Seabed morphology and sedimentary processes on high-gradient trough mouth fans offshore Troms, northern Norway

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Abstract

Trough mouth fans (TMF) situated at the mouths of formerly glaciated cross-shelf troughs are important palaeoclimatic archives. Whereas the sedimentary processes of large, low-gradient TMFs have received considerable interest, little attention has been paid to the other end member of this landform class, i.e. TMFs with higher slope gradients. Detailed swath-bathymetric data and seismic profiles from the continental margin offshore Troms, northern Norway cover three high-gradient TMFs (the Andfjorden, Malangsdjupet and Rebbenesdjupet TMFs; slope gradients generally between 1° and 15°), as well as inter-fan areas, which include two submarine canyons (the Andøya and Senja Canyon) and the Malangsgrunnen inter-fan slope. The present-day morphologies of the Andfjorden and Malangsdjupet TMFs have evolved from sediment transport and distribution through gully-channel complexes. The Andfjorden TMF has later been affected by a large submarine landslide that remobilized much of these complexes. The Rebbenesdjupet TMF is dominated by a number of small and relatively shallow slide scars, which are inferred to be related to small-scale sediment failure of glaciomarine and/or contouritic sediments. The canyons cut into the adjacent TMFs, and turbidity currents originating on the fans widened and deepened the canyons during downslope flow. The Malangsgrunnen shelf break and inter-fan slope acted as a funnel for turbidity currents originating on the upper slope, forming a dendritic pattern of gullies. A conceptual model for the high-gradient TMFs on the Troms margin has been compiled. The main sediment input onto the TMFs has occurred during peak glacials when the Fennoscandian Ice Sheet reached the shelf edge. The overall convex fan form and progradational seismic facies show that these glacigenic deposits were repeatedly distributed onto the fan. On the Andfjorden and Malangsdjupet TMFs, gully-channel complexes occur within such deposits. It is thus inferred that the steep slope of these TMFs promoted rapid transformation from small-scale slumps and debris flows on the upper slope, into partly erosive turbidity currents. These flows continued into the deep sea, thus promoting efficient sediment by-pass across the TMFs. This model can be applied to other TMFs situated at the mouths of other glaciated cross-shelf troughs. In contrast, low-gradient TMFs are found to be dominated by glacigenic debris flow deposits. Furthermore, gully-channels complexes demonstrating the presence of erosive turbidity currents on high-gradient TMFs are rare on low-gradient TMFs. Large submarine landslides occur at both high- and low-gradient TMFs.

Keywords: high-gradient trough mouth fans, gully, canyon, continental slope, submarine landslide, Troms

1 Introduction

Trough mouth fans (TMF) are confined depocentres of glacigenic sediments located at the mouth of transverse troughs on glaciated continental margins (Vorren et al., 1989; Vorren and Laberg, 1997). The TMFs have developed over successive late Cenozoic glacial-interglacial cycles by the delivery of large volumes of subglacial sediment to the termini of ice streams flowing along troughs, and subsequent re-deposition down the continental slope via massflows. TMFs therefore represent important palaeoclimatic archives in both northern and southern high-latitudes (Vorren and Laberg, 1997; Clausen, 1998; Dahlgren et al, 2005; Sejrup et al., 2005; Rebesco et al., 2006; Dowdeswell et al., 2008). Erosion and transport of glacigenic sediments to the margin was mainly achieved by fast-flowing ice streams overlying transverse shelf troughs during glacial maxima (Laberg and Vorren, 1995; 1996a; b; King et al., 1996; Vorren and Laberg, 1997; Dahlgren et al., 2005; Laberg et al., 2012). Conversely, when the ice retreated the sedimentation was focused on the inner shelves and fjords (Vorren et al., 1989; Sejrup et al., 1996). Inter-fan areas were generally sediment-starved during peak glaciations (Vanneste et al., 2007).

In general, the studied TMFs on the Norwegian margin are low-gradient features with angle of dip usually between 0.5 and 1°, e.g. the North Sea TMF and the Bear Island TMF (Vorren and Laberg, 1997). The main morphological elements of these TMFs are glacigenic debris flow (GDF) debrites (Vogt et al., 1993; Laberg and Vorren, 1995; King et al., 1996; Vorren and Laberg, 1997). Individual GDF debrites vary between 1 and 40 km in width, 5 and 60 m in thickness, and stretches 10 to more than 200 km into the deep sea (King et al., 1996; Vorren and Laberg, 1997). These have a lithology similar to their source, i.e. they comprise glacial diamicton derived from the shelf (e.g. Laberg and Vorren, 1995). The deposits were subsequently affected by sediment remobilization from major submarine landslides (Laberg and Vorren, 1993; 2000; Laberg et al., 2000; Haflidason et al., 2004; Bryn et al., 2005;

Hjelstuen et al, 2007) and gully-forming erosional currents (Vorren et al., 1989; Laberg and Vorren, 1995).

Whereas the surface morphology of the large and low-gradient TMFs have received considerable interest, little attention has so far been paid to the other end member of this landform class, i.e. TMFs holding a high slope gradient (>4°) (Ó Cofaigh et al., 2003; Batchelor and Dowdeswell, 2014), here termed high-gradient TMFs. In this study, multi-beam swath-bathymetric data sets are combined with 2D multi-channel seismic lines in order to investigate the seabed geomorphology of the continental slope off Troms, northern Norway (Fig. 1), which is comprised of three high-gradient TMFs with slope gradients generally varying between 1° and 15°; the Andfjorden, Malangsdjupet, and Rebbenesdjupet TMFs (Fig. 2). These high-gradient TMFs were fed by palaeo-ice streams which were active during glacial maxima including the LGM (the Last Glacial Maximum) (Ottesen et al., 2005; 2008; Rydningen et al., 2013, submitted), similar to their low-gradient counterparts both on the Norwegian margin (e.g. Vorren and Laberg, 1997) and on other glaciated margins (e.g. Aksu and Hiscott, 1992; Rebesco et al., 2006; Laberg et al., 2013). The aims of this study are to: 1) describe and discuss the seafloor morphology of the high-gradient TMFs, 2) identify the main sedimentary processes responsible for the formation of the recentmost part of these fans, and 3) compare and contrast the processes on high- and low-gradient TMFs.

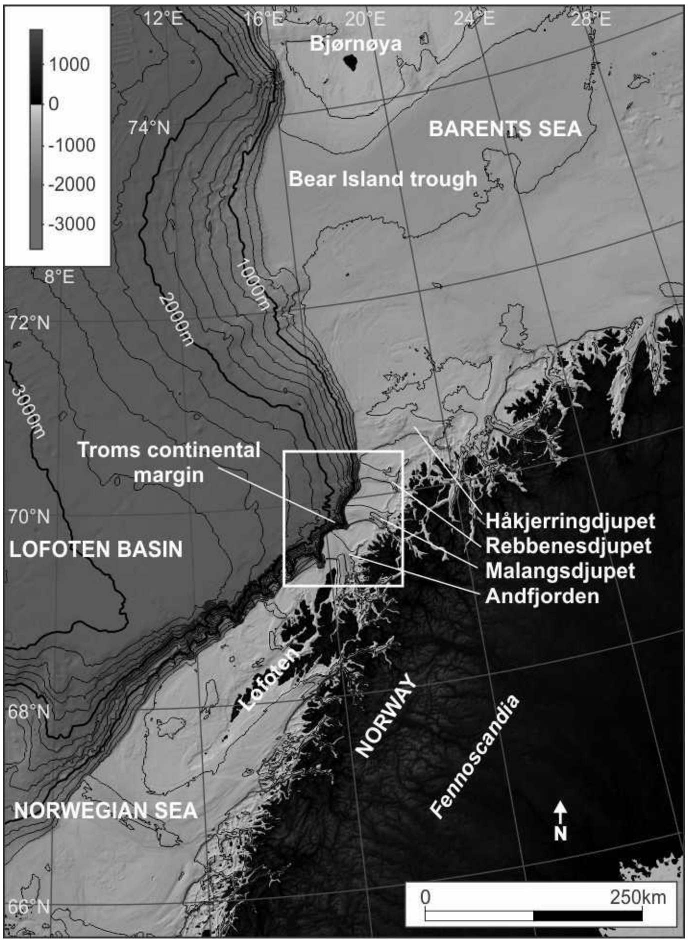

Fig. 1: Bathymetric map of the Norwegian Sea and the SW Barents Sea generated from the IBCAO database (Jakobsson et al., 2012). Contour interval is 200 m. The study area is indicated by the white box.

2 Physiographic and geologic setting

The present continental shelf off Troms is characterized by three deep cross-shelf troughs, Andfjorden, Malangsdjupet, and Rebbenesdjupet, which are separated by the shallow banks of Sveinsgrunnen and Malangsgrunnen (Fig. 2). The shelf break is situated at 100 to 300 m water depth and is located 30 to 60 km west of the islands of Senja and Kvaløya, respectively, and 10 km west of Andøya (Fig. 2). The continental slope is dominated by the Andfjorden, Malangsdjupet and Rebbenesdjupet TMFs. The fans are separated by inter-fan areas including two canyons, the Andøya and Senja canyons, and the slope west of the Malangsgrunnen bank (Fig. 2).

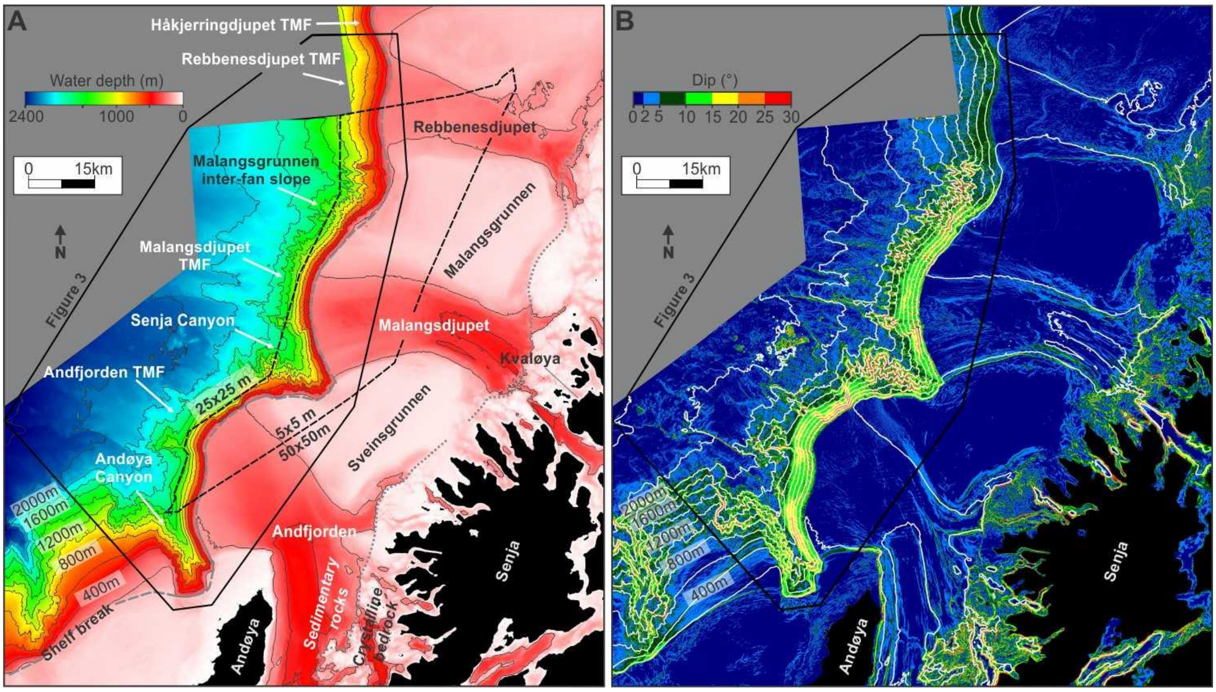

Fig. 2: The area of study. A: Bathymetric map of the continental shelf and slope outside Troms County, northern Norway. The dashed lines delimit data sets with different spatial resolution. B: Dip map of the seabed.

The 40 km long Andøya Canyon cuts into the slope and outer shelf west of the island of Andøya (Fig. 2). The width between the canyon shoulders is ~9 km, and the maximum incision is 1100 m (Laberg et al., 2007). The western sidewall of the canyon consists of drift sediments modified by sliding and slumping. Infilling of glacigenic sediments by the Andfjorden TMF make up the steep (20-25°) eastern sidewall, where gullies are frequent. Axial incision is inferred to be due to erosion by turbidity currents originating from the downslope flow of both glacigenic and drift sediments (Laberg et al., 2007).

The Andfjorden TMF has been partly affected by the Andøya Slide. Based on GLORIA long-range side-scan sonar data this slide was initially believed to cover an area of 9,700 km^2 (Dowdeswell et al., 1996; Laberg et al., 2000). Later, Rise et al. (2009), based on high-resolution swath-bathymetric data, restricted the extent of the slide affected area which was shown to include several larger and smaller slides.

Regional mapping of surface sediments and landforms on the continental slope offshore northern Norway has been carried out by Bugge (1983), Kenyon (1987), Taylor et al. (2000), and the Mareano program (www.mareano.no). The shelf is covered with up to 200 m of Quaternary sediments (Rydningen et al., submitted), consisting mainly of till, glaciomarine silt and clay, as well as iceberg turbate (Vorren et al., 1988; Vorren and Plassen, 2002; Bellec et al., 2009). Pronounced depocentres of glacigenic sediments, reaching over 1 km in thickness, are located at the trough mouths, forming the TMFs (Oljedirektoratet, 2010; Rydningen et al., submitted). They document focused glacial erosion of the shelf throughout the Quaternary (Dahlgren et al., 2005; Rydningen et al., submitted). Down to a water depth of about 1200 to 1500 m, sandy gravel, gravelly sand and muddy/sandy gravel dominate, while the deeper parts of the slope consist of mud and blocks/areas of stiffer sediments (Bellec et al., 2012a: b).

The Fennoscandian Ice Sheet advanced across the continental shelf off Troms twice during the last ~26 ka cal BP (Vorren and Plassen, 2002; Vorren et al., 2015). Fast-flowing ice streams carved out the cross-shelf troughs as they flowed towards the shelf break, while sluggish-flowing ice was situated on the banks (Ottesen et al., 2008; Rydningen et al., 2013). The deglaciation of the shelf was stepwise; the initial breakup of the ice started at the trough mouths, while the ice remained grounded on the banks. Most of the shelf was ice-free at 17.5 ka cal BP (Rydningen et al., 2013; Vorren et al., 2015).

The present oceanography of the area is influenced by three major water masses. The Norwegian Coastal Current is transporting low-salinity water with variable temperature northwards near the coast. This water overlies the relatively warm and saline Norwegian Atlantic Current, which extends down to between 500 and 600 m within the study area. This current splits in two branches; one part branches off to the southern Barents Sea, whereas the other branch continues northwards along the Barents Sea slope (Hansen and Østerhus, 2000;

Ślobowska-Woldengen et al., 2008). Below the Norwegian Atlantic Current, two cold-water masses are present: the Norwegian Sea Arctic Intermediate Water and the Norwegian Sea Deep Water. The border between these two water masses occurs typically at around 1000 m water depth (Buhl-Mortensen et al., 2012).

3 Data and methods

The data sets used in this study consist of swath-bathymetric data and commercial 2D-seismic lines. The Norwegian Hydrographic Service collected the swath-bathymetric data between 1990 and 2004 using Simrad EM100 and EM1002 multi-beam echo-sounders, and the data sets were provided to the University of Tromsø through the Norway Digital initiative. The data sets are available as UTM-points with 50x50 m horizontal spacing within 12 nautical miles from the shoreline. Further seawards, the data sets are available as 5x5 m points down to approximately 1000-1400 m water depth, and as 25x25 m points beyond this. The bathymetric data sets cover the Andfjorden and Malangsdjupet TMFs down to ~2400 m water depth, as well as the southern half of the Rebbenesdjupet TMF down to ~2100 m (Fig. 2). The gridding and visualization were done in ED50 UTM zone 32N using the Global Mapper® and Petrel® software. From these data sets, slope maps (e.g. Fig. 2B and 3A) and slope direction maps were generated. Parallel ship track lines and other artefacts were noted to avoid misinterpretations.

The upper sections of seismic lines from the Norwegian Petroleum Directorate, acquired between 2007 and 2009, were made available for this study. The seismic lines were visualized and analyzed in the Petrel® software of Schlumberger.

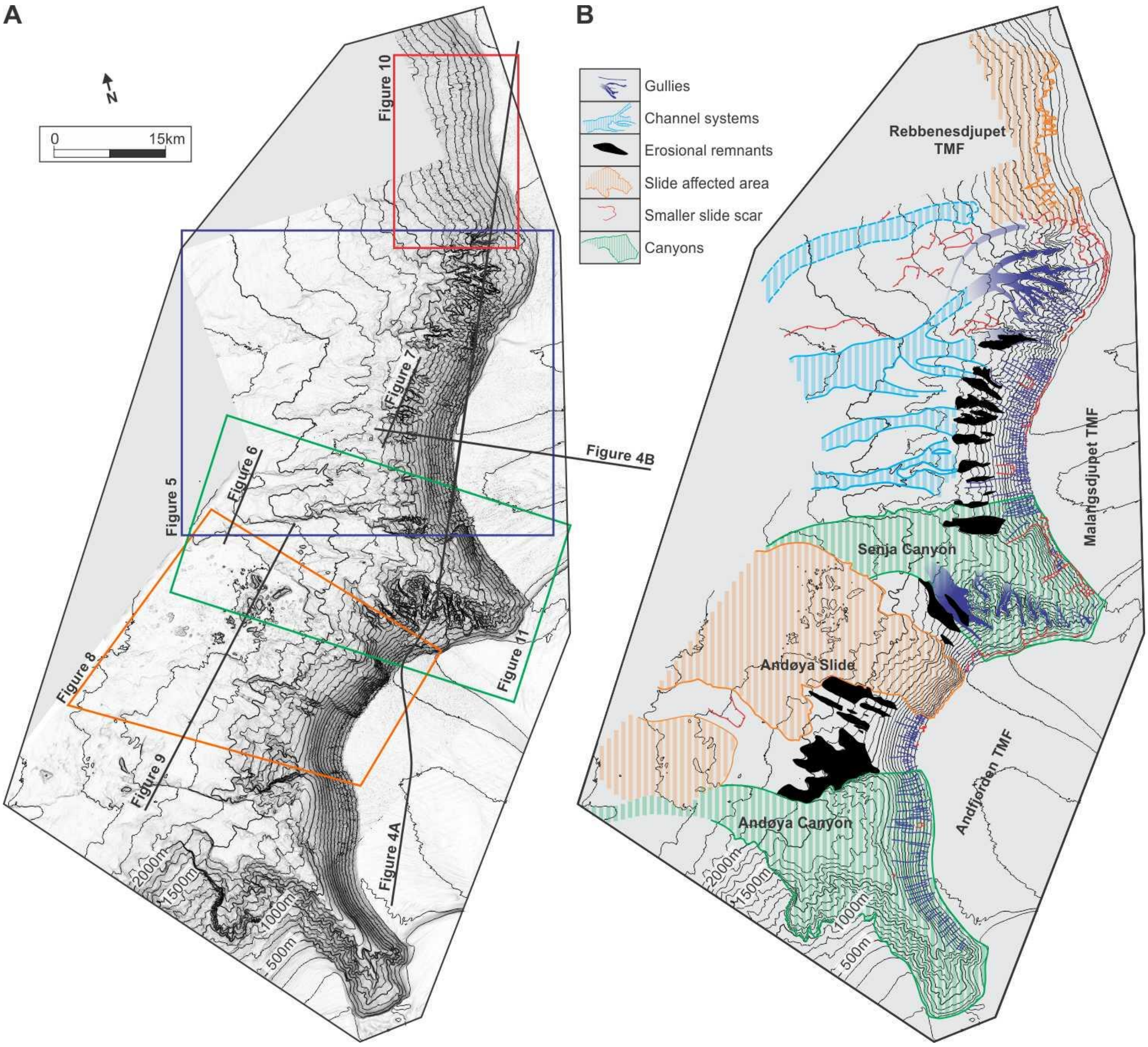

Fig. 3: The outer continental shelf and upper slope off northern Norway. See Fig. 2 for location. A: Slope gradient map. Areas of steep slopes have a darker colour. Locations of detail figures and seismic lines are indicated. B: Interpretation of landforms discussed in this paper. TMF=Trough Mouth Fan.

4 Results

The late Cenozoic seismic stratigraphy of the Troms continental margin is detailed in Rydningen et al. (submitted), and summarized below. Following this, the slope gradient and morphology of the three TMFs and inter-fan areas are presented (Fig. 3; also summarized in Table 1).

4.1 Seismic stratigraphy

The middle and outer shelf comprises late Cenozoic sediments which are subdivided into four seismic units: S1 (oldest) to S4, bounded by four regional horizons (T1-T4; Fig. 4A and B). Unit S1 is inferred to be of pre-Quaternary age and is completely buried by units S2-S4 (Rydningen et al., submitted).

Unit S2 comprises stacked, sub-parallel seaward-dipping clinoforms, interpreted to be dominated by suspension fallout and turbidity currents. Glaciomarine and glaciofluvial conditions prevailed during deposition of unit S2, which commenced at ~2.7 Ma (Rydningen et al., submitted). This unit outcrops on the lower slope of the Andfjorden and Malangsdjupet TMFs, at a water depth of ~1200 m (Fig. 4B).

Unit S3 comprises clinoforms with a steeper gradient, which are interpreted to mark a shift towards more intensified glaciations, including repeated advances of fast-flowing ice streams across the shelf, depositing subglacial deformation till at the shelf break. Later, these deposits were reworked by debris flows and turbidity currents and deposited on the slope (Rydningen et al., submitted). Together with unit S4, this unit makes up the present-day morphology of the Andfjorden and Malangsdjupet TMFs down to where unit S2 outcrops.

Unit S4 is a sheet-like deposit which covers the shelf and upper slopes of the Andfjorden and Malangsdjupet TMFs, as well as the entire Rebbenesdjupet TMF. The internal acoustic reflection configuration of the unit on the shelf is aggrading, with several internal unconformities which show evidence of former fast-flowing ice streams traversing the cross-shelf troughs. Thus, unit S4 also comprises subglacial deformation till (Rydningen et al., submitted). Below, we focus on the sea-floor morphology which represents the upper part of seismic unit S4 on the shelf and upper slope, and the outcropping units S3 and S2 on the lower slope (Fig. 4B).

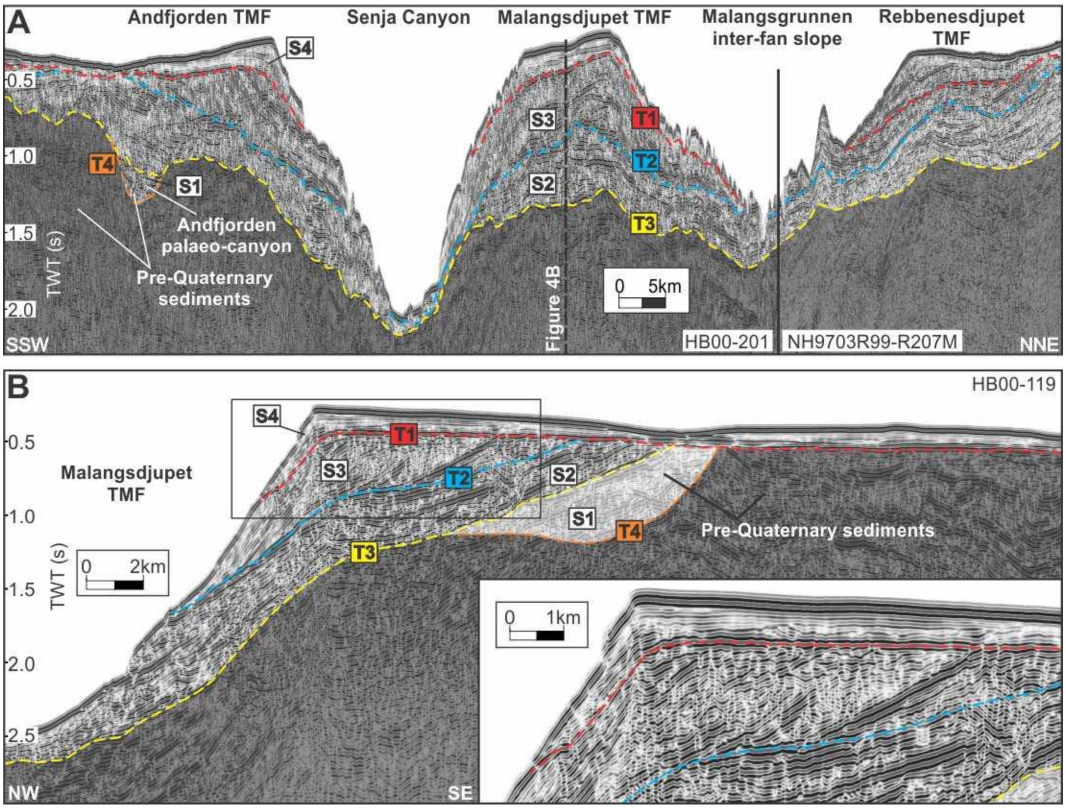

Fig. 4: Seismo-stratigraphic framework of the late Cenozoic sediments on the Troms margin (adopted from Rydningen et al., submitted). See Fig. 3 for location of profiles. A: Composite seismic strike line crossing the study area. B: Seismic dip line crossing the shelf break in the Malangsdjupet trough.

4.2 Continental slope gradient

From the convex-shaped shelf break to a water depth of ~1400 m, both the Andfjorden and Malangsdjupet TMFs are characterized by slope angles between 10° and 15° (Fig. 2B). Areas of highest gradient (~15° to ~35°) are associated with escarpments due to sliding/slumping and gravity flow erosion. At ~1400 m water depth a marked reduction in slope gradient occurs; between 1400 and 1600 m water depth the gradient of both fans is between 5° and 10°, before it decreases to below 5° between 1600 and 2000 m (Fig. 2B). From ~2000 m water depth the slope gradient is below 2° (Fig. 2B).

The Rebbenesdjupet TMF is generally characterized by a lower slope gradient. Similar to the other TMFs, this fan is steepest in the upper reaches, with gradients between 5° and 8° down to a water depth of 1200 m. Further downslope the gradient decreases to below 2°. Unlike the other TMFs, the gradient decreases more gradually seaward, i.e. this TMF has no pronounced circumference in its upper part (Fig. 2). The northern part of the Rebbenesdjupet TMF is coterminous with the southern part of the Håkjerringdjupet TMF (Fig. 1 and 2).

These TMFs have the steepest gradient reported from the Norwegian – Barents Sea – Svalbard continental margin and their gradients are comparable to TMFs and prograding wedges offshore the Antarctic Peninsula (Larter and Cunningham, 1993; Dowdeswell et al., 2004; Amblas et al., 2006), Greenland (Clausen, 1998; Nielsen et al., 2005; García et al., 2012), as well as the eastern Canadian margin (Batchelor and Dowdeswell, 2014).

4.3 Trough Mouth Fan morphology

4.3.1 Gully-channel complexes

The upper, steepest part of the Andfjorden and Malangsdjupet TMFs are dominated by a number of straight to slightly curved gullies (Fig. 3 and 5) which are relatively deep (5 to 50 m) compared with their width (100 to 500 m). Gullies both originate at the shelf break as small slide scars, some of which are partly buried in their upper reaches (see Fig. 12 in Laberg et al., 2007), and as single furrows between 100 and 200 m downslope of the shelf break. No connection to channels on the shelf has been observed.

The gullies represent the upper part of a gully-channel complex which dominates the morphology on the Malangsdjupet TMF (Fig. 5). Part of a similar system is located on the

Andfjorden TMF between the Andøya Slide and the Andøya Canyon (Fig. 3). The gullies show a dispersing character on the upper part of the complexes, probably due to the convex-shaped shelf break. The upper gully-dominated part can be followed to a water depth of ~1200 m, where downslope oriented and high-relief ridges occur (Fig. 5; see below). On the Malangsdjupet TMF the gullies from this depth merge into channels, which are distinguished from gullies in being wider (1 to 6 km). The channels are coalescing further downslope into three main channels (C1, C2 and C3) from a water depth of ~1800 m (Fig. 5). This is inferred to be controlled by the distribution and location of the high-relief ridges focusing the flows into the inter-ridge areas and channels. A cut-and-fill pattern is inferred from a seismic profile crossing the lower part of the channels (Fig. 6) showing lateral channel migration.

Based on a comparative study of gullies on Arctic and Antarctic margins, Gales et al. (2013) concluded that gullies likely evolve through either downslope erosion by turbidity currents, which may be initiated by discharges of sediment-laden subglacial meltwater, or through headward erosion by retrogressive mass failures, which may occur both during glacials and interglacials. Many of the straight gullies on the Troms margin are partly infilled on the upper parts of the TMFs. This most likely took place through the deposition of subglacial sediments during the LGM, and not during the present interglacial when the northward flowing Norwegian Current is erosive to a water depth between 500 and 600 m, below the shelf break. The fresh-looking gullies that are not infilled and thus are younger formed after the onset of ice recession, i.e. during the Holocene.

Based on the data at hand it is difficult to discriminate between an origin from erosion by sediment-laden bottom currents derived from a shelf break-terminating ice sheet, or small scale sediment failure during LGM for the partly buried gullies. For the Holocene gullies, an origin from sediment failure is favoured, since no indications of cold bottom-water formation in the troughs during the present interglacial have been reported.

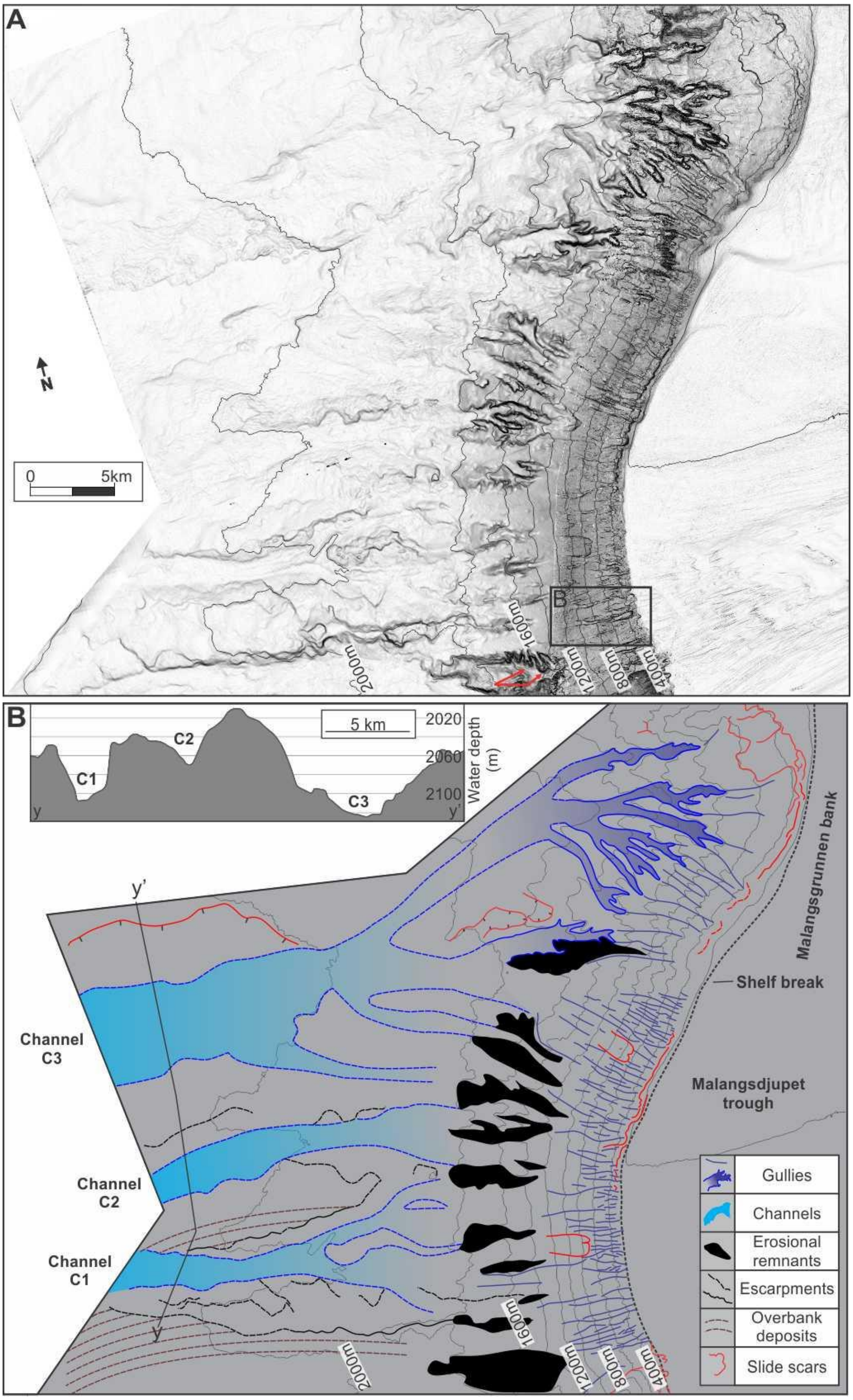

Fig. 5: The Malangsdjupet Trough Mouth Fan and the Malangsgrunnen inter-fan slope. See Fig. 3 for location. A: Slope gradient map. Red arrows indicate slide scars on erosional remnants. B: Interpretation of A. Gullies dominate the Trough Mouth Fan morphology down to 1200 m water depth, before they

merge into channels on the lower slope (C1, C2 and C3). The depths of the channels are illustrated by a bathymetric profile. The Malangsgrunnen inter-fan slope is dominated by slides and gullies forming a dendritic pattern merging into C3 on the lower slope.

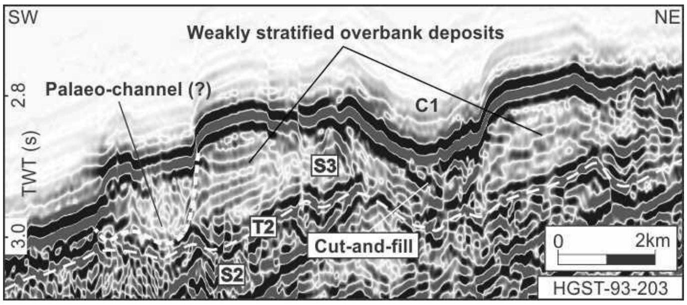

Fig. 6: Seismic profile across overbank deposits showing a weak internal stratification. Channel C1 erodes into the overbank deposit and has a cut-and-fill character. A possible palaeo-channel is located in the northern part of the Senja Canyon channel. See Fig. 3 for location.

4.3.2 Downslope-oriented ridges – erosional remnants

Distinct linear, high-relief ridges are found on the Andfjorden and Malangsdjupet TMFs at water depths between 1200 and 1800 m (Fig. 3 and Table 1). These features were also identified by Rise et al. (2009). The ridges are almost perpendicular to the contours, indicating that their overall form is a result of erosion by downslope oriented and gravity-driven processes (Rise et al., 2009). Their present relief is also due to erosion from a number of smaller slides (Fig. 5A). The ridges consist of stiff sediments (Bellec et al., 2012a; b). Internally, the ridges are characterized by medium- to high-amplitude reflections, which are truncated by the seabed (Fig. 7). Hence, the high-relief ridges are interpreted to be erosional remnants in conformity with Rise et al. (2009). The ridges are deposits from seismic unit S2, i.e. they are interpreted to represent an early glaciomarine to glaciofluvial phase of TMF growth (Rydningen et al., submitted), and they thus protrude and pre-date the upper succession of the TMFs (Fig. 4B).

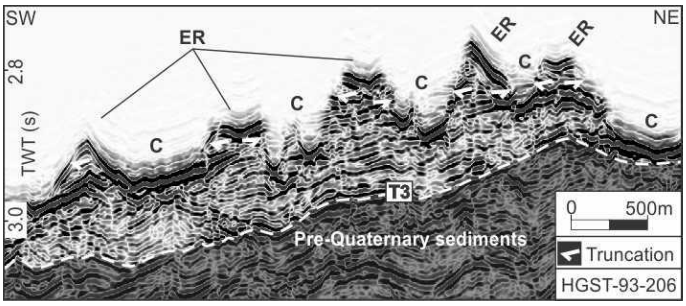

Fig. 7: Seismic profile across the erosional remnants (ER) and channels (C). Internal reflections within the erosional remnants are truncated by the seabed. See Fig. 3 for location.

4.3.3 Large-scale sliding – the Andøya Slide

The Andøya Slide is located on the central part of the Andfjorden TMF (Fig. 8). The slide scar is characterized by a pronounced bathymetric depression on the upper slope and a distinct headwall up to 300 m high, which cuts into the outer shelf. The slide scar has steep sidewalls up to 200 m high. Smaller, amphitheatre-like shaped scars, typically between 250 and 500 m wide, occur within the upper slide scar, some places forming a stair-case pattern (Fig. 8). Below these, down to 1700 m water depth, the seabed within the slide has a relatively low relief. Secondary escarpments and small slide blocks characterize the seabed morphology downslope from ~1700 m water depth. The slide scar keeps its width (between 7 and 11 km) to a water depth of ~2100 m, i.e. where the slope gradient is below 2°. Further downslope, the Andøya Slide has affected parts of the Senja Canyon, and the slide widens to more than 20 km. Large slide blocks dominate the morphology here (Fig. 8 and Table 1), and the displaced mass of remobilized sediments is characterized by a chaotic seismic facies (Fig. 9).

The relatively smooth seabed within the upper parts of the Andøya Slide, and the absence of high-relief ridges in this area, show a complete evacuation of failed masses. Within the slide scar, the stair-case pattern of scars indicates that sediments to different levels were affected. The sediment blocks are probably detached blocks of more consolidated sediments that moved for some distance and then stopped. These could originate from erosion of downslope-oriented ridges described above, which do not occur within the slide scar. Further into the basin (outside the data coverage), three large debris flow lobes have been identified (Dowdeswell et al., 1996; Laberg et al., 2000), implying a total run-out distance of at least 190 km for this event.

The sliding on the Andfjorden TMF conforms to most large-scale mass-movements on the Norwegian continental slope in that it cuts back all the way to the continental shelf break. The failures stop at the flat lying and overconsolidated glacial deposits, as for example the Storegga (Bugge et al., 1987; Haflidason et al., 2004), Trænadjupet (Laberg and Vorren, 2000) and Hinlopen-Yermak landslides (Vanneste et al., 2006). From the available seismic data, it is difficult to verify the nature of the base slide scar, i.e. if it is parallel to underlying strata and thus, if a stratigraphic interval within contouritic sediments represented a slip plane for the failure – as has been found to characterize other slides on the Norwegian slope (e.g. Bryn et al., 2005). This is due to low vertical resolution of the 2D seismic data and noise from the gullied seabed.

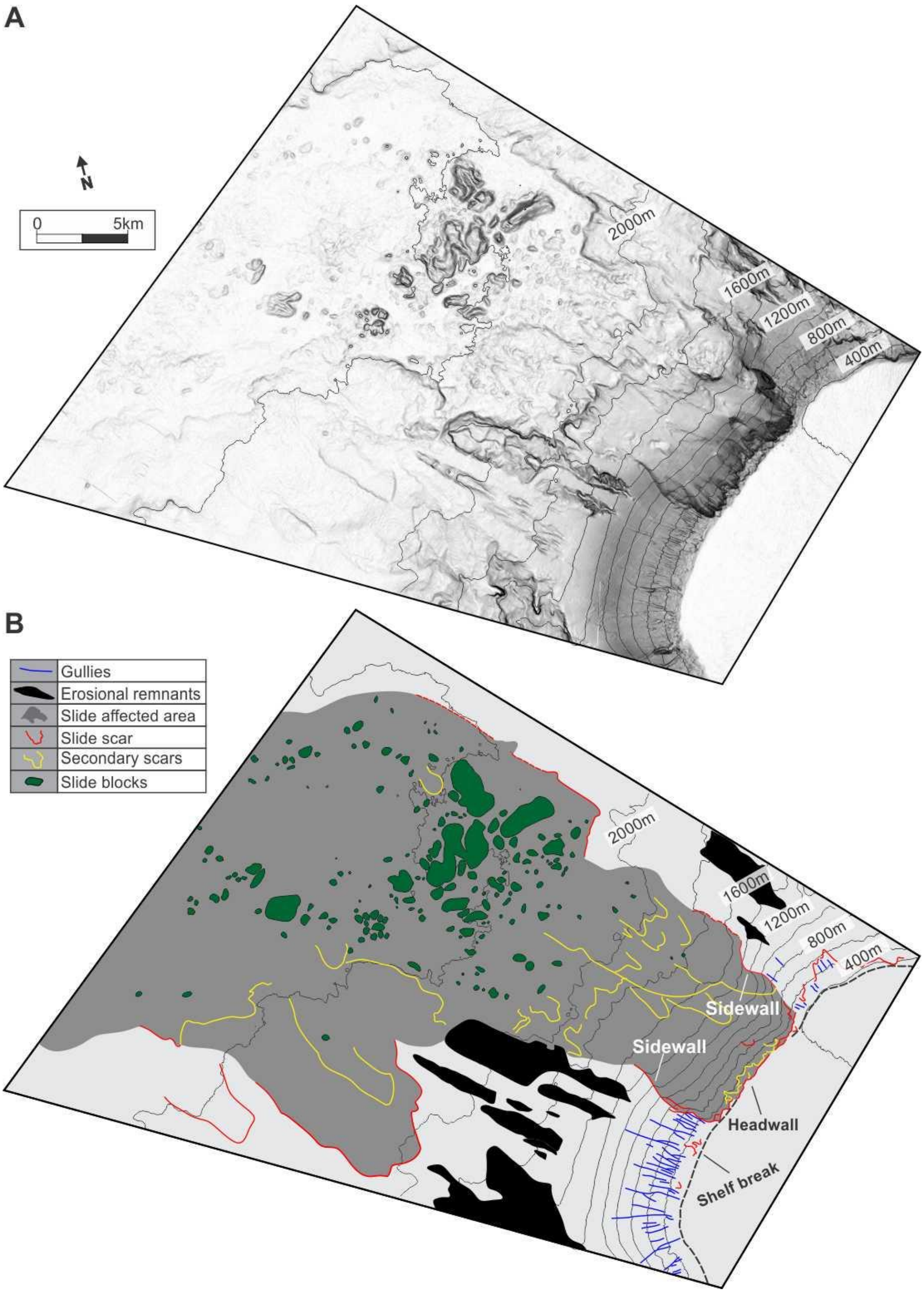

Fig. 8: The Andøya Slide on the Andfjorden Trough Mouth Fan. See Fig. 3 for location. A: Slope gradient map. B: Interpretation of A with the slide affected area in dark grey. The headwall of the Andøya Slide cuts into the shelf. Smaller amphitheatre-like scars, in places forming a stair-case pattern, occur in the uppermost part, while a low-relief terrain characterizes the slide scar down to 1700 m water depth. Secondary escarpments and small slide blocks characterize the seabed morphology further downslope.

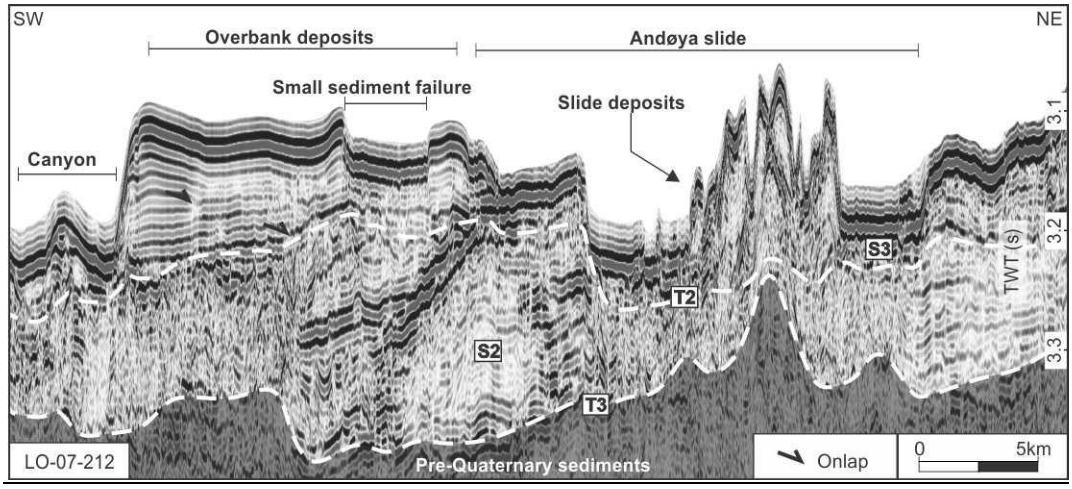

Fig. 9: Seismic profile crossing the Andøya Canyon, with its ancillary overbank deposits, and the Andøya Slide. Slide deposits within the Andøya Slide, which may constitute erosional remnant ridges, are indicated. See Fig. 3 for location.

4.3.4 Smaller slides – the upper Rebbenesdjupet TMF

The upper part of the Rebbenesdjupet TMF is dominated by a number of smaller landslides. Sliding has occurred downslope from a water depth of 400 to 600 m, between 100 and 300 m below the shelf break, and downslope to ~1300 m (Fig. 3). The slide scars includes irregular headwalls and several secondary escarpments, forming a stair-case pattern of scars that are typically between 10 and 30 m high (Fig. 10).

The headwalls include several smaller, amphitheatre-shaped segments. No sediment ridges or blocks were observed within the scars, indicating complete evacuation of the failed masses. The area upslope of the headwall is nearly completely devoid of landforms; except for a few smaller individual slides and gullies, and iceberg ploughmarks immediately below the shelf break (Fig. 10). Downslope from ~1300 m water depth, the slide scars become more indistinct and a subdued channel between 10 and 20 m deep and 2 to 3 km wide is observed (Fig. 3).

The stair-case slide scar configuration on the upper Rebbenesdjupet TMF indicates a retrogressive landslide development, similar to the Style 2 mass-movement identified by Baeten et al. (2013) on the continental slope offshore the Lofoten Islands (south of our study area). There, the headwall position was explained by an upslope decrease in slope gradient. The slope angle of the Rebbenesdjupet TMF, however, is gently increasing upslope making the influence of gradient less likely. Alternatively, this could be related to variations in composition and/or physical properties of the sediments of the upper Rebbenesdjupet TMF. Further studies are needed in order to clarify this.

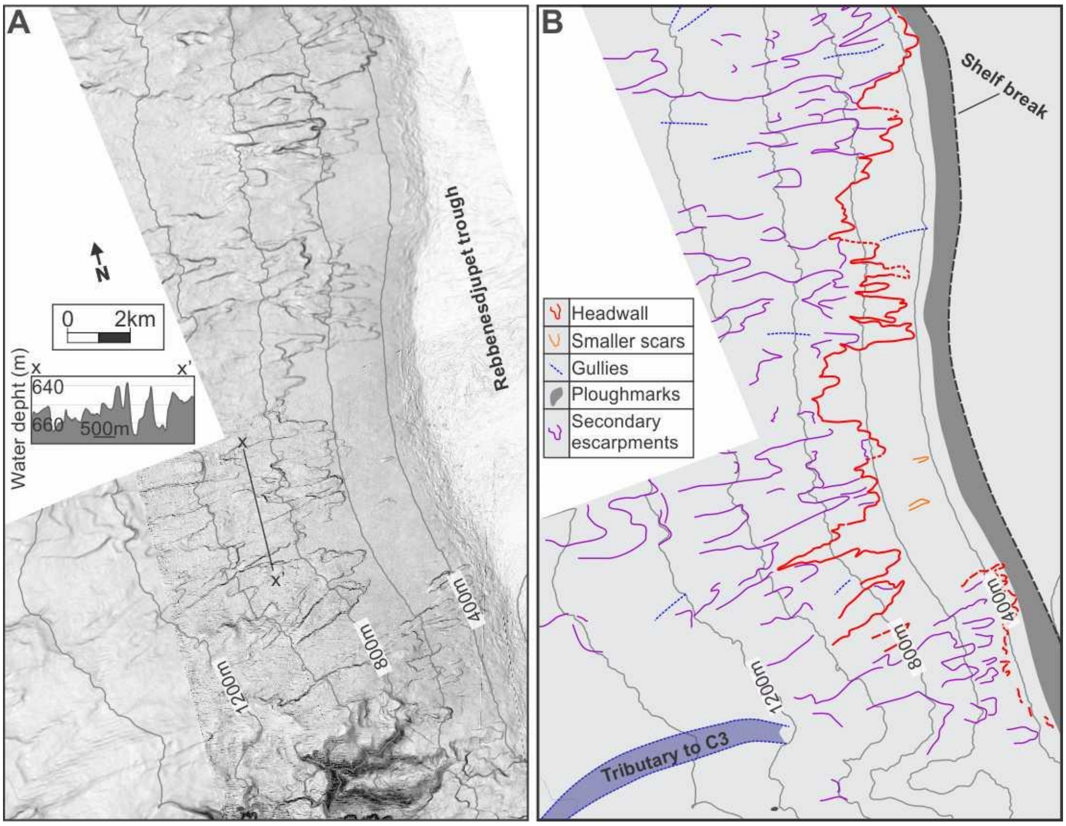

Fig. 10: The upper part of the Rebbenesdjupet Trough Mouth Fan. See Fig. 3 for location. A: Slope gradient map. Profile: The height of the slide scars is approximately between 10 and 30 m. B: Interpretation of A. A number of smaller landslides dominate the seabed morphology down to a water depth of ~1300 m. The slide headwall is irregular, and several secondary escarpments form a stair-case pattern downslope.

4.4 Inter-Trough Mouth Fan morphology

4.4.1 The Senja Canyon

A submarine canyon, here named the Senja Canyon, is located between the Andfjorden and Malangsdjupet TMFs. It is ~35 km long, as measured from the headwall to 2200 m water depth, and represents a curved feature incised into the continental slope and outer shelf. The headwall width is 6 km, and the canyon widens to a maximum of 20 km seaward (Fig. 11A). A topographic long-profile from the headwall shows an overall concave shape with channel gradient declining away from the shelf break (Fig. 11B). The canyon is V-formed in cross section, and it cuts into a maximum of 1000 m of inferred Quaternary sediments (Fig. 11C) (Rydningen et al., submitted).

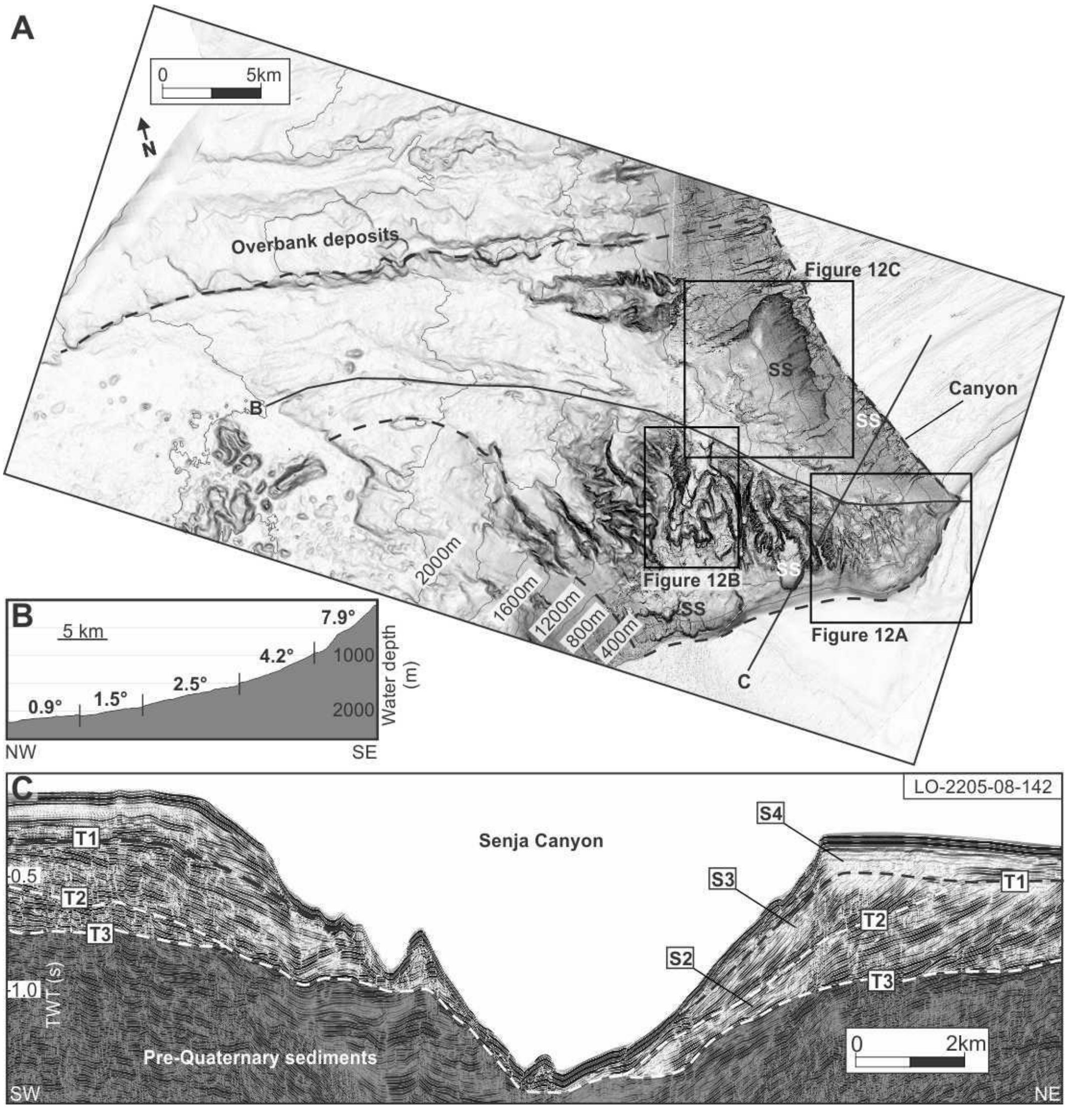

Fig. 11: The Senja Canyon. A: Slope gradient map of the Senja Canyon (outlined with dashed line). Overbank deposits are indicated. Profiles in B and C, as well as Fig. 12, are indicated. See Fig. 3 for location. B: Topographic long-profile from the headwall of the canyon. The Senja Canyon has an overall concave shape with channel gradients declining downslope. C: Seismic profile across the inner part of the canyon. The maximum incision of the canyon is 1000 m and it cuts into sediments of Quaternary age.

The uppermost part of the headwall forms the present shelf break at between 100 and 200 m water depth. Marginal moraines are situated at and close to the shelf break (Rydningen et al., 2013), and sediment ridges, indicating modern deposition of sandy sediments, tangentially approach the western part of the headwall area (Fig. 12A). The headwall morphology is smooth in its upper part and gullies originate a couple hundred meters below the shelf break.

These are partly buried in their upper reaches and coalesce with the main canyon channel downslope (Fig. 12A).

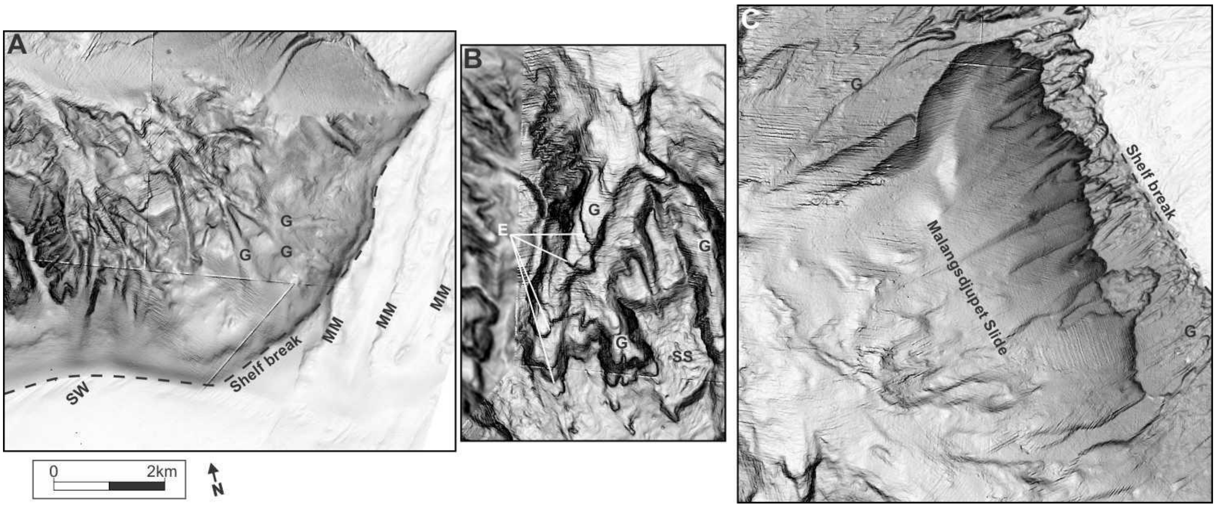

Fig. 12: Slope gradient maps of the Senja Canyon showing details of the headwall area (A), the western sidewall (B), and the eastern sidewall (C). See Fig. 11 for location. A: Marginal moraines (MM) and sediment waves (SW) are situated at and close to the shelf break. The canyon headwall is characterized by partly buried gullies (G) which join downslope. B: Slide scars (SS) and steep-sided gullies dominate the morphology on the western sidewall. Escarpments (E) are common along the gully thalwegs. C: Slide scars and gullies also dominate the eastern sidewall. The largest slide, the Malangsdjupet Slide, extends down to the base of the Senja Canyon.

The western sidewall forms part of the northern slope of the Andfjorden TMF. Close to the headwall, the western sidewall is smooth down to a water depth between 200 and 500 m, except for a submarine landslide (Fig. 11A). West of this, another slide dominates down to between 800 and 900 m (Fig. 11A). Further downslope, steep-sided gullies extend down to the base of the canyon (Fig. 11A, 12B and Table 1). The gullies are sinuous, and consist of several smaller tributary gullies. V-shaped escarpments are common along the gully thalwegs, indicating areas of higher erosion (Fig. 12B).

The eastern sidewall forms part of the southern slope of the Malangsdjupet TMF, and is also dominated by slides and gullies. The largest slide, here named the Malangsdjupet Slide, is characterized by a distinct bathymetric depression and clear-cut sidewalls, which extends down to the base of the Senja Canyon (Fig. 12C).

The main channel is the continuation of the gullies originating at the shelf break and can be traced downslope to the Andøya Slide. The channel most likely coalesced with the Lofoten Basin Channel outside the study area (Amundsen et al., 2015). Between 900 and 1600 m water depth the channel is between 1 and 2 km wide and relatively flat. Beyond this, the thalweg widens to ~10 km at 2200 m water depth. The inner, deeper part of the main channel keeps its identity to a water depth of ~2000 m, where it branches out (Fig. 11A). In its lower reaches, the northern part of the channel cuts into a weakly stratified sequence (Fig. 6). These sediments are probably overbank deposits accumulated from turbidity currents transported down the canyon channel, i.e. debris derived from the Andfjorden and Malangsdjupet TMFs. Channel C1 and C2 also erode these deposits. Similar overbank sediments are observed north of the Andøya Canyon channel (Fig. 9) (Laberg et al., 2005b; Amundsen et al., 2015).

In summary, the Senja Canyon owns its origin from an interplay of depositional and erosional processes. Both sidewalls are part of the TMFs immediately to the north and south, and sediment failure here, as well as in the headwall area generated gravity currents, focused into the deeper area between the fans where they eroded and thus deepened and widened the canyon. Glacigenic sediments from the Fennoscandian Ice Sheet at or near the shelf break, and sandy sediments from ocean current winnowing during interglacial conditions, were probably also routed through the canyon.

4.4.2 <u>The continental slope west of the Malangsgrunnen bank</u>

The shelf break at the outer Malangsgrunnen bank is concave. The continental slope has a concave long-profile, and the slope gradient is in general steeper than 5° down to ~1500 m water depth, before it decreases to below 2° at ~1800 m (Fig. 2B).

Slide scars which are sub-parallel to the shelf break dominate the upper slope morphology. These occur approximately between 100 and 200 m below the shelf break, and are less fresh-looking in the south (Fig. 5). Straight gullies occur downslope of the slide scars. These are best developed in the south, where they are typically 500 m wide, 60 m deep and extend down to 1100 m water depth. The gullies include one or two "waterfalls", below which they are wider (between 500 and 1200 m) and eroded to a deeper stratigraphic level. The gullies form a dendritic pattern merging into one channel at ~1700 m water depth. This channel merges with the C3 channel on the lowermost slope.

The slide scars are morphologically very similar to the slide scars on the upper Rebbenesdjupet TMF. The straight gullies have a similar morphology as the gullies on the upper TMFs, and are thus inferred to be of similar origin, i.e. formed by erosion from sediment-laden bottom currents during LGM or by small-scale sediment failures. Downslope, they merge with deeper gullies that were probably formed by retrogressive and small-scale mass-wasting, originating at the lower parts of the slope. Due to the overall concave-shaped form of the shelf break and its concave long-profile, the gully-forming flows originating at the shelf break were routed into the deeper gullies. The overall form of the slope acted as a funnel in focusing the downslope flow, forming the dendritic flow pattern.

To summarize, sediments originating from the northern Malangsdjupet TMF, as well as the continental slope immediately to the north, have been routed through the depression between the Malangsdjupet and Rebbenesdjupet TMFs. This did not, however, lead to the development of a typical canyon morphology including a V-formed cross-section, as observed in the Senja and Andøya canyons, possibly because less sediment was routed through this part of the slope. This may be due to little input from the area of the Rebbenesdjupet TMF, where mainly smaller slide scars have been identified.

5 Discussion

Below, the morphology and sedimentary processes of the studied high-gradient TMFs are addressed, before the findings in this study are compared to the results from high-gradient TMFs located elsewhere. Finally, sedimentary processes on high- and low-gradient TMFs are compared.

5.1 Morphology and sedimentary processes on high-gradient trough mouth fans on the Troms margin

The Malangsdjupet TMF is dominated by gully-channel complexes, and similar landforms are also found on the Andfjorden TMF. Thus, the evolution of both fans included sediment transport and distribution through gully-channel complexes. The Andfjorden TMF has more recently been affected by a large submarine landslide, which remobilized much of these complexes. The gradient and morphology of the Rebbenesdjupet TMF differs from the other fans: the gradient is lower, the studied part of the upper fan is dominated by a number of small and relatively shallow slide scars, and no upper-slope gullies have been identified. A similar morphology has not previously been reported from other TMFs; the only area of comparable features occurs on the continental slope offshore the Lofoten Islands (Fig. 1), an area dominated by contouritic sediments and glaciomarine deposits (Laberg et al., 2005a; Baeten et al., 2013). Thus, it is suggested that the uppermost succession on the Rebbenesdjupet TMF is dominated by glaciomarine and/or contouritic sediments affected by repeated small-scale sediment failure.

The difference between the upper succession of the Rebbenesdjupet TMF and the Malangsdjupet/Andfjorden TMFs may be related to the oceanography of the area. The Rebbenesdjupet TMF is located where the alongslope flowing Norwegian Atlantic Current splits into two branches: one flows north along the Barents Sea slope, while the other flows east entering into the Barents Sea. The two southern fans are located below the Norwegian

Atlantic Current (Hansen and Østerhus, 2000; Slubowska-Woldengen et al., 2008). It is speculated here that this current is mainly erosive where it affects the upper Andfjorden and Malangsdjupet TMFs, whereas deposition of contouritic sediments on the upper part of the Rebbenesdjupet TMF is related to a reduction in flow speed and/or a reduction of the water depth influenced by the Atlantic Current occurring where the modern current is splitting into two branches. Further studies are needed in order to verify this.

No contouritic sediments are observed on the available data, except for the indirect evidence by the small-scale sliding on the Rebbenesdjupet TMF. Thus, the main sediment input onto the TMFs has most likely occurred during peak glacials when fast-flowing ice streams within the Fennoscandian Ice Sheet transported sediments in an active subglacial layer to the grounding-line at the shelf break (Vorren and Plassen, 2002; Ottesen et al., 2005; Rydningen et al., 2013). The overall convex fan form and progradational seismic facies (Fig. 4; Rydningen et al., submitted) show that this muddy diamicton (Vorren et al., 1984) was repeatedly distributed onto the fan. On the Andfjorden and Malangsdjupet TMFs, gully-channel complexes occur within such deposits. It is inferred that the steep slope of these high-gradient TMFs promoted rapid transformation from small-scale slumps and debris flows on the upper slope, into partly erosive turbidity currents. This is because turbidity currents are known to have led to the formation of channel systems elsewhere in both high-latitude (e.g. Dowdeswell et al., 2004) and low-latitude (Posamentier and Kolla, 2003) continental margins. Also, similar gully-channel systems have not, in most cases, been reported from low-gradient TMFs dominated by GDF deposits (e.g. Laberg and Vorren, 1995; King et al., 1996; Davison and Stoker, 2002; García et al., 2012). The transformation from debris flows into turbidity currents, which involves extensive dilution of debris-flow material, observed in experiments by Hampton (1972), is probably a consequence of flow transformation due to the relatively high velocity caused by the steep slope gradient (Fisher, 1983). The transition from gullies to channels was probably controlled by the relief of the slope and the high-relief ridges, which routed the turbidity currents downslope.

Part of the turbidity currents originating from the upper Andfjorden and Malangsdjupet TMFs were routed into the Andøya and Senja Canyons, as well as the channel complex between the Malangsdjupet and Rebbenesdjupet TMFs, showing that the inter-TMF areas have also, to a large degree, evolved as a response to sediment input to the fans. These currents were erosive, forming the canyon thalwegs, and probably also influenced on the stability of the TMF deposits, triggering smaller and larger landslides by undercutting. As the channel at the mouth of the Senja Canyon turns south-westward in the lower part of the Andøya Slide, it is suggested that undercutting may also have influenced the stability of the continental slope sediments in the central part of the Andfjorden TMF.

The Andøya Slide affected part of the Andfjorden TMF and smaller slide scars are frequent on the continental slope off Troms. TMFs represent sediment depocentres that may be unstable due to periods of high sedimentation rate, and submarine landslides of size comparable to the Andøya Slide or larger have repeatedly affected other TMFs along the Norwegian – Barents Sea – Svalbard margin (Laberg and Vorren., 1993; 2000; Bryn et al., 2005; Vanneste et al., 2006). The Andøya Slide has been suggested to be of late glacial – Holocene age (Laberg et al., 2000). The results from this study support this interpretation, as progradation of glacigenic sediments, and gullies, mainly inferred to be of glacial origin, have not been identified within the slide scar.

From the above results a conceptual model has been compiled, summarizing the sedimentary processes acting on high-gradient TMFs (Fig. 13A). The model is based on the results from the fans of highest gradient, i.e. the Andfjorden and Malangsdjupet TMFs. In the model, large volumes of subglacial debris were transported beneath fast-flowing ice streams to the shelf break. These sediments were deposited as progradational units, which were subsequently partly subjected to a downslope remobilization as erosive turbidity currents forming gullies. Furthermore, high-relief ridges routed the turbidity currents into channels which may have continued into the deep sea basin. Also included in the model is large-scale sliding which may modify the morphology of high-gradient TMFs (Fig. 13A).

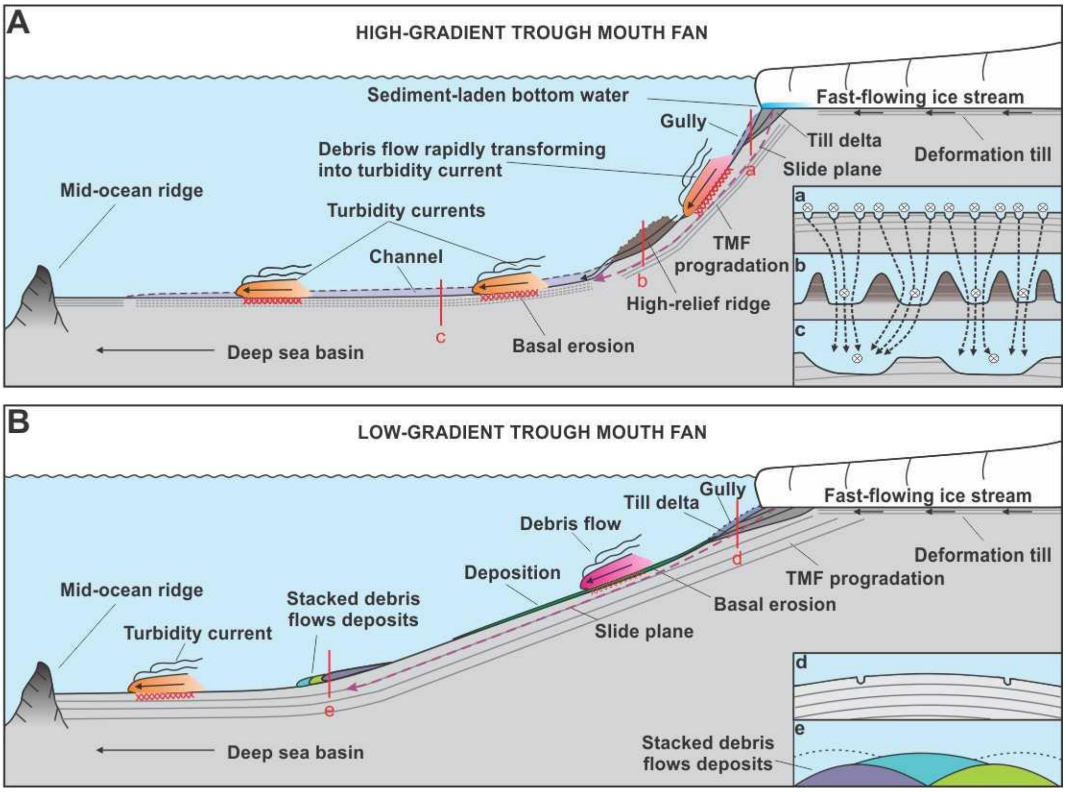

Fig. 13: Conceptual models of high-gradient (A) and low-gradient (B) trough mouth fans. See text for further discussion.

5.2 High-gradient trough mouth fans in other areas

Seaward-bulging depocentres with high gradients are found at glacial trough mouths at both northern and southern high latitudes (Table 2), and they are here regarded as high-gradient TMF-equivalents. In total, ten high-gradient TMFs (slope gradient >4°) have been identified outside high Arctic cross-shelf troughs (not including the Troms margin), including areas off South and East Greenland, Queen Elisabeth Island, and in the Baffin Bay (Batchelor and

Dowdeswell, 2014). Also, high-gradient TMFs are found on the margin off the Antarctic Peninsula (Table 2) (Tomlinson et al., 1992; Larter and Cunningham, 1993; Dowdeswell et al., 2004; Amblas et al., 2006).

Previous studies on high-gradient TMFs generally suffer from a limited access of bathymetric data (Table 2). An exception is the study by Amblas et al. (2006) off the Antarctic Peninsula, where swath-bathymetric data covering the inner shelf to the lower slope has been acquired. There, gullies at the upper slope and canyon-channel systems on the continental rise together form a complex dendritic pattern. However, the gullies vanish at the base of the slope, showing no apparent connection with the canyon-channel system downslope. Large sediment mounds are found between 500 and 1000 m above the canyon-channel axes, and are inferred to have formed from settling of suspension clouds from turbidity currents, caused by the considerable hydraulic jump at the base of the North Pacific Peninsula continental slope, where the slope gradient shifts from more than 18° to less than 4°. On the high-gradient TMFs on the continental margin off Troms, a mid-fan relief is instead dominated by high-relief ridges which probably focused turbidity currents into the channels on the lower part of the slope. Thus, the system described by Amblas et al. (2006) resembles the gully-channel complex on the high-gradient TMFs in this study. Nevertheless, differences are found in the transition from gullies to channels on the lower part of the slope. This may relate to the presence or absence of high-relief ridges.

Based on seismic data, Clausen (1998) described modern scars in the uppermost part of high-gradient TMFs on the SE Greenland margin and related these to slumps and slides. Canyons are absent and gullies are scarce on this part of the margin, suggesting that ‘unchannelized debris flows probably was the main process by which the slope prograded’ (Clausen, 1998). Till deltas, deposited at the shelf edge from grounded ice, were subsequently subjected to downslope redeposition, initiated as small-scale slope-failures. The sediment remobilization generated GDFs on the slope, which was either deposited as GDF debrites at the lower slope or passed into turbidity currents, identified from channels on the continental rise. As opposed to the upper-slope gullies routing turbidity currents downslope on the continental slope off Troms, the sediment transport across the upper TMFs on the SE Greenland margin appear to have occurred through unchannelized flows. In this regard it should be mentioned that the lack of gullies may reflect the data base available from this area, since gullies are most easily identified on swath-bathymetric data. Further downslope, similar characteristics as the Andfjorden and Malangsdjupet TMFs are found, with channels formed by turbidity currents continuing into the deep sea basin. However, Clausen (1998) identified GDF debrites on the lower slope, which are absent from the Troms margin TMFs.

In other studies on high-gradient TMFs off East Greenland (García et al., 2012) and the Antarctic Peninsula (Tomlinson et al., 1992; Larter and Cunningham, 1992; Dowdeswell et al., 2004) gullies on the upper slope merging into channels are common, testifying to turbidity currents being the main mode of transport for sediments across the slope (Table 2). Broadly, therefore, it is found that other high-gradient TMFs conform to the conceptual model shown in Fig. 13A. GDF debrites are scarce or absent on high-gradient TMFs, similar to the TMFs on the Troms margin. Also, gully-branching systems with similarities to the gully-channel complexes found here have been described on the Antarctic margin (Tomlinson et al., 1992; Dowdeswell et al., 2004; Amblas et al., 2006), and possibly on the East Greenland margin (García et al., 2012). In these areas, however, turbidity currents are inferred to form sediment waves or sediment mounds on the lower slope, probably as a consequence of the lower slope velocities caused by a gradient decrease. In contrast, turbidity currents are channelized through high-relief ridges on the Troms margin TMFs, thus maintaining their velocity downslope, and forming channels on the lower slope. Finally, downslope sediment transport from small-scale slides is common in other high-gradient TMFs, while large-scale slides are, unlike in this study, not described.

5.3 Processes on high- and low-gradient trough mouth fans – a comparison

Processes on the low-gradient end member of TMFs are well-studied (e.g. Vorren et al., 1989; Aksu and Hiscott, 1992; Vogt et al., 1993; Laberg and Vorren, 1995; King et al., 1996, 1998; Dowdeswell et al., 2008) (Fig. 13B). GDFs, originating at the upper slope, are found to extend onto the abyssal plain (Fig. 13B). The individual GDF debrites, the "building blocks" of low-gradient TMFs, can be mapped by side-scan sonar (Vogt et al., 1993) and swath-bathymetric data (Davison and Stoker, 2002), while buried debrites can be identified from seismic data as stacked mound forms extending downslope, deposited between older debrites (Laberg and Vorren, 1995; 1996a; b; King et al., 1996; Vorren and Laberg, 1997). The debris flows terminate on the lower fan, probably due to a decrease in slope gradient, and may continue as turbidity currents further into the basin (Fig. 13B). Work from the Bear Island TMF show that the lithologies of GDF debrites on the slope are similar to the till on the shelf, i.e. that little or no sediment sorting has taken place during downslope flow (Laberg and Vorren, 1995).

The TMF gradients are inferred to exert a fundamental control on the sedimentary processes and, hence, on the resulting TMF morphology and sediment composition (Ó Cofaigh et al., 2003; Piper and Normark, 2009). The gentler slope of low-gradient TMFs facilitate incremental outbuilding of the fan by debris-flow deposition, and would prevent rapid reworking of debris into turbidity currents (Fig. 13B) (Ó Cofaigh et al., 2003). In contrast, subglacial debris deposited at the Troms margin shelf break during peak glaciations was prone to be reworked into turbidity currents due to higher flow velocity on the steep slope, facilitating sediment transport into the deep sea (Fig. 13A), and thus maintaining the high gradient of the slope (a positive feedback loop). Also, the input of glacigenic sediments to this sector of the Norwegian margin was low compared to the areas to the north (Bear Island

TMF) and south (prograding wedge off Mid-Norway) (Rydningen et al., submitted), further promoting a steep continental slope. The steep Troms margin slope was possibly inherited from a likely original steep continental slope (Osmundsen and Redfield, 2011; Redfield and Osmundsen, 2013; Indrevær et al., 2013), inferred to have exerted a fundamental control on continental margin development throughout the late Pliocene – Pleistocene period of large-scale glaciations reaching the shelf break as discussed by Rydningen et al. (submitted).

Gullies, merging downslope, occur on the upper parts of the low-gradient Bear Island and Storfjorden TMFs in the SW Barents Sea (Laberg and Vorren, 1995; 1996a; Vorren et al., 1998). These gullies have a fresh relief and do not appear to contain any sediment infill, indicating that they were not formed during full-glacial conditions (Vorren et al., 1998). No gully-channel complexes were described on these fans. The low-angle Belgica TMF on the Antarctic margin has, on the other hand, a well-developed network of gullies and channels, interpreted to be related to the intermittent downslope transfer of sediments from the upper slope to the continental rise through turbidity currents (Dowdeswell et al., 2008). Some of these gullies are observed to cut through debrites on the slope, and the inferred turbidity-derived debris is overlying these. Thus, the processes taking place during the formation of the gullies were probably active during late stages of the peak glaciation and the following deglaciation, and possibly in phases subsequent to this.

In general, it appears that gullies on low-gradient TMFs post-date GDF activity and thus, mainly formed during the end of the LGM, the deglaciation, or subsequent to this (Vorren et al., 1998; Dowdeswell et al., 2008). In this study, it is observed both fresh-looking gullies, which probably originated as sediment-failures, and less fresh-looking gullies, inferred to have formed during full-glacial conditions by either sediment-laden bottom waters or small-scale failures. In any case, the gullies are inferred to have formed from turbidity currents originating at the steep upper slope (Fig. 13A). In contrast, on the low-gradient TMFs, debris flows formed on the upper slope. These eroded the substrate to a lesser degree, and deposited sediments as they moved downslope (Fig. 13B).

Large submarine slide scars on TMFs are well-studied from the Norwegian margin, including slide scars on the Bear Island TMF (Laberg and Vorren, 1993), the Hinlopen-Yermak TMF (Vanneste et al., 2006) and the North Sea TMF (Bryn et al., 2005). On other glaciated margins, such as the East Greenland margin (Vorren et al., 1998) and on the Belgica TMF (Dowdeswell et al., 2008), no major slide scars have been revealed on the seabed. On the Troms margin, the Andøya Slide has remobilized major parts of the Andfjorden TMF, while only smaller-scale mass-movements have occurred on the other TMFs, with the exception of the Malangsdjupet Slide. Thus, large-scale sliding can occur at both high-and low-gradient TMFs.

In summary, it is found that high-gradient TMFs facilitate the evolution of erosive turbidity currents, which contrasts with the low-gradient end member of TMFs where GDFs dominate. Also, the high number of gullies on the steep part of the Troms margin TMFs, with ancillary channels downslope, were likely important pathways for sediments across the slope, maintaining the steepness of the TMFs (Fig. 13A). Gullies on low-gradient TMFs are generally formed in late glacial and deglacial phases, and are thus not important for downslope flow during full-glacial conditions. Catastrophic events in the form of large-scale submarine landslides occur at both end members of TMFs.

6 Conclusions

- On the continental slope off Troms, northern Norway, the complex morphology of three high-gradient trough mouth fans (TMF) situated seaward of formerly glaciated cross-shelf troughs, as well as inter-fan areas, show extensive evidence of downslope transfer of sediments, involving formation of gullies, channels and slides.
- The Malangsdjupet TMF is dominated by gully-channel complexes, which is also found on the Andfjorden TMF outside an area dominated by a large submarine landslide (the Andøya Slide). Thus, both fans evolved by sediment transport and distribution through gully-channel complexes, while the Andfjorden TMF was affected by a large submarine landslide which remobilized much of these complexes.
- The Rebbenesdjupet TMF has a lower gradient and is dominated by a number of small and relatively shallow slide scars, inferred to be related to small-scale sediment failure of glaciomarine and/or contouritic sediments.
- The Andøya and Senja canyons, as well as the Malangsgrunnen inter-fan slope, make up the inter-fan areas. The canyons were cut into the adjacent TMFs, and they deepened and widened as turbidity currents were routed downslope. Mass-movements within the study area seem to have been triggered by undercutting from the canyons. The overall form of the Malangsgrunnen shelf break and inter-fan slope acted as a funnel in focusing downslope flow from upper-slope gullies and slides.
- The sedimentary processes on the high-gradient TMFs off Troms are summarized in a conceptual model. The main sediment input occurred during peak glacials when the Fennoscandian Ice Sheet reached the shelf edge and distributed glacigenic sediments onto the fans. Gully-channel complexes occur within these deposits on the Andfjorden and Malangsdjupet TMFs, which indicates that the steep slope of these fans promoted rapid transformation from small-scale slumps and debris flows on the upper slope, into partly

erosive turbidity currents. These may have extended into the deep sea, thus promoting efficient sediment by-pass across the TMFs. This model can be applied to other high-gradient TMFs situated at the mouths of other glaciated cross-shelf troughs.

- The TMF slope gradients are inferred to exert a fundamental control on the sedimentary processes and, hence, on the resulting TMF morphology and sediment composition. The building blocks for low-gradient TMFs, glacigenic debris flow debrites, are missing on the studied high-gradient TMFs. Instead, gully-channels complexes dominate, which are rare on low-gradient TMFs. Large-scale sliding appears to occur on both high- and low-gradient TMFs.

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8 Figure captions

Fig. 1: Bathymetric map of the Norwegian Sea and the SW Barents Sea generated from the IBCAO database (Jakobsson et al., 2012). Contour interval is 200 m. The study area is indicated by the white box.

Fig. 2: The area of study. A: Bathymetric map of the continental shelf and slope outside Troms County, northern Norway. The dashed lines delimit data sets with different spatial resolution. B: Dip map of the seabed.

Fig. 3: The outer continental shelf and upper slope off northern Norway. See Fig. 2 for location. A: Slope gradient map.. Areas of steep slopes have a darker colour. Locations of detail figures and seismic lines are indicated. B: Interpretation of landforms discussed in this paper. TMF=Trough Mouth Fan.

Fig. 4: Seismo-stratigraphic framework of the late Cenozoic sediments on the Troms margin (adopted from Rydningen et al., submitted). See Fig. 3 for location of profiles. A: Composite seismic strike line crossing the study area. B: Seismic dip line crossing the shelf break in the Malangsdjupet trough.

Fig. 5: The Malangsdjupet Trough Mouth Fan and the Malangsgrunnen inter-fan slope. See Fig. 3 for location. A: Slope gradient map. Red arrows indicate slide scars on erosional remnants. B: Interpretation of A. Gullies dominate the Trough Mouth Fan morphology down to 1200 m water depth, before they merge into channels on the lower slope (C1, C2 and C3). The depths of the channels are illustrated by a bathymetric profile. The Malangsgrunnen inter-fan slope is dominated by slides and gullies forming a dendritic pattern merging into C3 on the lower slope.

Fig. 6: Seismic profile across overbank deposits showing a weak internal stratification. Channel C1 erodes into the overbank deposit and has a cut-and-fill character. A possible palaeo-channel is located in the northern part of the Senja Canyon channel. See Fig. 3 for location.

Fig. 7: Seismic profile across the erosional remnants (ER) and channels (C). Internal reflections within the erosional remnants are truncated by the seabed. See Fig. 3 for location.

Fig. 8: The Andøya Slide on the Andfjorden Trough Mouth Fan. See Fig. 3 for location. A: Slope gradient map. B: Interpretation of A with the slide affected area in dark grey. The headwall of the Andøya Slide cuts into the shelf. Smaller amphitheatre-like scars, in places forming a stair-case pattern, occur in the uppermost part, while a low-relief terrain characterizes the slide scar down to 1700 m water depth. Secondary escarpments and small slide blocks characterize the seabed morphology further downslope.

Fig. 9: Seismic profile crossing the Andøya Canyon, with its ancillary overbank deposits, and the Andøya Slide. Slide deposits within the Andøya Slide, which may constitute erosional remnant ridges, are indicated. See Fig. 3 for location.

Fig. 10: The upper part of the Rebbenesdjupet Trough Mouth Fan. See Fig. 3 for location. A: Slope gradient map. Profile: The height of the slide scars is approximately between 10 and 30 m. B: Interpretation of A. A number of smaller landslides dominate the seabed morphology down to a water depth of ~1300 m. The slide headwall is irregular, and several secondary escarpments form a stair-case pattern downslope.

Fig. 11: The Senja Canyon. A: Slope gradient map of the Senja Canyon (outlined with dashed line). Overbank deposits are indicated. Profiles in B and C, as well as Fig. 12, are indicated. See Fig. 3 for location. B: Topographic long-profile from the headwall of the canyon. The Senja Canyon has an overall concave shape with channel gradients declining downslope. C: Seismic profile across the inner part of the canyon. The maximum incision of the canyon is 1000 m and it cuts into sediments of Quaternary age.

Fig. 12: Slope gradient maps of the Senja Canyon showing details of the headwall area (A), the western sidewall (B), and the eastern sidewall (C). See Fig. 11 for location. A: Marginal moraines (MM) and sediment waves (SW) are situated at and close to the shelf break. The canyon headwall is characterized by partly buried gullies (G) which join downslope. B: Slide scars (SS) and steep-sided gullies dominate the morphology on the western sidewall. Escarpments (E) are common along the gully thalwegs. C: Slide scars and gullies also dominate the eastern sidewall. The largest slide, the Malangsdjupet Slide, extends down to the base of the Senja Canyon.

Fig. 13: Conceptual models of high-gradient (A) and low-gradient (B) trough mouth fans. See text for further discussion.

9 References

Aksu, A.E., Hiscott, R.N., 1992. Shingled Quaternary debris flow lenses on the north-east Newfoundland Slope. Sedimentology 39, 193-206.

Amblas, D., Urgeles, R., Canals, M., Calafat, A.M., Rebesco, M., Camerlenghi, A., Estrada, F., De Batist, M., Hughes-Clarke, J.E., 2006. Relationship between continental rise development and palaeo-ice sheet dynamics, Northern Antarctic Peninsula Pacific margin. Quaternary Science Reviews 25, 933-944.

Amundsen, H.B., Laberg, J.S., Vorren, T.O., Haflidason, H., Forwick, M., Buhl-Mortensen, P., 2015. Late Weichselian – Holocene evolution of the high-latitude Andøya submarine Canyon, North-Norwegian continental margin. Marine Geology 363, 1-14.

Baeten, N.J., Laberg, J.S., Forwick, M., Vorren, T.O., Vanneste, M., Forsberg, C.F., Kvalstad, T.J., Ivanov, M., 2013. Morphology and origin of smaller-scale mass movements on the continental slope off northern Norway. Geomorphology 187, 122-134.

Batchelor, C.L., Dowdeswell, J.A., 2014. The physiography of High Arctic cross-shelf troughs. Quaternary Science Reviews 92, 68-96.

Bellec, V.K., Bøe, R., Thorsnes, T., Rise, L., Dolan, M.F.J., Elvenes, S., Lepland, A., Hansen, O.H., 2012a. Geologisk havbunnskart, Kart 69301600, September 2012, M 1: 100 000, Norges Geologiske Undersøkelse.

Bellec, V.K, Bøe, R., Thorsnes, T., Rise, L., Dolan, M.F.J., Elvenes, S., Lepland, A., Hansen, O.H., 2012b. Geologisk havbunnskart, Kart 70001600, September 2012, M 1: 100 000, Norges Geologiske Undersøkelse.

Bellec, V.K., Dolan, M.F.J., Bøe, R., Thorsnes, T., Rise, L., Buhl-Mortensen, L., Buhl-Mortensen, P., 2009. Sediment distribution and seabed processes in the Troms II area – offshore North Norway. Norwegian Journal of Geology 89, 29-40.

Bryn, P., Berg, K., Forsberg, C.F., Solheim, A., Kvalstad, T.J., 2005. Explaining the Storegga Slide. Marine and Petroleum Geology 22, 11-19.

Bugge, T., 1983. Submarine slides on the Norwegian continental margin, with special emphasis on the Storegga area. The Continental Shelf and Petroleum Research Institute, Trondheim, Publication 110, 152pp.

Bugge, T., Befring, S., Belderson, R.H., Eidvin, T., Jansen, E., Kenyon, N.H., Holtedahl, H., Sejrup, H.P., 1987. A giant three-stage submarine slide off Norway. Geo-Marine Letters 7, 191-198.

Buhl-Mortensen, L., Bøe, R., Dolan, M.F.J., Buhl-Mortensen, P., Thorsnes, T., Elvenes, S., Hodnesdal, H., 2012. Banks, troughs, and canyons on the continental margin off Lofoten, Vesterålen, and Troms, Norway. In: Harris, P.T., Baker, E.K. (Eds.), Seafloor geomorphology as Benthic Habitat. Elsevier Inc., Amsterdam, pp. 703-715, http://dx.doi.org/10.1016/B978-0-12-385140-6.00051-7.

Clausen, L., 1998. The Southeast Greenland glaciated margin: 3D stratal architecture of shelf and deep sea. In: Stoker, M., Evans, D., Cramps, A. (Eds.), Geological Processes on Continental margins: Sedimentation, Mass-Wasting and Stability. Geological Society, London, Special Publications 129, pp. 173-203.

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.

Davison, S., Stoker, M.S., 2002. Late Pleistocene glacially-influenced deep-marine sedimentation off NW Britain: implications for the rock record. In: Dowdeswell, J.A., Ó Cofaigh, C. (Eds.), Glacier-Influenced Sedimentation in High-Latitude Continental Margins. Geological Society, London, Special Publications 203, 129-147.

Dowdeswell, J.A., Kenyon, N.H., Elverhøi, A., Laberg, J.S., Hollender, F.-J., Mienert, J., Siegert, M.J., 1996. Large-scale sedimentation on the glacier-influenced polar North Atlantic margins: Long-range side-scan sonar evidence. Geophysical Research Letters 23, 3535-3538.

Dowdeswell, J.A., Ó Cofaigh, C., Noormets, R., Larter, R.D., Hillenbrand, C.-D., Benetti, S., Evans, J., Pudsey, C.J., 2008. A major trough-mouth fan on the continental margin of the Bellingshausen Sea, West Antarctica: The Belgica Fan. Marine Geology 252, 129-140.

Dowdeswell, J.A., Ó Cofaigh, C., Pudsey, C.J., 2004. Continental slope morphology and sedimentary processes at the mouth of an Antarctic palaeo-ice stream. Marine Geology 204, 203-214.

Fisher, R.V., 1983. Flow transformations in sediment gravity flows. Geology 11, 273-274.

Gales, J.A., Forwick, M., Laberg, J.S., Vorren, T.O., Larter, R.D., Graham, A.G.C., Baeten, N.J., Amundsen, H.B., 2013. Arctic and Antarctic submarine gullies – a comparison of high latitude continental margins. Geomorphology 201, 449-461.

García, M., Dowdeswell, J.A., Ercilla, G., Jakobsson, M., 2012. Recent glacially influenced sedimentary processes on the East Greenland continental slope and deep Greenland Basin. Quaternary Science Reviews 49, 64-81.

Haflidason, H., Sejrup, H.P., Nygård, A., Mienert, J., Bryn, P., Lien, R., Forsberg, C.F., Berg, K., Masson, D., 2004. The Storegga Slide: architecture, geometry and slide development. Marine Geology 213, 201-234.

Hampton, M.A., 1972. The role of subaqueous debris flow in generating turbidity currents. Journal of Sedimentary Research 42, 775-793.

Hansen, B., Østerhus, S., 2000. North Atlantic-Nordic Seas exchanges. Progress in Oceanography 45, 109–208.

Hjelstuen, B.O., Eldholm, O., Faleide, J.I., 2007. Recurrent Pleistocene mega-failures on the SW Barents Sea margin. Earth and Planetary Science Letters 258, 605-618.

Indrevær, K., Bergh, S. G., Koehl, J.-B., Hansen, J.-A., Schermer, E. R., Ingebrigtsen, A., 2013. Post-Caledonian brittle fault zones on the hyperextended SW Barents Sea margin: New insights into onshore and offshore margin architecture: Norwegian Journal of Geology/Norsk Geologisk Forening 93, 167-188.

Jakobsson, M., Mayer, L.A., Coakley, B., Dowdeswell, J.A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H.-W., Zarayskaya, Y.A., 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.B., 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.

Kenyon, N.H., 1987. Mass-wasting features on the continental slope of Northwest Europe. Marine Geology 74, 57-77.

King, E.L., Haflidason, H., Sejrup, H.P., Løvlie, R., 1998. Glacigenic debris flows on the North Sea Trough Mouth Fan during ice stream maxima. Marine Geology 152, 217-246.

King, E.L., Sejrup, H.P., Haflidason, H., Elverhøi, A., Aarseth, I., 1996. Quaternary seismic stratigraphy of the North Sea Fan: glacially-fed gravity flow aprons, hemipelagic sediments, and large submarine slides. Marine Geology 130, 293-315.

Laberg, J.S., Andreassen, K., Vorren, T.O., 2012. Late Cenozoic erosion of the high-latitude southwestern Barents Sea shelf revisited. Geological Society of America Bulletin 124, 77-88.

Laberg, J.S., Forwick, M., Husum, K., Nielsen, T., 2013. A re-evaluation of the Pleistocene behavior of the Scoresby Sund sector of the Greenland Ice Sheet. Geology 41, no. 12, 1231-1234.

Laberg, J.S., Guidard, S., Mienert, J., Vorren, T.O., Haflidason, H., Nygård, A., 2007. Morphology and morphogenesis of a high-latitude canyon; the Andøya Canyon, Norwegian Sea. Marine Geology 246, 68-85.

Laberg, J.S., Stoker, M.S., Dahlgren, K.I.T., Haas, H. d., Haflidason, H., Hjelstuen, B.O., Nielsen, T., Shannon, P.M., Vorren, T.O., van Weering, T.C.E., Ceramicola, S., 2005a. Cenozoic alongslope processes and sedimentation on the NW European Atlantic margin. Marine and Petroleum Geology 22, 1069-1088.

Laberg, J.S., Vorren, T.O., 1993. A late Pleistocene submarine slide on the Bear Island Trough Mouth Fan. Geo-Marine Letters 13, 227-234.

Laberg, J.S., Vorren, T.O., 1995. Late Weichselian submarine debris flow deposits on the Bear Island Trough Mouth Fan. Marine Geology 127, 45-72.

Laberg, J.S., Vorren, T.O., 1996a. The glacier-fed fan at the mouth of Storfjorden trough, western Barents Sea: a comparative study. Geologische Rundschau 85, 338-349.

Laberg, J.S., Vorren, T.O., 1996b. The Middle and Late Pleistocence evolution of the Bear Island Trough Mouth Fan. Global and Planetary Change 12, 309-330.

Laberg, J.S., Vorren, T.O., 2000. The Trænadjupet Slide, offshore Norway – morphology, evacuation and triggering mechanisms. Marine Geology 171, 95-114.

Laberg, J.S., Vorren, T.O., Dowdeswell, J.A., Kenyon, N.H., Taylor, J., 2000. The Andøya Slide and the Andøya Canyon, north-eastern Norwegian–Greenland Sea. Marine Geology 162, 259-275.

Laberg, J.S., Vorren, T.O., Kenyon, N.H., Ivanov, M., Andersen, E.S., 2005b. A modern canyon-fed sandy turbidite system of the Norwegian Continental Margin. Norwegian Journal of Geology 85, 267-277.

Larter, R.D., Cunningham, A.P., 1993. The depositional pattern and distribution of glacial-interglacial sequences on the Antarctic Peninsula Pacific margin. Marine Geology 109, 203-219.

Nielsen, T., De Santis, L., Dahlgren, K.I.T., Kuijpers, A., Laberg, J.S., Nygård, A., Praeg, D., Stoker, M.S., 2005. A comparison of the NW European glaciated margin with other glaciated margins. Marine and Petroleum Geology 22, 1149-1183.

Ó Cofaigh, C., Taylor, J., Dowdeswell, J.A., Pudsey, C.J., 2003. Palaeo-ice streams, trough mouth fans and high-latitude continental slope sedimentation. Boreas 32, 37-55.

Oljedirektoratet, 2010. Geofaglig vurdering av petroleumsressursene i havområdene utenfor Lofoten, Vesterålen og Senja, 81 pp., Accessible report on: http://www.npd.no. (In Norwegian).

Osmundsen, P. T., Redfield, T., 2011. Crustal taper and topography at passive continental margins. Terra Nova 23, 349-361.

Ottesen, D., Dowdeswell, J.A., Rise, L., 2005. 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, 1033-1050.

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.

Piper, D. J., Normark, W. R., 2009. Processes that initiate turbidity currents and their influence on turbidites: a marine geology perspective. Journal of Sedimentary Research 79, 347-362.

Posamentier, H.W., Kolla, V., 2003. Seismic geomorphology and stratigraphy of depositional elements in deep-water settings. Journal of Sedimentary Research 73, 367-388.

Redfield, T., Osmundsen, P., 2013. The long-term topographic response of a continent adjacent to a hyperextended margin: A case study from Scandinavia. Geological Society of America Bulletin 125, 184-200.

Rebesco, M., Camerlenghi, A., Geletti, R., Canals, M., 2006. Margin architecture reveals the transition to the modern Antarctic ice sheet ca. 3 Ma. Geology 34, 301-304.

Rise, L., Bellec, V.K., Bøe, R., Thorsnes, T., 2009. The Lofoten – Vesterålen continental margin, North Norway: Canyons and mass-movement activity. International conference on seafloor mapping for Geohazard assessment, 11-13 May 2009, Ischia, Italy. In: Chiocci, F.L., Ridente, D., Casalbore, D., Bosman, A. (Eds.), Rendiconti Online, Societa Geologica Italiana, Extended Abstracts 7, pp. 79-82.

Rydningen, T.A., Laberg, J.S., Kolstad, V., submitted. Late Cenozoic evolution of high-gradient Trough Mouth Fans and canyons on the glaciated continental margin offshore Troms, northern Norway – palaeoclimatic implications and sediment yield. Geological Society of America Bulletin.

Rydningen, T.A., Vorren, T.O., Laberg, J.S., Kolstad, V., 2013. The marine-based NW Fennoscandian ice sheet: glacial and deglacial dynamics as reconstructed from submarine landforms. Quaternary Science Reviews 68, 126-141.

Sejrup, H.P., Hjelstuen, B.O., Dahlgren, K.I.T., Haflidason, H., Kuijpers, A., Nygård, A., Praeg, D., Stoker, M.S., Vorren, T.O., 2005. Pleistocene glacial history of the NW European continental margin. Marine and Petroleum Geology 22, 1111-1129.

Sejrup, H.P., King, E.L., Aarseth, I., Haflidason, H., Elverhøi, A., 1996. Quaternary erosion and depositional processes: western Norwegian fjords, Norwegian Channel and North Sea Fan. In: De Batist, M., Jacobs, P. (Eds.), Geology of Silisiclastic Shelf Seas. Geological Society Special Publication 117, pp. 187-202.

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 B.P. Quaternary Science Reviews 27, 1476-1492.

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

Tomlinson, J.S., Pudsey, C.J., Livermore, R.A., Larter, R.D., Barker, P.F., 1992. Long-range sidescan sonar (GLORIA) survey of the Antarctic Peninsula Pacific margin. Recent Progress in Antarctic Earth Science. In: Yoshida, Y., Kaminuma, K., Shiraishi, K. (Eds.), Proceedings 6th International Symposium Antarctic Earth Science. Tokyo, pp. 423-429.

Vanneste, M., Berndt, C., Laberg, J.S., Mienert, J., 2007. On the origin of large shelf embayments on glaciated margins – effects of lateral ice flux variations and glacio-dynamics west of Svalbard. Quaternary Science Reviews 26, 2406-2419.

Vanneste, M., Mienert, J., Bünz, S., 2006. The Hinlopen Slide: A giant, submarine slope failure on the northern Svalbard margin, Arctic Ocean. Earth and Planetary Science Letters 245, 373-388.

Vogt, P.R., Crane, K., Sundvor, E., 1993. Glacigenic mudflows on the Bear Island Submarine Fan. EOS, Transactions American Geophysical Union 74, 449, 452-453.

Vorren, T.O., Hald, M., Lebesbye, E., 1988. Late Cenozoic environments in the Barents Sea. Paleoceanography 3, 601-612.

Vorren, T.O., Hald, M., Thomsen, E., 1984. Quaternary sediments and environments on the continental shelf off northern Norway. Marine Geology 57, 229-257.

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

Vorren, T.O., Laberg, J.S., Blaume, F., Dowdeswell, J.A., Kenyon, N.H., Mienert, J., Rumohr, J., 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., Lebesbye, E., Andreassen, K., Larsen, K.-B., 1989. Glacigenic sediments on a passive continental margin as exemplified by the Barents Sea. Marine Geology 85, 251-272.

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

Vorren, T.O., Rydningen, T.A., Baeten, N.J., Laberg, J.S., 2015. Chronology and extent of the Lofoten-Vesterålen sector of the Scandinavian Ice Sheet from 26 to 16 cal. Ka BP. Boreas, 10.1111/bor.12118. ISSN 0300-9483.