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Long-term record of Barents Sea Ice Sheet advance to the shelf edge from a 140,000 year record

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ABSTRACT

The full-glacial extent and deglacial behaviour of marine-based ice sheets, such as the Barents Sea Ice Sheet, is well documented since the Last Glacial Maximum about 20,000 years ago. However, reworking of older sea-floor sediments and landforms during repeated Quaternary advances across the shelf typically obscures their longer-term behaviour, which hampers our understanding. Here, we provide the first detailed long-term record of Barents Sea Ice Sheet advances, using the timing of debris-flows on the Bear Island Trough-Mouth Fan. Ice advanced to the shelf edge during four distinct periods over the last 140,000 years. By far the largest sediment volumes were delivered during the oldest advance more than 128,000 years ago. Later advances occurred from 68,000 to 60,000, 39,400 to 36,000 and 26,000 to 20,900 years before present. The debris-flows indicate that the dynamics of the Saalian and the Weichselian Barents Sea Ice Sheet were very different. The repeated ice advance and retreat cycles during the Weichselian were shorter lived than those seen in the Saalian. Sediment composition shows the configuration of the ice sheet was also different between the two glacial periods, implying that the ice feeding the Bear Island Ice stream came predominantly from Scandinavia during the Saalian, whilst it drained more ice from east of Svalbard during the Weichselian.

1. Introduction

High-latitude continental shelves have experienced multiple glacial advance and retreat cycles during the Quaternary (Dowdeswell et al., 1998; Ó Cofaigh et al., 2003; Svendsen et al., 2004a; Winsborrow et al., 2012; Patton et al., 2015). The ice dynamics and retreat of the Late Weichselian (29,000–14,000 years Before Present) ice sheets are quite well constrained because relatively well-preserved and dated sediments (Sættem et al., 1994; Vorren and Laberg, 1997; Landvik et al., 1998; Solheim et al., 1998) and submarine geomorphology (Ottesen et al., 2005; Andreassen et al., 2008; Winsborrow et al., 2010, 2012) allow reconstruction of ice sheet history. However, the most recent glacial advance and retreat reworked earlier sediments and overprinted older geomorphology, thereby obscuring the record of past ice behaviour. It is therefore difficult to reconstruct the timing of advance and retreat cycles and ice stream dynamics beyond the Late Weichselian (Ingólfsson and Landvik, 2013; Patton et al., 2015). An exception to this is the archive of continental-slope sediments which make up trough-mouth fans.

Trough-Mouth Fans are found at the outer margins of bathymetric cross-shelf troughs which extend across the continental shelf to the shelf edge (Batchelor and Dowdeswell, 2014). During full-glacial periods, these cross-shelf troughs are frequently filled by ice streams, which are curvilinear areas of fast-flowing ice that are critical to dynamics and stability of ice sheets (Ó Cofaigh et al., 2003; Schoof, 2007). Where ice streams overlie deformable sedimentary beds, exceptionally large volumes of debris can be transferred across the continental shelf (Dowdeswell and Siegert, 1999;

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Ó Cofaigh et al., 2003; Dowdeswell et al., 2010). Once deposited at the shelf edge, the glacial sediment is re-mobilised on the upper continental slope and redeposited by gravity-flow processes to form a Trough-Mouth Fan (Vorren et al., 1998; Nygard et al., 2005; Nygård et al., 2007). Sedimentary deposits that make up trough-mouth fans are therefore a potentially valuable long-term record of ice streams and their dynamics. This study focusses on the sedimentary record contained in the Bear Island Trough-Mouth Fan.

1.1. Regional setting

The Bear Island Trough-Mouth Fan is situated beyond the Bear Island cross-shelf trough (Fig. 1). The trough is about 150 km wide and 500 m deep at its mouth and served as a major drainage pathway for the Barents Sea Ice Sheet. The Bear Island Trough-Mouth Fan covers an area of 215,000 km^2 and has a volume of approximately 395,000 km^3 (Vorren and Laberg, 1997; Taylor et al., 2002a, 2002b). It is one of the largest sediment accumulations on Earth, with a volume comparable to submarine fans developed offshore of the World's largest rivers. Sediment accumulation here is episodic and its rate can be an order of magnitude greater than is seen on river-fed systems (Dowdeswell et al., 2010).

The Bear Island Trough-Mouth Fan extends from the continental shelf edge at water depths of ~500 m to over 3000 m in the Lofoten Basin (Fig. 1). The most recently active (Late Weichselian) part of the Bear Island Trough-Mouth Fan is at the northern end of the fan and covers ~125,000 km^2 (Taylor et al., 2002a, 2002b). Here, side-scan sonar mapping revealed a series of low backscatter, debris-flow lobes that radiate out from the top of the fan with runout distances of up to 490 km (Fig. 1; Laberg and Dowdeswell, 2016). Each of these numerous debris-flows is estimated to have remobilised ~15–20 km^3 of sediment. They are also thought to indicate the presence of ice at (or close to) the shelf edge (Vorren and Laberg, 1997; Taylor et al., 2002a). However, no previous study has dated a long record of stacked debris-flows on the Bear Island Trough-Mouth Fan due to the thickness of these debris-flow deposits (Laberg and Vorren, 1995).

In this study we demonstrate a novel methodology for understanding the growth and decay of ice streams by dating the times at which the Bear Island Ice stream was at the shelf edge. This is achieved using muddy distal deposits on the lower part of the Bear Island Trough-Mouth Fan beyond glacigenic debris-flows higher up the continental slope (Figs. 1 and 2).

1.2. Aims

Our aim is to address the following questions. First, can multiple glacigenic debris-flows on the Bear Island Trough-Mouth Fan be dated and can they be used to reconstruct a history of the advance and retreat of the Barents Sea Ice Sheet? Secondly, did the dynamics of the Barents Sea Ice Sheet vary between different advance and retreat cycles and can this information be elicited from glacigenic debris-flow deposits? As an example, does the lithofacies or geochemical composition of glacigenic debris-flows vary? Last, can we use glacigenic debris-flows to help understand the controls on marine-based ice sheet retreat?

2. Material and methods

The principal data source for this paper is a suite of gravity cores collected during cruise 64PE391 of the RV *Pelagia* to the Norwegian Sea in 2014. These cores are supplemented by gravity cores collected during cruises JR51 and JR142 of the RRS *James Clark Ross* in 2000 and 2006 respectively (Table 1). In addition, the paper uses geophysical data collected during cruises of the RV *Pelagia* in 2014 and RRS *James Clarke Ross* in 2000. These data comprise 3.5 kHz sub-bottom profiler records and 6.5 kHz GLORIA side-scan sonar imagery with a swath width of about 20 km.

2.1. Core logging

Cores were logged visually, identifying colour, facies and grain size. Cores were also analysed using a Geotek MSCL core logger for p-Wave velocity, gamma-ray density and magnetic susceptibility. Measurements were taken at a 0.5 cm resolution. X-radiographs of cores PE73 and PE75 were taken using an ITRAX μXRF core scanner. X-radiograph conditions were 60 kV and 45 mA, with a dwell time of 400 ms, at a resolution of 200 μm (Croudace et al., 2006).

2.2. Dating

2.2.1. Radiocarbon dating

Monospecific samples of the planktonic foraminifera *Neogloboquadrina pachyderma* sinistral from PE73 and PE75 were dated by Accelerator Mass Spectrometry (AMS). The radiocarbon ages were converted to calibrated ages (Cal years BP) using the Marine 13 database (Reimer et al., 2013).

2.2.2. Coccolithophore biostratigraphy

To provide accurate and robust datum horizons beyond radiocarbon dating, coccolithophore biostratigraphy was used. Toothpick hemipelagite samples were taken, from which species abundance counts were made. Species present were counted using a *Hitachi TM1000 SEM* which enabled high resolution (1000–10,000×) images to be taken. The species present in each sample were counted for abundance across 10 fields of view on the *SEM* at a magnification of 2000.

These abundance counts were then compared to coccolith abundances that had previously been made by Gard (1988) and Backman et al. (2009). These two studies demonstrated that abundances of *Emiliania huxleyi, Gephyrocapsa mullerae, Gephyrocapsa caribbeanica, Gephyrocapsa apperta, Calcidiscus leptoporus* and *Coccolithus pelagicus* could be calibrated to oxygen isotope stages in the polar North Atlantic. Each datum horizon is outlined in Table 2 and Fig. 3.

2.2.3. ITRAX μXRF geochemistry

ITRAX μXRF was used to collect high resolution (1 mm) major element geochemical records from four cores. Cores PE73, PE75, GC08 and JR142 were analysed using this method. Proxy dating was achieved by removing glacigenic debris-flow deposits from the cores to leave the hemipelagite μXRF records. The hemipelagite calcium (Ca) record was used as a proxy for $\delta^{18}O$ as changes should be primarily driven by changes to biogenic $CaCO_3$ production which is affected by changing surface water conditions, changing circulation patterns and sea level (Richter et al., 2001; Cheshire et al., 2005; Croudace et al., 2006; Rothwell et al., 2006; Lebreiro et al., 2009; Hibbert et al., 2010; Solignac et al., 2011; Hunt et al., 2013). Located on the distal areas of the Bear Island Trough-Mouth Fan, hemipelagite composition should therefore reflect open water conditions. The μXRF calcium record, combined with AMS dating and the Coccolith biostratigraphy enables a robust chronology of glacigenic debris-flows on the fan to be constructed.

2.3. Dating glacigenic debris-flows

Dating of glacigenic debris-flows on the Bear Island Trough-Mouth Fan was achieved in the upper part of the core using ^{14}C AMS dates. Average hemipelagic accumulation rates between