

Geological evolution of the Norwegian continental shelf between 61°N and 68°N during the last 3 million years

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The Late Pliocene-Pleistocene Naust Formation and equivalent sediments have been mapped on the Norwegian continental shelf between Sognefjorden and Lofoten (61°N to 68°N). During the last 2.8 million years the shelf has prograded up to 150 km westwards. More than 1000 m of sediments have been deposited in large areas around the outer shelf/upper continental slope. Most of the Naust Formation on the mid-outer shelf comprises prograding wedges, commonly thinning westwards and downlapping onto the top of the underlying Kai Formation. 3D seismic data from the shelf show iceberg ploughmarks on palaeo-surfaces buried below 400 m of sediment at the present-day shelf edge. Tentatively, the oldest observed ice-grooved surface is c. 2 million years old. In several hydrocarbon exploration wells, abundant angular gravel fragments, interpreted as ice-rafted debris (IRD), have been found in the lower parts of the Naust Formation. In addition to these observations, the very high depositional rates compared to the previous Tertiary period, support our view that most of the Naust Formation was deposited under glacial influence.

The Naust Formation is subdivided into five sequences. From oldest to youngest these are named N, A, U, S and T. Naust S represents the third last glaciation, whereas Naust T is from the last and second last glaciation. An upper regional angular unconformity (URU), best developed on the inner-mid part of the shelf, marks the boundary upwards to more flat-lying sedimentary units. These units mainly comprise tills, deposited during the last extensive glaciations on the shelf. The upper regional unconformity is over large areas off mid-Norway at the base of sequence Naust T and represents an erosional surface made by the Elsterian Ice Sheet.

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Introduction

The mid-Norwegian shelf has been an area of extensive oil and gas exploration during the last 25 years (Fig. 1). 2D and 3D seismic data, detailed bathymetry, geotechnical borings and exploration wells have generated much data on the shallow geology. During the last 15 years, exploration has also focused on prospects in deeper water (>500 m) on the continental slope and in the deep sea. The joint industrial Seabed Project was initiated in 1995 as one of several projects in the Norwegian Deepwater Programme (NDP), with the aim of acquiring knowledge of importance for deep-water licences. Several projects focusing on the shallow stratigraphy have been carried out, the main areas of interest being from the shelf edge and into deeper water. Stability assessment studies for the outer shelf/upper continental slope areas have constituted an important part of the work (McNeill et al. 1998, Bryn et al. 2005, Solheim et al. 2005).

The Storegga megaslide (Bugge 1983, Bugge et al. 1988) occurred c. 8000 years ago and affected a very large slope area with a runout several hundred kilometres into the deep sea. Some 3000 km³ of slide debris were mobilised, generating a tsunami that hit most of the Norwegian coast, Shetland, the Faeroes and Scotland (Bondevik

et al. 1997). The giant Ormen Lange gas field is located below the Storegga Slide Scar at c. 1000 m water depth (Fig. 1), and extensive scientific studies were carried out in order to investigate if a safe development of the gas field was possible (Solheim et al. 2005). One of these studies was mapping of the Late Pliocene-Pleistocene stratigraphy of the shelf and slope between the outlet of the Norwegian Channel (62°N) and Lofoten (68°N) (Rise et al. 2002, 2005). Later, this study was extended in the joint industrial Seabed Project (with Fugro, the British Geological Survey, the Geological Survey of Norway and 10 oil companies) increasing the seismic data base from the Ormen Lange Project (c. 25,000 km) to about 100,000 km (NDP 2004). The area was also enlarged southwards to include shelf areas north of Sognefjorden (61°N) (Fig. 1).

This paper summarises the development of the Norwegian continental shelf between 61°N and 68°N during the last 3 million years on the basis of the results from the last phase of the Seabed Project (Bugge et al. 2004, NDP 2004). The extended seismic data base has notably improved our understanding of the development of the margin, especially in the southern parts of the study area, compared to Rise et al. (2005). We now use a revised Naust stratigraphic nomenclature where the Naust Formation has been subdivided into five

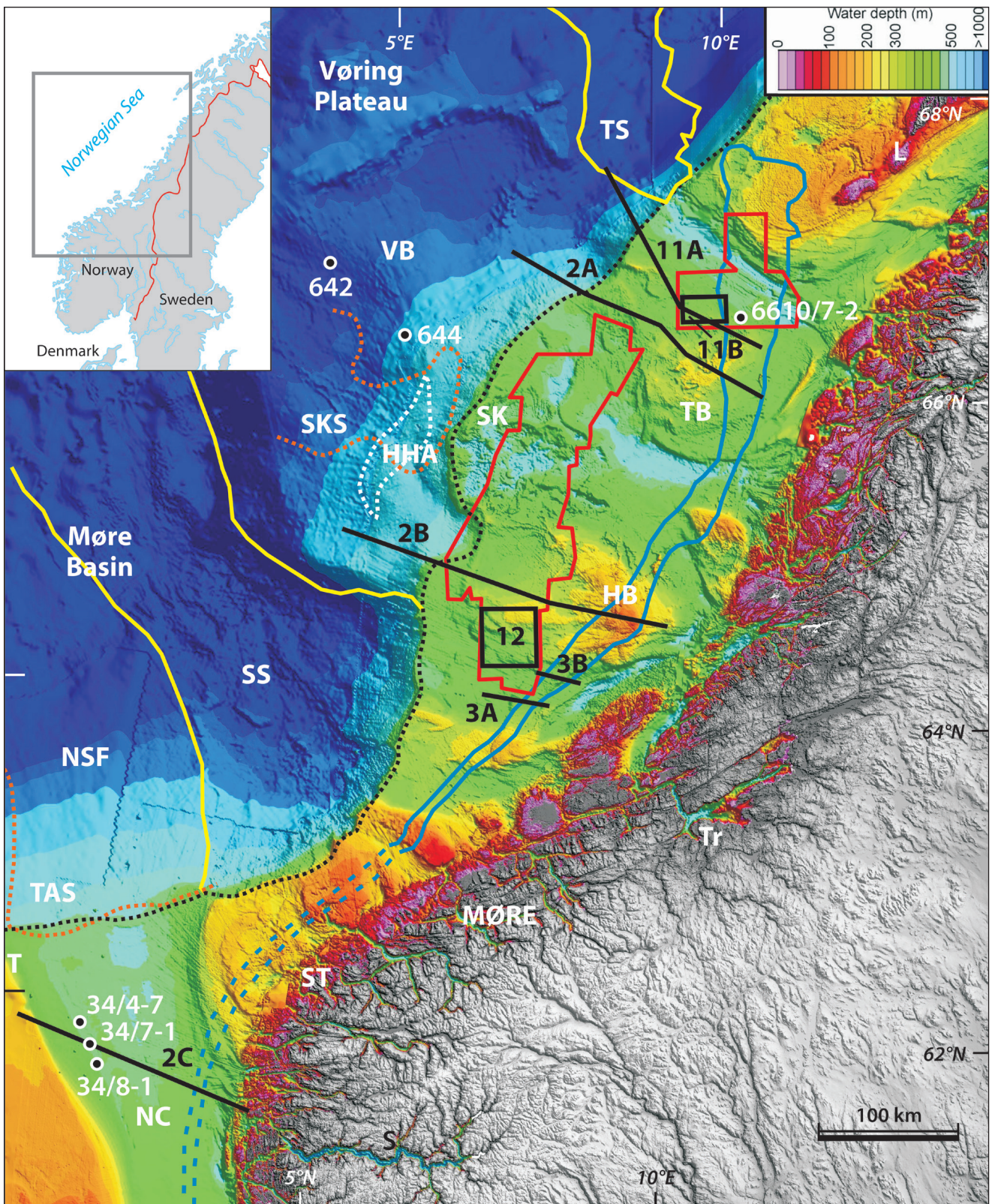


Fig. 1. Bathymetric map of the study area between Sognefjorden (S) and Lofoten (L). Red polygons – 3D-seismic survey areas. Blue outline – subcrop of Molo Formation. Blue stippled lines – subcrop of sediments equivalent to the Molo Formation. Thick black lines – seismic profiles (Figs. 2 and 3). Dotted black line – present shelf edge. NC - Norwegian Channel, NSF - North Sea Fan, ST - Stad, SKS - Sklinnadjupet Slide, SS - Storegga Slide, HHA - Helland-Hansen Arch (dotted white line marks the shallowest part of the dome), SK - Skjoldryggen, HB - Haltenbanken, TB - Trænabanken, VB - Vøring Basin, TS - Trænadjupet Slide, Tr - Trondheim, T - Tampen, TAS - The buried Tampen Slide.

sequences, named from oldest to youngest N, A, U, S and T (Bugge et al. 2004, NDP 2004, Rise et al. 2006). The sedimentary regime under which the huge volumes of sediments in the Naust Formation were deposited, and especially its lower parts, have been debated for a long time (Rokoengen et al. 1988, Henriksen & Vorren 1996, Rise et al. 2005). On the basis of 3D-seismic cubes we have studied geomorphic features on buried seismic surfaces, providing information about the processes involved in deposition and erosion of the Naust Formation. Only a few high-quality cores from the older

parts of the Naust Formation exist. These have been investigated in this study, mainly to look for indications of glacial influence during deposition.

Dalland et al. (1988) established the Naust Formation on the mid-Norwegian continental shelf as a Late Pliocene-Pleistocene section. The corresponding sediments in the North Sea Basin (outside western Norway, in the southern part of the study area) belong to the Nordland Group (Isaksen & Tonstad 1989), but have not been named as a specific formation. To include the sediments

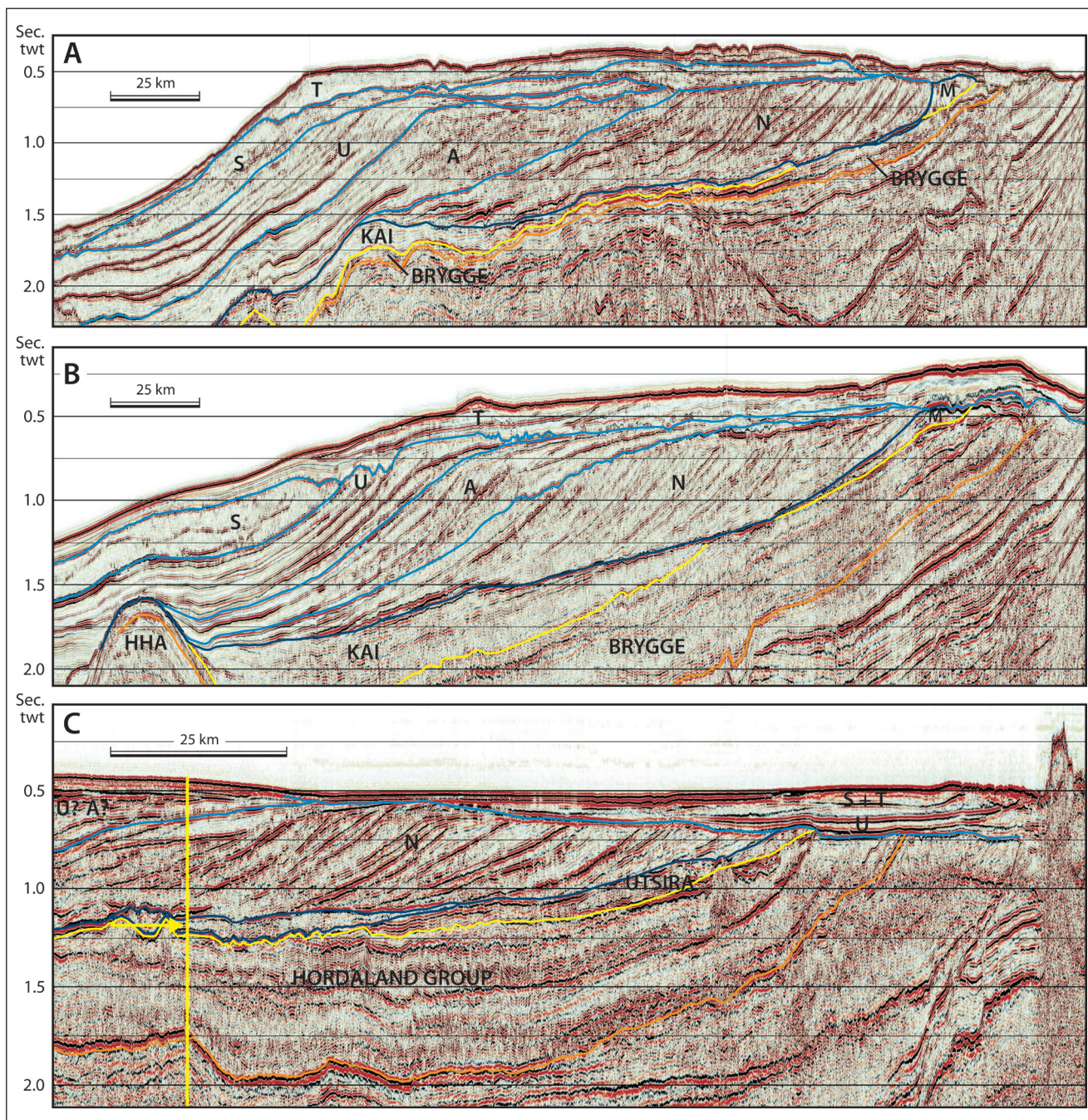


Fig. 2. Seismic profiles GMNR-94-106 (A), GMNR-94-310 (B) and NVGTI-92-105 (C). See Fig. 1 for locations. Yellow line in Fig. 2C marks the location of well 34/7-1 and the depth where the side-wall cores shown in Fig. 9 are taken (yellow arrow). N, A, U, S and T mark the different Naust sequences. HHA – Helland-Hansen Arch. M – Molo Formation.

for the whole study area, we refer to them as ‘the Naust Formation and Naust equivalents’.

Geological background

The present-day morphology of the mid-Norwegian continental shelf is mainly the product of rapid outbuilding (progradation) of the shelf during the last 3 million years (Rise et al. 2005). The continental shelf is less than 100 km wide off Møre in the south (62°N to 63°N), widens up to 250 km at 66°N, before narrowing to the north again. Off the Lofoten islands, the shelf is only 60–80 km wide. The mid-Norwegian continental shelf is characterised by shallow banks separated by cross-shelf troughs (Fig. 1). The banks have water depths between 50 m and 300 m, whereas the troughs have water depths between 150 m and 550 m. These troughs have been the former pathways for fast-flowing ice streams during several glaciations (Ottesen et al. 2005, Rise et al. 2005, Dowdeswell et al. 2006). The largest pathway for an ice stream is the Norwegian Channel, which is an 800 km long ice-generated trough parallel to the coastline off southern Norway, starting in the Skagerrak between Denmark and Norway and ending outside western Norway at 62°N. The trough is about 100 km wide west

of Norway, and is a major geomorphological feature of the North Sea (Longva & Thorsnes 1997, Sejrup et al. 2003, Ottesen et al. 2005). The Norwegian Channel has been excavated by ice streams during several glaciations. Based on dating of sediments near the base of the channel, Sejrup et al. (1995) suggested the age of the Norwegian Channel to be at least 1.1 million years. The Norwegian Channel ice streams transported glacial debris to the mouth of the trough, and up to 1500 m of sediments occur in the trough mouth fan (the North Sea Fan). The sediments mainly comprise glacial debris-flow successions interbedded with units of slide deposits (King et al. 1996, Nygård et al. 2005).

The bedrock of the Norwegian shelf comprises sedimentary units ranging in age from Triassic to Pliocene (Rokoengen et al. 1988, Sigmond 1992, 2002). The boundary between sedimentary and crystalline rocks is located 10–40 km west of the outer islands along the coast (Fig. 1). Due to basinward subsidence and extensive erosion of the inner part of the shelf, together with land uplift of the inner shelf and adjacent land areas, the units subcrop more or less parallel to the coast and decrease in age westwards (Bugge et al. 1984, Rokoengen et al. 1988). The coast-parallel, deltaic, Molo Formation was deposited from the coast off Møre (63°15'N) to the Lofoten Islands

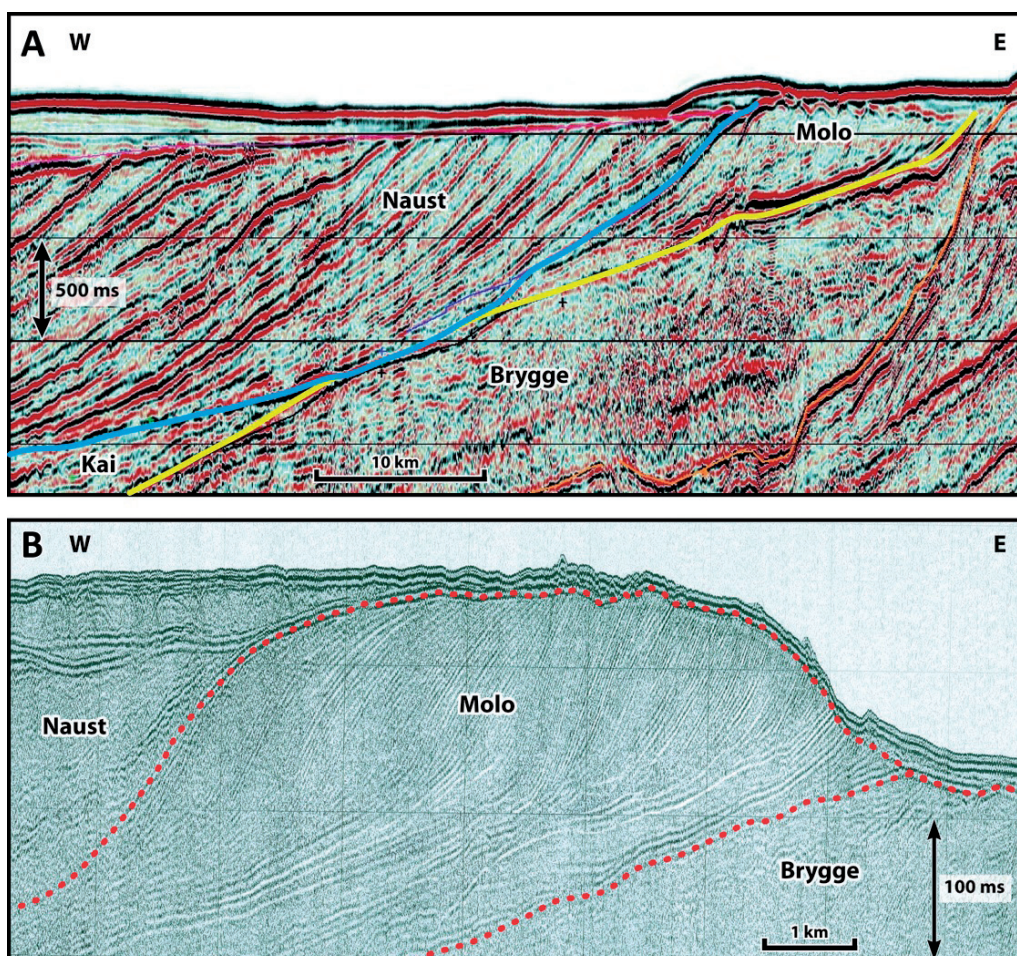


Fig. 3. (A) Seismic profile MB84-04 showing the transition between the Molo and Naust formations. See Fig. 1 for location. (B) High-resolution seismic line across the Molo Formation, located in Fig. 1.

(67°50'N), over a distance of c. 500 km (Henriksen et al. 2005) (Fig. 1). This formation has recently been re-dated as Late Miocene to Early Pliocene, and is interpreted as the shallow-water equivalent to the Kai Formation (Eidvin et al. 2007). The Molo Formation is dominantly sandy and was deposited by coastal progradation as a result of regional onshore uplift (Rokoengen et al. 1995, Henriksen & Weimer 1996, Eidvin et al. 2007). The Molo Formation has a characteristic seismic reflection pattern with densely spaced clinoforms which dip westwards at up to 10° (Fig. 3B). The bathymetry reveals varying resistance to erosion of the Mesozoic and Tertiary bedrock units. Sandy units, for example, commonly show a positive relief, in contrast to areas with fine-grained sediments which are generally located in depressions. The Naust Formation is underlain by the Brygge (55-16 My) and Kai (16-4 My) Formations (Dalland et al. 1988, NDP 2004). These formations are moderately deep to deep-marine deposits, and in the Møre and Vøring basins they are composed mainly of claystones or oozes deposited by hemipelagic or contouritic processes.

The Møre and Vøring basins have been major sedimentary depocentres (Blystad et al. 1995), and in some areas the pre-existing topography has been important for the present overall shape of the margin. For instance, the deep Møre Basin (63°N to 64°N) outside Møre (Fig. 1) has prevented a substantial shelf progradation, and in this area the shelf is very narrow. East of the relatively shallow Vøring Plateau (water depths between 1200 m to 1400 m), an extensive progradation has occurred into a basin of intermediate depths (Fig. 2B).

A series of compressional domes or arches of mainly Mid Cenozoic age has been important for determining the depositional pattern of the margin (Japsen & Chalmers 2000, Lundin & Dore 2002).

In the inner part of the shelf, the Mesozoic and Cenozoic sediments have been cut by erosion. The regional seismic lines show that the middle and outer parts of the mid-Norwegian continental shelf have subsided, whereas the inner shelf and the Norwegian mainland have been uplifted (Fig. 2). This means that much of the eroded sediment is preserved on the middle/outer shelf, and little on the inner shelf. Riis (1996) estimated a 'late' uplift to be c. 1000 m in southern Norway and about the same in northern Norway, the uplift centre being in the Lofoten area and farther north. The timing of the Neogene uplift phase is uncertain, and the Norwegian mountain range may already have been uplifted substantially before the first ice sheets covering Scandinavia reached the coastal areas about 2.8 million years ago (Jansen & Sjøholm 1991).

The depositional pattern of the last three glaciations has been mapped on the outer shelf by Rise et al. (2005). This has revealed the very dynamic nature of the ice sheets with changing depocentres from glaciation to glaciation. Shifts in the position of fast-flowing ice streams appear to

be the most important factor for changes in the location of sediment delivery to the shelf edge and upper slope (Dowdeswell et al. 2006).

The last major shaping of the shelf topography occurred during the Late Weichselian glaciation, and several types of morainic ridges and glacial lineations demonstrate the dynamic nature of the Scandinavian palaeo-ice sheet (Ottesen et al. 2005). Apart from places where major slides occurred, the topography has remained nearly unchanged since the ice sheet retreated to the coastal areas c. 13,000 years ago. After deglaciation, the Norwegian fjord systems acted as major sedimentary traps (Aarseth 1997). Only up to a few tens of metres of sediment associated with deglaciation, and Holocene sediments have been deposited in the deepest troughs on the shelf. At intermediate and shallow water depths non-deposition and winnowing of sediments by bottom currents have prevailed since the ice sheet retreated.

Seismic data and interpretation

The reflection seismic database consists of conventional 2D, high-resolution 2D, and exploration 3D seismic. The exploration 2D seismic lines have a relative low vertical resolution, but are well suited for studying the regional development of the Naust Formation. A few multi-channel, high-resolution 2D seismic lines of very good quality exist on the outer shelf and slope. The high-resolution analogue sparker data commonly recorded to 0.5 second two-way travel time (tw) cover the entire study area with a regular N-S, E-W grid with a line spacing of 10 x 25 km (Rise 1988). Interpretation was carried out on a work station for both 2D and 3D seismic surveys, applying the Seisvision software. The interpreted horizons (xyz-data) were exported, gridded and visualised in Geosoft. The volume of the different Naust sequences was computed as the difference between each of the surfaces. For time-depth conversion of the surfaces, a sound velocity of 2000 m/s was used.

The 3D-seismic data, which cover large parts of the outer shelf (Fig. 1), have a line spacing of 12.5 m or 25 m and a vertical resolution making it possible to detect small morphological features such as iceberg ploughmarks and glacial lineations a few metres deep. The largest 3D cube compiled by Statoil consists of several merged 3D surveys covering large parts of the outer shelf (Fig. 1). In addition, three 3D seismic surveys (ST9404, ST9604 and NLGS-95) have been utilised from northern Trænabanken and Trænadjupet covering an area of c. 3200 km² (Fig. 1).

The Naust Formation

The Naust Formation comprises the Late Pliocene-Pleistocene sediments on the Norwegian shelf, forming

a thick succession of prograding wedges and flat-lying sheet-like units, mainly of glacial origin (King et al. 1987, 1991, Rokoengen et al. 1995, Henriksen & Vorren, 1996, Eidvin et al. 1998, Dahlgren et al. 2005, Rise et al. 2005). At the beginning of this period, a huge increase in the supply of sediment occurred on the mid-Norwegian continental shelf. This was probably caused by the onset of glaciations in Scandinavia which, together with land uplift, led to major erosion. The Naust Formation is bounded by the coast-parallel deltaic Molo Formation in the east (Figs. 2 and 3). Base Naust is commonly recognised as a pronounced down-lap surface marking the boundary with the underlying Kai Formation.

Parts of the Naust Formation have been mapped in several subareas of the mid-Norwegian continental shelf

(Rokoengen et al. 1995, Henriksen & Vorren, 1996, King et al. 1996, Dahlgren et al. 2002, 2005, Hjelstuen et al. 2004) using a different stratigraphic nomenclature north and south of the Storegga Slide. Due to a complex and variable geology over the whole study area, a unified stratigraphy has been difficult to compile. An attempt to tie data across the slide area was made by McNeill et al. (1998). The shelf is narrow east of the central part of the Storegga Slide Scar, and some of the stratigraphy is missing in the area due to several huge slides within the Naust Formation which coalesce into the main slide scar (NDP 2004). Based on stratigraphic mapping in the Ormen Lange Project (Rise et al. 2002, 2005, Berg et al. 2005), a unified stratigraphy and nomenclature between 62°N and 67°N was proposed (Fig. 4).

Jansen & Sjøholm (1991) and Fronval & Jansen (1996) reported the onset of major glaciations in northern Europe at around 2.8 million years ago on the basis of the IRD (Ice-Rafted Debris) record from ODP boreholes 642, 643 and 644 located on the Vøring margin west of a major depocentre of the Naust Formation (Fig. 1). Eidvin et al. (2000) correlated the start of the deposition of the Naust Formation with this large increase in the supply of ice-rafted material.

The age of the different Naust Sequences is poorly constrained. This is due to the fact that very little cored material has been sampled from the petroleum wells (mainly cuttings), few index fossils occur and fossil faunas are sometimes extensively reworked. The proposed ages for the sequences must therefore be regarded as provisional, especially for the three oldest; N, A and U.

Shelf construction through Naust time

The development of the mid-Norwegian continental shelf through the three oldest Naust sequences (N, A and U) is shown in Figs. 2 and 5. These three sequences represent the period from c. 2.8 million years to the onset of the third last glaciation 300,000 to 400,000 years ago. During this period, a thick sequence of prograding wedges was deposited outside mid-Norway resulting in a seaward shelf break migration of up to 150 km. The most extensive progradation occurred in the area east of Skjoldryggen (c. 66°N) (Figs. 5 and 6).

Sequences Naust N and A comprise wedge-shaped units, deposited in a progradational pattern from southeast towards northwest (Figs. 2, 5, 6A, 6B). Progradation is especially clear east of the Vøring Plateau, between 64°N and 67°N. The low-angle clinofolds of the Naust Formation can normally be separated from the steeper foreset beds of the Molo Formation (Fig. 3). On the middle and inner shelf, the upper parts of the clinofolds are often cut by glacial erosion probably related to uplift of the inner shelf (Fig. 2). South of 64°N, the Møre shelf

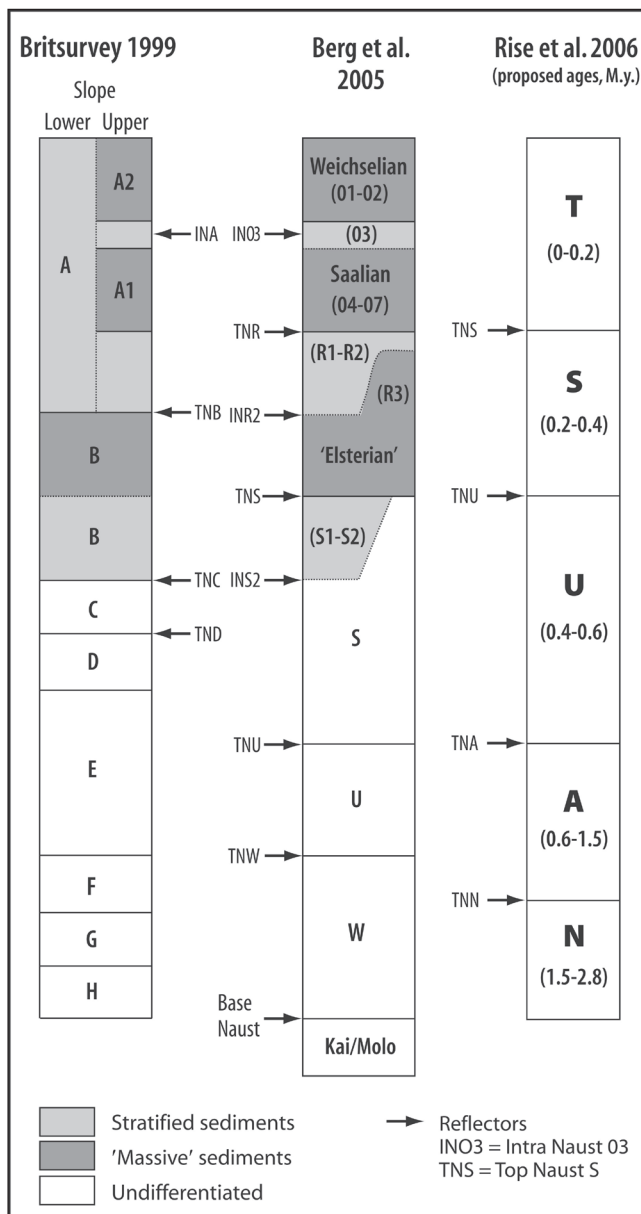
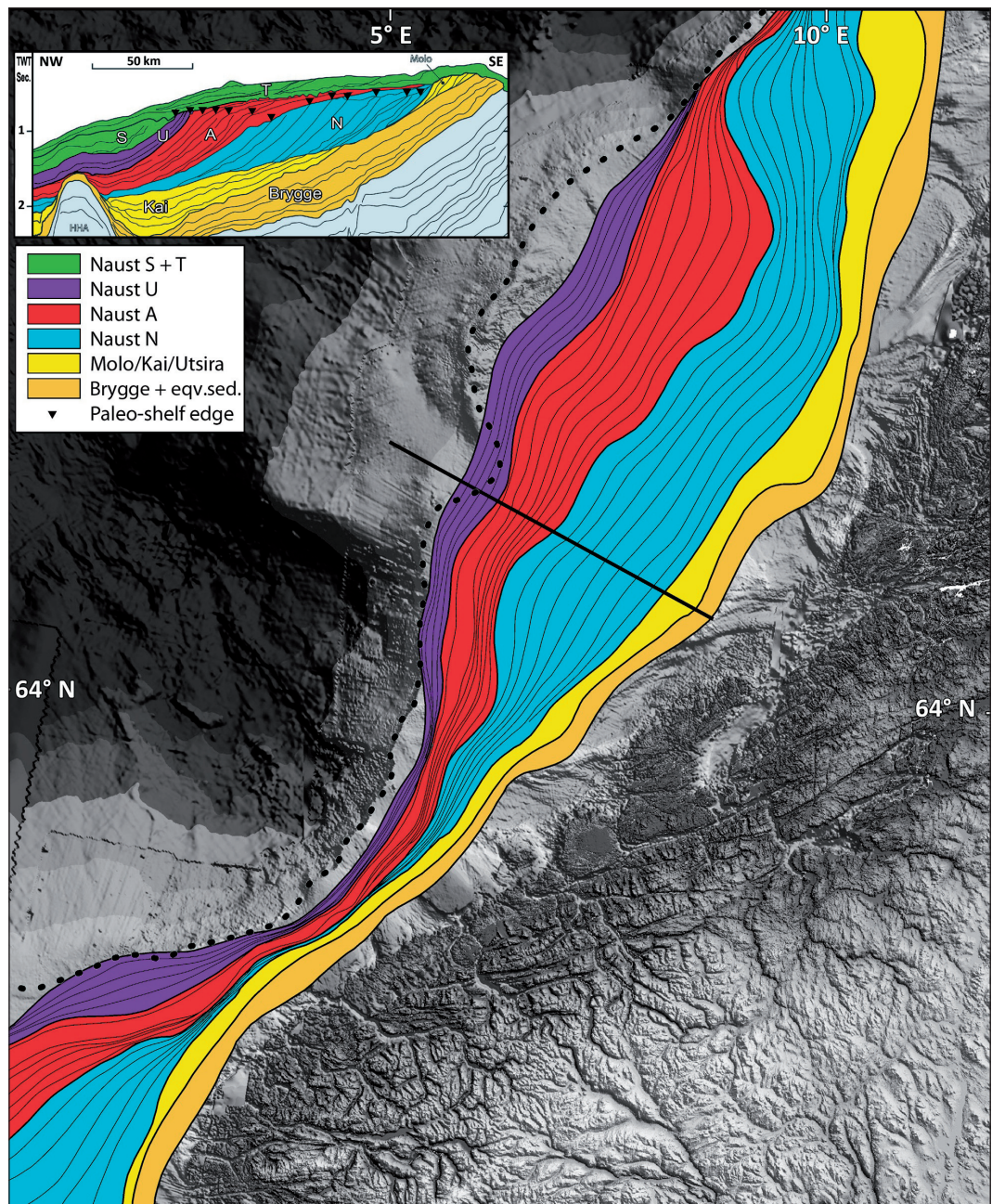


Figure 4. Diagram showing the Naust stratigraphic scheme (after Rise et al. 2006).

Fig. 5. Progradational pattern of the palaeo-shelf break through the Naust N, A, U time periods. Black line locates the geo-seismic profile across Haltenbanken shown in upper left corner. Yellow area – subcrop of Molo Formation and equivalent sediments; orange area – subcrop of Brygge Formation; black dotted line – present shelf edge.



is rather narrow, and the much deeper Møre Basin is located west of the shelf. This has resulted in steeper clinoforms and an aggrading pattern as sediments were dispersed towards the deep part of the Møre Basin. In parts of the Storegga Slide area, thick slide deposits constitute the upper part of the sequence. West of Norway between Sognefjorden and Stad (Fig. 1), a basin has been filled by sedimentary wedges built out towards the northwest (Fig. 2C).

Sequence Naust U comprises several aggradational and slope-building units, probably representing several glacial-interglacial cycles. Maximum deposition occurred along the present shelf edge, with a major depocentre in the Skjoldryggen area containing sediments up to

500 m thick. **Naust S** was mainly deposited seaward of the present shelf edge, and represents the third last glaciation (the Elsterian, 300,000-400,000 years ago), which was possibly the largest glaciation in continental Europe during the Late Cenozoic (Mangerud et al. 1996). A prominent depocentre is located in the Skjoldryggen area, where up to 400 m of glacial sediments are deposited (Rise et al. 2005). The depocentre is separated into two parts because of the buried Sklinnadjuget Slide that occurred shortly after Naust S was deposited, removing the central parts of the succession (Rise et al. 2006). In the south, up to 500 m of glacial sediments have been deposited on parts of the North Sea Fan (Fig. 6C).

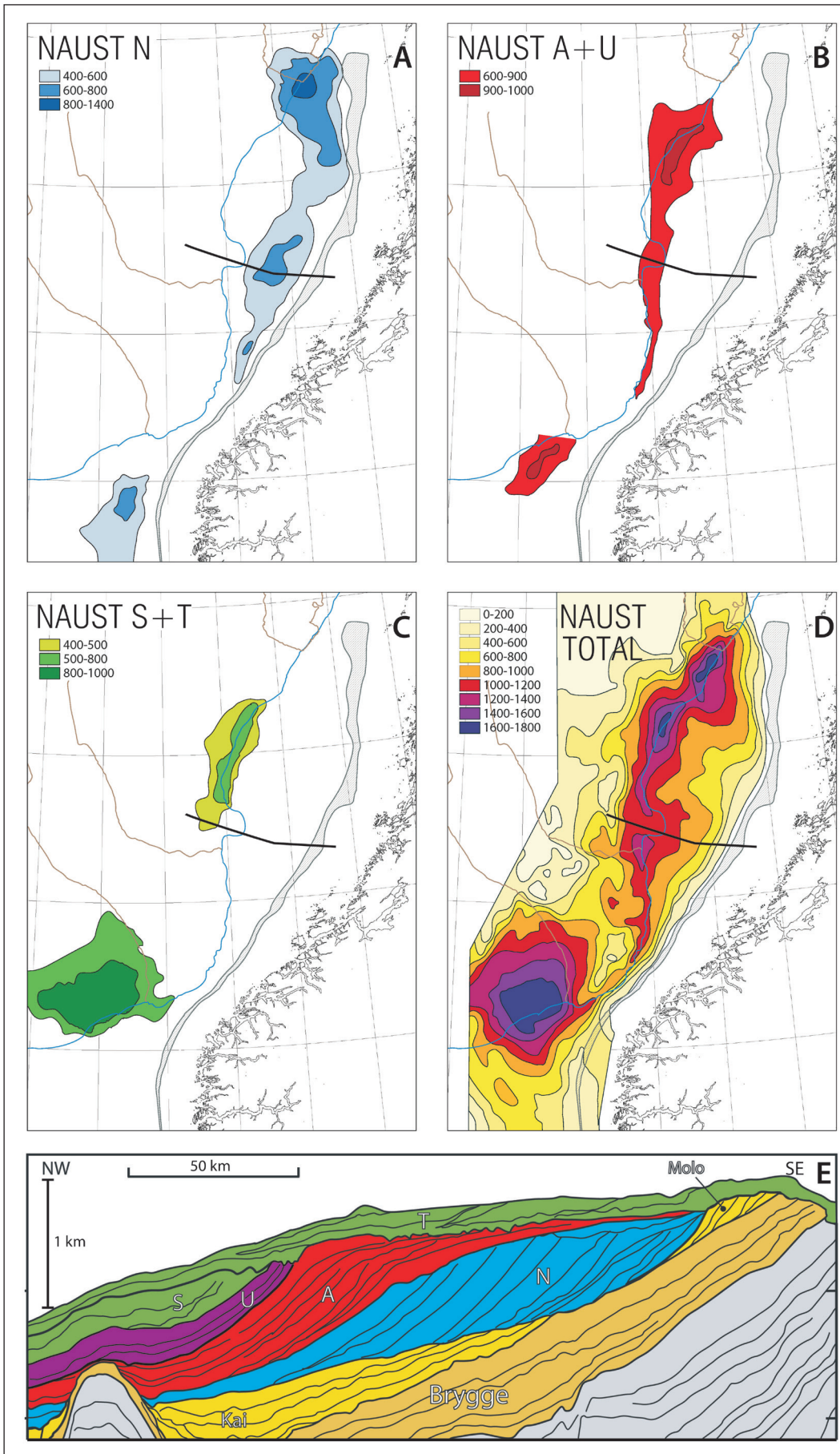


Fig. 6. Time thickness maps in milliseconds (two-way travel time) of the Naust Formation and equivalent sediments and the depocentres of the Naust sequences. A) Main depocentres for the Naust N sequence, B) Main depocentres for the Naust A+U sequences, C) Main depocentres for the Naust S+T sequences, D) Total Naust Formation thickness. Hachure shows the subcrop of the Molo Formation and equivalent sediments on the shelf. E) Geoprofile of seismic line GMNR-94-310 across Haltenbanken (location shown in A-D).

Sequence Naust T comprises mainly flat-lying units of massive or layered sediments from the last two glacial-interglacial cycles, the Saalian (140,000-300,000) and the Weichselian (10,000-115,000 years ago). In the south, an extensive depocentre is found on the North Sea Fan, with deposition of up to 700 m of sediments. This illustrates that the Norwegian Channel ice streams were very active during the last few glaciations (Nygård et al. 2005, 2007). The Tampen Slide is a large buried slide, c. 130,000 years old, located on the North Sea Fan (King et al. 1996, Nygård et al. 2005) (Fig. 1). This slide probably removed a large part of the Saalian sediments of the North Sea Fan. A pronounced depocentre is located in the Skjoldryggen area where 300-400 m of sediments make up the main Skjoldryggen Ridge and adjacent areas, showing that the glaciers were very active during this period.

During the last few glaciations, there is evidence that the ice sheet was divided into several fast-flowing ice streams (Ottesen et al. 2005). These were probably separated by ice domes with slow-moving ice (Ottesen et al. 2005, Rise et al. 2005). These ice streams deposited very large volumes of glacially derived sediments (Nygård et al. 2007).

The seismic profiles show a complex shelf architecture (Fig. 2). In many areas of the shelf, an upper regional unconformity is developed, marking a major change in stratal architecture (Rokoengen et al. 1995, Dahlgren et al. 2005). Over large areas off mid-Norway this surface is at the base of Naust T and represents an erosional surface made by the Elsterian Ice Sheet. However, the surface is complex and appears to have been cut at different times on different parts of the shelf. On the inner shelf this often represents an erosional surface from the last glaciation. In the Norwegian Channel west of Norway, the URU seems to be older than in other parts of the shelf.

Core studies

There is very little, high-quality, sediment/core material from the lower part of the Naust Formation (Naust N and A sequences) on the Norwegian continental shelf. Eidvin et al. (1998) and Eidvin & Rundberg (2001) investigated the lower part of the Naust Formation and Naust equivalent on the mid-Norwegian continental shelf and in the northern North Sea. Photographs illustrate and document the samples of side-wall cores and conventional cores from wells in the Tampen area (northern North Sea) and from well 6610/7-2 on Trænabanken on the mid-Norwegian continental shelf (Figs. 7-10). A core section in well 34/8A-1H with a silt- and sand-dominated diamicton containing pebbles of crystalline rocks is shown in Fig. 7. These samples have been taken at c. 720-740 m depth below the seabed and just above the underlying Utsira Formation. Eidvin & Rundberg (2001) interpreted these sediments as gravity

flows deposited in a glacial environment. A side-wall core from well 34/4-7 at 677 m depth below seabed is shown in Fig. 8 (Table 1). The sediment is silty/sandy with a crystalline pebble visible on the surface. A sieved fraction of a side-wall core from well 34/7-1 in the Tampen area is shown in Fig. 9 (See Fig. 2c for location). Most of the pebbles are from crystalline rocks showing an origin from the Norwegian mainland. In the Tampen area, the boundaries between the different Naust equivalent sequences are not very well constrained, but the core locations and sample depths suggest that they correspond to the oldest Naust sequence (Naust N) which is given a tentative age of 2.8-1.5 My (Rise et al. 2006) (Fig. 2C). The investigations by Eidvin & Rundberg (2001) indicate that the cored intervals are older than 2.4 My. The foraminiferal assemblages recorded from the cores are characterised by a benthic fauna containing Late Pliocene index forms and a



Fig. 7. Parts of a cored section in well 34/8A-1H from near the base of the Naust Formation equivalent (depth in m RKB). The sediments consist of a silt- and sand-dominated matrix with pebbles of crystalline rocks visible on the sliced surface. Further, many ice-rafted pebbles became visible when sample material from the core was dissolved and sieved. The sediments are interpreted as gravity flow deposits with a glaciomarine or glacial imprint (Eidvin & Rundberg 2001).



Fig. 8. A side-wall core viewed from two angles from the lower part of the Naust Formation equivalent in well 34/4-7 (depth in m RKB). A crystalline ice-rafted pebble is visible on the surface. Further pebbles became visible when the material was dissolved and sieved.

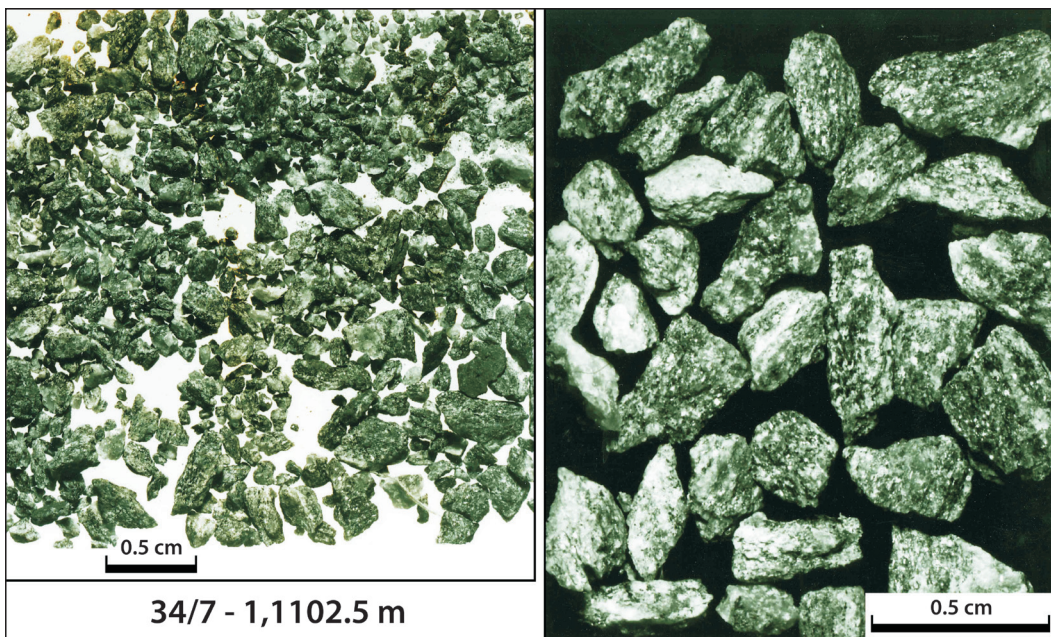


Fig. 9. A dissolved and sieved side-wall core (fraction larger than 0.5 mm) from well 34/7-1 containing a large number of pebbles of mainly crystalline rocks (depth in m RKB). The picture on the right is a magnification.

Table 1. High-quality core samples of IRD clasts from exploration wells from the deeper parts of the Naust Formation on the North Sea and mid-Norwegian shelf

Core name	Area	Depth (m) RKB	Depth (m) below seabed	Sequence	Figure
34/8A-1H	Tampen	1083	719	Naust N equivalent	7
34/8A-1H	Tampen	1100	736	Naust N equivalent	7
34/4-7	Tampen	1057	677	Naust N equivalent	8
34/7-1	Tampen	1102	749	Naust N equivalent	9
6610/7-2	Trænabanken	712	455	Naust N or A	10
6610/7-2	Trænabanken	986	729	Naust N or A	10

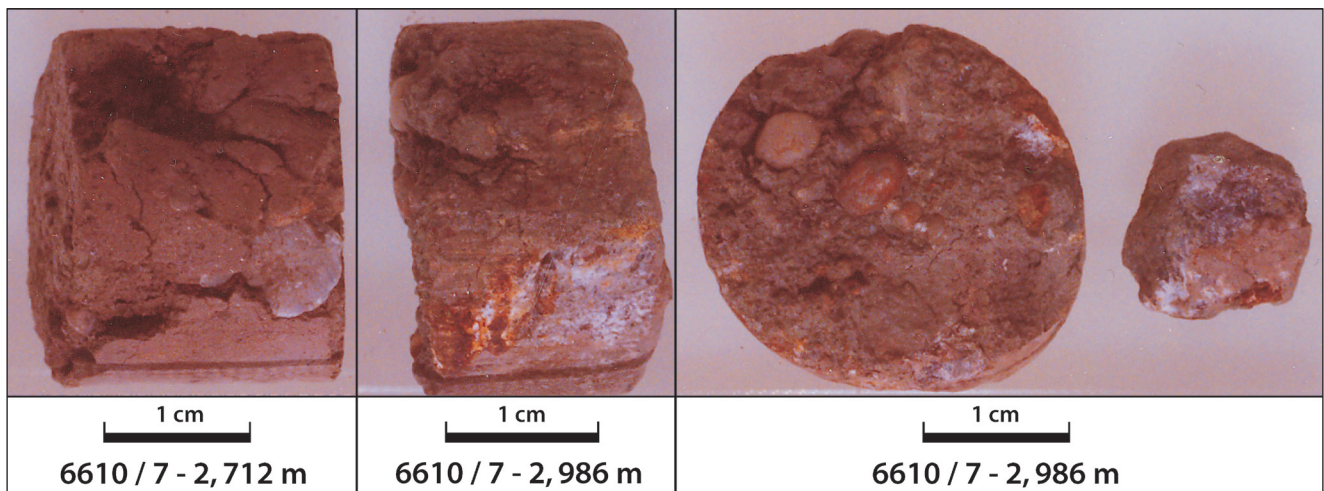


Fig. 10. Two side-wall cores from the lower part of the Naust Formation (Naust N) in well 6610/7-2 (Depth in m RKB). Ice-rafted pebbles are visible on the surfaces. The sample from 729 m below seabed (shown from two angles) is very close to the base of the Naust Formation. This core contains both angular and rounded pebbles. Some of the rounded pebbles are rust stained, and these are probably redeposited from the Upper Miocene-Lower Pliocene Molo Formation which subcrops not far to the east of the well.

planktonic fauna containing *Neogloboquadrina atlantica* (sinistral). On the Vøring Plateau the last occurrence of *N. atlantica* (sinistral) is no younger than approximately 2.4 My (Spiegler & Jansen 1989). A similar benthic and planktonic foraminiferal fauna is recorded in the side-wall cores from well 6610/7-2 on the Norwegian Sea continental shelf (Eidvin et al. 1998).

Side-wall cores from the lower part of the Naust Formation (455 m and 729 m depth below the seabed, Table 1) in well 6610/7-2 from Trænabanken show both angular and rounded pebbles from sedimentary and crystalline rocks (Fig. 10). All the samples reported here document a glacial environment in the oldest parts of the Naust Formation. However, some of the rounded pebbles are rust-stained, probably redeposited from the Upper Miocene-Lower Pliocene Molo Formation which subcrops not far east of the well. The lowermost sample is close to the base of the Naust Formation.

Sedimentary environment

At the beginning of the Naust period there was a huge increase in the supply of sediment to the mid-Norwegian shelf. Henriksen & Vorren (1996) attributed the deposition of the Naust Formation to glacial expansion over the shelf. Work under the NDP project (Bugge et al. 2004, NDP 2004) attributed the initial buildout of the Naust sediments to fluvio-marine and downslope processes without ice on the shelf. At the time of the onset of the shelf glaciations the shelf break was at the delta front of the Molo Formation, which implies that the glaciers had a much shorter distance to travel across the shelf at that time compared with today. Seismic mapping shows that the shelf has been built out from southeast

towards northwest from a linear source of some length (Fig. 5). A maximum progradation of 100 km from 2.8 to 1.5 Ma gives an average progradation of 80 m per thousand years. It is difficult to envisage how the huge sediment volume of the oldest parts of the Naust Formation could have been deposited over such a short time without being directly deposited by glaciers. This strongly suggests deposition by large ice sheets along the entire western margin, rather than deposition from point sources as, for example, by rivers whether glacier-fed or otherwise.

With the introduction of 3D seismic data it has become possible to image older, buried surfaces within the Naust Formation. These studies have revealed a number of diagnostic glacial landforms, such as streamlined mega-scale glacial lineations produced by fast-flowing ice streams (Clark 1993), or ploughmarks formed by iceberg keels (Dowdeswell & Bamber 2007). On Trænabanken, the oldest glacially influenced surface was located c. 350 m below the present sea floor, in the upper part of the Naust N sequence (tentatively 1.5 to 2.0 million years old) (Fig. 11A). A number of straight WSW-ENE-oriented and a few 'wavy' iceberg ploughmarks appear on this surface (Fig. 11B). The ploughmarks are up to a few metres deep and 150 m wide and have a maximum length of 8 km.

Another surface with glacial imprints is located c. 400 m below the present sea floor in the transition zone between the Naust A and N sequences in the outer Haltenbanken area (Fig. 12), with a tentative age of 1.5 million years. On this surface there is a series of parallel ridges generally a few metres high, with an average spacing of 350 m and an ESE-WNW trend (Fig. 12B). We interpret these ridges as glacial lineations found on the modern

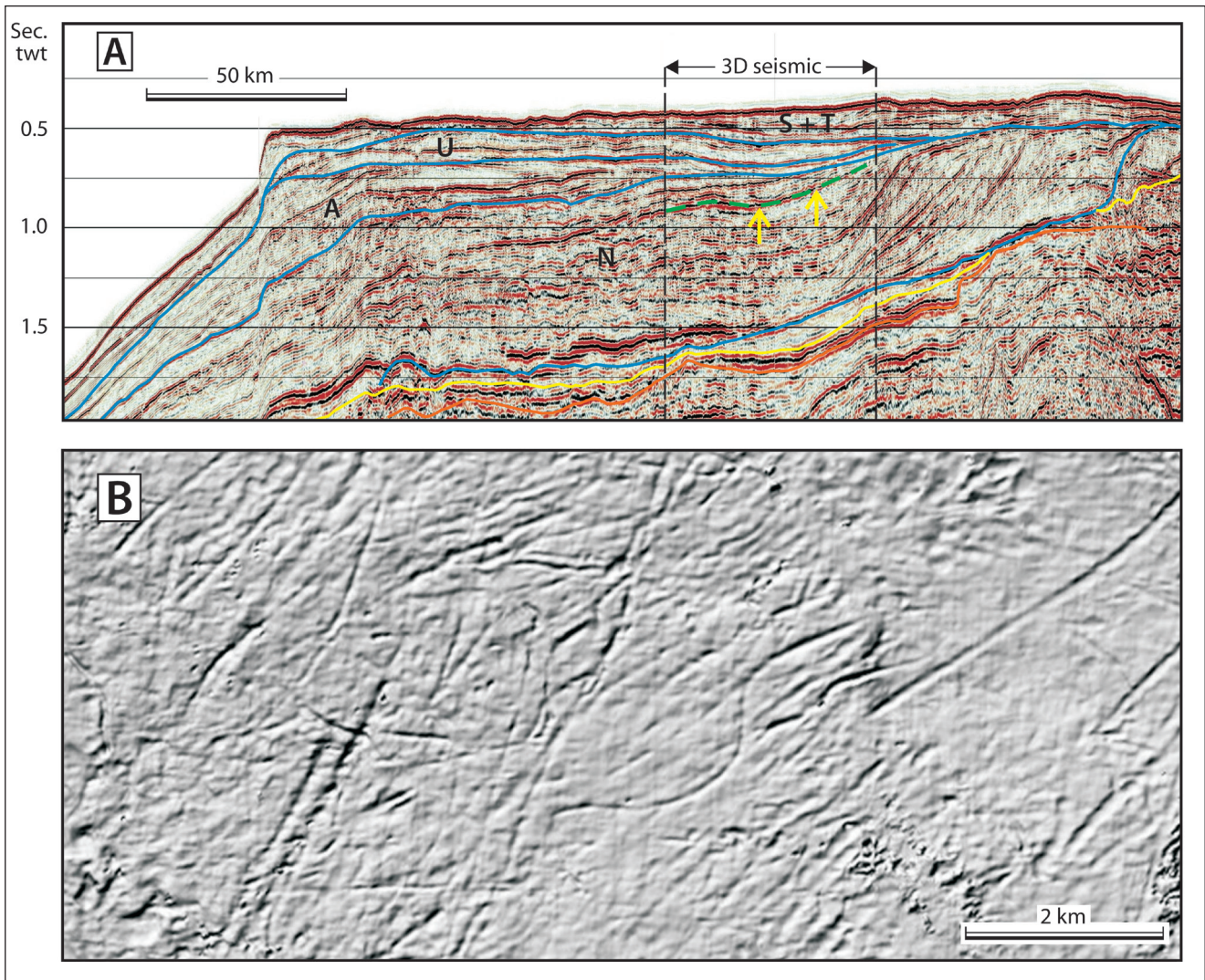
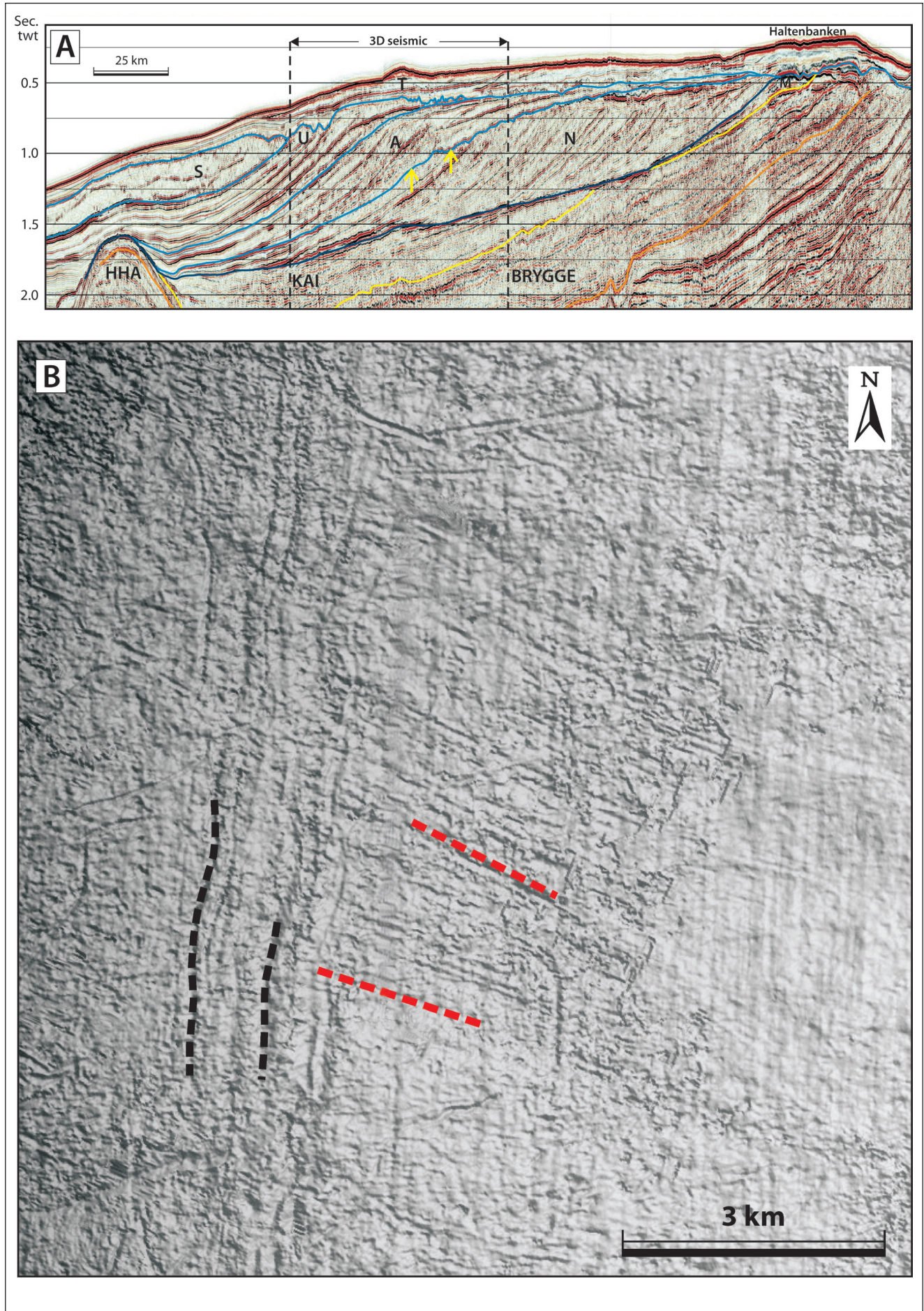


Fig. 11. (A) Seismic line GMNR-94-107 across Trænabanken. Yellow arrows locate the position of a buried surface shown in Fig. 11B. (B) A buried surface on Trænabanken (66°N, 9°E) 350 m below the modern sea floor with ice-berg ploughmarks (data from 3D-seismic cube NLGS-95). The surface is in the upper part of sequence Naust N, and is approximately 2 million years old. Most of the ploughmarks are rather linear, but some have a wavy appearance. The ploughmarks are a few metres deep, and may reach up to 150 m in width.

sea floor, formed during the last glacial maximum on the Norwegian shelf (Andreassen et al. 2004, Ottesen et al. 2005) or in Antarctica (Shipp et al. 1999, O'Cofoaigh et al. 2002). This is the oldest surface we have found with glacial lineations, which is taken as proof for grounded glaciers. The lineations disappear at the palaeo-shelf edge, 400 m to 500 m below the present sea floor. Ice-berg ploughmarks appear on the same surface and some of them show a nearly linear pattern. At the palaeo-shelf edge, several sub-parallel ploughmarks are found, some of them at least 15 km in length. They have a general north-south trend with a slight wavy appearance indicating that the ice-bergs drifted along the paleo-shelf edge. Both the ice-berg ploughmarks in the upper part of the oldest Naust sequence (Naust N), and the glacial lineations found in the transition zone between the Naust N and Naust A sequences, provide strong indications

that at least the upper part of the Naust N sequence was deposited in a glacial environment.

Fig. 12. (A) Seismic line GMNR-94-310 with location (yellow arrows) of the surface shown in Fig. 12B. (B) A buried surface c. 400 m below the modern sea floor (see Figure 12A for location) from 3D seismic data from Haltenbanken. Linear bedforms are interpreted to be glacial lineations (MSGL) (red stippled lines) and ice-berg ploughmarks (black stippled lines). The surface represents the top of sequence Naust N, approximately 1.5 million years old. The survey line orientation is north-south.



Conclusions

1. Marine geophysical investigations have resulted in a revised and unified stratigraphy for the Late Pliocene-Pleistocene sediments of the mid-Norwegian continental shelf (the Naust Formation) between Sognefjorden and Lofoten (61°N to 68°N). Glacially derived sediments constituting the Naust Formation have been built out up to 150 km west of the Molo Formation. The Naust Formation has been subdivided into five units, N, A, U, S and T, with N representing the oldest unit, S representing the third last and T the two last glaciations.

2. Studies of high-quality sedimentary cores from the Norwegian continental shelf have revealed clasts interpreted as ice-rafted debris in the lower parts of the Naust Formation. The major part of the clasts originate from crystalline rocks and are probably derived from the adjacent Norwegian mainland.

3. Seismic 3D data from the shelf have revealed sedimentary surfaces showing evidence for grounded ice sheets (glacial lineations) in the transition zone between the two oldest Naust sequences on the outer shelf (Naust N and A), approximately 1.5 million years ago.

4. Seismic 3D data from the shelf have revealed sedimentary surfaces with a glacial influence (iceberg ploughmarks) back to the upper part of the oldest Naust sequence (Naust N), approximately 2 million years ago.

5. All available information, i.e. glacial lineations, iceberg ploughmarks, IRD from the lower part of the Naust Formation, and the very high accumulation rate, support that the Naust Formation is mainly developed in a glacial environment.

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