Quaternary Science Reviews 68 (2013) 126–141

Contents lists available at SciVerse ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

The marine-based NW Fennoscandian ice sheet: glacial and deglacial dynamics as reconstructed from submarine landforms

Tom Arne Rydningen [a,b,*], Tore O. Vorren [a], Jan Sverre Laberg [a], Vidar Kolstad [b]

[a] Department of Geology, University of Tromsø, N-9037 Tromsø, Norway
[b] DONG Energy E&P Norge AS, Roald Amundsens Plass 1, N-9257 Tromsø, Norway

ARTICLE INFO

Article history:
Received 24 August 2012
Received in revised form
5 February 2013
Accepted 7 February 2013
Available online 16 March 2013

Keywords:
Ice streams
Mega-scale glacial lineations
Shear zone moraines
Last Glacial Maximum
Deglaciation dynamics

ABSTRACT

The configuration of the marine-based NW Fennoscandian ice sheet during the Last Glacial Maximum (LGM) and deglaciation is reconstructed using detailed swath bathymetry and high-resolution seismic data. The investigated area covers about 10,000 km^2 of the continental shelf off Troms, northern Norway. Large scale morphology is characterized by cross-shelf troughs, coast-parallel troughs and banks. Based on mega-scale glacial lineations (MSGL), lateral and shear zone moraines and grounding zone systems, the extent and dynamics of the ice sheet during the LGM are deduced. MSGL indicate fast-flowing ice streams in the cross-shelf troughs, while the glacial morphology on the banks indicates more sluggish ice here. The marine-based part of the Fennoscandian ice sheet was sourced from ice domes in the east via fjord and valley systems inshore. Using a balance flux approach, we estimate palaeo-ice stream velocities during the LGM to be approximately 350 m/year. Three deglaciation events have been reconstructed: i) During the Torsken-1 event the ice sheet halted or readvanced to form groundings zone wedges (GZW) and the Torsken moraine, ii) Several still-stands or readvances characterized the ice behaviour on the shallower banks during the Torsken-2 event, iii) During the Flesen event, prominent end moraines in the inner parts of the troughs and banks were deposited. The locations of the end moraines and GZW in the troughs indicate that the retreat of marine-based ice streams in areas of reverse bed slope was episodic, probably mainly due to the variation in widths of the cross-shelf troughs.

1. Introduction

During the Late Weichselian glacial maximum ice sheets in both the Arctic and Antarctic advanced across the continental shelf to reach the shelf break (Svendsen et al., 2004; Shaw et al., 2006; Livingstone et al., 2011). Submarine landforms were preserved on the seabed, revealing the temporal and spatial variability of these ice sheets, as well as their dynamics, (e.g. Ottesen et al., 2005a; Ó Cofaigh et al., 2008). Palaeo-ice sheet behaviour can be separated into fast-flowing ice streams and slower flowing ice, much like ice sheets in Antarctica and Greenland are today (Thomas, 2004; Rignot et al., 2011). Elucidating the response of such fast-flowing outlets to external forcing (e.g. sea level fluctuations and climate change) is critical for the understanding of how modern ice streams will respond to current and future climate change. Detailed seabed data is available for continental shelves and fjords, enabling regional interpretations of the submarine landforms. Here, we combine swath-bathymetry with high-resolution seismic data to investigate the seabed geomorphology of the formerly glaciated continental shelf off Troms, northern Norway (Fig. 1).

Approximately 20 palaeo-ice streams were active on the Norwegian continental margin, from the North Sea to Svalbard, during LGM (Ottesen et al., 2005a). On the continental shelf off Lofoten-Vesterålen-Troms (between 67°30′ and 70°30′) there were four marked ice streams; the Vestfjorden–Trænadjupet ice stream, the Andfjorden ice stream, the Malangsdjupet ice stream and one here named the Rebbenesdjupet ice stream (Fig. 1) (Ottesen et al., 2005a, 2008; Laberg et al., 2009). The former was by far the largest, covering an area of 20,000 km^2 from the inner parts of Vestfjorden to the shelf break. The three other ice streams (this study) each covered an area of approximately 700–1400 km^2.

The sediments in the outer Andfjorden trough have been described as a prograding wedge with an oblique slope profile, consisting of stacked glacigenic debris flows (Vorren and Plassen, 2002; Dahlgren et al., 2005). During the Late Weichselian glacial maximum, as well as during previous maxima, large quantities of

* Corresponding author. DONG Energy E&P Norge AS, Roald Amundsens Plass 1, N-9257 Tromsø, Norway. Tel.: +47 99 23 65 80.
E-mail addresses: tomry@dongenergy.no, tom_arne_r@yahoo.no (T.A. Rydningen).

0277-3791/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.quascirev.2013.02.013

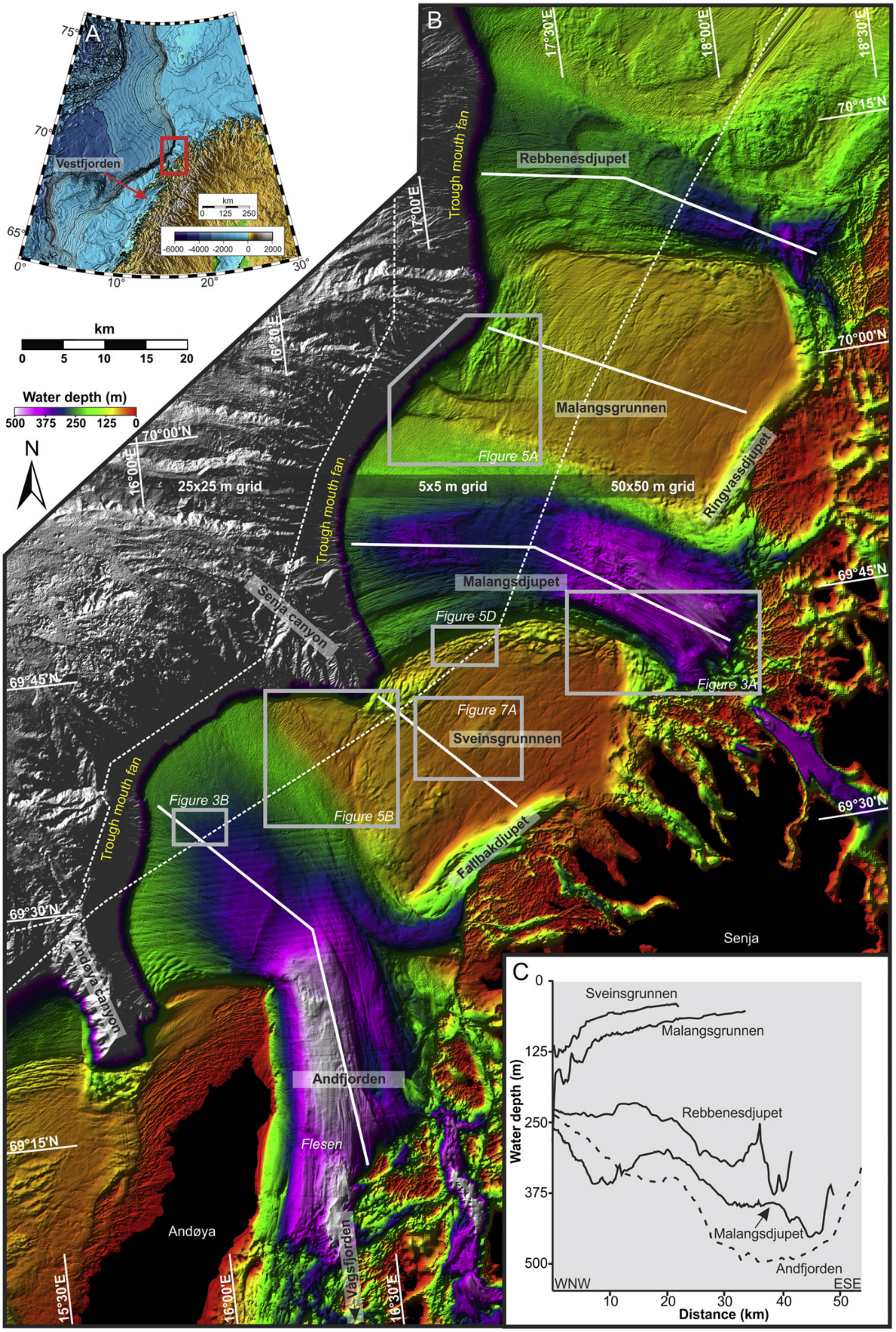

Fig. 1. A: Key map created using the Generic Mapping Tools (GMT) software (Wessel and Smith, 1998). B: Shaded bathymetry map of the study area outside Troms County, Northern Norway. Illumination is from SE. The dotted lines delimit different data sets with different spatial resolution. White lines locate bathymetric profiles shown in C at the bottom right corner.

glacigenic sediments were transported onto the continental margin (Vorren and Laberg, 1997; Dahlgren et al., 2005). These sediments are inferred to have been deposited at the shelf break as till wedges and later redistributed down the palaeo-slopes as gravity flows. It has been found that a major portion of these sediments were brought onto the continental shelf via fast-flowing ice streams in the cross-shelf troughs (Vorren and Laberg, 1997; Ottesen et al., 2005a).

Earlier studies of the seabed and subsurface sediments in the study area indicate several grounding zone systems in Andfjorden and Malangsdjupet (Holtedahl, 1940, 1953; Andersen, 1965, 1968; Rokoengen et al., 1979; Vorren et al., 1983; Vorren and Plassen, 2002; Ottesen et al., 2005a,b, 2008). These have been related to still-stands or readvances during the general retreat of the ice sheet from the continental shelf. Vorren and Plassen (2002) concluded that the ice sheet reached the shelf break twice during the last 26.3 ka cal BP (22 ka ^{14}C BP). The identification of flutes, or mega-scale glacial lineations (MSGL), in the troughs, has been taken as evidence for the location of palaeo-ice streams in these areas (Vorren and Plassen, 2002; Ottesen et al., 2005a,b, 2008). The origin of ridges on Malangsgrunnen and Sveinsgrunnen has been debated. In the early days a littoral origin was favoured (e.g. Holtedahl, 1940; Andersen, 1968; Rokoengen and Dekko, 1993, 1994). This was later falsified by Fjalstad and Møller (1994) and Møller (2000), showing that the offshore data was in conflict with the onshore shoreline data.

Mapping of landforms at the seabed has been carried out by the MAREANO project (www.mareano.no). This project confirms that the majority of the landforms were formed during the last glaciation.

In this study we aim to: 1) Evaluate the glacial geomorphology of troughs and banks in the study area, 2) Identify the spatial and temporal variations of ice flow and the glacier dynamics, and 3) Reconstruct the deglaciation patterns in the study area.

2. Physiography

The area of investigation covers about 10,000 km^2 of the continental shelf outside Troms, northern Norway. The large scale morphology is characterized by three shelf-crossing troughs, Andfjorden, Malangsdjupet and Rebbenesdjupet, separated by the banks of Sveinsgrunnen and Malangsgrunnen (Fig. 1). Two coast-parallel troughs are located east of these banks: Fallbakdjupet and Ringvassdjupet (not previously named). The contact between the Mesozoic rocks offshore and the crystalline bedrock inshore follows these troughs.

The banks have a smooth, seaward-dipping topography with water depths ranging from 30 to 170 m (Table 1 and Fig. 1). The troughs are WNW–ESE oriented elongated features with over-deepened thalwegs. Here, water depths vary from 80 to 515 m, and the troughs progressively deepen landwards and shallow towards their margins at the shelf break (Table 1 and Fig. 1). The troughs are narrowest in the inner/mid part, and widest at the shelf break. Water depth at the shelf break is significantly deeper in the troughs (>250 m) compared with the banks (100–150 m).

The continental slope is dominated by trough mouth fans (TMF) and canyons (Kenyon, 1987; Vorren et al., 1998; Taylor et al., 2000; Laberg et al., 2007b), and the slope gradient is among the steepest on the Norwegian continental margin, averaging at 10°, 9° and 4° in Andfjorden, Malangsdjupet and Rebbenesdjupet, respectively.

The continental shelf off Troms is presently dominated by two water masses: Atlantic water of the Norwegian Current and coastal water of the Norwegian Coastal Current. The former is flowing northwards along the outer shelf and upper continental slope, with some water masses entering the cross-shelf troughs (Sætre, 2007). The north-flowing Norwegian Coastal Current water dominates on the inner continental shelf lying as a westward thinning wedge over the Atlantic water. The seabed topography has a strong control on the distribution and horizontal circulation through the water column (Sundby, 1984).

Table 1
General morphometry of first-order landforms on the continental shelf off Troms. The lengths and widths are maximal values.

	Width (km)	Length (km)	Water depth (m)	Area (km^2)
Andfjord	40	60	80–515	1400
Sveinsgrunnen	40	25	30–140	820
Fallbakdjupet	5	28	150–300	180
Malangsdjupet	30	50	130–450	1100
Ringvassdjupet	5	15	100–170	50
Malangsgrunnen	30	35	50–180	970
Rebbenesdjupet	25	50	130–390	700

3. Data and methods

The swath-bathymetric data was collected by the Norwegian Hydrographic Service between 1990 and 2004 using Simrad EM100 and EM1002. Within 12 nautical miles from the shoreline the data is available as UTM-points with 50 × 50 m horizontal spacing. Outside this boundary the data is available as 5 and 25 m points (Fig. 1). The areas with highest resolution were gridded with 10 × 10 m horizontal spacing. The gridding and visualization were done in UTM zone 32 N using the Global Mapper® software. Different displays, artificial illumination sources and vertical exaggeration have been applied to the data to obtain the best possible imaging of the seabed morphology. In order to define the lateral extent of bedforms as precisely as possible, colour-scale slope shader and slope shader direction functions were used. In addition, parallel ship track lines and other artefacts were noted to avoid misinterpretations. The swath bathymetry data was provided to the University of Tromsø through the Norway Digital program.

The high-resolution seismic data was collected by the Norwegian Defence Research Establishment in 2001. The seismic lines are oriented NW–SE and cover mainly the shelf areas. A dominant frequency ranging from 110 to 130 Hz yields theoretical vertical resolution of 3–4 m (1/4 of the seismic wavelet, at an assumed shallow sediment velocity of 1600 m/s). The seismic data is of good quality above the first seabed multiple but below this most primary reflections are masked by noise.

Radiocarbon dates from earlier studies were calibrated according to Reimer et al. (2009).

4. Observations and interpretations

Systematic mapping of the continental shelf off Troms resulted in the identification of over 2000 individual glacial landforms (Fig. 2). These can be used to reconstruct the extent and behaviour of the ice masses during the LGM and the following deglaciation. Below we describe the characteristic geomorphology of the landforms, which is also summarized in Table 2.

4.1. Streamlined landforms

Distinct flow-parallel and streamlined landforms, or lineations, were observed as sets of linear to slightly curved ridges and furrows in the cross-shelf troughs (Figs. 2 and 3). In general, longer lineations are located in the inner parts of the troughs (Fig. 3A). The most elongated lineations occur in Malangsdjupet, with a length/width-ratio varying from 2:1 to 47:1, averaging at 13:1. A particularly high

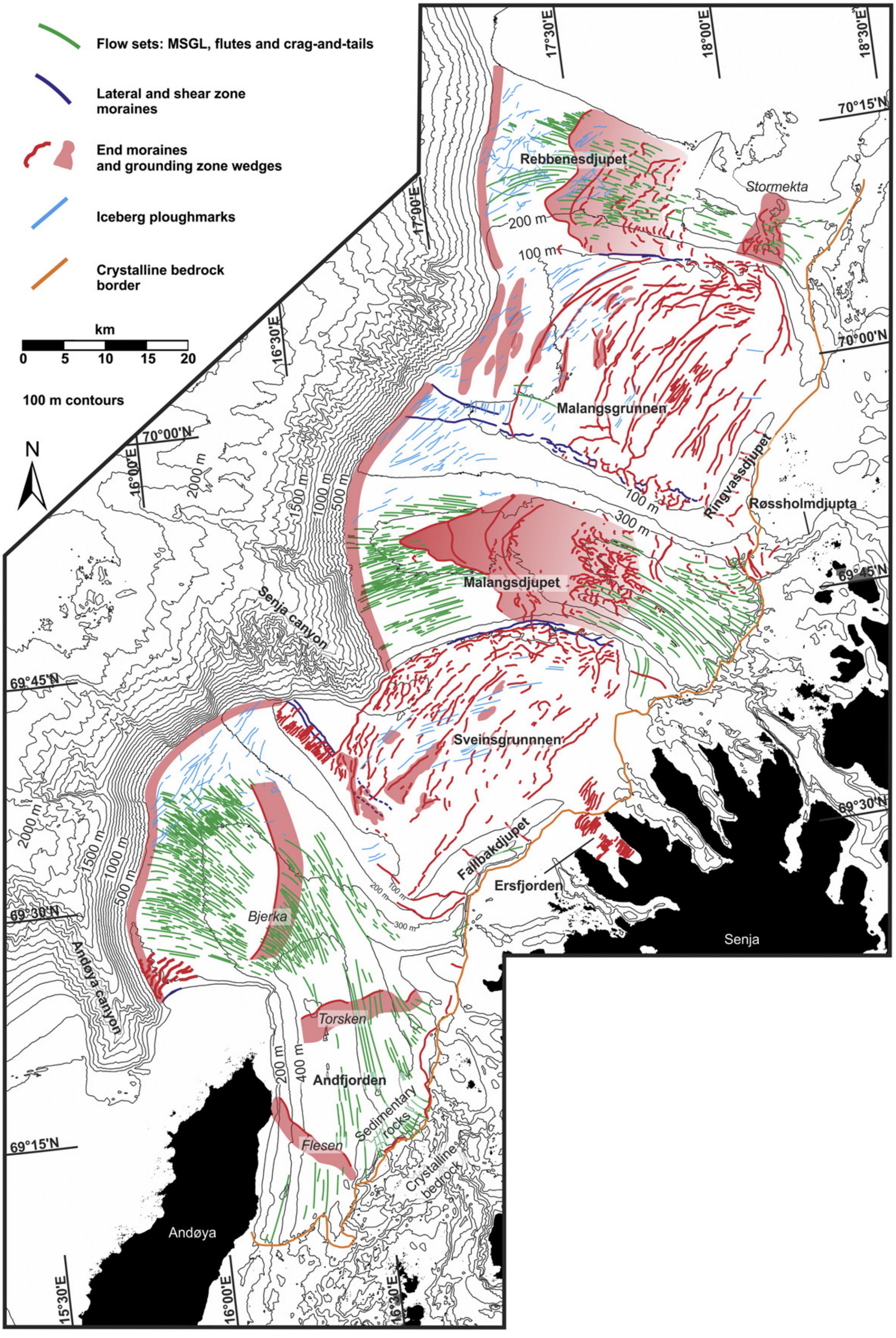

Fig. 2. Geomorphological map of the study area showing the glacial landforms identified on the continental shelf. Orange line denotes the contact between crystalline bedrock in the east and sedimentary rocks in the west. Bathymetric contour interval is 100 m.

Table 2
Dimensions of glacial landforms.

	Length (km)	Width (m)	Relief (m)	Transverse spacing (m)
Glacial lineations	0.2–15	100–200	1–60	100–500
Lateral moraines	0.5–15	50–300	1–15	N/A
Major grounding zone systems	Up to 20	10,000–12,000	8–100	N/A
Small recessional moraines	0.2–15	100–2000	5–20	100–1000
De Geer moraines	0.5–3	100	1	200–300
Iceberg ploughmarks	0.2–10	100–150	8	N/A

density of lineations was observed at the outer parts of Andfjorden (Fig. 3B). Streamlined lineations on the banks are mostly absent, except for two elongated ridges on Malangsgrunnen (Fig. 2).

In the inner parts of the troughs the lineations often initiate at bedrock knobs and narrow downstream forming crag-and-tails (Fig. 3A). All three cross-shelf troughs demonstrate a convergence of lineations towards the narrow mid-troughs and then divergence where they reach the shelf break (Fig. 2). In Malangsdjupet, the diverging pattern is less developed, and the lineations are largely confined to the deeper parts of the outer trough. Two larger elongated ridge systems in inner Andfjorden comprise several lineations. The ridge systems have a relief of approximately 90 m, lengths of 15 and 5 km, and widths of 5 and 1.7 km, respectively.

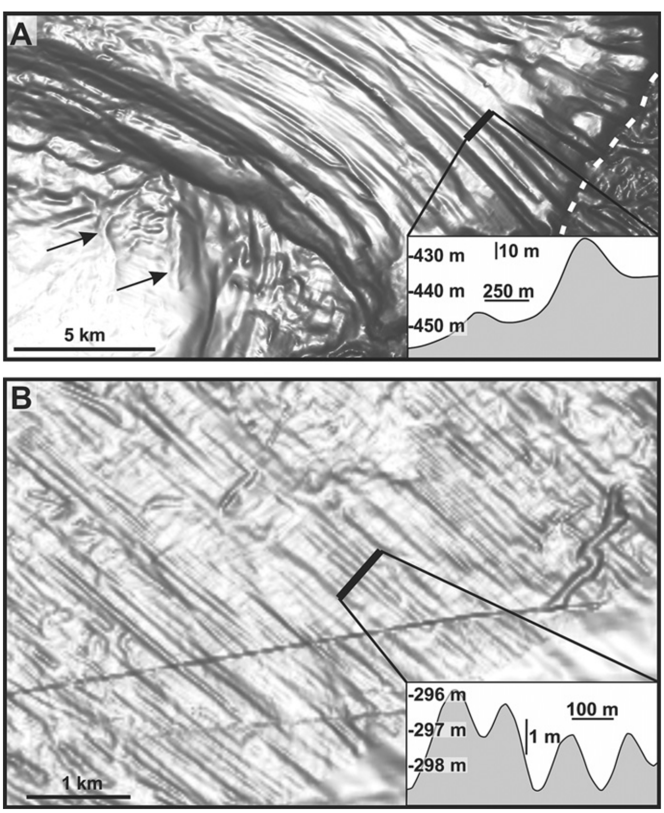

Fig. 3. Shaded relief image displaying mega-scale glacial lineations (MSGL), flutes and crag-and-tails in the cross-shelf troughs (see Fig. 1 for location). A: Inner parts of Malangsdjupet. MSGL initiate at the contact between the crystalline and sedimentary bedrock (broken line). The bathymetric profile shows lineations approximately 300 m wide and some exceeding 10 m height. Arrows indicate crosscutting marginal moraines on Sveinsgrunnen. B: Outer parts of Andfjorden where a high density of lineations is observed. The bathymetric profile shows that the lineations are approximately 100 m wide and 1 m high here.

The ridges have blunt stoss sides and tapered lee sides, and occasional protuberances on the proximal flanks.

Sediment cores from the ridges in Andfjorden contain glacial diamictons (Vorren and Plassen, 2002). Accordingly these streamlined landforms are interpreted as flutes, MSGL and crag-and-tails, formed subglacially, and herein collectively termed “glacial lineations”. Elongated landforms with length/width-ratios > 10 indicate formation beneath fast-flowing ice (Stokes and Clark, 1999), i.e. at a warm-based sole. Thicker ice generates greater insulation and more frictional heat which enhances basal meltwater production and lubricates the bed, with a positive feedback promoting fast flow (Paterson, 1994). An increase in heat production will also promote greater deformation, and will further enhance fast flow, as the ice viscosity is dependent upon temperature (Clarke et al., 1977). Finally, thicker ice allows the pressure melting point to be reached earlier than in thinner ice, making it more likely that fast flow is initiated in troughs (Winsborrow et al., 2010). Thus the elongated landforms in the troughs were most likely formed beneath relatively thick ice-streams in Andfjorden, Malangsdjupet and Rebbenesdjupet.

A long-going discussion persists regarding the genesis of MSGL, i.e. whether they are products of deposition, erosion, or their combination (Clark, 1993; Clark and Stokes, 2003; Ó Cofaigh et al., 2005). In this study, we find elongated ridges extending into the troughs, initiated at protrusions near the crystalline–sedimentary bedrock contact (Fig. 3A). These landforms are therefore depositional products, formed in lee-side basal cavities under the ice, created as the glacier flowed over the bedrock highs. For the outer parts of the troughs, no such bedrock knobs are observed upstream of the glacial lineations, such that other processes are likely responsible. One possibility is that converging ice at the narrowest parts of the troughs created sub-vertical shear zones within the glacier, with the formation of keels at the ice bed (Clark and Stokes, 2003). Hence, these lineations could be more erosional remnants than depositional products.

4.1.1. Flow sets of glacial lineations

As illustrated in Fig. 4, the glacial lineations were grouped into five flow sets based on their position in the cross-shelf troughs. A flow set is defined as an assemblage of landforms which demonstrate a spatial coherency and a glaciologically plausible pattern (Winsborrow et al., 2010). Lengths and widths were measured on a sample of these. These measurements are probably not reflecting the exact values for all of the lineations, as the width of the individual lineation may vary downflow. Some of the lineations are also overprinted by other landforms and buried by glaciomarine and marine sediments (see figure 2 in Vorren and Plassen, 2002). Also, differences in data quality between the inner and outer parts of the troughs influence the identification of lineations. However, the values are reliable enough to indicate changes throughout the data set.

A downflow increase in elongation ratio for the flow sets is observed: length/width-ratios greater than 10 (long and narrow) represent only 27% of occurrences in the inner troughs contrasting with 62% in the outer troughs. Of the lineations exceeding 2000 m in length in the outer flow sets, that is, the best preserved lineations, >85% in Malangsdjupet and >70% in Andfjorden and Rebbenesdjupet had an elongation ratio greater than 10:1 (Fig. 4). Hence, a high number of MSGL were found in the outer flow sets. We believe they relate to the LGM preserved through rapid deglaciation of the troughs. Grounding zone systems, described in Section 4.3, imply transportation of sediments to the mid/inner trough and associated re-moulding and burial of the LGM lineations, thus masking recognition of the (possibly denser) population of MSGL in the narrow middle parts of the troughs. The inner flow sets were probably formed during the deglaciation.

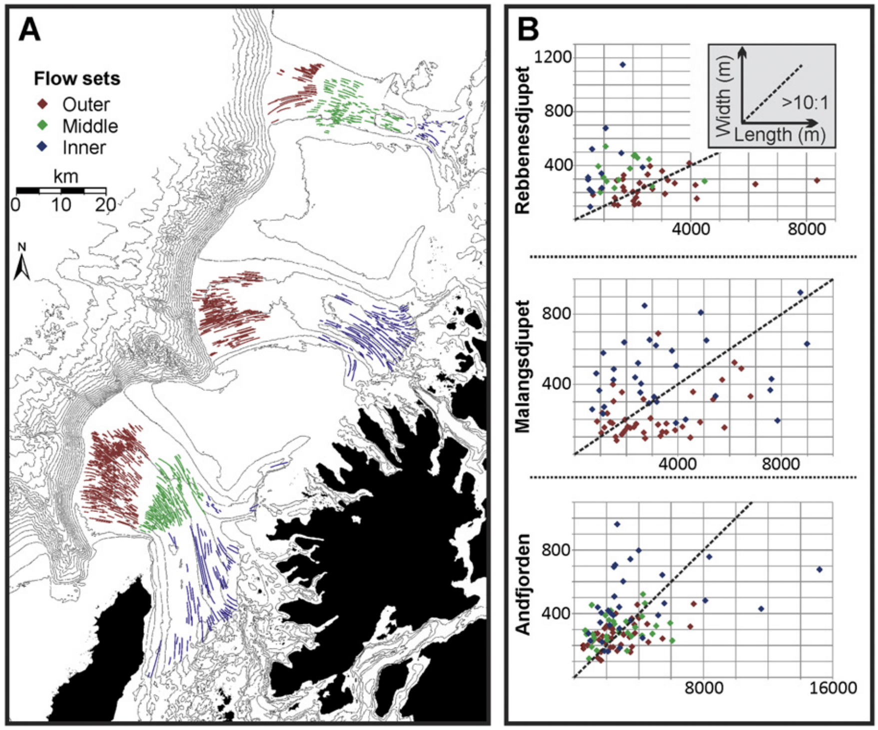

Fig. 4. A: The allocation of the inner (blue), middle (green) and outer (red) flow sets. See text for details. B: Measurements of lengths and widths of a sample of the flow sets. Lineations plotted below the dotted line have a length/width-ratio > 10, i.e. these are considered to be MSGL.

This proximal to distal increase in elongation ratio for the flow sets is similar to observations made in Antarctica (Wellner et al., 2001; Graham et al., 2009) and Canada (Stokes and Clark, 2002a), where greater length/width-ratios are related to greater ice flow velocities. In our study area it is evident that the streamlined landforms do not just record a single phase of palaeo-ice flow representing subglacial conditions during the LGM (Wellner et al., 2001; Graham et al., 2009). Rather, the bedforms are believed to be formed during the LGM as well as during the early deglaciation. The presence of grounding zone wedges (GZW) supports this interpretation (Figs. 2 and 4).

4.2. Ridges on the trough–bank transition

Longitudinal ridges occur in the border zones between the troughs and banks (Fig. 2). The most pronounced are sets of double ridges at the northern trough mouth flanks of Andfjorden and Malangsdjupet (Figs. 2, 5A and B). In Andfjorden, the ridges can be followed 9 km landwards from the shelf break before they are crosscut by younger ridges (Fig. 5B), while the ridges in Malangsdjupet are burying older ridges (Fig. 5A). Seismic profiles crossing the northernmost ridge on Malangsdjupet show a prograding reflection pattern (Fig. 5C).

Pronounced ridges are located at the northern margin of Sveinsgrunnen, and gradually smaller, more discontinuous ridges occur further onto the bank (Fig. 5D). The latter are parallel to the troughs, but often with an irregular appearance. The ridges have a relief of a few metres, lengths from 500 m to 15 km and widths ranging from 50 to 200 m. Similar ridges, although not that prominent, are observed along the margins of Malangsgrunnen–Malangsdjupet and Malangsgrunnen–Rebbenesdjupet (Fig. 2). The majority of the ridges exhibit a steeper flank towards the trough axis. On seismic profiles truncated clinoforms are observed at the trough–bank slopes, implying net erosion, likely via fast-flowing ice streams in the troughs (Fig. 5E).

We interpret the ridges at the northern trough mouth flanks to be lateral moraines, while the ridges found at the trough–bank borders are interpreted to be lateral shear zone moraines (LZSM). Lateral moraines are related to the lateral margins of the glacier, i.e. ice-free conditions prevailed distally to these (see further discussion below). LSZM indicate the lateral transition from fast-flowing ice in the troughs to passive ice on the banks, i.e. their formation is linked to the high stress gradient and resultant shear zone between fast- and slow-flowing ice at the ice-stream lateral margins (e.g. Bentley, 1987). The transition zones between domains of different velocities were probably prone to shearing at the base of the glacier. We propose that cracks developed along-flow into longitudinal cavities, and sediments derived from the erosive ice streams were then squeezed into these, partly filling them, in a mechanism similar to that invoked by Stokes and Clark (2002b). The LSZM at the southern rim of Malangsgrunnen fades out towards the shelf break, from which we infer a gradual northwards decrease in shear zone magnitude of the ice stream in Malangsdjupet.

Just as for MSGL, the presence of LSZM is one of the geomorphological criteria diagnostic of palaeo-ice streams (Stokes and Clark, 2001). As shown in Fig. 2, we infer LSZM at all trough–bank borders, except for the Andfjorden–Sveinsgrunnen transition. As noted by Stokes and Clark (2002b), LSZM are not always present in the geological record where ice streams were active. As such, the exact lateral extents of shear zones are not straightforward to determine. In addition, it is also difficult to separate LSZM from any subsequent (e.g. deglacial) formation of end moraines (see Section 4.3). We believe that the majority of the ridges are marginal moraines, and only a few of them represent LSZM (Fig. 2).

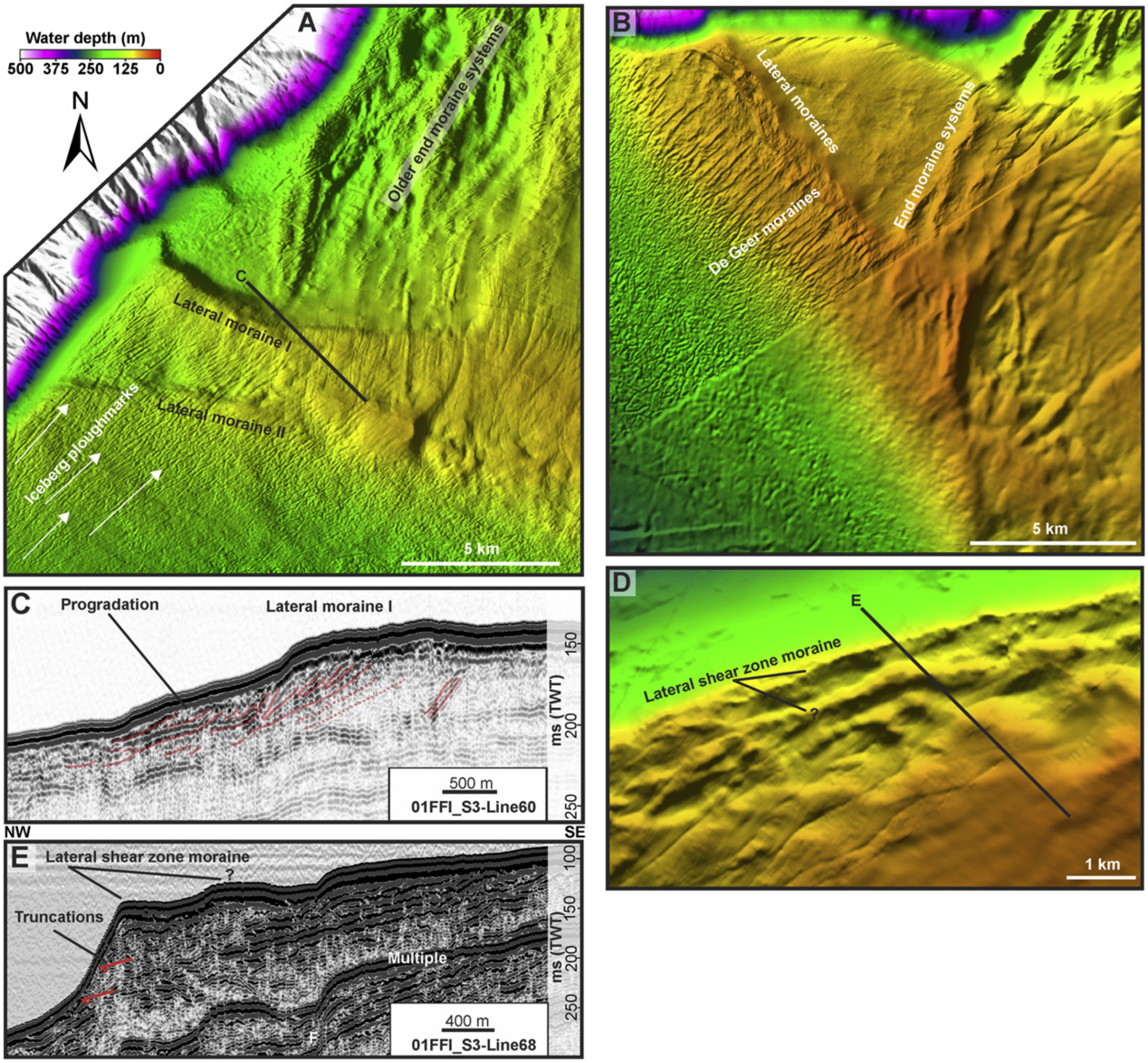

Fig. 5. Colour shaded relief images of lateral and shear zone moraines (see Fig. 1 for location). A: Outer parts of southern Malangsgrunnen. Lateral moraines extend to the shelf break, burying older end moraines. Iceberg ploughmark orientation indicated by white arrows. B: Outer parts of southern Sveinsgrunnen. Lateral moraines extend to the shelf break and are cross-cut and covered by younger end moraines and De Geer-type moraines. C: Seismic profile across a lateral moraine showing a prograding reflection pattern (see A for location of profile). D: Northern rim of Sveinsgrunnen showing prominent lateral shear zone moraines (LSZM). E: Seismic profile across LSZM (see D for location of profile). Truncated reflectors against the bank slope indicate ice stream erosion in the troughs.

4.3. Grounding zone systems

Here, we present new observations of grounding zone systems which both conform to those in the literature and new forms, not previously described. We differentiate between classic marginal moraines (morainal banks of Powell and Alley, 1997) and grounding zone wedges. Marginal moraines have a clear positive relief, contrary to grounding zone wedges, which are more subdued and tend to develop where vertical accommodation space may be restricted by a floating ice shelf (even if only of limited extent) (Dowdeswell and Fugelli, 2012). The Torsken and Stormekta moraines (Figs. 2 and 6A) have not been described before.

4.3.1. The Bjerka moraine

The Bjerka moraine was originally interpreted as a 1–4 km wide end moraine with a relatively limited spatial extent by Vorren and Plassen (2002). The greater detail afforded by swath-bathymetry allows the observation that the Bjerka moraine is more extensive, up to several tens of km northwards (Figs. 2 and 6A). It is likely that the moraine, in fact, reached the shelf break and was since overprinted by flutes (Vorren and Plassen, 2002). The Bjerka moraine has a concave form and is oriented NNE–SSW to N–S. It is covered with 5–50 m of glaciomarine and marine sediments (Vorren and Plassen, 2002). The highest relief of the ridge is approximately 25 m.

4.3.2. The Egga grounding zone wedges

The Egga moraines, now termed the Egga grounding zone wedges, are situated at the shelf break (Norwegian "Egga" refers to "the edge"). Generally, the wedges have a steep distal part conforming to the continental slope and a gentle proximal slope. As described by Vorren and Plassen (2002), seaward dipping clinoforms observed on seismic show that the wedges prograded towards the shelf break in Andfjorden. Similar patterns are recognized in the other troughs, as exemplified for Malangsdjupet in Fig. 6B. In addition, the glacial lineations record advances of the

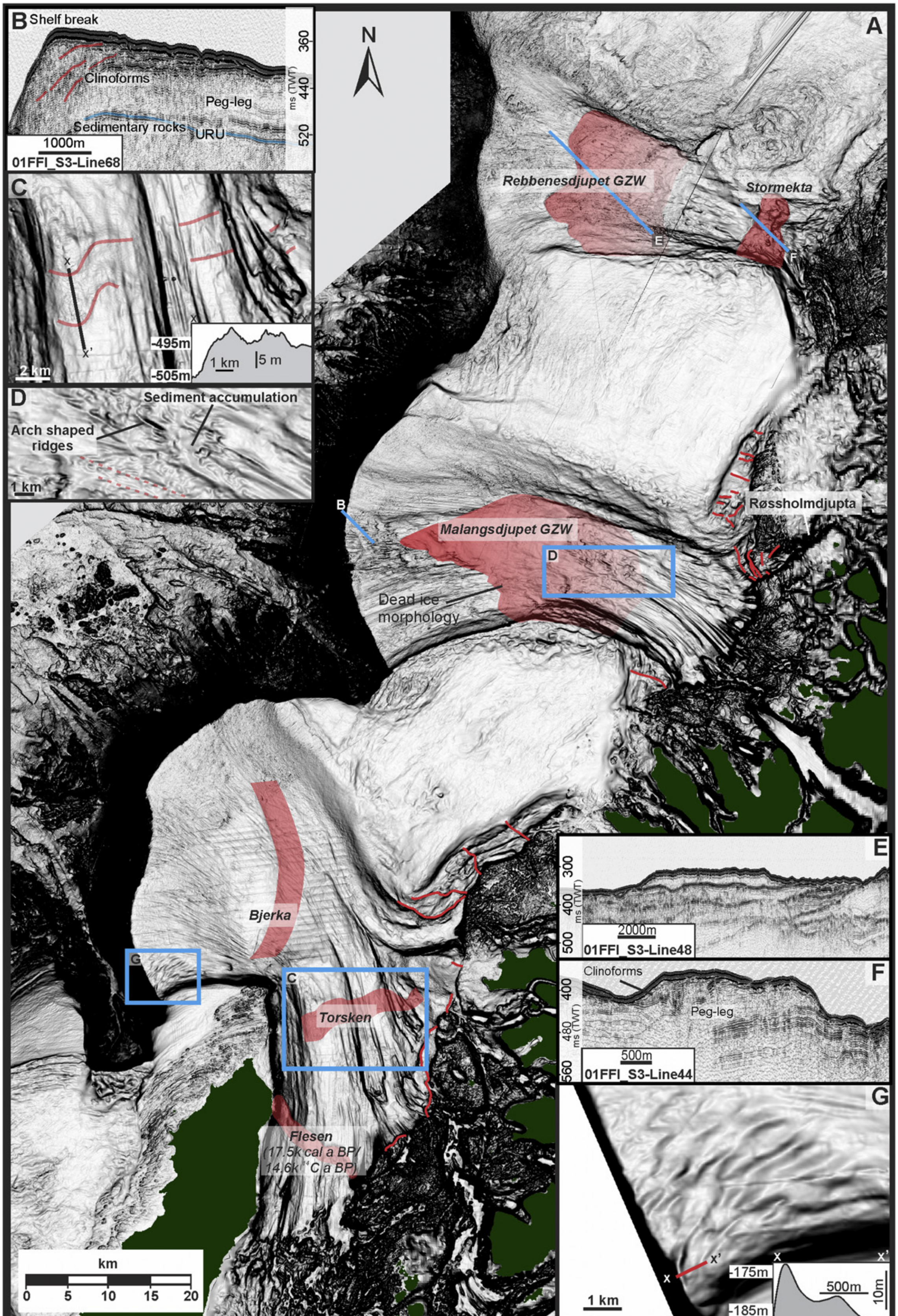

Fig. 6. A: Slope shader image of the continental shelf where end moraines and grounding zone wedges (GZW) in the troughs are indicated in red. Dead-ice morphology is also indicated. Blue lines are locations of seismic profiles. B: Seismic profile across the shelf break showing prograding clinoforms. The upper regional unconformity (URU) separates sedimentary rocks below and glacigenic sediments above. C: Slope shader image of the Torsken moraine. The bathymetric profile shows that the moraine has a ridge both in the distal and proximal part. D: Slope shader image of arch shaped ridges on the proximal part of the GZW in Malangsdjupet. Buried MSGL are indicated by red broken lines. E: Seismic profile across GZW in Rebbenesdjupet. The internal seismic character of the wedge is transparent. F: Seismic profile across the Stormekta moraine. Prograding clinoforms occur in the distal part. G: Detailed slope shader of ridges on outer Andfjorden.

glacier to the shelf break position. It is not clear to us if the GZW represents one or more glacial advances.

4.3.3. The Torsken moraine

The Torsken moraine is situated in middle Andfjorden located at the narrowest part of the trough (Fig. 6A and C). The moraine is 3 km wide with a relief varying from 8 to 15 m. The accumulation is widest and most prominent in the west. Here the accumulation has a ridge both in the distal and proximal part. The height of the accumulation decreases as it narrows eastwards towards the crystalline bedrock contact.

4.3.4. The Flesen moraine

The ridge-like Flesen end moraine (Vorren et al., 1983; Vorren and Plassen, 2002) is oriented NW–SE in inner Andfjorden (Fig. 6A). The moraine comprises two parallel ridges, and is widest in the western part (approximately 4 km), narrowing eastward before it terminates at the crystalline bedrock. The relief of the ridge varies from 20 to 40 m. The moraine can be followed up the steep slope of the western sub-trough of Andfjorden. The Flesen moraine is dated to 17.5 ka cal BP (14.6 ka ^{14}C BP) (Vorren and Plassen, 2002). A possible continuation of the moraine is observed approximately 13 km to the NE in Andfjorden, where a NNE–SSW trending sediment accumulation is located (Fig. 6A). The moraine is also located at a narrow part of the trough.

4.3.5. Grounding zone wedges in Malangsdjupet and Rebbenesdjupet

Major grounding zone wedges are observed crossing Malangsdjupet and Rebbenesdjupet about 7 km landwards from the shelf break (Fig. 6A). The wedge in Malangsdjupet is approximately 15 km wide, spanning the whole trough, and up to 20 km long. The highest relief is in the proximal part (approximately 100 m), and the accumulation has an approximate maximum thickness of 120 ms (TWT), corresponding to 100 m of sediments. The internal seismic character of this wedge is described as transparent by Ottesen et al. (2008). Several transverse-oriented ridges are observed crossing the wedge (Fig. 2). The distal part narrows into lobes, interpreted to represent limits of flow transport of sediments originating at the glacier terminus. The proximal flanks have an irregular topography, indicative of dead-ice morphology (Fig. 6A), as described by Rüther et al. (2011) from the outer Bjørnøyrenna sediment wedge in the SW Barents Sea. Distinct transverse-oriented arch shaped ridges with relief from a couple of metres up to 20 m occur in the proximal part of the GZW (Fig. 6D). The ridges are closely spaced and some are aligned. Some ridges superpose others, implying several generations of ridges. The ridges appear as single features as well as bundles, constituting an overall larger convex shape (Fig. 2). Single ridges extend 250–1000 m in length across the trough; while the ridge complexes could be followed up to 5 km. Sediment accumulations distal to some ridges overprint glacial lineations (Fig. 6D). The convex downflow shape indicates that the ridges were deposited and/or pushed at the ice front during still-stands or readvances of the ice margin.

The wedge in Rebbenesdjupet is approximately 16 km wide, again spanning the trough, and extends down-ice a length of 15 km. Highest relief is observed at the distal part (up to 25 m). The internal seismic character of the wedge is transparent (Fig. 6E) and thickness reaches 40 ms TWT, corresponding to 30 m of sediments. Seismic profiles demonstrate that the distal border of the wedge is sharp while the proximal border is indistinct. The proximal wedge is a thin (10 ms) but continuous lens (Fig. 6E). Similar to the Malangsdjupet wedge, transverse, abundant arcuate ridges superimpose the wedge. Glacial lineations are preserved between these ridges (Fig. 2).

4.3.6. The Stormekta moraine

A 4 km wide accumulation is observed in inner Rebbenesdjupet (Fig. 6A). The relief of the accumulation is generally 40–50 m and up to 80 m in the northern part. The top of the deposit has an irregular topography with several transverse ridges. The depocentre is, again located at the narrowest part of the trough. Seismic profiles crossing the ridge show clinoforms in its distal part (Fig. 6F). We interpret these to represent sediments deposited at or just up-ice of the glacier front, probably at a halt of the glacier during the deglaciation.

4.3.7. Smaller marginal morianes in the troughs

Transverse ridges are observed crossing Fallbakdjupet and Rebbenesdjupet. Also, ridges occur in front of Røssholmdjupta (Fig. 6A). The ridges vary in dimensions, with the largest being over 20 m high and 2 km long. In general, the ridges were 3–4 km wide, approximately 10 m high and 500 m long. We interpret these ridges to be marginal moraines.

4.3.8. Ridges in outer Andfjorden

On the shallow southern trough mouth of Andfjorden, at water depths from 180 to 225 m, SW–NE trending ridges are observed (Figs. 2, 6A and G). Their relief varies from 5 to 15 m, with spacing from 500 to 1000 m. The ridges have a wavy character in plan view, and several form a lobe towards the shelf break. Modelling studies suggest that there are strong bottom currents (up to 1.2 m/s) along the outer flank of Andfjorden (Bellec et al., 2010). These currents could create sediment waves, such as Bøe et al. (2009) describe in the Hola trough off Vesterålen. A similar genesis is possible for the features in Andfjorden. However, the orientation and lobate form of the ridges and the lack of rhythmic regularity characteristic of sandwaves suggest a glacial front origin, probably formed during the early deglaciation of the trough. Here, water depth is shallower compared to the central parts of the troughs, allowing the glacier to remain grounded for a longer time. Ice masses and sediments could therefore continue to flow towards the shelf break and accumulate as lobate formed ridges. Nevertheless, post-glacial modification of the ridges from bottom currents is likely.

4.3.9. Marginal moraines on the banks

Numerous transverse ridges are observed on the banks, stretching from a few hundred metres to 15 km long, with the majority being 2–3 km (Fig. 2). The heights and widths are approximately 5 m and 100–300 m, respectively. The majority of ridges are curved, with the convex part oriented NW. Ridge crests spacing is generally a couple hundred metres. The highest population of ridges is observed on outer Sveinsgrunnen (Fig. 2). Some of the ridges on the banks are cross-cutting (Figs. 3A and 7A). The majority of the ridges are asymmetrical in cross-section, with the gentle slope dipping landwards. Thrusted intervals and buried ridges are observed on seismic profiles (Fig. 7B).

Wider ridges (500 m to 2 km) with a greater relief (5–20 m) are observed near the shelf break on Malangsgrunnen (Fig. 5A). The water depth here is generally 30–50 m deeper than the rest of the bank. Internal thrusted intervals were observed on seismic profiles, similar to those mentioned above.

Small transverse parallel ridges are observed overprinting lateral moraines at the shelf break in both Andfjorden and in Ersfjorden, off Senja (Figs. 2 and 5B). The spacing between the ridges is fairly uniform, ranging from 200 to 300 m. The height of the ridges is about 1 m, and the lengths range from 500 to 3000 m.

Rokoengen and Dekko (1993) interpret some of the described ridges on Malangsgrunnen as beach ridges, whereas Fjalstad and Møller (1994) argue for a glacigenic origin. The observations made here indicate that the ridges are marginal moraines, probably

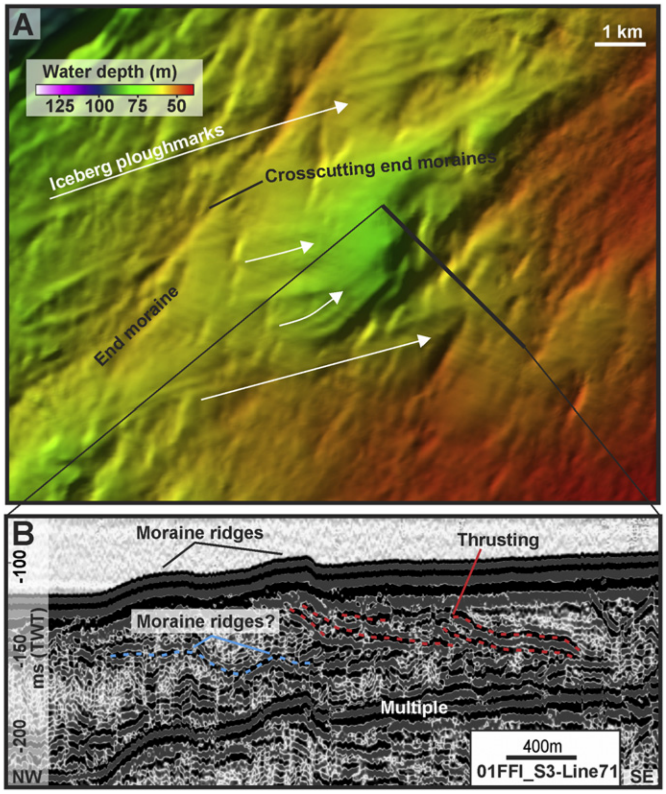

Fig. 7. A: Colour shaded relief image displaying end moraines on the central parts of Sveinsgrunnen (see Fig. 1 for location). Crosscutting end moraines and iceberg ploughmark orientation indicated (white arrows). B: Seismic profile across end moraines. Thrusted intervals indicate ice movement across the bank. Possible buried moraine ridges are indicated.

formed during still-stands or readvances superimposed on a general glacier retreat from the banks. The small ridges are interpreted as De Geer moraines, reflecting annual recession (Lindén and Möller, 2005) but similar, non annual ribbed moraines are just as likely. Such transverse ridges are typical of inter ice stream settings on shallow banks (Ottesen and Dowdeswell, 2009). The wider ridges at the shelf break on Malangsdjupet are probably older moraine ridges, as they are partly buried by younger lateral moraines.

4.3.10. The spatial distribution of grounding zone systems

Grounding zone systems superpose the flow sets, and are therefore related to the last deglaciation. An important exception to this is the Bjerka moraine, which will be discussed later. Spatial and temporal correlation of grounding zone systems among the troughs and between the troughs and the banks is not straightforward but we build some argument through similarities of setting and an internally consistent reconstruction. In the cross-shelf troughs we observe three end moraines; Torsken, Flesen and Stormekta. Two GZW are observed; one in each of the troughs of Malangsdjupet and Rebbenesdjupet. Based on similar size, morphology and position in the troughs, we believe that the GZW were formed synchronously or nearly so. Applying the same reasoning to the end moraines, we infer that the Stormekta and Flesen moraine were concurrent. The Torsken moraine and the GZW mark the outermost grounding episode during the deglaciation of the troughs. Hence, we infer these to be concurrent.

Bank to trough slopes are steep, preventing formation and/or preservation of moraines and complicating correlation attempts between the ice stream and banktop caps. Grounding zone systems are more numerous on the banks (Fig. 2), indicating several halts/readvances during the deglaciation. Also, grounding zone systems in the troughs are one order of magnitude wider and higher (Table 2). This suggests that the moraines on the banks record shorter lived events during the deglaciation (Lindén and Möller, 2005; Ottesen et al., 2007).

4.4. Iceberg ploughmarks

Curved furrows from iceberg-seabed interaction occur both in the troughs and on the banks (e.g. Figs. 2 and 7A). The depths of these vary from 1 to 8 m, with the deepest being located in the troughs. The lengths vary from a couple of hundred metres to 10 km. The widths of the furrows are from 100 to 150 m. The furrows are V- or U-shaped in cross-profile and levees are observed. In the outer, northern parts of the troughs the furrows are oriented sub-parallel to the shelf break (Fig. 5A), while they have a more random orientation landwards. On the banks, the furrows are oriented in an E–W direction. Several of these terminate towards the moraine ridges described above, and some end up in semi-circular depressions (Fig. 7A).

Iceberg scours are common features in front of marine glaciers, and were probably formed during the Late Weichselian deglaciation. Lien (1983) identified icebergs in Andfjorden, Malangsdjupet, and near the shelf break on Malangsgrunnen. He also identified iceberg scours close to the crystalline bedrock contact in Andfjorden. However, based on swath-bathymetry, Plassen and Knies (2009) interpret these as pockmarks. The iceberg scours observed on the banks in our study area have not been described earlier.

Iceberg drift direction during the deglaciation was probably heavily influenced by the Norwegian Current, which transported Atlantic water northwards alongside the shelf break during this time (Ślubowska-Woldengen et al., 2008). The icebergs closest to the shelf break were probably most influenced, while those with a more random trace, often in the troughs, were less so.

Icebergs scouring on the banks were smaller, given lesser draft, and this is reflected in shallower furrow depths. A clear relationship between the depth of a ploughmark and the size of the iceberg has been demonstrated (Dowdeswell and Bamber, 2007). The semi-circular depressions may be formed by larger icebergs that grounded either because they were too big to float, or by icebergs that rolled over and grounded on the seafloor as previously described by Bass and Woodworth-Lynas (1988) based on studies from the Labrador shelf.

5. Discussion

Based on mapping of the landforms, ice sheet configurations during the LGM and subsequent deglaciation events have been reconstructed (Figs. 8 and 9). The flow sets, lateral moraines and LSZM were used in the reconstruction of the glacier dynamics during full glacial conditions. Correlations of ice-marginal landforms formed the basis for reconstructing the ice sheet retreat from the continental shelf. The work of Vorren and Plassen (2002) is the most recent study of the glaciation/deglaciation history of the area. They suggest two LGM events (Egga-I and II) and two offshore deglaciation events (Bjerka and Flesen). We cannot identify with certainty an Egga-I event and therefore we will start our discussion on the glaciation/deglaciation history with the Bjerka event. In addition to the abovementioned we find two deglaciation events (Torsken-I and II), which gives a total of 5 glacial events in the submarine realm in this area which we will discuss: Bjerka, Last Glacial Maximum, Torsken-1, Torsken-2, and Flesen.

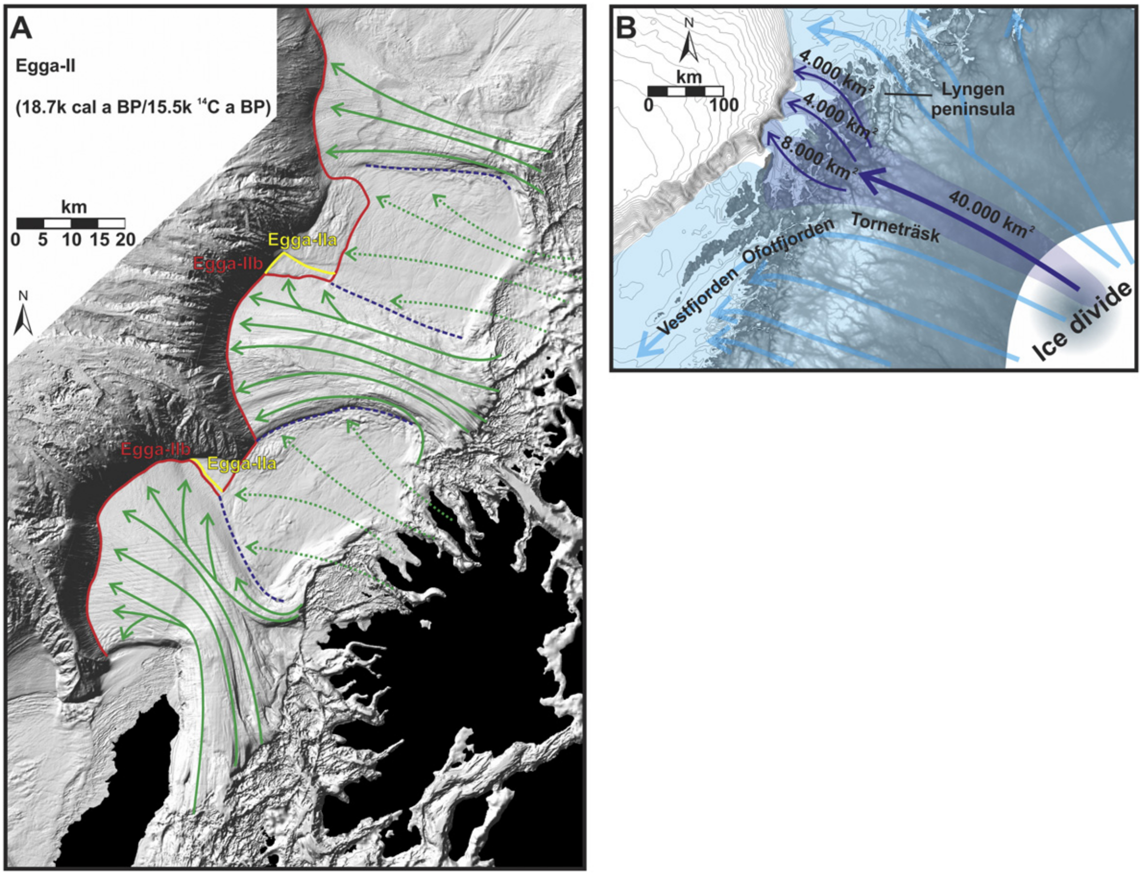

Fig. 8. A: Reconstruction of the ice configuration on the continental shelf during the LGM (Egga-II). Yellow and red lines indicate ice positions during Egga-IIa and Egga-IIb, respectively. Unbroken and broken green lines indicate fast and sluggish ice flow direction, respectively. Dashed blue lines indicate shear zones between fast-flowing and passive ice. B: Tentative reconstruction of major drainage routes for the Fennoscandian Ice Sheet during the LGM is drawn on the map from Jakobsson et al. (2012). Drainage areas are indicated with dark blue shading and numbers. Ice flow directions are indicated with arrows.

5.1. The Bjerka event

We speculate that the concave extension of the Bjerka moraine across Andfjorden is due to a dominating source of glacier ice draining from Senja and Sveinsgrunnen. The accumulation of ice masses in the deeper basins further east (Vågsfjorden: see Fig. 1) needed more time to build up and source the ice stream in Andfjorden. Thus the Bjerka event probably occurred in an early stage of the ice sheet build up, before the ice stream in Andfjorden received substantial ice from the S/SE.

It is not straightforward to determine either the relative or the absolute age of the Bjerka event. Vorren and Plassen (2002) suggested that it occurred between their Egga-I and II events, i.e. approximately 23.5 ka cal BP (19.7 ka ^{14}C BP).

5.2. The Last Glacial Maximum (Egga-II) – reconstructions and ice stream velocities

Several geomorphic and stratigraphic studies concluded that an ice sheet covered the continental shelf off Troms during LGM (Andersen, 1965; Andersen, 1968; Vorren et al., 1983; Vorren and Plassen, 2002; Ottesen et al., 2008). The glacier flow pattern has been reconstructed on a regional scale along the western margin of the Fennoscandian ice sheet and the Barents Sea/Svalbard ice sheets by Ottesen et al. (2005a). In a study from the coastal parts of northern Norway, Ottesen et al. (2008) propose palaeo-ice streams in the cross-shelf troughs separated by passive ice on the banks during the LGM.

LSZM demarcate the abrupt transition between fast-flowing ice in the troughs and passive ice on the banks. The lateral moraines deposited by the ice streams near the shelf break on Sveinsgrunnen and Malangsgrunnen mark the absolute lateral extent of the glacier during the LGM. These occur as double ridges, implying two glacial advances during Egga-II (Egga-IIa and Egga-IIb; see Fig. 8A).

There exists no absolute age determination for the Egga-II event. Vorren et al. (1988) suggest that the Fennoscandian Ice Sheet receded from the Endleten moraine on Andøya about 18.7 ka cal (15.5 ka ^{14}C BP). This event was later tentatively correlated with the diamicton tG from cores in outer Andfjorden, i.e. the Egga-II event (Vorren and Plassen, 2002). A diamicton is also described from Malangsdjupet (Vorren et al., 1983), which could reasonably be correlated to the Andfjorden diamicton.

MSGL extend to the shelf break in each of the cross-shelf troughs, and TMF dominate the slope morphology (Fig. 1). This indicates ice-streams under full-glacial conditions with focused sediment delivery to the trough mouths (Vorren and Laberg, 1997; Stokes and Clark, 1999) (Fig. 8A). The general absence of streamlined landforms, with the exception of flutes on Malangsgrunnen (Fig. 2), indicates slower moving ice on the banks. We infer that the ice was thin here, and possibly cold based during the LGM. The glacier margins on Sveinsgrunnen and Malangsgrunnen did not extend to the shelf break everywhere. An ice-free triangle shaped area north of the lateral moraines is inferred on Sveinsgrunnen

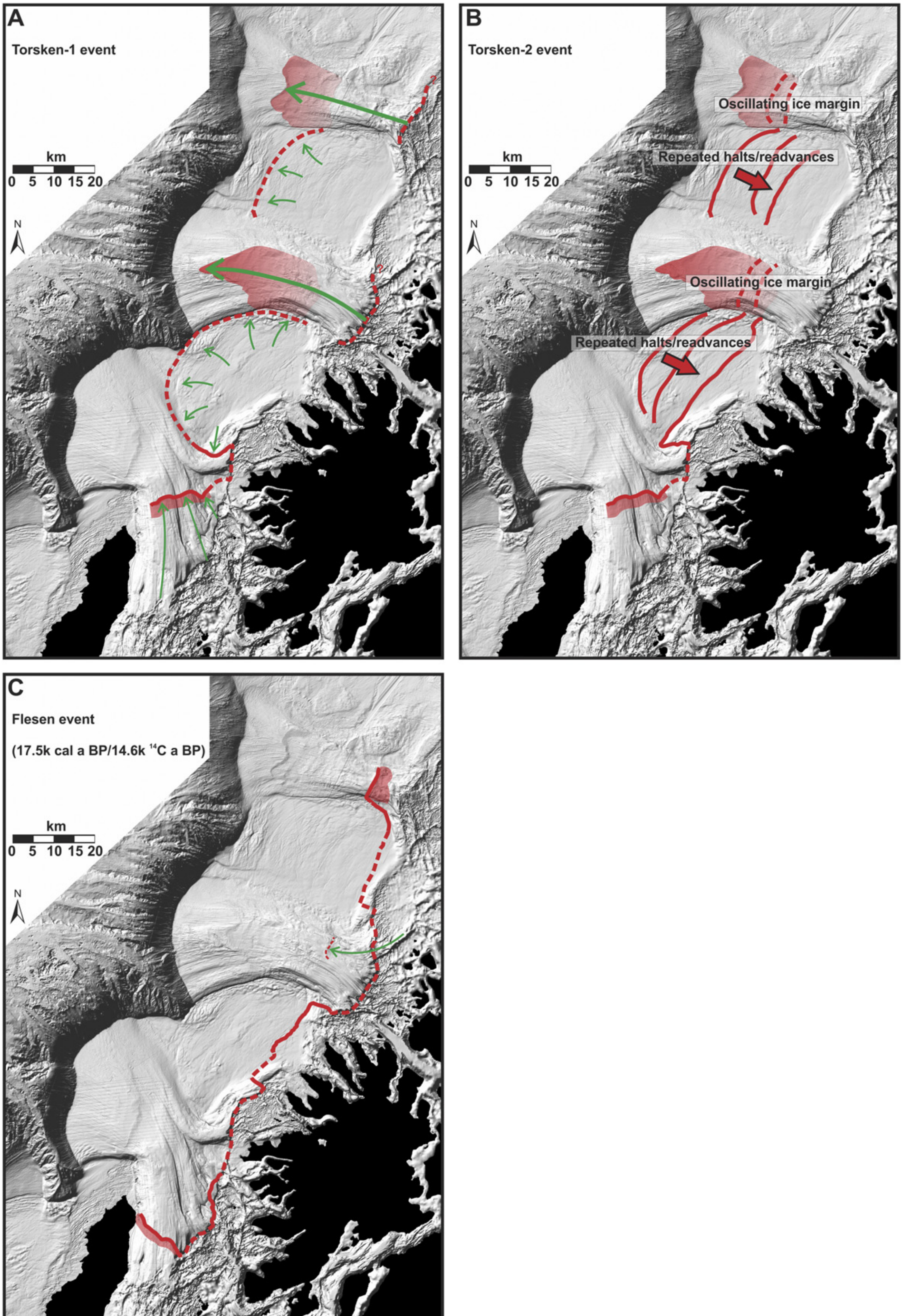

Fig. 9. Three-stage reconstruction of the deglaciation events of the northwestern Fennoscandian Ice Sheet based on geomorphic mapping. Green arrows indicate ice flow direction. Red line indicates ice front position. Dashed red line indicates tentative ice front position. A: The Torsken-1 event. B: The Torsken-2 event. C: The Flesen event.

(Fig. 8A). The lateral moraines on southern Malangsgrunnen are partly burying end moraines near the shelf break, making the latter older than the LGM. We infer that the maximum ice position at LGM on Malangsgrunnen was located inshore of the wider end moraines described in Section 4.3 (Fig. 8A).

During the LGM, a major cold-based ice dome (Kleman and Hättestrand, 1999), modelled to be more than 2 km thick, was overlying the north-eastern parts of Sweden (Lambeck et al., 1998; Siegert et al., 2001). Ice masses moved radially outwards from this ice dome. From a regional map of mainland Norway and Sweden we estimated the drainage area to the Andfjorden–Malangsdjupet–Rebbenesdjupet (AMR) system (Fig. 8B). This separate drainage area is bounded by the Vestfjorden–Trænadjupet drainage system to the south (Ottesen et al., 2005a,b; Laberg et al., 2009), and the vast Barents Sea drainage system to the north (e.g. Winsborrow et al., 2010). The Torneträsk–Ofotfjorden area was probably an important drainage route for the northern parts of the Vestfjorden–Trænadjupet system, and thus the southern limit of the drainage to the AMR system. The suggested northern ice drainage boundary through AMR is tentative. We infer that ice drained northwards to the east of the Lyngen Peninsula, based on the overall orientation of valleys and fjords. On the western margin of the ice sheet the high relief topography of the fjord systems steered the ice drainage to the continental shelf (Ottesen et al., 2005a).

Based on the orientation of fjords and valleys inshore of the troughs, we defined a 40,000 km^2 catchment area for ice draining to the AMR system during LGM (Fig. 8B). From the overall topography it seems unlikely that each of the troughs received identical ice mass from the common source area in the east. As an estimate, we suggest that Andfjorden and Malangsdjupet each received 40% of these ice masses, while Rebbenesdjupet received 20%. From the drainage areas we can calculate the palaeo-ice stream velocities during LGM for each of the troughs using a balance flux approach (Clarke, 1987), as has been done for the Vestfjorden–Trænadjupet area (Ottesen et al., 2005a). We assume a full-glacial snow precipitation of 0.25 m/year, which, multiplied with the drainage area, gives the mass input. We use the width and water depths at the trough mouths (Table 1) for calculating the cross section for ice discharge. Using these values, balance velocities of about 350 m/yr are calculated for the palaeo-ice streams. If we instead calculate with an equal amount of ice drainage to the three troughs we get velocities of 330, 310 and 480 m/yr for Andfjorden, Malangsdjupet and Rebbenesdjupet, respectively. These crude estimates are comparable to modern ice stream velocities in the Antarctic ice sheet, which typically flow from a couple hundred metres to a few km/year (Rignot et al., 2011). The Vestfjorden–Trænadjupet palaeo-ice stream was calculated to flow at a rate of 750 m/yr (Ottesen et al., 2005a) using the same approach as this study. This is approximately twice the velocity of the AMR ice streams and can be explained by a larger drainage area to the Vestfjorden–Trænadjupet system, which was 150,000 km^2. Using a different approach, Vorren and Laberg (1996) calculated the velocity in the greater Bear Island Trough Ice Stream to be 2.5 km/yr, i.e. one order of magnitude higher than the velocities in this study.

5.3. The deglaciation events

5.3.1. The Torsken-1 event

The Torsken events are named after the submarine Torsken moraine. On the continental shelf off Troms, the deglaciation probably began with a breakup of ice streams in the troughs. Water depths are greatest here and the ice sheet is therefore more prone to calving in these areas. The trough beds are sloping landwards (Fig. 1C), promoting rapid calving of icebergs, which preserved flow sets at the outer trough beds. The trough mouths are deeper in the central parts, hence detachment of ice streams most likely started here. We suggest that calving embayments formed in the troughs in the initial deglaciation phase, with some ice remnants at the shallower trough flanks.

We suggest that the glacier de-grounded and retreated rapidly to the Torsken moraine in Andfjorden, where it re-grounded, and deposited the moraine. Based on the progressive deepening of the seabed landwards in Malangsdjupet and Rebbenesdjupet, it is likely that the GZW here is a result of a readvance after halting at the crystalline–sedimentary bedrock contact. On the banks the glaciers spread out radially, terminating at the shelf break and bank rims (Fig. 9A).

5.3.2. The Torsken-2 event

In the Torsken-2 event the ice on the banks also started to retreat. We believe that the high frequency of marginal moraines (Fig. 2) testify to an initial, slow and gradual retreat of the glacier, with small halts/readvances (Fig. 9B), probably facilitated by the progressively shallowing seabed landwards. Readvances during the Torsken-2 event are indicated by crosscutting moraines on both banks.

The glacier in Andfjorden probably remained at the Torsken moraine during this event. In the other troughs, ice front locations were probably within the area of the GZW (Fig. 9B). Precise positions are difficult to ascertain, as no clear correlation between the moraines on the banks and in the troughs could be detected.

5.3.3. The Flesen event

The Flesen event, named after the Flesen moraine, is tentatively correlated southwards and onshore to the moraines of Kirkeraet and Gårdsraet on Andøya by Vorren and Plassen (2002). Based on our data, the Flesen moraine has been correlated with marginal moraines further north, as shown in Fig. 9C. This implies that major parts of the ice sheet had retreated to the crystalline–sedimentary bedrock contact. However, some ice remained grounded on the inner parts of the banks, in the coast-parallel troughs, as well as at the locations of the Flesen and Stormekta moraines. A possible local readvance of a glacier out Røssholmdjupta into Malangsdjupet is possible, as indicated in Fig. 9C. However, the landforms observed here could also be interpreted as retreat features.

5.4. Deglaciation dynamics of cross-shelf troughs

The earliest deglacial deposit in Andfjorden, unit tF, contains very little ice-rafted detritus (Vorren and Plassen, 2002). Fine grained laminated sediments dominate (Vorren et al., 1983). This suggests that the calving and evacuation of icebergs were rapid, preventing melt-out of ice-rafted debris in these waters (Vorren and Plassen, 2002). In our study we find preserved flow sets at the trough mouths, supporting an initial rapid deglaciation of the glaciers in the troughs (the Torsken-1 event).

The seafloor topography acts as an important parameter in the deglaciation dynamics of cross-shelf troughs. Where the seabed progressively deepens inshore, the glacier is particularly sensitive to changes such as thinning of the ice or sea level rise. Once initial retreat is triggered the ice recedes into deeper water and retreat can become catastrophic (Thomas, 1979). However, our data show that the ice stream retreat following the LGM was episodic, recorded by grounding zone systems, as have been described from Vestfjorden, south of our study area (Knies et al., 2007; Laberg et al., 2007a).

The morphology of the cross-shelf troughs off northern Norway are similar to those off Antarctica, i.e. they have a landward sloping profile and are overdeepened in their inner reaches (Anderson, 1999). Ó Cofaigh et al. (2008) and Dowdeswell et al. (2008) show that the relative rapidity of palaeo-ice-stream recession from such bathymetric troughs can be inferred from diagnostic suites of glacial landforms. Three styles of ice stream retreat were inferred: fast, episodic and slow. The episodic retreat is characterized by MSGL interrupted and overprinted by transverse GZW on the inner-mid shelf (Dowdeswell et al., 2008; Ó Cofaigh et al., 2008). Variations in the style of ice stream retreat between troughs indicate that ice streams did not respond uniformly to external forcing at the end of the Last Glacial cycle. Ó Cofaigh et al. (2008) infer that the difference in glacier retreat pattern between seemingly similar troughs reflects the dominance of more local controls such as drainage basin size and bathymetry.

Sea-level fluctuations have a potential important control on the retreat dynamics of ice streams. A rising relative sea level would destabilize the marine terminating ice streams by detachment from the base and retreat of the ice margin. In the opposite case a rapid isostatic rebound, if faster than rising eustatic sea level, could stabilize the ice front, allowing for a halt in the deglaciation and the formation of grounding zone systems. In our case we find the latter scenario unlikely, given the great water depth the grounding zone systems are located at (Fig. 1). Also, data from Andøya indicate a rather stable relative sea level, between 35 and 38 m a.s.l., during the period ca 22.2–18.3 ka cal BP (18.5–15 ka ^{14}C BP) (Vorren et al., 1988). Following this, the relative sea level dropped and stabilized around 12 ka cal BP (10.2 ka ^{14}C BP). This implies that the cross-trough moraines and GZW identified in our study would have been formed at a higher relative sea level than at present. Thus, sea level fluctuations have not been very important for the glacial readvances during the deglaciation.

Retreat dynamics would also have been affected by changes in the ice sheet itself. An increase in the transfer of ice masses from the interior of the ice sheet could have slowed down the retreat and eventually grounded the glacier. In Fig. 10 a conceptual model of the glacier retreat across a cross-shelf trough is presented. During the LGM, the glacier was grounded all the way to the shelf break, providing basal drag to the ice streams (Fig. 10A). At the onset of the deglaciation the calving increased, probably as a consequence of thinning ice streams (Fig. 10B). This reduced the overall basal drag in the cross-shelf troughs, resulting in a reduction of upglacier directed forces, allowing for a marine drawdown of ice mass from the interior of the Fennoscandian Ice Sheet (Fig. 10C). The increased amount of ice mass to the cross-shelf troughs together with the reverse bed slope could have stabilized and halted the ice front (Fig. 10D).

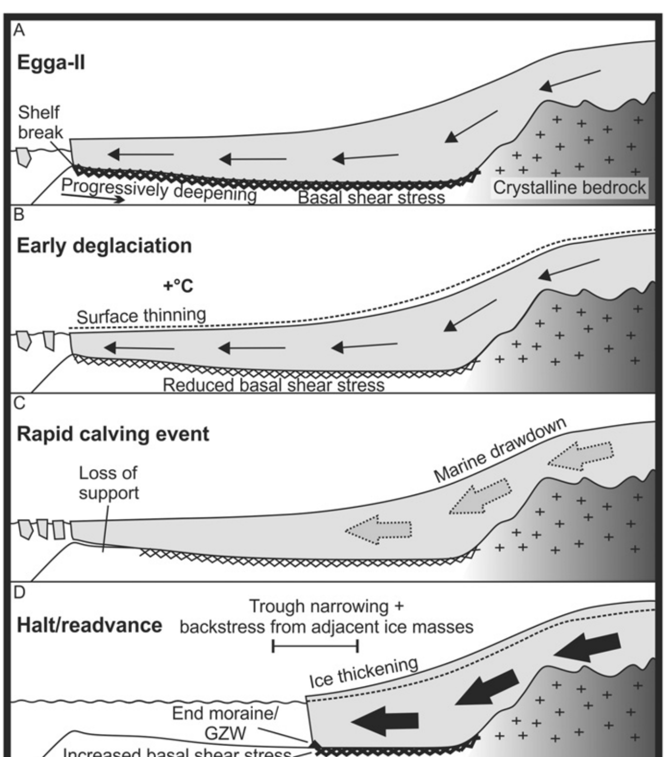

Fig. 10. A conceptual model of the glacier retreat along the cross-shelf troughs on the north-Norwegian continental shelf: see text for details.

According to the law of continuity the ice flow velocities were highest at the narrowest passage of the troughs. This is confirmed by the convergent and divergent appearance of the flow sets from the LGM and the deglaciation (Fig. 2), showing streamlined flow towards the narrowest passage. Conspicuously, the grounding zone systems from the final deglaciation are also situated where the troughs are narrowing (Fig. 6). Based on this we suggest that the morphology of the cross-shelf troughs acted as important controls on the deglaciation. The reverse bed slope facilitated the first rapid release of icebergs and glacier recession. As the ice front retreated towards the narrower parts of the troughs the ice flux increased (Fig. 10D). This slowed down the recession, and eventually halted the ice front, and the grounding zone systems were formed. Also, upglacier-driven forces, or backstress, from ice masses on adjacent land areas could possibly have stabilized the glacier front in the trough by providing an additional source of resistance to ice flow at the trough narrowings (Fig. 10D). A dynamic numerical simulation of an Antarctic ice stream retreat on a reverse bed slope supports this view (Jamieson et al., 2012). Modelling of the retreat of the Marguerite Bay Ice Stream following the LGM shows a highly nonlinear retreat, with several ice-front stabilizations on a reverse-sloping bed. These transient stabilizations have been demonstrated to be caused by lateral drag as the ice stream narrowed (Jamieson et al., 2012).

In conclusion, our data show that there were marked similarities in the dynamics of the individual palaeo-ice stream retreats from the continental shelf following the Egga-II. In agreement with the studies of Ó Cofaigh et al. (2008) and Dowdeswell et al. (2008), as well as the simulations done by Jamieson et al. (2012), our findings imply that the retreat of marine-based ice sheets is not necessarily catastrophic, even in areas of reverse bed slope. In our study area trough width probably exerted the most important control on the halts/readvances of the ice front during the deglaciation.

6. Conclusions

- Glacial landforms formed by the Late Weichselian Ice Sheet are preserved on the north Norwegian continental shelf. Flow sets of mega-scale glacial lineations, flutes and crag-and-tails characterize the seabed in the cross-shelf troughs. These are locally overprinted by larger grounding zone systems in the form of end moraines and grounding zone wedges (GZW). At the trough–bank flanks, lateral moraines, as well as lateral shear zone moraines occur. A high density of smaller end moraines occur on the banks. Iceberg ploughmarks are observed both in the cross-shelf troughs and on the banks.
- The flow regime can be differentiated by an inner, middle and outer flow set. We observe an increase in elongation ratio from the inner parts of the troughs to the shelf break. The pristine preservation of the mega-scale glacial lineations near the shelf break suggests that they were formed late, presumably at or immediately after the Last Glacial Maximum. The middle flow sets were probably formed at the same time, and later partly buried by GZW. The inner flow sets are probably the youngest, formed during the deglaciation.

- We estimate a total drainage area of 40,000 km^2 for the Andfjorden–Malangsdjupet–Rebbenesdjupet drainage system. Palaeo-ice stream velocities are estimated to be approximately 350 m/yr.
- The absence of glacial lineations on the banks indicates more sluggish flowing ice here during LGM. The transition zones to the fast-flowing ice in the troughs were abrupt.
- Small non-glaciated areas existed on the outermost parts of the banks during full-glacial conditions.
- The deglaciation ocurred in three events: the Torsken-1, Torsken-2 and Flesen events. The marine based ice streams retreated rapidly from the trough mouths and halted or readvanced to mid-, inner trough positions, depositing GZW and end moraines.
- The ice remained grounded on the banks during the early part of the deglaciation. During the Torsken-2 event, ice retreated from the banks with several small still-stands or readvances. During the Flesen event, the ice had retreated to the inner parts of the banks.
- Despite the reverse bed slope, the ice stream retreat across the shelf following the LGM was episodic. The trough width was probably the most important factor controlling the ice stream retreat dynamics.

Acknowledgements

This work was financially supported by the Research Council of Norway, Front Exploration AS and Dong Energy E&P Norge AS through their funding of an Industrial Ph.D. position to the first author. We are grateful to the Norwegian Defence Research Establishment for providing high-resolution seismic data, Noortje Dijkstra for commenting upon an early version of the manuscript, Stine Furnes Hauge for commenting on the English text and Edward (Ned) King for valuable comments and discussions. Finally, we thank Editor Neil Glasser, referee Anne Hormes and three anonymous referees for their constructive reviews.

References

Andersen, B.G., 1965. Glacial chronology of Western Troms, North Norway. Geological Society of America Special Paper 84, 35–54.
Andersen, B.G., 1968. Glacial geology of western Troms, North Norway. Norges Geologiske Undersøkelse 256. 160pp.
Anderson, J.B., 1999. Antarctic Marine Geology. Cambridge University Press, Cambridge. 289pp.
Bass, D.W., Woodworth-Lynas, C., 1988. Iceberg crater marks on the sea floor, Labrador Shelf. Marine Geology 79, 243–260.
Bellec, V.K., Bøe, R., Rise, L., Slagstad, D., Longva, O., Dolan, M.F.J., 2010. Rippled scour depressions on continental shelf bank slopes off Nordland and Troms, Northern Norway. Continental Shelf Research 30, 1056–1069.
Bentley, C.R., 1987. Antarctic ice streams: a review. Journal of Geophysical Research 92 (B9), 8843–8858.
Bøe, R., Bellec, V.K., Dolan, M.F.J., Buhl-Mortensen, P., Buhl-Mortensen, L., Slagstad, D., Rise, L., 2009. Giant sandwaves in the Hola glacial trough off Vesterålen, North Norway. Marine Geology 267, 36–54.
Clark, C.D., 1993. Mega-scale glacial lineations and cross-cutting ice-flow landforms. Earth Surface Processes and Landforms 18, 1–29.
Clark, C.D., Stokes, C.R., 2003. Palaeo-ice stream landsystem. In: Evans, D.J.A. (Ed.), Glacial Landsystems. Arnold, London, pp. 204–227.
Clarke, G.K.C., 1987. Fast glacier flow: ice streams, surging, and tidewater glaciers. Journal of Geophysical Research 92, 8835–8841.
Clarke, G.K.C., Nitsan, U., Paterson, W.S.B., 1977. Strain heating and creep instability in glaciers and ice sheets. Reviews of Geophysics and Space Physics 15, 235–247.
Dahlgren, K.I.T., Vorren, T.O., Stoker, M.S., Nielsen, T., Nygård, A., Sejrup, H.P., 2005. Late Cenozoic prograding wedges on the NW European continental margin: their formation and relationship to tectonics and climate. Marine and Petroleum Geology 22, 1089–1110.
Dowdeswell, J.A., Bamber, J.L., 2007. Keel depths of modern Antarctic icebergs and implications for sea-floor scouring in the geological record. Marine Geology 243, 120–131.
Dowdeswell, J.A., Fugelli, E.M.G., 2012. The seismic architecture and geometry of grounding-zone wedges formed at the marine margins of past ice sheets. Geological Society of America Bulletin 124, 1750–1761.
Dowdeswell, J.A., Ottesen, D., Evans, J., Ó Cofaigh, C., Anderson, J.B., 2008. Submarine glacial landforms and rates of ice-stream collapse. Geology 36, 819–822.
Fjalstad, A., Møller, J.J., 1994. Submerged and tilted coastal features off Troms, northern Norway: a comment. Norsk Geologisk Tidsskrift 74, 241–244.
Graham, A.G.C., Larter, R.D., Gohl, K., Hillenbrand, C.-D., Smith, J.A., Kuhn, G., 2009. Bedform signature of a West Antarctic palaeo-ice stream reveals a multi-temporal record of flow and substrate control. Quaternary Science Reviews 28, 2774–2793.
Holtedahl, O., 1940. The Submarine Relief off the Norwegian Coast, with Bathymetrical Map in Seven Sheets of the Norwegian Coastal Waters and Adjoining Seas. Det Norske Videnskaps-Adademi i Oslo. 43pp.
Holtedahl, O., 1953. Noen sub-marin-geologiske undersøkelser utenfor Norges vestkyst. Norsk Geologisk Tidsskrift 32, 235–237.
Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J.A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H.W., Zarayskaya, Y., Accettella, D., Armstrong, A., Anderson, R.M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J.V., Hall, J.K., Hell, B., Hestvik, O., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S.V., Pedrosa, M.T., Travaglini, P.G., Weatherall, P., 2012. The international bathymetric chart of the Arctic Ocean (IBCAO) Version 3.0. Geophysical Research Letters 39. http://dx.doi.org/10.1029/2012GL052219.
Jamieson, S.S.R., Vieli, A., Livingstone, S.J., Cofaigh, C.Ó., Stokes, C.R., Hillenbrand, C.-D., Dowdeswell, J.A., 2012. Ice stream stability on a reverse bed slope. Nature Geoscience Letters 5, 799–802.
Kenyon, N.H., 1987. Mass-wasting features on the continental slope of Northwest Europe. Marine Geology 74, 57–77.
Kleman, J., Hättestrand, C., 1999. Frozen-bed Fennoscandian and Laurentide ice sheets during the Last Glacial Maximum. Nature 402, 63–66.
Knies, J., Vogt, C., Matthiessen, J., Nam, S.-I., Ottesen, D., Rise, L., Bargel, T., Eilertsen, R.S., 2007. Re-advance of the Fennoscandian Ice Sheet during Heinrich Event 1. Marine Geology 240, 1–18.
Laberg, J.S., Eilertsen, R.S., Salomonsen, G.R., Vorren, T.O., 2007a. Submarine push moraine formation during the early Fennoscandian Ice Sheet deglaciation. Quaternary Research 67, 453–462.
Laberg, J.S., Eilertsen, R.S., Vorren, T.O., 2009. The paleo-ice stream in Vestfjorden, north Norway, over the last 35 k.y.: glacial erosion and sediment yield. Geological Society of America Bulletin 121, 434–447.
Laberg, J.S., Guidard, S., Mienert, J., Vorren, T.O., Haflidason, H., Nygård, A., 2007b. Morphology and morphogenesis of a high-latitude canyon: the Andøya Canyon, Norwegian Sea. Marine Geology 246, 68–85.
Lambeck, K., Smither, C., Johnston, P., 1998. Sea-level change, glacial rebound and mantle viscosity for northern Europe. Geophysical Journal International 134, 102–144.
Lien, R., 1983. Pløyemerker etter isfjell på norsk kontinentalsokkel (Iceberg scouring on the Norwegian continental shelf), vol. 109. IKU Publication. 147pp.
Lindén, M., Möller, P., 2005. Marginal formation of De Geer moraines and their implications to the dynamics of grounding-line recession. Journal of Quaternary Science 20 (2), 113–133.
Livingstone, S.J., Ó Cofaigh, C., Stokes, C.R., Hillenbrand, C.-D., Vieli, A., Jamieson, S.S.R., 2011. Antarctic palaeo-ice streams. Earth-Science Reviews 111, 90–128.
Møller, J.J., 2000. Submerged littoral sediments, beach ridges and wave-cut platforms off Troms, North Norway: revisiting old questions. Norsk Geologisk Tidsskrift 80, 203–212.
Ó Cofaigh, C., Dowdeswell, J.A., Allen, C.S., Hiemstra, J.F., Pudsey, C.J., Evans, J., Evans, D.J.A., 2005. Flow dynamics and till genesis associated with a marine-based Antarctic palaeo-ice stream. Quaternary Science Reviews 24, 709–740.
Ó Cofaigh, C., Dowdeswell, J.A., Evans, J., Larter, R.D., 2008. Geological constraints on Antarctic palaeo-ice-stream retreat. Earth Surface Processes and Landforms 33 (4), 513–525.
Ottesen, D., Dowdeswell, J.A., Rise, L., 2005a. Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: the 2500-km-long Norwegian–Svalbard margin (57°–80°N). Geological Society of America Bulletin 117 (7–8), 1033–1050.
Ottesen, D., Dowdeswell, J.A., 2009. An inter-ice-stream glaciated margin: submarine landforms and a geomorphic model based on marine-geophysical data from Svalbard. Geological Society of America Bulletin 121, 1647–1665.
Ottesen, D., Rise, L., Knies, J., Olsen, L., Henriksen, S., 2005b. The Vestfjorden–Trænadjupet palaeo-ice stream drainage system, mid-Norwegian continental shelf. Marine Geology 218, 175–189.
Ottesen, D., Dowdeswell, J.A., Landvik, J.Y., Mienert, J., 2007. Dynamics of the Late Weichselian ice sheet on Svalbard inferred from high-resolution sea-floor morphology. Boreas 36, 286–306.
Ottesen, D., Stokes, C.R., Rise, L., Olsen, L., 2008. Ice-sheet dynamics and ice streaming along the coastal parts of northern Norway. Quaternary Science Reviews 27, 922–940.
Paterson, W.S.B., 1994. The Physics of Glaciers. Pergamon Press, Oxford. 480pp.
Plassen, L., Knies, J., 2009. Fluid flow structures and processes: indications from the North Norwegian continental margin. Norsk Geologisk Tidsskrift 89, 57–64.
Powell, R.D., Alley, R.B., 1997. Grounding-line systems: processes, glaciological inferences and the stratigraphic record. In: Barker, P.F., Cooper, A.K. (Eds.), Geology and Seismic Stratigraphy of the Antarctic Margin. Antarctic Research Series, vol. 2. American Geophysical Union, Washington, DC, United States, pp. 169–187.
Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F.,

Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. Intcal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. Radiocarbon 51 (4), 1111–1150.

Rignot, E., Mouginot, J., Scheuchl, B., 2011. Ice flow of the Antarctic ice sheet. Science 333, 1427–1430.

Rokoengen, K., Bugge, T., Løfaldli, M., 1979. Quaternary geology and deglaciation of the continental shelf off Troms, North Norway. Boreas 8, 217–227.

Rokoengen, K., Dekko, T., 1993. Submerged and tilted coastal features off Troms, northern Norway. Norsk Geologisk Tidsskrift 73, 198–208.

Rokoengen, K., Dekko, T., 1994. Submerged and tilted coastal features off Troms, northern Norway: a reply. Norsk Geologisk Tidsskrift 73, 245–247.

Rüther, D.C., Mattingsdal, R., Andreassen, K., Forwick, M., Husum, K., 2011. Seismic architecture and sedimentology of a major grounding zone system deposited by the Bjørnøyrenna Ice Stream during Late Weichselian deglaciation. Quaternary Science Reviews 30, 2776–2792.

Shaw, J., Piper, D.J.W., Fader, G.B.J., King, E.L., Todd, B.J., Bell, T., Batterson, M.J., Liverman, D.G.E., 2006. A conceptual model of the deglaciation of Atlantic Canada. Quaternary Science Reviews 25, 2059–2081.

Siegert, M.J., Dowdeswell, J.A., Hald, M., Svendsen, J.-I., 2001. Modelling the Eurasian Ice Sheet through a full (Weichselian) glacial cycle. Global and Planetary Change 31, 367–385.

Ślubowska-Woldengen, M., Koç, N., Rasmussen, T.L., Klitgaard-Kristensen, D., Hald, M., Jennings, A.E., 2008. Time-slice reconstructions of ocean circulation changes on the continental shelf in the Nordic and Barents Seas during the last 16,000 cal yr BP. Quaternary Science Reviews 27, 1476–1492.

Stokes, C.R., Clark, C.D., 1999. Geomorphological criteria for identifying Pleistocene ice streams. Annals of Glaciology 28, 67–74.

Stokes, C.R., Clark, C.D., 2001. Palaeo-ice streams. Quaternary Science Reviews 20, 1437–1457.

Stokes, C.R., Clark, C.D., 2002a. Are long subglacial bedforms indicative of fast ice flow? Boreas 31, 239–249.

Stokes, C.R., Clark, C.D., 2002b. Ice stream shear margin moraines. Earth Surface Processes and Landforms 27, 547–558.

Sundby, S., 1984. Influence of bottom topography on the circulation at the continental shelf off northern Norway. Fiskeridirektoratets Skrifter Serie Havforskingsundersøkelser 17, 501–519.

Svendsen, J.I., Alexanderson, H., Astakhov, V.I., Demidov, I., Dowdeswell, J.A., Funder, S., Gataullin, V., Henriksen, M., Hjort, C., Houmark-Nielsen, M., Hubberten, H.W., Ingólfsson, Ó., Jakobsson, M., Kjær, K.H., Larsen, E., Lokrantz, H., Lunkka, J.P., Lyså, A., Mangerud, J., Matiouchkov, A., Murray, A., Möller, P., Niessen, F., Nikolskaya, O., Polyak, L., Saarnisto, M., Siegert, C., Siegert, M.J., Spielhagen, R.F., Stein, R., 2004. Late Quaternary ice sheet history of northern Eurasia. Quaternary Science Reviews 23, 1229–1271.

Sætre, R., 2007. The Norwegian Coastal Current: Oceanography and Climate. Institute of Marine Research, Trondheim. 159pp.

Taylor, J., Dowdeswell, J.A., Kenyon, N.H., 2000. Canyons and late Quaternary sedimentation on the North Norwegian margin. Marine Geology 166, 1–9.

Thomas, R.H., 1979. The dynamics of marine ice sheets. Journal of Glaciology 24, 167–177.

Thomas, R.H., 2004. Greenland: recent mass balance observations. In: Bamber, J.L., Payne, A.J. (Eds.), Mass Balance of the Cryosphere: Observations and Modeling of Contemporary and Future Changes. Cambridge University Press, pp. 393–436.

Vorren, T.O., Edvardsen, M., Hald, M., Thomsen, E., 1983. Deglaciation of the continental shelf off Southern Troms, North Norway. Norges Geologiske Undersøkelse 380, 173–187.

Vorren, T.O., Laberg, J.S., 1996. Late glacial air temperature, oceanographic and ice sheet interactions in the southern Barents Sea region. In: Andrews, J.T., Austin, W.E.N., Bergsten, H., Jennings, A.E. (Eds.), Late Quaternary Palaeoceanography of the North Atlantic Margins. Geological Society Special Publication. Geological Society of London, London, pp. 303–321.

Vorren, T.O., Laberg, J.S., 1997. Trough mouth fans – palaeoclimate and ice-sheet monitors. Quaternary Science Reviews 16 (8), 865–881.

Vorren, T.O., Laberg, J.S., Blaume, F., Dowdeswell, J.A., Kenyon, N.H., Mienert, J., Rumohr, J.A.N., Werner, F., 1998. The Norwegian–Greenland Sea continental margins: morphology and late Quaternary sedimentary processes and environment. Quaternary Science Reviews 17, 273–302.

Vorren, T.O., Plassen, L., 2002. Deglaciation and palaeoclimate of the Andfjord–Vågsfjord area, North Norway. Boreas 31, 97–125.

Vorren, T.O., Vorren, K.-D., Alm, T., Gulliksen, S., Løvlie, R., 1988. The last deglaciation (20,000 to 11,000 B. P.) on Andøya, northern Norway. Boreas 17, 41–77.

Wellner, J.S., Lowe, A.L., Shipp, S.S., Anderson, J.B., 2001. Distribution of glacial geomorphic features on the Antarctic continental shelf and correlation with substrate: implications for ice behavior. Journal of Glaciology 47, 397–411.

Wessel, P., Smith, W.H.F., 1998. New, improved version of the generic mapping tools released. EOS Transactions of the American Geophysical Union 79, 579.

Winsborrow, M.C.M., Andreassen, K., Corner, G.D., Laberg, J.S., 2010. Deglaciation of a marine-based ice sheet: Late Weichselian palaeo-ice dynamics and retreat in the southern Barents Sea reconstructed from onshore and offshore glacial geomorphology. Quaternary Science Reviews 29 (3–4), 424–442.