

Holocene sedimentary processes in the Andøya Canyon system, north Norway

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Abstract

The Andøya Canyon system is the most pronounced of the ten canyon systems identified on the Norwegian continental margin. None of these canyon systems is linked to any present active drainage area and are interpreted to have been basically non active since the last glacial maximum and the deglaciation period. Our knowledge on these canyon systems is however still limited as no high-resolution stratigraphical or acoustic data sets are available from these areas. The main target for analysing the long term history of the Andøya Canyon has been to study the distal accumulation part of this system in the Lofoten Basin. The Lofoten Basin area is characterized by repeated stacks of extensive turbidite units where the details of the stratigraphical succession can be studied in undisturbed settings. About 3000 km² of high-resolution multibeam data (EM300) along with three gravity cores have been collected from the Lofoten Basin area. The analyses carried out on the cores revealed that the predominant process results in single turbidite units interbedded with thin units of hemipelagic sedimentation. The radiocarbon dating revealed that turbidites have been transported through this channel system at least twice during the Holocene. The two uppermost dated turbidite sequences give a maximum age of 7.9 ka ¹⁴C BP for the lower sequence and an age of ca. 4.0 ka ¹⁴C BP for the upper sequence. The upper sequence is of a similar age as the Trænadjupet Slide failure whereas the lower sequence indicates an age close to the Storegga Slide failure event, taking into consideration the erosive lower boundary of that sequence. The location of the investigated cores, which are far away from both the Trænadjupet Slide and the Storegga Slide, indicate that the instability in these canyon systems during the Holocene period has most probably been influenced by these large-scale failure events. What triggered the release of these turbidites is still not understood, but earthquakes or tsunami waves associated with the mega scale Trænadjupet Slide and the Storegga Slide events are considered to be the most likely mechanism at least during the Holocene Interglacial period.

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1. Introduction

The most pronounced submarine canyon system on the Norwegian continental margin is the Andøya Canyon and

the associated Lofoten Basin Channel (Fig. 1). The canyon, which is deeply incised (1100 m) into the narrow Lofoten shelf area, is ca. 40 km long from the headwall at the shelf break to ca. 2100 m water depth. It continues another 350 km downslope as a narrower distinct channel-like feature, named the Lofoten Basin Channel, ending into the Lofoten Basin at ca. 3200 m water depth (Laberg et al.,

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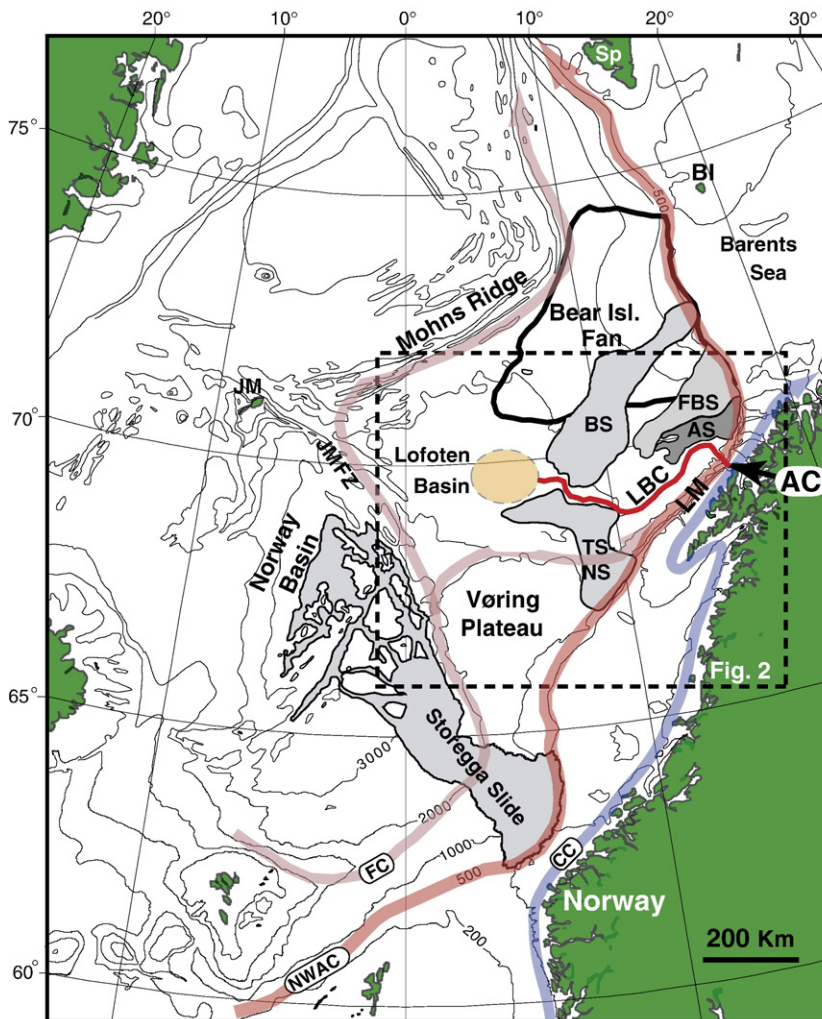


Fig. 1. Bathymetric overview map of the Norwegian Sea and the adjacent margin areas with the location of the exposed large submarine slides, the outline of the Andøya Canyon system including the accumulation area in the Lofoten Basin and the outline of the Bear Island Fan. The Andøya Canyon (AC) and the associated Lofoten Basin Channel (LBC) is marked with a red line. The outline of the main pathways of the surface current system is shown: in blue for the Coastal Current (CC), in reddish for the Norwegian Atlantic Current (NWAC) and in brownish colour the Færoe Current (FC). LM stands for the Lofoten Margin.

2000; Taylor et al., 2000, 2003; Laberg et al., 2005; Cofaigh et al., 2006; Laberg et al., 2007–this volume). In addition to the Andøya Canyon have also nine canyon systems been identified by Taylor et al. (2000) on the ca. 300 km long Lofoten margin area, but they are of a much smaller scale (Fig. 2). The Lofoten Basin Channel is also receiving sediments from these nine canyon systems. They are considered to be much less active sedimentary transport systems than the Andøya Canyon as the fan-like deposits found outside their distal gorges on the continental rise are of a rather small-scale size (Laberg et al., 2000; Taylor et al., 2000, 2003; Laberg et al., 2005). All these canyon systems are interpreted to have been passive transport systems since the end of the Last Glacial

Maximum (LGM), as none of them are linked to any presently active terrestrial drainage systems (Vorren et al., 1998; Laberg et al., 2000). The sediments accumulated into these canyons at present are mainly reworked sediments eroded by the strong along-slope surface current prevailing on the upper slope and/or they are of biogenic origin created by the high primary production found in this area. The canyons are acting as a trap for these sediments.

Many of the canyon systems on the Lofoten margin are morphologically associated with transverse troughs formed by outlet glaciers from the Lofoten mountain area during glacial periods (e.g. Bugge, 1983; Yoon et al., 1991). The close linkage between the transverse troughs on the Lofoten shelf and the location of the submarine

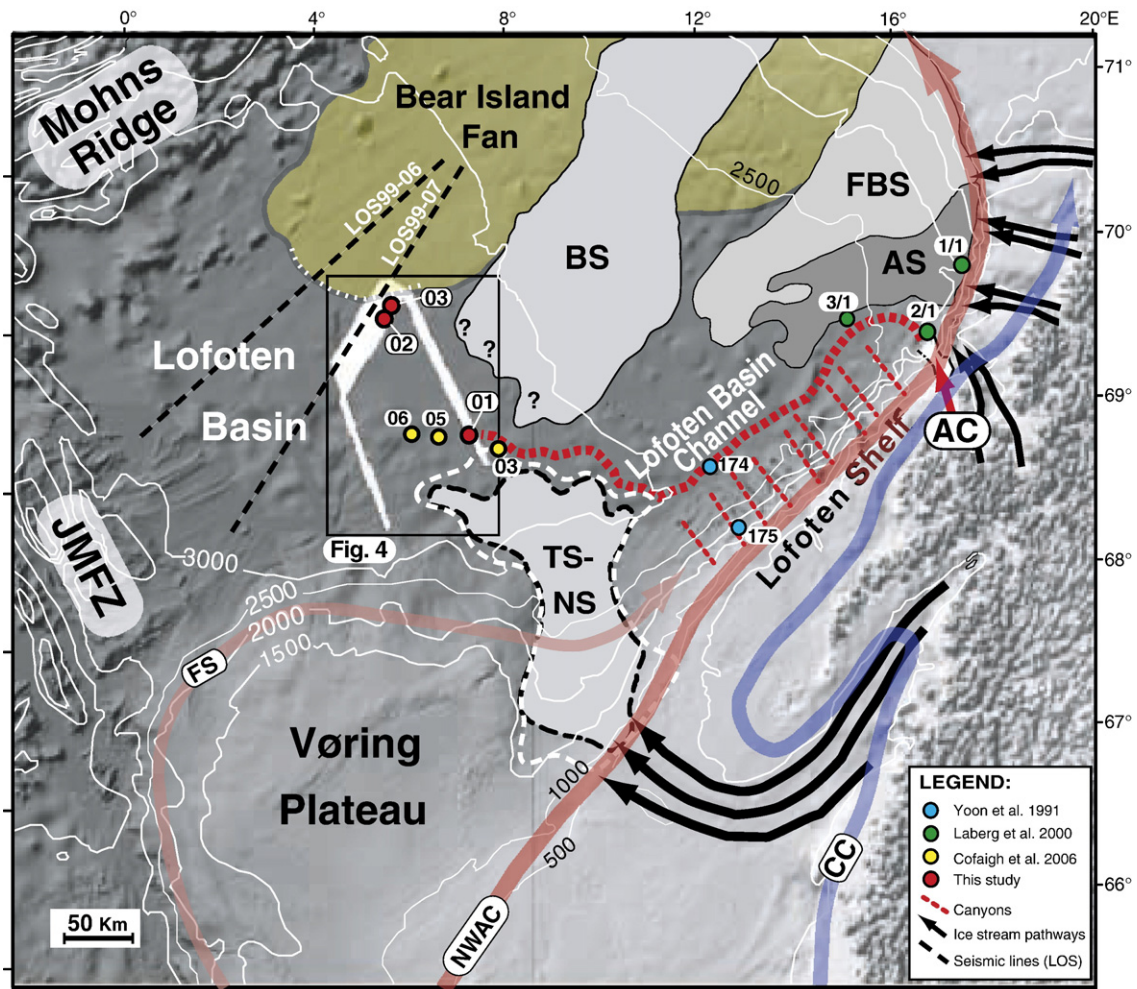


Fig. 2. A shaded bathymetrical map of the study area with inserted 500 m depth contours from the GEMCO data set (in white). The location of the multibeam swath areas (white stripes), the regional profiles (black dashed lines) and the location of retrieved cores (red dots) and the published cores available from the Andøya Canyon system are shown. The cores shown are also listed in Table 1. Due to a low resolution map is the location of the canyons (red dash lines) on the Lofoten Margin only tentatively marked. The exception is the Andøya Canyon (AC).

canyon heads close to the troughs outlet means that the sediments transported out to the shelf have been delivered directly into the canyons and transported directly to the continental rise and further out to the Lofoten Basin through the Lofoten Basin Channel (Fig. 3). As the sediment supply to the Lofoten self and the slope is mainly coming from the local mountain arc the progradation of the Lofoten margin has been moderate compared with elsewhere along the Norwegian margin (e.g. Vorren et al., 1998; Dowdeswell et al., 2002; Hjelstuen et al., 2004; Sejrup et al., 2005).

Our knowledge on the nature and rates of sedimentary processes taking place in these canyons and the associated Lofoten Basin Channel system is however still fairly limited as the available regional data sets are

mainly consisting of a low resolution GLORIA (6.5 kHz) side scan sonar data (Taylor et al., 2000). A number of high-resolution acoustic surveys have recently been carried out in this area, using side scan sonar (TOBI 30 kHz and MAK 30 and 70 kHz), sub-bottom profiler (TOBI 7 kHz and MAK 5 kHz), and EM120 multibeam swath bathymetry records (e.g. Taylor et al., 2000, 2002; Dowdeswell et al., 2002; Laberg et al., 2005; Cofaigh et al., 2006; Laberg et al., 2007-this volume), but so far the data coverage is limited to restrictive areas. Only few sediment cores have so far been retrieved from the Lofoten margin, including the canyons, channels, and the abyssal basin system (Fig. 2). They have been studied in detail for their stratigraphy and the sedimentary fabric, whereas only one core from a site within the lower

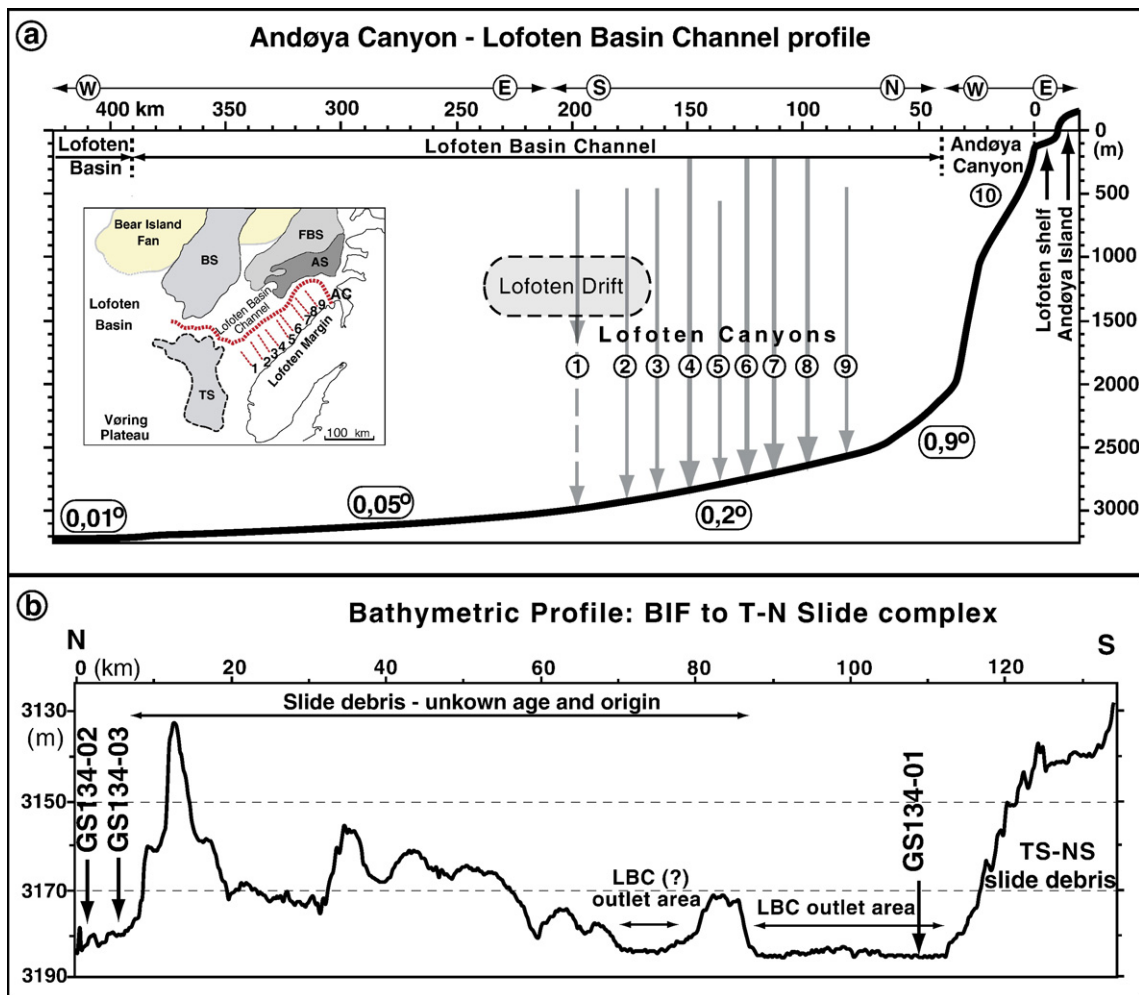


Fig. 3. a) A simplified bathymetric profile along the Andøya Canyon and the Lofoten Basin Channel pathway system. The tentative location of the minor Lofoten Margin (LM) canyons and where they enter the Lofoten Basin Channel is shown, b) Bathymetric profile across the gateway between the Bear Island Fan in north and the Trænadjupet–Nyk Slide complex in south. The profile is following one of the multibeam track lines shown in Fig. 4 and represents the lowest passage for sediments transported from the Andøya Canyon and the Lofoten margin canyon systems and into the Lofoten Basin area. The location of the cores studied is shown with red dots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Andøya Canyon system has been dated (Fig. 2, Table 1). The dated core and stratigraphy available from the Andøya Canyon system provide valuable information on the Holocene sediment accumulation, rate prevailing inside the upper part of the canyon system (Laberg et al., 2000). Based on a single core stratigraphy it is, however, difficult to estimate what this finding means in terms of type and frequency of downslope processes prevailing in the Lofoten canyon systems and the associated Lofoten Basin Channel. In an attempt to understand better this unique high-latitude sedimentary system, more systematic studies of the long term history of these canyons are needed in the accumulation area. The most continuous long term sediment archive for the canyon systems is

preserved in the abyssal accumulation area in the Lofoten Basin. High-resolution seismic and sediment core analyses of the abyssal sediments will give a better knowledge of the present sedimentation processes acting in these preserved canyon systems and will also give a new dimension to the glaciation history in the Lofoten area.

The main objective is to study the sedimentation history of the Lofoten canyons and the associated Lofoten Basin Channel system by examine the stratigraphical setting of the sediments in the accumulation area in the Lofoten Basin. A special focus will be on identifying the type, magnitude and frequency of the sedimentary processes prevailing in the system.

2. Physiographic and oceanographic settings

2.1. Physiography

The shape and architecture of the Lofoten margin area have the typical character of a low latitude river-fed continental margin as for example found off Portugal. The ca. 300 km long Lofoten margin contrasts with other glaciated margins, from Ireland to Spitsbergen, in physiography, sediment distribution and history of vertical motion (e.g. Eldholm et al., 1979; Løseth and Tveten, 1996). The glaciated European margin areas have prograded enormously during the Pliocene and Pleistocene and have been repeatedly modified by glacigenic processes (e.g. Vorren et al., 1998; Hjelstuen et al., 2004; Ceramicola et al., 2005; Dahlgren et al., 2005; Hjelstuen et al., 2005; Sejrup et al., 2005), while the progradation of the Lofoten margin has been slow during both, the Tertiary and the Quaternary period, due to a low sediment flux from the Lofoten archipelago (Tsikalas et al., 2001). This contrast is also demonstrated by the narrow shelf (10–30 km) off Lofoten and the relative steep slope (2.5° on average), which is deeply incised by submarine canyon systems (Figs. 2 and 3). The ten identified submarine canyon systems are different in size, but most of them are mature in character and must have developed over a long time period (Taylor et al., 2000). Only the Andøya Canyon has been described in detail (Laberg et al., 2000, 2005, 2007-this volume).

Table 1
Location, water depth and length of cores available from the study area and discussed in this study

Core ID	Depth (m)	Recovery (cm)	Geographical coordinates		Reference
			Latitude (N)	Longitude (E)	
GS134-01	3185	180	69° 23.75'	06° 47.88'	This study
GS134-02	3208	125	70° 09.55'	05° 16.83'	This study
GS134-03	3206	240	70° 13.92'	05° 25.28'	This study
JM95-1/1	17445	18	69° 50.00'	16° 23.00'	Laberg et al., 2000
JM95-2/1	1975	472	69° 35.00'	15° 30.00'	Laberg et al., 2000
JM95-3/1	2614	131	69° 45.00'	14° 00.00'	Laberg et al., 2000
JR51-GC03	3150	41	69° 12.50'	07° 16.94'	Cofaigh et al., 2006
JR51-GC05	3233	48	69° 17.00'	06° 12.00'	Cofaigh et al., 2006
JR51-GC06	3234	132	69° 19.54'	05° 38.79'	Cofaigh et al., 2006

The location of the cores is plotted on the map in Fig. 2.

Most of the ice streams in this area have advanced from the Lofoten mountain arc. However, the ice stream feeding the Andøya Canyon advanced from the main Fennoscandian Ice Sheet to the shelf edge through the Andfjord trough and developed a pronounced end moraine system at the shelf edge at the northern boundary of the Andøya Canyon (Andersen, 1968; Vorren et al., 1983; Vorren and Plassen, 2002). The dimension of the Andfjord trough and the size of the end moraine complex illustrate also the difference between the erosive and fast flowing ice stream from the Fennoscandian Ice Sheet and the gentler Lofoten mountain ice streams (Ottesen et al., 2005). The strong backscatter signature obtained from the GLORIA imagery mosaic of the Lofoten slope also supports the studies by Laberg et al. (2000) and Taylor et al. (2002) that the Andøya Canyon has been the most active sediment transport system in recent time on the Lofoten margin. Recent studies on the age of the moraine complex and the deglaciation history of the Andfjord area revealed that the ice stream reached the shelf break prior to 22 ka ¹⁴C BP, retreated at ca. 22 ka ¹⁴C BP and readvanced to the shelf edge at ca. 16–15 ka ¹⁴C BP. The last retreat of the glacier from the Andfjord shelf edge moraine complex and the onset of the deglaciation is at ca. 14.6 ka ¹⁴C BP (Vorren and Plassen, 2002).

The Lofoten Basin Channel system is the main sediment transport pathway from the canyons out to the abyssal Lofoten Basin (Figs. 2 and 3). The channel follows the base of the continental slope south-westwards at the distal end of all the nine other identified canyons on the Lofoten margin, before it turns westward across the flat (0.1°) Lofoten Basin Channel area (3100–3150 m water depth) and ends where it meets the Lofoten Basin at ca. 3200 m depth. A simplified profile of the canyons and the channel system with assumed gradients along the route is shown in Fig. 3.

The accumulation area in the Lofoten Basin is at approx. 3200 m water depth, almost flat (0.01°), dipping slightly southwards from the Barents Sea Fan in the north towards the Jan Mayen Fracture Zone (JMFZ) in the south (Fig. 1). The continental rise east of the Lofoten Basin is characterised by low relief. The topography is most pronounced in the eastern part of this area, where channels from the Lofoten margin are entering the flat (0.01–0.02°) area of the Lofoten Basin (Fig. 3).

2.2. Oceanography

The present ocean-surface circulation in the eastern Norwegian Sea is dominated by two near-surface branches of the warm northward-flowing Atlantic Current (AC) (Figs. 1 and 2). The warmer eastern branch of this current

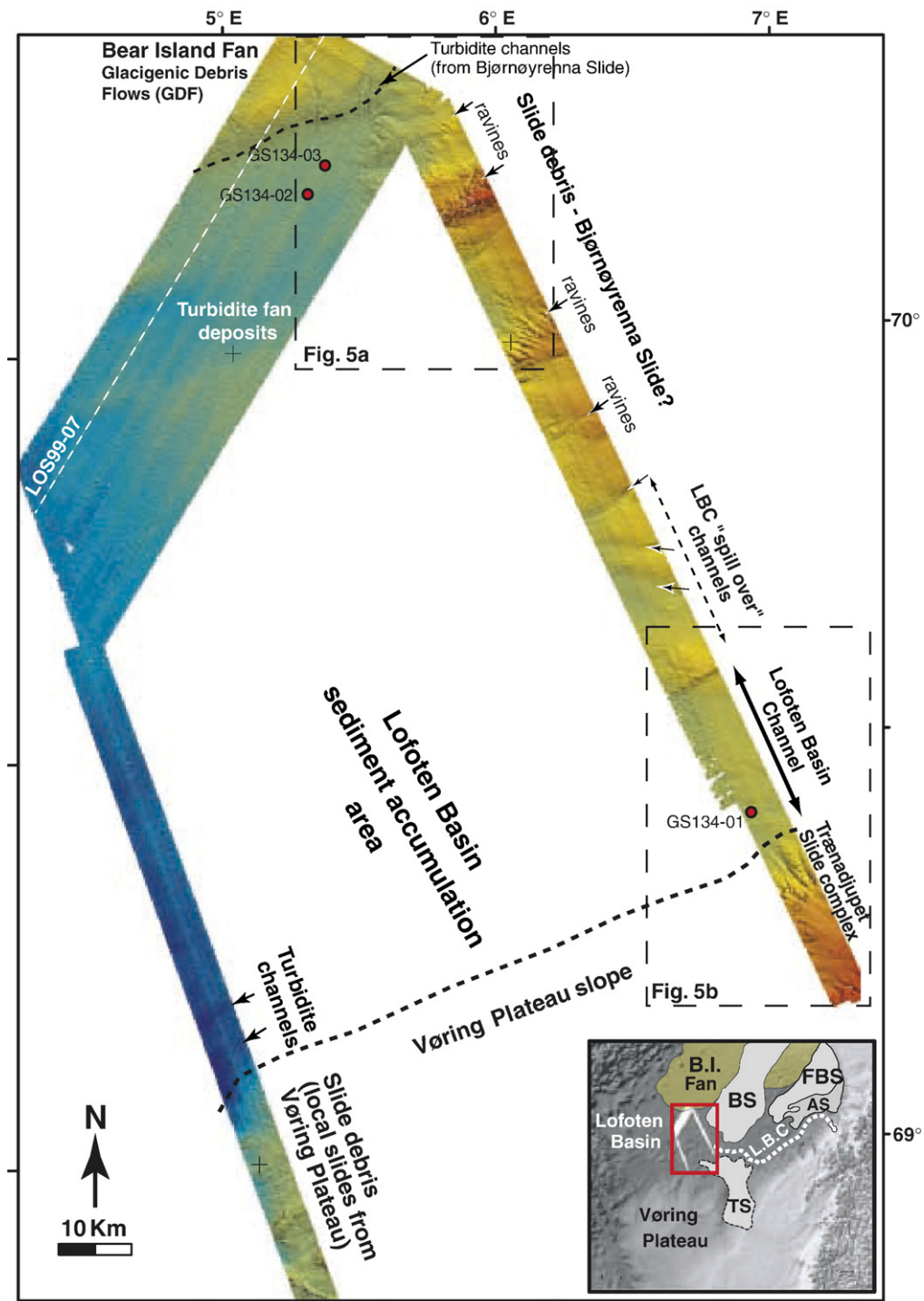


Fig. 4. Colour shaded multibeam swath imagery from the study area in the Lofoten Basin and the distal Lofoten Basin Channel area. Inserted on the map is the location of the cores retrieved and the regional pinger line LOS99-Line 07. A tentative morphosedimentary-morphostructural interpretation of the seafloor sediments is given. The location of the study area is shown with a yellow frame on the inserted map and in Fig. 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

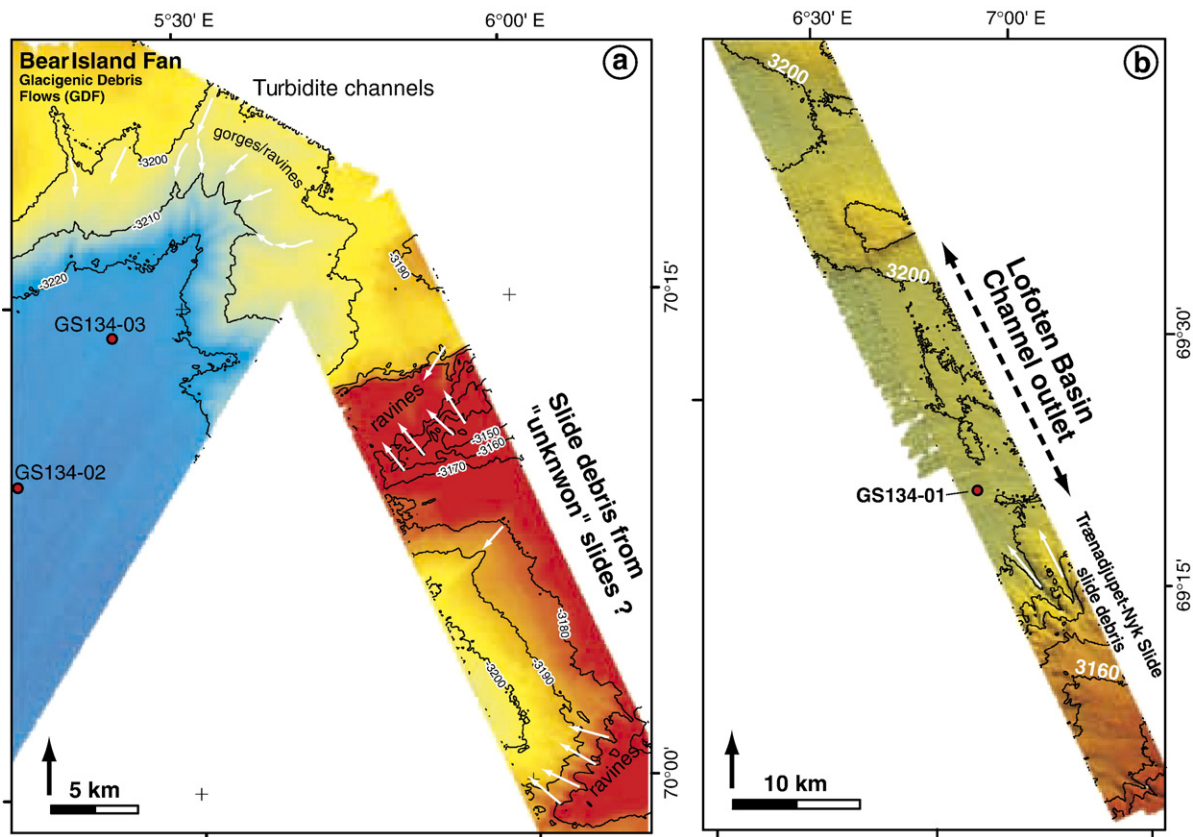


Fig. 5. Colour shaded swath bathymetric imagery areas selected from the multibeam swath transect shown in Fig. 4. Inserted on the imagery are 10 m depth. a) A close-up-view of the north-eastern part of the study area, b) A close-up view of the Lofoten Basin Channel outlet area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

is known as the Norwegian Atlantic Current (NWAC), whereas the western branch is known as the Færoe–Shetland current (FC). The NWAC is bound topographically to the shelf break and the upper continental slope, while the FC departs around the outer Vøring Plateau and merges with the NWAC off Lofoten (Poulain et al., 1996; Orvik et al., 2001; Orvik and Niiler, 2002; Jakobsen et al., 2003; Orvik, 2004). The lower boundary of the NWAC is at 500–600 m water depth off the Lofoten margin with velocities up to 110 cm s^{-1} (Poulain et al., 1996). Recent studies on the NWAC current have revealed current velocities of over 100 cm s^{-1} at the shelf edge along the Storegga margin (Alendal et al., 2005). On the Lofoten the current velocities so far measured are frequently 70 cm s^{-1} on the shelf south of the Andøya Canyon (Orvik et al., 1995). The recent high-resolution multibeam swath bathymetry mapping of the shelf around the Andøya Canyon clearly supports the strong NWAC impact on seabed winnowing in this area (Laberg et al., 2007-this volume). The effect of winnowing is expected to extend down to the lower boundary of the warm surface current at

ca. 500 m water depth similar to that experienced in the Storegga area (Haflidason et al., 2005). Below that boundary the sediments will accumulate on the slope, mainly trapped in the deep submarine canyons due to a reduced current speed there. The only dated core available from the Lofoten slope has been retrieved from a site inside the Andøya Canyon at a depth well below the lower boundary of the NWAC (Fig. 2). The dating results show that the sedimentation rate has been high ($>60 \text{ cm/ka}$) during the Holocene but outside the canyon the rate is 1 cm/ka (Laberg et al., 2000). High Holocene sedimentation rates ($40\text{--}50 \text{ cm/ka}$) have also been obtained in the deepest part ($>500 \text{ m}$ depth) of the Andfjord Trough east of the Andøya Canyon (Plassen and Vorren, 2002).

3. Data set and methodology

3.1. Geophysical data

The high-resolution seismic profiles available from the Lofoten Channel and Lofoten Basin area were acquired

with a 4 kHz pinger system during 1999 (Fig. 2). The signal was band-pass filtered between 2–5 kHz. The data quality is variable, in general a penetration of less than 30 meters (assuming a sound velocity of 1500 m/s in the sediments) in layered flat-lying sediments. Commonly, the signal is severely attenuated also on a flat seabed. The signal was recorded on an Octopus 360 system, and paper copies were used for interpretation. The vertical resolution is estimated to be around 0.8 ± 0.2 m.

The swath bathymetry data were obtained in 2003 using a Simrad EM300 multibeam echo sounder system. The system has a maximum ping rate of 10 Hz, with 135 beams per ping and a nominal sonar frequency of 30 kHz, which gives an optimum balance between small dimensions, narrow beams and good range capability. The pulse length used was 5 ms and the theoretical depth resolution is 10 cm. The survey was organised to achieve a 30–50% overlap with each parallel line to achieve high quality coverage. The raw data set has been processed with Simrad's Neptune and Cfloor software and gridded with a cell size of $25 \text{ m} \times 25 \text{ m}$. A total of 3000 km^2 of high-resolution multibeam data (EM300) were collected from the outer Lofoten Basin Channel and the Lofoten Basin area (Fig. 2).

3.2. Cores

Three gravity cores (11 cm in diameter) were raised from the outer Lofoten Basin Channel–Lofoten Basin area from a water depth of 3185 to 3208 m (Figs. 2, 4 and 5; Table 1). The cores were cut into two sections, split lengthways and the split sections passed through the GEOTEK™ Multi-Sensor-Core-Logger (MSCL) for determining density and magnetic susceptibility every 0.2 cm (Fig. 6). The cores were also, digitally photographed (Geocolour II) and X-radiographed before being visually described and analysed for the undrained shear strength.

The shear strength was tested down the core using the Swedish cone technique. Analyses were generally carried out at 5 cm intervals, whereas in some sections the core was investigated at 3 cm intervals. For each measurement at 3 cm two readings were taken and the values averaged. The points were evenly spaced to minimise the effects of the core walls and the adjacent readings. The penetration of the cone was then converted into a value for the shear strength using tables from Hansbo (1957) and calculated in kilo Pascal (kPa) (Fig. 6).

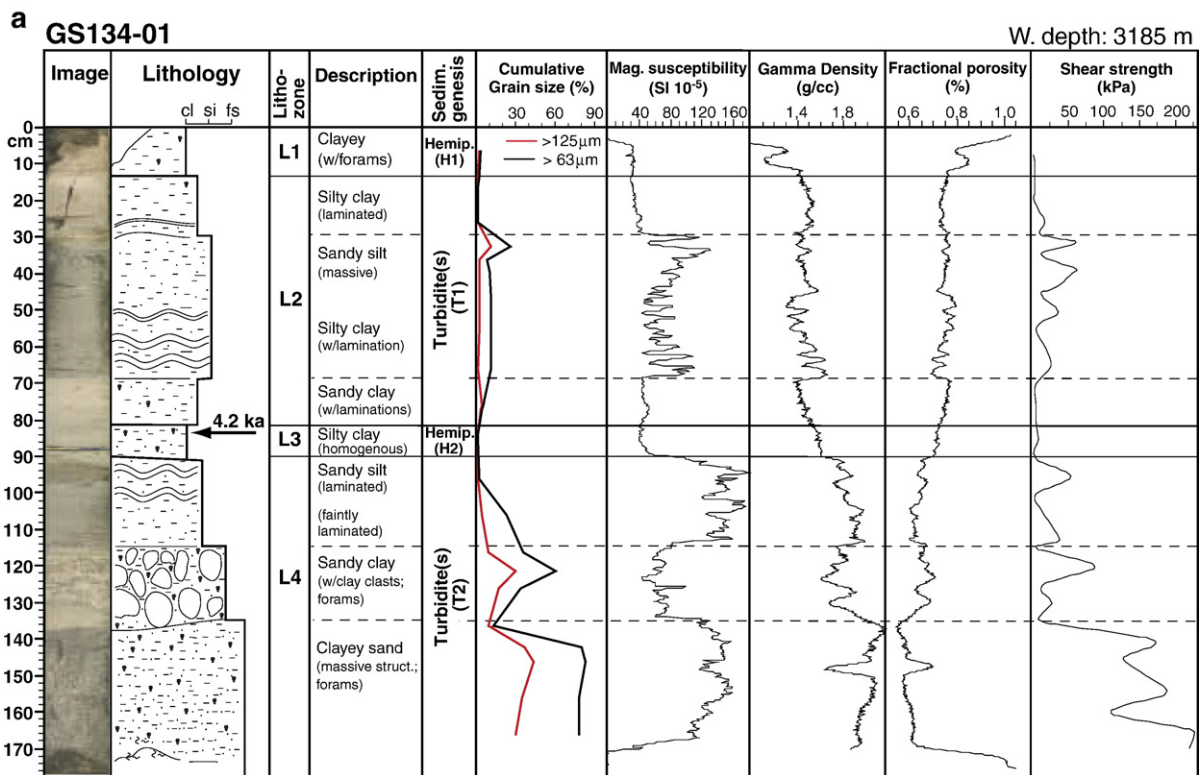


Fig. 6. The lithostratigraphy of the cores studied with colour image and the location of the interval and the results of the ^{14}C dating. A summary of the interpretation is provided in Fig. 8. a) core GS134-01GC, b) core GS134-02GC and c) core GS134-03GC. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

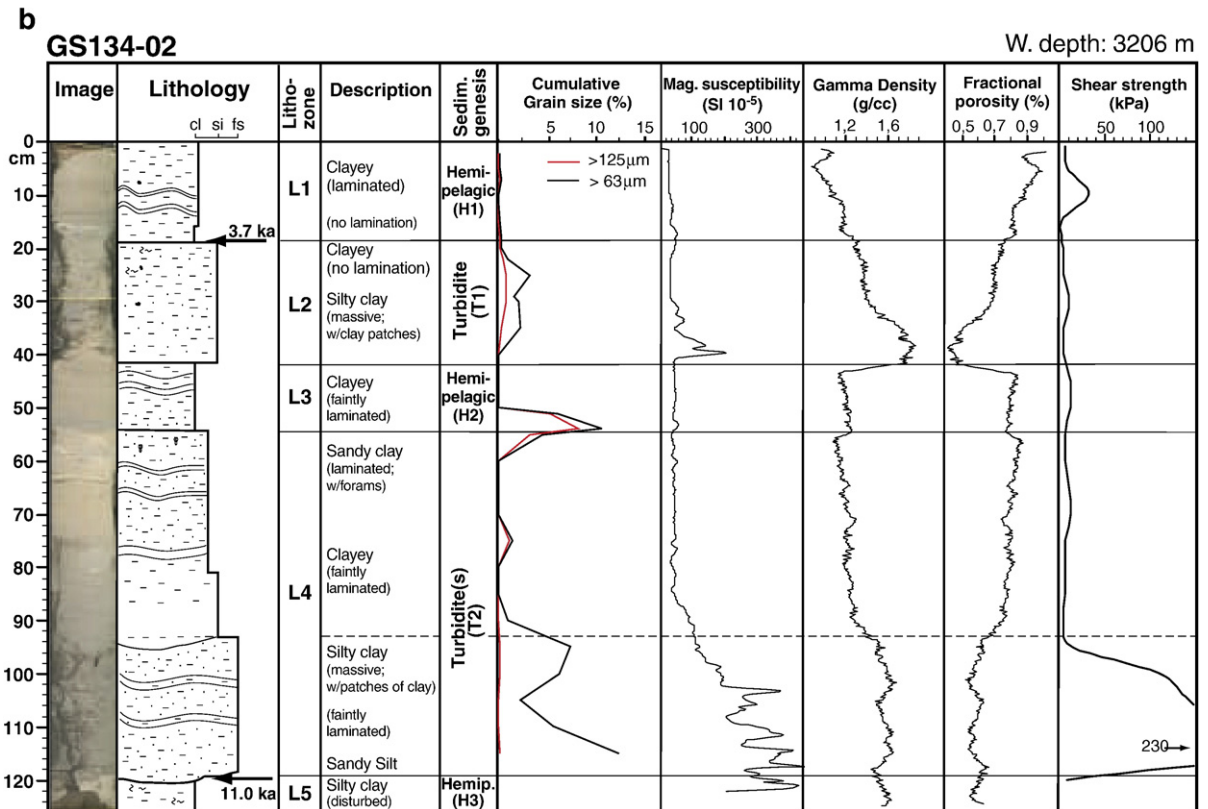


Fig. 6 (continued).

The cores were sub-sampled for analysis including grain size, moisture content and micropaleontology. The cores were sampled downcore every 5 cm, and additionally at 1 cm and 0.5 cm intervals around lithological boundaries. Samples were 0.5 cm thick.

The samples were submerged in distilled water and agitated for 72 hours, to split particle flocculates, before sieving through progressively smaller meshes (1 mm, 150 μm, 125 μm, and 63 μm). The sediment collected on each sieve was dried and weighed. The distribution of sediment finer than 63 μm was analysed, to 2 μm, with the Micrometrics Sedigraph 5100. Data from the sieving and the Sedigraph were combined and analysed using the GRADISTAT program (Blott and Pye, 2001) to calculate grain-size distribution statistics and curves. Samples were described using the methods of Folk and Ward (1957).

The radiocarbon dating method, ¹⁴C AMS (acceleration mass spectrometry), has been used to date the studied cores. Four samples from different stratigraphical intervals from undisturbed parts of each of the cores have been selected (Table 2; Fig. 6). A minimum of 6–7 mg of hand-picked planktonic foraminiferal species *Neoglobquadrina pachyderma* (dextral/sinistral), *Globigerina quinqueloba*

and *Globigerina bulloides* were collected for dating. The dating analyses have been carried out at the Beta Analytical Laboratory in Miami, United States. The dates obtained in the cores have been corrected for marine reservoir age (−400 yrs) and calibrated based on Stuiver et al. (1998) and were converted to calendar ages using the Calib 4.4 software (Stuiver and Reimer, 1993).

4. Results

4.1. Sea floor morphology and seismostratigraphy

Based on the processed multibeam data a detailed topographic map of the sea bed is presented in Figs. 4 and 5. The Lofoten Basin itself forms a very flat area extending from 3220 m in the northeast dipping 10 m (approximately 0.01°) towards the southeast 70 km away. The colour shaded bathymetric map from the north-eastern part of the study area is covering the ca. 140 km passage between the elevated Bear Island Fan in the north and the prominent Trænadjupet–Nyk Slide complexes in the south (Fig. 4). The lowest part of this passage is a 25 km section closest to the Trænadjupet–Nyk Slides. This is the present outlet of

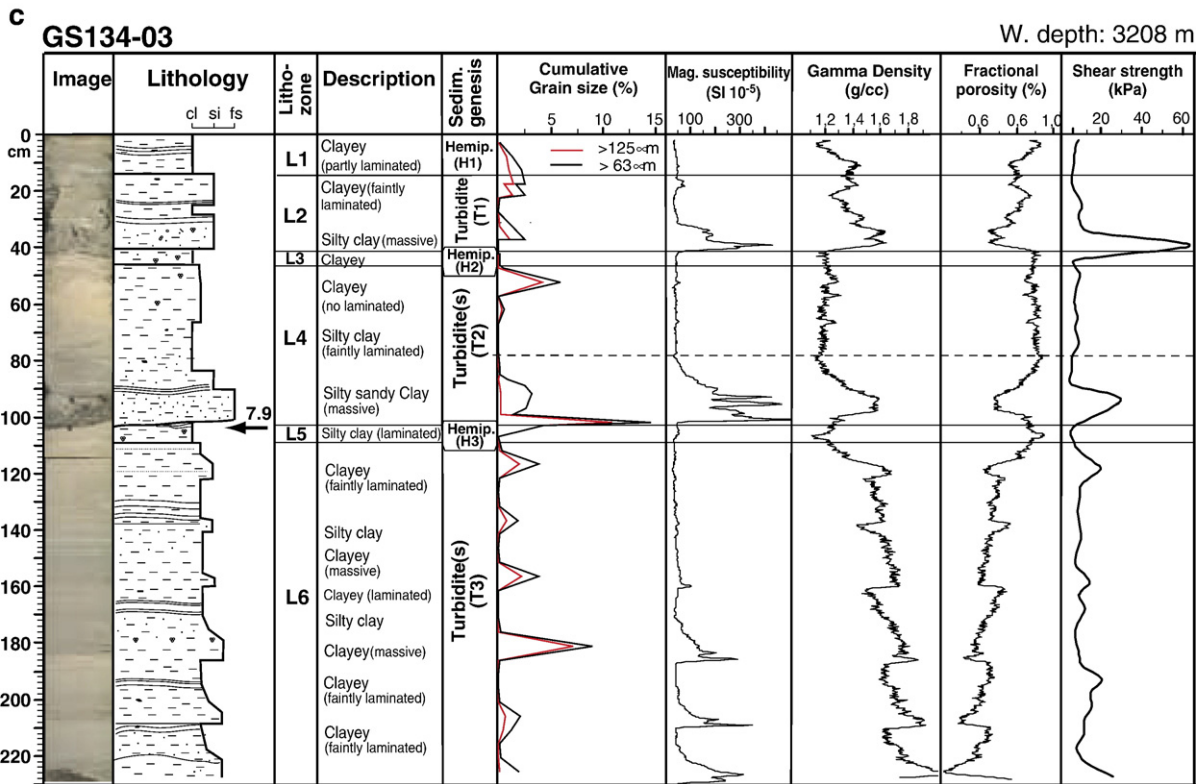


Fig. 6 (continued).

the Lofoten Basin Channel (LBC) entering the Lofoten Basin at 3200 m water depth. The area north of the LBC outlet is 20–50 m higher and dissected by small-scale gorges or ravines (Figs. 4 and 5a). The bottom topography found closest to the Bear Island Fan deposits (Fig. 3) has a hummocky topography dissected by a high density of ravine-and gorge-like features, whereas the bottom closest to the LBC outlet has a more smoother topographical image, and is only dissected by a few narrow channel-like features (Fig. 5b). The location of the LBC from the Lofoten slope and out to the Lofoten Basin is based on maps and images presented by Taylor et al. (2000, 2002), Laberg et al. (2005), Cofaigh et al. (2006) and present data

sets (Fig. 2). A bathymetric profile across the study area (N–S) illustrates the details in the topography and the precise location and the shape of the deepest part of the LBC system entering the Lofoten Basin sediment accumulation area (Fig. 3). Recent studies by Laberg et al. (2005) have also demonstrated that the LBC system seems to be the main transport route for the sediments coming from the Lofoten slope. Inside the LBC are also identified areas characterised by sediments waves and the sediments are sandy, whereas the sediments in the accumulation area outside the channel outlet are more fine grained and characterised by a smooth seafloor (Laberg et al., 2005; Cofaigh et al., 2006). The core sites selected

Table 2
Summary of the AMS radiocarbon dates of the studied cores

Core ID	Depth (cm)	Material (species)	Lab. ref. no.	¹⁴ C yrs (uncorrected)	St. dev. (1 s)	¹⁴ C yrs (res. corrected)	Calendar yrs BP average
GS134-01	82.5–84.0	Pl. forams	Beta-194767	4600	40	4200	4760
GS134-02	18.0–19.2	Pl. forams	Beta-194768	4130	40	3730	4160
GS134-02	119.0–120.0	Pl. forams	Poz-9661	11470	70	11070	12890
GS134-03	102.0–103.5	Pl. forams	Beta-194769	8320	50	7920	8840

Location in Figs. 2 and 4.

for the present study are based on the newly acquired EM300 multibeam data set and on the previously collected pinger profiles (Figs. 3 and 4).

4.2. Regional seismostratigraphy

The two regional high-resolution pinger profile lines from the study area are representing the regional stratigraphical setting characterising the upper ca. 50 m within the basin area (Fig. 2). Fig. 7 shows a typical example from the upper 40 m of the Lofoten Basin accumulation area with the sediments ponding between the relict basaltic topographical highs created within the Mohns Ridge rift-zone.

In general, the upper sediment column of the basin is layered and characterised by thin plain parallel units of turbidites and/or hemipelagic sediment units, where the

common thickness of each layer is ca. 0.5–1 m. Some of these sedimentary layers can be traced around in the basin for up to tens of kilometres where the unit is more than 2–3 m thick. One such regional marker horizon (L1) has been identified within the upper 20 m of the basin stratigraphy (Fig. 2). The horizon consists of seismically transparent material, and is in general between 2 and 4 m thick (Fig. 7). This unit (L1) is surveyed across an area of at least $2 \times 10^{10} \text{ m}^2$ which, if one assumes an average thickness of 2.5 m, equates a volume of $\sim 45 \text{ km}^3$ of sediment.

One of the pinger profiles, line LOS99-07, is located close to the core sites GS134-02 and GS134-03 (Figs. 4 and 7). The cores have been projected on the closest pinger profile section to demonstrate that the core stratigraphy gives a representative view of the regional sedimentation and structure of the Lofoten Basin area. The results of the core analyses show that sediments are composed

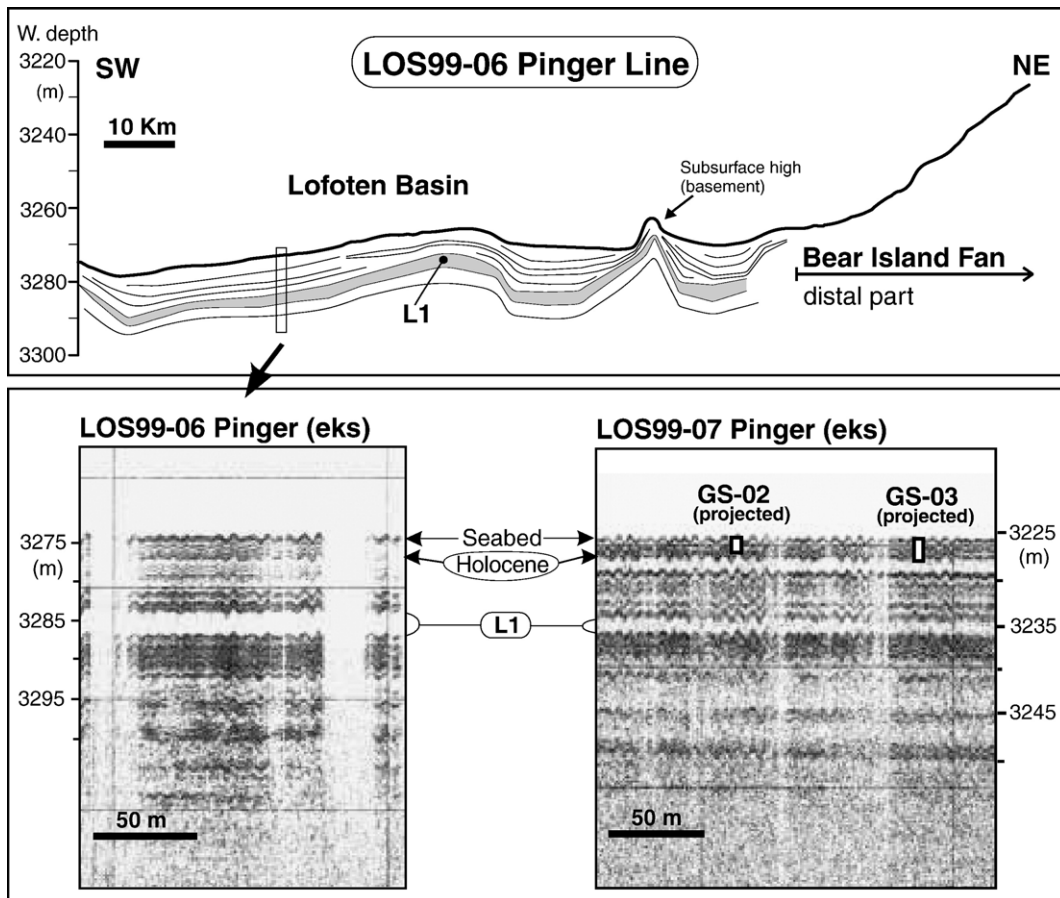


Fig. 7. Interpreted pinger (4 kHz) profile (top) from line LOS99-Line 06 with an example of the acoustic signature from the Lofoten Basin area. Location of the line is shown in Fig. 2. The acoustic signature (bottom) is an example of the character and of the resolution of the pinger records from the area. The L1 turbidite unit is one of the thick regional units that can be traced around in the Lofoten Basin. The age of this unit is interpreted to be the end of Last Glacial Maximum (LGM). The upper transparent turbidite unit is interpreted to mark the initiation of the Holocene period. The penetration of the cores GS134-02 and GS134-03 is shown on pinger line LOS99-07. The location of the line and the cores is shown in Fig. 4.

dominantly of turbidites and interbedded hemipelagite deposits. This genetic interpretation fits very well with the thin laminated plane parallel seismic signature on the pinger profiles (Fig. 7). A similar laminated seismic signature has also been found within the accumulation area in two short pinger profiles acquired from other sites within the Lofoten Basin area (Laberg et al., 2005).

4.3. Core stratigraphy

The cores have been divided into several lithological units based on visual description, texture, colour, X-radiography and detailed magnetic susceptibility and gamma ray density core logging results (MSCL). The core stratigraphy in all the three studied cores shows a similar succession characterised by 20–120 cm thick units of turbidites (single or multiple) interbedded with 10–15 cm thick units of hemipelagic deposits (Fig. 6). Most of the turbidite units consist of a stack of two or more turbidites, except the uppermost turbidite unit (T1) in cores GS134-02 and GS134-03 which is interpreted to consist of a single turbidite sequence. In the present study the main emphasis has been laid on identifying the lower and the upper boundary of the turbidite units rather than identifying the respective Bouma zones of the turbidite sequences. The turbidite units will therefore be treated as single stratigraphical units and represent sedimentary processes that are instantaneous compared with the slow continuous sediment deposition characterising the hemipelagic sediments. The hemipelagic units can also be dated in the studied cores with aid of in situ planktonic foraminifera.

4.3.1. Core GS134-01

Core GS134-01GC has been divided into four informal lithozones, named L1–L4 (Fig. 6a): *Lithozone L4* (89–178 cm). The lower boundary of this unit is not formally defined due to a lack of penetration. The unit is characterised by a high sand content and a high variation in the amplitude of the magnetic susceptibility (MS) (40–170 SI 10^{-5}) and the undrained shear strength values (10–225 kPa). The gamma density is in general high within the unit except for some minor drops. A major shift in the MS amplitude and the shear strength at 140 cm and at 115 cm depths divides the unit into three characteristic informal sub-units. The lowermost one (136–178 cm) consists of dark olive grey muddy sand with scattered grains of gravel, organic matter and a large amount of forams. The structure is massive with a uniform sand content of 80%. The middle sub-unit (115–136 cm) consists of an olive brown matrix that contains olive grey clay clasts. The matrix is compounded by very poorly sorted sandy mud with high abundance of forams and rhyolitic

tephra grains of Vedde Ash (10.3 ka ^{14}C BP; Birks et al., 1996), morphological character. The clasts are however, predominantly made of clay with sporadic forams. The total sand fraction, mainly comprising forams, constitutes 20–55% of the sediments. The uppermost sub-unit (89–115 cm) consists of olive grey very poorly sorted sandy mud with a sand content decreasing to 5% in the upper part and a structure shifting from faintly laminated to more prominently laminated or wavy-like structures upwards. The MS is, however, very high (150–180 SI 10^{-5}) indicating that the sediments of this sub-unit must have originated from the same source area. The lithozone is interpreted to consist of two and possibly three separate turbidite depositional phases, but treated stratigraphically as one unit in the present study.

Lithozone L3 (81–89 cm). The lower boundary is characterised by a significant drop in the MS, from 160 SI to 40 SI 10^{-5} and a contemporaneous decrease in the density. The shear strength drops also and is uniform and less than 10 kPa through the unit. The lower part of the unit consists of 98–99% homogenous silt and clay, whereas the sand fraction mainly consists of planktonic forams. The unit is interpreted to be a hemipelagic deposit based on the physical properties and uniform foraminiferal fauna assemblage within the unit. A sample for ^{14}C dating was taken at 82.5–84 cm depth.

Lithozone L2 (13–81 cm). This is a composite lithozone consisting of three informal sub-units. The lower boundary of the lowermost unit is characterised by a moderate increase of the coarse grain size, where the sand fraction is around 6%, and an increased amplitude of the magnetic susceptibility. The colour is olive brown and the structure laminated with only sporadic forams. The unit is interpreted to consist of possibly two separate turbidite depositional phases, but is in the present study treated stratigraphically as a sequence of stacked, graded beds.

Lithozone L1 (0–13 cm). The lower boundary of this unit is defined by a moderate increase in the coarse grain-size fraction mainly due to an increase in the planktonic foraminiferal content, decrease in the gamma density and an increase in the water content. The sediment is organic rich but without internal structures. The unit is interpreted to be a hemipelagic deposit based on the physical properties, the uniform foraminiferal content and the homogenous faunal assemblage.

4.3.2. Core GS134-02

Core GS134-02GC has been divided into five informal lithozones, named L1–L5 (Fig. 6b): *Lithozone L5* (120–126 cm). The lower boundary of unit L5 is not formally defined due to a lack of penetration. The sediments are light olive brown coloured, silty clay and structurally

disturbed due to deformation by the core catcher. The undrained shear strength is low (10 kPa). The unit is tentatively interpreted to be a hemipelagic deposit based on the physical properties, fine-grained sedimentation and homogenous fauna assemblage.

Lithozone L4 (51–120 cm). The lower boundary of the unit is erosive in character marked by a high magnetic susceptibility (MS) values ($420 \text{ SI } 10^{-5}$), and a rapid increase in the undrained shear strength, peaking at 230 kPa only 5 cm from the lower boundary. This is a composite lithozone consisting of two informal sub-units. The lower unit (93–120 cm) is characterised by very high MS values ($100\text{--}420 \text{ SI } 10^{-5}$) and high shear strength (20–230 kPa) in a unit of sandy silt sediments with a sand content of 5–12%. The structure is massive with evidence of some clay clasts. The upper unit (51–93 cm) is characterized by low MS values, low shear strength and a sand content <5%. The sediments are clay-rich and laminated or partly laminated. The unit is interpreted to consist of possible two turbidite depositional phases, but treated as one stratigraphical event.

Lithozone L3 (41–51 cm). The lower boundary of this unit is defined with a rapid increase from 3% to 10% in the sand size fraction and a minor increase in the gamma density. The colour change is also prominent shifting from a greyish-brown to a dark grey colour at the lower boundary. The MS is uniformly low ($40 \text{ SI } 10^{-5}$) through the unit and the gamma density values are uniform through the unit. The unit is faintly laminated increasing upward where the clay-rich sediments are also finer grained. Based on this lithological characters and a homogenous fauna assemblage is the unit interpreted to be a hemipelagic deposit. The unit has been subsampled for dating at an 8.0–19.2 cm depth (Table 2).

Lithozone L2 (19–41 cm). The lower boundary of unit L2 is distinct by an increase in the coarse grain-size distribution and rapid increase in MS (from 50 to 200 SI) and a significant increase in the sediment density. The unit consists of dark grey silty clay and patches of dark greyish-brown clay at the bottom and the top. The structure is massive and the sediment is well sorted at the bottom and the top. The unit is interpreted to consist of one turbidite depositional event.

Lithozone L1 (0–19 cm). A drop in the sand size content characterises the lower boundary of the unit and a shift in the colour hue from dark greyish-brown to dark grey. Low MS value ($40\text{--}50 \text{ SI } 10^{-5}$) and decrease in the gamma density dominates. The water content is high and the unit is found to be clayey and partly laminated in the upper part. The unit is interpreted to be a hemipelagic deposit based on the lithological characters and the homogenous foraminiferal assemblage.

4.3.3. Core GS134-03

Core GS134-03GC has been divided into six informal lithozones, named L1–L6 (Fig. 6c): *Lithozone L6 (107–230 cm).* The lower boundary of unit L6 is not formally defined due to a lack in penetration. The unit consists of greyish-brown clayey sediments varying between sections with partly laminated and massive structures. This is a composite lithozone consisting of possible four informal sub-units. The sediments are poorly sorted with a sand fraction around 2–3% characterised by well defined sand-richer layer with a peak around 5–8%. The gamma density is generally high through the unit, whereas the MS values varies systematically from a pronounced spike ($250\text{--}300 \text{ SI } 10^{-5}$) gradually decreasing to the minimum background values of $30\text{--}40 \text{ SI } 10^{-5}$. The unit is interpreted to consist of one, possibly four separate turbidite depositional phases, but in the present study they are treated stratigraphically as one event.

Lithozone L5 (102–109 cm). The unit is characterised by fine grain-size distribution and high water content. A pronounced shift in the colour from dark greyish brown to light olive brown characterizes also the lower boundary. The gamma density ($1.1\text{--}1.2 \text{ g/cc}$) and the MS values ($40\text{--}50 \text{ SI } 10^{-5}$) are low. The sediments are partly laminated with a low concentration of forams. The unit is interpreted to be a hemipelagic deposit based on the lithological characters and the foraminiferal content. It has been subsampled for dating at 102–103.5 cm depth (Table 2).

Lithozone L4 (48–102 cm). The lower boundary of unit L4 is erosional and is characterised by a rapid increase in grain size and in shear strength values. The MS increases to its highest values ($500 \text{ SI } 10^{-5}$) concordant with a spike in the sand fraction reaching a value of 16%. These high values decrease gradually and are found to be approximately constant in the upper part of the unit. The structure is massive or without any visible lamination, but shows a faint lamination within a short section in the middle part of the unit. The unit is interpreted to consist of one turbidite depositional event.

Lithozone L3 (43–48 cm). The lower boundary is defined by a drop in the coarse grain-size distribution. The water content is higher than in the unit below and the colour shifts from greyish-brown to light olive brown. The sediments consist of silty clay with a faint stratification. The MS values, gamma density as well as shear strength is low. Based on the lithological characters and the homogenous faunal assemblage, the unit is interpreted as a hemipelagic deposit.

Lithozone L2 (12–43 cm). The coarse grain size, MS, gamma density and shear strength values show a rapid increase at the lower boundary of the unit. The colour varies from dark grey to greyish-brown and the structure is mainly

Lithozone L1 (0–12 cm). The lower boundary is distinct by a fining in the grain-size distribution. The unit consists of olive brown coloured clayey sediments with high water content and faintly laminated structures. The amount of forams was too low to be subsampled for dating of the lower boundary. The fauna assemblage was uniform in character. The unit is interpreted as a hemipelagic deposit.

The age model for the three cores is based on four AMS dates (Table 2), the Vedde Ash regional tephrochronological marker (10.3 ka ^{14}C yrs BP; Birks et al., 1996) and on

regional sedimentation rate estimates (Fig. 8). The Vedde Ash tephra is not found as a distinct stratigraphical layer but as a reworked deposit through the entire lithozone L6 in core GS134-03. This lithozone must accordingly be younger than the deposition of the Vedde Ash (10.3 ka ^{14}C yrs BP) (Figs. 6c and 8). The location of the cores in the Lofoten Basin, far from the accumulation areas in the submarine canyons (Laberg et al., 2000) or in the depressions or troughs in the adjacent shelf areas (Plassen and Vorren, 2002), means that the normal sedimentation rate in the study area can be considered to be the same as found for the northern Norwegian Sea. The values commonly used for the Holocene in this area can vary from 3 to 5 cm/ka (e.g. Samthein et al., 1995; Hafslidson et al., 1998) influenced by the location in relation to the surface current system and the local bottom morphology

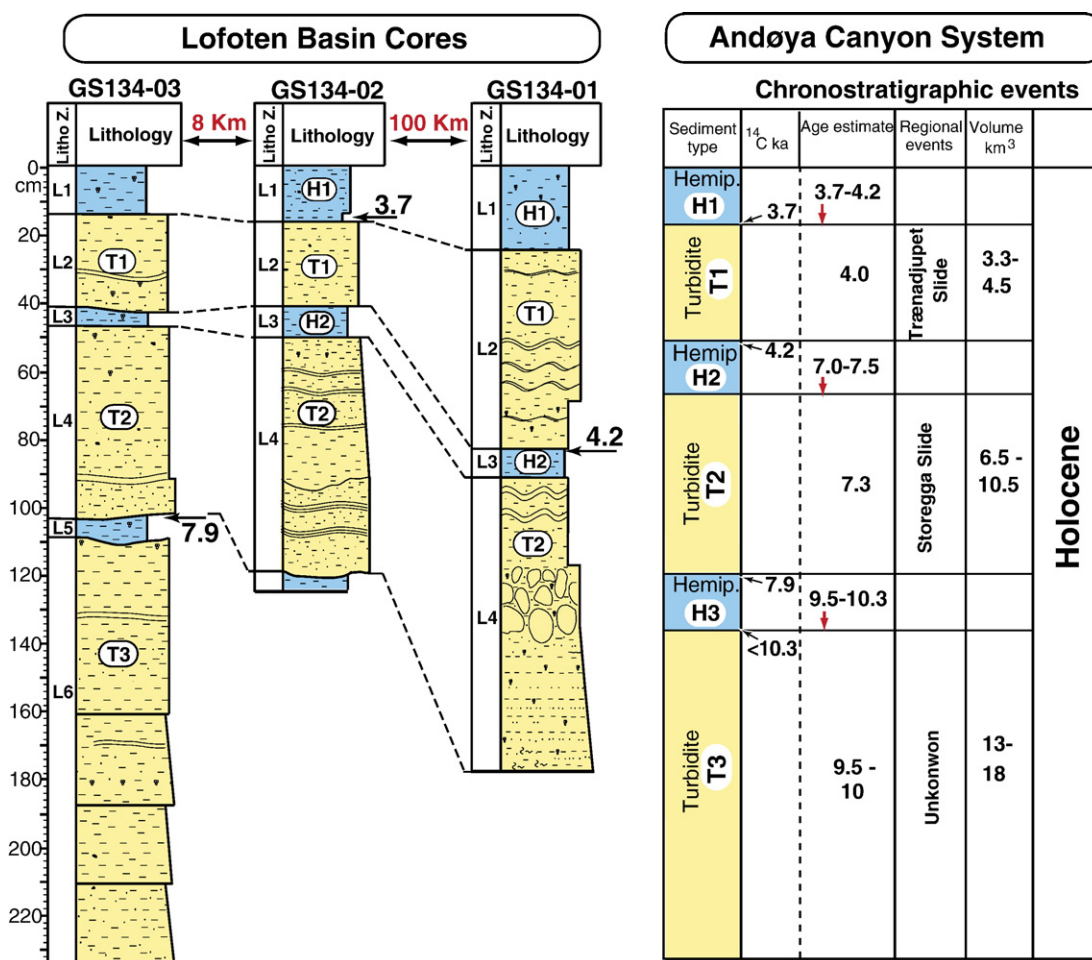


Fig. 8. Summary of the lithostratigraphical and sediment genetic interpretation of the cores studied. The numbers (red) between the core headings represents the distance in km between the core sites. The chronostratigraphical events found in the cores sections and the known regional slope failure events are summarised in the columns on the left. The age estimate gives an overview over the radiocarbon dates and the age interval of the hemipelagic boundaries based on present knowledge. The age of the turbidites is considered to be the best fit age, taking all the dating and stratigraphical information into consideration. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 1). One radiocarbon dating is available from the lower boundary of the hemipelagic unit L1 in core GS134-02 (Fig. 6 b). The unit is resting on the top of the youngest turbidite unit (T1). This turbidite unit is interpreted to be the same in all the three cores from the Lofoten Basin (Fig. 8), based on the ^{14}C date from the basal part of the hemipelagic unit in core GS134-02 and the regional sedimentation rate values (3–5 cm/ka) that prevail in the study area.

A great effort has been made to date the upper and the lower boundary of the three hemipelagic units in the same core sections to construct an independent chronological framework for the turbidite events identified in the cores. This has not always been possible as the thickness of the undisturbed hemipelagic units is usually only just a few centimetres and the concentration of forams varies within these units, limiting the possibility to date both the lower and the upper boundaries of the units. Additionally the dating results therefore have also been supported by using the sedimentation rate values of 3–5 cm/ka as well as the stratigraphical succession found in all the cores (Fig. 8).

The uppermost turbidite unit (T1) in all cores is covered by a layer of hemipelagic deposits of approximately the same thickness, which is dated to have an age of 3.7 ka ^{14}C yrs BP (GS134-02). This is considered to be a minimum age of the turbidite unit as the thickness of the interval sub-sampled for valid dating represents by itself a few hundred years. Additionally, to verify the age of the turbidite (T1) unit, the upper boundary of the underlying hemipelagic unit (H2) has been dated by one ^{14}C sample in core GS134-01. The x-radiography of the boundary zone shows that the turbidite is resting on this hemipelagic unit without creating any apparent disturbance or erosion. The ^{14}C age of 4.2 ka BP achieved thus represents a maximum age as the sub-sampled interval for dating is representing a few hundred years. The age of the uppermost turbidite (T1) unit found in all cores is therefore bracketed between a maximum age of 4.2 ka ^{14}C yrs BP and a minimum age of 3.7 ka ^{14}C yrs BP (Fig. 8).

The thickness of the undisturbed hemipelagic unit H2 resting on turbidite unit T2 is uniform around 9 cm in cores GS134-01 and GS134-02. In core GS134-03 this unit is slightly thinner as the top of the unit has been removed by the overlying turbidite (T1). The thickness of the undisturbed hemipelagic unit H2 represents therefore an age span of around 2–3 ka years. This means that the age of the top of the turbidite unit T2 can be from ca. 7.2 ka ^{14}C yrs BP to ca. 6 ka ^{14}C based on the average hemipelagic sedimentation rate of 3 to 5 cm/ka. To get a better grip on the age of the turbidite unit T2, the top of the underlying hemipelagic unit H3 has been ^{14}C dated in core GS134-03. The visual description and the x-ray analyses show that the

turbidite (T2) has eroded into the top layers of hemipelagic unit H3. The undisturbed sub-sampled interval right below the base of the turbidite gives an age of 7.9 ka ^{14}C yrs BP which must therefore be considered as a maximum age. The age of the turbidite unit T2 is therefore bracketed between the maximum age of 7.9 ka ^{14}C yrs BP of the eroded hemipelagic unit H3 and the minimum age of ca. 7 ka ^{14}C BP acquired from the overlying undisturbed unit H2.

The age of the lowermost turbidite unit T3 is derived from the thickness of the hemipelagic unit H3 resting on this unit in core GS134-03. This H3 unit is ca. 8 cm thick representing an age span of 1.5–2.5 ka. The detection of volcanic tephra grains from the Vedde Ash layer in the turbidite unit T3 sediments means that the maximum age of the unit can be as much as 10.3 ka ^{14}C yrs BP. The minimum age based on the thickness of the undisturbed hemipelagic unit resting on the turbidite gives an age of 9.5–10 ka ^{14}C for the top of this turbidite unit.

5. Discussion

All channel-like features that were mapped on the 130–140 km long multibeam swath imagery transect, covering the eastern Lofoten Basin area are either narrow with a ravine-like morphological structure (Figs. 4 and 5a) or very broad and shallow and represent the main outlet of the LBC (Figs. 4 and 5b). Sediments released from the Lofoten margin and the adjacent slope area must pass through this channelized area to enter the Lofoten Basin. The accumulation areas found immediately outside the channel outlets are smooth and non-erosive in shape which supports the interpretation that the sediments were entering the Lofoten Basin under a low energy conditions (Fig. 3). The undisturbed hemipelagic deposits found interbedded between the turbidite units in all studied cores support this pattern of a non-erosional depositional regime prevailing in the Lofoten Basin accumulation area (Figs. 7 and 8).

The deepest part of the multibeam transect (Fig. 4) covered a 25 km wide and smooth channel-like area situated close to the slide debris from the Trænadjupet–Nyk slide complex (Fig. 5b). The location of the LBC outlet in this area fits well with the published acoustic data sets (e.g. Taylor et al., 2000, 2002; Dowdeswell et al., 2002; Laberg et al., 2005; Cofaigh et al., 2006) of the pathway (Fig. 2). The approx. 5 km channel basin located 10 km north of the main outlet channel can also be an extended part of the LBC system, but a better acoustic coverage of this area is needed for confirmation. This narrower channel outlet is nevertheless considered to be the northernmost extension of the LBC outlet area entering

the Lofoten Basin. This is supported by the regional bathymetry and the known outer boundaries of the morphology induced by the Trænadjupet–Nyk slide and the glacial debris flows related to the BIF both to the north and to the south of the studied transect area (Fig. 2). The ravine-like features identified in the northern part on the multibeam transect, must therefore be related to a different downslope transport system than the more pronounced LBC system. The morphological small-scale character of these channels is also different from those found in the LBC outlet area (Fig. 5). The cores retrieved from these two different systems, i.e. core GS134-01 from the LBC outlet and cores GS134-02 and GS134-03 from the northern part, show overall the same stratigraphical and sedimentological pattern, but the grain-size distribution in the cores from the northern part is distinctively finer than in the LBC outlet area. The grain-size distribution curves are also found to be similar within the different turbidite units from the same core section as illustrated by the cumulative grain-size distribution for the studied cores (Fig. 6). This indicates that the same sedimentary regime must have prevailed in these two particular areas, at least during the Holocene time period. The large distance between the northern core sites and the core retrieved from the LBC outlet area means that these cores can hardly be a part of the same sediment transport system. Whereas the LBC is associated with the distal part of the Andøya Canyon the small-scale gorge and ravine channel systems in the northern part of the transect area (Fig. 5a) are most probably related to a small-scale downslope system associated with the Bear Island Fan or the Bjørnøyrenna Slide (BS) (Figs. 1 and 2). As the depth of the Lofoten Basin area decreases eastward or towards the outlet of the channel system found in the east, it is assumed that the turbidites that entered the Lofoten Basin through these channels must also be derived by the same sedimentary systems that delivered the turbidite deposits all over the basin. They are identified on the sub-bottom profiles as thin subparallel units (Figs. 2, 4 and 6). The interpretation of the sub-bottom profiles suggests that turbidites dominate the upper 30 m of the basin deposits (Fig. 7). Only the upper 2.5 m of these have been cored, dated and analysed for sediment genesis. The results are summarised in Fig. 8 showing that the upper ca. 2.5 m of the sediment column is of Holocene age and the sediments indeed consist alternately of thin beds of hemipelagites and thick units of turbidite deposits.

The three Holocene turbidites volumetrically comprise ca. 85–90% of the sediments found in the basin, whereas hemipelagites comprises ca. 10–15% of the sediments. Based on the regional sub-bottom profiles and the shape and topography of the basin the turbidites are interpreted to cover about 13–15,000 km² of the Lofoten Basin area. The

turbidite sequences within the numbered turbidites units (see Fig. 8) are interpreted to have been released within a short time span and transported through the channel systems and into the Lofoten Basin accumulation area. The volume estimate of the three turbidite units is therefore treated uniformly for the whole basin and presented as one number in Fig. 8. From the sub-bottom profiler records an acoustically transparent sediment body (L1) has been traced around the entire basin (L1 on Fig. 7) and in terms of the extent, thickness and seismic character can be interpreted as a megaturbidite, according to Bouma (1987). This large-scale feature, covers an area of approx. 2×10^{10} m², and contains a volume of ca. 45 km³ of sediment. The age is assumed to be around the last glacial maximum; however, the lack of core control prevents accurate age dating.

A high precision dating of the turbidite units will always be hampered by the low sedimentation rate prevailing in the area and the low concentration of datable marine carbonate in the samples. However, the combination of radiocarbon dates taken above and below the turbidite units and sedimentation rate calculation of the age of the three identified turbidite units has been bracketed into a fairly narrow time frame. The youngest turbidite unit (T1) is dated to be around 4.0 ¹⁴C ka yrs BP in age or close to the age of the Trænadjupet Slide, dated to 4.0 ¹⁴C ka yrs BP (Laberg and Vorren, 2000; Laberg et al., 2002). The Trænadjupet Slide is found on the continental slope southeast of the Lofoten Basin and probably affected the investigated sites. Turbidite T2 (7.9 ¹⁴C ka yrs BP) falls close in time with the Storegga Slide, which has been dated to 7250 ± 250 ¹⁴C BP (Hafliðason et al., 2004, 2005). However, the Storegga Slide failure occurred some 500 km farther south and no direct input from that slide could have entered to Lofoten Basin (Fig. 1). Therefore, if T2 is associated indirectly with the Storegga Slide event, the trigger of the turbidite unit found in the Lofoten Basin might have been by a strong earthquake or by the Storegga tsunami wave known to have travelled northwards along the coast and the shelf. Recent studies have found a strong impact of the Storegga tsunami wave in the coastal area north of Lofoten (Bondevik and Rasmussen, 2005). This impact, equal to the wave height found close to the Storegga headwall, has tentatively been explained by strong coastal bottom currents transformed northward with high energy (Bondevik and Rasmussen, 2005; Lynett and Lui, 2006). A considerable amount of sediments is found to have been trapped in the Andøya Canyon (Laberg et al., 2000) during the Holocene. Other canyons or depressions on the Lofoten slope probably also accumulated and preserved sediments during the

Holocene time. Following a large earthquake and/or regional tsunami waves created in association with the release of Holocene mega slides as the Trænadjupet Slide and the Storegga Slide, sediments on the Lofoten slope became unstable and were transported through the channel systems and deposited as unified turbidite units in the Lofoten Basin (Figs. 1 and 8). Thus, it is assumed that T1 and T2 are related to events with a regional impact as they are found in cores, both outside the Lofoten Basin Channel and outside the gorges and ravines on the outer Bear Island Fan or the Bjørnøyrenna slide deposits. It has not been possible to link T3 to any known event in the region, but the age of the turbidite unit is tentatively dated to be around 9.5–10 ka ^{14}C BP.

6. Conclusions

A detailed study of sediment cores GS134-01GC, GS134-02GC, and GS134-03GC, based on lithological, physical properties analyses and radiocarbon datings, has shown that the sedimentary processes responsible for sediment deposition in the area of the Lofoten Basin consist of semi-regular events of turbidity current deposits interbedded with hemipelagic sediments. The upper ca. 2.5 m of the stratigraphic column covering the Holocene time period consists of two distinctive turbidite units, comprising 85–90% of the deposits, and of two hemipelagic units, comprising ca. 10–15% of the deposits in the basin.

The chronological analysis, based on the radiocarbon dating method ^{14}C AMS and sedimentation rate estimates have placed the youngest turbidite event (turbidite unit T1) at ca. 4.0 ^{14}C ka yrs BP whilst the other turbidite event T2 is defined at around 7–7.5 ^{14}C ka yrs BP. The oldest turbidite unit defined in the cores is tentatively dated to be ca. 9.5–10 ^{14}C ka yrs BP in age. The two youngest turbidite events appear to be closely linked to the two mega slide events, Trænadjupet Slide (4.0 ^{14}C ka yrs BP) and the Storegga Slide (7.25 ka ^{14}C yrs BP). The oldest turbidite unit so far cannot be related to any known regional event.

Instability of the slope sediments related to large earthquakes as well as high bottom current velocities following passage of a high tsunami wave are considered the most likely triggering factors that could have released the turbidite events found in the Lofoten Basin accumulation area.

The Lofoten Basin Channel system and other minor channel systems, found to have delivered sediments into the Lofoten Basin area, have been active during the Holocene. The instability of these systems is strongly related to regional large-scale events that seem to have

influenced the release of slope sediments and contributed to a considerable accumulation through the entire Holocene. The volume of these two turbidite events has been estimated to be around 3.3–4.5 km³ for unit T1 and 6.5–10.5 km³ for unit T3, respectively. These values indicate that a large part of the sediments deposited within the drainage area of the Lofoten Basin as hemipelagic sediments could have been involved in each of the failure events and subsequently was transported into the Lofoten Basin as a part of the turbidite.

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