Late Quaternary seismic stratigraphy and geological development of the south Vøring margin, Norwegian Sea

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Abstract

High-resolution seismic data and sediment cores show that an up to 280 m thick sedimentary sequence has been deposited on the south Vøring margin, off mid-Norway, the last ca 250 ka. The sedimentary succession has been divided into six seismic units, dominated by hemipelagic sediments. Five wedge-shaped massive sequences, of marine isotope stages 8, 6 and 2, interfinger the hemipelagic deposits on the upper slope. The wedge-shaped sequences represent glacigenic debris flows that have been fed by till transported to the shelf edge by grounded ice sheets during maximum glaciations. The hemipelagic units show well-defined depocentres, of various thicknesses, on the upper continental slope. Seismic facies interpretation indicates that the sediment distribution locally has been controlled by currents. Commonly, the hemipelagic units are characterised by parallel and continuous reflectors. However, the second youngest unit identified, deposited between 15.7 and 15.0 \(^{14}\)C ka BP, is acoustic transparent. We suggest that this unit has been sourced by along-slope transported meltwater plume deposits, released during the initial stage of the last deglaciation of the Norwegian Channel. The hemipelagic sedimentation rates have varied considerably throughout the studied time period. Until ca 21 \(^{14}\)C ka BP the rates did not exceed 1.4 m/kyr, whereas during the Last Glacial Maximum the rates increased and reached values of about 36 m/kyr before decreasing again at ca 15 \(^{14}\)C ka BP. Observation of iceberg scourings, of MIS 8 age, about 800 m below the present day sea level, suggest that the south Vøring margin has subsided by a rate of 1.2 m/kyr in the Late Quaternary.

1. Introduction

The Vøring margin, off mid-Norway (Fig. 1), has for the last 20 years been the location for both commercial interests and geological/geophysical scientific studies. The investigations have to a large degree dealt with the tectonic evolution, crustal structure, rifting and breakup of the margin segment (e.g. Eldholm et al., 1989; Skogseid et al., 1992, 2000; Doré et al., 1999; Mjelde et al., 2003). However, studies have also focused on vertical movements and Cenozoic sediment stratigraphy (e.g. Skogseid and Eldholm, 1989; Stuevold and Eldholm, 1996; Hjelstuen et al., 1999), whereas Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) legs have increased our knowledge on sedimentary environments and paleoclimatic changes within the region (Henrich et al., 1989; Jansen et al., 1989). In spite of the broad investigations, rather few studies (e.g. Dahlgren et al., 2002; Dahlgren and Vorren, 2003) have in detail focused on the Late Quaternary margin evolution, when Fennoscandia and the adjacent continental shelf periodically were covered beneath extensive ice sheets.

The Quaternary sediments on the mid-Norwegian continental margin strongly reflect changes related to climatic oscillations (King et al., 1987; Jansen et al., 1989, 1990). Thus, this area is important when describing geological evolution and sedimentary processes acting on glacial continental margins. Increased hydrocarbon exploration on continental slopes has also caused the need for studies of geological processes within these environments. Furthermore, knowledge on

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the sedimentary regime off mid-Norway is also of importance for the geological understanding of the continentalslope to the south. This, as it is believed that similar deposits as the Quaternary sediments on the south Vøring margin were deposited in the Storegga Slide region (Fig. 1) before the Storegga Slide event removed these sediments for about 7200 14C years ago (Haflidason et al., 2003).

In this study we present interpretation of recently collected high-resolution seismic data, that in combination with shallow cores make it possible to address, in detail, the Late Quaternary geological evolution of the south Vøring margin. We aim to: (1) establish a Late Quaternary seismic stratigraphy, (2) map any changes in sediment distribution and sedimentation rates through time, (3) identify source areas, and (4) study sedimentary processes.

2. Geological background

2.1. Structural setting and morphology

The structural configuration of the Vøring margin includes the Trondelag Platform, the Voring Basin and the Voring Marginal High (Fig. 1), and is a result of post-Caledonian lithosphere extension (e.g. Brekke, 2000), which culminated with break-up of the Norwegian–Greenland Sea at the Paleocene–Eocene transition for about 55 million years ago (Skogseid
et al., 1992, 2000). The Cretaceous Vøring Basin was structured into several ridges and heights in the Late Paleocene–Early Eocene, and throughout Cenozoic time domes and arches evolved within the basin (Fig. 1) (Doré and Lundin, 1996; Hjelstuen et al., 1997; Lundin and Doré, 2002). These structural elements have played a major role for the sediment distribution on the continental margin throughout the Tertiary and Quaternary.

The Vøring margin is furthermore characterised by a broad continental shelf with bank areas and cross-shelf troughs (Fig. 1). Along the western part of the shelf, close to the shelf edge, a 100 km long, 200 m high and 10 km wide moraine ridge complex, the Skjoldryggen, has evolved. The continental slope is broken by the Vøring Plateau (Fig. 1), a broad marginal plateau at a water depth of about 1100 and 1400 m. Mud diapirs are locally rising tens of metres above the seafloor in this region and disturb the smooth plateau seabed (Hjelstuen et al., 1997; Hovland et al., 1998). The slope bathymetry also reflects the major slide events, i.e. the Storegga and Trænadjupeit slides, which affected the Norwegian continental margin in the Holocene (Laberg and Vorren, 2000; Laberg et al., 2002; Bryn et al., 2003) (Fig. 1).

2.2. Glacial history and ocean circulation pattern

The climate on the Northern Hemisphere started to decline during the Miocene, and at about 12 Ma the first occurrence of ice rafted material (IRD) is observed on the Vøring margin (Fronval and Jansen, 1996); probably indicating that ice caps large enough to reach the Norwegian coast existed. Throughout the Late Pliocene-Pleistocene time period stepwise increase in the amount of IRD supply to the continental slope reflects the intensification in the Northern Hemispheric glaciations (Henrich et al., 1989; Jansen and Sjøholm, 1991).

The first extent of an ice sheet to the shelf edge within the studied region is suggested at about 1.1 Ma (Haflidason et al., 1991). However, repeated ice sheet advances across the mid-Norwegian continental shelf have only been documented since ca 0.5 Ma (Dahlgren et al., 2002), culminating with the Last Glacial Maximum (LGM) in the Late Weichselian. Around 15 $^{14}$C ka BP LGM terminated and the final deglaciation of the Norwegian margin occurred (Vorren and Plassen, 2002; Dahlgren and Vorren, 2003; Sejrup et al., 2003). We note that Nygård et al. (2004) identified an ice readvance, the Bremanger Event, on the Norwegian shelf in the time period between ca 15 and 13.3 $^{14}$C ka BP, i.e. when the main Fennoscandian deglaciation was well underway. The repetitive glaciations caused erosion of the continental shelf and formed the present day morphology of the Trondelag Platform (Fig. 1), where the troughs acted as pathways for ice streams (Ottesen et al., 2001, 2002).

The present hydrographic regime within the studied region is dominated by three water masses: Norwegian Coastal Current water, Norwegian Current Atlantic water, and the deep-water in the Norway Basin. The Atlantic water, which has a salinity of about 35% and temperatures of 6–9°C (Henrich and Baumann, 1994), covers the outer continental shelf and the uppermost continental slope down to a water depth of about 600–700 m, and is sharply bounded both towards the Norwegian Coastal Current, which has a salinity of <33%, and the Norway Basin deep-water having salinities >34.9% and temperatures <0°–1°C (Thiede et al., 1989).

It appears that the seabed sediment distribution is strongly affected by the characteristic of the overlying water masses. The sea floor beneath the Atlantic water consists of sorted sand or gravelly lags. Terrigenous mud of variable thickness covers the sea floor between 700 and 1200 m, whereas in water depths >1200 m, a less than 20 cm thick cover of foraminiferal ooze with a high carbonate content has been deposited (Holmedahl, 1981; Sejrup et al., 1981). Throughout the Late Pliocene-Pleistocene time period the magnitude of the Norwegian Current has varied. Between ca 2.6–1.0 Ma Atlantic water intruded the Norwegian–Greenland Sea only episodically, whereas from about 1 Ma the Norwegian Current was strengthened (Henrich and Baumann, 1994).

3. Data and methods

Two IMAGES cores, two boreholes and about 3000 km with deep-tow boomer profiles define the main database in this study (Fig. 1). Mini-sleeve gun records and a 3D survey have also been investigated.

3.1. Images cores and boreholes

IMAGES cores MD99-2289 and MD99-2291 are giant piston cores sampled during the 1999 IMAGES-V cruise. MD99-2289 is 23.69 m long and was raised from a water depth of 1262 m, near the northern Storegga Slide scar (Figs. 1–3). From this core, sediment samples have been taken every 2–10 cm for stable isotope and magnetic susceptibility measurements and for analyses of bulk intensities of selected chemical elements (Berstad, 2003). The core has been dated by using Accelerator Mass Spectrometry (AMS) on 12 monospecific samples of the planktonic foraminifera species Neogloboquadrina pachyderma (sin) (Fig. 3). The 25.75 m long IMAGES core MD99-2291 is taken on the upper continental slope, in a water depth of 577 m (Fig. 1). Ninety sub-samples have been taken from this core for analyses of bulk density, porosity, water content, and grain-size distribution (Knorr, 2000). The
The core chronology is based on six radiocarbon (AMS) dates on samples of *N. pachyderma* (sin) (Fig. 3).

Borehole 6404/5, which is 310 m long, was done in a water depth of 966 m whereas the 123.6 m long borehole 6405/2 is localized only 5 km east of MD99-2291 (Fig. 1). The recovery for both boreholes is low, only between 8.5 and 11.6%. Radiocarbon analyses, based on *N. pachyderma* (sin), paleomagnetic analyses, strontium isotope analyses and amino acid diagenesis were obtained to establish an age model for the boreholes (Haflidason et al., 1998, 2001). The preparation and counting procedures for the foraminiferal analyses were in accordance with methods described by Feyling-Hansen (1958) and Meldgaard and Knudsen (1979). The lithological descriptions are based on visual inspection, X-radiographs, sediment petrography and geochemical measurements of carbon content and total organic carbon.

### 3.2. Seismic data

A regional grid of deep-tow boomer (DTB) profiles (Fig. 1), collected by the British Geological Survey (BGS) and Norsk Hydro in 1993 and 1996–97, respectively, have been interpreted. The BGS data, which were collected along the northern flank of the Storegga Slide (Fig. 1), are of high quality and have a maximum penetration of about 300 milliseconds (ms) two-way traveltime (twt) (Evans et al., 1996). The Norsk Hydro data are collected by a Huntec DTB system operating at a frequency of 8 kHz. These data have a penetration of 100–200 ms (twt) and show variable quality, thus making the stratigraphic control locally uncertain.

Along the surveyed Norsk Hydro DTB profiles, mini-sleeve gun data were also collected. These profiles have been used to establish seismic stratigraphic control beyond the range of the DTB. Furthermore, a 3D survey from the Helland-Hansen Arch has been studied (Fig. 1).

### 4. Seismic stratigraphy and chronology

The Cenozoic succession on the Voring margin has been divided into three formal units (Dalland et al., 1988): the Eocene to Oligocene Brygge Formation (Fm), the Miocene to Early Pliocene Kai Fm, and the Late Pliocene to Recent Naust Formation. Rokoengen et al. (1995) and McNeill et al. (1998) subdivided the Naust Fm into several units, and at present five units, W (oldest), U, S, R and O (Fig. 2), have been identified (Norsk Hydro, 2003). Naust units W, U and S are characterised by westward dipping high-amplitude reflectors that separate sediment packages showing weak layering or a chaotic seismic pattern (Fig. 2). Naust R is dominated by a seismic massive sediment unit, whereas Naust O, which is the focus of this paper, is composed of well-stratified sediments and seismic massive wedge-shaped units (Fig. 2). As will be discussed later, Naust O has been deposited throughout the last ~250 ka.

#### 4.1. Naust O

Seven sequence boundaries, Rf1–Rf7, have been identified within Naust O (Figs. 3–5). To be able to tie the core data with the seismic profiles (Fig. 3), an interval velocity of 1500 m/s is suggested for the sediment sequences above Rf5, whereas an interval velocity of 1600 m/s has been used for the underlying deposits.

The oldest reflector mapped, Rf1, defines the upper boundary of the Naust R unit (Figs. 4 and 5). Rf1 is...
Fig. 3. Correlation of identified Naust O seismic sequences (Se1–Se5) and sequence boundaries (Rf1–Rf7) to geotechnical boring: Hafidason et al. (1998, 2001) and IMAGES cores (Knorr, 2000; Berstad, 2003). The radiocarbon dates have been corrected for the marine reservoir effect by 400 years (Stuiver et al., 1998). Estimated sedimentation rates are based on maximum sequence thicknesses as observed in the seismic data. Core locations in Fig. 1. G: Glacigenic; GM: Glacimarine; M: Marine; MIS: Marine isotope stage; MS: Magnetic susceptibility; WD: Water depth.
been divided into five sub-units, Se1 (oldest) to Se5. Lower and Upper Naust O, where Upper Naust O has been divided into five sub-units, Se5 6. Seismic sequences identified sequence boundaries. cores also confirm the age constraints of the upper three identified in Naust O. Seismic correlation to the other framework has been established (Knorr, 2000) (Fig. 3). and are easily traceable throughout the data set. For amplitude continuous reflectors in the seismic profiles, accuracy of the seismic tie. significantly towards the IMAGES core, reducing the seismic line. The sedimentary sequences also thin that the core is located about 600 m from the closest correlation to MD99-2289 is complicated by the fact maximum age for Rf4. It should be noted that the core is located about 20 m, suggesting a maximum reflector within this core, whereas Rf6 is correlated to a core level dated to about 16.2 14C ka BP (Fig. 3). This age therefore represent a maximum age for Rf4. It should be noted that the correlation to MD99-2289 is complicated by the fact that the core is located about 600 m from the closest seismic line. The sedimentary sequences also thin significantly towards the IMAGES core, reducing the accuracy of the seismic tie.

Reflectors Rf5, Rf6 and Rf7 are observed as high amplitude continuous reflectors in the seismic profiles, and are easily traceable throughout the data set. For IMAGES core MD99-2291, a good geochronological framework has been established (Knorr, 2000) (Fig. 3). Rf5 coincides with a level dated to about 16.2 14C ka BP within this core, whereas Rf6 is correlated to a core depth of about 15 m, suggesting a maximum reflector age of 15.7 14C ka BP. At a level of 2.8 m in MD99-2291 an age of 15.0 14C ka BP has been found. Rf7 is tied to a level just below this age; therefore we suggest 15.0 14C ka BP as a minimum age for the uppermost reflector identified in Naust O. Seismic correlation to the other cores also confirm the age constraints of the upper three identified sequence boundaries.

5. Seismic sequences

Reflector Rf3 divides Naust O into two main units: Lower and Upper Naust O, where Upper Naust O has been divided into five sub-units, Se1 (oldest) to Se5 (Fig. 3). The seismic data reveal that the sub-units either are acoustic transparent or are composed of continuous parallel medium to high amplitude reflectors. On the uppermost slope, Rf2, Rf4, Rf5 and Rf6 coincide with wedge-shaped seismic massive units (T1–T4 in Figs. 3–5).

5.1. Acoustic well-stratified units

Lower Naust O, which is limited by Rf1 and Rf3, is dominated by parallel to sub-parallel reflectors. In a local area over the southern Helland-Hansen Arch non-continuous reflectors and a slightly chaotic seismic pattern characterise the unit (Fig. 4). Borehole 6405/2 (Fig. 3) shows that the upper part of the unit consists of sandy silt with sporadic occurrence of gravel, changing into gravelly, sandy mud near the lower sequence boundary (Haflidason et al., 1998, 2001). The sediment distribution of the Lower Naust O unit envisages a main depocentre in a water depth of 800–1000 m, close to the northern Storegga Slide scar (Fig. 6). Within the depocentre the sediments are reaching a thickness >200 ms (twt). A local depocentre has also evolved within the Sklinnadjuvet Slide scar, where the seismic profiles show that Lower Naust O has a bounded depositional pattern (Figs. 6 and 7).

The five sub-units of Upper Naust O are all, except for Se4, dominated by parallel, medium to high amplitude reflectors (Fig. 4). The geotechnical borings show that units Se1 and Se2 consist of sandy silty mud, which changes into silt in the uppermost part of Se2. IMAGES core MD99-2291 indicates that the well-layered Se3 unit consists of clay with various amounts of sand and silt, whereas the youngest sub-unit identified, Se5, is composed of silty sand on the upper slope.

During deposition of Upper Naust O, the depocentre on the southern Voring margin persisted (Fig. 6), reaching a maximum thickness of 115 m (twt) near the northern scar of the Storegga Slide. During deposition of sub-units Se1, Se2, and Se3 (Fig. 3) the main part of the sediments were deposited in water depths between 500 and 800 m, i.e. along the upper continental slope (Fig. 7). For unit Se5 the isopach map shows a well-defined depocentre, reaching a maximum thickness of about 15 m, within a water depth of about 1000 m (Fig. 7).

We note that the acoustic well-stratified units locally are disturbed by pockmarks, vent-like features, mud diapirs (Fig. 7) and small-offset faults (Evans et al., 1996; Hjelstuen et al., 1997; Bryn et al., 1998; Fulop, 1998; Gravdal, 1999; Bouriak et al., 2000; Gravdal et al., 2003). The fluid expulsion features, in addition to observation of bottom simulating reflectors (BSRs) (Mienert et al., 1998), imply that shallow gas is, or has been, present in the sediments.
Fig. 4. (a) Line drawing of E–W trending DTB profile (NH9651-109). Profile location in Fig. 1. Rf1–Rf7: identified sequence boundaries; T2–T3: massive seismic units. (b) Oblique view of Naust R surface. Based on interpretation of Helland-Hansen 3D survey, and modified from Nygård et al. (2000). Curvi-linear features represent iceberg ploughmarks. (c) DTB example showing seismic facies characteristics of the Naust O unit.
Fig. 5. DTB profile (NH9753-302) (above) and interpretation (below) showing seismic facies characteristics of Naust O sediments, identified sequence boundaries (Rf1–Rf7) and mapped massive seismic units (T1–T4). Profile location in Fig. 1.
5.2. Transparent units

Unit Se4 is limited by reflectors Rf6 and Rf7, and is characterised by an acoustic transparent seismic pattern (Figs. 4 and 5). Weak layering is locally observed. Thus, Se4 differs significantly in its seismic facies appearance from the other Upper Naust O sub-units. This difference is also documented in MD99-2291, where Se4 corresponds to lithological unit L3 that is composed of silty clay and minor amounts of material > 150 μm (Fig. 3). The isopach map reveals that an elongated depocentre, reaching a maximum thickness of about 20 m, developed along the upper continental slope during Se4 deposition (Fig. 8).
5.3. Seismic massive units

Unit T1 represents the oldest massive unit mapped within Naust O. The unit reaches a maximum thickness of 250 ms (twt), and is restricted to the continental slope just west of Skjoldryggen (Fig. 9). It extends down to a water depth of about 1200 m, and is dominated by an acoustically non-structural signature. A few internal continuous reflectors are locally observed, and the unit split up into several smaller-sized acoustic transparent lobes at its westernmost tip. On the uppermost continental slope the T1 surface shows an irregular appearance; elsewhere the surface of the unit is very smooth (Figs. 4 and 5).

Units T2 and T3 show large variations in extent and thickness within the study area (Fig. 9), and are separated from each other by a less than 10 ms (twt) thick well-laminated sequence (Figs. 4 and 5). Whereas T2 is limited to the southernmost study area, the above-lying T3 unit can be identified along the entire continental shelf and upper slope. The limited extent of T2 may be due to the erosive nature of the T3 unit. Both units, which extend down to a water depth of 600–800 m in the southern part of the study area, are commonly characterised by an acoustic homogeneous and non-structural acoustic seismic facies (Fig. 2). Locally, internal medium amplitude reflectors divide the units into lobe-shaped lenses. The uppermost identified seismic massive unit within Naust O, T4, is restricted to the continental shelf, where it reaches a maximum thickness of about 100 ms (twt) (Fig. 9). T4, which has an erosive base and an irregular upper surface, has a similar seismic facies as units T1–T3.

The seismic massive unit within Naust R reaches a maximum thickness of about 350 ms (twt) (Fig. 9). The unit pinches out in water depths between 1200 and 1400 m. In depths <800 m the Naust R surface is characterised by curvi-linear scours (Fig. 4), whereas down-lapping reflectors are observed near the base of the unit (Fig. 2). In water depths >1000 m the Naust R massive unit is composed of well-defined lobes (Fig. 10).

Dahlgren and Vorren (2003) found from analyses of two gravity cores from the northern Vøring margin that their mapped Naust A2 unit, which correlates to T3 in this study, has high density, relative high shear strength (about 30 kPa) and is composed of sand, silt and clay where the sand fraction is dominated by quartz grains. The deposits are furthermore unsorted and contain clasts of striated sedimentary and angular crystalline bedrock fragments. Borehole 6405/2 penetrates the outermost parts of T3 and T2 in our study area; showing that T3 consists of silty sand with gravel and
pebbles, whereas T2 is characterised by silty sediments and laminated sand-rich zones that sporadically contain gravel. Borehole 6405/2 also penetrates the uppermost part of the seismic massive sequence within Naust R (Haflidason et al., 1998, 2001), revealing that it is composed of gravelly sandy silt and/or silty sand with clasts.

6. Margin subsidence

The amount of subsidence and local variations in subsidence rates strongly influence the distribution and geometries of sedimentary units. Differential subsidence may also influence the evolution of structural elements, as has been suggested for the Helland-Hansen Arch on the Voring margin (Fig. 1) (Stuevold et al., 1992). The study area subsided rapidly due to thermal cooling just after margin break-up at ca 55 Ma, and throughout the Eocene time period the Voring margin subsided by about 1000 m (Eldholm et al., 1989). The subsidence was most rapid in the west, diminishing eastwards. Subsidence analyses in wells along the Atlantic margin have further revealed low subsidence rates, commonly <2 cm/kyr, during the Oligocene and Miocene, whereas increased rates, up to ca 10 cm/kyr, are observed during the Pliocene time period (Cloetingh et al., 1990).

The characteristic of the linear criss-crossing features observed at the Naust R surface (Fig. 4), about 800 m below the present day sea level, make us infer that they represent iceberg ploughmarks. Our seismic records show that the present day seabed, in water depths less than ca 500 m, is heavily scoured by icebergs that calved off a waning ice margin during the last deglaciation of the Norwegian continental shelf. This observation is also supported by side-scan sonar data from the northern flank of the Storegga Slide (Gravdal, 1999), the North Sea Fan region (Nygård et al., 2002) and the eastern part of the Faroe-Shetland Channel (Masson, 2001). Furthermore, and as will be discussed later, the upper part of Naust R has a minimum age of MIS 8. Thus, if we assume that icebergs only reached a
maximum water depth of about 500 m during previous glaciations, the Voring margin has subsided by ~300 m since MIS 8; giving a maximum margin subsidence rate of ~1.2 m/kyr during the last ca 250 ka.

Based on identification of paleo-ice sheet grounding lines, Dahlgren et al. (2002) found similar Quaternary subsidence rates for the northern Voring margin. High Quaternary subsidence rates have also been reported elsewhere along the Norwegian continental margin. King et al. (1996) estimated a minimum subsidence rate of 0.8 m/kyr for the northern North Sea margin, whereas along the Svalbard margin subsidence rates of up to 0.48 m/kyr have been found (Solheim et al., 1996). Cloetingh et al. (1990) related the increased rates to major changes in the spreading direction and spreading rate along the Mid-Atlantic spreading ridge.
Nonetheless, the high sediment input to the mid-Norwegian margin during the Pleistocene time period must also have influenced on the observed rates. It has been inferred from modelling that sediment loading can amplify the subsidence by an order of 2–4 (Gvirtzman, 2001). Most likely the high rates are a result of a complex interaction between sediment loading, eustacy and tectonic events, as also have been suggested by Jordt et al. (2000).

7. Margin evolution

The detailed chronology and seismic facies characteristics of the south Vøring margin sedimentary succession (Fig. 3) make it possible to identify, and to study, sedimentary processes that have been acting on a continental margin through a glacial–interglacial cycle.

7.1. Glacial environments

7.1.1. Glacigenic sediments

Seismic correlations show that our identified massive units coincide with sequences on the continental shelf, which King et al. (1987, 1991) ascribed to be of a glacigenic origin. The seismic ties envisage that the “Upper Till” unit identified by King et al. (1987) correlates to our unit T4, whereas the “Middle Till” unit (King et al., 1987) corresponds to T3, and possibly T2, on the slope. We also note that the massive units show a similar seismic facies as sediments which on the Canadian and West Shetland continental margins have been interpreted to represent glacigenic material (Stoker, 1997; Stravers and Powell, 1997; Josenhans and Lehman, 1999; Hewitt and Mosher, 2001), even though seismic facies cannot be used conclusively to identify, or distinguish between, different lithologies and genesis. The uppermost identified shelf sequence of King et al. (1987, 1991) is cored SE of Skjoldryggen (Settem et al., 1996), showing that the anticipated glacigenic unit consists of silty, sandy clay with some gravel. High shear strength and overconsolidation characterise these deposits (Rokoengen and Frengstad, 1999). Shallow coring from the Haltenbanken area (Fig. 1) also reveal the glacigenic nature of the mid-Norwegian shelf sediments (Haflidason et al., 1991), even though a direct correlation to the continental shelf units of King et al. (1987, 1991) has not been established.

Our chronostratigraphy (Fig. 3) show that T1–T4 have been deposited in time periods when ice caps covered the Norwegian mainland and the adjacent continental shelf (Fig. 3). Unit T1 coincides with reflector Rf2 (Fig. 5), showing that the lowermost mapped massive Naust O unit is related to MIS 6. Units T2–T4 coincide with sequence boundaries Rf4, Rf5 and Rf6; thus suggesting that these units were deposited at about 21, 16.2 and 15.7 \( ^{14} \text{C} \) ka BP, i.e. during LGM (MIS 2).

Studies of a large number of cores from the northern North Sea have shown that LGM is divided into two phases (Sejrup et al., 1994, 2000): A first phase between ca 29–22 \( ^{14} \text{C} \) ka BP and a final phase between about 18.5 and 16 \( ^{14} \text{C} \) ka BP, with open marine conditions in the northern North Sea between ca 22 and 18.5 \( ^{14} \text{C} \) ka BP. Valen et al. (1996) confirmed this observation, finding that the Scandinavian ice sheet had retreated to the Norwegian coast by ca 20 \( ^{14} \text{C} \) ka BP. Sejrup et al. (1994) concluded that the Scandinavian ice sheet coalesced with the British ice sheet as early as ca 29 \( ^{14} \text{C} \) ka BP. Boulton et al. (2002) have however questioned ice sheet confluence as early as this, as radiocarbon dates suggest ice free regions on the Scotland mainland until ca 26 \( ^{14} \text{C} \) ka BP.

From the Andoya region, northern Norway, it has also been reported that the Fennoscandian ice sheet advanced twice during LGM; i.e. between about 23 and 22 \( ^{14} \text{C} \) ka BP and from 18 to 14.5 \( ^{14} \text{C} \) ka BP (Vorren and Plassen, 2002). We further note that Dahlgren and Vorren (2003) from IRD maxima, deposition of stratified diamicton and glacigenic debris flows suggested five ice sheet fluctuations during LGM on the northern Vøring margin. The chronology and stratigraphical positions of units T2–T4, divided as they are by a thin layer of well-stratified sediments, thus suggest at least three LGM ice sheet fluctuations within the study area.

The chronology of the Naust O massive units and their relationship to glacial periods indicate that the massive Naust R unit must be older than MIS 6. On the other hand, amino acid stratigraphy (Haflidason et al., 1998, 2001) suggests that the uppermost part of this unit is younger than MIS 9. Hence, we suggest MIS 8 as a minimum age for Naust R.

7.1.2. Deposition mode

Different depositional models have been proposed for transportation and distribution of glacigenic material on continental margins. Fifteen years ago King et al. (1987) established the till-tongue model, which described the wedge-shaped massive slope units (Fig. 5) on the Voring margin as purely deposits from grounded ice sheets. Since then, this model has been modified (King, 1993) and distribution of glacigenic material on continental slopes is today commonly considered to be related to different mass movements (e.g. Stoker, 1997; Stravers and Powell, 1997). The glacigenic unit within Naust R has the best data coverage, including both 2D and 3D seismic, and is thereby suitable for a detailed study of processes acting during deposition. It is however reasonable to assume that units T1–T4 have been deposited in a similar way.
The geometry of Naust R, with its flat surface bounded westward by a sharp edge in a present day water depth of 700–800 m, suggests that a paleo-continental shelf and a paleo-shelf edge have existed further to the west at MIS 8 time then at present continental shelf and a paleo-shelf edge have existed. The observed ploughmarks at the Naust R surface (Fig. 4), in addition to the sediment characteristics of the unit, imply that an ice sheet could have extended all the way out to the observed paleo-shelf edge. If so, the glacigenic material of Naust R has been transported, and deposited, by a grounded ice sheet. The internal down-lapping reflectors within this unit (Fig. 2) might thus in fact represent a westward prograding till delta (Alley et al., 1989), developed beneath a westward growing ice sheet. The 3D data show that the down-lapping reflectors bound lobe-like structures, having an internal facies compatible with mass movements during deposition (Fig. 10d). Observation of internal flat-lying surfaces within Naust R might represent erosional surfaces caused by previous shelf edge glaciations.

In water depths > 800 m the Naust R massive unit is thinning (Figs. 2, 9 and 10a), and seismic cross sections (Fig. 10b) show that it display a similar seismic pattern as glacigenic debris flows (GDFs) which build the huge trough mouth fans on the Norwegian-Barents Sea margin (Laberg and Vorren, 1995; Sejrup et al., 1996; Elverhøi et al., 1997; King et al., 1998; Nygård et al., 2002). Thus, to summarize, we suggest that during MIS 8 time, and also during deposition of units T1–T4, tills were transported beneath a grounded ice sheet to the shelf edge where the glacigenic material was redistributed downslope by gravity flows (Fig. 11a). This model is also supported by results from the North Sea Fan to the south (Nygård et al., 2004) and studies from the northern part of the Voring margin (Dahlgren et al., 2002).

The T3 unit shows that the gravity flows on the continental slope have eroded into the underlying stratified sediments during deposition. However, in water depths > 600 m T3 lose its erosional effect, and the glacigenic material has been deposited conformable above the underlying stratified sediments. Compared to the GDFs observed on the North Sea Fan, which have been found as far out as 500 km from the shelf edge (Nygård et al., 2004), the gravity flow lobes on the Voring margin have a much shorter run-out distance. This may be due to differences in the physical properties of the source material, amount of sediment delivered to the shelf edge and differences in flow mechanisms (Marr et al., 2002).

### 7.1.3. Source areas and sediment pathways

The isopach maps of the Naust O glacigenic units reach their maximum thickness at the mouth of shallow troughs that intersect the continental shelf (Fig. 9). It has been inferred that these troughs acted as ice stream pathways during maximum glaciations (Ottesen et al., 2001). Thus, it is reasonable to anticipate that the main part of the sediments have been transported by the canalised ice streams to the shelf edge, where the material was deposited in depocentres at the ice stream front.

### 7.2. Glacimarine environments

#### 7.2.1. Sedimentation rates

Throughout the last ca 250 ka the maximum average sedimentation rates on the south Voring margin have been about 1.0 m/kyr. However, as is well documented for the Upper Naust O unit (Fig. 3) the rates have varied significantly from this value through time. Between MIS 8 and MIS 5e, during deposition of Lower Naust O, the maximum average sedimentation rates did not exceed 1.4 m/kyr. Low rates, <0.5 m/kyr, persisted on the margin throughout MIS 5, 4 and 3, before increasing at about 21$^{14}$C ka BP; most likely as a consequence of the LGM ice advance. Dahlgren and Vorren (2003) have reported a similar change in the accumulation rates at the northern Voring margin. Within the study area the sedimentation rates reached a maximum (36 m/kyr) between 16.2 and 15.7 $^{14}$C ka BP, when the well-laminated Se3 unit was deposited (Fig. 3). High sedimentation rates, up to 27 m/kyr, persisted between 15.7 and 15.0 $^{14}$C ka BP, during the initial phase of the final deglaciation of the Norwegian continental shelf. A significant drop in the sedimentation rates took thereafter place at ca 15 $^{14}$C ka BP (Fig. 3), and core MD99-2291 reveals that the Holocene accumulation rates were as low as 0.1 m/kyr on the upper continental slope. Similar drops, when going from glacial to fully interglacial conditions, have also been reported from the western Svalbard margin (e.g. Andersen et al., 1996) and from the Laurentide shelf (Andrews, 2000). We note however that high Holocene rates are observed in the Storegga Slide scar (Fig. 1), where an up to 25–30 m thick sediment package has been deposited since ca 7.2 $^{14}$C ka BP (Sejrup et al., 2004).

#### 7.2.2. Depositional pattern and source areas

The isopach maps of the Lower and Upper Naust O units show that the Pleistocene hemipelagic sediments have been deposited in major depocentres on the upper continental slope, in front of the shallow Suladjupet Trough (Figs. 6–8). As the Holocene Storegga Slide event (Fig. 1) has removed large quantities of sediments from the More margin, it is not possible to infer if the identified depocentres have extended further to the south or not.

When discussing possible source areas and depositional environments for the hemipelagic Naust O sequence, the following two points must be taken into consideration: (1) The sediments have been transported,
Fig. 11. Schematic models of the south Vøring margin during: (a) glacial maximum, (b) late glacial/early deglaciation and (c) interglacial. Present day seabed sediment distribution and ocean currents are shown.
deposited and/or reworked under the influence of along-slope currents, and (2) The sediment distribution reflect a local point source on the Voring margin. Current influenced sediments are commonly observed in the seismic sections as various types of mounded features (Faugères et al., 1999), and Laberg et al. (1999, 2001) have identified several typical current-related deposits on the Norwegian continental margin. On the Voring margin the isopach map of the Lower Naust O unit shows a well-defined depocentre within the Sklinnadjuvet Slide scar (Fig. 6). The depocentre is identified as a mounded structure within the seismic sections (Fig. 7). Similar features are also locally observed along the westernmost edge of the glacigenic T1 unit, thus showing that bottom currents have influenced the sediment distribution within the study area in pre-MIS 5e time. Observation of truncated reflectors within water depths of about 750–900 m, along the eastern edge of the Se5 depocentre (Fig. 7), also indicate that along-slope currents have affected the sediment distribution the last 15 ka.

Even though the seismic records show that oceanic currents affected the Late Quaternary depositional pattern, we infer that the currents mainly have had a local effect, and influenced the sediment pattern only in places along the margin were it is likely that strong currents could be initiated, as for instance within slide scars. As shown, the accumulation of sediments increased in periods when the Fennoscandian ice sheet extended onto the continental shelf (Fig. 3). Thus, a major part of the sediments in the well-stratified Naust O sub-units must have been delivered by icebergs and suspension fall-out in front of a grounded ice margin (Fig. 11). It is also likely that the margin configuration (Fig. 2) prior to the deposition of Naust O has affected the sedimentary distribution pattern the last ca 250 ka.

7.2.3. Meltwater plumes

In the region from the North Sea Fan to the central part of the Voring Plateau well-dated sediment cores show that the sedimentation rates on the Norwegian margin have varied considerably throughout the last 30 ka (Fig. 8). Both on the North Sea Fan and on the Voring margin the accumulation rates increased at about 25 14C ka BP. On the southwestern part of the North Sea Fan the rates declined at about 20 14C ka BP, whereas high rates persisted on the Voring margin until ca 15.0 14C ka BP. In the time period preceding 15.7 14C BP well-laminated sediments were deposited on the margin. However, as is revealed both from seismic facies pattern and lithology a major change in the depositional environment occurred at 15.7 14C BP (Figs. 3 and 4). This change in depositional environment occurred at about the same time as the start of the deglaciation of the Norwegian Channel (Fig. 8), which had been occupied by an ice stream during LGM (e.g. Sejrup et al., 2000). We infer that large amounts of meltwater were released from this waning ice stream, and that along-slope currents transported the sediment-laden meltwater, as a plume, towards the Voring margin. Gradually, the fine-grained sediments settled out in the upper to 20 m thick Se4 unit on the Voring Plateau (Figs. 8 and 11b).

8. Conclusions

The Late Quaternary evolution of the south Voring margin has been studied by the use of high-resolution seismic data and sediment cores. The sedimentary succession (Naust O) has been divided into six hemipelagic units, separated by the medium to high amplitude reflectors Rf1 (oldest) to Rf7. The seismic profiles reveal that the units either are acoustic transparent or are composed of parallel reflectors. On the upper continental slope four massive seismic units, T1–T4, interfinger the hemipelagic sediments.

The seismic massive units continue onto the continental shelf and are composed of glacigenic material. During maximum glaciations, when the ice sheets reached the shelf edge and ice streams occupied the shallow troughs on the continental shelf, the glacigenic material was transported to the shelf break by grounded ice sheets where gravity flows distributed the glacigenic sediments down slope (Fig. 11a). The isopach maps show that the depocentres of these sediments are at the mouth of shallow troughs (Fig. 9).

Throughout the entire Late Quaternary time period the south Voring margin has been a major depocentre for hemipelagic sediments (Figs. 6–8). The sediment succession reaches a maximum thickness of about 350 ms (twt), i.e. about 280 m (assuming a velocity of 1600 m/s), within the study area. Locally, these sediments have been influenced by current activity, as is exemplified by the mounded deposits within the Sklinnadjuvet Slide scar (Fig. 7).

The sedimentation rates on the margin have varied considerably through time. Low average rates existed on the south Voring margin in pre-LGM times. During LGM the sedimentation rates increased dramatically, reaching a peak of 36 m/kyr between 16.2 and 15.7 14C ka BP. High rates persisted on the margin between 15.7 and 15.0 ka 14C BP, when Naust O sub-unit Se4 was deposited. We relate the deposition of this unit to the last deglaciation of the Norwegian continental shelf, assuming that Se4 has been fed by sediments from a meltwater plume released from the disintegrating Norwegian Channel Ice Stream and transported to the south Voring margin by along-slope currents (Fig. 11b). Throughout the Holocene the sedimentation rates on the margin have been low, and erosion by oceanic currents occurred on the upper slope (Fig. 11c).
The high sedimentation rates which periodically have been observed on the Voring margin during the Pleistocene time period have presumably affected the margin subsidence. Observation of iceberg ploughmarks about 800 m below the present day sea level suggest that the margin has subsided by about 300 m through the Late Quaternary, indicating maximum subsidence rates of 1.2 m/kyr since MIS 8.

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