1 Seabed Morphology and Shallow Sedimentary Structure of the Storfjorden and 2 Kveithola Trough-Mouth Fans (North West Barents Sea)

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1 Abstract

2 This study aims to present an overview of the seafloor morphology and shallow
3 sedimentary structure of the Storfjorden and Kveithola Trough Mouth Fans (TMFs) on the
4 northwestern Barents Sea continental margin. Data have been compiled from two
5 International Polar Year (IPY) cruises (SVAIS, of the *BIO Hespérides* and EGLACOM of the
6 *R/V OGS-Explora*) that yielded 15,340 km² of multi-beam bathymetry and 9,500 km of sub-
7 bottom seismic profiles. In this area, the continental shelf edge defines three wide and
8 subdued sedimentary lobes forming Storfjorden TMF, one single lobe on Kveithola TMF, and
9 three inter-TMF areas on the continental slope. The two northernmost lobes of Storfjorden
10 TMF (Lobes I and II) are composed by thick (up to 50 m) sequences of glacially derived
11 debris flow deposits interbedded with thin a few metres de-glacial and interglacial deposits. A
12 network of upper slope gullies incises these debris flow deposits as a consequence of
13 subglacial meltwater release at or near the shelf break. Gullies evolve into channels whose
14 morphologic evidence disappears midslope, leaving place to a subdued chevron-like
15 morphological pattern inherited by the preceeding glacial maximum debris flow deposits. A
16 drastic change occurs on the continental slope of Storfjorden TMF Lobe III and Kveithola
17 TMF, where are several translational submarine landslides mostly originated in the upper
18 slope, the majority of which detach at the contact between Middle Weishelian glacial
19 debris flows and the overlying acoustically laminated plumites. Dendritic canyon systems
20 only develop in inter-TMF areas. The data suggest that TMF continental slope progradation
21 depends on short-lived episodes of extreme sedimentation during glacial maxima and during
22 the early deglaciation phase, and that an important controlling factor is the mechanism of ice
23 stream retreat from the continental shelf edge. We suggest that the two northern Storfjorden
24 sub-ice streams were composed by thicker and perhaps faster ice progressively draining a
25 distal and larger ice source mainly located on Svalbard. Conversely, the southernmost
26 Storfjorden sub-ice stream and the Kveithola ice stream were fed by a local, smaller marine-
27 based ice dome grounded on Spitsbergenbanken. The ice dome persisted after the LGM,
28 maintaining a local ice drainage system close to the shelf edge whose sedimentary evidence
29 can be found on the continental slope of the southern lobe of Storfjorden TMF and Kveithola
30 TMF. The high degree of lateral variability in the style of sedimentation on TMF slopes
31 suggests that ice stream dynamics may vary considerably within the same glacial trough, and
32 that such variability affects the long-term development of the architecture of TMFs.

1

2 **Introduction**

3 Trough mouth fans (TMFs; Nansen, 1904, Vogt and Perry, 1978; Vorren et al., 1988;
4 1989) are sedimentary depocentres characterized by outbuilding of the upper slope in a
5 seaward-convex sedimentary fan made of alternating prograding and aggrading sequences
6 that derive primarily from debris flows accumulation at the front of glacial troughs on
7 continental shelves (e.g. Dahlgren et al., 2005, Vorren and Laberg 1997; Laberg and Vorren
8 1995). These troughs hosted ice streams, which have been suggested as the main mechanism
9 of glacial sediment erosion and transport to the shelf edge during sea level low-stands in
10 periods of glacial maxima. Conversely, it is assumed that much less sediments is deposited on
11 the continental slope between different phases of glacial maxima and during interglacial
12 periods (Dowdeswell and Siegert, 1999; Nygård et al., 2002; Dowdeswell et al., 2004; 2006).

13 The increasingly detailed studies of the sedimentary record of TMFs in the southern and
14 northern hemisphere have made it possible to refine the TMF depositional model. It is
15 assumed that the internal sedimentary structure is primarily controlled by slope gradient,
16 morphology of the continental shelf, amount subglacial melt water release, and glacial regime
17 of the ice sheet. The interplay between the various processes influencing the TMF
18 development results in varying rates of glacial advance and retreat within each TMF (Ó
19 Cofaigh et al., 2008) and in a variety of morphologies and sedimentary architectures of TMFs
20 (Ó Cofaigh et al., 2003; Dowdeswell et al., 2002).

21 However, it seems evident that the sediment accumulation on the slope of TMFs is not
22 exclusively caused by glacial debris flows. Contourite (Van Weering et al., 2008) and/or
23 settlement of subglacial meltwater plumes (Taylor et al., 2002) can also contribute to the
24 build-up of TMF. Furthermore, repeated events of sediment mass transport often remove or
25 obliterate substantial parts of sedimentary slope section, and make it difficult to investigate
26 full TMF sequences (Elverhøi et al., 2002; Dimakis et al., 2000). Many details remain to be
27 clarified regarding the degree of complexity of the ice streams dynamics within an ice trough
28 and how such complexity reflects in continental slope deposition and erosion.

29 The SVAIS and EGLACOM projects pursue a multi-disciplinary analysis of the marine
30 sedimentary record of TMFs in order to identify the paleo-extent of ice sheets during glacial
31 periods, and to improve our understanding of the ice streams dynamics, the mechanisms of

sediment delivery to the ocean, and the paleoceanographic conditions throughout glacial cycles, with special emphasis to deglaciation periods.

This study is an introductory comprehensive overview of the seafloor morphology and shallow sedimentary structure of Storfjorden and Kveithola TMFs in the northwest Barents Sea (**Fig. 1**) that follows a detailed analysis of the outer Kveithola Trough (Rebesco et al., 2011a). This analysis is aimed at resolving the questions of whether the high-resolution macro-scale structure of a single TMF may reflect multiple continental ice sources within the same paleo-ice stream, of what is the degree of spatial and temporal variability of ice streams retreat after the Last Glacial Maximum (LGM), and of how glacial dynamics controls continental slope accretion and erosion. The study area was chosen because of three main reasons:

1) The Storfjorden glacial system is relatively small and is sustained by a small catchment area with local provenance from the emerged land of Svalbard and the submerged Spitsbergenbanken (Elverhøi et al., 1998; Mangerud et al., 1998). Compared to major glacial systems such as Bjørnøya Trough or the Norwegian Channel, the relatively short distance from source of ice to calving areas in the Storfjorden glacial system has resulted in relatively short residence times of ice in the ice stream and, therefore, a relatively rapid response to climate periods;

2) The glacial evolution of Spitsbergen is relatively well known from continental studies (e.g. Landvik et al., 1998; Mangerud et al., 1998) and provides a useful tie to the marine record collected in this study;

3) The Storfjorden glacial depositional system is relatively poorly known (e.g. Hjelstuen et al., 1996; Vorren and Laberg, 1996), with lack of high resolution bathymetric information and systematic grids of high resolution seismic prior to this study.

Study area and geological setting

The study area (**Fig. 1**) is located in the northwest Barents Sea continental margin, between Spitsbergen and Bjørnøya.

The Barents Sea is bounded to the west and north by passive continental margins that formed during the Early Eocene opening of the Norwegian-Greenland Sea in the northern north Atlantic, and the Eurasian Basin in the Arctic Ocean. Rifting between Greenland and

Spitsbergen began at a later stage, during the Early Miocene. However, the first evidence of oceanic spreading and therefore of a deep oceanic gateway between the Arctic and Atlantic oceans in the Fram Strait dates to the Late Miocene, about 10 Ma (Engen et al., 2008).

The post-rift depositional sequences are overlain by prominent Pliocene and Pleistocene prograding wedges, which resulted from a significant increase in the sediment input from the margins of the Barents Sea and the Svalbard Archipelago (Solheim et al., 1998). This induced a seaward migration of the shelf break of up to 150 km in places. Terrigenous sediments were initially of fluvial and glacio-fluvial origin, while from the Middle Pleistocene onwards, they originated from subglacial sediment discharge from ice streams grounded at the shelf edge to form TMFs (Forsberg et al., 1999; Dahlgren et al., 2005).

Factors that favoured the late Neogene massive sediment discharge on the Barents Sea continental margins are tectonic uplift, that determined the presence of an easily erodible sedimentary substratum on the continental shelf, and climatic deterioration towards colder periods that culminated with the increased erosion by grounded ice (e.g. Elverhøi et al., 1998; Ó Cofaigh et al., 2003).

Continental ice gradually occupied the Barents Sea during the onset of the northern hemisphere glaciations. In the Late Pliocene (3.6-2.4 Ma), the ice sheet reached the continental shelf only in the northern Barents Sea during short-term episodes of ice expansion. From the Late Pliocene to the Middle Pleistocene (2.4 -1.0 Ma) the ice sheet expanded towards the southern Barents Sea from the Scandinavian Peninsula. It was only after 1.0 Ma that the ice sheets expanded over the entire Barents Sea reaching the shelf edge during glacial maxima (Vorren and Laberg, 1997; Knies et al., 2009).

The Barents Sea is underlain by a broad continental shelf characterized by shallow banks separated by deeper glacial troughs. The glacial troughs hosted the major ice streams that drained fast ice towards the continental shelf break. Banks hosted slow moving ice with less erosive capacity. The continental shelf seabed morphology allows reconstructing past ice drainage within the Barents Sea ice sheet (**Fig. 1**; Winsborrow et al., 2009).

The Storfjorden Trough (**Fig. 1**) is 254 km long, about 40 km wide in the inner continental shelf and up to 125 km wide at the shelf edge. It covers approximately an area of 38,000 km². Water depth along the trough axis varies between 150 m around its rim and 420 m recorded in its middle part. The Storfjorden TMF extends from the shelf break

(approximately 420 m water depth) towards the Knipovich ridge, in water depth of about 2300 m. Its average gradient varies between 0.2° and 1.8° (Vorren and Laberg, 1996).

The Storfjorden TMF began to develop approximately in the Late Pliocene (2.3-2.5 Ma), even if records of older sediments date back to 55 Ma (Hjelstuen et al., 1996; 2007). The main progradation of the fan lasted until 0.2 Ma, with a fast prograding phase between 1.3-1.5 and 0.2 Ma (Hjelstuen et al., 2007; Knies et al., 2009). In the last 0.2 Ma, sedimentation appears to be more evenly distributed on the entire northwest Barents Sea margin, including the Storfjorden TMF, as a consequence of the decreased sediment input and the lateral spread of sediment particles by contour currents and melt water plumes (Vorren et al., 1998).

The Kveithola Trough is a small E-W trending cross-shelf glacial trough located between Storfjorden Trough and Bjørnøya. First reported by Vorren et al. (1998), it has been identified as a potential source of melt water to the continental slope by Fohrmann et al. (1998). The seafloor in Kveithola Trough is characterized by families of E-W trending mega-scale glacial lineations that record a fast flowing ice stream draining the Svalbard and Barents Sea ice sheets during the LGM. Glacial lineations are overprinted by transverse Grounding-Zone Wedges (GZW) that give rise to a staircase bathymetric axial profile of the trough. The sedimentary drape deposited on top of the GZWs accumulated at a very high rate in the order of 1 m ka⁻¹ (Rebesco et al., 2011a).

Data and Methods

All data presented in this article (**Fig. 2**) were collected during *BIO Hespérides* IPY Cruise SVAIS (Longyearbyen, July 29 – August 17 2007) and R/V *OGS-Explora* IPY Cruise EGLACOM (Kristinsund, July 07 – August 04 2008). Ship navigation was secured by means of D-GPS and inertial navigation systems (Kongsberg Seapath 200 on board the *BIO Hesperides* and Ixsea PHINS onboard the *OGS-Explora*). The joint multibeam bathymetric survey area covered by the SVAIS and EGLACOM cruises is about 15,340 km² (8,220 km² and 7,120 km² respectively). The total length of acquired sub-bottom profiler data is nearly 9,500 km.

Bathymetry

The *BIO Hespérides* employed multi-beam echo-sounders Simrad EM120 (operating at a mean frequency of 12 kHz) and Simrad EM1002S (operating at a mean frequency of 95

kHz) for deep and shallow water sounding respectively. Both echo-sounders were calibrated prior and during the survey. The sound velocity profile was obtained with the launch of nine XBT probes throughout the survey.

The *R/V OGS-Explora* employed multi-beam echo-sounders Reson MB8150 (operating at a mean frequency of 12 kHz) and MB8111 (operating at a mean frequency of 100 kHz) for deep and shallow water sounding respectively. Both systems were calibrated during the preceding cruise. The sound velocity profiles were obtained with 6 casts of the Reson SVP24 Sound Velocity Probe and XBT launches. In addition, continuous velocity values used to perform the dynamic beam steering are provided by the keel mounted Navitronic SVP71 sound velocity probe.

On the *BIO Hespérides*, multi-beam bathymetric data were logged using Simrad's Mermaid system and processed with Caris HIPS and SIPS V 6.1. Data processing included a careful manual editing of all beams in order to remove acquisition noise caused by rough sea conditions. The data of the Simrad EM120 echo-sounder were negatively affected especially in deep waters by a down-ward deflection of the sea bottom profile on the port side beams. The cause of this artefact was later identified by Kongsberg in the ship keel acoustic window and corrected in post-processing.

On the *R/V OGS-Explora*, multi-beam bathymetric data were logged and processed with the Reson PDS2000 V 2.5.3.2 software. For datasets of both cruises, editing steps included: 1) application of calibration parameters (time-pitch-roll-yaw) and sound velocity profiles to the swaths; 2) editing of spurious navigation points; 3) application of beam number, depth, quality, nadir and statistic filters for every line and 4) manual editing of each line.

The final Digital Terrain Model was produced from the combined data set with 75 m grid spacing and exported to ArcGis V 9.3 for data analysis and display. Additional software used for better data visualization and analysis were Surfer 8.0, Global Mapper 11, Fledermaus View 3D, Mirone 1.4.0.

Subbottom profiling

The Kongsberg TOPAS PS 18 hull-mounted parametric sub-bottom profiler was used on the *BIO Hespérides* simultaneously with multi-beam data acquisition. The profiler uses two primary frequencies ranging between 16 and 22 kHz to produce a narrow beam secondary frequency ranging between 0.5 and 6.0 kHz. All data were sampled at 16 kHz and stored both

1 in the raw proprietary format and SEG-Y format. During the cruise all TOPAS profiles were
2 imported in Seismic Micro-Technology's Kingdom Suite 8.3 software after some SEG-Y
3 header editing using Gedco's Vista 7.1. The data quality was excellent throughout the cruise
4 with the exception of a few days with bad sea state.

5 The hull-mounted Benthos CAP-6600 sub-bottom chirp profiler was used on the *R/V*
6 *OGS-Explora*. This echo-sounder uses a sweep of acoustic frequencies ranging between 2 and
7 7 kHz. Communication Technology's SwanPro acquisition software was used to collect the
8 data in XTF format and subsequently converted to SEG-Y. At OGS an integrated
9 interpretation of all data was performed using Seismic Micro-technology's Kingdom Suite.

10 The conversion from two-way travel time to depth is made using a reference sound
11 velocity in sediments equal to 1500 m s^{-1} . This implies a probable underestimation of
12 thickness that ranges from approximately 0% in the uppermost metres of sediments to 6.5 –
13 13.3% in the deepest units imaged by the sub-bottom profiler, in which the sound velocity
14 could be ranging easily between 1600 and 1700 m s^{-1} .

16 Results

17 The morphology of the outer continental shelf and mid-upper continental slope of the
18 Storfjorden and Kveithola TMFs is described using the combined multibeam bathymetric
19 dataset from the two surveys (**Fig. 3**) merged with the grid produced by the Geological
20 Survey of Norway (Ottesen et al., 2006).

21 Outer continental shelf morphology

22 The overview bathymetry available in the area (**Fig. 3**; Ottesen et al., 2006) reveals that
23 the outer fan-shaped part of Storfjorden Trough comprises three large lows (broad channels)
24 separated by elevations (outer banks) close to the shelf edge. The water depth in theses
25 channels increases from north to south (340 m, 364 m, and 378 m respectively). The
26 northernmost bank, here defined Outer Bank 1 is 317 m deep, while the southern Outer Bank
27 2 is 344 m deep (**Fig. 3**). A smaller sized 358 m deep outer bank is also present close to the
28 shelf edge in the middle part of Kveithola Trough (Rebesco et al., 2011a). A prominent fan-
29 shaped bathymetric step of about 100 m of elevation defines the transition between the outer
30 and middle shelf (BS in **Fig. 3**).

The high resolution seafloor morphology of the southern Storfjorden Through outer continental shelf is dominated by three types of seabed features (**Figs. 3 and 4A**): 1) Linear or slightly curved furrows of apparently random strike, with either V-shaped or U-shaped profile, 2) Large-scale lineations, composed of two families of large ridge-groove rectilinear structures each composed of three to four parallel grooves bounded by marginal sediment ridges. These large-scale lineations are about 1.5 km wide, up to 20-25 km long, 15 to 20 m deep with a NNE-SSW trend. The marginal ridges are less than 10 m high above the surrounding seafloor, (**Figs. 4A, 4B**). 3) A lobate moraine is present close to the shelf edge. The moraine has a highly curved shape in plain view, with a NNE-SSW direction of elongation, is about 8 km wide and about 20 m high. The external part of this moraine appears to be interrupted by a groove-ridge structure (**Fig. 4A**).

Continental slope and shelf edge morphology

The continental shelf edge defines three broad and morphologically subdued sedimentary prograding lobes in the Storfjorden TMF, each separated by an outer shelf bank. Each of these sectors defines areas of the continental slope with distinctive seabed morphology.

Storfjorden TMF Lobe I

The continental shelf edge on Lobe I is located approximately along the 420 m isobath and separates a nearly flat continental shelf from an upper continental slope dominated by an extensive network of gullies (**Fig. 5A**). The uppermost slope is characterized by a steep (in places exceeding 3°) and narrow (about 1 to 2 km) segment bordering the shelf edge (**Fig. 5B**). Further downslope, the slope gradient decreases to a rather uniform value between 0.5° and 1.5°. Gullies never cut back deeply into the continental shelf, are typically 5 to 20 km long and extend downslope to 900-1000 m water depth. They are nearly straight or have a low sinuosity, and are generally less than 10 m deep with respect to the surrounding seafloor. The gullies side slope angle is about 1°, locally up to about 2.5°. The spacing between gullies varies between 200 and 1000 m. The gullies branch in the uppermost steepest slope into a third-order dendritic network of short tributary gullies. Their cross section profiles changes from V-shaped to U-shaped in deeper water attaining the morphological characteristics of continental slope channels with a typical width of about 1 km.

The morphologic evidence of gullies and channels disappears in water depths deeper than about 1200 m, where the sediment surface of the continental slope is made of an

1 alternation of subdued highs and lows producing a subtle chevron morphologic pattern
2 elongated in direction approximately perpendicular to the contour lines. Individual chevrons
3 show a mounded topography when displayed in cross section and develop in most instances at
4 the mouth of gullies and channels. The apex angle of the chevrons is about 30°.

5 *Storfjorden TMF Lobe II*

6 Off the continental shelf edge of Lobe II the segment of steepest slope is narrower than
7 in Lobe I, usually not exceeding 1 km in width (**Fig. 6**). Elsewhere, the average slope
8 gradients of the slope are similar to Lobe I. The gullies depth, width and the side slope angle
9 in the uppermost slope are comparable to those of Lobe I. However, the density of gullies is
10 higher in Lobe II, with inter-gully spacing as short as about 100 m, while the dendritic pattern
11 on the uppermost slope often reaches the fourth order tributary level, with confluences of
12 tributary gullies with the first order gully found at about mid-slope. The gullies length is up to
13 20 km.

14 Also the gullies of Lobe II change the cross profile from V-shaped to U-shaped at about
15 mid slope, in water depth between 700 and 1000 m, attaining a morphology more typical of
16 straight or low sinuosity continental slope channel. Evidence of early stage of gully
17 development (inset in **Fig. 6A**) are observed in this water depth range, resulting in broader
18 anastomosed channels patterns that include relict segments of the continental slope
19 completely surrounded by channels (**Fig. 6A**). The side slope of the anastomosed channels is
20 steeper than that of the gullies upslope, reaching 2.5° - 5° (**Fig. 6B**). Mid-slope channels can
21 attain a incision profile exceeding 30 m with respect to the surrounding seafloor and can be
22 more than 1 km wide. These continuous gully channels generated from the gullies capture
23 system have a width up to 2-3 km.

24 Gullies disappear on Lobe II in water depths deeper than about 1000 m, leaving place to
25 a chevrons morphologic pattern.

26 *Storfjorden TMF Lobe III*

27 A drastic morphologic change occurs on the continental slope of Lobe III with respect to
28 that of Lobes I and II (**Fig. 7**). The slope angle is steeper (up to 3°) in a narrow segment right
29 off the continental shelf edge. This segment widens from about one kilometre to nearly 10 km
30 in the southernmost area of Lobe III throughout the transition to the slope of the Kveithola
31 TMF further to the SE. The overall morphologic pattern of the continental slope is disturbed

by changes induced by amphitheater-like depressions of various sizes reflecting the head and side walls of submarine landslides.

In the northern part of Lobe III the discontinuous gullies that develop on the upper continental slope are wider (200-500 m), deeper incised (7-14 m) and longer (20-50 km) than the ones observed on Lobes I and II. Furthermore, they are straight with tributaries of only second order. These branching gullies are found only in the uppermost slope section. As in Lobes I and II the gullies widen and deepen downslope leaving place at about 1200 m to a set of elongated chevron-like lobes.

To the south of these gullies, a wide sector of the upper continental slope is characterized by shallow crescent-shaped submarine landslides scars (**Fig. 7**). The largest of them (Landslide 1 in **Fig. 7**) shows lateral scarps 35-40 m high and 3° to 4° steep that reach the continental shelf edge. The slope gradient within the scars ranges between 1° and 2°. The area enclosed by the shelf edge and the lateral scarps, as imaged by our surveys, covers an area of 1120 km². Southeast of this scar, there are at least 12 additional minor bowl-shaped depressions on the upper continental slope each corresponding to submarine landslides. The scarps bounding these depressions range from 15 to 30 m in height. **Table I** summarizes the morphologic parameters of the 5 largest submarine landslides in this sector of the margin.

Kveithola TMF

The coalescence between Storfjorden and Kveithola TMFs is outlined by a rather sharp change in the direction of morphological lineations produced by the different orientation of the glacial troughs on the continental shelves (NE-SW and E-W respectively) (**Figs. 3, 7, 8A**). The upper continental slope of Kveithola TMF is steeper than that of Storfjorden TMF, with a steep upper slope segment as wide as 10 km, characterized by straight gullies (**Figs. 7A and 8A**). In the middle slope of Kveithola TMF we also find several bowl-shaped depressions and elongated scars produced by submarine landslides. The most prominent of these is an elongated feature with a complex head area located in 1300 m water depth. The scarps here are 30 m high, about 20 km long and enclose an area of about 50 km².

Inter-TMF areas

Inter TMF areas are those facing the seaward-concave parts of the continental shelf edge not associated with glacial troughs. Within the survey area, these are found in the

northernmost part, bordering the northern edge of Lobe I of the Storfjorden TMF, between Storfjorden and Kveithola TMFs, and south of Kveithola TMF (**Fig. 3**).

The best example of the morphological characteristics of these parts of the margins is displayed south of Kveithola TMF (**Fig. 8**). Moving away from the trough mouth, the continental slope contains increasingly large and deep straight channels that develop networks of small canyons in the upper slope converging at about 1000 m water depth into major canyons. The previously described gullies-channels-chevron morphologic transition, from the upper to mid-slope, is absent here. Between Storfjorden and Kveithola TMFs, the inter-TMFs area is confined to the upper slope, because the two TMFs lobes merge at about 1000 m water depth. The seafloor morphology is characterized by larger and deeper gullies intersected with bowl-shaped scarps (**Fig. 7**).

North of Lobe I of Storfjorden TMF is a tiny lobe facing a minor continental shelf trough northwest of which is an inter-TMF (**Fig. 3**) part of the slope in which long-running gullies are imaged from shelf edge to mid-slope.

Continental slope shallow seismic structure

From top to bottom the continental slope of the Storfjorden and Kveithola TMFs displays 4 major recent seismo-stratigraphic units here labelled from top down A to D. These seismic units are mostly differentiated on the basis of their seismic character, geometry, and reflector terminations. As we will show below, the areal distribution of these seismic units is strongly tied to the morphological features observed on multibeam bathymetry.

Recent TMF stratigraphy

The deepest and poorly imaged Unit D has an irregular upper boundary and hummocky internal configuration. The acoustic basement of the sub-bottom profiles is made of rather continuous faint reflectors interpreted as the base of Unit D (**Figs. 9, 10**), whose thickness is at least 40 ms twt (in excess of 30 m). Below several large scars in the Storfjorden TMF, where the acoustic window penetrates deeper in the stratigraphic section (**Fig. 11A**) evidence for a deeper unit below Unit D with a similar succession of subunits of alternating high amplitude continuous reflectors with intervals made of adjoining transparent lenses.

Unit C is characterized by high amplitude parallel to subparallel reflectors with high lateral continuity (**Fig. 9B, C** and **Fig. 10**). The unit is composed of an upper high amplitude part (C₁) with thickness of about 10 ms twt (approximately 7.5 m), and a lower subunit with

an average lower amplitude, at interval even faint amplitudes (transparent) (C₂) with thickness up to 15 ms twt (about 11 m). The maximum thickness of Unit C is therefore less than 20 m. Only a few paleo-gullies are observed cutting in Unit C. No direct relationship has been found between superficial paleo-gullies and Unit C. However, paleo-gullies appear to be draped by Unit C (**Fig. 10A, C**) so that we infer that the paleo-gully formation is older than Unit C. The sliding surface of submarine landslides corresponds to the base of Unit C.

Unit B is thick and omni-present in the surveyed continental slope of Storfjorden TMF Lobes I and II. In Storfjorden TMF Lobe III and in Kveithola TMF, Unit B is occasionally missing or it is reduced to individual lenses with thickness ranging from nearly zero to 20-30 ms twt (approximately 15 - 22.5 m; **Fig. 9C**). The basal reflector is often erosive. Where the unit is thinnest, a clear infill of erosive incisions in the underlying Unit C (paleo-gullies, or paleo-channels) is observed (**Fig. 9C**).

The majority of the continental slope of Storfjorden and Kveithola TMFs is draped by a recent Unit A (**Fig. 9**). Unit A is of variable thickness ranging approximately 3.75 m on Storfjorden TMF Lobes I and II (**Fig. 9B, 10A, 10B**), to about 15 m on Storfjorden TMF Lobe III and Kveithole TMF (**Fig. 11C**). This unit is always composed of two parts: an upper part (A₁) that varies from being completely transparent on Storfjorden TMF Lobes I and II, to roughly acoustically stratified as on Storfjorden TMF Lobe III and Kveithole TMF; a lower part (A₂) that is high amplitude and continuously acoustically stratification.

Internal structure of gullies, channels, canyons, and chevron morphology

Tributary gullies are clearly draped by recent sediments (Unit A; **Fig. 9B, C**; see TMF stratigraphy below). Conversely, the sedimentary drape appears to be absent on first order gullies and slope channels, which cut into Unit A (**Fig. 9B**).

The chevron-shaped elevations reflect a buried lobed structure, draped by recent high amplitude reflectors. This lobed structure is composed of stacks of irregular acoustically transparent lenses with overall hummocky internal configuration (Unit B; **Fig. 10A**; see TMF stratigraphy below). These deposits are characterized by poor lateral continuity and amplitude of reflectors, and extreme variability of thickness, varying from 0 to 70 ms twt (0 to approximately 50 m or more; **Fig. 10B**).

The Inter-TMF area south of Kveithola TMF displays the typical V-shaped cross profile of the canyons with very little acoustic penetration, due either to the acoustic energy

dispersion in response to the irregular topography, or to the hardness of the thalweg (**Fig. 10C**). Where the seafloor morphology is smoother (inter-canyons areas), sediments appear with parallel reflectors throughout.

Internal structure of areas bounded by scarps

Areas bounded by major scarps and bowl shaped depressions are typically characterized by truncation of the upper sedimentary units (**Fig. 11 A,B**). In many instances the depressions are filled with deposits characterized by transparent acoustic facies or a more chaotic response (**Fig 11**). In some instances the original stratigraphy can still be recognized. These observations allow interpreting these areas as submarine landslides. Submarine landslides of the Storfjorden TMF Lobe III and the Kveithola TMF are translational, with headwall and lateral scarps clearly cut into Units A₂, B (if present) and C (**Fig. 11**; see TMF stratigraphy below). The landslides detachment level seems to be the base of Unit C. In some instances, compressional ridges compose the submarine landslides accumulation zone (**Fig. 11B**). Unit A₁ appears to drape the slide deposits as well as the exposed detachment surface (**Fig. 11A, B**). The volume of sediments removed by the major landslides from the TMFs assuming that the slope before the landslide was continuous between the lateral walls is approximately 33 km³ for Landslide 1 and 2 km³ for Landslide 2. For Landslide 1, the largest submarine landslide in the surveyed area there is no evidence of a basal deformation-accumulation zone, at least within the surveyed area. Also, the headwall scarp of the landslide is not evident because it coincides with the continental shelf edge.

Discussion

The seabed morphology and shallow seismic stratigraphy illustrate the high degree of lateral variability of sedimentary processes within the Storfjorden and Kveithola TMFs upper and middle continental slope and outer shelf. Such changes are evident not only in the sedimentary record since the LGM, but also in the preceding glacial cycles.

Morpho-genesis on Storfjorden TMF

Mass transport and deposition of glacial diamicton

Similar to other TMFs and continental slopes of glacially influenced continental margins, the most dominant morphogenetic sedimentary process on Storfjorden TMF is mass

transport and deposition of diamictons from debris flows originated by the sediment discharge from ice streams grounded at the shelf edge (e.g. Tripsanas and Piper, 2008; Dowdeswell et al., 2008; Ó Cofaigh et al, 2003; Andersen et al 1996; Vorren et al., 1989). Sediments transport to the shelf edge, through a subglacial layer of deformation till (e.g. Hooyer and Iverson, 2000) lead to rapid build-up of unstable sediment in front of the ice streams at the shelf break. Frequent slope failures creates subglacially-derived debris flows on the continental slope. Formation of these deposits can only be generated during relatively short episodes of glacial maxima that occur at the end of glacial stages, when the ice stream grounding line in glacial troughs reaches the continental shelf edge. Deposition is rapid and takes place in a short period (e.g. Rise et al., 2005), with extremely high sedimentation rates up to 172 cm ka^{-1} estimated by Laberg and Vorren (1996) in Storfjorden TMF, or even 600 cm a^{-1} by Dimakis et al. (2000).

On the middle slope of the Storfjorden and Kveithola TMFs, the lateral amalgamation of subdued sedimentary elevations made of glacially derived debris flow deposits generates the distinctive chevron morphology of the seabed (**Figs. 3 to 5**). The elevations are elongated downslope and have a symmetrical profile in cross section. It is noteworthy that they are only a few tens of metres high while their horizontal dimension can be of several kilometres. For a better visualization of these features an enhanced vertical exaggeration has been used and appropriate light incidence direction that also amplified noise level in the data.

On the middle slope of Storfjorden Lobes I and II it is the shallowest stratigraphic occurrences of these amalgamated 50 m thick, chevron-like debris flow deposits (Unit B). Their morphological expression has been preserved at the seafloor because of the thin drape (a few metres) of Unit A in this area (**Figs. 10A, B and 12**). Conversely, subglacially-derived debris flow deposits on Storfjorden TMF Lobe III and Kveithola TMF are confined in isolated lenses only a few metres thick (**Fig. 9C, 11A**) and do not retain a morphological expression. In the latter case where the debris flows occur on the upper, steeper continental slope, they are presumably of relatively lower viscosity and generated by quick mass transport, laterally confined to local bathymetric lows and do not leave morphologic evidence. Their trace can be found elsewhere in changes in acoustic back-scatter if the sedimentary drape is sufficiently thin (e.g. Taylor et al., 2002; Ó Cofaigh et al, 2003) and in the seismic profiles as lenses of more acoustically transparent units.

The narrow steep segment of the uppermost continental slope ($3\text{-}5^\circ$), right off the

continental shelf edge observed both on Storfjorden and Kveithola TMFs finds its origin in the amalgamation of till deltas (*sensu* Alley, 1989), till tongues (*sensu* King, 1991) or diamict aprons (*sensu* Hambrey et al., 1991; 1992) produced at the continental shelf-edge during the short periods of glacial maxima. Due to the proximity of the glacial source, these sediments are highly unsorted and have a higher repose angle with respect to upper and middle slope sediments which underwent certain, though limited, degree of reworking and sorting in the area.

The uppermost debris flow deposits represented by seismic Unit B obliterate completely the pre-existing seafloor morphology by filling pre-existing seafloor incisions (paleo-gullies and channels) and entirely sealing the debris flow deposits from the previous glacial maxima (Unit D) (**Fig. 10B**).

Erosion by subglacial meltwater discharge

Another important morpho-genetic sedimentary process that contributed to the shaping of the present Storfjorden and Kveithola TMFs continental slope is the erosion that produces the dendritic gully system on the upper slope. Gully have formed into the glacial debris flow deposits (Unit B) and are draped, at least partly, by the sediments of Unit A (**Figs. 9B, C, 12**).

Our data provide no evidence that the termination of the gullies on the middle continental slope coincides with the sedimentary elevations made of glacial debris flow deposits. The erosion of the gullies, therefore, is most likely produced by density flows generated at the shelf edge and capable to incise by about 10 m the amalgamated diamict aprons of the steepest upper slope. The energy of these flows must decrease downslope as a consequence of slope-angle reduction, until, generally within 20 km from the source, the flows lose their ability to erode as the gullies disappear in the morphology.

These observations coincide with the scenarios necessary for the generation of high energy subglacial jet-flows (e.g. Powell, 1990; Syvitski, 1989). Jet-flows consist of mixed fresh meltwater and glacial sediments released under high hydrosotatic head near the base of the water column at the terminus of tidewater glaciers. In our case such conditions occur at the beginning of post glacial maximum warming, with a rapidly rising sea level, when the ice stream grounding line is near the shelf edge, and when high meltwater release froms streams mixs with surrouding medium. Therefore, based on the acoustic record and supported by ¹⁴C AMS dating (Lucchi et al., 2011) the above described process occurs after the glacial

1 maximum, in the early stage of deglaciation, and produces the low-profile and wide gullies
2 eroded into the glacigenic debris flow deposits. Because of the low hydrostatic head beyond
3 the initial 20 km from the source, we infer that these density flows do not develop to proper
4 turbidity currents (Hunter et al., 1991). The absence of classic continental slope canyons
5 and/or channel-levee complexes on the Storfjorden and Kveithola TMFs further supports the
6 absence of major turbidity current systems on these slopes. Nevertheless, the change in cross
7 profiles of the gullies from V- to U-shape in the downslope direction, likely reflects the
8 generation of some turbidity flows, most likely induced by slope instability along the gully
9 flanks, where the Unit A sediment drape attains locally slopes of 2.5–3°. Low energy turbidity
10 currents are therefore responsible for the absence of an appreciable drape in the mid-slope
11 channels, and perhaps for gully and channel capture observed on Storfjorden TMF Lobe II.

12 We infer that at least on Storfjorden TMF Lobes I and II gully activity ceases shortly
13 after the onset of deglaciation as the grounding line retreats and jet flows remain confined to
14 the grounding zone wedges and do not reach the continental shelf edge. The bathymetric step
15 BS in the middle Storfjorden Trough (**Fig. 3**) may represent such a wedge formed after the
16 LGM. In this way gullies become draped by a thin post-glacial hemipelagic sediment layer
17 (Unit A). On Storfjorden TMF Lobe III and Kveithola TMF, the greater depth and width of the
18 gullies, their longer extension on the upper slope, the lower tributary order, combined with the
19 greater thickness of the stratified lower part Unit A₂ suggest a prolonged input of deglacial
20 meltwater sediment discharge at the continental shelf edge.

21 The morphology of the gullies observed on Storfjorden and Kveithola TMFs is
22 comparable to that observed on the upper slope of the Belgica TMF on the West Antarctica
23 margin, which correspond to a low-angle fan developed in front of a large glacial trough. The
24 gullies of the NW Barents Sea reflect the same trend of increasing depth, width and length of
25 the gullies with increasing slope angle observed on the West Antarctic margin (Dowdeswell
26 et al., 2008a). However, on the steepest upper slope of the West Antarctic margin, the gullies
27 differ not only for their size, but also for cutting back retrogressively into the shelf edge as
28 landside scars (Noormets et al., 2009). Such character is not observed on the NW Barents
29 Sea. Here, the shelf edge is always located on the narrow steepest segment of the upper slope
30 that we interpret as amalgamation of till deltas, which in this case resist to slope failure, with
31 some exceptions in the proper landside scars cutting into the shelf edge on Kveithola TMF.
32 We do not interpret this observation as an evidence of reduced meltwater discharge during the
33 deglaciation of the North Western Barents Sea. Rather, we think that the rapid response of the

Barents Sea ice sheet to warming, sea level rise, and isostasy made the grounding line in the main troughs retreat episodically and faster from the shelf edge (Rebesco et al., 2011a; Winsborrow et al., 2009) than in Pine Island Bay, Belgica Trough, and Marguerite Bay on the West Antarctic margin, where comparable datasets exist (Noormets et al., 2009; Dowdeswell et al., 2008a). Thus the sedimentary effects (erosion and deposition) of meltwater discharge have shifted from the continental shelf edge to the inner portions of the shelf in GZW systems (Rebesco et al., 2011a; Lucchi et al., 2011; Winsborrow et al., 2009; Andreassen et al., 2008; Dowdeswell et al., 2008b).

Continental slope instability

The third major morphogenetic process, identified only on the Storfjorden TMF Lobe III and Kveithola TMF continental slopes, is that of sediment mass transport originated by submarine landslides. This type of sediment mass transport significantly differs from glacial maxima glacigenic debris flows generated by sediments transport to the shelf break through a subglacial layer of deformation till. Continental slope instability generates negative or concave relief (see also Bull et al., 2009). The sediment removal corresponds to up to 40-50 m in thickness. The translational domain is often recognizable as an elongated seafloor depression confined by lateral scarps. The toe domain is recognizable in sub-bottom profiler data from the smallest submarine landslides as monoclinical folds and possibly thrust faults (**Fig. 11B**). The data coverage does not include the toe domain of the major slides, nor those whose detachment has occurred in deepest water.

The detachment surface of the observed landslides occurs at the boundary between the interlaminated sediments deposited during periods of deglaciation (plumites, Unit C), and the underlying glacigenic debris flows deposited during the preceding glacial maximum (diamicton, Units D). Both sediment types represent episodes of extremely rapid sediment accumulation but are very different in sedimentology as water content and shear strength (Lucchi et al., 2011).

Submarine landslides are typical seabed features of the North Atlantic and Arctic glacial continental margins (Vorren et al., 1998; Cherkis et al., 1999; Dimakis et al., 2000; Elverhøi et al., 2002; Hjelstuen et al., 2007; Leynaud et al., 2009). We infer from the translational character and the fact that most observed failures root at the base of Unit C, that the most important sedimentological process, preconditioning the generation of submarine landslides in the southern part of Storfjorden TMF and Kveithola TMF, is the rapid deposition of a thick

sequence of fine-grained, high water content plumites (Units A and C). These plumites deposited preferentially on the upper continental slope as a consequence of the initial subglacial meltwater outbursts when the ice stream is grounded at or near the continental shelf edge. It is reasonable to assume that the rapid loading from glaciogenic debris flow deposits during glacial maxima induces a decrease in the effective stress and reduces shear strength, due to increased pore pressure, relatively to the underlying overconsolidated diamicton (Unit D), thus reducing slope stability (Lucchi et al., 2011; Rebesco et al., 2011b; see also Laberg and Camerlenghi, 2008; Berg et al., 2005; Bryn et al., 2005). Polar continental margins where such a lithologic alternation of sediments does not occur are almost entirely built of glacial debris flow deposits, and remain stable over time holding very steep angles. This situation is typical of many Antarctic margins where continental slopes are characterized by sediment starvation during interglacial periods (Rebesco and Camerlenghi, 2008). Other factors that could contribute to the instability of the slope are subsequent perturbations of the static equilibrium (Owen et al., 2007), such as earthquakes induced by isostatic rebound (Kvalstad et al., 2005) and/or gas charging (Vogt et al., 1999; Bünz et al., 2005) possibly following methane hydrate phase changes (Mienert et al., 2005).

The high accumulation rate of plumites on the upper slope of Storfjorden TMF Lobe III and Kveithola TMF reflects a long lasting proximity of the grounding line to the shelf edge, as a consequence of the proximal ice source, located on Spitsbergenbanken. It also reflects the existence of different, lithologic, pre-conditioning factors from the rest of Storfjorden TMF. This observation supports the role of the coupling of episodes of extremely high sedimentation rates during short periods of glacial maxima and early deglaciation. The ice stream dynamics therefore, not only determines factors of construction and progradation of TMFs, but also it preconditions continental slope destruction by mass wasting in the form of submarine landslides. As observed in other polar continental margins (e.g. Rebesco and Camerlenghi, 2008; Donda et al., 2008; Diviacco et al., 2006; King et al., 1996) the changing dynamics of the ice sheet is reflected in a generally decreasing magnitude of the event through time since the onset of the glacial conditions on the continental margin.

Deep erosion of the continental slope on inter-TMF areas

An additional important morpho-genetic process outlined by this study is the canyon formation aside of the TMFs. The Storfjorden and Kveithola TMFs are coalescent sedimentary systems. South of Kveithola TMF, protected from major ice flow during glacial

periods by Spitsbergenbanken, is a small sector of the margin where there is no outbuilding of a fan due to the lack of a glacial trough. The margin morphology is here similar to any non-glacial continental margin. The average slope is steeper than on TMFs, and a dendritic pattern of deep, V-shaped incision determines the development of a submarine canyon system by the action of turbidity currents. The continental slope drainage system conveys the density flows into a major channel on the lower continental slope, whose track is lost outside the bathymetric coverage. It is likely that this canyon-channel system participates in the sediment transport that ultimately merges with the INBIS channel–fan system, previously reported on the continental margin north of Bjørnøya TMF (Laberg et al., 2010; Laberg and Vorren, 2000). A higher density of gully incisions is observed in the small areas of the upper continental slope in between the Storfjorden and Kveithola TMFs and north of the Storfjorden TMF (**Fig. 8A**). Similarly, canyon-channel-fan systems develop on northern North Atlantic glacial margins aside from major TMFs (e.g. Lofoten Basin and Greenland Basin; Ó Cofaigh et al., 2006; Dowdeswell et al., 2002).

TMF continental slopes resist the formation of canyon-channel systems as a consequence of the action of short-lived erosional agents (low-energy density flows generated on the continental shelf by hyperpycnal flows) and increased resistance of the subglacially-derived diamict to erosion of canyon heads. The development of canyon-channel systems aside from TMFs is attributed primarily to the absence or reduction in thickness of glacial debris flow deposits as a consequence of the absence of major ice streams as sediment source during glacial maxima.

Relative chronology of sedimentary events

The seismic stratigraphy reconstructed for the shallow sediments of the Storfjorden and Kveithola TMFs allows the identification of the following series of sedimentary events related to the glacial evolution of the northwestern Barents Sea (**Fig. 12; Tab. II**).

The two episodes of accumulation of glacial debris flow deposits (Units B and D) represent the last episodes of Weichselian glacial maxima when the grounding line of the ice streams reached the continental shelf edge. The uppermost Unit B represents therefore the LGM, dated between approximately 23–19 ka after Mangerud et al. (1998) and revised recently between 24.0 and 23.5 calibrated ka BP (Jessen et al., 2010) in this area. The deeper Unit D probably correlates with the preceding episode of maximum advance of the grounded ice during the Middle Weichselian glacial maximum (approximately 65 to 60 ka; Mangerud

et al., 1998).

Unit C separating the last glacial maxima units must be composed by prevailing terrigenous sediments deposited in the relatively warm interglacial period corresponding to 60-24 ka BP (MIS 3). The lower part of this unit (C₂) is probably composed of a higher degree of hemipelagic sediments reflecting a longer distance of the grounding line from the continental shelf edge. The re-advance of the grounding line is represented therefore by the increasing acoustic lamination in C₁ leading to the deposition of the LGM deposits of Unit B.

The de-glaciation sedimentary record is provided by acoustically laminated Unit A₂ most likely composed by plumites, the products of deposition of subglacial melt water sediment suspension (Lucchi et al., 2011; Jessen et al., 2010) representing the progressive retreat of the grounding line from the outer to the inner continental shelf. The timing of this sedimentary event is identified between 14.8 and 14.3 ka BP by Jessen et al. (2010) in cores from Storfjorden TMF Lobe I, and II. However, the larger thickness of Unit A₂ on Storfjorden TMF Lobe III and the Kveithola TMF suggests either longer duration of this event or a much rapid rate of deposition (3.2 cm a⁻¹, Lucchi et al., 2011). The results obtained on Storfjorden and Kveithola TMFs appear to contrast the co-existence of glacial debris flows and outbursts of subglacial meltwater discharges observed in Trinity TMF on the Newfoundland margin (Tripsanas and Piper, 2008).

The Holocene deposition of hemipelagic sediments not influenced by glacial processes is represented by the acoustically transparent character of Unit A₁.

Implications for the evolution of the Svalbard/Barents Sea Ice Sheet (SBIS)

The continuous regional lateral extent and relatively homogeneous thickness of seismic Unit D provide evidence that the Storfjorden and Kveithola paleo-ice streams reached the shelf edge during the Middle Weichselian glaciation (MIS 4). The same cannot be said for the LGM, because the extent of Unit B is not continuous and the thickness of the debris flow deposits is highly variable even within the Storfjorden TMF.

The three coalescent lobes forming the Storfjorden TMF, are variable in sedimentary structure and morphological patterns and can be interpreted as the result of erosion and deposition from three sub-ice streams flowing within the same Storfjorden glacial trough (**Fig. 13**) and draining different ice catchment/source areas. Storfjorden sub-ice streams I and II flowed along the axis and northern part of the Storfjorden glacial trough draining the large

1 and distal areas of Spitsbergen-Brentsø-Edgeøya (through Storfjorden *sensu strictu*), and
2 Hopenbanken respectively. We infer that these sub-ice streams were composed by thicker and
3 perhaps faster moving ice providing an advanced sedimentary load of glacial debris flows to
4 the continental slope. This sediment load must have been much higher than of the
5 southernmost Storfjorden sub-ice stream III and Kveithola ice streams. The two sub-ice
6 streams diverged on the outer continental shelf, and became separated by an area of thinner and
7 slower ice over Outer Bank 1 (**Fig. 13**). Conversely, Storfjorden sub-ice stream III and
8 Kveithola ice stream were fed by a local, marine-based smaller ice sheet grounded on
9 Southwestern Spitsbergenbanken according to the geometry of the small ice troughs. The ice
10 flow probably generated thinner and slower ice providing less volume of sediment to the
11 continental slope. Sub-ice stream III was separated from sub-ice stream II by a thinner, slow-
12 moving ice on Outer Bank 2. Similarly, ice stream flow divergence within Kveithola Trough
13 determined a formation of an outer shelf bank at the shelf edge (Rebesco et al., 2011a).

14 The thin post-LGM sedimentary drape on the continental slope of Storfjorden Lobes I
15 and II (**Fig. 12**) suggests a faster and/or more recent retreat of the grounding line from the
16 continental shelf edge of these two sub-ice streams, leading to a condensed deposition of
17 glacial melt water sediment suspension (laminated deglaciation Unit A₂) and hemipelagic
18 post-glacial Unit A₁. We suggest the first retreat of the grounding line occurred by about 70-80
19 km to the bathymetric step BS, if this can be considered as a GZW similarly to Kveithola
20 Trough (Rebesco et al., 2011a). Conversely, the much larger thickness of the post LGM
21 sedimentary drape on Storfjorden TMF Lobe III and Kveithola TMF suggests that the
22 grounding line of the two feeder ice streams remained close to the continental shelf edge for
23 longer time, and ice retreat was slower, thus determining an expanded sequence of glacial
24 melt water sediment deposition (laminated deglaciation Unit A₂) and post-glacial hemipelagic
25 deposition (Unit A₁) on the upper continental slope.

26 It is believed that a marine based ice dome persisted on Spitsbergenbanken after the
27 LGM, the westernmost part of which maintained a local ice drainage system close to the shelf
28 edge whose sedimentary evidence can be found on the continental slope of Storfjorden TMF
29 Lobe III and Kveithola TMF.

30 The seismo stratigraphic record outlined in **Figure 12** shows that while deposition
31 during the Middle Weichselian glacial maximum (Unit D) was expanded and uniform all
32 over the Storfjorden and Kveithola TMFs, the acoustically laminated layers deposited

between this glacial maximum and the LGM (Unit C) are more than twice in thickness on Storfjorden TMF Lobe III and Kveithola TMF than on Storfjorden TMF Lobes I and II. Therefore the depocentres of the two last deglaciations is found on the upper slope of Storfjorden TMF Lobe III and Kveitehola TMF, and correlates with the occurrence of submarine landslides, whose headwall is indeed mostly located on the upper continental slope.

Conclusions

The analysis of 15,340 km² of multi-beam bathymetry and 9,500 km of sub-bottom seismic profiles have provided a innovative image of the high resolution seafloor morphology and shallow sediment structure on the continental slope and continental shelf edge of Storfjorden and Kveitehola TMFs, in the northwestern Barents Sea. The major findings of this study are the following:

- 1) The continental slope of both TMFs is composed of a steepest uppermost narrow segment produced by the amalgamation of diamict aprons, from which a dendritic system of gullies can be followed down to mid slope, where they leave place to a chevron-like morphology made of alternation of subdued highs and lows elongated downdip. Proper canyons and channels are present only on those parts of the continental slope not facing the mouth of glacial troughs (inter-TMF areas).
- 2) Based on regional morphology of the outer continental shelf and sedimentary characteristics inferred in this study, Storfjorden TMF can be divided into three depositional lobes, each separated by a shallower bank on the outer continental shelf.
 - a. Northern Lobes I and II are similar in morphology. They consist out a continuous LGM glacialigenic debris flow deposit up to 50 m in thickness incised by gullies on the upper slope and draped by a thin (< 4m) post-LGM, sedimentary drape. The chevron-like morphology of the middle slope is the expression fo the relict LGM seafloor morphology.
 - b. Southern Lobe III bears striking morphological and sedimentological differences. The continental slope is generally steeper, and the middle and upper slope are occupied by several submarine landslides scars, side scarps and translational areas that obliterate the glacially-derived morphology. The upper slope gullies are deeper,

longer and wider than those in the other two lobes. LGM debris flows deposits are discontinuous and often reduced to lenses with a maximum thickness of about 20 m. Conversely, the post-LGM sediments are much thicker than those in the northern lobes, and are made of a laterally continuous acoustically laminated unit.

3) Kveithola TMF bears morphological characteristics similar to Storfjorden TMF Lobe III.

4) Middle Weichselian glacial maximum debris flow deposits are uniformly distributed along the studied margin, and are separated by the overlying LGM debris flow deposits (where present) by a thick (up to 20 m) acoustically laminated unit.

5) The network of gullies is thought to be generated by subglacial meltwater jet-flows released at the grounding line when this is near the shelf break during the inception of deglaciation. Meltwater and sediment plumes produced during glacial retreat are thought to be responsible for the laminated acoustic facies. Gully formation therefore post-dates the LGM and marks a short period of early stage deglaciation. As the grounding line retreats from the shelf edge, gully incision is replaced by a drape of deglacial laminated, plumite deposits, followed by an acoustically transparent postglacial hemipelagic drape. The occurrence of a thick layer of post LGM plumites on Storfjorden TMF Lobe III and Kveithola TMF suggests that the grounding line persisted close to the shelf edge for a longer time than in the rest of Storfjorden TMF.

6) The focussing of submarine landslides on the upper slope of the southern part of Storfjorden TMF and Kveithola TMF is a consequence of the rapid deposition of a thick sequence of fine-grained, high water content plumites. Therefore, continental margin destruction by mass transport deposits reflects the behaviour and evolution of the ice stream, which remained grounded close to the continental shelf in this part of the margin..

7) Dendritic canyon systems, more typical of low latitude continental slopes, only develop in inter-TMF areas due to the generation of turbidity flows formed in sediment in which the glacial debris flow component is reduced, or absent..

8) The three coalescent lobes forming the Storfjorden TMF are the result of erosion and deposition from three sub-ice streams flowing within the same Storfjorden glacial trough. Storfjorden sub-ice streams I and II were composed by thicker and perhaps faster ice that drained a distal and larger ice source, located mainly on Svalbard Hopenbanken. Conversely, Storfjorden sub-ice stream III and the Kveithola ice stream were fed by a

1 local, smaller-size ice sheet grounded on the southeastern part of Spitsbergenbanken.
 2 Therefore, a marine based ice dome must have persisted on Spitsbergenbanken after the
 3 LGM, maintaining a local ice drainage system close to the shelf edge whose sedimentary
 4 evidence can be found on the continental slope of Storfjorden TMF Lobe III and Kveithola
 5 TMF.

6 9) This study has demonstrated that ice stream dynamics and the resulting sedimentary
 7 products on TMF can contain a high level of spatial and temporal variability within an ice
 8 trough. The data suggest that TMF continental slope progradation depends on short lived
 9 episodes of extreme sedimentation during glacial maxima and the early deglaciation
 10 phase. The multiple sub-ice stream structure identified in the glacial trough causes a
 11 focussing of de-glacial sediments on one sector of the upper slope. This is a consequence
 12 of the presence of a long lasting marine based ice dome, draining into the same glacial
 13 trough fed by distant and larger ice catchment areas. Such varying conditions in ice
 14 dynamics are reflected in different architectures of the continental margin in the same
 15 TMF, and appear control the sediment residence time on the continental slope.

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FIGURE CAPTIONS

Fig.1 – Colour bathymetry of the western Barents Sea obtained from the grid of the International Bathymetric Chart of the Arctic Ocean (IBCAO) after Jakobsson et al. (2008) (URL: <http://www.ibcao.org>). Grid resolution 1.5 km. Dotted red line: Regional LGM extent from Landvik et al. (1998) and Vorren et al. (1989). Blue arrows: Direction of flow of the main LGM ice streams draining the Svalbard/Barents Sea Ice Sheet according to Andreassen et al. (2008), Andreassen and Winsborrow (2009), and Dowdeswell et al. (2010). Purple areas: extent of TMFs from Sejrup et al. (2005): KF: Kongsfjorden Fan; IF: Isfjorden Fan; BeF: Bellsund Fan; SF: Storfjorden Fan; BIF: Bear Island Fan. The red box outlines the SVAIS-EGLACOM study area. Bold black dotted line: Inferred glacial drainage area of the Storfjorden-Kveithola depositional system.

Fig. 2 - Ship tracks from *BIO Hespérides* SVAIS and R/V *OGS-Explora* EGLACOM cruises. Contour interval 100 m. Grey-scale shaded-relief bathymetry results from a merge of the grid of the International Bathymetric Chart of the Arctic Ocean (IBCAO) after Jakobsson et al. (2008) <http://www.ibcao.org> (horizontal resolution 1.5 km) and a grid produced by the Geological Survey of Norway (Ottesen et al., 2006; horizontal resolution 0.5 km). Illumination from azimuth 340°, 45° incidence angle, no vertical exaggeration.

Fig. 3 – Merge of three bathymetric data sets over the study area: 1) High resolution, grey-scale shaded-relief bathymetry of the Storfjorden and Kveithola TMFs resulting from the SVAIS and EGLACOM bathymetric grids on the middle – upper continental slope and outer

shelf. Horizontal resolution 200 m. Illumination from the north, incidence angle 40°, azimuth 355°N. 2) Shaded relief bathymetry from the Geological Survey of Norway (Ottesen et al., 2006; horizontal resolution 0.5 km). Contour lines at 100 m interval. In order to outline small bathymetric changes on the outer shelf, a colour scale has been applied between 200 and 420 m water depth. 3) International Bathymetric Chart of the Arctic Ocean (IBCAO) after Jakobsson et al. (2008) <http://www.ibcao.org> (horizontal resolution 1.5 km) on the continental slope outside the survey area. Contour lines at 100 m interval.

Fig. 4 - A). Grey-scale shaded relief bathymetry of a part of Storfjorden outer continental shelf. Illumination is from the NNW (335°), incidence angle 30°. **B)** Sub-bottom profiler L 69 representative of the main morphological elements of a part of the Storfjorden outer continental shelf. The vertical exaggeration in the subbottom profiler is 60x.

Fig. 5 – A) Grey-scale shaded relief bathymetry of the continental slope of Storfjorden TMF Lobe I. **B)** Slope gradient of the same area imaged in A. Illumination is from the N (355°), incidence angle 40°. Note the artefacts induced by slope-parallel ship tracks and by mismatch in water depths between the two surveys. The relatively even topographic relief of the area causes a low signal-to-noise ratio. Outline of the area in **Fig. 3**. Sub-bottom profile L8 is imaged in **Fig. 10B**. See text for discussion.

Fig. 6 – A) Grey-scale shaded relief bathymetry of the continental slope of Storfjorden TMF Lobe II. **B)** Slope gradient of the same area imaged in A. Illumination is from the N (355°), incidence angle 40°. Note the artefacts induced by slope parallel ship tracks. The relatively even topographic relief of the area causes a low signal-to-noise ratio. Outline of the area in **Fig. 3**. Sub-bottom profiles L4, L12 and L13 are imaged in **Figs. 9A, 9B, and 10A** respectively. See text for discussion.

Fig. 7 – A) Grey-scale shaded relief bathymetry of the continental slope of Storfjorden TMF Lobe III. **B)** Slope gradient of the same area imaged in A. Illumination is from WNW (240°), incidence angle 60°. Note the artefacts induced by slope parallel ship tracks. The relatively even relief of the area causes a low signal-to-noise ratio. Outline of the area in **Fig. 3**. Sub-

bottom profiles L11, L25, and L34-35, are imaged in **Figs. 9C, 11B, and 11A** respectively.
See text for discussion.

Fig. 8 - A) Grey-scale shaded relief bathymetry of a part of the Kveithola TMF and the inter-TMF continental slope south of it. B) Slope gradient of the same area imaged in A. Illumination is from the NNW (340°), incidence angle 60°. Note the very steep slope angles (in excess of 10°) associated with the canyon system that do not exist on the Storfjorden TMF continental slope. Sub-bottom profile LIT-EG-43 is imaged in Fig. **10C**. See text for discussion.

Fig. 9 – Sub-bottom profiler lines representative of the main morphological and shallow stratigraphic elements of the Storfjorden TMF. A) Gullies of the upper slope of Lobe II and acoustic units. Profile direction parallel to the contours. B) Gullies on the middle continental slope of Lobe II and acoustic units. Profile direction parallel to the contours. C) Acoustic stratigraphy of the middle slope on Lobe III. Note the larger thickness of Unit A and the limited vertical and lateral extent of Unit B compared to Lobe II. See text for discussion. See location of profiles in **Figs. 6A and 7A**.

Fig. 10 - Sub-bottom profiler lines representative of the main morphological elements of the Storfjorden TMF and Kveithola TMF. A) Glacial debris-flow deposits (Unit B) generating the chevron seafloor structures with mounded profile, draped by Unit A, on Storfjorden TMF Lobe II. Profile direction parallel to the contour. See location of profiles in **Fig. 6A**. B) Acoustic evidence of paleo-gullies. Acoustic energy dispersion in correspondence of the paleo-gullies not always allows the recognition of the stratigraphic relationships. However, the downward inflection of the entire package of reflectors of Unit C at the edge of the paleo-gullies indicates that paleo-gullies are cut in Unit D, draped by Unit C, and sealed by Unit B. Profile direction approximately parallel to the contour. See location of profiles in **Fig. 5A**. C) Acoustic evidence of canyons incised in the continental slope south of the Kveithola TMF. The steep slope and depth of incision of these features are not found on the Storfjorden and Kveithola TMFs. See text for discussion. See location of profiles in **Fig. 8A**.

Fig. 11 - Sub-bottom profiler lines representative of the submarine landslides on Storfjorden TMF Lobe III and Kveithola TMF. Note that seismic Unit B is limited in thickness and is laterally discontinuous in the area of the submarine landslides. A) Lateral scarps of submarine landslide 2 on the Kveithola TMF. Note that removal of Units A, B, and C allows acoustic energy to penetrate into deeper stratigraphic units otherwise not imaged. Profile direction parallel to the contours. B) Dip-profile of submarine landslides on the upper slope. Note the translational character of the submarine landslide and the compressional ridges and thrusts at the toe of the deposit. The detachment surface appears to be the base of Unit C. See text for discussion. Profiles are located in **Fig. 7A**.

Fig. 12 - Preliminary shallow seismo-stratigraphic scheme of the upper slopes of the Storfjorden and Kveithola TMFs from. See Table II for units characteristics. For the conversion from two-way travel time to depth see chapter “Methods” in text.

Fig. 13 – Summary of the morphologic characteristics of the Storfjorden and Kveithola TMF systems. See legend for explanation of symbols. The shaded relief bathymetry of the continental shelf areas results from a merge of the grid of the International Bathymetric Chart of the Arctic Ocean (IBCAO) after Jakobsson et al. (2008) ; URL: <http://www.ibcao.org> and a grid produced by the Geological Survey of Norway (Ottesen et al., 2006). Horizontal resolution is 0.5 km. Large red arrows identify major ice streams during the LGM as inferred from the morphologic and shallow seismo-stratigraphic analysis. The ice catchment area feeding Storfjorden TMF Lobe III and Kveithola TMF is thought to result from a local marine-based ice dome residing on Spitsbergenbanken until after the retreat of the two main Storfjorden ice streams feeding Lobes I and II. See text for discussion.

Table I - Submarine landslides in the southwest of Storfjorde Fan (Lobe III).
Main morphological features.

Submarine landslides	Depth range (m)	Lenght (km)	Headwall lenght (km)	Headwall depth (m)	Area (km ²)	Volume removed (km ³)
Landslide 1	500-2200	60	15.5	Upper slope (500 m)	1120	33
Landslide 2	1400-2200	30	8.5	Mid slope (1000 m)	70	0.4
Landslide 3	600-800	6.3	3.2	Upper slope (600 m)	20	not calculated
Landslide 4	600-800	6.5	2.1	Upper slope (600 m)	10.7	not calculated
Landslide 5	600-800	1.2	1.3	Upper slope (600 m)	4.7	not calculated

Table II - Relative chronology of seismic units and presumed characteristics following Mangerud (1996) and Jessen et al. (2010).

Unit	Presumed lithology	Presumed age	Presumed glacial conditions	Presumed Marine Isotopic Stage
A1	Hemipelagics	Holocene	Interglacial	MIS 1
A2	Terrigenous	Upper Weischelian/Holocene	Last Deglaciation. Ice sheet retreating from the continental shelf edge	MIS 2/1
B	Glacial debris flow deposits	Upper Weischelian	Last Glacial Maximum	MIS 2
C	Terrigenous and Hemipelagics	Middle Weischelian	Glacial. Ice sheet away from continental shelf edge	MIS 3
D	Glacial debris flow deposits	Middle Weischelian	Glacial Maximum. Ice sheet at continental shelf edge	MIS 4

Figure

Pedrosa et al. Fig. 1

Pedrosa et al. Fig. 7

Pedrosa et al., Figure 12

Pedrosa et al., Fig. 13

Table I - Submarine landslides in the southwest of Storfjorden Fan (Lobe III).
Main morphological features.

Submarine landslides	Depth range (m)	Length (km)	Headwall length (km)	Headwall depth (m)	Area (km²)	Volume removed (km³)
Landslide 1	500-2200	60	15.5	Upper slope (500 m)	1120	33
Landslide 2	1400-2200	20	8.5	Mid slope (1000 m)	50	2
Landslide 3	600-800	6.3	3.2	Upper slope (600 m)	20	not calculated
Landslide 4	600-800	6.5	2.1	Upper slope (600 m)	10.7	not calculated
Landslide 5	600-800	1.2	1.3	Upper slope (600 m)	4.7	not calculated

Table II - Relative chronology of seismic units and presumed characteristics following Mangerud (1996) and Jessen et al. (2010).

Unit	Presumed lithology	Presumed age	Presumed glacial conditions	Presumed Marine Isotopic Stage
A1	Hemipelagics	Holocene	Interglacial	MIS 1
A2	Terrigenous	Upper Weichselian/Holocene	Last Deglaciation. Ice sheet retreating from the continental shelf edge	MIS 2/1
B	Glacial debris flow deposits	Upper Weichselian	Last Glacial Maximum	MIS 2
C	Terrigenous and Hemipelagics	Middle Weichselian	Glacial. Ice sheet away from continental shelf edge.	MIS 3
D	Glacial debris flow deposits	Middle Weichselian	Glacial Maximum. Ice sheet at continental shelf edge	MIS 4