously been interpreted as glacial till (Sejrup et al. 1994; Haflidason et al. 1995; Nygård et al. 2007). Our findings support this interpretation, and from the sediment lenses, shear planes and zones and banding in the diamicton, we interpret U1 to be a subglacial traction till (Evans et al. 2006; Ò Cofaigh et al. 2007; Reinardy et al. 2011).

The locally prominent flat reflectors (FIRs) within the till may be the boundary between the soft till representing the depth of the deformation layer at the time of deglaciation and stiff tills found below. Similar features have been identified in palaeo-ice stream beds on the shelves surrounding the Antarctic Peninsula (Ó Cofaigh et al. 2007; Reinardy et al. 2011) and in West Antarctica (King et al. 2009). Furthermore, Sejrup et al. (1995) reported denser sediments lower in the till at the Troll site in the Norwegian Channel. King et al. (2009) observed the formation of MSGLs underneath Rutford Ice Stream formed in the soft, dilatant till, and suggested that the stiffer tills surrounding the soft till may have experienced basal sliding. Most of the deformation of sediments underneath an ice stream occurs in the upper layers of the soft till, that is, the upper 3–25 cm, as reported from the bed of Whillans Ice Stream (formerly known as Ice Stream B; Engelhardt & Kamb 1998; Evans et al. 2006). Above the FIRs commonly found at 5–6 m depth below unit 2, the soft till was built up gradually, with the parts experiencing deformation moving up as the soft till became thicker, i.e. a subglacial traction till as described by Larsen et al. (2004).

Unit U2, characterized by an acoustic laminated facies, has previously been interpreted to be of glaciomarine origin and to have been deposited between the time of deglaciation and the end of the Younger Dryas.

Fig. 5. TOPAS sub-bottom profile from the continental shelf to the inner part of the Skagerrak. Distinct reflectors R1–R3 are located between U1 and U2 (R1), U2 and U3 (R2) and above U3 (R3). The location of the line is shown in Figs 1 and 3. Note vertical exaggeration. The large feature in (C) is underlain by bedrock and is probably not a GZW.

Fig. 6. Bathymetric data showing iceberg ploughmarks in the outer part of the Norwegian Channel. The location of the inset profile is shown by the red line crossing the largest ploughmarks. Figure location in Fig. 1.
Identification of ice-rafted debris in this unit in the investigated cores and the new dates supports this. Unit U2 is generally thicker on the side of the trough farthest from the Norwegian coast (Figs 4, 7), which is most likely due to ocean currents along the Norwegian coast (Longva & Thorsnes 1997). We also note that U2 and U3 are much thinner in the outermost parts of the Norwegian Channel. This might be due to influence of ocean currents, mainly the Norwegian Atlantic Current (Lekens et al. 2009), along the continental slope. The U2 unit sediments are thicker on the western side of the outer part of the Norwegian Channel (Fig. 4A), which Sejrup et al. (2016) related to deposition by the drainage of ice-dammed lakes south of Dogger Bank through the Ling Bank Drainage Channel during the unzipping of the NCIS and the British Ice Sheet sometime during 18.5–17 ka. Here, we suggest that the unzipping can be further constrained to the earlier part of that range, based on the available dates and the age-distance model (Fig. 8).

The uppermost mapped seismic unit, U3, is interpreted to consist of hemipelagic sediments, of Holocene age, deposited under marine conditions (Sejrup et al. 1989, 1994; Longva & Thorsnes 1997; Rise et al. 2004, 2008).
**NCIS retreat style and chronological constraints**

The MSGGLs mapped in the Norwegian Channel indicate fast-streaming ice consistent with the estimates of ice-stream velocity in the Norwegian Channel between 20 and 19 ka at ~3 km a⁻¹ by Nygård et al. (2007).

Dowdeswell et al. (2008) presented a framework whereby the landform assemblages found on the bed can be used to reconstruct the style of retreat of a palaeo-ice stream. The NCIS ice-marginal landforms presented in this study fit with the general model of Dowdeswell et al. (2008). The landforms may indicate that the retreat of the grounding line of the NCIS was episodic and/or slower in the outer parts of the Norwegian Channel than in the Skagerrak. The pattern of retreat may have changed once the grounding line retreated past the topographical threshold outside Stavanger, where no GZW-s occur. Inside this threshold, the retreat therefore seems to have been more rapid. Reverse-sloping beds, that is, beds that slope from the continental shelf edge, are thought to be inherently unstable (Schoof 2007). However, Jamieson et al. (2012) and Jones et al. (2015) showed that retreat along a reverse-sloping bed does not necessarily need to lead to a collapse of marine-based ice streams. Nevertheless, the presence of MSGGLs without any ice-marginal features seems to suggest that the grounding-line retreat in the inner part of the Skagerrak was continuous. However, in parts of the inner Skagerrak mass-wasting fans deposited on top of the glacial till (Longva et al. 2008) may have removed and/or buried ice-terminal landforms. These mass-wasting fans are derived from sediments from the shallower parts of the Norwegian Channel in the Skagerrak and have been deposited in the deeper parts of the trough sometime after deglaciation (Longva et al. 2008).

Iceberg ploughmarks in the Norwegian Channel are visible on the sea floor and can be discerned buried beneath units U2 and U3 (Figs 4B, 5C, 6). The visible ploughmarks can be found in the mid-Norwegian Channel, where there is a threshold of shallower water, meaning that larger icebergs that could float freely in the Skagerrak would drive their keels into the seabed around the threshold. The iceberg ploughmarks in the mid-Norwegian Channel are found at depths of down to 280 m b.s.l. (Figs 5C, 6). Because these ploughmarks are ploughed into an area where U1 sediments are very thin (Fig. 5C), they are of an uncertain age and could theoretically have been made during the deglaciation or the Younger Dryas when the outer Oslofjorden was a large calving bay (Fig. 9). Therefore we suggest that most of them are from immediately after deglaciation, as, if the Younger Dryas icebergs were large enough, we would expect to find iceberg scours from the NCIS at greater depths, especially due to the lower sea levels during the deglaciation. In comparison, the ploughmarks outside Lista (Fig. 4B) are buried and have undisturbed sediments covering them dated to c. 16.6 cal. ka BP. These ploughmarks are visible in the upper part of U1 and the lower part of U2, making the different units slightly harder to distinguish. The ploughmarks in the Skagerrak are found at around 430 m b.s.l. (Fig. 4B). Assuming a present-day sea level, the icebergs responsible would need to have a vertical thickness of almost 500 m. Factoring in the higher sea level in the Skagerrak during deglaciation, about 130 m higher than the present (Peltier et al. 2015), the icebergs would have to have been even larger.

The available dates from the Norwegian Channel directly above the contact with the till are found distributed from the North Sea Fan off the continental shelf edge, to the Skagerrak (Figs 1, 8, Tables 1, 2).

The lower part (below 1810 cm) of the glaciomarine sediment in GS-12-171-04PC is disturbed and contains two radiocarbon dates (16.8 and 17.7 cal. ka BP) that are reversed. However, the sediments show signs of icebergurbation in the seismic data and the core, with entire slabs of sediment rearranged vertically. Furthermore, the date of 17.7 cal. ka BP fits with the deglacial chronology from other parts of the Norwegian Channel, where the Troll area and the Skagerrak was deglaciated at around 18.4 and 17.6 cal. ka BP, respectively. Therefore, we consider the older date to better reflect the deglaciation of the Norwegian Channel outside Lista. Seismic data from the area also show evidence of turba tion (Figs 4B, 7D). Another possibility is that the terrestrial ice advanced from southern Norway into the eastern part of the channel after retreat of the ice stream, as suggested by Raunholm et al. (2003).

GS12-172-11PC (17.2 cal. ka BP; Figs 1, 7C) only has one date and is considered to represent a time slightly after the deglaciation due to a lower sedimentation rate or a later start of marine sedimentation following deglaciation. This is supported by the proximity of the core to the well-dated Troll cores 3.1 (Lehman et al. 1991) and 8903 (Sejrup et al. 1994; Haflidason et al. 1995), which yield basal dates of 17.9 and 18.4 cal. ka BP, respectively.

This may also be the explanation for the relatively young age (17.8 cal. ka BP) from core GS12-172-12GC (Figs 1, 7A). The North Sea Fan dates (19.7, 19.2...
and 19.1 cal. ka BP; Table 1) delimit the retreat of the grounding line from the continental shelf edge through basal dates of glaciomarine sediments deposited above glacigenic debrisflows deposited whilst the NCIS reached the shelf edge (King et al. 1998; Sejrup et al. 2003).

The dates from the core GS14-191-01CC are in stratigraphical order (after redating of an outlier (Fig. 7E)) and the basal date of 17.6 cal. ka BP fits with the deglacial dates from Denmark of 17.7 and 17.6 cal. ka BP at Lønstrup and Skagen, respectively (Knudsen et al. 1996; Richardt 1996). In addition, the deglacial age of 17.6 cal. ka BP at core GS14-191-01CC fits with the cosmogenic exposure dates from the Göteborg Moraine in southwestern Sweden, which have a mean age of 16.2 ka (Fig. 1; Larsen et al. 2012; Anjar et al. 2014).

The dates from the cores on Jæren, from the sites Eigebakken and Stemmavatn (Fig. 1, Table 1), with basal dates of 17.5 and 17.1 cal. ka BP, respectively (Paus 1989; Knudsen 2006; Sejrup et al. 2009), also show that the area was deglaciated after the Troll area (Lehman et al. 1991; Sejrup et al. 1994).

Svendsen et al. (2015) presented cosmogenic exposure ages from the island of Utsira. These dates suggest a deglaciation of the Norwegian Channel c. 1.5 ka earlier than previously published and new radiocarbon dates (Fig. 8, Table 1). However, the presented dates from the channel show a good fit with the existing radiocarbon dates from adjacent parts of Norway and Denmark and the cosmogenic exposure ages from southwestern Sweden. The internal consistency of the radiocarbon dates from the Norwegian Channel and southwestern Swedish cosmogenic exposure dates suggests that the samples from the island of Utsira (Svendsen et al. 2015), have inherited ages from prior exposure as also mentioned by Svendsen et al. (2015). This is further supported by a recent study by Briner et al. (2016), who showed the likelihood for inheritance at this location due to deep accumulation of $^{10}$Be favoured by light glacial erosion and long exposure times, making the ages significantly older. This, together with the wealth of other dates mentioned above, lead us to disregard the cosmogenic exposure ages from Utsira.

Based on these new and existing dates (Fig. 1, Tables 1, 2), we present an age-distance model for the deglaciation of the NCIS (Fig. 8). The retreat of the model is shown as having been linear, even though the retreat was episodic, as shown by the GZWs and end moraines, especially in the outer parts of the Norwegian Channel. This linearity is due to the distances involved, where the paucity of reliable ages would make a more detailed retreat pattern very

Fig. 9. Reconstruction of ice-sheet margin position in the North Sea during the last deglaciation. The reconstruction is based on this study and modified from Sejrup et al. (2016), Houmark-Nielsen et al. (2012), Stroeven et al. (2016), Anjar et al. (2014) and Hughes et al. (2016). YD = Younger Dryas.
uncertain. GZWs need stillstands or re-advances to accumulate. However, the length of the standstills or re-advances necessary is difficult to quantify. The retreat rate in Fig. 8 can therefore be considered a mean retreat rate for the deglaciation of the Norwegian Channel. The available dates from the inner part of the Norwegian Channel suggest a collapse in the Skagerrak, with marine ice-sheet instability on the reverse-sloping bed. From Lista (GS12-172-04PC), where the ice front retreated by c. 17.7 ka (Figs 7D, 8), to the Arendal terrace (GS14-191-01CC, c. 17.6 ka; Fig. 7E), a distance of about 180 km (Fig. 8), the retreat rate would have been much higher than 450 m a\(^{-1}\) at around 1800 m a\(^{-1}\).

Our results suggest a rapid retreat of the marine-based NCIS during the last deglaciation of the Fennoscandian Ice Sheet, with the Norwegian Channel being deglaciated in about 1500 years, from 19.1 to 17.5 ka.

### NCIS retreat rates and comparisons with other ice streams

The ice retreated from the continental shelf edge at around 19.1 ka and reached the Troll area at around 18.7 ka. The grounding line reached the Jären area at around 18.1 ka and the Skagerrak at 17.6 ka, before retreating to the Swedish west coast at around 17.5 ka. This gives a mean retreat rate of the NCIS of 450 m a\(^{-1}\).

Ice-stream retreat rates in Antarctica vary considerably amongst ice streams (Table 3; Livingstone et al. 2012; Larter et al. 2014), with mean retreat rates along the whole trough from 15 m a\(^{-1}\) in Belgica Trough to 80 m a\(^{-1}\) in Marguerite Bay (Shipp et al. 1999, 2002; Hillenbrand et al. 2010; Smith et al. 2011; Livingstone et al. 2012). The upper values of the Drygalski Basin range are similar to the mean retreat rate along the entire Norwegian Channel (Table 3). By comparison, the mean retreat rates of all Antarctic ice streams were much lower than that of the NCIS (Table 3).

Palaeo-ice stream beds have mostly been investigated in West Antarctica and the Antarctic Peninsula, such as Pine Island Bay and Marguerite Bay (Graham et al. 2010; Jakobsson et al. 2012; Jamieson et al. 2012; Livingstone et al. 2013), even though a study of Mackay Glacier in East Antarctica has recently been published (Jones et al. 2015). These troughs are similar to the Norwegian Channel in that they are deeper in the inner parts compared to the outer. Even though the ages of the Antarctic retreat do not coincide with the retreat of the NCIS, the patterns of retreat are similar, with GZWs and end moraines deposited by the retreating ice streams. MSGLs and other forms of glacial lineations are also found in all the formerly glaciated troughs. Work by Jamieson et al. (2012) and Jones et al. (2015) suggests that Marguerite Bay and Mackay Glacier, respectively, differ from both the Norwegian Channel and Pine Island Bay in that the Marguerite Bay Ice Stream seems to have remained stable even as it retreated across a reverse-sloping bed, whilst GZWs on the reverse-sloping bed in front of Mackay Glacier suggest slowdowns during retreat.

In Greenland, the deglaciation of the Uummannaq Ice Stream has been investigated (Roberts & Long 2005; Roberts et al. 2013). Based on available dates, the deglaciation of the ice stream has been estimated at 30 m a\(^{-1}\) (Roberts et al. 2013). In the southwestern part of Greenland, Winsor et al. (2015) investigated the mean retreat rates of outlet glaciers in four fjords (Table 3). Kelley et al. (2013) reported upper values of retreat for the Disko Bugt similar to the Drygalski Basin in Antarctica (Table 3; Shipp et al. 1999; Livingstone et al. 2012) and the Norwegian Channel. Overlapping with the retreat rates calculated by Kelley et al. (2013), Ó Cofaigh et al. (2013) calculated retreat rates between 22–275 m a\(^{-1}\) in the Disko Trough. On the southeastern coast of Greenland, Helheim Glacier retreat rates were calculated to be higher than 80 m a\(^{-1}\) (Hughes et al. 2012).

Table 3 furthermore shows that in northwestern Europe, the Irish Sea Ice Stream retreat rate and the shelf-edge area outside Andfjorden in north Norway are higher than the Antarctic and Greenlandic retreat rates, but lower than the Norwegian Channel.

### Conclusions

Based on the mapping of glacial landforms, interpretation of depositional environments and new radiocarbon dates from the Norwegian Channel, combined with previously published results from the region, we conclude as follows:

- The seismic profiles and the core data allow us to divide the deglacial and postglacial sediments into three units that represent a subglacial till (U1), a glaciomarine unit

### Table 3. Compilation of palaeo-ice stream retreat rates from Antarctica, Greenland and NE Europe.

<table>
<thead>
<tr>
<th>Palaeo-ice stream</th>
<th>Mean retreat rate along the whole trough (range in mean retreat rates) (m a(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgica Trough</td>
<td>15 (7–55) Hillenbrand et al. (2010); Livingstone et al. (2012)</td>
</tr>
<tr>
<td>Marguerite Bay</td>
<td>80 (36–150) Livingstone et al. (2012)</td>
</tr>
<tr>
<td>Drygalski Basin</td>
<td>76 (23–317) Shipp et al. (1999); Livingstone et al. (2012)</td>
</tr>
<tr>
<td>Uummannaq</td>
<td>30 Roberts &amp; Long (2005); Roberts et al. (2013)</td>
</tr>
<tr>
<td>Nuuk</td>
<td>65 Winsor et al. (2015)</td>
</tr>
<tr>
<td>Paamut</td>
<td>25 Winsor et al. (2015)</td>
</tr>
<tr>
<td>Qaqortoq</td>
<td>30 Winsor et al. (2015)</td>
</tr>
<tr>
<td>Disko Bugt</td>
<td>(30–450) Kelley et al. (2013)</td>
</tr>
<tr>
<td>Disko Trough</td>
<td>(22–275) Ó Cofaigh et al. (2013)</td>
</tr>
<tr>
<td>Helheim Glacier</td>
<td>80 Hughes et al. (2012)</td>
</tr>
<tr>
<td>Irish Sea</td>
<td>220 Chiverrell et al. (2013)</td>
</tr>
<tr>
<td>Andfjorden</td>
<td>310 Vorren &amp; Plassen (2002)</td>
</tr>
<tr>
<td>Norwegian Channel</td>
<td>450 This study</td>
</tr>
</tbody>
</table>
The grounding line of the NCIS started to retreat by stillstands off western Norway, a more rapid retreat outside Jæren, before the NCIS possibly collapsed once the grounding line reached the Skagerrak. The grounding line of the NCIS started to retreat from the continental shelf edge at c. 19 ka and the Norwegian Channel was completely deglaciated at c. 17.5 ka. The average retreat rate for the entire Norwegian Channel was 450 m a⁻¹. The pattern of the retreat of the Norwegian Channel Ice Stream is broadly similar to Antarctic ice streams such as the Marguerite Bay Ice Stream and the Pine Island Bay Ice Stream, with similar landform assemblages found on the palaeo-ice-stream beds. However, the mean retreat rates estimated for most of the other ice streams are generally lower (15–310 m a⁻¹).

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