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

Hans Petter Sejrup et al.

Mapping methodology

As the northern North Sea deglaciated the deeper parts were immediately inundated by the sea and deposition of glacial marine sediments dominated. Higher ground (e.g. southern North Sea) remained terrestrial, and subject to subaerial erosional and depositional processes, including the influence of large river systems, lacustrine environments and mass movements. With Holocene sea level rise, these land areas were first exposed to shore and then shallow marine processes resulting in extensive areas of sand-cover and its mobilisation. This is evident in the large number of sand waves especially in the southern parts (Fig. 1B).

Deciphering the glacial landscape below these Holocene features is a challenge. Where possible we used information from the shallow seismic data to separate out the glacigenic from the Holocene features. Sometimes we found the glacial landscape to be partly modulated by Holocene sand sedimentation, and with sand ridges often preferentially positioned (anchored) atop of glacial ridges (Fig. DR1C).

In Fig. DR1B we summarise our mapping, categorised as the following features:

Ice front position; these include well-defined, often arcuate ridges of undisputable glacial origin (end moraines) and curved features with a more wedge shaped cross-profile (grounding zone wedges) likely reflecting a longer stillstand of the ice margin or higher sedimentation rates. In some areas, especially in the SE part of the North Sea, internal structures and change in the roughness of the glacial terrain are indicative of ice front positions even if no clear ridge can be observed continuously along such boundaries. For the southwestern part of the North Sea the Bolders Bank limit has been included as a feature indicating maximum position of LGM ice in the North sea (Cameron et al., 1992).

Lateral Shear Zone Moraines (LSZM); ridges of till, metres in amplitude and tens of kms in length and typically straighter than end moraines or grounding zone wedges have been
interpreted as depositional ridges (Fig. DR1C) formed parallel to flow where glacial ice masses with different velocities join. *Lateral Moraines* have generally a more straight geometry than the LSZMs. We interpret the Tampen Moraine (Fig. 1A) as a typical lateral moraine.

*Channels;* linear incisions on the sea bottom or in the shallow subsurface (visible with acoustic tools) which may have been occupied by subglacial water flow during the last glacial phases.

*Lineations;* streamlined lineations of subglacial origin have been indicated in some areas but not extensively mapped as these features are often masked by postglacial processes and are usually only apparent on seismic data.

*Inclined ledges;* these features resemble terraces or steps but that are inclined longitudinally. They are found on the SW flank of the Norwegian Channel (Figs. 1B and DR1B) and are partly constructional forms developed in sediments interpreted to be of subglacial origin. Their mechanism of formation is unclear, but their location adjacent to a relatively narrow and shallow part of the channel suggests they were instrumental in the feeding of ice from the NCIS up onto the North Sea Plateau.
Figure DR1. Selected seismic (TOPAS) examples supporting the interpretations of landforms. Locations in Fig. 1A. A) Profile crossing the Tampen Moraine (TM) and ice marginal landforms (IML) associated with ice from the Norwegian Channel. Shells from the upper till associated with the Tampen Moraine have been dated to 22.4 cal. ka BP and three foraminiferal dates on a sand unit below till in this area are dated to c. 30 ka (Table DR1). The more irregular landscape (see inset) comprises overprinted moraines recording younger ice flow from the Shetland region of the BIS. Smooth Holocene sand (HS) bodies are recognised on top of the more irregular surface. Locally depressions in this surface are filled with acoustic laminated deposits likely to be of glacimarine origin (GM). B) From the Norwegian Channel towards southwest. Laminated glacial marine sediments are superimposed by acoustically transparent Holocene sediments in the channel. The acoustic homogeneous package under the Inclined Ledges (IL) can be traced into the upper till in the
channel. The irregular glacial morphology between the IL and the mapped ice front position (IFP) are underlain by sediments most likely representing till and tectonized acoustic laminated units, all partly masked by Holocene sand accumulations. C) Profile across a series of ridges interpreted to represent Lateral Shear Zone Moraines (L) on the Viking Bank. Note how the glacial morainic landscapes have been draped by Holocene sand (HS) accumulations. The faint reflectors under the hills represent the last glacial phase and the white patches represent parts where the sand is thick enough to mask out the acoustic signal. D) Ice marginal landforms (IMLs) south of Fladen Ground indicating a northwards retreating ice margin. GM ~ glacialmarine sediments.

Dates related to the last glacial phases

Absolute dates, which have been related to the last glacial phases of the North Sea, are available from the surrounding land areas (Shetland, Scotland, east coast of England, western Norway and Jutland) and from the North Sea itself (Fig. 1A and Table DR1). As seen from Fig. 1A most of the dates from the North Sea, are from sediment cores raised from the northern parts, which were below sea level during the last glacial stages, providing marine sequences with radiocarbon datable marine carbonate fossils. When appropriate, AMS $^{14}\text{C}$ dates mentioned have been converted to calendar age by using the CALIB v.7.0.2 program (Stuiver and Reimer, 2013) and the integrated marine reservoir correction curve and $^{12}\text{C}/^{13}\text{C}$ correction from Intcal13/Marine13 (Reimer et al., 2013) and $\Delta R$ set to zero.
Radiocarbon dates and cosmogenic exposure ages related to the last glacial phases in the North Sea (Birnie and Harkness, 1993; Borge, 2014; Graham et al., 2010; Hall and Jarvis, 1989; Holtedahl and Bjerkli, 1982; King et al., 1998; Knudsen et al., 1996; Krog and Tauber, 1974; Lehman et al., 1991; Lekens et al., 2006; Mangerud, 1977; McCabe et al., 2007; Nygard et al., 2004; Paus, 1989; Paus, 1990; Peacock, 2003; Peacock and Long, 1994; Penny et al., 1969; Phillips et al., 2008; Raunholm et al., 2004; Richardt, 1996; Rise and Rokoengen, 1984; Rokoengen and Rise, 1989; Ross, 1996; Sejrup et al., 1994; Sejrup et al., 2015; Sejrup et al., 2009; Sejrup et al., 1987; Svendsen et al., 2015). Especially for the coastal areas the list of dates is not complete, but the selection here is the most critical for our reconstruction. The radiocarbon dates have been calibrated to calendar year using the same procedure (see Data and Methods in main text) in order to make the dates comparable.

References for Supplementary Material


Paus, A., 1989, Late Weichselian Vegetation, Climate and Floral Migration at Eiebakken, South Rogaland, Southwestern Norway: Review of Palaeobotany and Palynology, v. 61, no. 3-4, p. 177-203.


