NGU Report 2002.015

Large scale development of the mid Norwegian shelf and margin with emphasis on the last 3 million years.

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REPORT

Report no.: 2002.015	ISSN 0800-3416	Grading: Confidential 3 years

Title:
Large scale development of the mid-Norwegian shelf and margin with emphasis on the last 3 million years.

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County:		Commune:	
Map-sheet name (M=1:250.000)		Map-sheet no. and -name (M=1:50.000)	
Deposit name and grid-reference:		Number of pages: 200 Map enclosures: 2	Price (NOK):
Fieldwork carried out:	Date of report: 15.05.2002	Project no.: 2922.00	Person responsible: Astrid Lyså
Revision no.: 01	Date of revision: 20.11.2002		

Summary:

This study intends to elucidate the evolution of the mid-Norwegian margin, with emphasis on the last c. 3 million years when the Naust Formation was deposited. The main objective has been to improve the knowledge of offshore depositional sequences through time. Emphasis has been given to improve the understanding of large-scale depositional systems, and to link this information to areas where risk analyses have been performed based on detailed investigations.

The main results are presented in Executive Summary and in Summary & Conclusions.

Keywords: Marine geology	Glacial geology	Plio-Pleistocene
Mid-Norwegian shelf	Storegga slide	Seismo stratigraphy

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LARGE-SCALE DEVELOPMENT OF THE MID-NORWEGIAN SHELF AND MARGIN WITH EMPHASIS ON THE LAST 3 MILLION YEARS

Executive summary

This study intends to elucidate the evolution of the mid-Norwegian margin, with emphasis on the last c. 3 million years (Ma) when the Naust Formation was deposited. The main objective has been to improve the knowledge of offshore depositional sequences through time. Emphasis has been given to improving our understanding of large-scale depositional systems, and to link this information to areas where risk analyses have been performed based on detailed investigations.

Sea-floor spreading and crustal processes

The present large-scale morphology of the mid-Norwegian shelf is the end result of a long geological history. The architecture of the mid-Norwegian passive margin became established in earliest Eocene (c. 55 Ma) when sea-floor spreading was initiated in the Norwegian-Greenland Sea. Magmatic processes below the crust have been important for constructing the 'fundament' of the margin, and thus influencing the present shelf morphology. At the Vøring margin large amounts of magma were added to the crust, and due to this process ('underplating') the wide positive bathymetric feature called the Vøring Plateau was buoyantly held up (Fig. 1). It appears that the underplating was unevenly distributed, and therefore some segments of the margin subsided more than others. The Lofoten and Møre margins represents areas being predisposed to major slope instability.

Onshore uplift and influence of glaciations

A period of strong tectonic uplift of western Norway occurred in pre-Naust time (Neogene uplift phase), and due to a colder and wetter climate, snow started to accumulate in the mountain range. Ice caps were formed, and glaciers flowed towards the lowland and the coastal zone. Deeply chemically weathered bedrock, as well as older unconsolidated sediments on the lowlands west of the mountain range, was easily eroded and transported towards the sea. The depositional environment in Late Pliocene is poorly understood, and several processes may have been important (e.g., wave erosion of an uplifted inner shelf, erosion/transport by rivers and glaciers). A very rapid construction of the mid-Norwegian continental shelf took place during this period. Glaciers are an effective transport agent, and we suggest that the ice thickened and grew large enough to reach the shelf areas also during several of the early glaciations.

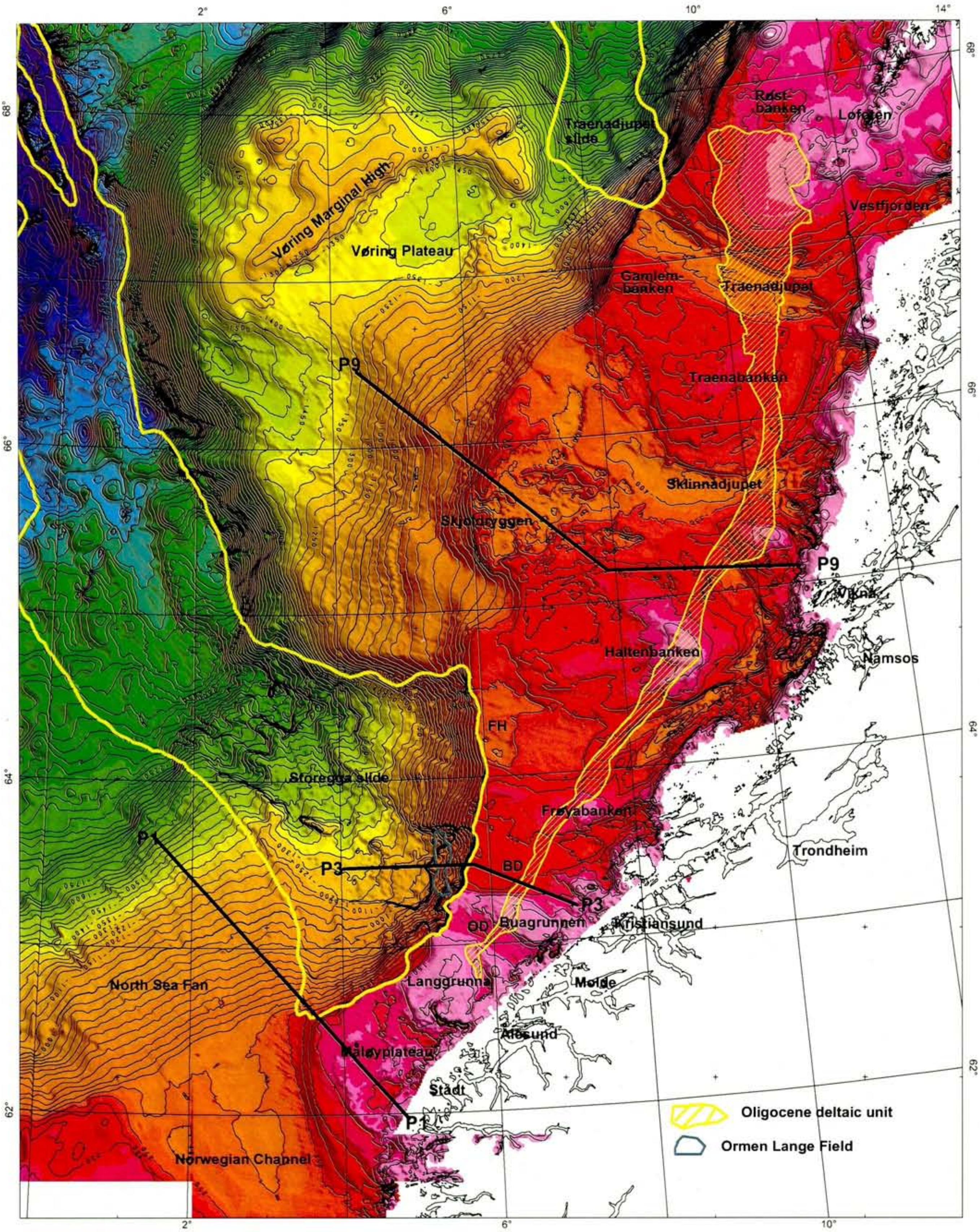


Figure 1 Overview map of the mid-Norwegian shelf. Profiles P1, P3 and P9 are shown in figure 3. FH = Frøyabankhola, BD = Buadjupet, OD = Onadjupet.

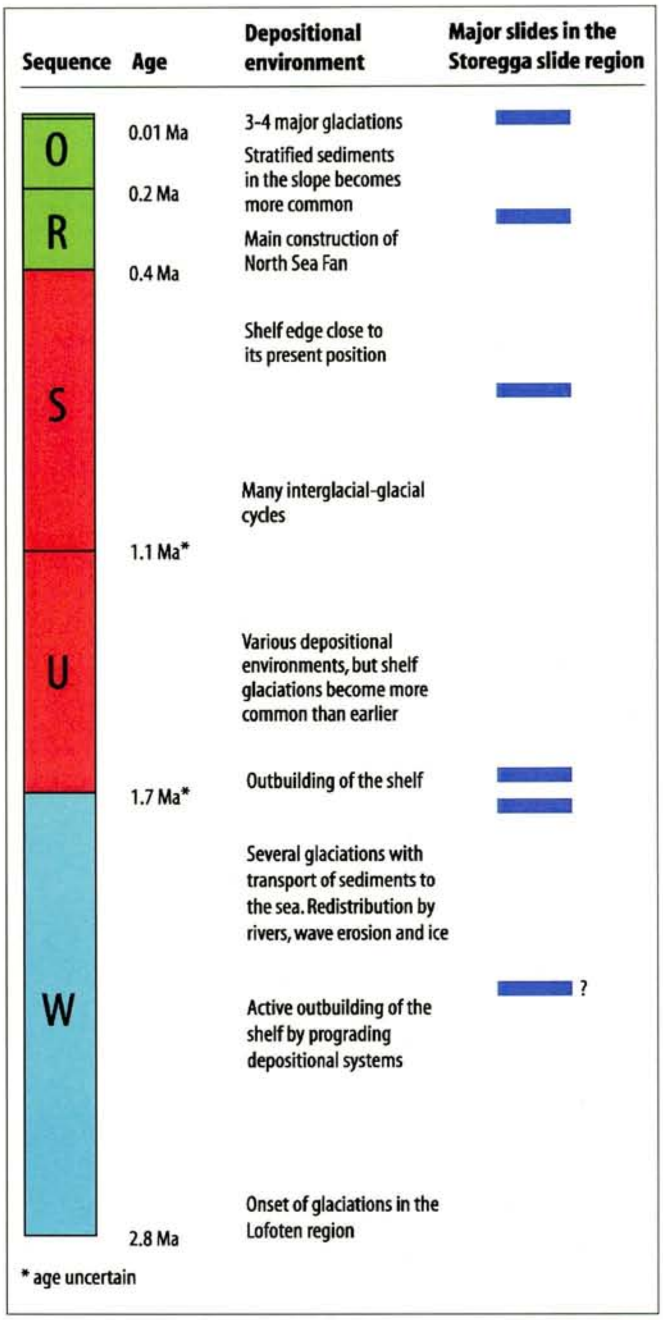


Figure 2 Stratigraphic chart of the Naust Formation – with proposed ages and major events.

Late Pliocene and Pleistocene sediments – up to 2000 m thick

During the Late Pliocene and Pleistocene, the last 3 million years, large quantities of glacially-derived material were transported westward from the mainland, gradually building out the current shelf (Figs. 1, 2 and 3).

The distribution of these sediments, superposed on the already established margin architecture, set the stage for the major submarine Storegga and Trænadjupet slides, which are located at the moderately steep Møre margin and the steep Lofoten margin, respectively.

This sediment succession - the Naust Formation - was deposited west of a characteristic deltaic unit of Oligocene age (36-25 Ma). This deltaic unit is composed mainly of sand and was deposited parallel to the coast from Lofoten to Møre. Prior to 3 Ma, the existing shelf had subsided, and a basin of at least 500 m water depth had been formed west of the deltaic unit. In extensive areas centred along the present shelf edge, more than 1000 m of sediments were deposited, with a maximum thickness of nearly 2000 m. In the study area, these sediments represent a large part of the deposits accumulated during the last 60 million years.

The largest accumulations took place east of the Vøring margin where the shelf edge gradually moved 100-150 km west. Large domes at base Naust, located west of the present shelf edge, decreased the dispersal of sediments towards the deep ocean. The narrow Møre shelf extended westwards only 30 to 50 km during the same period. This much smaller width of the shelf, is mainly the result of a steeper slope between the shelf and the deep basin (i.e., more accommodation space) (Fig. 3). In addition, the Møre shelf also received less sediments than the adjacent mid-Norwegian shelf to the north, and the northern North Sea to the south. The sediments commonly show an aggrading ('slope-building') pattern of sheet-like units, because sediments were widely dispersed into the deep Møre Basin. Another factor contributing to the narrowness of the Møre shelf is the presence of a series of older major slides which occurred on the slope adjacent to the Møre shelf. However, these events have only reduced the shelf width to a moderate extent - (in total, probably less than 10 km).

At the North Sea Fan (Fig. 1), a slope-building sequence of sediments is present. The sediments were widely dispersed down the slope towards northwest, and there was only a limited progradation (outward growth) of the shelf edge .

Subdivision of the Naust Formation

In this study, the Naust Formation has been subdivided into 5 sequences, each comprising several units. In chronological order from oldest to youngest these are W, U, S, R and O. The ages of the oldest sequences are very uncertain, but Sequence R is probably 200,000-400,000 years old. Sequence O represents the last two glacial-interglacial cycles, and spans 0 to 200,000 years in age. In order to illustrate the large-scale development during the last 3 million years, isochron maps showing the thickness in milliseconds two way travel time (ms twt) of Sequences W, U+S and R+O were compiled (Fig. 4). The ms twt-values are in most areas fairly equal to the thickness in metres.

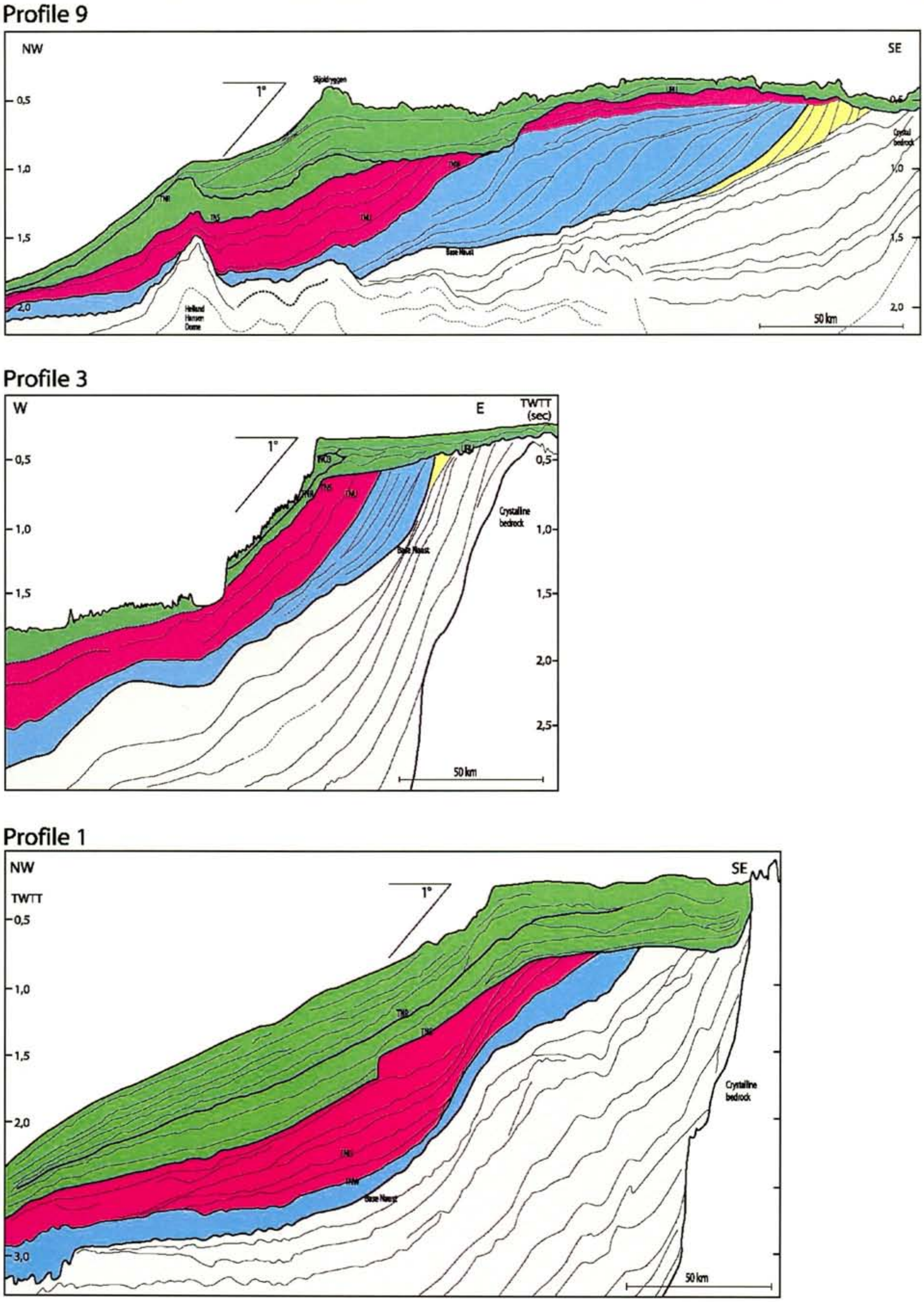


Figure 3 Interpreted seismic profiles showing the main Naust sequences. See Fig. 1 for location. Naust W – blue; Naust U+S – red; Naust R+O – green; Oligocene 'delta' – yellow.

Naust W (proposed age 2.8-1.7 Ma)
The oldest sequence (W) is very thick (c. 1400 m) in the outer Trænadjupet region, indicating a sediment source in the Lofoten/ Vestfjorden area and sediment transport towards southwest (Figs. 4 and 5). We infer that glaciers were the most important transport agent, but coastal erosion and currents may also have been active processes. Farther south, an active building out of the shelf occurred during this period, with a depocentre in outer Haltenbanken. In the Møre region and farther south, the sequence is much thinner, indicating that the first periods of glaciation were of lesser importance in the southern part of the study area.

Naust U & S (proposed age 1.7-0.4 Ma)
During the next period, large volumes of sediment were transported across the shelf (Sequence U+S), and the shelf edge extended out close to its present position. Parts of the oldest Sequence W were glacially eroded between Haltenbanken and Trænabanken, and redistributed farther west (Figs. 4 and 5). During this period, the glacial processes in the southern region became more important than earlier. The Norwegian Channel Ice Stream became active, and up to 400 m of sediments were deposited at the mouth of the channel.

Naust R & O (proposed age <0.4 Ma)
During the Mid-Late Pleistocene period several ice sheets advanced to the shelf edge (Fig. 6). In this period the Norwegian Channel became a very important ice-drainage route.

Deposition during peak periods of the glaciations
The main outward growth of the margin occurred during the most extensive periods of glaciation, when the ice sheet(s) reached the shelf edge. Close to the mouth of the Norwegian Channel, a nearly 1000 m-thick sediment succession (Fig. 4), consisting mainly of debris-flow lenses, shows that the channel was a very important drainage route for the Scandinavian Ice Sheet during the last three or four glaciations (Sequences R+O). The marine ice sheets extended to the entire shelf edge at several times during these glaciations, and deposited significant volumes of sediment at the margin. In the northern areas, the main ice drainage occurred between Haltenbanken and Trænabanken, resulting in a depocentre along the huge Skjoldryggen ridge at the shelf break. A very active, ice-drainage system occurred between Frøyabanken and Buagrunnen (Fig. 1), depositing thick glacigenic sediments on the upper slope.

Deposition during 'quiet' periods – 'weak' sediments from interglacial and interstadial periods
The durations of the peak glacial periods when ice reached the shelf edge were apparently quite short compared with periods of limited ice cover on the shelf, and ice-free periods. During these long periods, normal marine and/or distal glacial marine deposition prevailed on the slope and outer shelf, depositing stratified fine-grained sediments. Such sediments are commonly weaker in terms of their geotechnical properties than glacial debris deposits (i.e., they are more likely to act as glide planes for sliding). The depositional pattern shows an

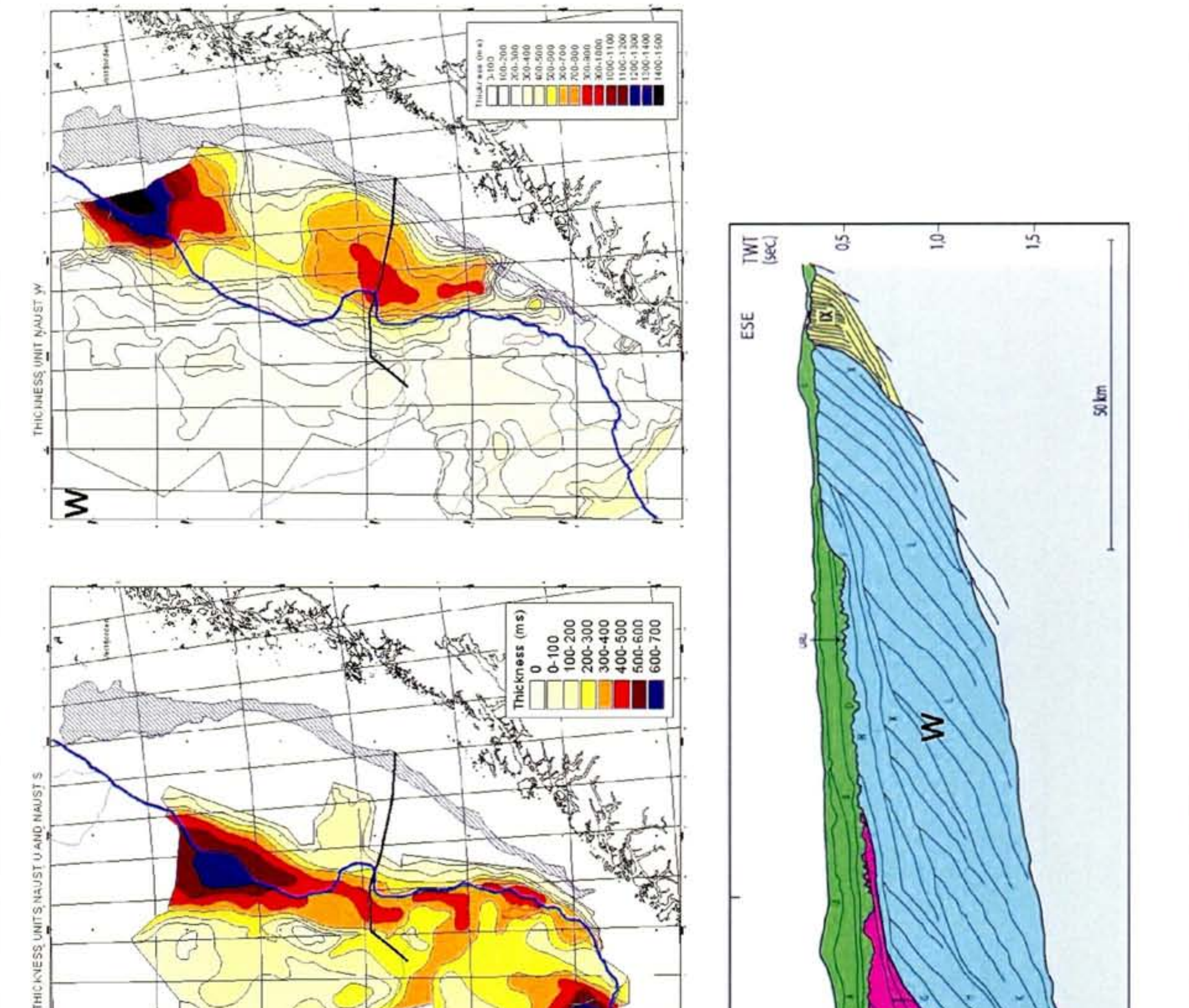


Figure 4 Isochron maps of the Naust sequences, and geo-seismic profile. Thickness in milliseconds two way travel time (twt). Blue line: present shelf edge.

influence of strong contour-parallel currents with erosion/transport mainly in the upper slope and deposition in the lower/middle slope. These contouritic deposits are commonly mounded, being up to 150 m thick where they infill deep slide scars.

Slides older than 8000 years

Several older (pre-8000 year) major sliding events have occurred in the area of the Storegga Slide. Few slide scars are seen below the shelf adjacent to the Storegga Slide, but slide events possibly occurred also during deposition of Sequence Naust W. The second last major slide in the Storegga area is probably in the order of 300,000 years old. This slide appears similar to the Storegga Slide in several ways: 1) it has a comparable areal extent; 2) occurred shortly after a major glaciation; and 3) weak layers in the upper part of the underlying stratified sediments served as glide planes. The third last major slide may be in the order of 600,000 years old.

Links between glaciations and slides

The three last major slides seem to be cyclic events, occurring after an extensive glaciation (Fig. 6). It is, however, important to note that there is no indication of major sliding in the Storegga area after the second last glaciation (Saalian). During this glaciation, up to 200 m thick glacigenic deposits were deposited above stratified sediments in the slope area where we today see the deepest incision of the Storegga Slide. The ice used the same transport routes across the shelf during the last glaciation (Weichselian), and totally about 300 m of glacigenic sediments were deposited on the upper slope before the Storegga Slide occurred.

In the area of the North Sea Fan, several large slides have occurred. Thick stratified sediments seem to be uncommon in this area, and as the slides have developed on slopes with angles in the order of 0.5 degrees, they are even more difficult to explain than the slides in the Storegga area (1-1.5 degrees slope angle). In contrast, shelf margins around Antarctica and Greenland with much steeper slopes seem to be stable.

Stable margin between the Storegga and Trænadjupet/Nyk slides

The different slides at the northern flank of the Storegga area show a similar slide development as the Storegga Slide, and terminate in the thick stratified sediments in this area. Large local slides are not observed, indicating that sliding here is associated with major regional events. Although a slide event may be related to a collapse feature in the Helland Hansen Arch, the wide margin between the northern flank of the Storegga Slide and the Trænadjupet/Nyk slides has been stable over the last 3 million years.

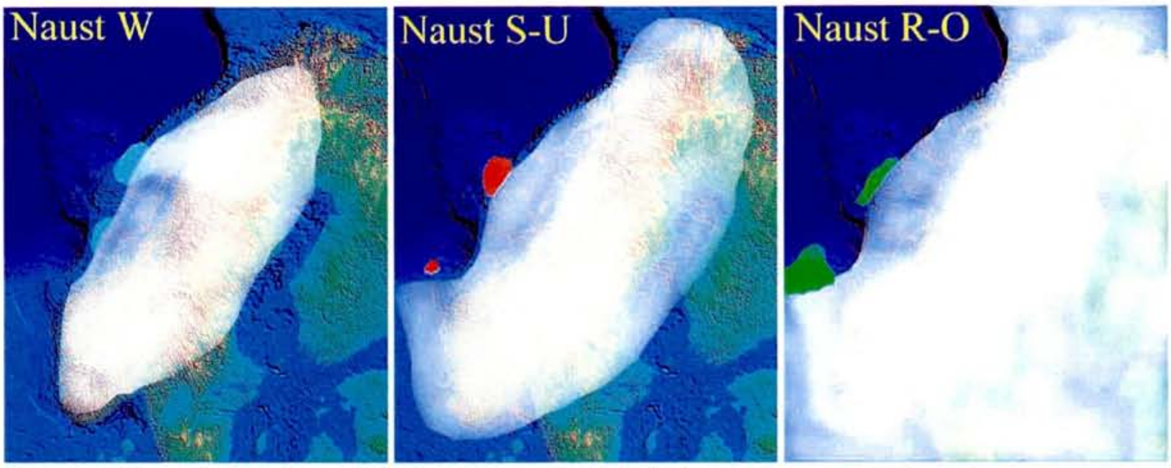


Figure 5 Snapshots of possible ice cap and related Naust depocentre location, at various stages of the deposition of the Naust Formation. These are intended as illustrations, not as exact reconstructions.

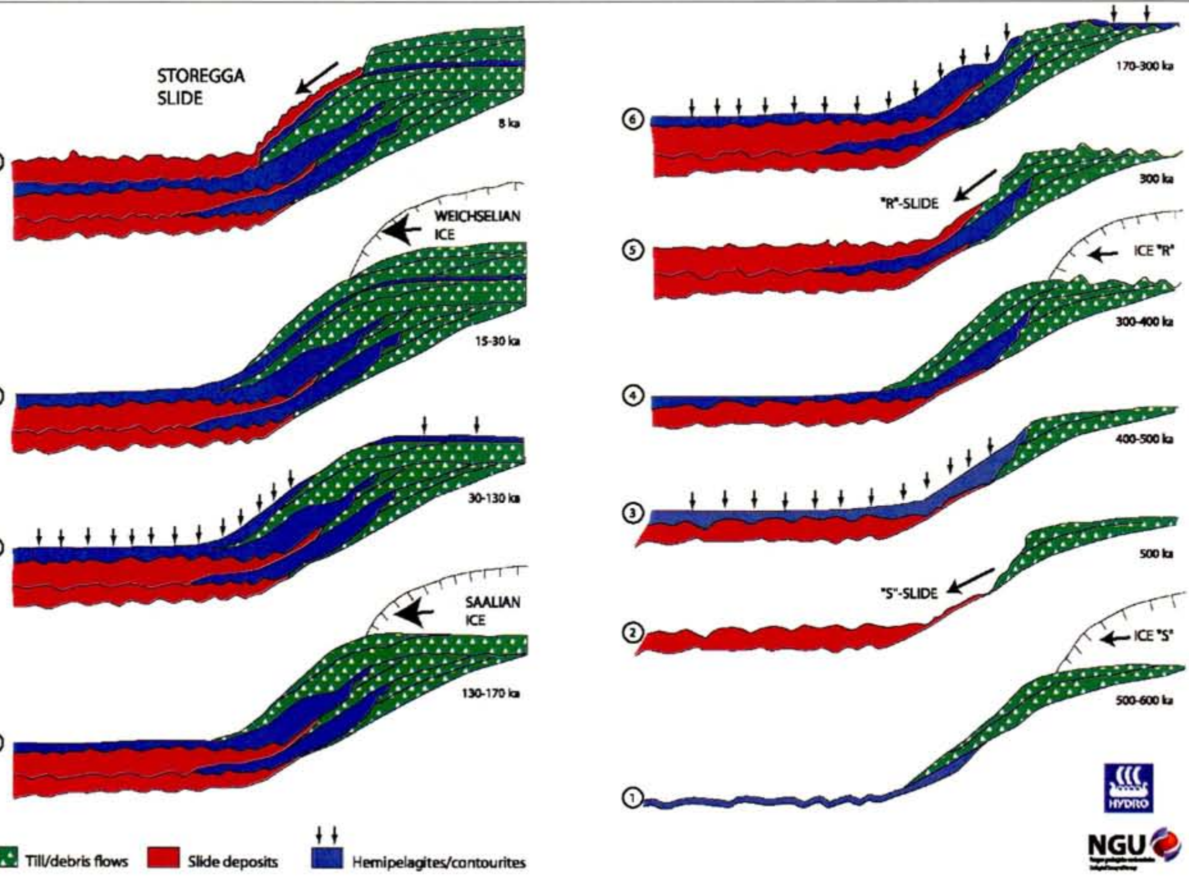


Figure 6 Development of the Møre shelf and slope during the last c. 0.5 million years. The major slides seem to be cyclic events occurring after extensive glaciations. Note that the weak fine-grained sediments infilling the slide scars, acted as glide planes for the slides.

Summary and conclusions

The large-scale architecture of the mid-Norwegian shelf and margin is a result of sea-floor spreading and crustal processes during the last 55 million years (Ma)
The architecture of the mid-Norwegian passive margin was established by earliest Eocene time (c. 55 Ma) when sea-floor spreading was initiated in the Norwegian-Greenland Sea. The final margin configuration reflects a long and complicated geological history, including over 300 million years of episodic rifting, but the strongest influence was imposed during the final phase of Paleocene rifting. In particular, the Iceland Plume profoundly influenced the rifting and margin architecture, and led to the development of the North Atlantic Volcanic Province.

The margin architecture with the distribution of large quantities of Late Pliocene and Pleistocene glacially derived material, predisposed certain areas to major slope instability. Moreover, the Jan Mayen and Bivrost Lineaments, two presumed major basement weaknesses, coincide with the location of the Storegga and Trænadjupet Slides, respectively.

With respect to margin architecture, the distribution of magmatic underplating appears to have had a significant influence on the slope of the margin. The Vøring Plateau was strongly underplated, i.e. much melt were added to the continental crust, and thermal subsidence was supressed. The slide areas occur in somewhat steeper parts of the margin and lack so-called marginal highs at the foot of the slope; effects that both can be related to less underplating.

At least the Jan Mayen Lineament can be inferred to have undergone repeated motions during the Cenozoic, following break-up (i.e., Eocene to Present). However, the lineaments are generally devoid of evidence of historic earthquakes.

During the last c. 3 Ma, an up to 2000 m thick sediment succession, was deposited in the shelf and margin areas. In the study area, these sediments represent a large portion of the total amount deposited during the last c. 60 Ma. This extremely high sedimentation rate can be related to an extensive uplift of the mainland/adjacent shelf and the establishment of glaciations.
Sediment source. Unconsolidated sediments possibly occurred in the lowlands west of the mountain range, and were present on the inner part of the continental shelf. The crystalline and metamorphic bedrock was probably deeply chemically weathered, and thereby easily accessible for erosion.

Mainland uplift. Neogene uplift in Norway was considerable, with uplift centres in Lofoten and southern Norway. The innermost part of the shelf was uplifted, and sediments were exposed for marine erosion.

Ice caps and glaciers. During the Neogene, the climate became colder and ice caps were formed. Glacial erosion efficiently removed available sediments. We suggest that during this period several of the early ice caps grew large enough to reach the shelf areas.

We believe that glacial erosion was the dominant denuding process on the mainland, and possibly also on the inner shelf. Most of the sediments were probably transported to the coastal zone and the shelf by glaciers and marine ice sheets. During sea level low-stands; periods of an emerged shelf developed, and rivers as well as coastal erosion were important agents in recycling sediments and transporting them towards the basin.

The wide shelf at Haltenbanken - Trænabanken is a result of extensive prograding/ aggrading deposition into a basin of intermediate depth with a gently dipping basin floor. During the last 3 Ma, the shelf edge moved 100-150 km westwards. Less sediment was supplied to the Møre shelf, but the narrow shelf is mainly the result of the presence of a steeper slope towards a much deeper basin.
The commonly sheet-like units at the Møre margin show an aggrading pattern as sediments were dispersed towards the deeper parts of the basin, resulting in a limited outbuilding of the shelf. Several large slides have occurred in the slope adjacent to the Møre shelf, but these events have contributed only to a limited degree to making the shelf narrower (<10 km is suggested).

In order to illustrate the development of the shelf and margin throughout Late Pliocene and Pleistocene, three isochron maps of the five defined sequences were made: Naust W (oldest), Naust U+S and Naust R+O.

During Late Pliocene (Sequence Naust W, proposed age 2.8 - 1.7 Ma) most sediments were deposited in the Lofoten-Haltenbanken area, indicating that the influence of glaciations was most pronounced in the northern part of the study area.
The thickest Naust W sediments (>1400 ms twt thickness) are found in the outer Trænadjupet region, and the southwesterly dip of the strata indicates a sediment transport from a source area in the Lofoten/Vestfjorden region. The sediments were probably transported southwestward by glaciers, but marine erosion and redistribution by currents may have been important. The Lofoten region became a less important sediment source area during later phases of the outbuilding. Also farther south, an active construction of the shelf occurred with a more than 900 ms twt thick succession on outer Haltenbanken. At Møre, and farther south, the sequence is much thinner, indicating that the first period of glaciations was of less importance in the southern part of the study area.

During Early-Mid Pleistocene (Sequences U+S, proposed age 1.7 – 0.4 Ma) ice sheets transported sediments to the shelf edge along the entire margin, building out the shelf edge to a position close to the present.
The isochron map of sequences U+S shows a depocentre (>600 ms twt) in the outer Trænabanken region, indicating focused ice drainage across southern Trænabanken and the northwestward continuation of Sklinnadjupet. Farther south, there was a quite considerable transport of sediments to the shelf edge, and it is evident that the glacial environment in the southern region became more important than earlier. The Norwegian Channel Ice Stream became active in this period, and up to 600 ms twt of sediments were deposited at the mouth of the channel.

During the Mid-Late Pleistocene (Sequences R+O, proposed age 0.4 - 0.01 Ma), several ice sheets advanced to the shelf margin. The Norwegian Channel became a very important ice drainage route.
The increasing importance of the Norwegian Channel Ice Stream during the deposition of the younger parts of the Naust Formation is clearly shown by the isochron map of the youngest sequences (R+O). A maximum thickness of more than 1000 ms twt close to the mouth of the Norwegian Channel reveals that the channel was a major drainage route for the Scandinavian Ice Sheet during the last three or four glaciations. In northern areas, the main ice drainage occurred between Haltenbanken and Trænabanken, resulting in a large depocentre along the prominent Skjoldryggen ridge. Large ice streams coalesced between Frøyabanken and Buagrunnen, depositing thick glacigenic diamictons on the upper slope. Contour-parallel currents deposited fine-grained stratified sediments in the mid-lower slope, the thickest in the area of the Storegga Slide.

The maximum age of the Naust Formation is 2.8 Ma. The age of the three oldest sequences (W, U, S) are poorly constrained.
Chronostratigraphic investigations have yielded deviating results, and the age of the three oldest mapped sequences are very uncertain. Seismic correlation to three different investigations resulted in the following ages for Naust W: a) 2.8-2.3 Ma, b) 2.8 - <1.1 Ma, and c) older than 1.1 Ma.

From a combination of the seismic stratigraphy and different chronostratigraphic investigations, the following ages are suggested for the sequences:

Naust W:	2.8 - 1.7 Ma
Naust U:	1.7 - 1.1 Ma
Naust S:	1.1 - 0.4 Ma
Naust R:	0.4 - 0.2 Ma
Naust O:	< 0.2 Ma

Unit R3 represents the third last, extensive glaciation to have reached the shelf edge, but the age is somewhat uncertain and some data indicate that it may be older than the third last glaciation (Elsterian). Sequence R may thus represent two glacial - interglacial cycles. Eemian sediments (130 -115 ka) are found in several samples/cores and correlate with the Intra Naust O3 horizon (INO3). The mapping of this horizon has therefore been important in order to distinguish between deposits from the Weichselian (115-10 ka) and the Saalian (200-130 ka), which are both represented by Sequence O.

Over large shelf areas, the upper regional unconformity (URU) represents a clear boundary, commonly with flat-lying sediments above truncated older strata. URU was possibly developed during several glaciations, and the last erosive shaping of the surface is of varying age in different areas. Most of the sediments found above the URU represent the three last glaciations.
The URU was previously thought to represent the boundary between glacial sediments of Pleistocene age and underlying bedrock.

In mid-outer shelf areas where the URU is very well defined, the development may be related to the combined effect of a period of shelf uplift with an increased erosional impact of the glaciations. The last shaping of the surface in the northern part of the area seems to be related to a major glaciation that deposited the thick Sequence R beyond the shelf edge. At the outer shelf north of Haltenbanken and at Trænabanken a sequence of older, flat-lying sub-units occurs, and URU is difficult to define or interpret. The development of the URU and the uplift/subsidence history of different parts of the mid-Norwegian shelf remains poorly understood.

The final erosional shaping of the URU in the Norwegian Channel is interpreted to have occurred at c.1.1 Ma, and here this erosion roughly corresponds with deposition of Sequence S. The relationship between erosion and deposition may in some areas be vague, but commonly the formation of URU seems to correspond to the deposition of the glacigenic debrites in sequences R and S.

In the period after the URU was formed, the inner shelf appears to have experienced a slight uplift, whereas the outer shelf subsided. Quantification is uncertain, and the subsidence has varied.

The general development on the mid-Norwegian shelf, with erosion on the inner shelf, transport /erosion on the mid shelf, and deposition on the outer shelf and slope, seems to coincide with a continuous subsidence on the outer shelf. In areas where several palaeo-shelf surfaces are observed, they commonly show a decreasing northwestward dip in younger surfaces.

As the average westward dip of the URU is generally greater than the dip of the present sea floor, a subsidence of the outer shelf is probable. The topography of the URU, however, is variable, and due to lack of knowledge of the dip of the original surface, it is impossible to estimate subsidence rates.

Prominent iceberg scours at a depth of at least 1000 m below the present sea level occur at the top of the thick unit R3. These deposits correspond to a major glacial impact in the northern areas, and enormous icebergs were possibly produced during the final shelf-edge break-up of this ice sheet. If no margin subsidence occurred after the grooves were formed, the largest icebergs would have grounded at 850-900 m water depth. As far as we know, such dimensions of Antarctic icebergs have never been reported, and it therefore seems likely that the margin must have subsided since the ice scours were formed c. 300,000 years (?) ago. Quantification of the subsidence, however, will be highly speculative.

The Norwegian Channel Ice Stream supplied a great volume of debris to the North Sea Fan during the last three-four glaciations. A few other ice streams supplied debris directly to the margin, but most ice streams from the mainland fed ice/debris to the extensive marine ice sheet, and were of indirect importance for the development of the shelf and margin. The ice sheet(s) operated on a wide scale, were mainly erosive at an inner-mid shelf position, and commonly deposited the transported debris on the outer shelf and beyond the shelf edge.

The transparent and acoustically massive, seismic facies commonly observed in till tongues and sediment wedges at the shelf edge are possibly related to deposition from extensive ice sheets operating on a wide front. Such deposits commonly show a sharp pinch out in the upper slope. In contrast, trough mouth fans deposited from fast-flowing ice streams supplying debris to the shelf edge usually comprise numerous debris-flow lenses, commonly distributed far downslope from the ice-grounding zone.

Several ice streams flowed periodically across the Møre shelf (Buadjupet, Onadjupet), and the short distance to the glaciated mountain range may indicate a rapid response to climatic changes. A fast-flowing ice stream supplied debris to the slope off Trænadjupet during the two last glaciations. The area between Haltenbanken and Trænabanken (Sklinnadjupet), has during the last three to four glaciations been the main ice-drainage route in the northern areas.

The third last glaciation reaching the shelf edge was very extensive, and deposited up to 300 m of glacigenic material on the slope (unit R3).

The glaciation(s) during the Elsterian Complex seem to have been most extensive in the Haltenbanken - Trænabanken region, and most of the debris (unit R3) was deposited beyond the shelf edge. The final shaping of the upper angular unconformity (URU) seems to be related to this major glacial event. The ice sheet reached the shelf edge along the entire margin. Although the thickness of the R3 unit south of the Haltenbanken area was less than farther north, the glaciation was also extensive along the margin adjacent to the Storegga Slide. Parts of these deposits were subject to a major sliding event in the Storegga area at the end of the glaciation. Glacigenic debris-flows were deposited at the North Sea Fan, but the amount was far less than during the Weichselian, indicating that the Norwegian Channel Ice Stream was only moderately active during this period.

Thick stratified sediments (units R1/R2) on the shelf and slope indicate a long period with ice-free conditions, and/or a period with a high supply of marine/glaciomarine sediments.

Above the glacigenic debris in unit R3, stratified sediments accumulated on the slope (units R1/R2). Up to 150 m thick deposits occur where deep slide scars exist in the Storegga area, and the deposition seem to be largely controlled by contour-parallel currents. These sediments correspond to stratified sediments on the shelf, locally being up to 100 m in thickness in the outer Haltenbanken region and commonly 10-30 m east of Skjoldryggen. During interglacials, the input of marine sediments to the shelf was negligible, and possibly most of the sediments were glaciomarine, deposited mainly during a period when the ice sheet did not extend beyond the inner shelf. It is, therefore, possible that the thick stratified sediments represent deposition during two glacial-interglacial cycles.

During the second last glaciation (the Saalian), the ice sheet deposited a lobate-shaped unit on the outer shelf and margin in the Skjoldryggen region. The Saalian Ice Sheet did not extend to shelf edge in the outer Trænabanken and Haltenbanken regions.
The lobate shape of the unit, including several of the prograding till tongues within the unit, indicate that ice from a large area on the mainland coalesced between Haltenbanken and Trænabanken, and became a major ice stream. On the outer part of the shelf, the ice masses had enough space to operate on a wider front, and lost the character of a fast flowing ice stream. The ice was thus incorporated into the extensive ice sheet, with an abundant supply of debris to the outer grounding zone where wedge-shaped till tongues commonly formed.
As the till tongues prograded successively westwards, the grounding zone of the ice sheet finally reached the shelf edge. The grounding zone was possibly fairly stationary at the shelf edge during the deposition of the youngest till tongues. The deposited debris extend up to 50 km west of the present shelf edge, where the unit shows sharp 'pinch out'.

An ice stream from Vestfjorden followed Trænadjupet to the shelf edge, and the first main shaping of this transverse trough probably occurred in this period. The Saalian ice sheet did not extend to shelf edge in the outer Trænabanken region.

The Saalian ice sheet did not deposit glacigenic debris beyond the shelf edge in the area between Skjoldryggen and Frøyabanken. Several northwestward prograding till tongues in the Haltenbanken region, however, show evidence of an active ice front with deposition in a mid to outer shelf position.

Very thick Saalian glacigenic deposits occur at the shelf edge and upper slope off Møre. The main ice drainage was located between Buagrunnen and Frøyabanken, and in Onadjupet.
The thickest deposits (270 ms twt) are found in the upper slope just north of the central Storegga slide scar, in the area of Storneset. On the upper slope west of Buagrunnen a thick segment of the unit remains, evidently not affected by sliding. Reconstruction of the original deposits indicates that a depocentre of glacigenic sediments up to at least 200 m thick existed at the shelf edge/upper slope from outer Frøyabanken to Langgrunna, with a centre outside the present Buadjupet.

The sediments have the character of a trough mouth fan ('the Buadjupet fan'), indicating that ice streams supplied much of the material. Ice streams from the mainland coalesced to a major ice stream between Frøyabanken and Buagrunnen, and another ice stream flowed out through Onadjupet farther south.

Thick Saalian sediments occur along the shelf edge of the Måløy Plateau, indicating that the ice sheet extended to the shelf edge along the entire region. The Norwegian Channel Ice Stream was moderately active during the Saalian, depositing much less debrites than during the Weichselian.

The stratified sediments representing the period between the peak Saalian and Weichselian glaciations are thin compared to the equivalent unit in the previous ice-free period.

Most of these glaciomarine and marine sediments occur on the slope, and as the unit is commonly less than 40 m thick, the contourite development is less evident. As no sliding occurred after the Saalian glaciation, there was no relief available for effective catchment of such sediments. The deposition represents a period of possibly more than 100,000 years with ice-free conditions on the outer shelf. On the outer Haltenbanken, a c.15 m thick layer of stratified sediments occurs beneath the Weichselian tills. The Eemian INO3-horizon is inferred to be within this layer, which acted as the main slip plane in the northern part of the Storegga Slide.

The extensive Late Weichselian Ice Sheet extended to the shelf edge along the entire margin.
At least two main phases of ice advance to the shelf edge occurred during the Late Weichselian. Glacigenic deposition beyond the shelf edge appears to have occurred mainly during the last glacial maximum 27,000 – 16,000 ^{14}C-years before present. Onshore data indicate an ice-free period within this time interval. The prominent ridge at the shelf edge west of Sklinnadjupet (Skjoldryggen) was formed as a terminal moraine, with a final shaping of the topography during a late advance. The very irregular topography east of Skjoldryggen probably represents the effects of glaciotectonic processes. Earlier Weichselian ice sheets are unlikely to have reached the shelf edge in the northern area. The Late Weichselian advances were locally erosive on the outer shelf.

The ice sheet probably operated on a wide basis, with enhanced ice drainage in some areas. A prominent ice stream flowed out Vestfjorden/ Trænadjupet, supplying debris to the slope. Another major ice stream probably flowed in the northwest continuation of Sklinnadjupet.

In the outer part of Haltenbanken and its adjacent upper slope, an up to 150 m-thick wedge comprising several till tongues occurs above stratified sediments. Farther south, the Storegga Slide displaced and remoulded these glacigenic sediments, utilizing the INO3 horizon within the stratified sediments as a glide plane.

The Weichselian Ice Sheet was very dynamic on the Møre shelf. Active ice streams flowed in the main troughs. Thick glacigenic deposits accumulated on the upper slope. An inferred combined Weichselian / Saalian depocentre with c. 300 m of glacigenic debris was located in the upper slope where the deep Storegga slide scar occurs.
Seismic data show a complex geology with several depositional and erosional cycles. Due to the short distance to the mountain areas, it is likely that the ice reached the shelf edge in this area several times during the Weichselian. Our interpretation shows that ice streams flowed in the main transverse troughs. The Storegga Slide removed most of the glacigenic deposits beyond the shelf edge, but a unit at least 100 m thick was deposited on the upper slope west of the main ice-drainage routes. These sediments accumulated above the very thick Saalian deposits in the same area. Most likely, the last two glaciations deposited as much as c. 300 m of debris in the depo-centre. This depocentre, located above thick contourites of Sequence R, coincides with the deepest slope incision of the Storegga Slide. Therefore, it seems plausible that parts of the Storegga Slide development are related to the location of this depocentre.

The Norwegian Channel Ice Stream was very active during at least three periods of the Weichselian. Debris-flow deposits accumulated on the North Sea Fan, up to 400 m thick.
The North Sea Fan is the largest and most prominent trough mouth fan sequence in the study area, and comprises numerous debris-flow lenses. Northwest of the grounding line, sediments were redistributed by debris-flows transporting sediments into the deep ocean on slopes of only 0.3-0.7 degrees. The development of the fan indicates that the Weichselian ice probably was located differently from earlier glaciations. An ice accumulation centre over southeastern Norway and adjacent parts of Sweden may support the evidence of immense ice streaming along the entire Norwegian Channel, originating in the deep Skagerrak trough.

Several large slides have occurred in the same area as the Storegga Slide. The second last, mega slide occurred approximately 300,000 years before the Storegga Slide.
The second last major slide in this area accumulated up to 200 m of slide deposits. This slide occurred at the end of the third last extensive glaciation, or shortly after the deglaciation, but the age of this glaciation is uncertain (within the age window of 200-400 ka). An indirect 'age approach' has been applied in the northern slope where the top of the slide scarp is sharply defined within a thick succession of stratified sediments. Comparison of this level and the Eemian INO3-horizon, indicates that an age of 300-400 ka is more likely than 200-300 ka. This indicates a period of approximately 300,000 years between the second last major slide and the Storegga Slide. The length of the period between the second and third last slide is probably in the same order.

The slides seem to be cyclic events. Weak layers within the stratified sediment sequences acted as slip planes. The second and third last major slides in the Storegga area occurred 'close' to the end of an extensive glaciation.
The seismic data indicate that the second and third last slide occurred after a peak glaciation, but it is impossible to be specific about the exact timing. The present data show that thick contourites preferentially infill slide scars, and in the eastern slope there are no indications of sliding or instability in these stratified sediments. It is therefore likely that the slides occurred shortly after the deglaciation of the shelf (0- 20,000 years?). As for the Storegga Slide, stratified sediments were utilized as slip planes for the older slides.

No major sliding event is observed in the Storegga Slide area at the end of the extensive Saalian glaciation.
Although glacigenic deposits up to 200 m thick were deposited on the upper slope off the Møre shelf, no major sliding event occurred after the Saalian glaciation. As these sediments were located above thick contourites in the area of the central Storegga Slide, this accumulation may have been a 'pre cursor' for parts of the Storegga Slide development. As mentioned above, the Tampen Slide, located on the North Sea Fan, possibly occurred in early Weichselian time.

On average, the frequency of major sliding events is less than the frequency of extensive glaciations.

Three slide scars corresponding to different slides are found above each other some kilometres north of the Storegga Slide. The location coincides with Bright Spot reflections beneath, and a Bottom Simulating Reflector.
We have not studied this possible relationship in detail, but the observation may be of importance and should be followed up in other investigations. Two of these slides represent major events, and the slides probably developed retrogressively towards the north. The third slide is a very small and local event at the northern flank of the Storegga Slide.

The eastern slope adjacent to the Vøring Plateau (between the Storegga Slide and the Nyk Slide/Trænadjupet Slide) is regarded to have been a stable segment of the margin for a long time.
A possible slide removing parts of Sequence Naust R may be associated with a major collapse event in the Helland Hansen Arch, but as there are only a few seismic lines in this area, the interpretation is uncertain. Although some local sliding events can be recognised, the seismic data show that this part of the margin has been stable during the development of the Naust Formation.

1. INTRODUCTION

This study intends to elucidate the evolution of the mid-Norwegian margin, with emphasis on the last c. 3 million years when the Naust Formation was deposited. The main objective has been to improve our knowledge of offshore depositional sequences through time. Emphasis has been given to improving the understanding of large-scale depositional systems, and to link this information to areas where risk analyses have been performed based on detailed investigations. The development of the outer margin from break up in earliest Eocene time (c. 55 Ma) when seafloor spreading was initiated in the Norwegian-Greenland Sea and until the start of deposition of the Naust Formation is outlined.

Several large studies have established a regional geological/seismostratigraphic framework for the Møre/Vøring basin areas. During several stages and phases of the Seabed Project the evolution, stratigraphy and depositional environment of the continental slope have been studied. The focus of this study has been to extend the stratigraphy from the continental slope onto the shelf and link this with the glacial geology on the Norwegian mainland.

Scope of work

Approximately 25,000 line kilometres of seismic data, comprising most of the 2D high resolution seismic data from the Seabed Project in addition to conventional exploration 2D seismic lines on the shelf have been utilised in this study. The basis has been interpretation from Svitzer and Norsk Hydro of key reflectors, and these are extended onto the shelf. The regional shallow seismic data base from IKU has been utilised on the shelf areas, especially in the study of the sequences above the Upper Regional Unconformity (URU). During the summer 2001 a seismic survey of high resolution 2D seismic data were collected by Norsk Hydro, and these data were incorporated into the study.

Our main objectives have been:

-Link the seismic stratigraphy of the slope and shelf areas, and correlate/extrapolate available chronostratigraphic data.

- Extend the stratigraphic framework in the Naust Formation established in the Haltenbanken area southwards to the Møre shelf (east of the Storegga slide).

- Interpret Base Naust and some other key horizons, north of 65 °N, in order to improve the understanding of the Haltenbanken-Trænabanken region.

- Extend the stratigraphic framework established in the northern part of the Norwegian Channel/Måløy plateau northwards to the Møre shelf.

- List all stratigraphic nomenclature used in the different studies in a correlation table. Propose a common stratigraphic nomenclature for the area.

- Make an overview of published datings of sample/borehole material on the shelf, and relate them to the seismic stratigraphy.

- Summarize relevant knowledge of glaciations/interglacials, climate, topography, uplift and propose a correlation to the offshore development.

-Improve and extend the Seabed Project geological model to include the development of the mid-Norwegian shelf during the Plio-Pleistocene (Naust Formation).

2. CENOZOIC DEVELOPMENT OF THE MARGIN

2.1 Introduction

The major post-glacial Storegga and Trænadjupet submarine slides occurred along the Jan Mayen and Bivrost Lineaments respectively, two major tectonic boundaries that subdivide the Norwegian passive margin. Conditions necessary for sliding to occur at these sites relate largely to: 1) the margin architecture, and 2) the distribution of the major Plio-Pleistocene glacio-marine deposits. This summary focuses on tectonic factors that have played roles in shaping the margin architecture, thereby indirectly influencing the slide events.

Since submarine slides are gravitational phenomena, factors governing slope angle are of importance. On a passive margin, the slope is to a first order dictated by subsidence following break-up. Subsidence is essentially a thermal cooling effect governed by the degree of pre-break up thinning of the lithosphere. The Norwegian passive margin was subject to episodic extension between the Late Devonian collapse of the Caledonian Orogen and final rifting in Late Paleocene (e.g. Doré et al. 1999). Paleocene rifting was strongly influenced by the Iceland Plume (a hotspot). As a consequence of the plume influence, this final phase of rifting as well as break-up of the continent was marked by intense and voluminous magmatism; as a result one of the worlds largest igneous provinces developed (e.g. Saunders et al. 1997). Separation between Greenland and Norway was initiated in Early Eocene when the Norwegian – Greenland Sea began to open (e.g. Talwani and Eldholm 1977).

Greenland and Norway separated along a line running obliquely across the older rift grain, resulting in a progressively narrower rift margin northwards on the Norwegian side (Fig. 2.1.1). As a result, the Lofoten margin is narrow while the adjacent Vøring margin segment is wide. In addition, the Paleocene rifting was more focussed along the Lofoten margin, resulting in a significantly steeper slope. The Møre margin is narrower than the Vøring margin due to an original step in the margin at the East Jan Mayen Fracture Zone. The conjugate East Greenland margin shows the opposite relationship, being narrow to the south and wide to the north.

Subsidence along the entire Norwegian-Greenland Sea margins was also strongly affected by the degree of magmatic underplating beneath the crust. Because underplating suppresses the subsidence (e.g. White 1997), areas with less underplating developed steeper slopes. This was the case for Lofoten margin and the northernmost Møre to southwestern Vøring margin. These two areas coincide with the Storegga and Trænadjupet slides.

Post-break up deformation has also influenced the mid-Norwegian margin, which is marked by a series of mid-Cenozoic compressional domes (Lundin and Doré 2002). Onshore, two Neogene uplift areas have been proposed (Riis 1996). The onshore uplifted areas are of much larger dimension than the mid-Cenozoic offshore domes. One such onshore uplifted area is situated in the greater Lofoten area, and the other is centred in Jotunheimen in southern Norway. The high altitude of these areas probably preconditioned early growth of ice caps during the Neogene climatic deterioration (Fig. 2.1.2) (Eyles 1996, Zachos et al. 2001). The location of the uplifts in turn appear to have governed the flow of major glaciers and thereby indirectly influenced the distribution of the Plio-Pleistocene deposits on the shelf (Section 2.7).

The westward prograding Neogene deposits are dominated by Late Pliocene to Pleistocene sediments. Approximately 50% of the entire Cenozoic section on the shelf was deposited during the Plio-Pleistocene. A volumetrically small but laterally Oligocene unit can be grouped with the Plio-Pleistocene sediments based on geometry, but the origin of the sediments is likely different. The Oligocene deltaic unit was deposited in a non-glacial environment related to a relative sea level drop (Rokoengen et al. 1995), possibly caused by minor uplift of the shelf during mid-Cenozoic compression (Lundin and Doré 2002)

The Jan Mayen and Bivrost Lineaments are very likely related to major basement weaknesses, and the lineaments lie beneath the break-away areas of the Storegga and Trænadjupet Slides respectively (Section 2.3). Although reactivation can be inferred to have taken place repeatedly in the Cenozoic along at least the Jan Mayen Lineament (Doré and Lundin 1996), there is no recorded modern seismic activity associated with either lineament, nor are there any reported signs of recent fault offset. Based on the NW-trend of the lineaments and the small angle to the direction of current maximum horizontal stress, a significant strike-slip component would be expected should slip occur. Considering that the slide paths follow the NW-trend of the lineaments, it is conceivable that any visible offset at the seafloor was removed by the slides. Should strike-slip offset exist in the subsurface, this would not necessarily be easy to recognize in the seismic data sets. While possible seismic activity along the lineaments remains speculative, it appears clear that the lineaments have influenced the margin architecture, and that they indirectly have played a role in the slide events.

It has been suggested that strain accumulated during the glacial periods, was released by major earthquakes upon deglaciation (Olesen et al. 2000). Fault scarps, rock avalanches, and gravity faults onshore Norway support the concept. Post-glacial earthquakes of magnitude 7.3-7.6 have been estimated in northern Norway and Sweden (Stuoragurra and Pärve Faults respectively). Recent mapping in the Romsdalen area (Blikra et al. 2001) has revealed a several km long post-glacial reverse fault with c. 2-3 m displacement. While there is no proof that the Romsdalen fault activity was of a magnitude that could have triggered the Storegga Slide, its presence at least demonstrates the potential importance of post-glacial faulting in the general region.

2.2 Influence of break-up magmatism on Norwegian margin architecture

Break-up of the margins surrounding the Northeast Atlantic and Norwegian-Greenland Sea were strongly affected by the presence of the Iceland plume, a hotspot rooted at the core-mantle boundary. A major effect of the plume was to elevate the asthenosphere temperatures, which together with extension resulted in large-scale magmatism prior to and during break-up. The magmatism occurred as extrusives over the margin edges, intrusives into the sedimentary basins and basement, and as underplating of the crust. The region subject to this magmatism has been called the North Atlantic Volcanic Province (NAVP), and extends from the Charlie Gibbs Fracture Zone in the SW to the Lofoten margin in the north (Fig. 2.2.1), a distance of c. 2000 km. Across the trend of the rifted margins, magmatism is seen to have affected a region stretching from Baffin Island in Eastern Canada to the British Isles, a pre-drift (pre seafloor spreading) distance of c. 2000 km. Broadly speaking, the plume-induced magmatism occurred within a more or less circular area with a diameter of c. 2000 km. The pulse of magmatism occurred between Late Danian (c. 62 Ma) and break-up in earliest Eocene (c. 55 Ma) (e.g. Saunders et al. 1997).

With respect to the margin architecture, underplating plays a role. Underplating relates to decompressional melting of the mantle, whereby melts rise buoyantly and pond beneath the continental crust, where they reach a density equilibrium (White and McKenzie 1989). The addition of this melt at the base of the crust effectively increases the thickness of the continental crust, and thus suppresses thermal subsidence. As may be expected, the underplated material has not been evenly distributed along the length of the NAVP margins, which has resulted in differential subsidence. Other factors influencing the subsidence patterns and margin architecture are: 1) the degree of thinning of the lithosphere by rifting, and 2) sedimentary loading.

Detailed studies of seismic facies along volcanic passive margins led to the advent of seismic volcanostratigraphy (Planke et al. 1999). Application of this seismic mapping technique to the mid-Norwegian passive margin permitted definition of areas subject to different types of volcanism during break-up (Berndt et al. 2001). Of particular interest are the observations of margin segments subject to subaerial versus submarine volcanism (Fig. 2.2.2). The difference between subaerial and submarine volcanism can be attributed to variations in the degree of underplating. Areas subject to subaerial volcanism are associated with large amounts of underplating, while areas of submarine volcanism are less underplated. Therefore, an important element of the margin architecture can be attributed to the spatial distribution of underplating.

Along the Norwegian margin a correlation is seen between the sites of the Storegga and Trænadjupet submarine slides and margin segments where submarine volcanism prevailed (Figs. 2.2.2 and 2.2.3). Because the outer margin of these less underplated areas subsided somewhat more than adjacent areas, higher slope angles developed inboard of these areas during the passive margin subsidence following break-up (Fig. 2.2.4).

Various amounts of underplating also resulted in a different expressions of the transition area between continental and oceanic crust. Areas of significant underplating developed prominent marginal highs which may have acted as buttresses for the toe area of potential slide areas, thereby reducing the likelihood of sliding (Fig. 2.2.5). Conversely, areas of less underplating lack these marginal highs. These relationships were first proposed by Berndt (2000).

2.3 Influence of basement weaknesses and rifting history on architecture

The basement grain (weaknesses) of the Norwegian margin is dominated by northeast and northwest trends, and a subordinate north trend (Doré et al. 1997). Of particular interest to the Storegga and Trænadjupet Slides are the NW-trending Jan Mayen and Bivrost Lineaments (Figs. 2.2.3, 2.2.4 and 2.2.6). The break-away area of Storegga and Trænadjupet Slides are located along the landward projection of these lineaments respectively.

The East Jan Mayen Fracture Zone (EJMFZ) is a prominent oceanic transform that once linked the Aegir and Mohns spreading ridges (Fig. 2.1.1). The fracture zone forms a shear margin boundary along the SW edge of the Vøring Basin, marking the step between the Møre and Vøring marginal highs. The Jan Mayen Lineament is a diffuse landward continuation of the EJMFZ and defines an apparent shift between the Møre and Vøring Basin axes and flanks (e.g. Brekke 2000). Thus, while the oceanic fracture zone is very clear, the possible landward continuation is more vague.

The presence of a major lithospheric shear zone along the Jan Mayen Lineament is corroborated by Late Paleocene (c. 56 Ma) alkaline intrusions south of the Frøya High (Bugge et al. 1980; Prestvik et al. 1999). It is difficult to perceive how these mantle-derived igneous plugs could have penetrated this relatively thick portion of the margin without utilizing pre-existing steep weaknesses. Torske and Prestvik (1991) and Prestvik et al. (1999) even suggest that the Jan Mayen Lineament weakness extended well into the central East Greenland margin. Their argument is based on the presence of similar age and type intrusions onshore Greenland. If so, it is likely that Jan Mayen weakness determined the major step in the margin that formed when the Norwegian Sea opened (the step between the Møre and Vøring Basins). This would be conceptually similar to the way the Senja Fracture Zone developed along the old De Geer Zone.

Other circumstantial evidence supporting that the lineament likely is a steep major basement weakness include: 1) the en echelon distribution of mid-Cenoozic domes along the lineament (Fig. 2.3.1), 2) distribution, thickness and quality of Paleocene reservoir sandstones in the Ormen Lange area, and 3) segmentation of the Ormen Lange field (6305/5-1 and 7-1 lying within the gas accumulation while 6305/1-1 to the north is dry). Based on regional maps, it is possible to infer changes in the local basin shapes above the lineament. This is revealed by comparison of the isochron maps for Neogene (Fig. 2.3.2) and the Eocene to Oligocene (Fig. 2.3.3).

The distribution and shape of these local basins through time is here only outlined in the broadest sense. Nevertheless, it appears conceivable that local inversion related to lateral motions along the Jan Mayen Lineament may have been the cause of the noted sedimentary thickness changes rather than large-scale basin inversion. On a more detailed level, based on seismic data from the Ormen Lange Dome, it appears that the Early Paleocene sequence has been inverted (Fig. 2.3.4). In contrast to the Jan Mayen Lineament, the Bivrost Lineament, is a prominent and visible tectonic boundary between the Lofoten area and the Vøring Basin (Blystad et al. 1995), but it does not appear to continue into a significant oceanic fracture zone. Neither the new magnetic map by NGU (Olesen et al. 1997), nor bathymetric maps reveal any obvious major oceanic transform outboard of the lineament. Thus, this continental weakness is well expressed but the oceanic fracture zone is not. It appears clear that the lineament acted as a major transfer zone during the Mesozoic rifting history. The narrow Lofoten margin is characterized by large simple half grabens, and the Paleocene stretching of this margin occurred over a narrower zone than along the Vøring margin.

Although the Hedda Dome (informal name for dome in PL 220) (Fig. 2.3.1) lies along the Bivrost Lineament it is not clear if the dome can be related to lateral motions along the lineament. However, it does appears clear that during Neogene uplift of the Lofoten margin the Bivrost Lineament acted as a hinge zone between the Vøring Basin and Lofoten margin (Brekke 2000).

2.4 Mid-Cenozoic compressional deformation

Mid-Cenozoic compressional deformation is well known on the mid-Norwegian margin (e.g. Blystad et al. 1995; Doré and Lundin 1996, Vågnes et al. 1998). It now appears clear that such domes also are present on the conjugate East Greenland margin (Lundin and Doré 2002).

Dating of the domes on the mid-Norwegian margin suggest several compressional events, possibly indicating a pulsating nature of the deformation. The driving mechanism for the compression is suggested to be plume-enhanced spreading (broadly speaking ridge push). A possible cause of the pulsating compression may be discrete periods of high flux in the Iceland Plume (White and Lovell 1997).

Of particular interest to the present study are the domes located along the East Jan Mayen Lineament, and the possible relationship between the compressional events and the location of the Lower Oligocene delta off mid-Norway (next section).

The East Jan Mayen Lineament can be inferred to have experienced periodic slip during Cenozoic. Several domes lie en echelon along the lineament, and have different histories. The trend of the domes is consistent with the expected strain caused by sinistral reactivation of a NW-trending basement lineament (e.g. Sylvester 1988). Based on thickness relationships and well control Lundin and Doré (2002) interpret that doming of the Ormen Lange Dome primarily took place between 1) Middle Eocene and Early Oligocene, and 2) in Early Miocene. The Nora and Edwarda Domes (informal names) developed in mid- to Late Eocene and in the Miocene. An unnamed dome situated SW of the Ormen Lange Dome is of Miocene age (Vågnes et al. 1998). The Modgunn Arch formed in the Miocene, although an older event is not precluded.

The southern part of the Helland Hansen Arch appears to have formed between Middle Eocene and end Oligocene. The northern part of the arch developed in Early Miocene. Determining the timing of the growth of the Helland Hansen Arch is complicated due to apparent development of the east flank by loading of the Late Pliocene and Pleistocene prograding shelf (Stuevold et al. 1992; Kjeldstad et al. 1999). Thus, the Helland Hansen Arch may initially have been an asymmetric west-verging monoclinal fold, or at least a broader asymmetric fold. A north-trending Plio-Pleistocene dome extends between the central to northern Helland Hansen Arch and the Gjallar Ridge area (Fig 2.3.1). This Plio-Pleistocene dome as well as the eastern flank of the Helland Hansen Arch are strong candidates for load-induced folding related to the Plio-Pleistocene progradation of the shelf.

The top Oligocene structural map (Fig. 2.3.2) reveals the compressional folds clearly. When this structural surface is compared with the Neogene isopach map (dominated by the Plio-Pleistocene sediments) it is clear that a significant thick deposit rests directly inboard of the Ormen Lange and Helland Hansen Arch (Fig. 2.3.2). The load from this thick sequence can be inferred to have gradually forced down the east flank of the arch. Since the Plio-Pleistocene sequence formed by westward progradation, modification of this major fold occurred over time. Conceptually, the sedimentary load acted as a rolling pin moving westward over pre-existing, but initially more weakly expressed fold structures.

2.5 Oligocene delta – a response to mid-Cenozoic compression?

A deltaic deposit mapped between the southern tip of the Lofoten Islands and the southern Trøndelag Platform (Figs. 2.3.1) (Henriksen and Weimer 1996) could indirectly indicate mild compression and associated uplift of the shelf. The deposit is named the Molo Formation (Gustavson and Bugge 1995), after a positive bathymetric feature related to the formations subcrop against seafloor. Rokoengen et al. (1995) classified this as delta-like coastal deposit, that probably formed in a wave-dominated environment with extensive long-shore drift. Henriksen and Weimer (1996) interpreted the deposit to be of Late Pliocene to Pleistocene age based on seismic data. More recently, Eidvin et al. (1998) dated the formation to Oligocene, based on biostratigraphic and Sr-isotope data. According to Eidvin et al. (1998) this unit was deposited in an inner shelf environment and is onlapped by the voluminous Late Pliocene to Pleistocene prograding glacial deposits off mid-Norway, implying a hiatus of c. 20 Ma.

The 10-15 degree dipping clinoforms of the Oligocene sediments are steeper than those of Late Pliocene - Pleistocene age, and the unit also stands out lithologically and biostratigraphically. The N-S extent of the Oligocene deltaic unit lies inboard of the compressional domes on the Norwegian margin (Fig. 2.3.1), and its age falls within the first phase of doming of the major Helland Hansen Arch and Ormen Lange Dome. Rokoengen et al. (1995) interpreted that the formation formed by a relative drop in sea level. Lundin and Doré (2002) suggest that the relative sea level drop was caused by mild uplift of the shelf in response to mid-Cenozoic compression.

2.6 Neogene uplift

The Fennoscandian mountain range consists of two higher regions, separated by the low-lying Trøndelag region. The mountain shape is an effect of two superposed uplift events, the first being of Palaeogene age and the second of Neogene age (Riis 1996).

The region of Palaeogene uplift extends from an 800 m high in central southern Norway to its 1400 m culmination in northern Sweden (Riis 1996), and it has been related to the Paleocene phase of extension that led to opening of the Norwegian Sea. The Neogene uplifts on the other hand are two separate highs, centered on the Lofoten area and the Jotunheimen area (Fig. 2.6.1). These uplifts are approximately 1000 m in magnitude and modulated the Paleogene uplift into the current mountain shape.

Other widely spaced Neogene uplift areas are recognized along the margins surrounding the Norwegian-Greenland Sea (Fig. 2.6.2). In addition to the two mentioned areas in Norway, uplifted areas are Svalbard, East Greenland, Scotland, and the Faroe Islands. A large part of the Barents Sea shelf was also uplifted and eroded. The Neogene uplifts are recognized as a topographic precondition for nucleation and growth of ice sheets as the climate deteriorated in Late Cenozoic (Eyles 1996).

The interpreted initiation of uplift differs between workers. Stuevold and Eldholm (1996) interpret that the domes started growing in Late Oligocene or earliest Miocene and were amplified by the Late Pliocene to Pleistocene Northern Hemisphere glaciation. Their dating of the onset is based on recognition of IRD prior to 2.6 Ma in ODP wells 642-644. Interpretation of Apatite-fission track (AFT) data forms the basis for Rohrman and van der Beek's (1996) proposal of onset of tectonic uplift of the southern Norway dome at c. 30 Ma; the magnitude and rate of uplift as well as associated denudation increased through the Neogene. The Neogene part of the Lofoten uplift has a strong Plio-Pleistocene component (Riis 1996). In Svalbard, onset of uplift has been loosely constrained between earliest Oligocene and Pliocene (36-5.5 Ma) based on geologic observations (Vågnes and Amundsen 1993). Mapping of major peneplanation and weathering surfaces onshore Norway and on offshore seismic data, led Riis (1996) to interpret a Pliocene and Pleistocene age for the Neogene uplifts.

Various mechanisms have been proposed for the Neogene uplifts. Stuevold and Eldholm (1996) conclude that a thermal origin is likely, and suggest shallow convection, or a period of high flux from the Iceland Plume. Rohrman and van der Beek (1996) put forth a model of aesthenospheric diapirism and associated partial melting. These topics are indeed intricate, and are beyond the scope of this summary.

Without doubt, the sedimentary record reveals significantly higher rates of deposition during the Late Pliocene to Pleistocene, when 50% or more of the Cenozoic sediments on the shelf were deposited.

2.7 Asymmetric shape of the Neogene uplifts

The progradation of the Plio-Pleistocene glacial wedge on the mid-Norwegian shelf is not evenly distributed, but consist of a distinct thick deposit on the Trøndelag Platform and inner Vøring Basin (Fig. 2.6.1), and the North Sea fan which is located in the southern Møre Basin near the northern North Sea boundary. The largest deposit on the entire Norwegian margin is the Bjørnøya fan shed southward off the SW Barents Sea shelf.

The shape of the paleic surface in southern Norway is recognized to be asymmetric (steeper to the west) by Holtedahl (1960) (Fig. 2.7.1). This is also the case for the Lofoten uplift (Riis 1996). However, the latter area is more complicated because the uplift straddles the mainland and the strongly rifted Lofoten margin. Riis (1996) relates the development of the Norwegian Channel to late uplift of the southern Norway dome. Likewise, he relates subsidence of the Lofoten margin to uplift of the Lofoten island chain.

2.8 Recent earthquakes

Analyses of recently recorded and historically documented earthquakes on- and offshore Norway have been reported by Olesen et al. (2000), Dehls et al. (2000), and Byrkjeland et al. (2000) and are only briefly mentioned here.

Of particular interest is the conclusion by Olesen et al. (2000) that several magnitude 7+ earthquakes occurred shortly after deglaciation of northern Fennoscandia (c. 9300 year BP). It is suggested that strain was able to accumulate beneath the large inland ice sheet for 10,000 years or more, to be released in large earthquakes upon deglaciation. The c. 80 km long Stuoragurra reverse fault is a major post-glacial structure in Finnmark, and was associated with an estimated magnitude 7.3 earthquake. The Pärve Fault, near the Norwegian-Swedish border was larger yet, with an estimated magnitude of 7.6. While no conclusive evidence was found by Olesen et al. (2000) for major post-glacial faulting in southern Norway, there are indications of earthquake-generated rock avalanches and gravitational faults. Recent mapping in the Romsdal area has revealed a significant reverse fault, several km in length and with c. 3 m displacement (Blikra et al. 2001).

A compilation of seismic activity by Byrkjeland et al. (2000) reveals a correlation between the major Plio-Pleistocene depocenters and earthquakes (Fig. 2.8.1). It is also evident that concentrations of earthquakes exist near the west flank of the two Neogene domal uplifts in Norway.

2.9 Vigrid diapir field

As mentioned in Section 2.3 several independent factors suggest that a deep-seated basement weakness exists along the Jan Mayen Lineament. Another possible NW-trending basement weakness may underlie the Vigrid diapir field (Figs. 2.9.1 and 2.9.2) (Hjelstuen et al. 1997). The diapir field is well expressed at seafloor (Fig. 2.9.3), and trends c. 15 degrees more westerly than the Jan Mayen Fracture Zone.

The diapir field is marked by a weak positive bathymetric ridge that can be followed from near the Vøring Escarpment to the NW flank of the Helland Hansen Arch, a total distance of c. 150 km. The diapirs affect the Pliocene and younger sediments, but do not seem to disturb deeper horizons like the diapir field around the Vema Dome does. Although no deep-seated basement weakness is defined in the area before, the linear diapir distribution and bathymetric expression point to the presence of such a weakness. Where the diapir field intersects the Helland Hansen Arch it is possible to distinguish possible collapse features.

The orientation of the diapir field is perpendicular to the orientation of the Kolbeinsey Ridge, and thus runs parallel its SE-directed ridge push. The origin of the diapir field is not clear, but it could originate from fluid release associated with seismic slip along a pre-existing deep-seated weakness. Alternatively, the weakly compressive stress from the ridge push may have opened faults and fractures permitting fluids to escape. No earthquakes are known along the trend of the diapir field (Olesen et al. 2000; Byrkjeland et al. 2000).

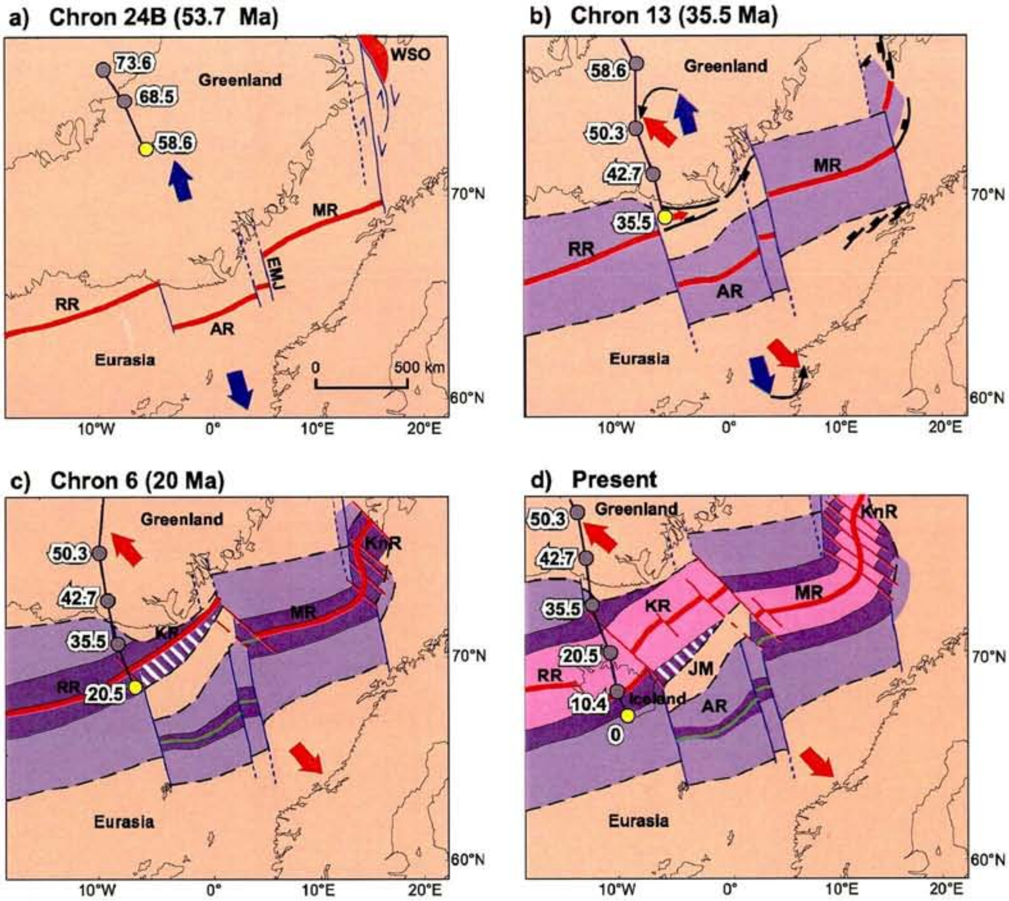


Figure 2.1.1. Plate tectonic evolution of Norwegian-Greenland Sea (from Lundin and Doré, 2002) . Grey and yellow dots mark the position of the Iceland Plume center; grey dots mark previous positions and yellow dots the approximate position at each reconstruction. Position of Iceland Plume center is from Torsvik et al. (2001). Note how the continents break up obliquely along the Mohns Ridge (MR).

Abbreviations: AR = Aegir Ridge; EJM = East Jan Mayen Fracture Zone; JM = Jan Mayen microcontinent; KR =Kolbeinsey Ridge, KnR = Knipovich Ridge; MR = Mohns Ridge; RR = Reykjanes Ridge

a) Initiation of seafloor spreading. The relative plate motion vector (blue arrows) is given by the trend of East Jan Mayen Fracture Zone and Senja Fracture Zone - Hornsund Fault Zone (blue lines). The West Spitsbergen Orogeny (WSO) took place in a restraining bend along the Senja Fracture Zone system.

b) Major plate reorganisation and change in direction of relative plate separation (from blue to red arrows). Rifting and associated magmatism occurred in East Greenland, along the SW Barents Sea margin, and possibly along the mid-Norwegian margin south to the northern Vøring Basin. The West Spitsbergen Orogeny was terminated. For the first time, the Iceland Plume center becomes directly aligned with an evolving spreading axis.

c) The Kolbeinsey Ridge propagated northward in East Greenland (between Chron 13 and 6C) and eventually separated the Jan Mayen microcontinent from East Greenland. Linkage between the Kolbeinsey and Mohns Ridges was achieved by development of the West Jan Mayen Fracture Zone (red lines). The Aegir Ridge was abandoned. Oblique opening of the NW-trending Senja Fracture Zone - Hornsund Fault Zone initiated the Knipovitch Ridge.

d) The plate configuration established following linkage of the Kolbeinsey and Mohns Ridges has been maintained to the Present.

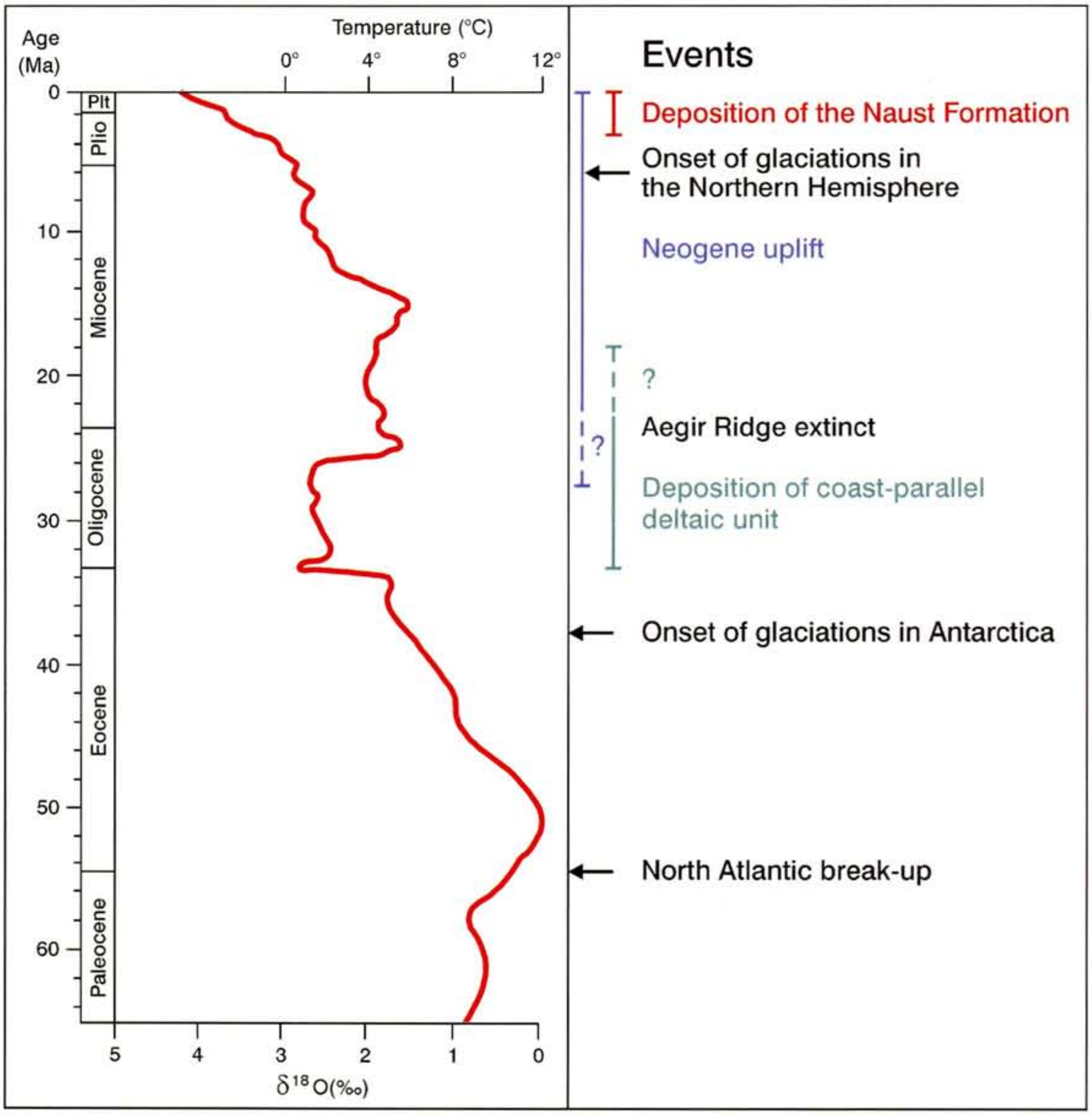


Figure 2.1.2 Generalized global deep-sea "temperature" curve during the last 65 Ma with major events related to the development of the mid-Norwegian margin. The deep-sea oxygen isotope records ($d^{18}O$) are based on several DSDP and ODP sites. After the ice sheets in Antarctica were established, the curve reflects both temperature and ice volume. After Zachos et al. 2001.

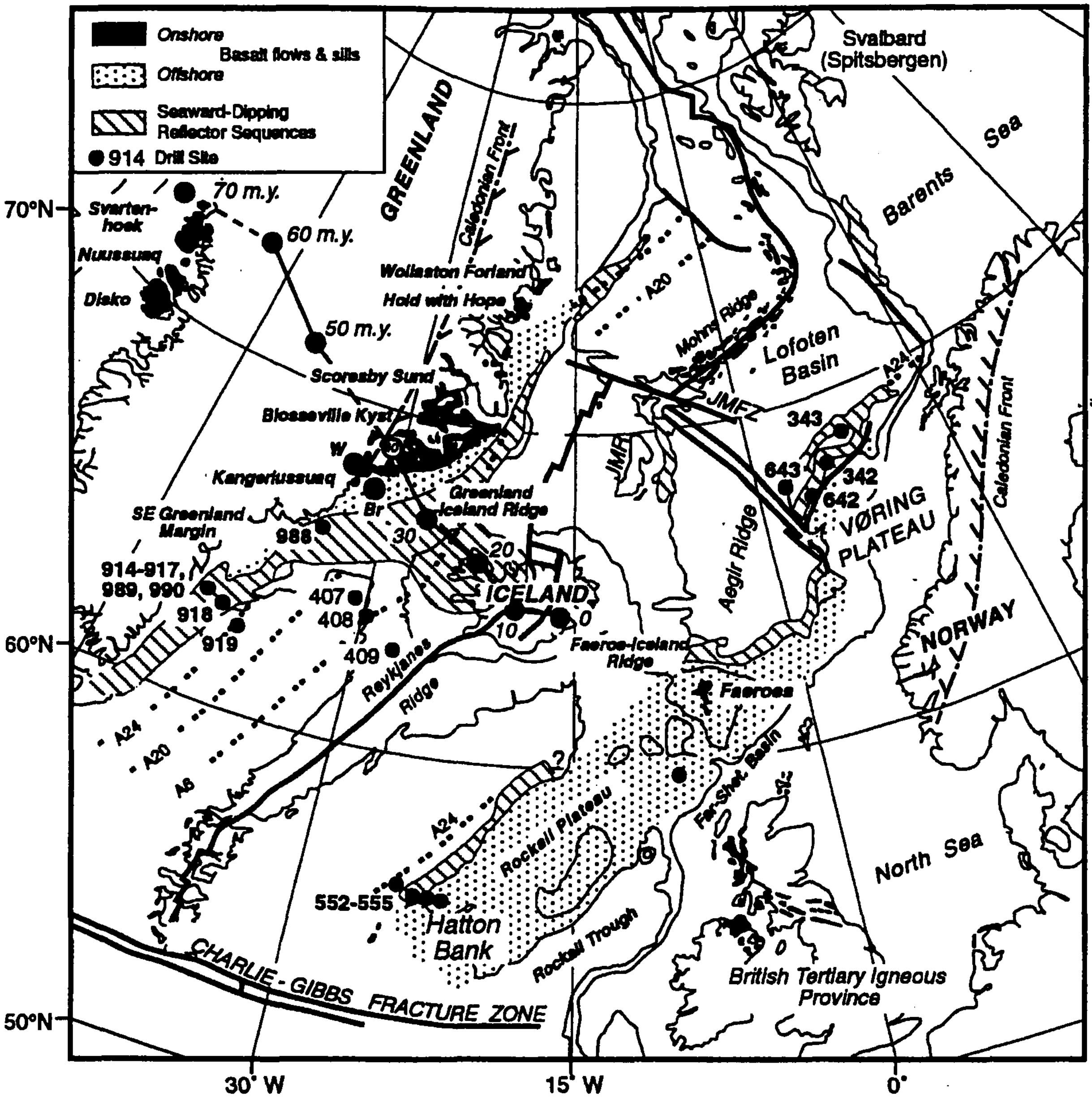


Figure 2.2.1. North Atlantic Igneous Province. After Saunders et al. 1997.

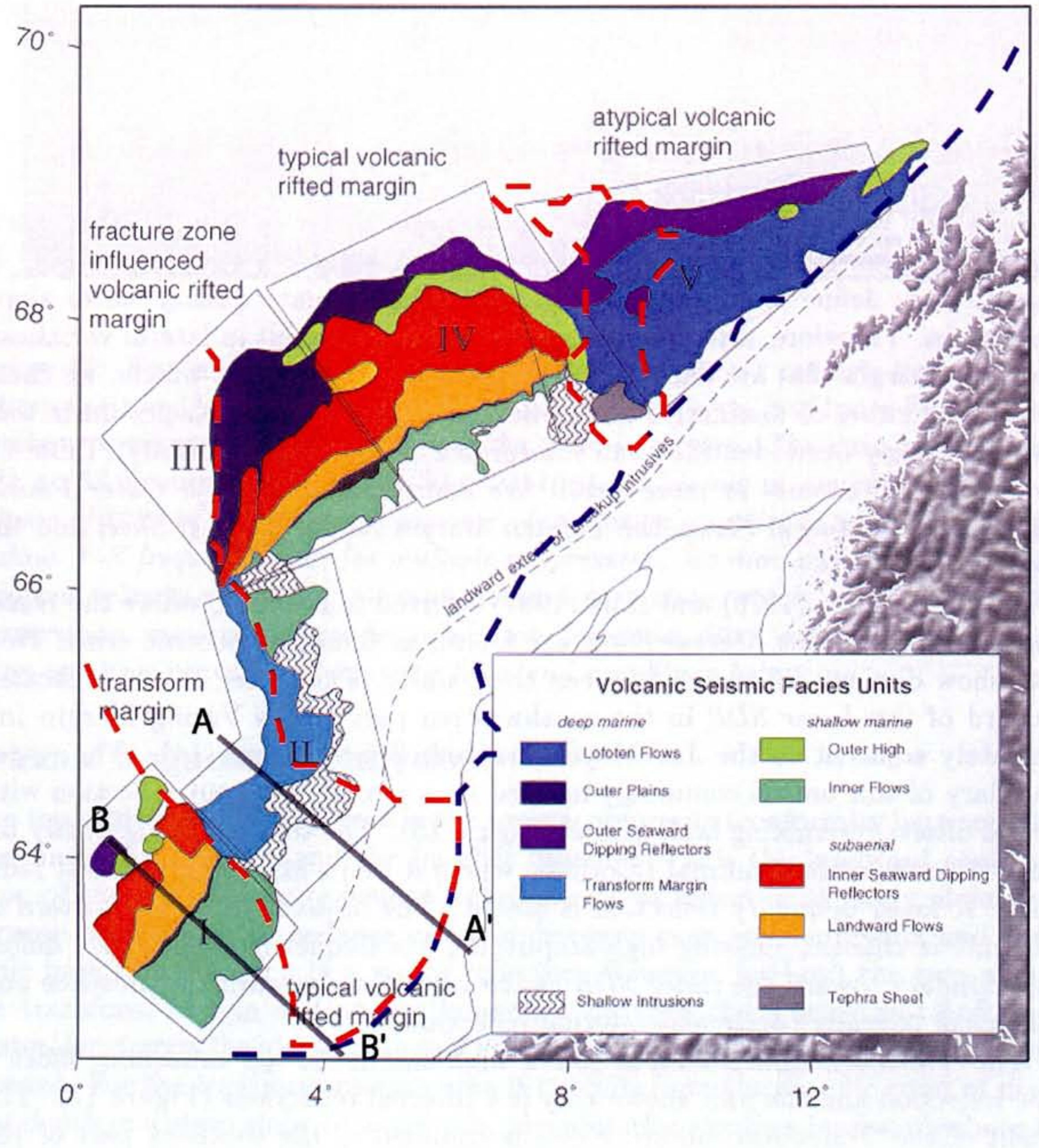


Figure 2.2.2 Distribution of volcanic seismic facies (From Berndt et al. 2001). Red dashed lines mark limit of Storegga and Trænadjupet Slides. Dark Blue dashed line marks the shelf edge. Transects A-A' and B-B' refer to idealized cross sections (Fig. 2.2.5). Note correspondence between slide location and margin segment associated with submarine volcanism. These areas are furthermore underlain by the Jan Mayen and Bivrost Lineaments (Figs. 2.2.3, 2.2.4 and 2.2.6).

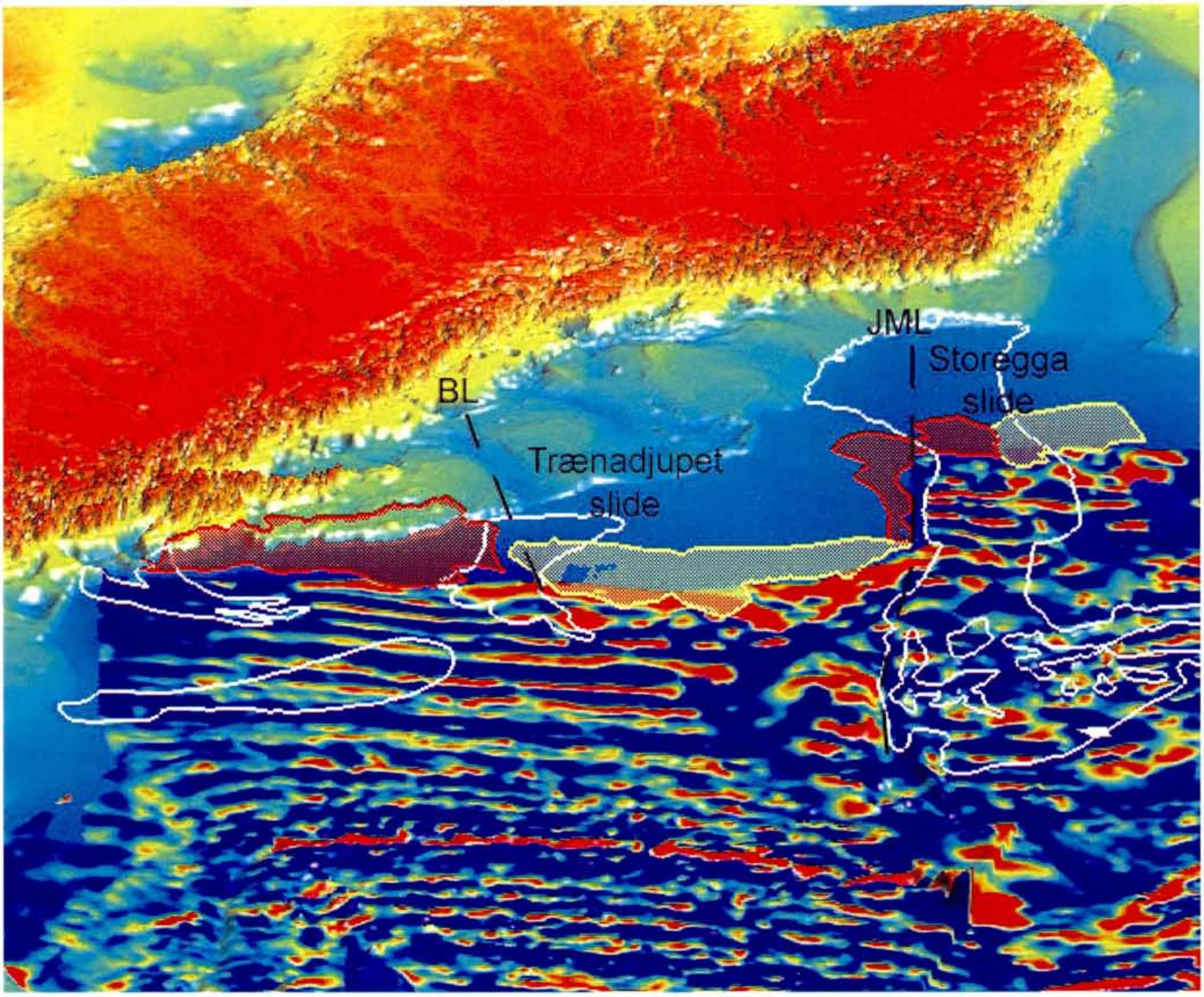


Figure 2.2.3 Birdseye view SE from the Norwegian Sea toward mainland Norway. Magnetic anomalies related to oceanic crust are overlain on the bathymetry. Outlines of major submarine slides are shown in white. Red dotted areas = submarine volcanism. Yellow dotted areas = subaerial volcanism. BL = Bivrost Lineament, JML = Jan Mayen Lineament. Volcanostratigraphic outlines are simplified after Berndt et al. 2001 (Fig. 2.2.2).

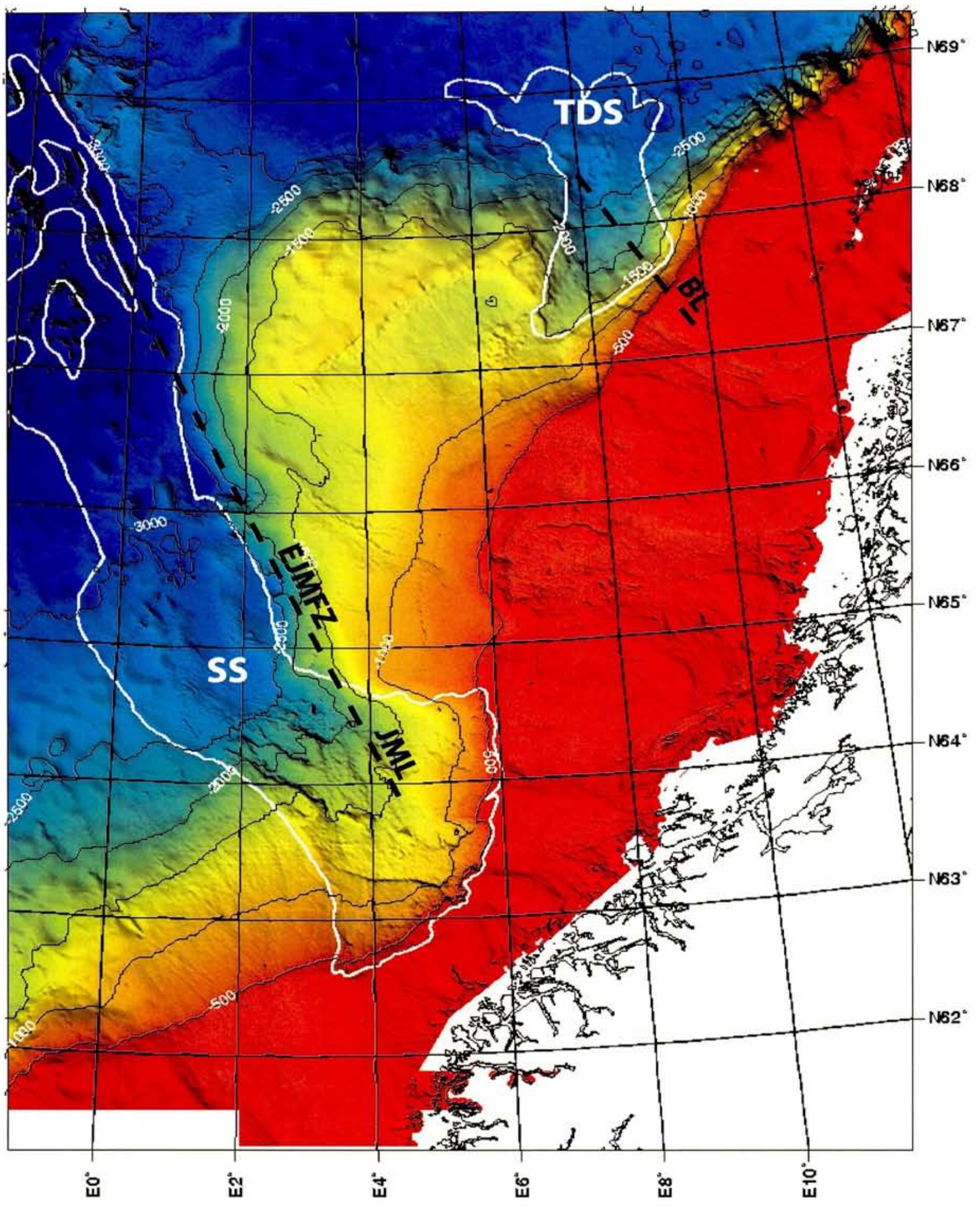


Figure 2.2.4 Mid-Norwegian bathymetry and coastline overlay of sites of Storegga and Trænadjupet Slides (white). Marked with black dashed lines are the Jan Mayen and Bivrost Lineaments. Abbreviations: BL = Bivrost Lineament; EJMFZ = East Jan Mayen Fracture Zone; JML = Jan Mayen Lineament; SS= Storegga Slide; TDS = Trænadjupet Slide.

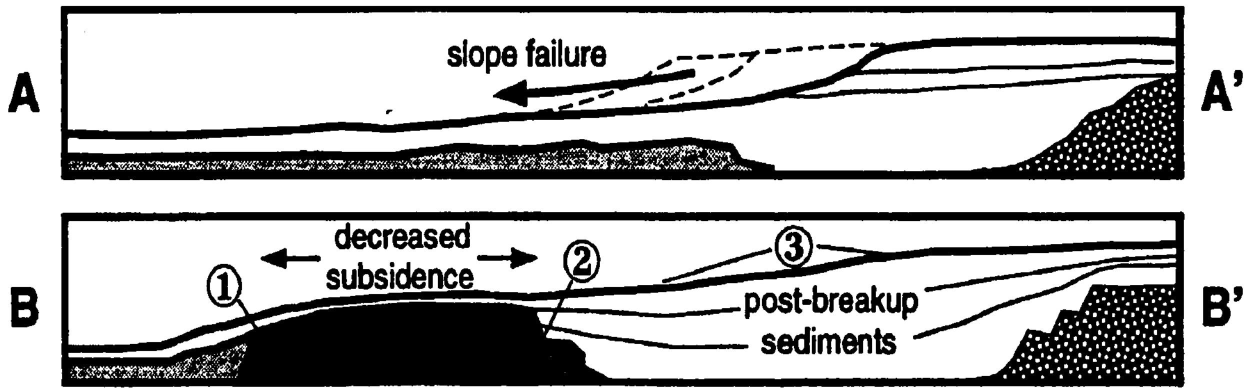


Figure 2.2.5 Idealized cross sections across margin segments without (A) significant underplating and associated marginal high and (B) with significant underplating and associated marginal high. For schematic location see Fig. 2.2.2 Numbers in B-B' suggest influence on slope stability by the magmatic elements: 1) high shear strength of slope material due to shallow buried basalts, 2) barrier against deep-carving slides, 3) small slope angle due to reduced subsidence (From Berndt 2000).

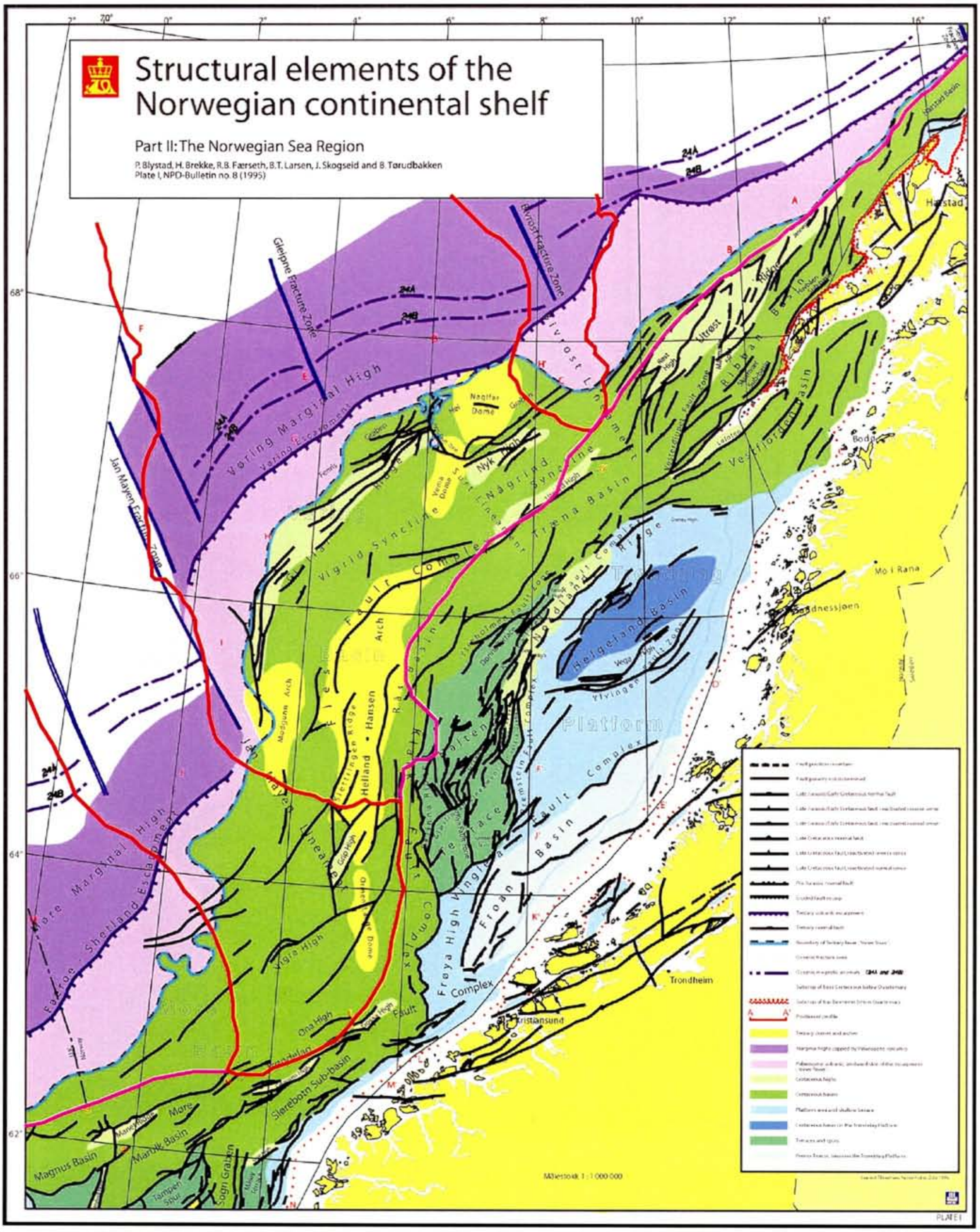


Figure 2.2.6. Structural nomenclature map of mid-Norwegian margin. Modified after Blystad et al. (1995). Red lines mark limit of Storegga and Trænadjupet Slides. Pink line marks the present shelf edge.

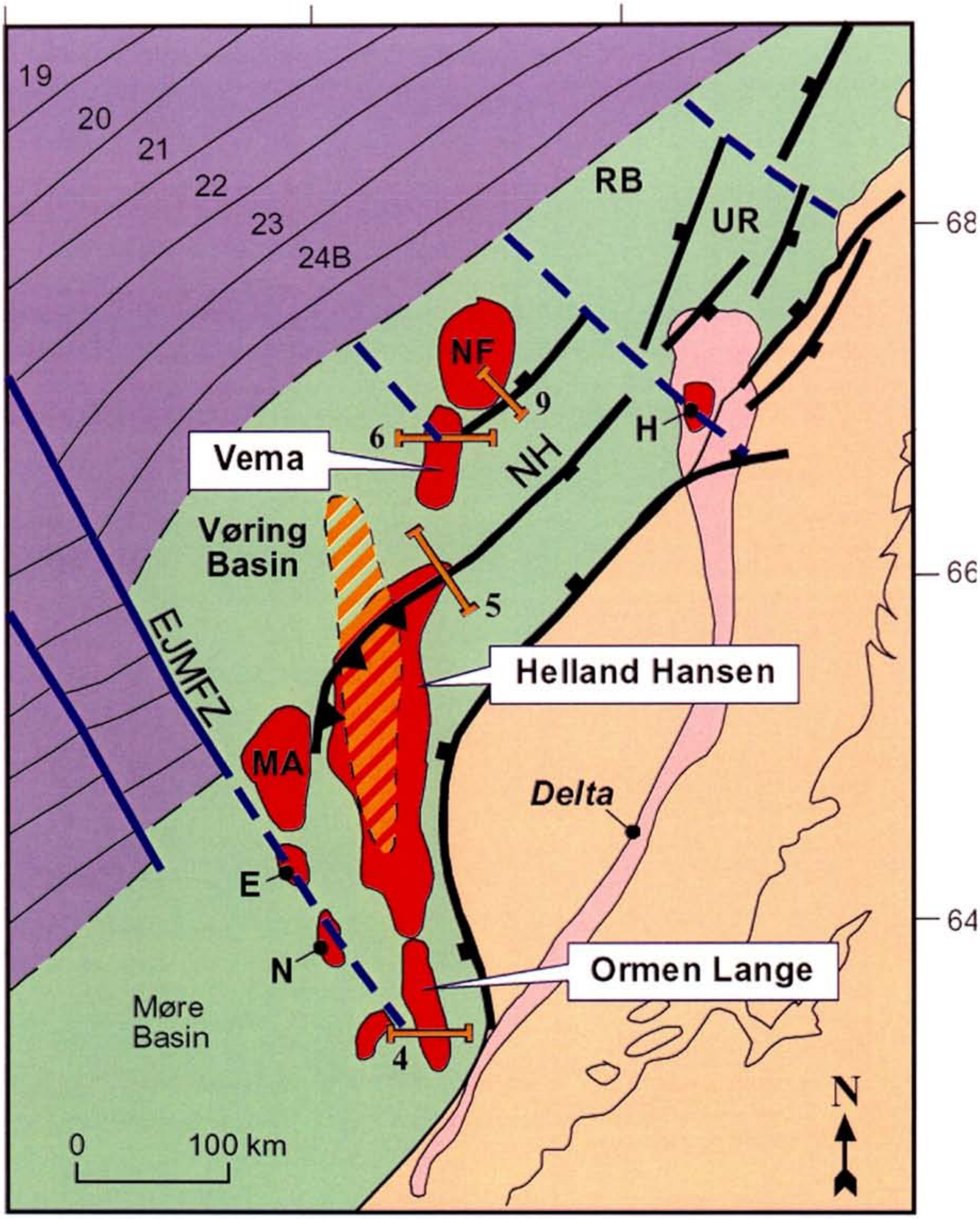
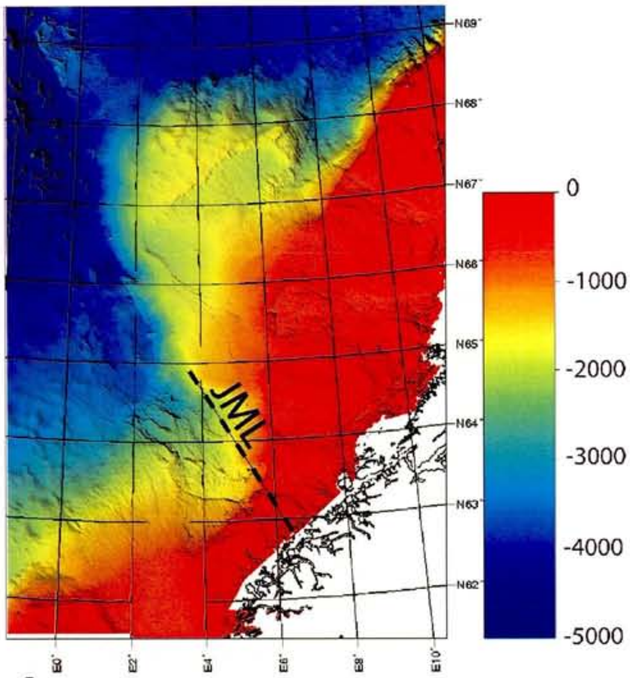
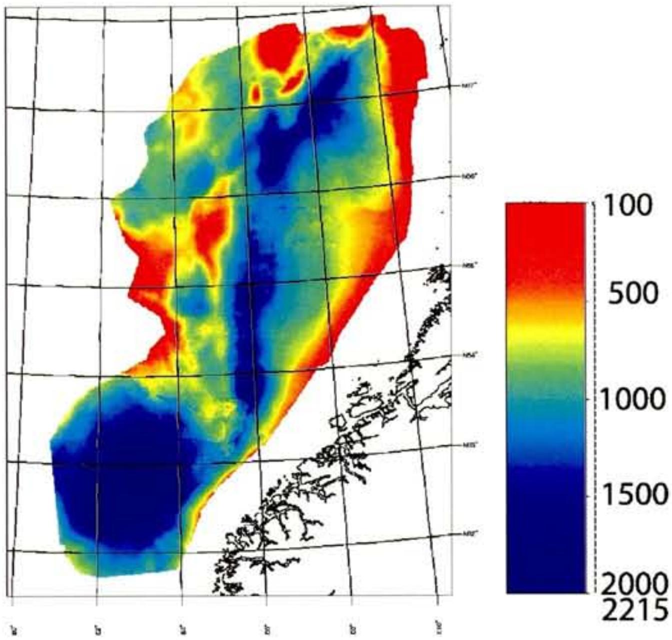


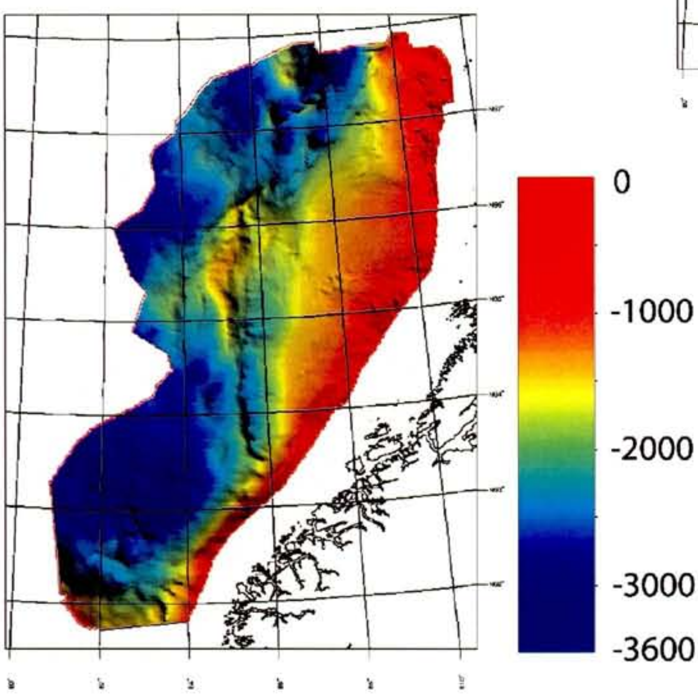
Figure 2.3.1 Mid-Cenozoic domes on the mid-Norwegian margin (red), a Plio-Pleistocene dome (orange dashed), and the Lower Oligocene delta (pink). After Lundin and Doré (2002). Abbreviations: E = Edwarda (informal name), EJMFZ = East Jan Mayen Fracture Zone, H = Hedda (informal name). MA = Modgunn Arch, N = Nora (informal name), NF = Naglfar Dome, NH = Nyk High, RB = Ribban Basin, UR = Utrøst Ridge. Numbers along lines on oceanic crust (purple) refer to magnetic chrons.



A



C

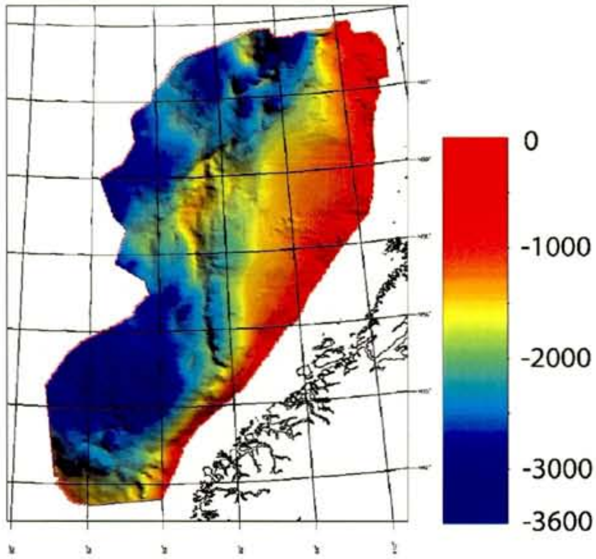


B

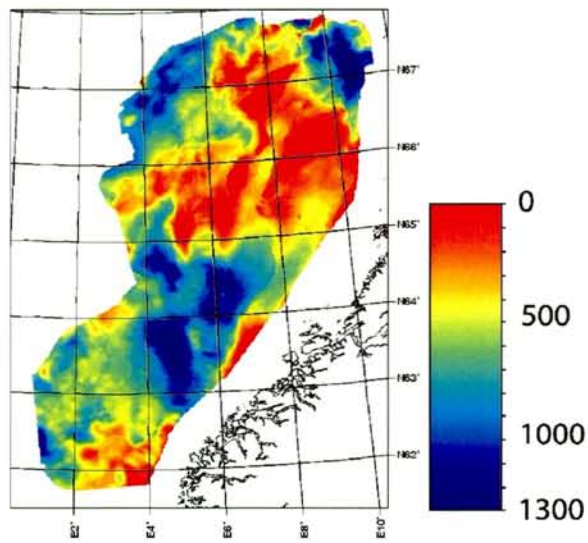
Figure 2.3.2 Regional TWT structure maps (ms) and isochron map.

A) Bathymetry
B) Top Oligocene time structure map (kindly provided by Statoil ASA)
C) Neogene isochron map

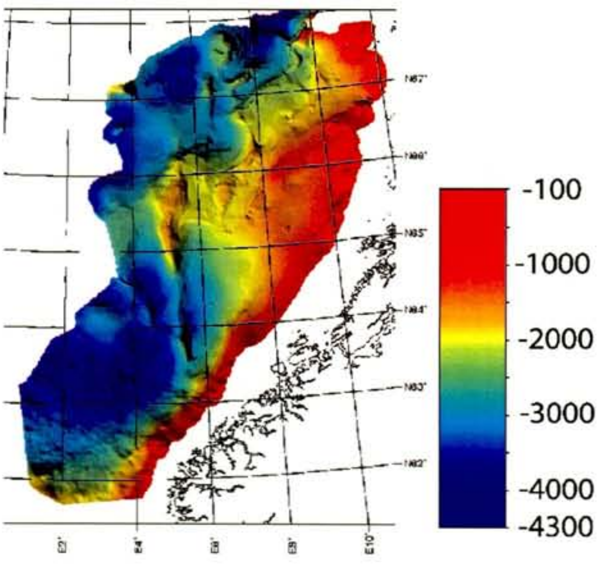
Note the thick deposit of Neogene strata inboard of the Helland Hansen Arch. Note also the thin deposits along the trend of the Jan Mayen Lineament (JML in A) (see Fig. 2.3.3 for comparison)



A



C



B

Figure 2.3.3 Regional TWT time structure maps (ms) and isochron map.

A) Top Oligocene time structure map (Statoil interpretation)
B) Top Paleocene time structure map (Statoil interpretation)
C) Eocene & Oligocene isochron map

Note the local depocentres along trend of the Jan Mayen Lineament (see Fig. 2.3.2 form comparison)

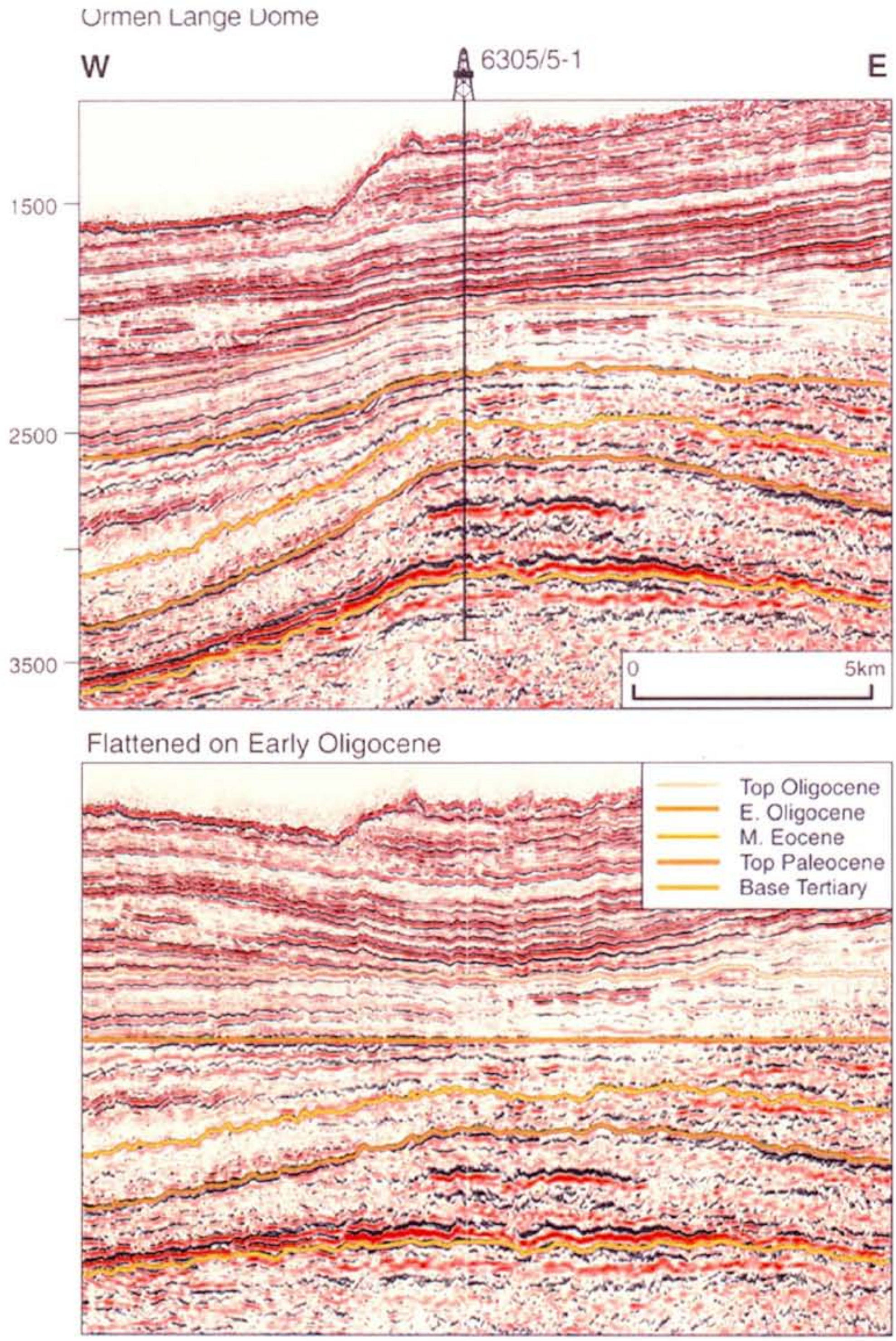


Figure 2.3.4. Seismic section through the Ormen Lange Dome, illustrating the pulsed nature of compressional doming and the inversion of a Paleocene depocenter. After Lundin and Doré (2002)

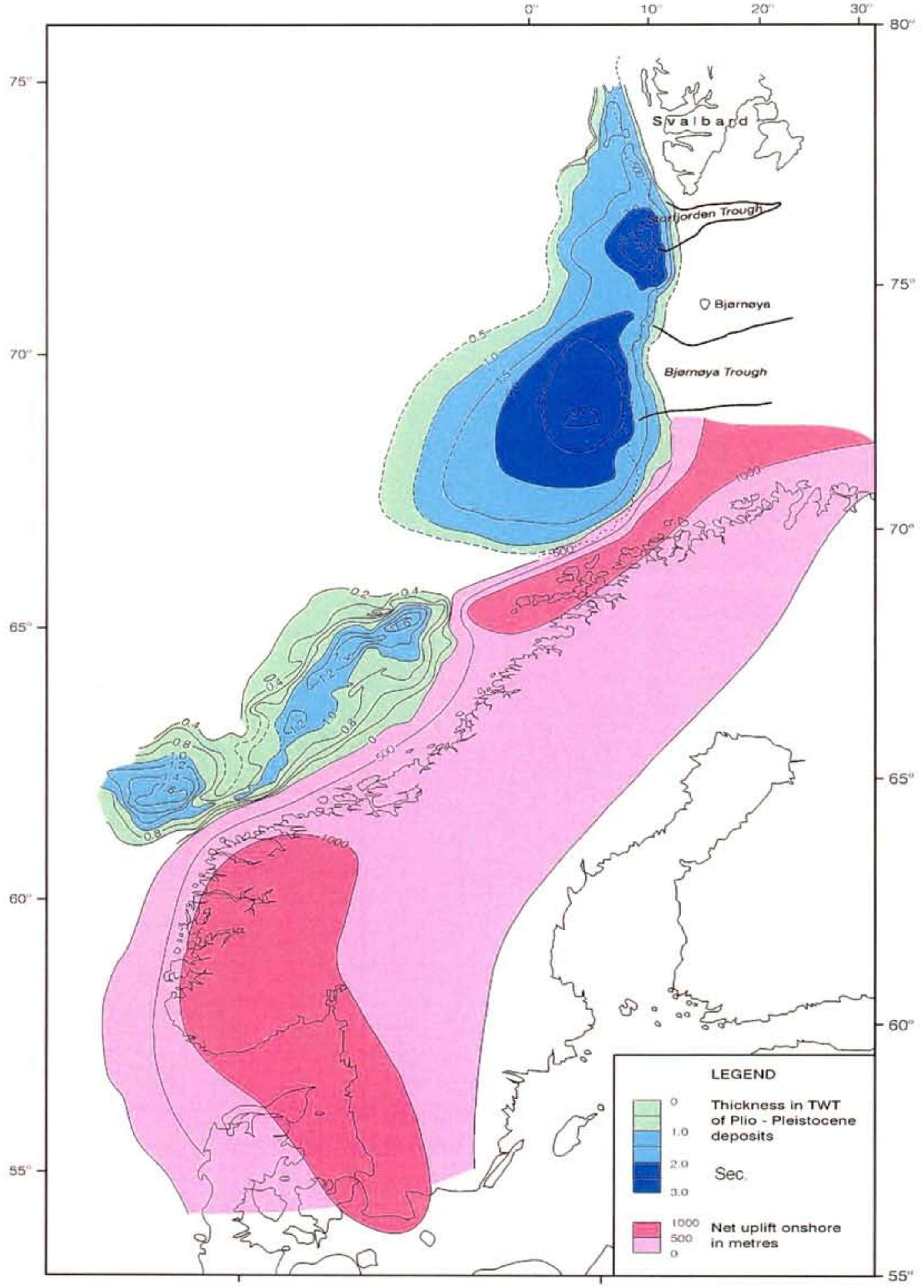


Figure 2.6.1 Map illustrating Neogene (Plio-Pleistocene) net uplift (red) and TWT isopach thickness of the Plio-Pleistocene glacial deposits offshore (green-blue). After Riis (1996), Faleide et al. (1996), and Eidvin et al. (1998)

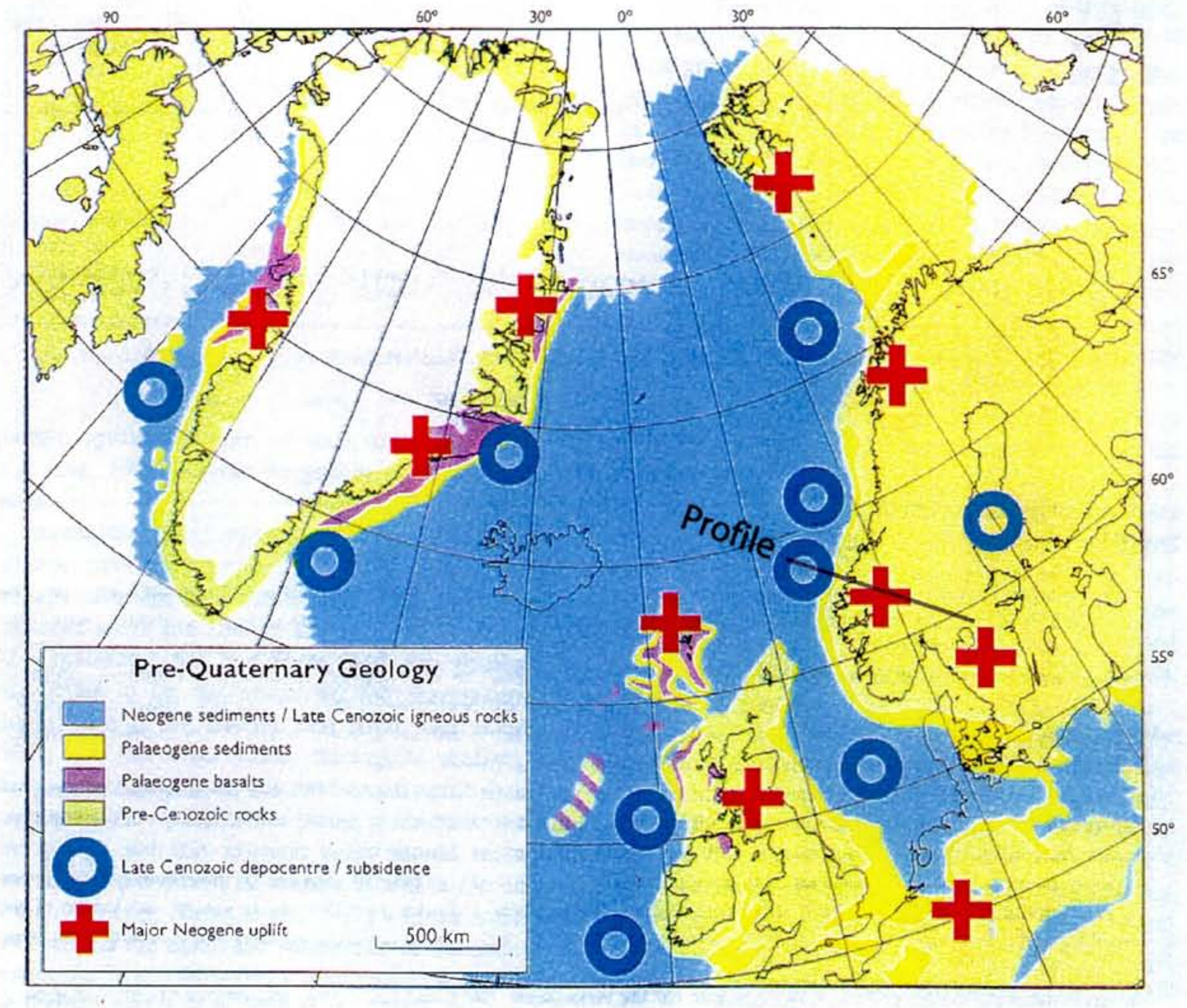


Figure 2.6.2 Sites of Neogene uplifts (red crosses) and subsidence (blue circles). Modified from Japsen and Chalmers 2000.

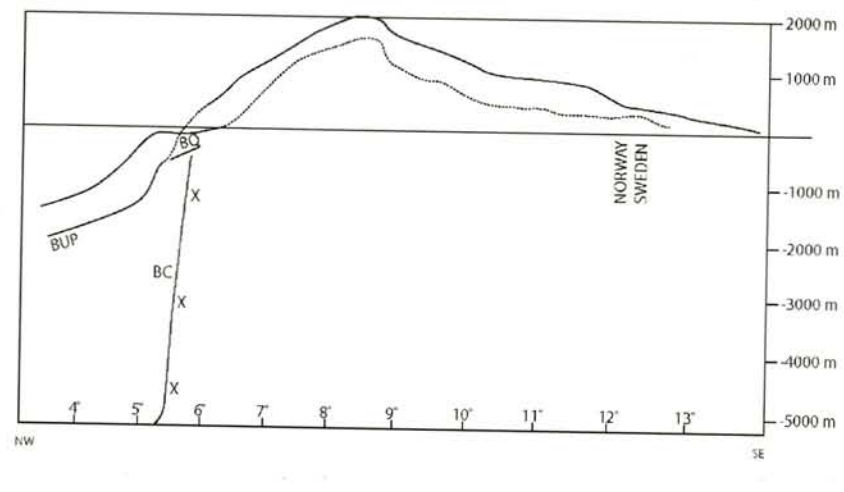


Figure 2.7.1 Topographic profile across southern Norway. Note the asymmetry. Solid line = summit level. Dashed line = mean height. After Riis & Fjeldskaar (1992).

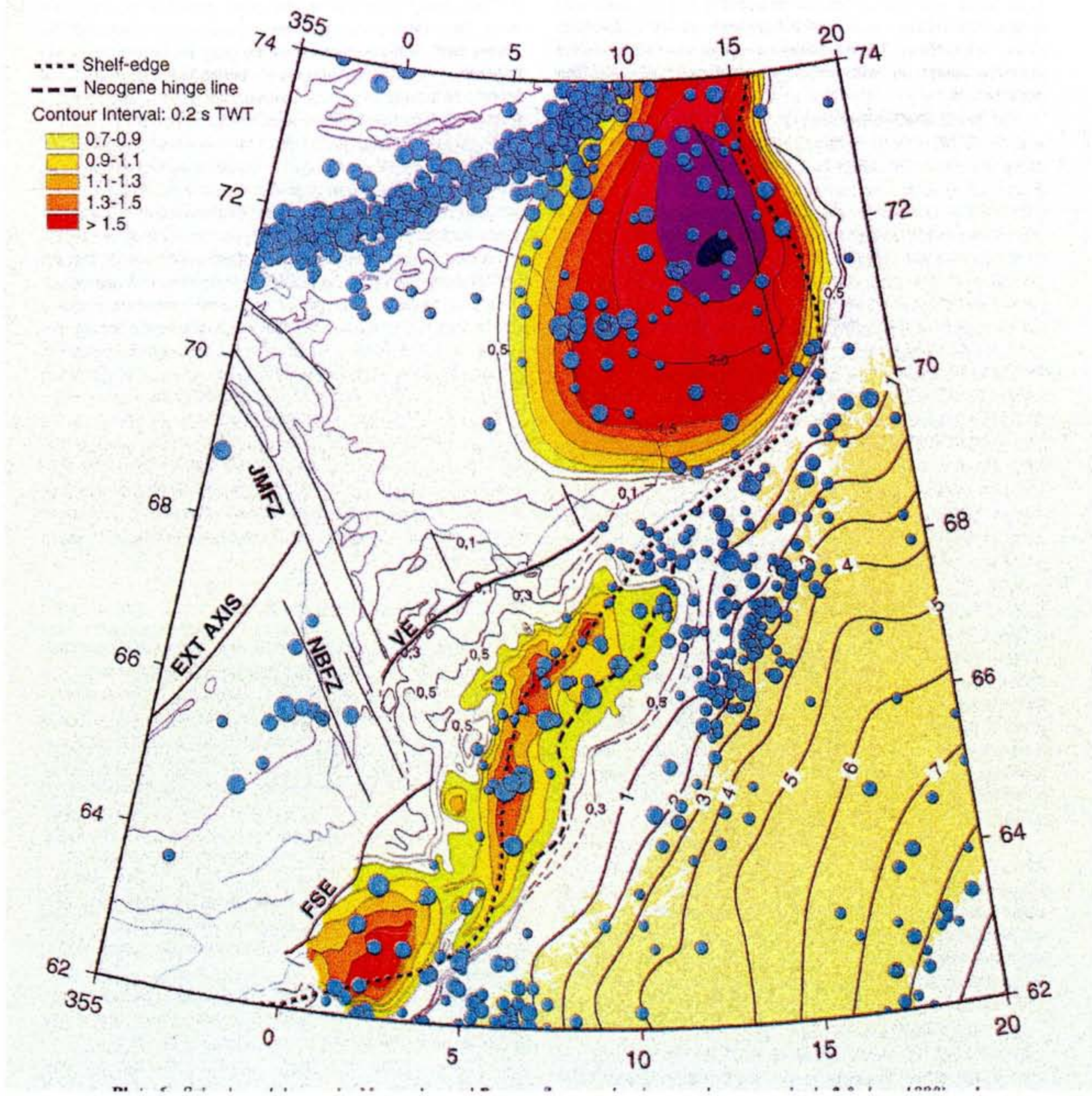


Figure 2.8.1 Seismic activity on the mid-Norwegian and Barents Sea margins. Events shown are above magnitiude 3.0 recorded after 1880. Isopachs of the Plio-Pleistocene are shown in TWT thickness. After Byrkjeland et al. 2000.

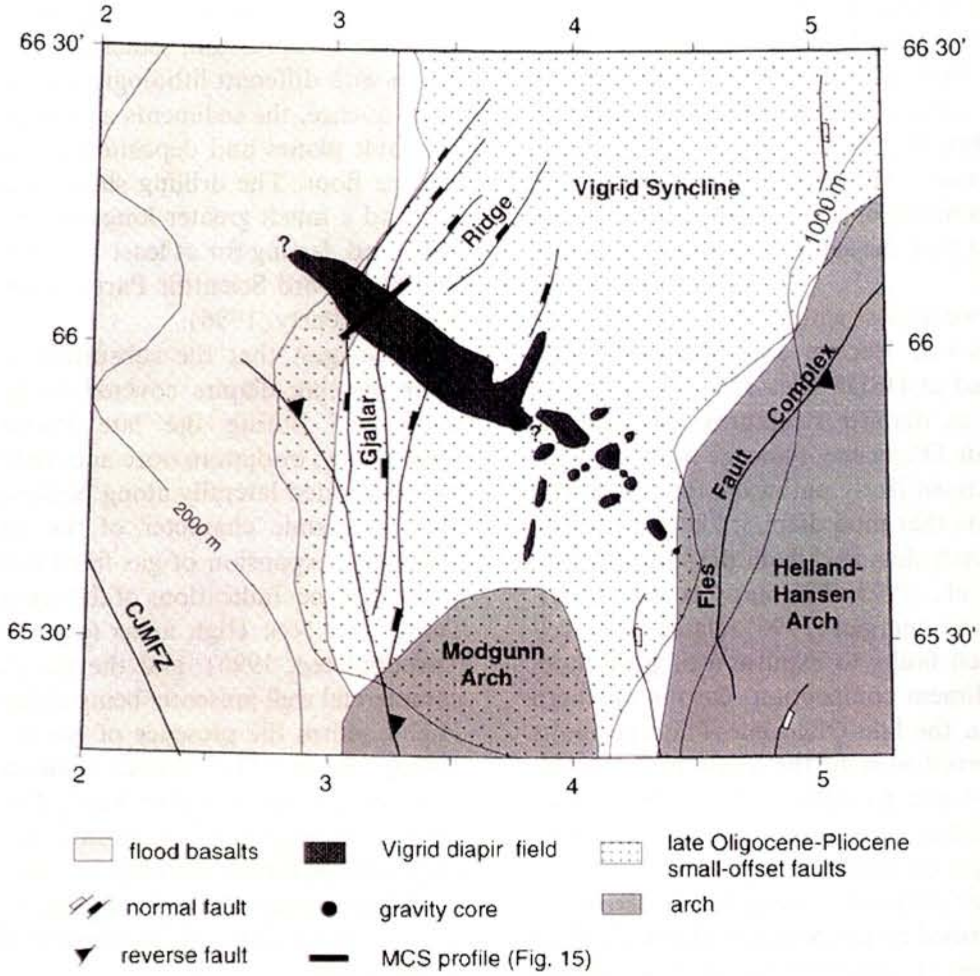


Figure 2.9.1 Location map showing the Vigrid diapir field, near the SW Vøring Basin margin. The diapir field trends c. 15 ° more westerly with the Jan Mayen Fracture Zone. After Hjelstuen et al. 1997.

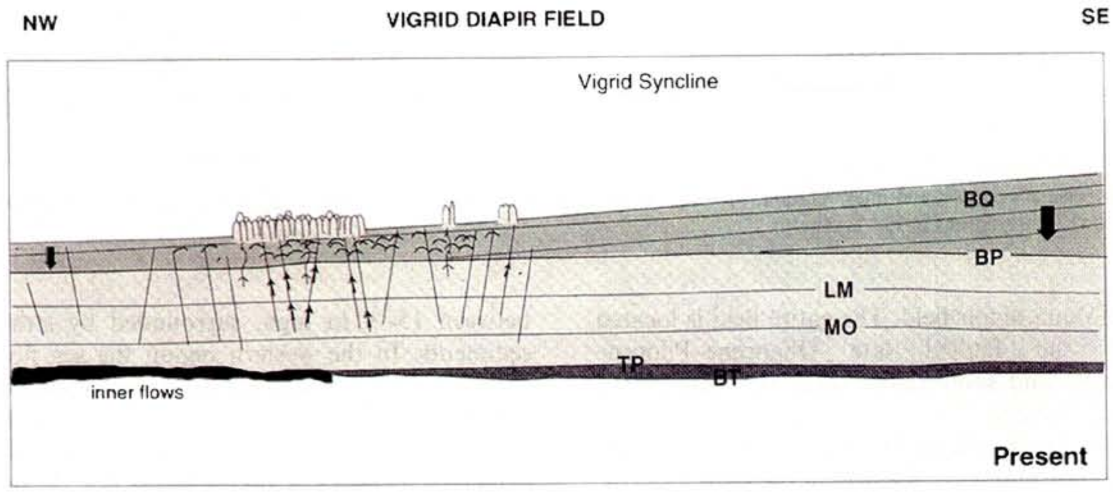


Figure 2.9.2 Geoseismic section through the Vigrid diapir field. After Hjelstuen et al. 1997.

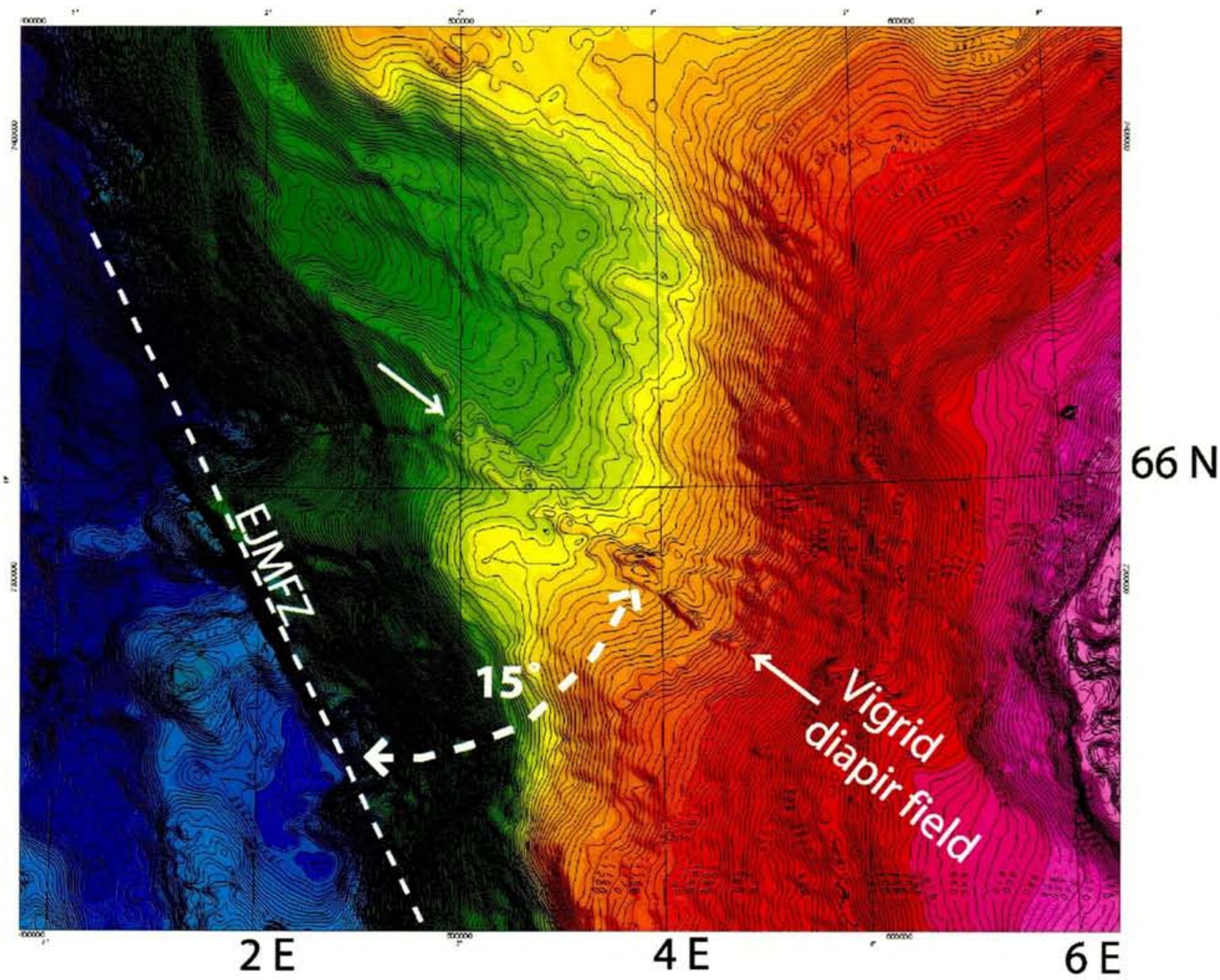


Figure 2.9.3 The Vigrid diapir field is a clear bathymetric feature that trends c. 15° oblique to the East Jan Mayen Fracture Zone (EJMFZ).

3. GLACIAL HISTORY – SUMMARY OF PREVIOUS WORK

Several previous onshore, nearshore and shelf studies are relevant for the regional understanding of the geological development on the slope. Some of these investigations may be poorly known, and a summary of the main results is given below.

3.1 Quaternary glaciations on land – an overview

This section reviews present-day knowledge of variations of the Scandinavian ice sheet throughout the Quaternary mainly based on on-shore records. Focus is on the western (mid-Norwegian) part of the ice sheet, but for completeness some comparisons are made to other regions. Also, focus is on the younger part of the record for which most information exists. Age of sediments in million or thousand years before present is denoted Ma and ka, respectively.

Stratigraphical information from selected literature

Evidence of the pre-Weichselian glaciations by the Fennoscandian Ice Sheet (Fig. 3.1.1) has mainly been derived from areas close to the southern limits of the ice sheet, especially in the Netherlands, Germany and Poland. During the last two decades an increasing number of sites with sub-till sediments have been found on land in Scandinavia (Lundqvist 1981; Andersen and Mangerud 1989; Hirvas et al. 1988; Mangerud 1991a; Larsen et al. 1992; Olsen et al. 1996; Bargel et al. 1999) and in the North Sea and along the Norwegian continental margin (Vorren 1992; Sejrup et al. 1994; Gatliff et al. 1994; Sejrup et al. 1995; Vorren and Laberg 1996). The dating of these successions and their correlation to specific glaciations, has posed problems with regard to relationship between the various types of information. Along the western coast of Norway marine sediments interbedded with tills, have been found at several locations. Based on amino acid ratios, biostratigraphy and radiocarbon-dates, chronologies for these marine events have been suggested (Andersen et al. 1981; Mangerud et al. 1981; Miller et al. 1983; Sejrup 1987). In addition, cave sediments, datable with the U-series method, have been investigated on Møre (Larsen et al. 1987; Larsen and Mangerud 1989). Chronologies for ice free periods along the coast of western Norway, through the Weichselian, have been proposed and tentatively correlated to the IRD content recorded in Norwegian Sea cores (Larsen and Sejrup 1990; Larsen et al. 1992; Baumann et al. 1995; Mangerud et al. 1996).

The last glacial maximum

The last glacial maximum (LGM) is rather well-mapped all around the peripheries of the Scandinavian ice sheet (Fig. 3.1.2). However, mounting evidence suggests that the maximum position was more asynchronous than hitherto believed (Larsen et al. 1999), even though remarkably synchronous along the western margin (Olsen 1997), and that ice-sheet variations were more rapid and complex than assumed previously (Olsen et al. 2001a, b, c). Still the thickness of the ice sheet during the last glacial maximum is a matter of considerable debate.

Ice streams
New investigations along the continental margins of the Nordic seas have shown that large ice streams at several locations traversed the shelves, dumping glacigenic sediments in large depocentres (glacially fed fans) on the continental slopes, during major glaciations. These ice streams were important transport agents for the erosion products from the Fennoscandian shield across the shelf and into to the deep sea. Within the deep sea fans there are long records of glaciation (King et al. 1996; Laberg and Vorren 1996a, b; Sejrup et al. 1996; Vorren and Laberg 1997). It also seems clear that extensive glaciation of Norway could have prevailed, without ice streams developing. It has been suggested that the Norwegian Channel Ice Stream (NCIS) only occurred during maximum size southern Fennoscandian glaciation with a dispersal centre over the Baltic (Sejrup et al. 1998).

Early to middle Pleistocene glaciations (Age 0.13-2.5 Ma)
Probably the most extensive and relatively well-dated record of large extension of the Fennoscandian ice sheet is found in the Netherlands. Parts of the Netherlands comprise the southern extension of the North Sea basin and a relatively complete series of Quaternary fresh/shallow marine deposits are present. The climatic oscillations recorded in the older part of the succession have been dated with the palaeomagnetic method (Zagwijn 1985; Zagwijn 1989; Zagwijn 1992). Within the Dutch succession (Fig. 3.1.1) direct evidence of glaciations in the form of tills are found for beds referred to the Saalian and Elsterian. In older deposits there are clasts of Scandinavian origin, but a glaciogenic origin might not always be the case. The Hattem Beds with an age around 1.1 Ma contain coarse-grained Scandinavian erratics, are found in sediments which are interpreted to be of glacifluvial origin and has evidence for ice-push (De Jong and Zagwijn 1984). Most authors agree that these beds reflect a large glaciation of Fennoscandia which probably reached the Netherlands. This glaciation of the Netherlands was correlated with the Fedje glaciation by Sejrup et al. (1995), cf. figure 3.1.1. The evidence for subsequent glaciation in the Netherlands is found in the glacifluvial Werdinge beds, which have been assigned an age of around 0.5 Ma (De Jong and Maarleveld 1983). In the Netherlands the extension of tills of Saalian and Elsterian age have been mapped. The Weichselian ice sheets never reached so far south-west.

Evidence of Scandinavian glacial ice, in the form of tills of Elsterian, Saalian and Weichselian age is reported from Germany (Ehlers 1983). For a comparison with the reconstruction of the last glacial maximum (Fig. 3.1.2), a reconstruction of much larger ice sheet of Saalian age (c. 130,000 – 170,000 years) is included as figure 3.1.3z.

Thus there seems to be a general agreement between the record of maximum glaciation in the northern North Sea/western Norway and that for glaciation along the southern border of the ice sheets (Fig. 3.1.1). However, it is also clear that there is good evidence for restricted glaciations over southern Norway when the ice sheet never reached these southern areas. During deposition of the extensive Mid- and Early Pleistocene marine unit in the Norwegian Channel, ice streams did not develop. The IRD content related to this unit is always lower than during the Younger Dryas period recorded on the same location (Haflidason et al. 1995; Sejrup et al. 1995). The implication being that available data suggests that for a period of c. 600,000 years glaciations were mainly restricted to within the coastline of western Norway (Fig. 3.1.1).

In the northern part of Scandinavia the oldest tills has been assumed to be of isotope stage 10 age (Olsen et al. 1996; Olsen 1998). The chronology is based on luminescence dating and successions of tills interbedded with waterlain sediments and palaeosols, and with magnetic susceptibility as an important correlation tool. The extension of this glaciation is not known, but the onland evidences indicate extension at least to the coast, i.e. the ice sheet was at least of the Younger Dryas ice-sheet size. In addition, there is seismic evidence for several periods of pre-Weichselian Fennoscandian glaciations which have reached the shelf area in the southwestern Barents Sea, but the dating of these are poor and it is therefore difficult to correlate these events with the onland record (Vorren et al. 1990; Vorren and Laberg 1996, 1997). However, the maximum extension of these multiple Early to Middle Pleistocene glaciations have reached sizes considerably larger than the Younger Dryas ice sheet. At least three times in this period the glacial extensions seem to have reached a size comparable to the LGM, and the two youngest of these events are attributed to the Saalian glaciation (Vorren and Laberg 1996).

Late Pleistocene (Weichselian) glaciations (Age 12-115 ka)

Through the last decades a number of Weichselian glaciation curves, based mostly on the same sites and types of evidence, have been published for western Norway (Larsen and Sejrup 1990; Mangerud 1991b; Larsen et al. 1992; Mangerud et al. 1996; Sejrup et al. 2000; Olsen et al. 2001b). These curves are quite similar in terms of number of glacial events and climatic amplitude of the interstadials, however, some different opinion exists on the timing of pre-LGM interstadials. Below we present a summary of earlier published evidence that form the basis for the new Weichselian glaciation curves we propose for the region (Fig. 3.1.4).

Early to Middle Weichselian (Age 30-115 ka)

Most of the best described and well-documented Early to Middle Weichselian glacial records from Norway are found in the western part of the country. Thus the glaciations of this time period focus on this area (Fig. 3.1.4a). The first Weichselian glacial event recorded in western Norway was assumed to be the Gulstein Stadial, evidenced by a glacimarine silt superimposing Eemian sediments at the Fjøsanger site (Mangerud et al. 1981). The glacimarine silt is capped by a somewhat more coarse grained sediment with fauna indicating slightly more ameliorated climatic conditions (The Fana Interstadial), another glacimarine silt (Silt E) and on top a till (the Bønes till) (Mangerud et al. 1981). This succession has been used in reconstructions of Early Weichselian glaciation history of western Norway (e.g. Larsen and Sejrup 1990; Mangerud 1991c). At the Bø site on Karmøy (Andersen et al. 1983; Sejrup 1987), a marine sand (Torvastad sand) was found above Eemian marine sediments. The Torvastad sand is capped by a till (The Karmøy Diamicton) which is overlain by marine sand of the Bø Interstadial, followed by another till (The Haugesund Diamicton). The Karmøy succession was placed stratigraphically on top of the Fjøsanger beds in the previous mentioned reconstruction. Consequently, the Eemian was succeeded by a prolonged period of restricted glaciation before the first major Weichselian advance onto the shelf after some 80 ka (Fig. 3.1.4a). This was followed by a deglaciation, and relatively mild conditions before the second advance just before 40 ka (Fig. 3.1.4a), the latter also found in cave records in western Norway (Larsen et al. 1987). For the Bø Interstadial, ages ranging from 40 to 80 ka have been proposed (Miller et al. 1983). We note that the new glaciation curve (Sejrup et al. 2000; Fig. 3.1.4a), better matches IRD values from the Norwegian Sea (Baumann et al. 1995) than the glaciation curves published earlier based on a different chronology (Larsen and Sejrup 1990; Mangerud 1991c; Baumann et al. 1995).

Late Weichselian (post Ålesund interstadial; age 12-30 ka)

In terms of determining absolute ages of Late Weichselian glacial records, including the last glacial maximum, the most interesting new development is that glacial records in caves in western Norway (Larsen et al. 1987; Larsen and Mangerud 1989; Valen et al. 1996), can be securely tied to an absolute chronology in Greenland ice cores (cf. Fig. 3.1.5; Mangerud et al. in prep.). In caves on the coast of western Norway glacilacustrine sediments signalling presence of the Scandinavian ice sheet (stadials) is interbedded with blocky sediments signalling ice-free (interstadial) conditions (Larsen et al. 1987). The Laschamp and Mono Lake geomagnetic excursion (L and ML in Fig. 3.1.5) are found in the glacilacustrine cave sediments and can be correlated with the Greenland ice cores. The 'ML' glacial record in the caves (Fig. 3.1.5) represents a time when the ice sheet passed the Norwegian coastland towards its last glacial maximum position on the continental shelf edge. This new chronology is used to date the post 40 ka glacial events for the coast of Norway as portrayed in figure 3.1.4.

Glaciation curves

The three presented glacial variation curves are from the south-western, the central and the northern parts of Norway, respectively (Fig. 3.1.4a-c). The glacial maximum in the SW is thought to be the older of the two major Late Weichselian glacial advances (LGM in Fig. 3.1.4a) because it occurred at a time when there was contact between Fennoscandian and British ice in the North Sea (Sejrup et al. 1994). This was followed by a retreat at least to within the present coastline, the Hamnsund interstadial (Valen et al. 1996), and a second advance (Tampen in Fig. 3.1.4), but evidently without contact to British ice (Sejrup et al. 1994). The same type of multiple glaciations onto the continental shelf is also evident in the two northern glaciation curves (Olsen 1997; Olsen et al. 2001a, b, c; Fig. 3.1.4b-c), but in these cases the ice sheet advanced during three phases separated by ice-retreat intervals. The two youngest of these ice advances, being the most extensive ones, reached both the Late Weichselian glacial maximum position at the shelf edge.

Ice streams and marine sediments

It is also clear that the large Norwegian Channel Ice Stream (NCIS) has operated several times during maximum type glaciations. The NCIS was active during the Tampen readvance, during the last glacial maximum and during the large glaciations prior to this (Larsen et al. 2000; Sejrup et al. 2000). The latter explaining the occurrence of marine in situ clays of Sandnes interstadial age more than 200 metres above present sea level at Jæren (Janocko et al. 1997; Sejrup et al. 1998, 1999; Larsen et al. 2000), as well as correlated sediments with an element of marine fossils located at similar altitudes in the Mjøsa region of southeastern Norway (Olsen and Grøsfjeld 1999) and in the inland of Trøndelag (Olsen et al. 2001).

The late glacial period (Age 12-15 ka)

Late glacial deglaciation chronologies are also presented in figure 3.1.4a-c. Furthermore it is clear that most cirque glaciers beyond the Younger Dryas ice sheet margin (except for a few on the outermost coast) formed as remnants of the ice sheet during deglaciation and expanded during Younger Dryas (Larsen et al. 1984; Larsen et al. 1998). Reactivation of isolated parts west of the inland ice sheet is also recorded during the Preboreal Chron from the Svartisen area at the Arctic Circle (Blake and Olsen 1999) and in the area northwest of Majavatn in Nordland (Svensson 1959).

Glacial extension during LGM compared to the Saalian glacial maximum
A map showing the maximum position of the entire ice sheet at the last glacial maximum is shown as figure 3.1.2 (Svendsen et al. 2001). Comparing this with figure 3.1.3 it becomes evident that the last glacial maximum had a much smaller ice sheet than the older Saalian glaciation. This is particularly the case for the southern and eastern extension whereas the western parts of the ice sheets were rather similar simply because the continental shelf edge is a barrier to further westwards expansion.

Ice thickness during the LGM interval
The lateral extension of an ice sheet (Fig. 3.1.2) is much easier to reconstruct than the thickness. This is because the ice front is characterized by end moraines, sandur plains, outwash fans etc. whereas its upper boundary in many cases is above the terrain leaving no traces or the traces are difficult to interpret. In figure 3.1.2 elevation contours are indicated for the Scandinavian ice sheet. This is based on a glaciological model taking into consideration the outer limits of the ice sheet. Obviously this model presents an ice sheet too thick on the outermost coast of Norway. Adding to this is that the model has much too crude resolution to give any meaningful information about an ice sheet that probably had several instead of just one ice dome. The volume of ice through the last 30,000 years (i.e. through the last glacial maximum and the deglaciation) is shown in figure 3.1.6. Although the volume change can be modelled relatively well (Fig. 3.1.6), the vertical distribution of ice cannot be extrapolated simply because lateral positions are so asynchronous. Many mountains, especially in western and northern Norway has an upper area with in situ weathered rocks, so-called block fields.

Trimlines and ice free areas
The lower limit of the block field is often a relatively sharp boundary, trimline, to a zone characterized by tills and other glacigenic deposits (Fig. 3.1.7). This trimline has by many authors (e.g. Nesje et al. 1988) been interpreted to represent the upper ice sheet boundary during the last glacial maximum, the implication being that many mountains were nunataks at the time. The trimline can have formed in many different ways (e.g. Ballantyne et al. 1997), and overconsolidation values in sub-till sediments from western Norway suggest that the ice sheet extended well above the block field in the Vestnes area of western Norway (Larsen et al. 1995). Until the trimline boundary is more thoroughly understood and well dated its significance in terms of estimating ice-sheet elevation is dubious. Thus the question of nunataks during the last glacial maximum is still open, although it seems like the highly reactive ice sheet portrayed as glaciation curves (Fig. 3.1.4) would require a multi-domed situation. This means that ice-free/ice-covered peaks may have varied considerably through space and time.

Comparison with the Barents Sea region, and the Danish and Russian records
During the maximum glacial extents of the Quaternary, the northern margin of the Fennoscandian Ice Sheet coalesced with the marine-based Barents Ice Sheet (Fig. 3.1.2). There are several indicators suggesting that the ice sheet over Svalbard and the Barents Sea experienced a larger extent during the Early Quaternary than later. The most significant

seismic reflector in the Barents Sea, and along the Svalbard shelf, is the Upper Regional Unconformity (URU) that separates the underlying sedimentary rocks from the overlying glacial deposits (Solheim and Kristoffersen 1984). The URU is interpreted to represent a major shift in the style of glaciation from a period of net glacial erosion to one of net deposition (Solheim et al. 1996) which occurred around 1 Ma (Faleide et al. 1996). Evidence for extensive Early Quaternary ice sheets is also found at the Yermak Plateau NW of Svalbard, where ODP Site 910 revealed sediments interpreted to have been overconsolidated by a grounded glacier prior to 660 ka (Flower 1997). The overlying sedimentary succession reflects a continuous deposition with no evidence of glacier overriding at any later stage of the Quaternary (Flower 1997). Both studies show evidence for a shift in the mode of glaciation in the region from laterally extensive, actively eroding ice sheets ca 1.0-0.7 Ma, to a long interval with less vigorous glaciations as we know them from the Late Quaternary.

As with the North Sea Fan to the south (see above), large fans were deposited off the major troughs that run across the Barents and Svalbard shelf. The onset of deposition of such fans off Bjørnøyrenna was close to 600 ka (Laberg and Vorren 1996b), clearly showing that repeated glaciations reached the shelf break in these areas during the mid and late Quaternary. Stratigraphic studies on Svalbard (e.g. Miller et al. 1989; Landvik et al. 1992; Mangerud et al. 1992) have resulted in well-documented reconstructions of the elapse of the last interglacial/glacial cycle of the area (Larsen et al. 1992; Mangerud et al. 1996; Mangerud et al. 1998). These reconstructions suggest that glaciers reached the shelf edge around 110, 60 and 20 ka BP, and that glacial ice persisted in the northern Barents Sea from the termination of the Eemian until c. 50 ka BP. Based on this succession of events, Mangerud et al. (1996) suggested that the high latitude Svalbard/Barents Ice Sheet fluctuated with a 41 ka frequency, similar as assumed by Olsen et al. (1996) for the northern part of the Fennoscandian Ice Sheet, compared to the 23 ka for the southwestern part of the Fennoscandian Ice Sheet suggested by Larsen and Sejrup (1990).

As discussed above the last glacial maximum in the southwestern part of the ice sheet occurred at around 32 ka (Fig. 3.1.8). This is in contrast to a maximum position of the same ice sheet in Russia at c. 17 ka (Fig. 3.1.8). Thus there was a time delay of some 15 ka of the maximum position in the northeast compared with the southwest. This was probably caused by topographic and internal dynamic factors in the ice sheet during growth more than external climatic factors. Firstly, the main sources of precipitation in the North Atlantic lead to initial expansion of glaciers in the western Scandinavian mountains followed by rapid ice advance through the present fjords towards the west. The maximum position in the west was reached relatively quickly due to preferential growth in the area of maximum precipitation and also because this position (the continental shelf edge) is a topographic barrier to further westwards growth. Towards the east and northeast no such barrier exists, and the maximum position was attained as the ice divide gradually shifted eastwards during further growth.

This gradual shift in the ice divide is actually represented in the Danish stratigraphy with initial ice expansion from the north shifting to easterly ice-flow directions through time as the ice divide(s) moved eastwards (Fig. 3.1.8). An important implication of the highly asynchronous outer limits of the ice sheet is that it never looked like what we at present are able to reconstruct (Fig. 3.1.2). At the time when the maximum position was finally reached in Russia, deglaciation was well underway along the western peripheries (Fig. 3.1.2). Thus figure 3.1.2 must be viewed as maximum positions obtained by the ice sheet over an integrated time period of 15,000 years.

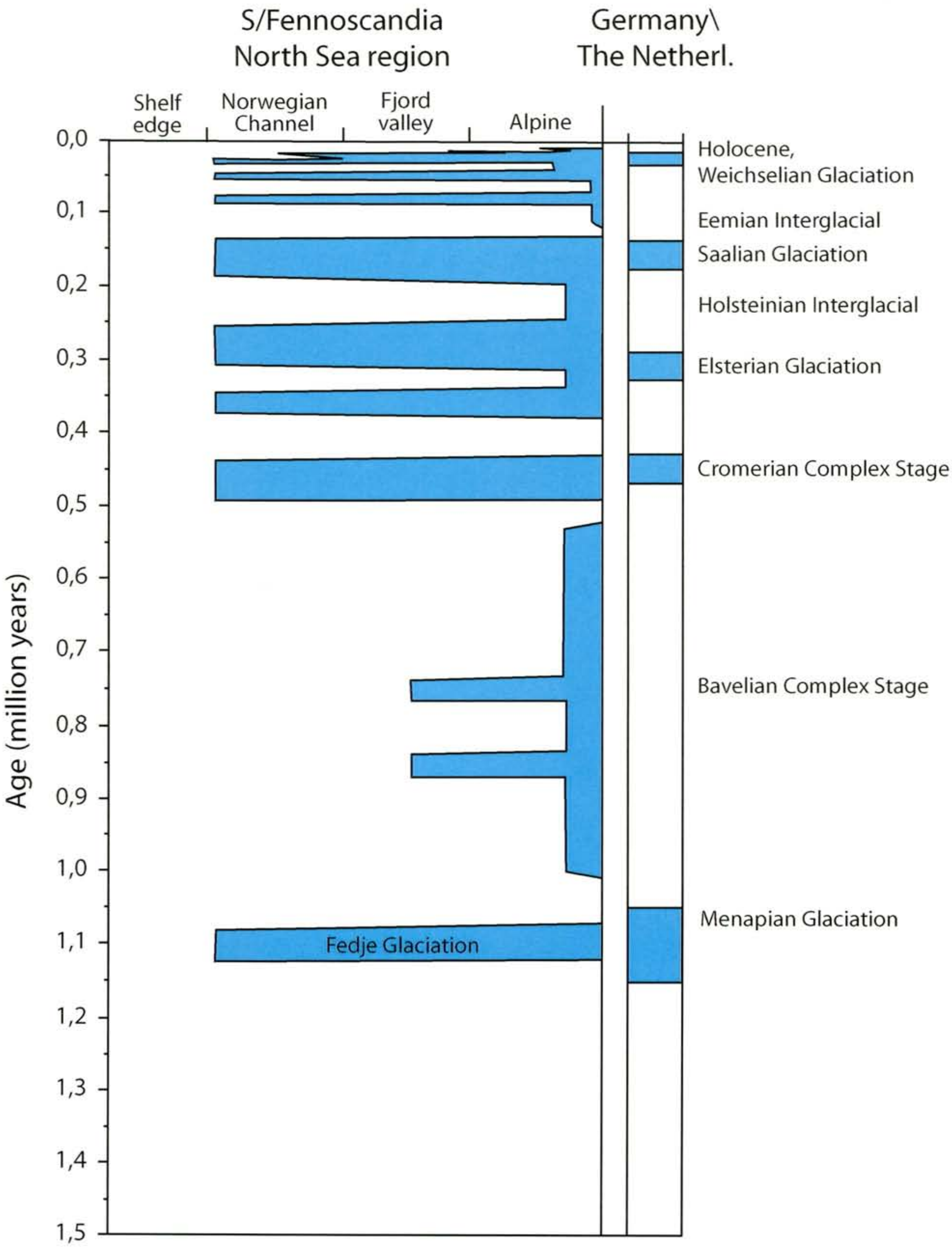


Figure 3.1.1 Glaciation curve for western Norway for the entire Pleistocene correlated with records in the Netherlands and Germany (after Sejrup et al. 2000)

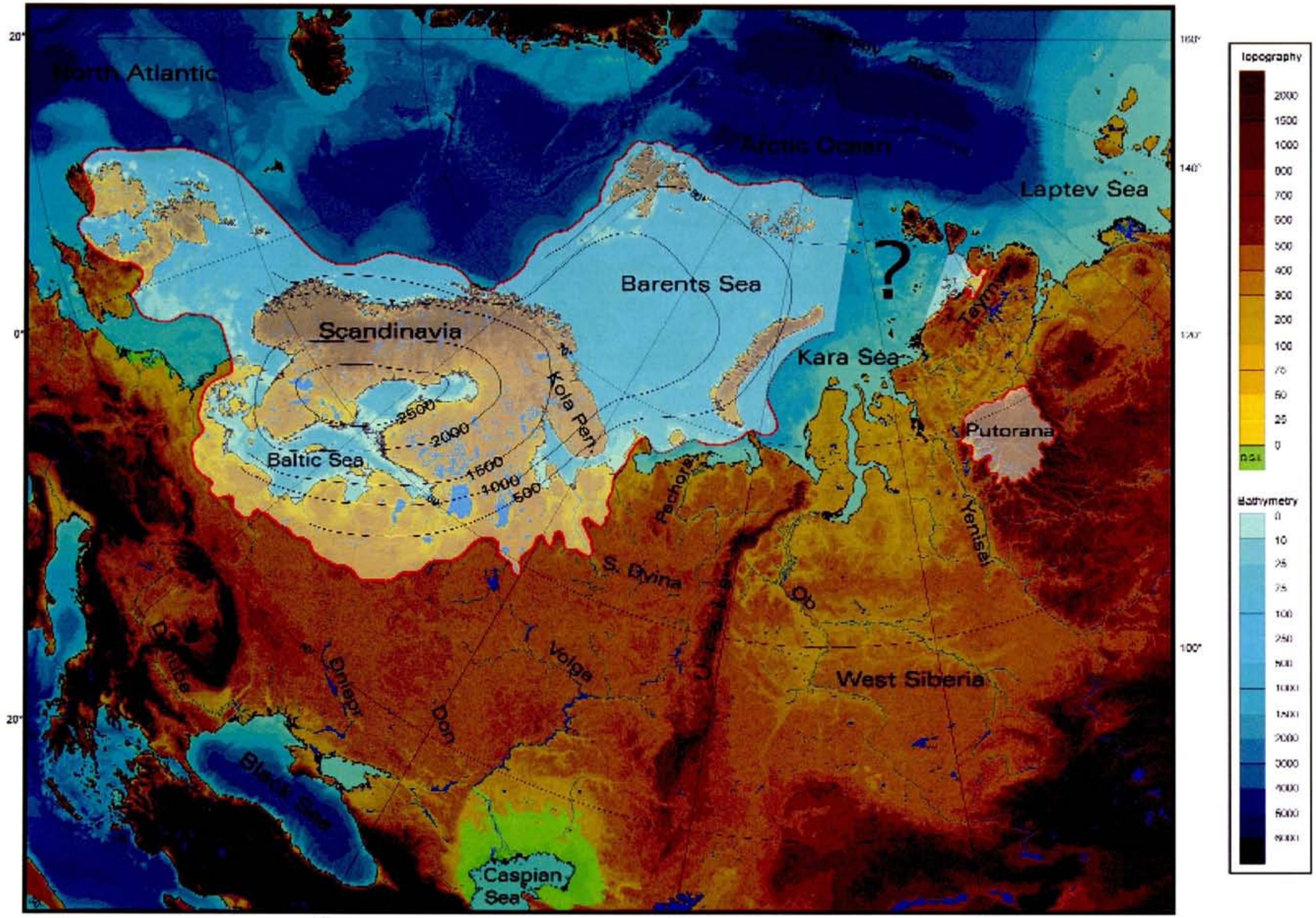


Figure 3.1.2 Map showing the Scandinavian, the British and the Barents/Kara Sea ice sheets during the last glacial maximum (after Svendsen et al. 2001).

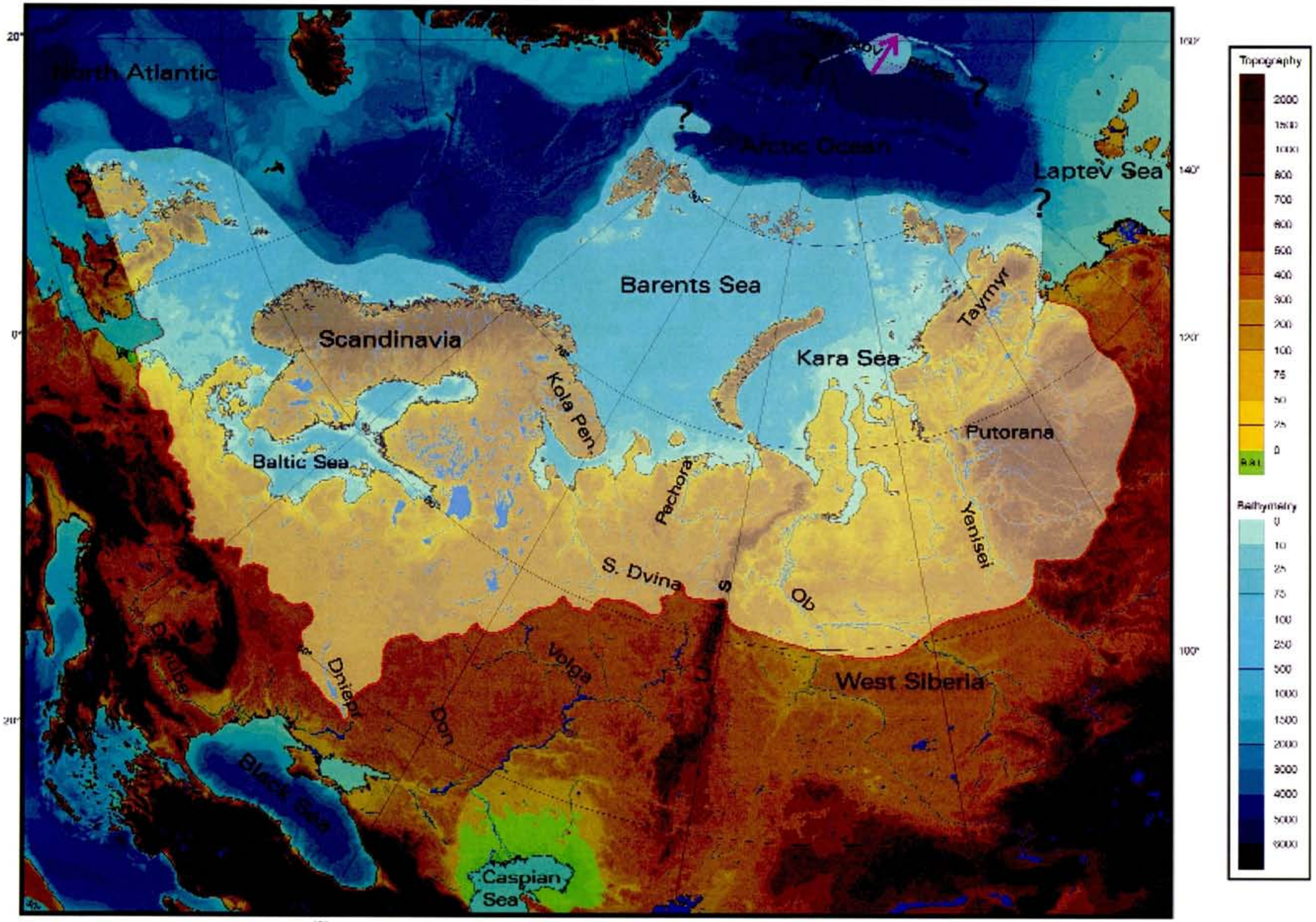


Figure 3.1.3 Map showing the north-European ice sheets during the Saalian (after Svendsen et al. 2001).

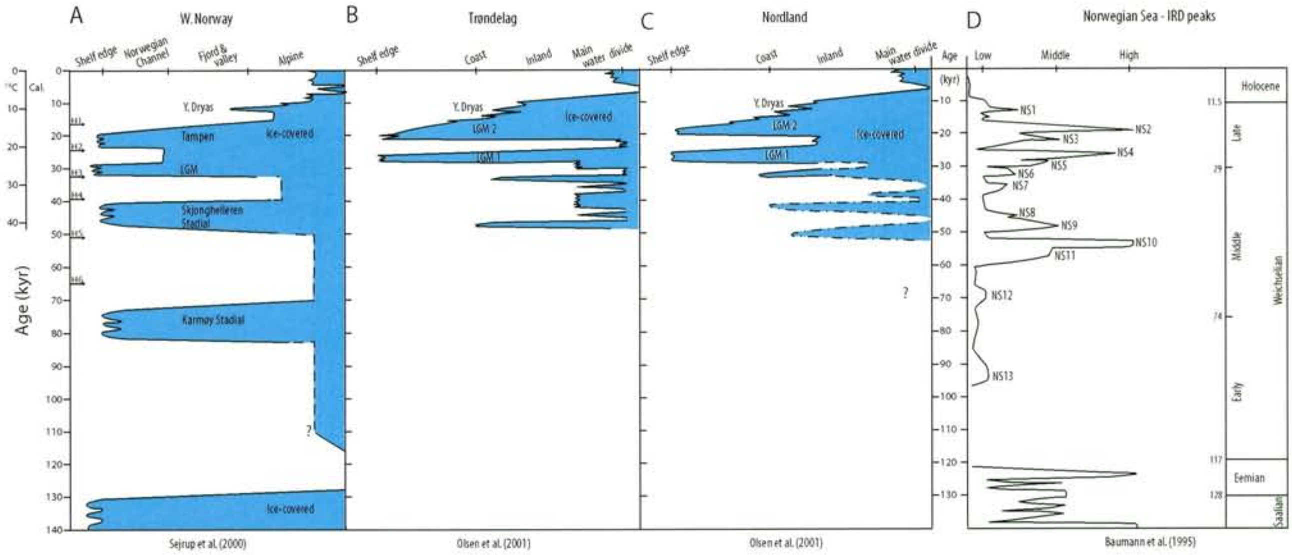


Figure 3.1.4 Weichselian glaciation curves for SW Norway (A), mid Norway (B) and northern Norway (C) compared with IRD records and Heinrich events (D). Compiled from Sejrup et al. 2000, Olsen et al. 2001b, and Baumann et al. 1995, respectively.

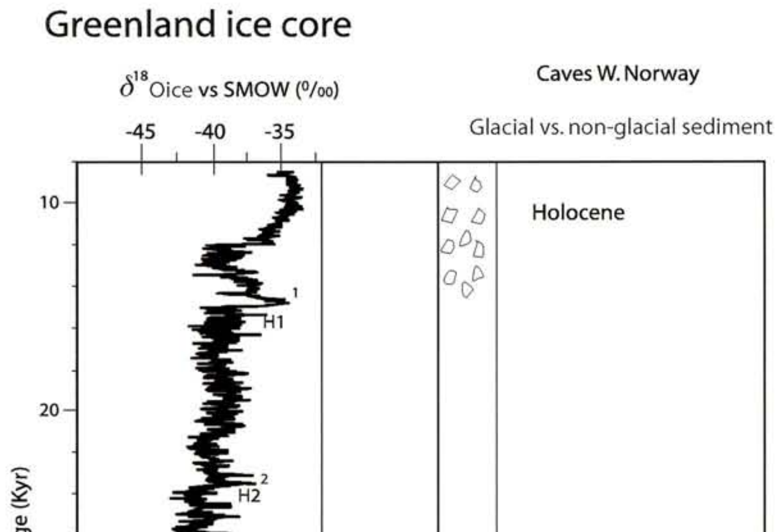


Figure 3.1.5 Correlation scheme between western Norwegian glacial records from caves and Greenland d18O records in ice cores showing climate variations. Based on data in Larsen et al. 1987, Valen et al. 1996 and Voelker et al. 2000.

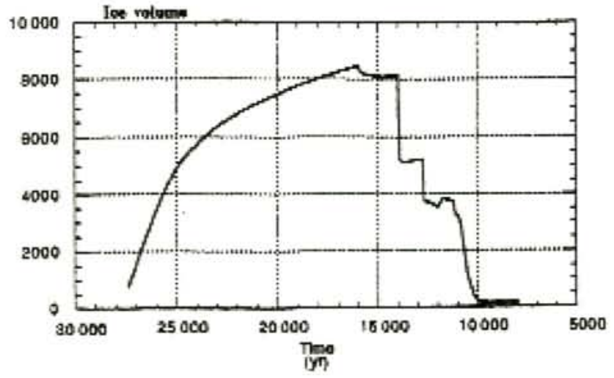


Figure 3.1.6 Changes in ice volume for the combined Barents/Kara and Scandinavian ice sheets over the last 30,000 years (after Dowdeswell and Siegert 1999).

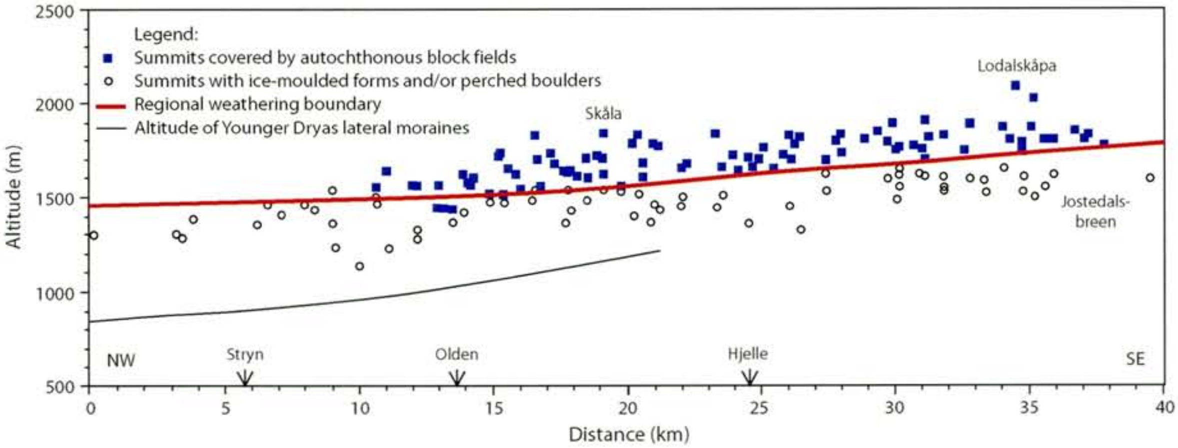


Figure 3.1.7 Diagram from western Norway showing an upper zone with block fields (blocky in situ weathered rock) separated by a trimline (red) from a lower zone where the overburden is represented mainly by tills (after Nesje et al. 1988).

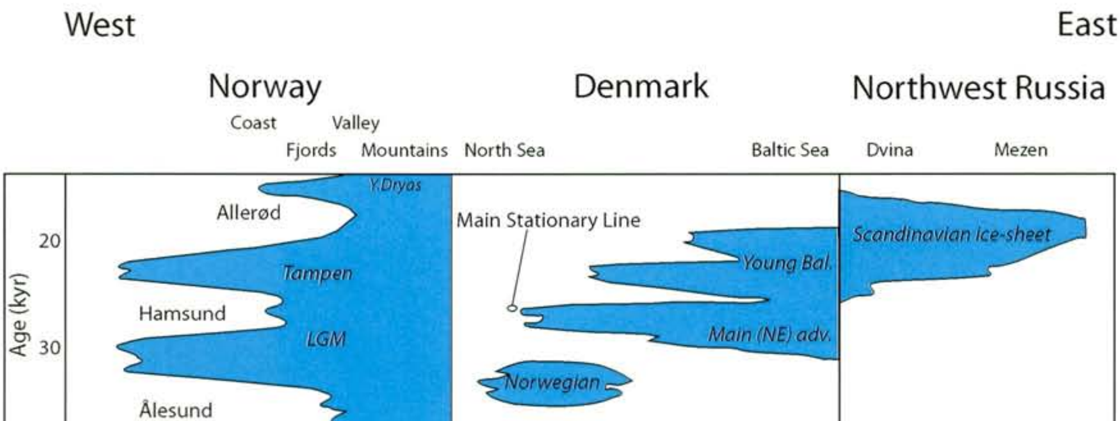


Figure 3.1.8 Comparisons of Middle to Late Weichselian glacial variations of the Scandinavian ice sheet in western Norway, Denmark and northwestern Russia. Compiled from Sejrup et al. 2000, Houmark-Nielsen et al. 2001, and Larsen et al. 2001, respectively.

3.2 Late Pliocene-Early Pleistocene prograding wedges

During the early investigations of the mid-Norwegian continental shelf (c. 1970-1985) most researchers dealing with Quaternary geology applied single-channel seismic data. A pronounced angular unconformity (URU) was recognized in several areas, and this was interpreted as the strict boundary between westward dipping bedrock sequences and a commonly flatlying succession of tills and glaciomarine sediments. In some areas the angular unconformity was more vague, or was hidden below the seabed multiple.

The petroleum exploration in the area greatly increased the database on the shelf, and interpretation of digital seismic combined with information from exploration wells gave an increased understanding of the development of the shelf during Late Pliocene and Pleistocene (Amaliksen et al. 1989; Rise and Rokoengen 1991; Rokoengen et al. 1995; Henriksen and Vorren 1996). In these studies evidence was found of a glacial environment existing on the shelf before URU was formed.

Northern North Sea (61°-62°N)

Eidvin and Rundberg (2001) presented a cross-section showing the post-Oligocene succession in the Norwegian part of the northern North Sea (Fig. 3.2.1). The Naust Formation comprises a basal sequence below thick prograding Upper Pliocene sediments, and a Pleistocene sequence at the top. The Upper Pliocene complex is characterized by thick, north-westward prograding clinoforms downlapping against the underlying surface. The Upper Pliocene strata (up to 700 ms twt thick) comprise a number of individual sequences. These are separated by several truncation surfaces (Fig. 3.2.1). The middle truncation surface is the most pronounced and can be mapped across the entire northern North Sea.

The Pleistocene sequence was identified above URU, being clearly developed as an angular unconformity in the Norwegian Channel (Fig. 3.2.1). The Plio-Pleistocene sediments in the northern North Sea appear to have a very similar depositional pattern as seen on Haltenbanken and Trænabanken.

Haltenbanken (64°-65°N)

A regional stratigraphy was established between 64° and 65°N dividing the upper Pliocene and Quaternary sediments overlying IKU Bedrock Units IX and X into 11 informal units separated by regional reflectors (Rise and Rokoengen 1991; Rokoengen et al. 1995). The delta-like coastal unit IX that was the lowermost unit in this study was mapped in the eastern part of the shelf from Møre to Lofoten (Rokoengen et al. 1988). This unit formed the basis for the Plio/Pleistocene sediment wedge increasing to more than 1500 m thickness at the shelf edge (Naust Formation). An interpreted SE-NW profile ending at the shelf edge slightly south of 65°N shows the Naust unconformity and the architecture of sediment wedges above (Fig. 3.2.2, profile 2).

The seven units defined between the Base Naust horizon and URU (units L to E) consist of large scale north-westward prograding clinoforms, and these units have gradually built out the shelf edge. Some of the units are sheet-like with erosional boundaries in the inner more horizontal part. They thicken above descending palaeo-slopes, thinning farther westwards and commonly down-lap on older horizons. Several angular unconformities are developed below URU in the middle and inner part of the shelf, and parts of the older units have been eroded and transported further out and deposited at the palaeo shelf edges.

An important result from the interpretation of Rise and Rokoengen (1991) is that the glacial deposition seems to have started much earlier than assumed from the previous regional mapping by IKU and others, and that sediments from many glaciations are preserved.
The base of unit IKU-I represents a very pronounced unconformity in the Njord-Draugen area (at c. 0.5-0.6 s. twt, and clearly below URU), with the corresponding surface dipping down to c. 1.5 s. twt close to the present shelf edge (Fig. 3.2.2, profile 1). Soil investigations at the Draugen platform site (Haflidason et al. 1991; T. Eidvin, pers. comm.) show that the lower part of the borehole comprises Pleistocene sediments (till, proximal glaciomarine sediments and interglacial deposits). This borehole (Figs. 5.2.1, 7.2.2) terminated in the lower part of unit IKU-I, and the sediments show that ice sheets grounded on the shelf a long time before URU was formed. It is likely that the angular unconformity at base of unit IKU-I was formed by glacial erosion, although we have no data that proves this assumption. For reference to the later descriptions, it should be noted that the base of unit IKU-I is located much deeper than horizon Top Naust W (TNW) defined in this study.

Trænabanken - Lofoten (66°-68°N)
The deposional architecture of the Late Pliocene - Pleistocene wedges in this area is similar to the Haltenbanken region (Unit C in Fig. 3.2.3). Henriksen and Vorren (1996) defined twelve depositional sequences based on conventional seismic. The deposition of the sequences is thought to reflect a gradual climatic deterioration, resulting in regional advances of major ice sheets across the continental shelf. Glacigenic sediments deposited at the shelf edge were later reworked by gravity flow processes down the continental slope. Mapping of the sequences showed that the Lofoten area and adjoining shelf were important source areas during an early stage of the shelf development (isopach sequence 4 in Fig. 3.2.4). This area decreased in importance during later phases of the outbuilding, when E –W progradation from more southerly provenance areas seem to have dominated (isopach sequence 12 in Fig. 3.2.4).

3.3 Sediments above the Upper Regional Unconformity (URU) on the shelf

Norwegian Channel and North Sea Fan (60°-62°30′N)
The Norwegian Channel is a dominant morphological feature, separating the Norwegian mainland from the North Sea Plateau. The origin of the 'channel' has been frequently debated in the literature during the last century as described by Holtedahl (1993); tectonic, fluvial and glacial processes have been proposed. More than 100 years ago Helland (1885) proposed that a glacier flowed along the axis of the Norwegian Channel and caused the over-deepening in the Skagerrak (>700 m water depth). The observation of mega-scale lineations on top of the Late Weichselian till surface parallel to the axis of the channel (Longva and Thorsnes 1997), as well as detailed morphological /stratigraphical investigations on Jæren (Sejrup et al. 2000), have confirmed that a huge ice stream flowed in the channel along the coast south, southwest and west of Norway.

The upper Cenozoic geology between 60° and 62°N was mapped by BGS (British Geological Survey) and IKU (Continental Shelf Institute, Norway), based on regional shallow seismic profiling and sampling, and presented joint maps (Rise et al. 1984). They recognized several depositional units and erosional surfaces in the Norwegian Channel. The oldest till (the Eastern Trench Formation) was thought to be of Saalian age, and the upper till (the Norwegian Trench Formation) was interpreted to be a till from the last (Weichselian) glaciation. A north to north-northwestward ice flow in the channel was proposed for both the Saalian and the Weichselian ice streams (Rokoengen and Rønningsland 1983; Rise and Rokoengen 1984).

Based on correlation to exploration wells near the Måløy Plateau, the angular unconformity (URU) was considered to predate glaciations in the area and was attributed to fluvial and marine erosion near the sea level (Rokoengen and Rønningsland 1983). Revised age assignments of the foraminifers from the Måløy Plateau wells (Eidvin et al. 1991) have given a Pleistocene age for deposits above URU. Detailed stratigraphical investigations of a long geotechnical boring (>200 m) in the Norwegian Channel (Troll field, borehole 8903) convincingly show that the sediments above URU are of Pleistocene age (Sejrup et al. 1995).

Borehole 8903 has been tied to a revised seismostratigraphic framework in the Norwegian Channel interpreted by King et al. (in prep.), with suggested correlation to the stratigraphy on the North Sea Fan (King et al. 1996; King et al. 1998; Sejrup et al. 1996, 2000). An interpreted seismic E-W section across the Norwegian Channel close to borehole 8903 is shown in Fig. 3.3.1, with suggested tie to the core stratigraphy presented by Sejrup et al. (1995) (Fig. 3.3.2). The investigation of the Troll core combined with the seismo-stratigraphical studies have led to a much better understanding of the development of the Norwegian Channel and the related margin processes. A suggested correlation from the Troll borehole to the North Sea Fan is shown in Fig. 3.3.3. Some of the conclusions made by the authors are listed here:

-The till (unit A) found directly above the angular unconformity has been tentatively dated to 1.1 Ma. This is the oldest evidence of a Fennoscandian ice sheet reaching its maximum position on the shelf edge.

-This inferred initial glaciation was followed by a long ice-free period in the Early and Middle Pleistocene (c. 0.5 million years suggested duration). In this period (representing several climatic cycles) the ice sheet did not extend to the shelf edge, and dominantly layered marine/glaciomarine sediments (unit B) were deposited in the Norwegian Channel.

-Four or five till units and associated erosion surfaces represent increased glacial activity during the last 0.5 Ma. During these extensive glaciations much of the eroded material was transported along the axis of the Norwegian Channel to the North Sea Fan. The sediments beneath the fast moving ice stream was transported to the end of the grounded area at the shelf edge, and redistributed downslope as glacigenic debris-flows (Fig. 3.3.3).

- The ice advance depositing till unit N (i.e. Eastern Trench Formation) is assumed to be of Saalian or Early/Middle Weichselian age. Three Weichselian advances (depositing till unit R, i.e. Norwegian Trench Formation) seem to have occurred, possibly interlayered with thin sediments deposited during ice-free conditions in interstadial periods. A large proportion of the preserved glacigenic debris-flows on the North Sea Fan are associated with the Weichselian advances. The debris-flow deposits are present up to 300 km from the shelf break, having moved on slopes of gradients between 0.3° and 0.7°.

- The uppermost unit S represents the glaciomarine and marine sediments which were deposited after the ice retreated from the shelf edge c. 15,000 ^{14}C-years ago. The amount of stratified sediments of marine/glaciomarine origin on the fan is very small (<2 m thick).

- Four large sliding events have been mapped on the North Sea Fan, and during these events large quantities of previously deposited debris-flow sequences were transported to the deep sea. The large slides moved on a slope with gradients in the order of 0.5°. The large-scale positive form of the fan shows that the constructive processes (glacigenic debris) far exceeded the destructive slides.

Måløy Plateau and Møre shelf (62°- 63°N)
The shallow Måløy Plateau is located east of the outlet of the Norwegian Channel. In the early investigations of the region the thickness of the Pleistocene sediments was underestimated (Rokoengen 1980; Rokoengen and Rønningsland 1983; Rise et al. 1984), mainly due to erroneous datings in exploration wells near by. The angular unconformity is located c. 400 m below the plateau, with a thick succession of numerous Pleistocene units above (Fig. 3.3.4). The pronounced glacial erosion surface below unit N, was previously believed to be the base Pleistocene. This erosional event removed thick sediment packages west of the Måløy Plateau, and left parts of the plateau as an erosional remnant. North-westward moving ice extending from the mainland and partly coalescing with the Norwegian Channel Ice Stream, have later modified the topography.

The lower half of the Pleistocene deposits is poorly mapped below the shallowest part of the Måløy Plateau, because the seabed multiple hid the information below. Recent 3D-seismic investigations have shown parallel megascale lineations towards north at some of the old Pleistocene horizons (A. Nygaard, pers. comm.). This indicates that at least some periods occurred with northward ice movement below the present Måløy Plateau during early (and middle?) Pleistocene. It should be noted that the eastern part of these palaeo-icestreams were directed towards the shelf edge in the southern part of the Storegga area. The Saalian and Weichselian ice-streams seem to have followed the present Norwegian Channel.

Several generations of coastal, sub-aqueous deltaic-like prograding packages (without topsets) and distal bottomsets have been deposited above the angular unconformity directly west of the crystalline basement zone at the Måløy Plateau (Rokoengen and Rønningsland 1983). Similar prograding facies are seen also further south along the coast, located in the eastward continuation of the flat-lying and stratified unit B sediments in the Norwegian Channel (Fig. 3.3.1). Most of these sediments have, however, been removed by glacial erosion. A possible explanation is that the ice margin was stable for a long period in the coastal zone directly east of the 'deltas', and that the prograding sediments were deposited in periods with a generally high meltwater supply. An alternative explanation could be that fjords were filled with sediments, and that rivers in the ice-free periods terminated in the outer coastal zone.

The upper shallow shelf offshore Møre (east of the southern half of the Storegga Slide) was mapped by Rokoengen (1980). He divided the Quaternary sediments (0 – 200 m thick) into two main groups (older and younger drift), both comprising several seismic units. Consistent mapping of the units in the 'oldest drift' was found difficult and the general stratigraphy was shown on vertical sections (Fig. 3.3.5). The 'youngest drift' was believed to represent the last glaciation, and different stages of the deglaciation, tentatively assigned to the period 12-13 ka ^{14}C. Mapping of the units shows that they occur as complex linear zones that mainly lie parallel to the present coastline. The interpreted bedrock surface was found similar to the present topography, with banks, trenches and depressions clearly recognized and with higher relief than the present sea floor.

Rokoengen (1980) inferred that the sea level 30-40 km from the present coastline was about 150 m below the present sea level directly after the last deglaciation. Evidence from this conclusion came from sea-floor photographs and various analyses on several samples. The palaeo-geography was tentatively reconstructed, indicating that large areas of the shelf between 62°-63°N possibly could have been located above the sea level at that time (Fig. 3.3.6).

Møre and Trøndelag shelf (63°-65°N)
The bedrock geology and the Quaternary deposits in this area were described by Bugge et al. (1976, 1978) and Bugge (1980). The upper regional unconformity (URU) was interpreted to represent the interface between the underlying bedrock and the Quaternary sediments (Fig. 3.3.7). Quaternary deposits are up to 300-350 m near the shelf edge with a general trend of thinning towards the coast. Average thickness is about 125 m. The 'older drift' is much thicker than the 'younger drift', and is located mainly in the mid to outer part of the shelf. It comprises a complex suite of old Quaternary units, and several events of strong glacial erosion made mapping difficult. Bugge (1980) mapped three glacial units representing the last glaciation and deglaciation stages occurring as coast-parallel zones of glaciomarine clay and till. The outer unit (i.e. the Storegga moraine) reaches to the shelf edge in the southern part of the area where the Storegga Slide partly cut it. Radiocarbon datings of shells suggested a maximum age for the Storegga moraine of about 13 ka.

Rise and Rokoengen (1988) subdivided the sediments above the upper angular unconformity in the Haltenbanken area into four main units (IKU-D, -B, -A and –U at top) (Fig. 3.2.2). The study showed that the glacial history of the Haltenbanken south area is very complex with a number of large and small ice-front oscillations, and correlation to the till-tongue stratigraphy of King et al. (1987) farther north was found difficult. The typical irregular or undulating surface forming the base of unit IKU-D was interpreted to represent a prominent angular unconformity in most of the studied area (north of the Draugen and Njord fields). Many older units pinch out at this boundary or are eroded (Fig. 3.2.2). Dominantly layered sediments of supposed glaciomarine/marine origin were deposited in the depressions of this surface (unit IKU-D, up to 50-100 m thick). The stratification becomes less evident where the unit thins above palaeo-highs.

Several till tongue units are found in the above-lying unit B, but northwest of the outermost till tongue, acoustically stratified sediments occur. The sediments are c. 20 m thick and deposited above the stratified sediments in unit D (Fig. 3.3.8A). Unit A comprises a thick sequence of till-tongues in the north-western part of Haltenbanken, deposited above the stratified facies of unit B (Fig. 3.3.8B). The uppermost unit U was interpreted to represent the last glacial maximum and various Late Weichselian deglaciation stages (i.e. 'younger drift' mapped by Bugge 1980). Unit IKU-U is commonly thin, but may exceed 100 ms twt in thickness (in the 'trough' between 64° and 64°30'N).

Shelf north of Haltenbanken (65°-67°30'N)
King et al. (1987, 1991) carried out a detailed study of the Quaternary seismo-stratigraphy in the area 65°-67°30'N based on the interpretation of a regular grid of nearly 10,000 km analogue sparker data. A regional angular unconformity was identified in most of the area, and interpreted to represent the interface between Pleistocene glacial deposits and Mesozoic and Tertiary sediments. This erosion was interpreted to be glacial in the inner (eastern) portions of the shelf, but King et al. (1987) proposed that there was evidence to suggest a subaerial drainage in Pliocene time in the outer (western) part. The Pleistocene deposits consist of an up to 400 m thick succession of glacial till interbedded with thin layers of stratified glaciomarine sediments. East of the shelf edge the Quaternary section mainly comprises thick deposits of glacial till. The relationship between till/glacigenic debris-flows and glaciomarine sediments is best developed near the edge of the continental shelf (Fig. 3.3.9).

The Quaternary stratigraphy was interpreted in terms of a conceptual model for deposition of till and glaciomarine sediment on the continental shelf ('the till-tongue model'). Three major units were recognized (Lower, Middle and Upper Till), and each unit was divided in a number of sub-units denoted till tongues. A till tongue consists of a wedge-shaped deposit characterized by seismically incoherent reflections ('glacial till'), often with 'stratified glaciomarine sediments' deposited above. The beds of the glaciomarine unit are commonly thin and gradually terminate in the massive till ('the root') (Fig. 3.3.9). A map of the till tongues of King et al. (1987) is shown in Fig. 3.3.10.

The Lower Till was assumed to represent the first major glaciation on the shelf. It failed to reach the outer shelf region except for at the area just south of Trændjupet, and terminated at a water depth of approximately 600-700 m below the present sea level. *The Middle Till* represents the largest glacial event of the area, extending beyond the shelf edge to water depths of 800-1000 m below the present sea level. Its internal stratigraphy is made up of 12 till tongues, the largest was mapped for 350 km along the shelf edge. A large portion of the Middle Till was removed by glacial erosion especially at the central and inner part of the shelf. *The Upper Till* was assumed to represent the Weichselian glaciation on the shelf and was intermediate in magnitude. It generally extended to the shelf edge, terminating at a water depth of 500-600 m below the present sea level.

Mogensen (1986) interpreted the same data as King et al. (1987) east of 8°E (central and eastern part of the shelf east of Skjoldryggen including the Sklinnabanken area). He divided the Quaternary in five depositional sequences (each subdivided into several units), separated by continuous erosional reflectors. According to Mogensen (1986) huge ice-streams flowed out Sklinnadjupet, and resulted in glacial erosion in several periods. He postulated 14 oscillations of the grounding line from the mainland/coastal area onto the shelf, and that at least four of them reached the shelf edge. King et al. (1987) did not use the term ice streams, and was of the opinion that ice sheets advanced regionally seaward to the shelf (and at least two of them to the shelf edge). The ice sheets partly eroded the central and inner part of the shelf, and were constructive on a broad scale in the outer part of the shelf (including the Skjoldryggen area). Based on the evidence of strong erosion at the flanks of Trænadjupet, King et al. (1987) postulated that this trough had been formed by ice draining out Vestfjorden.

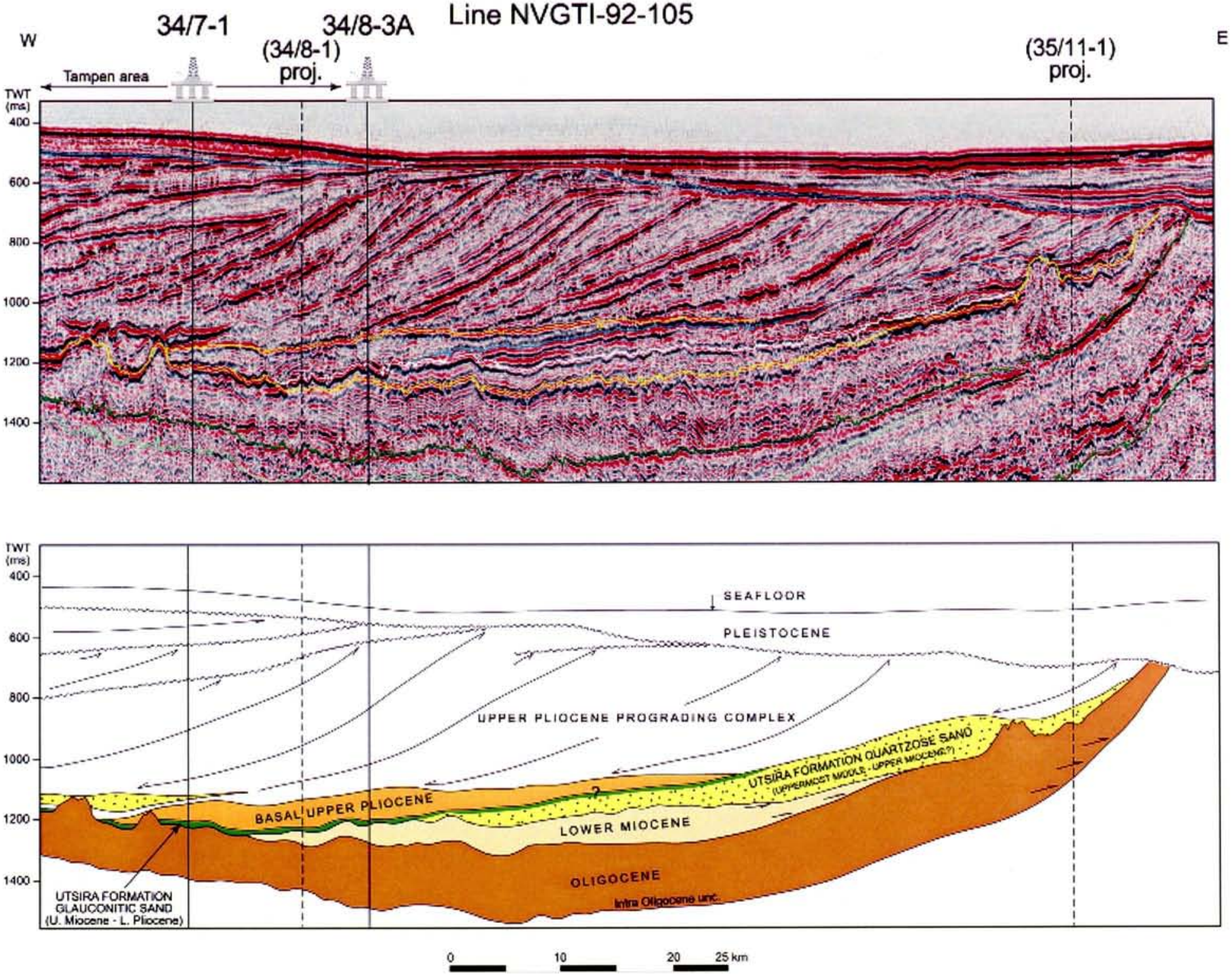


Figure 3.2.1 E-W profile from the Norwegian Channel to the Snorre area (northern North Sea), showing the major depositional sequences (after Eidvin and Rundberg 2001).

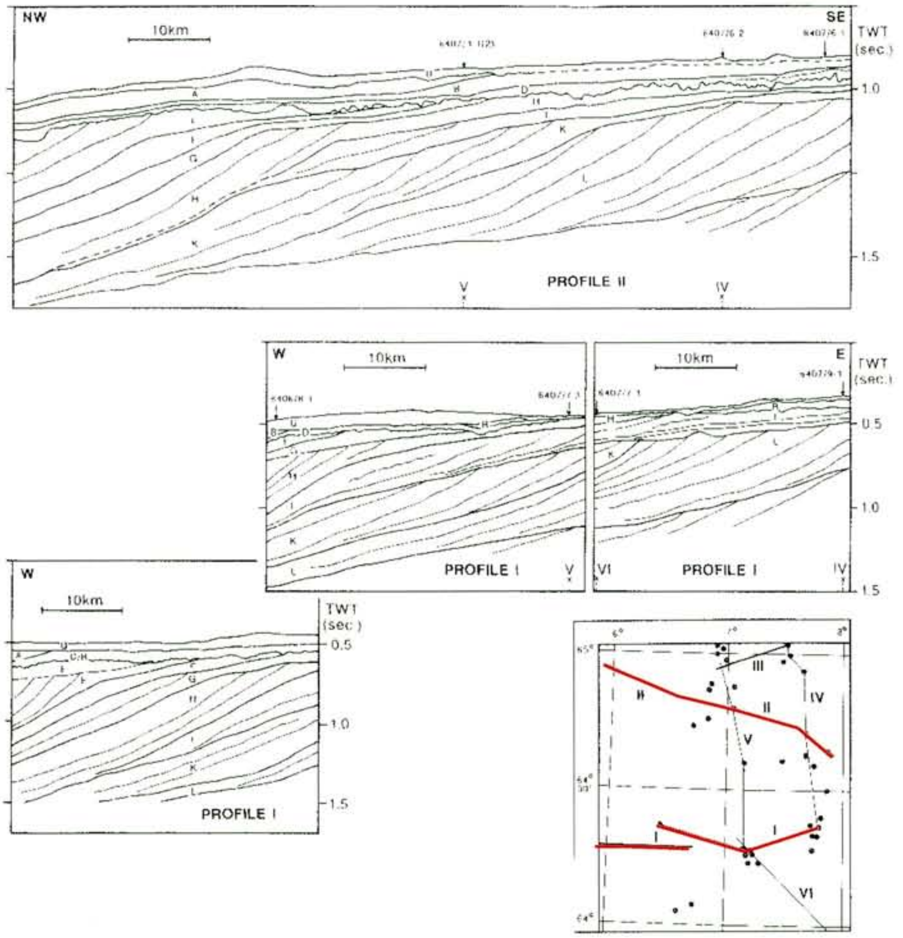


Figure 3.2.2 Geoseismic profiles I and II (red) showing the Late Pliocene/Pleistocene stratigraphic units in the Haltenbanken area (after Rokoengen et al. 1995). Units E, F, G, H, I, K and L comprise prograding subunits of the Naust Formation, while U, A, B and D represent subunits above the Upper Regional Unconformity (URU). Well 6407/9-1 (see profile 1) is located in the Draugen area.

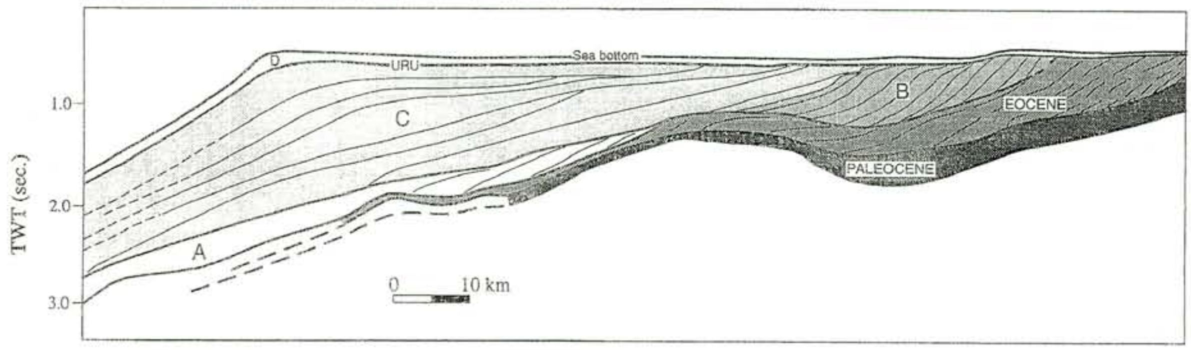


Figure 3.2.3 Schematic cross section of the Cenozoic stratigraphy on the northern part of the mid-Norwegian continental shelf. Unit C represents the Late Pliocene/Pleistocene prograding sequence (after Henriksen and Vorren 1996).

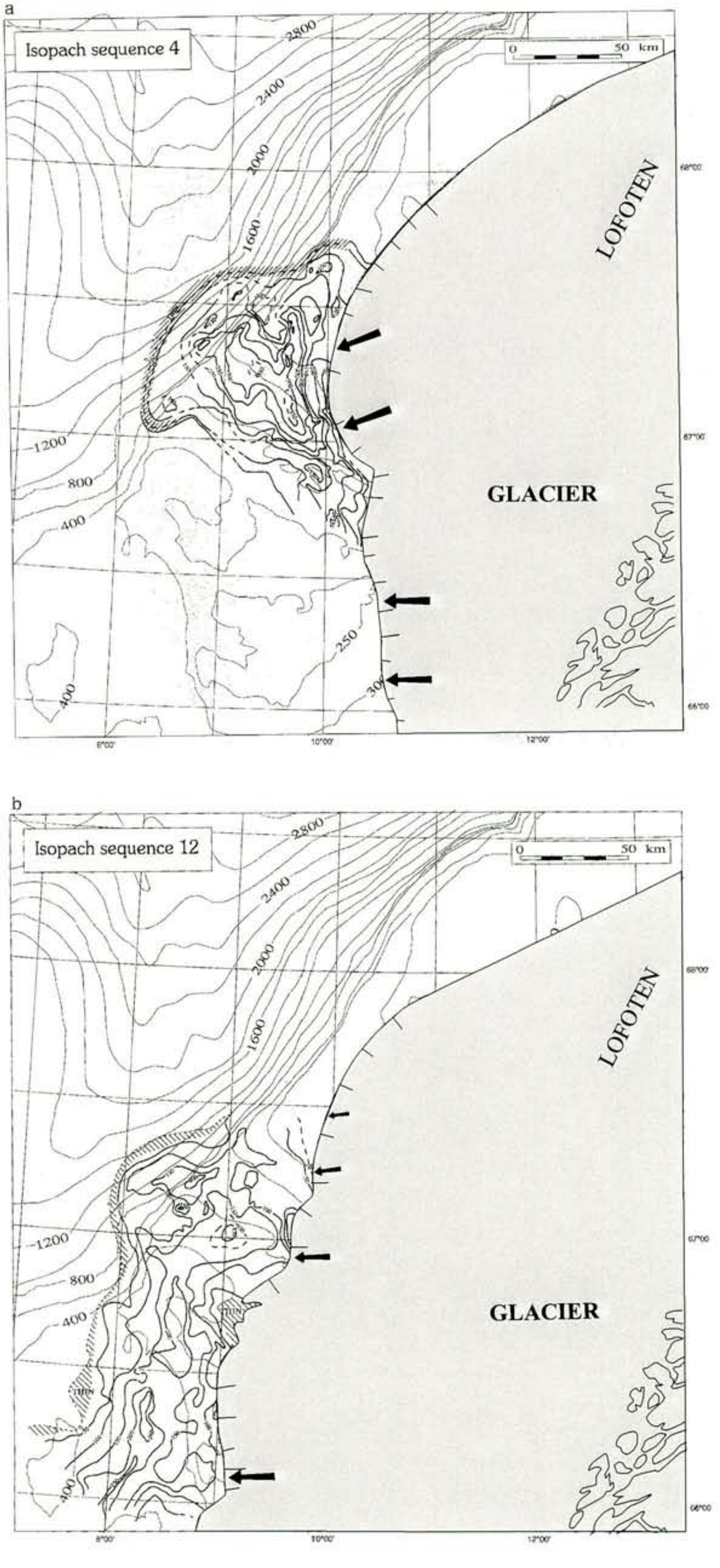


Figure 3.2.4 Palaeogeographic reconstructions of the northern part of the mid-Norwegian continental shelf during the Late Pliocene-Early Pleistocene from the earliest (a) to the latest (b) phase of the outbuilding. Arrows indicate ice movement and direction of sediment transport (after Henriksen and Vorren 1996).

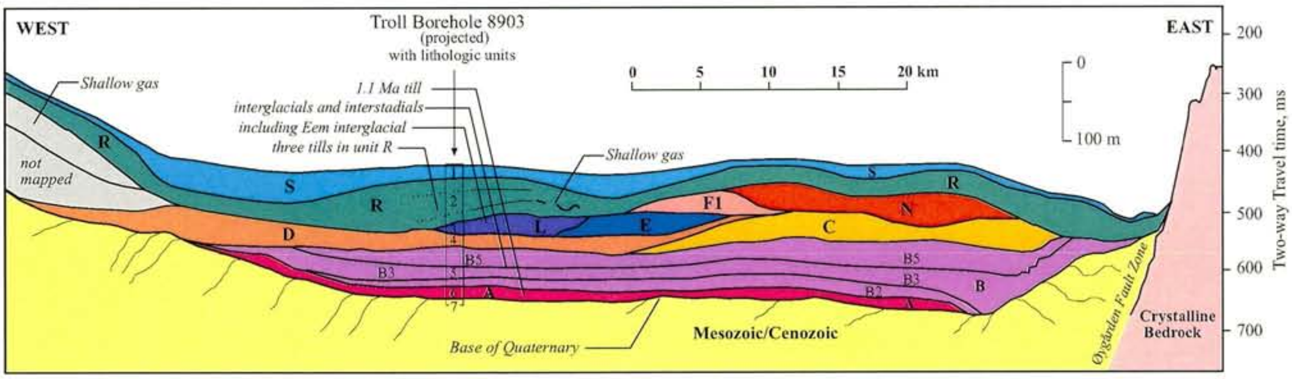


Figure 3.3.1 East-west profile showing the Quaternary stratigraphic units in the Norwegian Channel at about 60° 38' N. Proposed correlation to the Troll borehole 8903 (see Fig. 3.3.2) is marked on the profile (after King et al. in prep.).

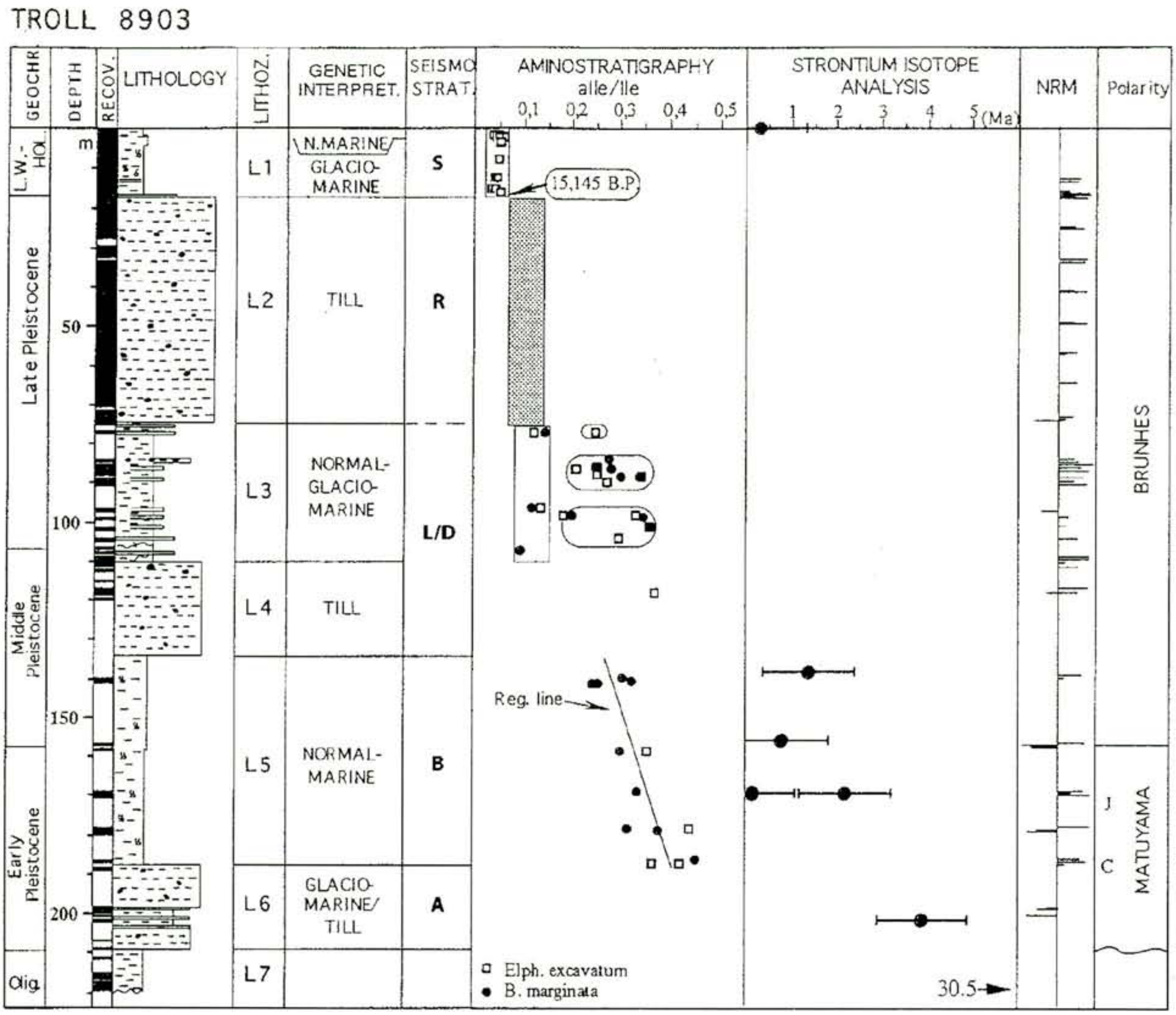


Figure 3.3.2 Chronostratigraphy of borehole 8903 at the Troll Field (after Sejrup et al. 1995).

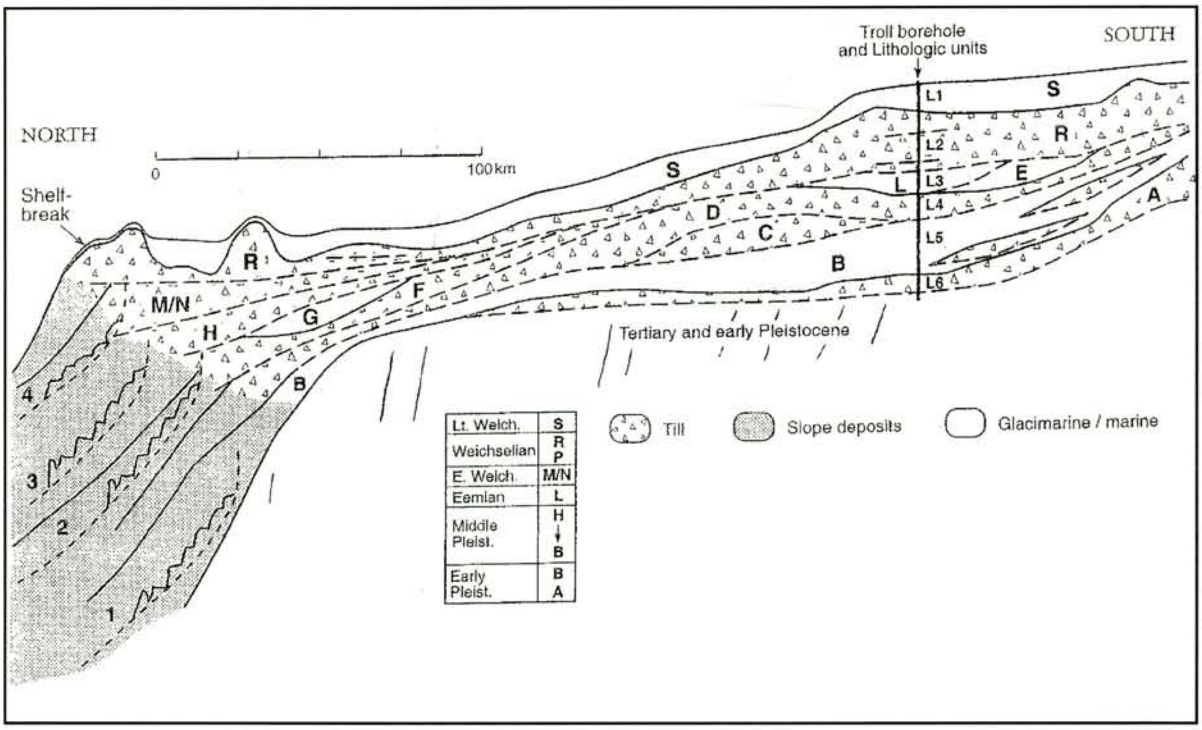


Figure 3.3.3 Profile along the Norwegian Channel from south of borehole 8903 and towards the North Sea Fan (after Sejrup et al. 2000).

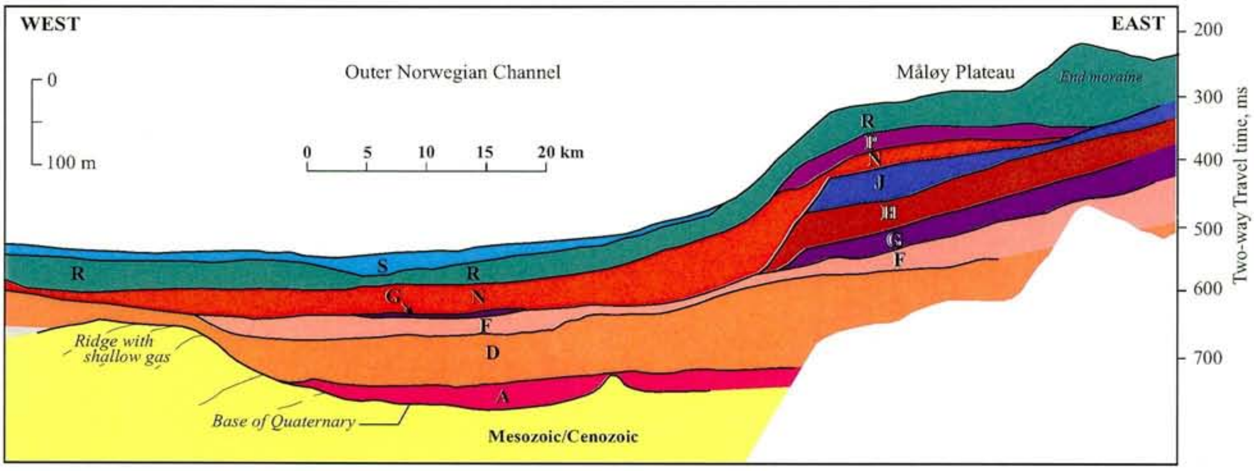


Figure 3.3.4 East-west profile showing the Quaternary stratigraphic units in the Norwegian Channel and the Måløy Plateau at about 62°N (after King et al. in prep).

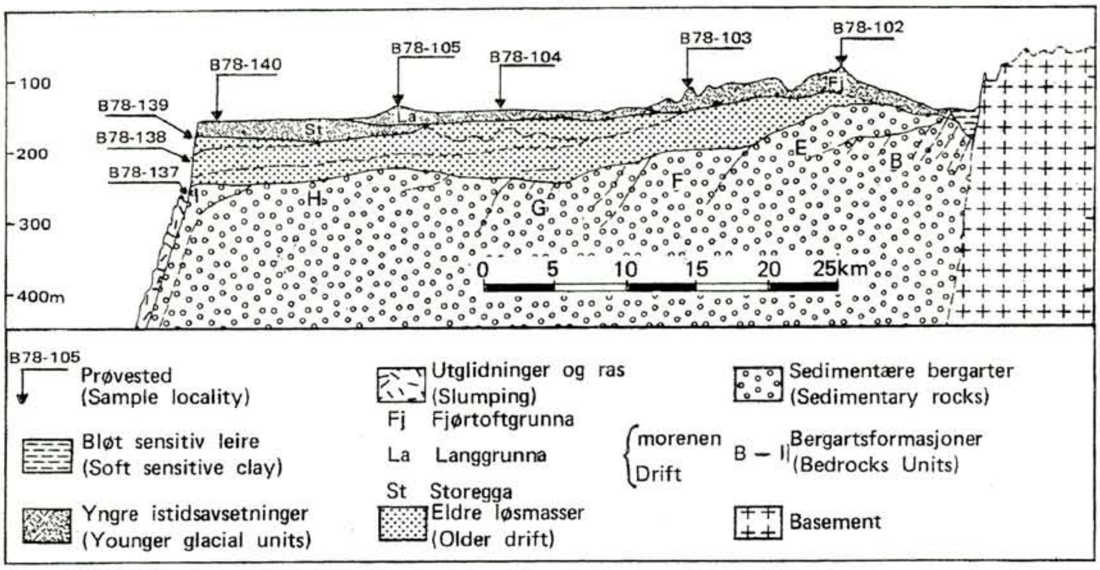


Figure 3.3.5 SE-NW profile showing interpreted bedrock units and Quaternary sediments at c. 63°N (Langgrunna) (after Rokoengen 1980).

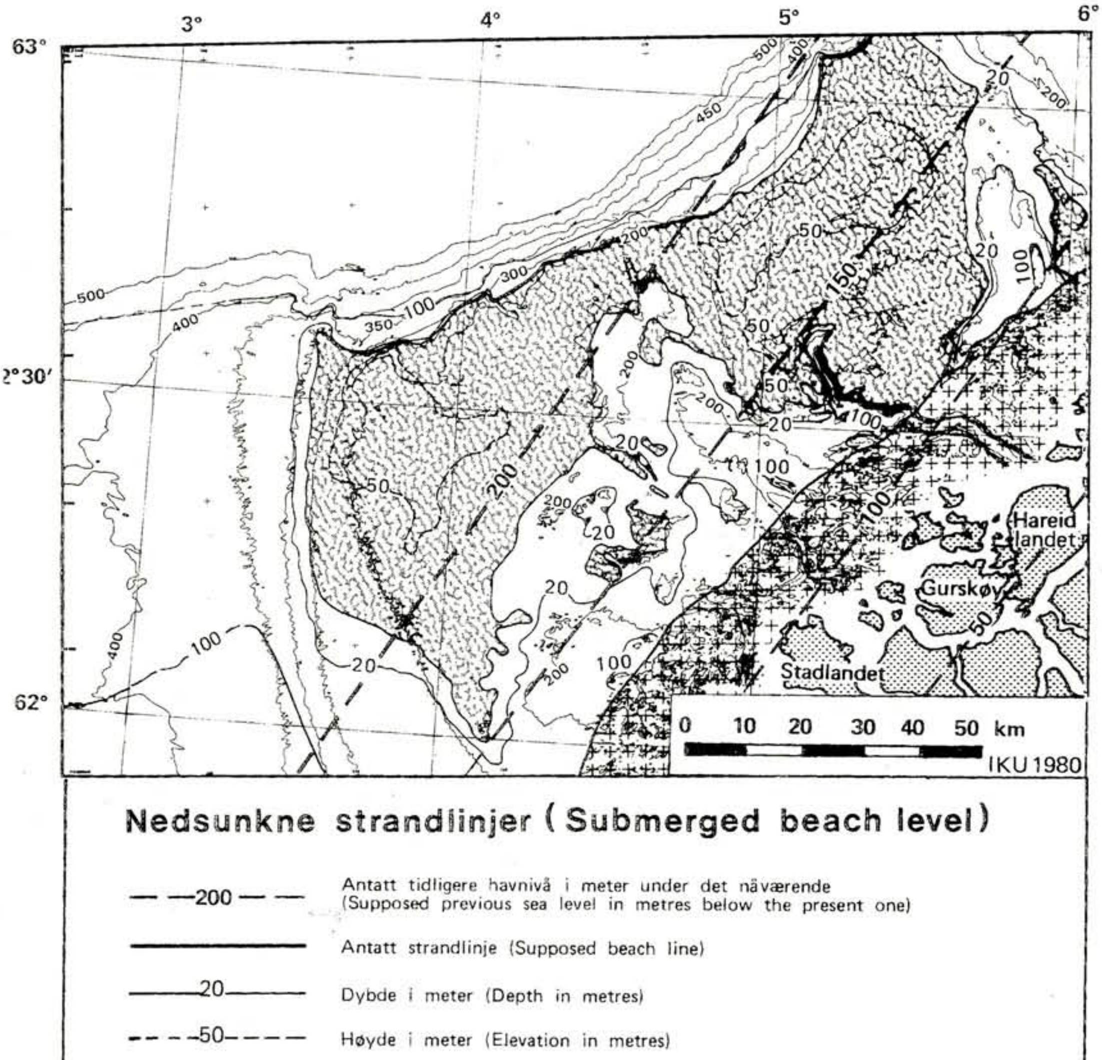


Figure 3.3.6 Suggested palaeogeography during the formation of deep submerged beaches off Møre (after Rokoengen 1980).

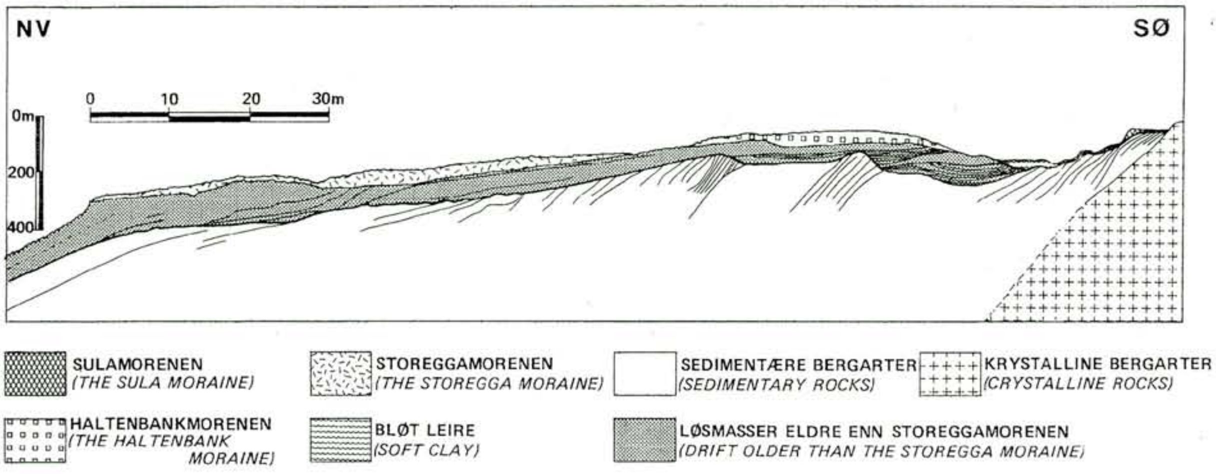


Figure 3.3.7 Profile from the southern end of Frøya across Frøyabanken to the shelf edge (after Bugge 1980).

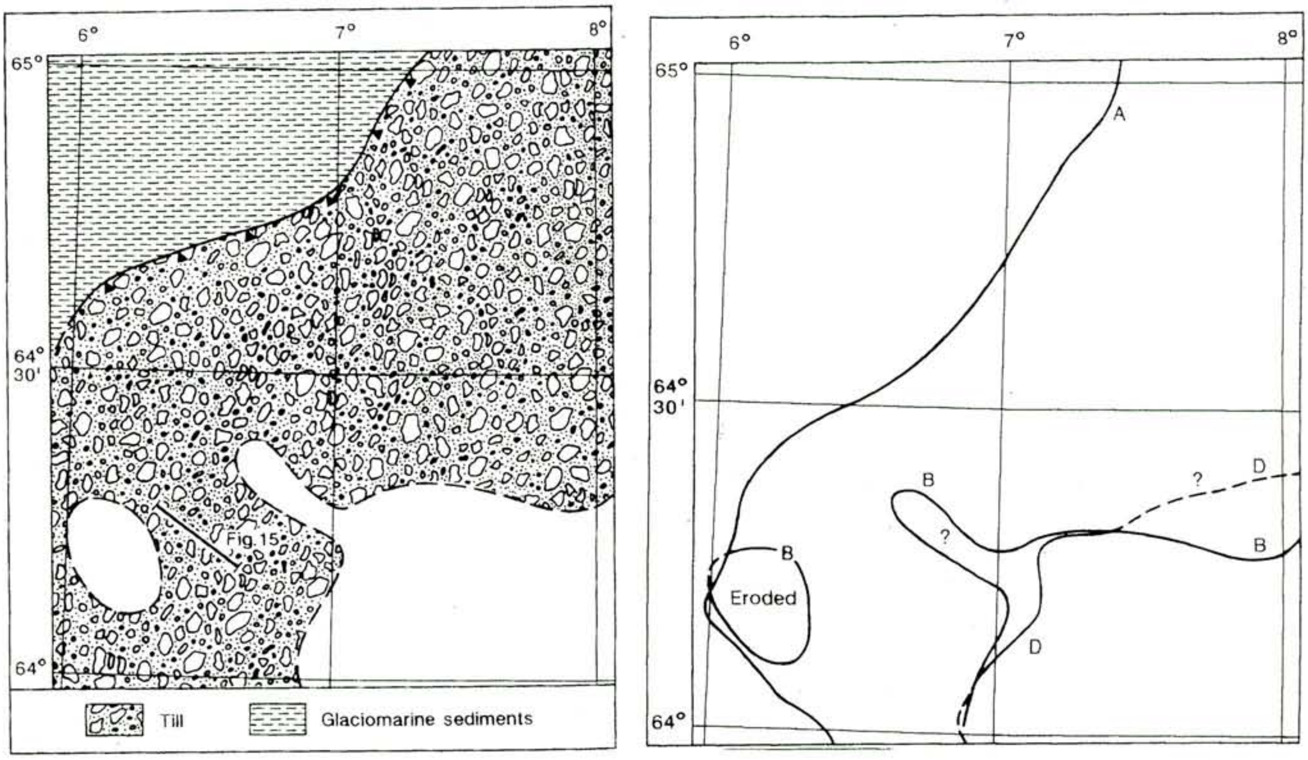


Figure 3.3.8A Distribution and depositional facies of unit IKU-B in the Haltenbanken area (after Rokoengen et al. 1995).

Figure 3.3.8B Pinchout of units IKU-D, -B and –A in the Haltenbanken area. The units occur west of the pinchout lines. Unit IKU-U covers the whole area with Quaternary sediments (after Rokoengen et al. 1995).

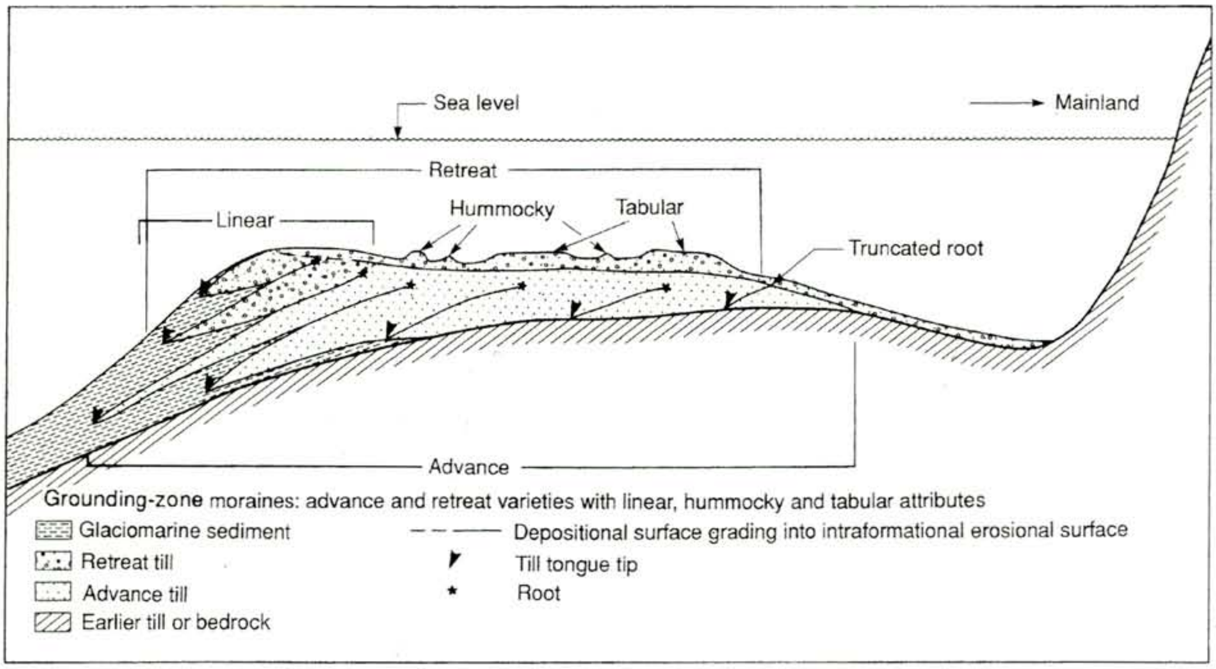


Figure 3.3.9 Diagrammatic section across the mid-Norwegian Shelf, showing the elements of a till tongue stratigraphy during a complete glacial cycle (after King et al. 1991).

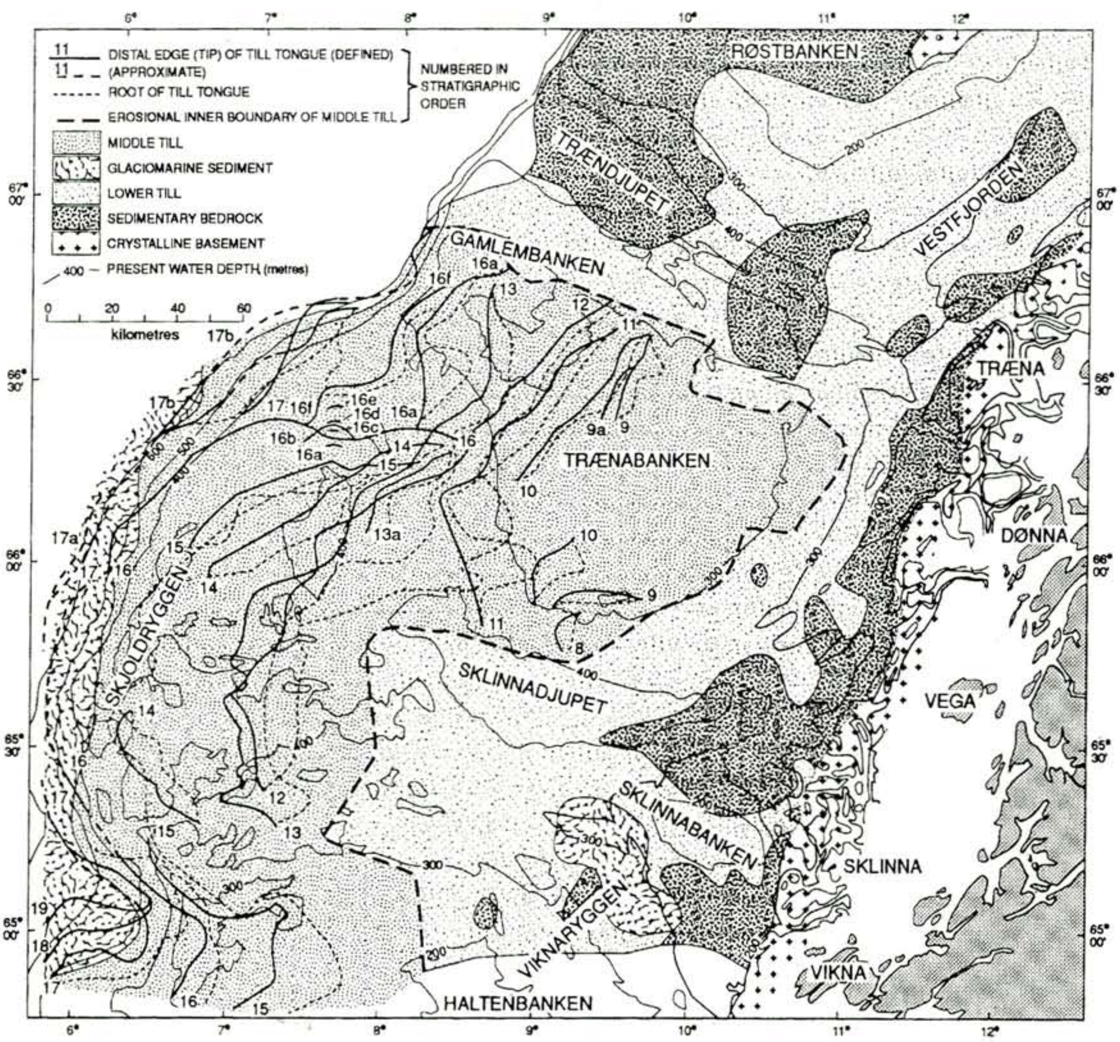


Figure 3.3.10 Map of different till tongues in the Middle Till (after King et al. 1991).

4. DATABASE AND WORK APPROACH

4.1 Project database

Bathymetry
The bathymetric database comprises two data sets:

1) Norsk Hydro - a regional bathymetric data set covering the whole mid-Norwegian margin, including the shelf, slope and deep sea. These data sets have a cell size of 200 m, and are compiled from several sources, including single- and multibeam echo-sounder data, and data from digital seismic lines.

2) Norwegian Hydrographic Service (NHS) - a data set covering the mid-Norwegian Continental Shelf and the upper slope, collected by NHS with a single-beam echosounder. Profile spacing is 500 m or closer.

The two data sets have been integrated in order to make a regional map of best possible quality. Because the NHS data set generally is of higher quality on the shelf, these data have been given preference in that area. Thus, the NHS data covers the shelf and upper slope (down to 500-1000 m), while the Norsk Hydro data set covers the deeper areas (Fig. 4.1.1, Enclosure 1).

Seismic data
The digital seismic lines made available in the study are shown in figure 4.1.1. A total of approximately 25,000 profile kilometres of digital seismic data were included in the project. Most seismic profiles from the Seabed Project were included in this study. The data comprise reprocessed exploration 2D multichannel seismic data as well as high resolution multichannel seismic data in addition to some deep tow boomer and mini airgun profiles. High resolution 2D multichannel seismic data cover mainly the continental slope and partly the outer shelf. Surveys: NH9651, NH9753, NH9754, NH9956.

In addition some profiles of very high quality acquired in 2001 were included in the data base. Specific surveys and profiles are:
NH0163: Profile 101, 102, 103, 201, 212, 301, 302, 304, 403, 405, 1204, 1303, 1408 and 1409.
NH0169: Profile 202, 301, 303, and 304.

The shelf and upper slope seismic data base includes mainly (non-reprocessed) conventional 2D seismic data. Most profiles were cut below 2.0, 2.5 or 3.0 seconds. Some of these conventional profiles are of very good quality, however, most profiles are of medium to poor resolution. Particularly in the shallow shelf areas, where removal of multiples has been problematic, the upper portion of the profiles are of poor quality.

Specific surveys and profiles are:

GM1I85: profiles 11, 110, 112, 113, 114 and 115
GMNR94: profiles 104, 105, 107, 202 and 310
SMB: profiles 204, 405, 406, 409 and 410
GMT 84: profiles 204, 207, 403, 406, 407, 408, 409, 410, 411, 412 and 415
MNT 2: profiles 09 and 1A
MNT 86: profiles 01, 02, 03, 04, 05, 06 and 07
MNT 92: profiles 01, 03, 04, 05, 06, 07, 09, 10, 11, 12, 12, 14 and 15
TB 84: profiles - 01, 02, 03, 04, 05, 07, 08, 09, 10, 11, 12, 13, 14, 15, 16, 17, 18 and 19
GFI 85: profiles 211 and 212
NM1: profiles 207, 411 and 426
GMM 94: profile 301
NRT 94: profile 03
SPT 94: profile 406
VBT 94: profile 003
GMS1 91: profile 11
HR 89: profiles 40 and 48
VNM1: profiles 426 B, 207 B and 411

The following MB-lines have been used:
MB 07-84 and 13-84
MB 2-91, 6-91 and 13-91
MB 7-92, 8-92, 9-92, 12-92 and 14-92
MB 6330, 6410 and 6445

Survey ST-8501 includes 106 lines on the outer Haltenbanken area with a relatively close profile spacing (5 km east, 3 km north). These profiles have been useful for linking the shelf stratigraphy with the slope stratigraphy. However, very few profiles extending from this survey and further east on the shelf were available. Generally, the available seismic surveys have either been acquired on the shelf, or on the slope and in the deep sea. Consequently, few profiles overlap between different surveys, resulting in large areas without overlap between the shelf and the slope.

IKU regional grid of analogue sparker data (10-15 km spacing in a NW-SE direction and approximately 25 km spacing in a NE-SW direction) covers most of the mid-Norwegian shelf (Rise 1988). Most records have a vertical scale of 0.5 s. These profiles have been used for interpretation of younger sequences.

Well data

The most comprehensive biostratigraphical study of Cenozoic sediments on the mid-Norwegian Continental Shelf was carried out by Eidvin et al. (1998) and Eidvin and Rundberg (2001). We have correlated the interpretations of Eidvin et al. (1998) to the seismostratigraphic framework applied to this study, using the following wells (Enclosure 1):

6607/5-1 Outer shelf, north of Skjoldryggen (seismic profile MNT92-04)
6607/5-2 Upper slope, north of Skjoldryggen (seismic profile MNT92-04)
6506/12-4 Haltenbanken northwest (seismic profile MNT 86 04)
6610/7-1 Inner Trænabanken (seismic profile MNT 9206)

Geotechnical borings
The following geotechnical borings have been available to the study (see Enclosure 1):
6404/5-GB1 south-west of Helland Hansen
6405/2-GB1 east of Helland Hansen
6606/3-GB1 south of Vema Dome/Nyk High
6704/12-GB1 south-east of the Gjallar ridge
6305/5 (Site 99), Storegga Slide, central Ormen Lange area
6305/5 (Site 22), Storegga Slide, northern flank of slide scar 3
6305/8 (Site 19_2) east of Storegga Slide, outer shelf (Buadjupet)
6305/9 (Site 20) east of Storegga Slide, outer shelf (Buadjupet)

Detailed analyses of the geotechnical boring samples have been carried out by Norwegian Geotechnical Institute (NGI). The University of Bergen used the recovered samples for lithological and chronostratigraphical analysis (Haflidason et al. 1998, 2001). Data from geotechnical boreholes at the Draugen Platform Site and at the Smørbukk fields have also been applied in this study (Mogensen and Rise 1988; Haflidason et al. 1991; Rise and Rokoengen 1991).

Images cores.
In 1999, several continuous cores were collected with the French ship Marion Dufresne. Data from two of these cores have been used (see Enclosure 1):
MD99-2289, located on the northern flank of the Storegga slide (23.7 m core length, 1262 m water depth).
MD99-2291, located on the slope southwest of Skjoldryggen (25.8 m core length, 577 m water depth).

These cores have been examined partly on the ship, and partly at the University of Bergen.

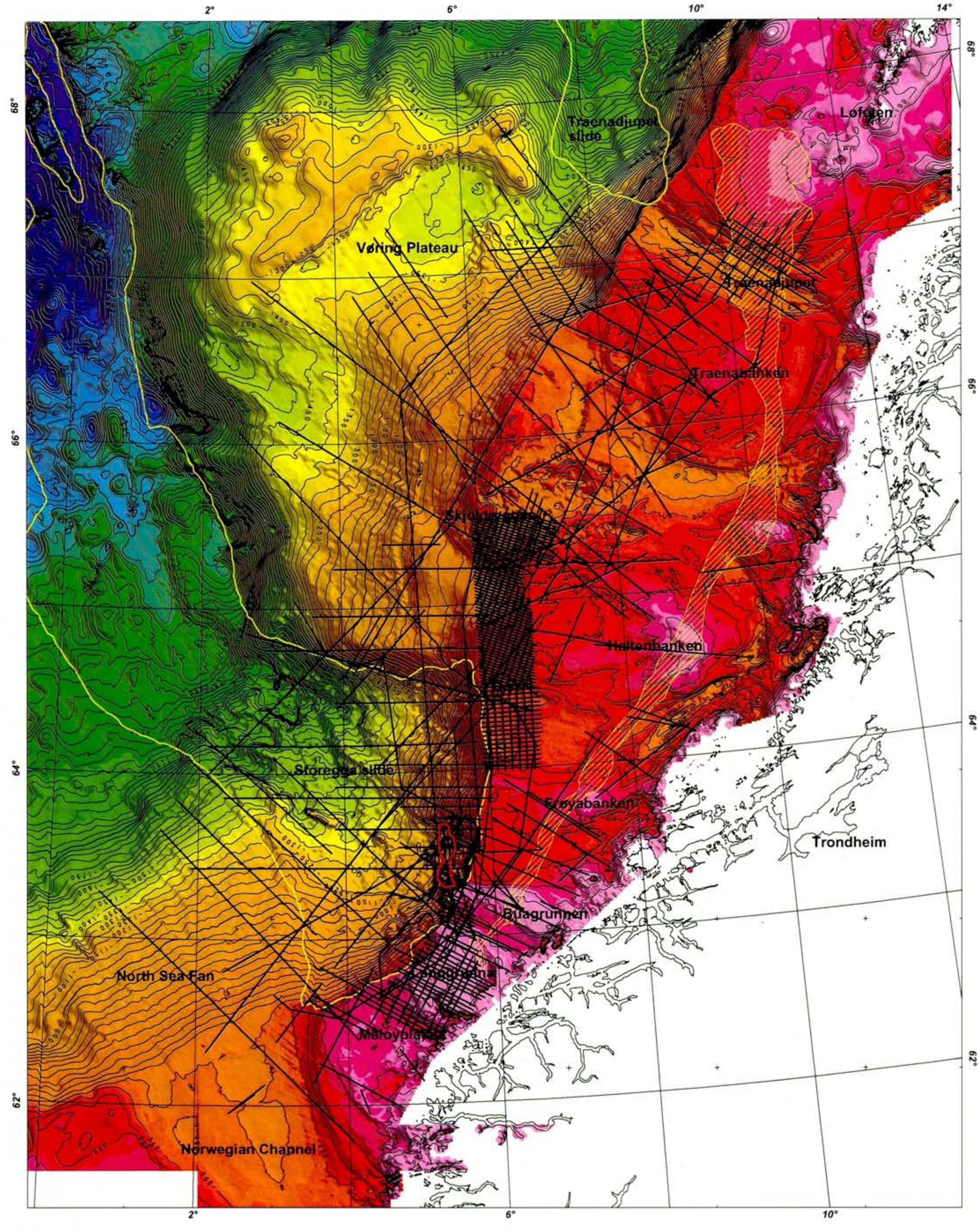


Figure 4.1.1 Digital seismic database applied in this study.

4.2 Work approach

Work approach during the first phase of the project

Before the early investigations of the Storegga Slide (Bugge 1983; Bugge et al. 1987, 1988) only very limited information was available from the mid-Norwegian continental slope. Various investigations carried out during different phases of the Seabed Project have significantly increased the understanding of the stratigraphy and geological processes on the slope. The data and interpretation reported in Phase III of the Seabed Project (Britsurvey 1999) has been the basis for our interpretation of the shelf stratigraphy in this study. As the deep impact of the Storegga Slide and older slides in the area made it difficult to correlate the stratigraphy north and south of the slide, two separate sets of stratigraphic nomenclatures have been applied, with suggested correlations across the Storegga Slide (Fig. 4.2.1).

The main objective of this study has been to establish a consistent seismo-stratigraphic correlation for the entire mid-Norwegian shelf and margin. During the first stage the interpretation work was based on reflectors established by Britsurvey (1999), using data examples in the Britsurvey reports and examples forwarded by Norsk Hydro as 'starting points' from which the seismostratigraphic framework could be extended from the basin area to the shelf.

Britsurvey subdivided the Naust Formation into units A to H north of the slide, and into units O to W to the south. Correlation across the Storegga Slide had been found difficult, as several episodes of sliding had removed a considerable part of the Naust stratigraphy. Another complicating factor was the complexity of the various depositional systems along the margin, and that very few profiles on the shelf were available. Britsurvey (1999) proposed a correlation between some of the reflectors north and south of the slide, but noted that this correlation should be treated with caution. A revised version of this correlation scheme is shown in figure 4.2.1 (Svitzer 2002).

In our database few of the digital profiles on the shelf could be tied to the Seabed Project profiles on the slope, and particularly in some areas east of the Storegga headwall an open profile-grid made the tie difficult. It was therefore, often necessary to use long 'tie loops' with various cross-profiles in order to tie the stratigraphy between the slope and shelf. Old analogue seismic data (IKU, mainly sparker lines) occasionally provided some useful ties, but the seabed multiple generally made the correlation of deeper horizons difficult. Many of the conventional seismic profiles were of poor resolution in the upper part, particularly in shallow areas where unsuccessful seabed multiple removal were common. Most of the defined units pinch out or are truncated at the regional unconformity east of the present shelf edge. Because few cross-profiles exist in this 'sub-crop' area, the north-south correlation of some units was fairly uncertain in the southern part of the Møre shelf.

Work approach during the last phase of the project

Based on recent work (at Norsk Hydro), developing a more detailed geological model in the Ormen Lange area (Norsk Hydro 2001), Britsurvey's (1999) nomenclature for the southern area was applied. A detailed subdivision of several previously defined units was made, based on seismic correlation to soil borings directly east of the headwall and within the Storegga Slide. The main reflectors of the revised Ormen Lange stratigraphical framework were extended regionally in order to obtain a consistent stratigraphy for the entire mid-Norwegian margin (recent Norsk Hydro study). Several data examples from this study were applied in order to ensure a correct tie to shelf areas. As the main sequence boundaries TNS and TNR are at the top of stratified units in the lower slope, and these sediments commonly pinch out in the middle-upper slope, only minor reinterpretations were necessary during the last stage of the interpretation. Therefore, in most of the area a consistent tie between the slope and shelf has been obtained.

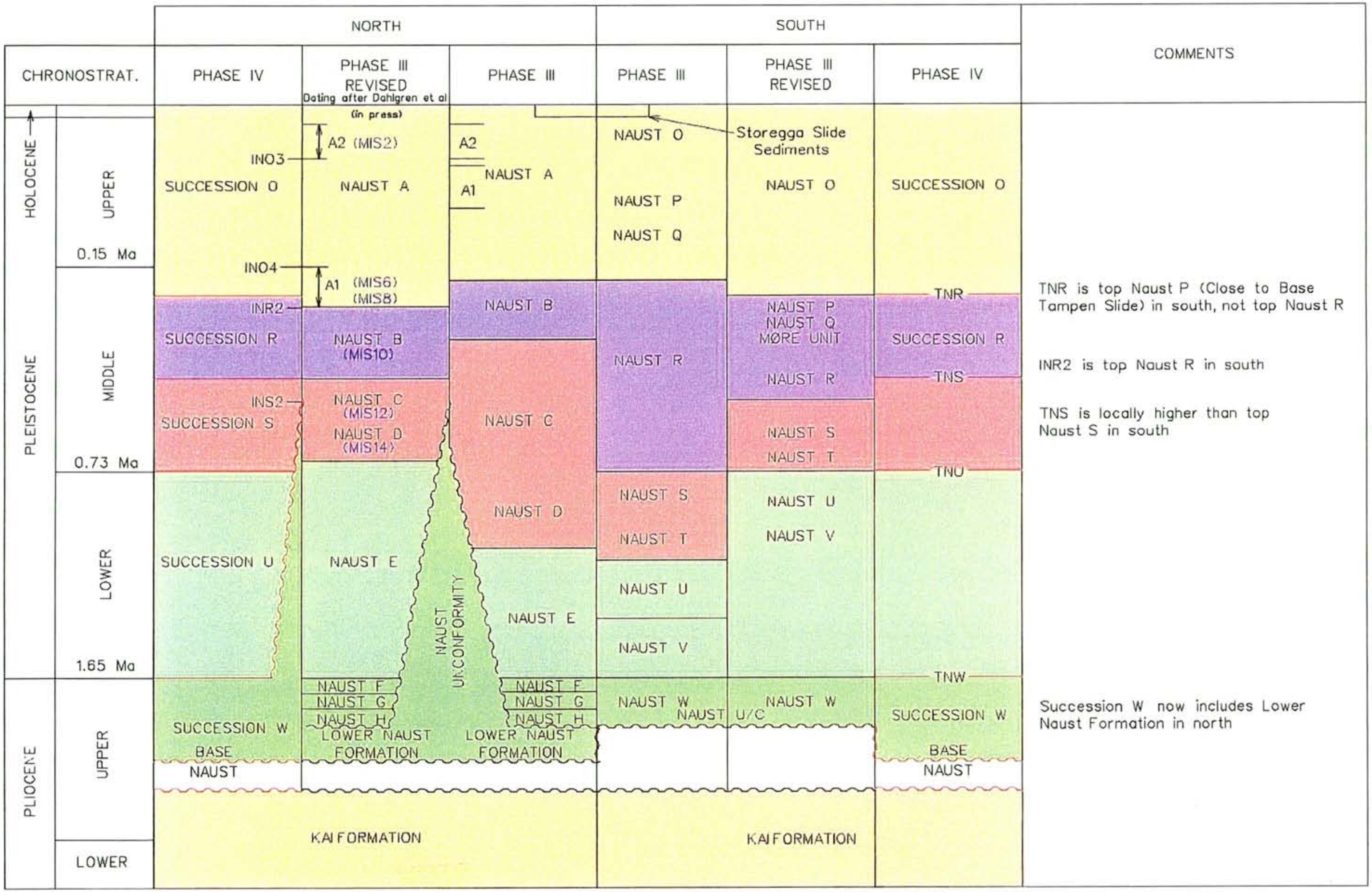


Figure 4.2.1 Seismo-stratigraphic framework for the mid-Norwegian continental margin, established during the Seabed Project (after Svitzer 2002).

5. SEISMIC STRATIGRAPHY AND SUBDIVISION OF SEQUENCES

The Naust Formation has been subdivided into five seismic sequences in chronological order from oldest to youngest (W, U, S, R, O), each of them comprising several units (Tab. 5.1.1). The youngest Sequence O represents the last two glacial-interglacial cycles, comprising mainly glacigenic sediments from the Saalian and Weichselian glaciations. Sequence R represents one or two glacial-interglacial cycles, whereas the three oldest sequences (W, U, S) represent several cycles. The sequences commonly comprise several units. In the northern area the units appear as acoustically massive, and stratified sediments make up only a very small portion of the stratigraphy. South of Skjoldryggen, the amount of stratified sediments increases beyond the margin, being most evident in the slopes adjacent to the Storegga Slide. Stratified sediments seem to be less common in the North Sea Fan.

In this chapter we present the stratigraphic subdivision, with emphasis on the regional development of combined sequences. In addition to several interpreted vertical sections illustrating the shelf to slope development through Naust time, we also present isochron maps (sequence(s) W, U+S and R+O) and time structure maps (Base Naust, Top Naust W). A further stratigraphic subdivision of sequences R and O, with a model for the geological development during the last three or four glacial – interglacial cycles, is given in Chapter 6.

Attempts to tie different chronostratigraphic data (geotechnical boring at Draugen, commercial wells, ODP well 644A) into the seismostratigraphic framework show large discrepancies. Based on the available database, we have not been able to understand why there is an age conflict. The proposed ages for the sequences must therefore be regarded as uncertain, particularly for Naust S, U and W. A summary of chronostratigraphic investigations, together with a discussion of the conflicting ages, is presented in Chapter 7.

Within large areas of the study area, a prominent angular unconformity (URU) separates a flat-lying upper sediment succession from westerly dipping sediments beneath. The work in this project, as well as previous investigations (Rokoengen et al. 1995), has shown that it is difficult to consistently follow the same erosional surface regionally. In some areas URU is poorly defined, and the term has been applied for a corresponding erosional reflector within a flat-lying sediment succession. It is also clear that different angular unconformities occur in some regions, and that the term URU applied in this report covers unrelated surfaces of different age. A further discussion of this 'diachronous surface' is given in Section 5.4.

5.1 Seismic stratigraphy and depositional model

A correlation scheme of the various stratigraphic nomenclatures applied in the different studies is shown in Table 5.1.1. To clarify the correlation between the different studies, we have, in the upper part, distinguished the stratified sediments from sediments with a more 'massive' seismic character (tills, debris flows and mass flows). Britsurvey (1999) defined seismic units which could be followed regionally, whereas in the Ormen Lange area a sequence stratigraphic approach was applied for the upper part of Sequence S (above horizon

INS2), and for definition of sequences R and O (Norsk Hydro 2001). These sequences comprise one or several massive units (glacigenic debris, slide deposits), and each of them also includes an overlying stratified unit. The Sequence boundaries (TNS, TNR) therefore do not correspond to lithological boundaries, but represent the start of major glaciations beyond the shelf edge. Top Naust S (TNS) and TNR are defined at the top of thick stratified deposits in the slope, and continue at the top of the underlying prograding glacial unit, east of where the contourite-like sediments pinch out.

North of the Storegga Slide area, the stratified sediments are commonly thinner or absent, but TNS is well defined at the base of the thick glacigenic unit R3. The thickest stratified sediments occur above unit R3, and TNR has been interpreted within these sediments corresponding to the base of the Saalian till tongues. The three oldest defined sequences comprise several depositional cycles, and the top of Sequences Naust W and Naust U corresponds to the horizons TNW and TNU defined by Britsurvey (1999) in the southern area.

The background for the new interpretation approach is described below (Norsk Hydro 2001).

Geological model based on depositional cycles
The revised seismic stratigraphy in the Ormen Lange area (Norsk Hydro 2001) is based on recent seismic interpretations of the existing 2D and 3D database, and applies the stratigraphy in the southern area (Britsurvey 1999) as the main framework. Several subunits have, however, been defined in order to correlate the seismic data with the stratigraphy observed in geotechnical borings acquired in 1999 and 2000. The seismic stratigraphy coincides mostly with the lithostratigraphy, as well as with the geotechnical stratigraphy (Norsk Hydro 2001).

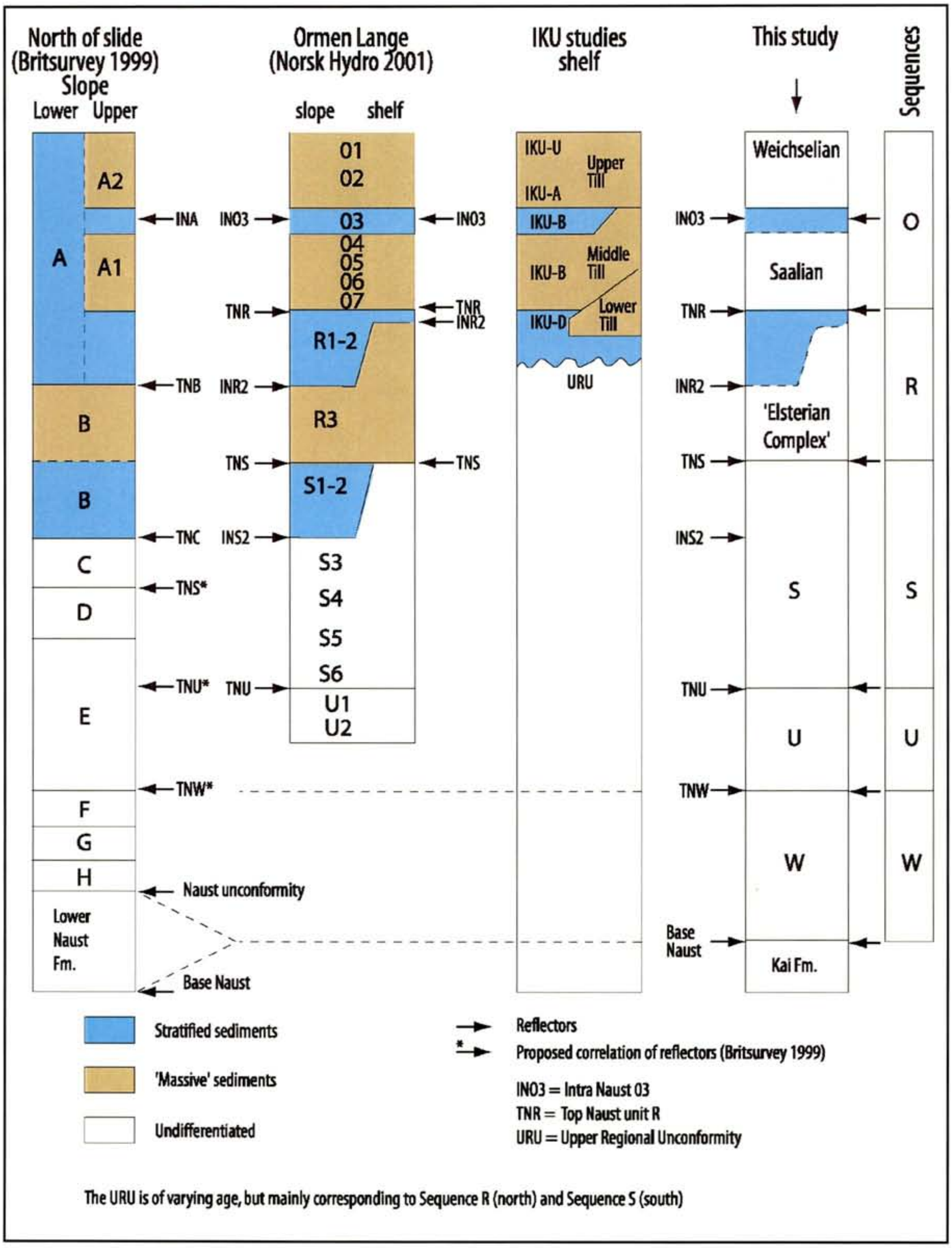
The applied sequence stratigraphic approach is linked to a proposed depositional model that seems to explain several large sliding events in the Storegga region (Norsk Hydro 2001). Up to three types of deposits at the margin are related to each glacial - interglacial sequence cycle (see Fig. 6, Executive Summary):

1. Prograding deposits, composed mainly of glacial debris flows deposited during extensive glaciations. These are seismically chaotic or transparent sub-units, usually showing a down-lapping relationship onto the underlying, layered sediments (sub-units S3, R3 and O7-O4).

2. Slide and slump deposits. These mainly represent large slide events which took place after ice retreat. As the slides mostly bypassed the upper slope, these deposits are generally thickest in the mid-lower slope and basin. They commonly show an erosive base, and are related to a slide-scar up-slope. Older stratified sediments acted as detachment levels for the slides. The most typical deposit of this type is the Storegga Slide sediments. Horizons INS2 and INR2 represent the surface of two large palaeoslides in the Ormen Lange area (slides 'S' and 'R'), and the base of stratified sediments.

3. Glacomarine and marine sediments, deposited during glacial and interglacial periods. The sediments are commonly seismically stratified, and in places reach great thickness on the mid to lower continental slope. They are commonly mounded, with indications of migration both up and along slope (contourite-like sediment bodies). The sediments consist of silty clay (sub-units S1/S2, R1/2 and O3).

Table 5.1.1 Scheme showing the defined sequences (Naust W, U, S, R and O) and horizons applied in the present study. Correlation with other studies is shown. The stratigraphy corresponds to the Ormen Lange study (Norsk Hydro 2001).



5.2 Presented seismic sections and description of mapped sequences

To illustrate the shelf to slope development of the Naust Formation, several interpreted seismic sections are presented either as line drawings or as data examples (Figs. 5.2.2 to 5.2.17). Most of the sections comprise several seismic lines (Tab. 5.2.1), and the location is shown in figure 5.2.1. In the description of the depositional sequences reference will be made to these lines. The Naust Formation is subdivided into five sequences, presented in different colours:

Naust R and Naust O:	Green. Representing the last three or four glacial/interglacial cycles.
Naust U and Naust S:	Red.
Naust W:	Blue. Representing the oldest sequence.

The different maps presented in this report are based on our interpretation in the shelf areas, and imported grids from interpretations made by Norsk Hydro, farther west. The following reflectors have been mapped: INO3, TNR, INR2, TNS, INS2, TNU, TNW and Base Naust. In addition, the Base IKU-E reflector of Rise and Rokoengen (1991) are interpreted in parts of the study area, in order to link the stratigraphy of the present study with that developed earlier in the Haltenbanken area.

The gridding was done with a cell size of 1 km. In areas of poor line coverage or poor data quality, the grids may be rather incomplete. The contours from some of the maps have therefore been redrawn manually, in order to make better illustrations. The maps are presented either as time structure maps or isochron maps.

Table 5.2.1 List of data examples and line drawings of seismic profiles. The location of the profiles is shown in figure 5.2.1

Fig. no.	**Profile**	**Profile name**	**Area**	**Presented as data example**	**Presented as line drawing**
5.2.2 5.2.3	P1	GMT84 403 GMT84 204 MB 9-92	MÅLØY PLATEAU NORTH SEA FAN	YES	YES
5.2.4	P2	MB-7-92 GMT84 408	LANGGRUNNA-STOREGGA SLIDE	NO	YES
5.2.5	P3	NH9651-101 MB12 92A NH9956-405 GM1I85114	BUADJUPET-STOREGGA SLIDE	NO	YES
5.2.6	P4	NH0163-101 HR8948	FRØYABANKEN WEST STOREGGA SLIDE	NO	YES
8.2.1	P5	NH0163-301	STOREGGA SLIDE AREA	YES	NO
8.2.2	P5_sub	NH0163-301	STOREGGA SLIDE AREA	YES	NO
8.2.3	P6	NH0163-201	STOREGGA SLIDE NORTH	YES	NO
5.2.7	P7	NH9651-202 NH9651-109 ST8501-423 GMT84 415	NORTH OF STOREGGA SLIDE HALTENBANKEN	NO	YES
5.2.8 5.2.9	P8	NH9651-110 MNT 86-04	HALTENBANKEN NORTH	YES	YES
5.2.10 5.2.11	P9	GMNR94-105 GMNR94-105A GMNR94-105B	SKJOLDRYGGEN HALTENBANKEN NORTH	YES	YES
5.2.12 5.2.13	P10	NH9651-407 NH9753-403 MNT-9202	NORTH OF SKJOLDRYGGEN AREA	YES	YES
5.2.14	P11	NH9651-407 NRT 9403 MNT 9204 MNT9206	NORTH OF SKJOLDRYGGEN TRÆNABANKEN TRÆNADJUPET	YES	NO
5.2.15 5.2.16	P12	NH9753-205 NRT94 TB 13 84	NORTH OF STOREGGA SLIDE SKJOLDRYGGEN TRÆNABANKEN	YES	YES
5.2.17	P13	NH0163-304 NH0163-1303 NH0169-202	HALTENBANKEN FRØYABANKEN BUAGRUNNEN LANGGRUNNA MÅLØY PLATEAU	NO	YES
8.4.1 b	P14	MB 84-2 ST8501-303	FRØYABANKEN WEST	YES	NO
8.4.1 a	P15	MB 15-84	FRØYABANKEN WEST	YES	NO
6.1.3	P16	NH0169-301	MÅLØY PLATEAU STOREGGA SLIDE	YES	NO
8.3.1	P17	NH0163-302 NH9956-202	STOREGGA SLIDE	YES	NO
8.1.1	P18	NH0163-1303	BUAGRUNNEN	YES	NO

5.3 The 'deltaic' coast-parallel unit (Molo Formation)

The Molo Formation (Gustavson and Bugge 1995) is very characteristic on the sparker profiles, but also evident on several conventional seismic lines. The proximal part, believed to be dominated by sand, has shown greater resistance to later glacial erosion than the assumed more fine-grained sediments below and above. The lateral continuity from Møre to Lofoten (Fig. 5.2.1) suggests a very large and uniform sediment supply (Bugge et al. 1984; Rokoengen et al. 1988; Sigmond 1992; Henriksen and Weimer 1996).

The Molo Formation consists mainly of sand in the upper part (Knarud et al. 1982). The internal reflectors dip at c. 10°. The unit thins rapidly towards the west, although the distal part of the unit locally may be fairly thick. In some areas, a moat channel occurs east of a mounded sediment body, indicative of strong contour-parallel currents. The Molo Formation represents a period with extensive deltaic and coastal progradation. The age of the formation has been frequently debated, and both an Early Pliocene and an Oligocene age have been proposed. Recent studies of side-wall cores seem to point to an Early Oligocene to Early Miocene age (Eidvin et al. 1998, T. Eidvin, pers. comm. 2002). The younger Naust Formation of Late Pliocene-Pleistocene age has a very different seismic character.

5.4 The Naust Formation

Before the Naust Formation was deposited, a deep to medium-deep basin existed west of the Molo Formation. The topography of this basin (Fig. 5.4.1) and the various depositional systems throughout the last c. 3 million years controlled the infilling of the basin. Both the Naust Formation and the Molo Formation apparently downlap on the same basal surface, and chronostratigraphic investigations show a hiatus of at least 15 million years. Base Naust is commonly seen as a down-lapping surface, and in some shelf areas it also appears as a clear angular unconformity. At the outermost shelf and beyond the shelf edge, the layers above and below are generally conformable, possibly resulting in a less confident interpretation of Base Naust in some areas.

The Naust Formation comprises numerous depositional sequences, and the lower half of the formation is commonly seen as a low-angle, prograding, depositional system (Figs. 5.2.8-5.2.11). Erosion of older sediments and re-deposition beyond the palaeo shelf edge(s) are evident, and the seismic character indicates very active and possibly varying depositional systems. North of Frøyabanken, where the basin floor has a gentle dip towards the west, the basin was gradually filled with sediments, resulting in a westward progradation of the shelf edge during Late Pliocene-Early Pleistocene. The upper part of the formation shows increasing aggrading pattern upwards. West of Møre, the basin was much deeper, resulting in steeper dips. The commonly sheet-like units show an aggrading pattern as sediments were dispersed towards the deep part of the basin, resulting in a limited outbuilding of the Møre shelf. The Naust Formation shows a maximum thickness of 1750 ms twt along the present shelf edge (Fig. 5.4.2). Farther west, the formation becomes gradually thinner. The depocenter of the North Sea Fan is pronounced, being mainly related to deposition by the Norwegian

Channel Ice Stream. This ice stream flowed from the Skagerrak to the mouth of the Norwegian Channel west of Stadt (62°N) during several glacial periods. The northernmost depocenter is located along the present shelf edge from outer Haltenbanken to Røstbanken.

A maximum thickness of c. 1100 ms twt is found along the shelf edge, adjacent to the deep incision of the Storegga Slide. In general, the thickness is less than 1000 ms twt in the Storegga Slide area, with a general decreasing trend westwards. Although several slide and slumping events have transported parts of the sediments to the deep ocean, we believe that the Storegga Slide area received less sediments during Naust time than the adjacent areas to the south and north. The sediment source areas east of the Storegga Slide is much less in extent than the areas to the south and north, both regarding fluvial and glacial systems. The shallow banks on the Møre shelf (Langgrunna and Buagrunnen) possibly emerged several times during sea level low-stands, and wave erosion and recycling of sediments down-slope may have been considerable. Another process of importance in this area is contour-parallel currents, depositing thick stratified sediments on the slope. These sediments are mainly derived from the southwest.

Upper Regional Unconformity (URU)

During the early investigations of the shelf (c. 1970-1985), URU was defined as an angular unconformity that separates the underlying sedimentary rocks from overlying glacial deposits. Several studies have shown that a glacial environment existed on the shelf before URU was formed (see Section 3.2). URU is commonly seen as an angular unconformity that marks a change of the sedimentation style in the Naust Formation from prograding to aggrading.

At Haltenbanken, URU is defined at the irregular erosion surface of base unit IKU D, where truncation of underlying, dipping strata is evident. Detailed mapping in this area (Rokoengen et al. 1995) clearly illustrates that the term URU lacks a proper definition. In the southern part of Haltenbanken (Draugen – Njord area) this erosional reflector becomes shallow and is poorly defined, and here a much older horizon represents the prominent angular unconformity (base IKU unit I within the Naust W sequence). Similar interpretation problems are also seen in other areas. For instance, the very well developed angular unconformity seen in the palaeo-trough from Sklinnadjupet towards Skjoldryggen is difficult to trace confidently at Trænabanken. Between Sklinnadjupet and northern Haltenbanken, 'URU' continues as an erosional reflector within a flat-lying sediment succession.

It is evident that the formation of URU is controlled by several factors. The various ice drainage systems and the thermal conditions at the base of the ice sheet are important, but also the variable subsidence/uplift of different regions influences the erosional impact of glaciations on the shelf. The importance of these factors has varied during different glaciations, and may explain why URU is of a different age and nature in various regions or even within adjacent areas. The ice-sheet configuration over the land areas and the shelf topography has also varied, and influenced the erosional impact through time. In many areas the present URU is probably a result of erosion during several glaciations.

The variable erosional impact of different glaciations is very well illustrated in the Norwegian Channel. In the channel south of Norway, URU was formed by strong glacial erosion during

Late Weichselian, but in adjacent areas at the northern flank of the channel (south of Arendal / Jæren), URU was developed during one or several Early or Mid Pleistocene glacial event (Longva and Thorsnes 1997). Here, the last ice stream in the Norwegian Channel only eroded the underlying sediments to a limited degree. URU at the Troll Field is inferred to be 1.1 Ma, formed by the first ice stream flowing along the axis of the Norwegian Channel (Sejrup et al. 1995). It is difficult to understand how the first marine glaciation could have excavated the Norwegian Channel (i.e. URU), and we believe that the channel must have an older glacial history. In the last 1.1 Ma, none of the ice sheets/ice streams managed to erode into URU in the channel west of Norway. The glacial erosion of the Weichselian ice streams in the channel between Bergen and the shelf margin is not particularly evident, although these glacial events resulted in the deposition of a very thick unit of debris flows on the North Sea Fan.

In the southern part of the Måløy Plateau, URU is also clearly developed, here apparently being related to the deposition of Sequence S (Fig. 5.2.3). URU is variously well defined in the narrow and shallow Møre shelf. The relationship between erosion and deposition is partly unclear, and we suggest that URU may correspond to both Naust S and R (Figs. 5.2.4, 5.2.5). In the region between Frøybanken and Trænabanken, URU seems mainly to be related to strong glacial erosion caused by the major ice sheet(s) that deposited the thick debris flows in unit R3 beyond the shelf edge (Figs. 5.2.7, 5.2.10, 5.2.11). This angular unconformity is suggested to be 0.4 Ma. The reason why this angular unconformity is so pronounced in this area may indicate that URU is a combined result of a period with shelf uplift before the R3-glaciation(s), and very erosive ice sheets/ice streams on the shelf. A flat-lying sediment succession of Sequence S between northern Haltenbanken and Sklinnadjupet, indicates that this area was in a 'sheltered position' with limited glacial erosion (Figs. 5.2.8, 5.2.10). URU is of variable character at Trænabanken, and difficult to follow throughout the area. In Trænadjupet, a Weichselian ice stream made the last shaping of URU.

5.5 Sequence Naust W (proposed age 1.7–2.8 Ma)

Britsurvey (1999) defined the TNW horizon in the southern part of the area. In this study, we have traced the reflector farther northwards. Commonly, the horizon is located slightly below reflector IKU-E, defined on Haltenbanken by Rokoengen et al. (1995).

Bounding surfaces
Naust W is the oldest sequence, bounded by the Base Naust and Top Naust W horizons (Figs. 5.4.1, 5.5.1). The character of the lower bounding surface, Base Naust, is described in Section 5.4. The upper bounding surface is of variable character throughout the area, but is often seen as a good regional seismic marker. In the Ormen Lange area, it is seen as a downlap surface of TNU and internal reflectors within Naust U. North of the Storegga Slide, horizon TNW is commonly subparallel to adjacent reflectors. Just east of the Helland Hansen Arch and Vema Dome, TNW down-laps at Base Naust. Sequence Naust W reappears on the western side of these domes. Above the northern margin of the Storegga Slide, the surface lies within a thick conformable sequence of well-bedded deposits. East of where TNW is truncated by an upper angular unconformity (URU), URU represents the upper boundary (Fig. 5.2.7). It should be noted that URU represents different erosional surfaces within the study area (see Section 5.4).

As the original TNW horizon east of the palaeo shelf break is preserved only in parts of Haltenbanken and Trænabanken, the original sequence has been thicker in the eastern part.

Geometry/ Facies
Southwest and west of Buagrunnen the sequence is commonly less than 300 ms twt thick (Fig. 5.5.2), and is made up of several aggrading sheet-like units on the slope and in the basin (Figs. 5.2.2, 5.2.4 and 5.2.5). Although more than 400 ms twt is deposited at the North Sea Fan, the sequence comprises only 20-30 % of the Naust Formation in this area.

At Frøyabanken (Fig. 5.2.6) the sequence is thicker, and the sheet-like units start to show a down-lapping relationship. North of Frøyabanken, the Base Naust horizon becomes a very gentle westward sloping surface (Fig. 5.4.1), and the oldest units in the sequence show a distinct down-lap at the basin floor.

Profiles 7, 8 and 9 (Figs. 5.2.7, 5.2.8 and 5.2.10) show that the shelf edge was gradually built out in the Haltenbanken region during Naust W time, to a position only 30-50 km east of the present. Several depositional units occur, being acoustically massive with a fairly uniform thickness. They commonly down-lap on Base Naust, although also on-lap occurs (Fig. 5.2.9). Old angular unconformities occur within Naust W in the eastern part of the shelf (Fig. 5.2.7), indicating several cycles of strong erosion. We suggest that this was mainly glacial erosion, but both fluvial and wave erosion may periodically have been important. The seismic data also indicate frequent recycling of sediments, with transport/erosion on the inner part of the shelf and deposition beyond the palaeo shelf edge(s).

In the outer part of the palaeo basin, west of the present shelf edge in the Haltenbanken area, units commonly thin westward and show a more aggrading pattern. In this area, stratified sediments occur together with more acoustically massive units. The units pinch out towards the eastern flank of the Helland Hansen Arch. They become absent or very thin above it, but reappear on the western side (Fig. 5.2.8). Deposition controlled by contour-parallel currents seems to be uncommon, although some mounded sub-units on-lapping the slope may indicate that such deposits occur.

A mounded stratified unit appears (>200 ms twt thickness) below the northeastern corner of the Storegga Slide. In that area, several younger contourite-like sediment bodies are located (see Fig. 8.2.3), indicating that contour-parallel currents have been prevailing on the slopes of the Møre basin throughout Naust time.

The isochron map (Fig. 5.5.2) shows two large depocenters. The southernmost shows a maximum of more than 900 ms twt in outer Haltenbanken. The northernmost is located in the Trænabanken region, with a centre near outer Trænadjupet. In that area, the sediment thickness reaches more than 1400 ms twt. The northern part of profile 12 (Figs. 5.2.15, 5.2.16), located fairly close to the area of maximum thickness, shows a southwesterly prograding pattern indicating a sediment source in the Lofoten/Vestfjorden area.

Depositional environment/Processes
In the Trænabanken/Trænadjupet area, Henriksen and Vorren (1996) concluded that the oldest part of their Naust sequence (comparable to parts of Naust W) was originally deposited in a

position proximal to a grounded ice sheet. Mapping of the sequences indicated that the Lofoten area and adjoining shelf was an important source area during an early stage of the shelf outbuilding (see Fig. 3.2.4). According to Henriksen and Vorren (1996), the Lofoten area is less important during later phases of the outbuilding. As the northern depocenter is far away from any interpreted fluvial systems, we suggest a glacial explanation, but wave erosion of an uplifted area and transport to the basin by down-slope currents may have been important processes. The distinct down-lap of the clinoforms against the basin floor (Fig. 5.2.16), and high-amplitude reflections in the distal part, possibly indicate that sand accumulated in the lower part of the basin. The pronounced reflections may also be indications of the presence of gas.

Between the two areas of maximum thickness, in the Sklinnadjupet region, the sequence comprises less than 500 ms twt of sediments. Much of the sequence has been removed by later glacial erosion (Figs. 5.2.12, 5.2.13). The last main shaping of the URU occurred during the third or fourth last glaciation (related to Unit R3), but the isochron maps (Fig. 4, Executive Summary) indicate that strong glacial erosion in Sklinnadjupet also occurred much earlier. It is difficult to quantify the amount of removed sediments, but at least 200 m is suggested.

It is generally agreed that the Late Pliocene-Pleistocene prograding wedges are a result of Neogene uplift and glaciations along the mountain range. The early glacial period is commonly believed to have been a time of moderate glaciations, mainly supplying debris to the coastal zone and inner shelf. The main transporting agent is proposed to have been rivers, crossing the emerged shelf during periods of lowered sea level (Norsk Hydro 2001). However, till units are found at Draugen in unit IKU-I, which is a part of Sequence W. Also, the upper, flat-lying part of Sequence W in the Trænabanken area has a glacial character, indicating early glaciations on the shelf (seen on IKU sparker lines). Another factor indicating that glaciations on the shelf were more important than previously thought is the very high depositional rate. The dominant grain size in the lower part of the Naust Formation is clay/silt, and well logs only show a few, thin layers of sand (Rise and Rokoengen 1991).

Fluvial systems are less efficient transporting agents than ice sheets, and would probably also have brought more sand to the shelf and margin. Erosion of an uplifted inner shelf may, however, have been important in order to recycle sediments towards the basin. Although the depositional environment has varied (glacial, glaciomarine, marine, glaciofluvial, fluvial), we suggest that extensive glaciations onto the shelf were important for the rapid outbuilding of the shelf during Naust W time. In general, the units are sheet-like with extensive distribution on the palaeo-slopes, indicating redistribution of sediments by various down-slope processes. The isochron map of Naust W (Fig. 5.5.2) shows that the first period with glaciations was most important in the northern part of the study area.

5.6 Sequences Naust U and S (proposed age 0.4 - 1.7 Ma)

Naust U lies between the TNW and TNU horizons, and its top is defined in the Ormen Lange area as a down-lap surface. The sequence is thickest (>200 ms) close to the shelf break in the

Storegga area, with distal thinning. TNU is partly difficult to follow confidently to the north, and the sequence probably comprises mainly thin debris-flow units. The time thickness map of Naust U shows that the sequence is absent above the Helland Hansen Arch (Svitzer 2002).

Naust S lies between the TNU and TNS horizons. The time thickness map of the sequence shows that the main depocenters occur to the north of the Helland Hansen Arch and at the North Sea Fan (Svitzer 2002). The upper part of Sequence S almost completely covers the Helland Hansen Arch and the Vema Dome regions. Naust S makes up most of the composite Naust U/S sequence described below.

Bounding surfaces
Horizon TNW represents the basal surface, and Top Naust S (TNS) the upper bounding surface. East of where TNS is truncated by an upper angular unconformity (URU), URU represents the upper boundary of the combined sequences (Fig. 5.2.7). In the Storegga Slide area, TNS represents the top of stratified sediments (contourites infilling large slide scars of 'Slide S'). This horizon has been traced to the northern flank of the Storegga Slide, where it occurs as a reflector within a thick succession of stratified sediments. In the slope farther north, TNS is well defined, as it represents the base of the overlying, thick, glacigenic unit R3.

Geometry/ Facies/ Depositional environment
Sequences U and S comprise several units, and the sediments probably represent several glacial-interglacial cycles. In order to obtain an overview of the margin development during Naust U and S time, an isochron map of the combined sequences has been made (Fig. 5.6.1).

Maximum deposition of Naust U and S occurred along the present shelf edge, and locally slightly west of it. The northern depocenter (>600 ms twt thickness) is located in the outermost Trænabanken area (Fig. 5.6.1). All the units deposited on the slope in this area appear to be acoustically massive (Figs. 5.2.13, 5.2.16, 5.2.17), and many of them are fairly thick. Some units thin down-slope, and pinch out in the middle-lower slope. Other units are of fairly even thickness, or may thicken in the lower part of the slope. Stratified sediments in the northern area are uncommon, and this probably indicates that various types of down-slope processes dominated. The location of the depocenter seems to correspond with ice drainage across the shelf, with a focused flow across southern Trænabanken and the northwestward continuation of Sklinnadjupet. The prominent angular unconformity (URU) seen in this area probably had its first glacial shaping during this period. The upper part of Sequence W was eroded and transported towards the depocenter (Figs. 5.5.2 and 5.6.1).

In northwestern Haltenbanken, parts of the sequences S and U occur on the shelf (Figs. 5.6.1, 5.2.9 and 5.2.11), being protected from glacial erosion. This area is located southwest of Sklinnadjupet, which was a very important ice-drainage route during the last three or four glaciations. Preserved Naust U/S sediments east of the palaeo shelf break may indicate a higher subsidence in that area. In the middle-lower slope west of Haltenbanken, several units of stratified sediments occur between more acoustically massive units (Fig. 5.2.9). The thickest stratified unit is up to 70 ms twt thick.

Farther south, the thickness is commonly 300-400 ms twt in the slope, and the sequences in the upper slope are made up of acoustically massive wedges and sheet-like units. Although some units thin down-slope, an aggrading depositional pattern is most common. A seismic line of very high resolution some kilometres north of the northeastern corner of the Storegga Slide (NH0163-103), shows that sequence S comprises many sheet-like, acoustically incoherent units that commonly pinch out in the mid-slope and interfinger with stratified sediments. The depositional environment in the Storegga Slide area is complex, with glacigenic debris, slide deposits and stratified sediments.

In the southernmost depocenter (North Sea Fan) there are sediments up to 600 ms twt thick. The well-defined depocenter shows that the initial glacial shaping of the Norwegian Channel started during this period. The last shaping of URU, at the Troll Field, is inferred to be 1.1 million years old (Sejrup et al. 1995). The URU cut deeply into the prograding Plio-Pleistocene wedges (Fig. 3.2.1), and we infer that more than one ice stream was necessary to erode the trough. As the present URU roughly seems to correspond to the deposition of Sequence S, the first major ice stream in the Norwegian Channel possibly occurred during Naust U time (1.1-1.7 Ma).

5.7 Sequences Naust R and O (proposed age <0.4 Ma)

Sequence Naust R lies between horizons TNS and TNR, its top being defined in the Ormen Lange and Skjoldryggen areas as the top of contourites beneath a glacigenic debris-flow unit (Table 5.1.1). West of where the glacigenic debris flows in sequence O pinch out, TNR is defined as a horizon within a well-bedded sediment succession. In the south, TNR is at or very close to the base of the Tampen Slide (Fig. 5.2.3). In the north, Naust R comprises the previously defined Units Naust B and the lowermost part of Unit A (Britsurvey 1999).

Sequence Naust O lies between horizon TNR and the sea bed. It comprises several sub-units, and also includes the Storegga Slide sediments. A detailed description of the geological development during Naust R/O time is outlined in Chapter 6. An overview of the composite Naust R and O sequence is presented below.

Bounding surfaces
On the outermost shelf and west of the shelf edge, Top Naust S represents the basal surface for the composite Naust R/O sequence. East of where Sequence R pinches out or is truncated, URU represents the basal surface (Fig. 5.2.7). The sea bed represents the top of the combined sequences, and the bathymetric database has been applied for construction of the isochron map (Fig. 5.7.1).

Geometry/ Facies/ Depositional environment
The largest depocenter is in the North Sea Fan, with a maximum thickness of more than 1000 ms twt close to the mouth of the Norwegian Channel. The debris-flow deposits thin towards the north. It is evident that the Norwegian Channel Ice Stream was a very important drainage route for the Scandinavian Ice Sheet during the last three to four glaciations. Comparison of the isochron maps (Fig. 4, Executive Summary) convincingly shows an increased importance of glacial sediment transport along the Norwegian Channel with younger ages.

A depocenter with a maximum thickness of more than 700 ms twt occurs along the shelf edge in the Skjoldryggen area, (Fig. 5.7.1). The thickness is, however, more than 300 ms twt in large areas along the slope. The first major glaciation was very erosive on the shelf, and deposited thick debris-flow deposits (unit R3) widely distributed on the slope off Haltenbanken -Trænabanken (Fig. 5.2.11). The sediment transport was mainly westwards along Sklinnadjupet. Stratified sediments occur, and make up most of the succession at the northern flank of the Storegga Slide.

At the Storegga Slide escarpment, the thickness of the sequences is 300-400 ms twt in thickness. A large slide ('R-slide') removed parts of unit R3 in the slope, and the Storegga Slide removed a considerable part of the sequences where the deepest slide scar is located. A maximum thickness of more than 600 ms twt was possibly present in the upper slope off Buagrunnen - Frøyabanken. In the slope, a complex stratigraphy with contourites, glacigenic debris and slide deposits is present (see Fig. 8.2.3), whereas slide deposits dominate in the basin (see Fig. 8.2.1).

The ice sheet /ice streams reached the shelf edge at Møre during all the last glaciations (Figs. 6.1.2, 6.3.2, 6.4.3), with the most active ice flow occurring between Frøyabanken and Buagrunnen.

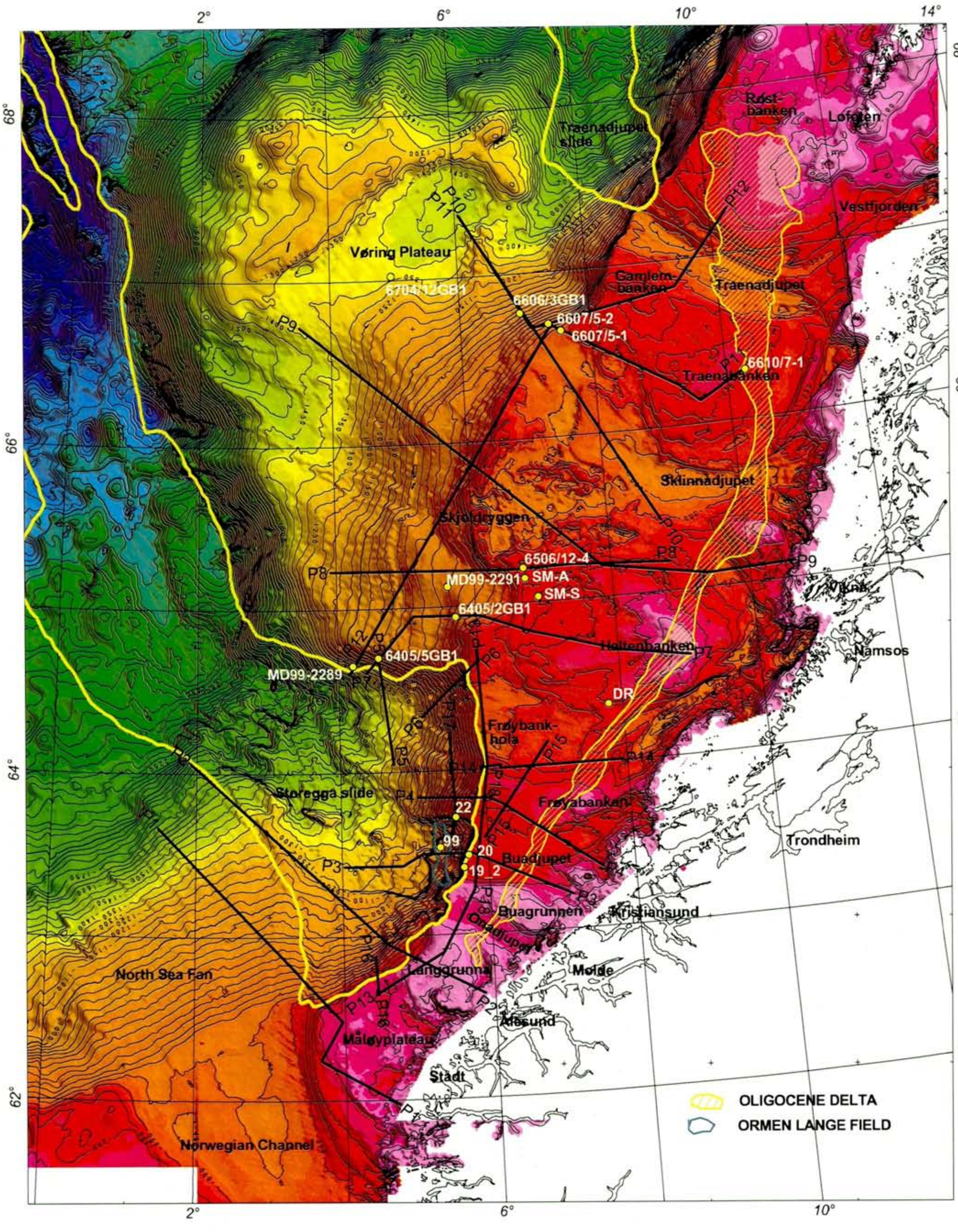
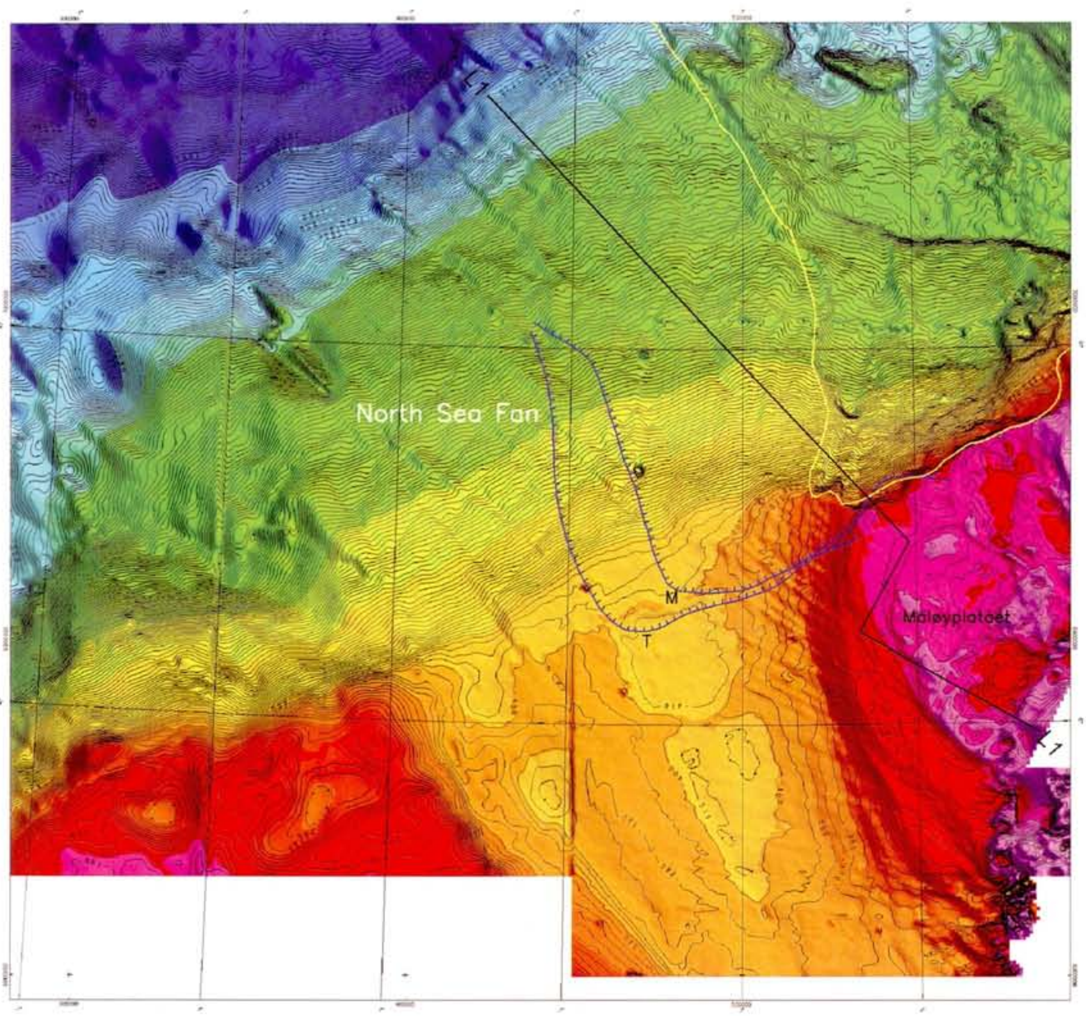


Figure 5.2.1 Bathymetric map with presented seismic profiles, exploration wells and geotechnical drilling sites. The profiles are either presented as data examples and/or line drawings. See table 5.2.1. DR-Draugen, SM-S – Smørbukk South, SM-A – Smørbukk Alfa.



Profile1

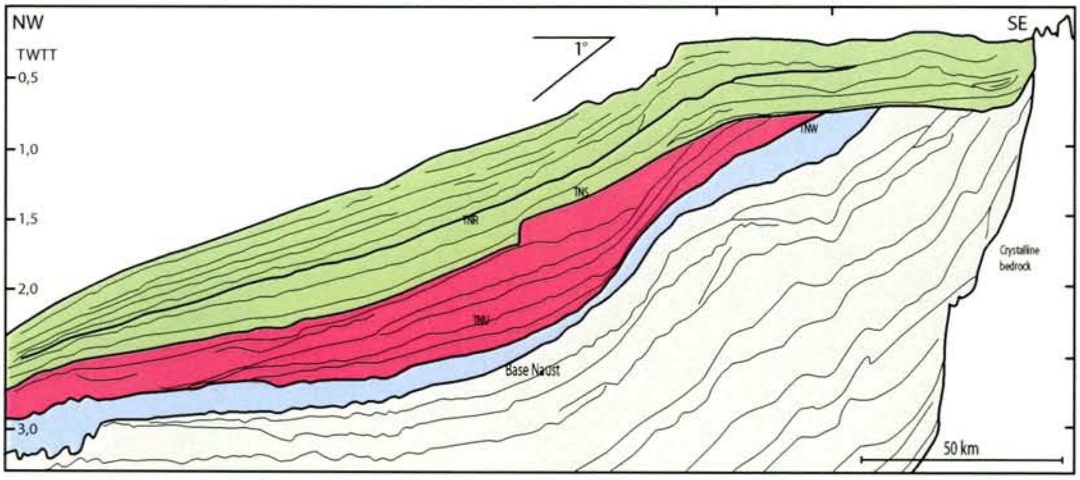


Figure 5.2.2A) Bathymetric map of the outlet of the Norwegian Channel and the North Sea Fan. The North Sea Fan has mainly been built out during the last 1 million years. T- Tampen Slide, M – Møre Slide.

Figure 5.2.2B) Line drawing of seismic composite profile 1. Blue – Naust W, red – Naust U & S, green – Naust R & O. See table 5.2.1 for reference to applied seismic lines.

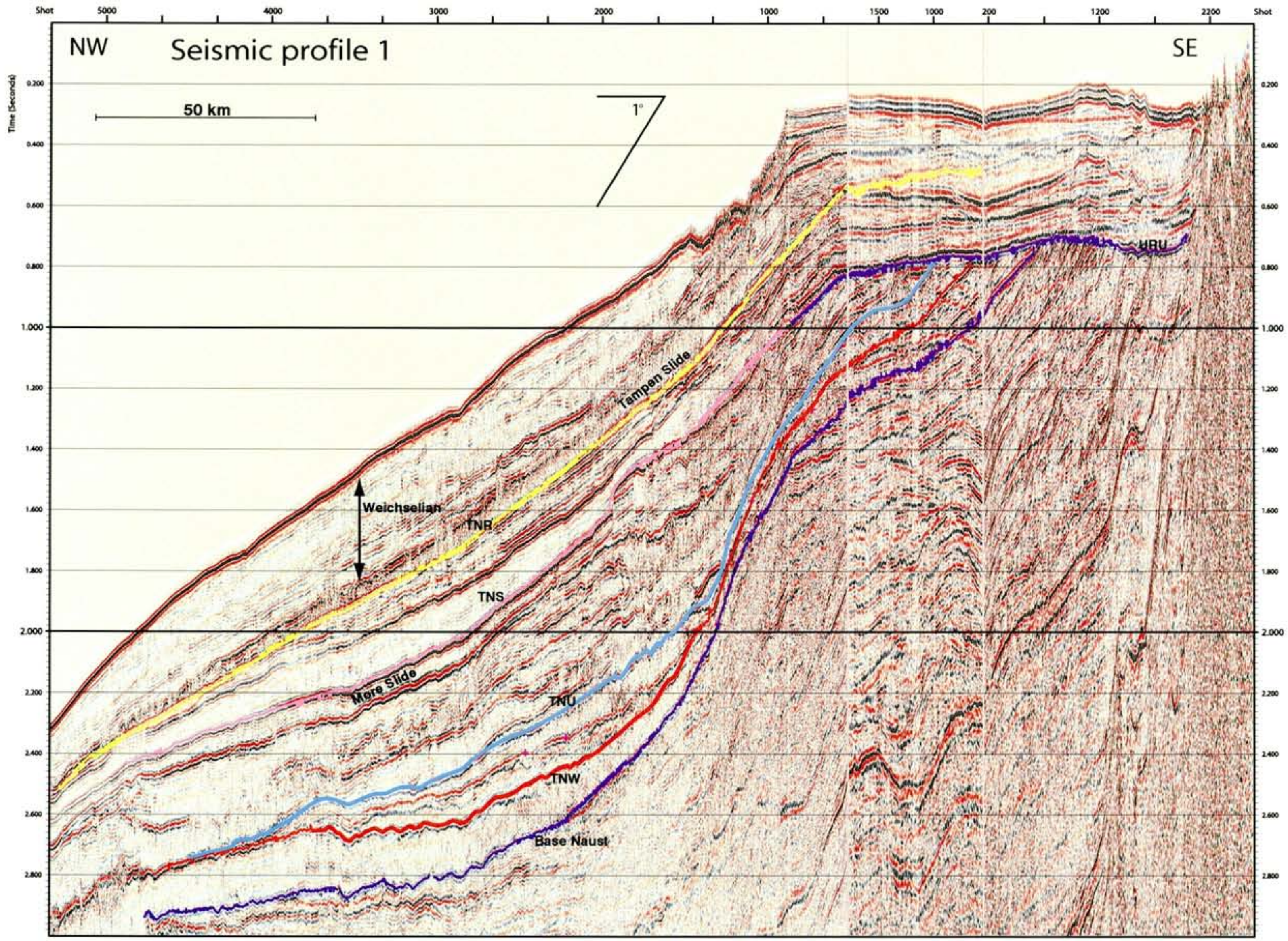


Figure 5.2.3 Interpreted seismic composite profile 1. See figure 5.2.2A for location and table 5.2.1 for reference to applied seismic lines.

Profile 2

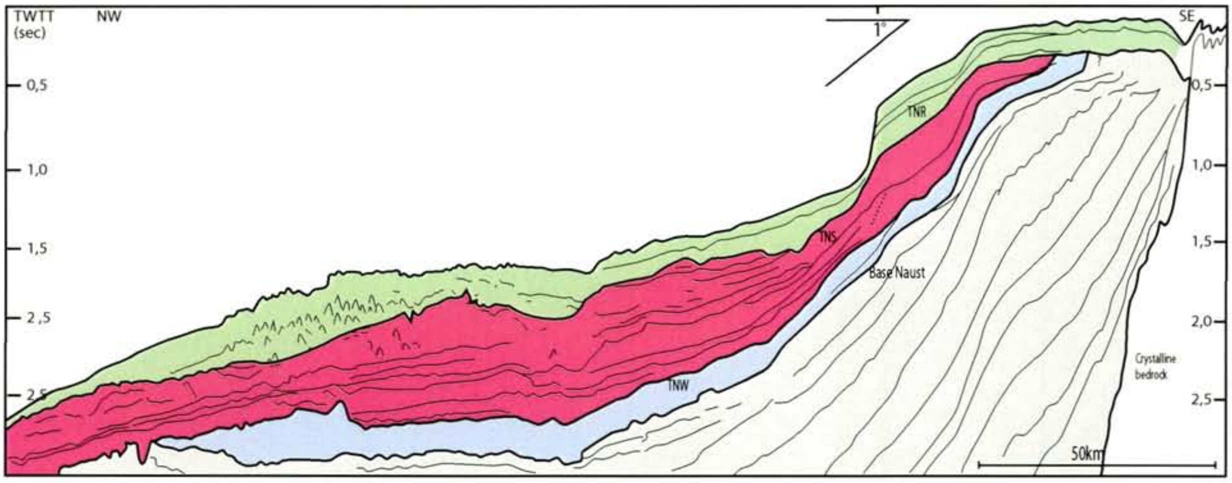


Figure 5.2.4 Line drawing of seismic composite profile 2 from Langgrunna into the Storegga slide area and onto the North Sea Fan. Blue – Naust W, red – Naust U & S, green – Naust R & O. See figure 5.2.1 for location and table 5.2.1 for reference to applied seismic lines.

Profile 3

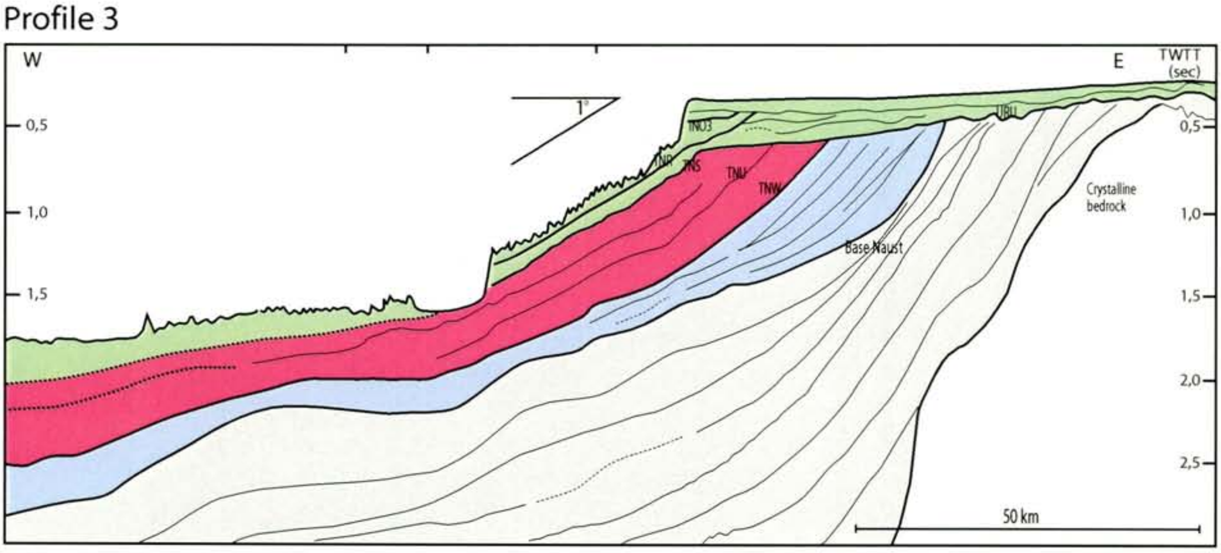


Figure 5.2.5 Line drawing of seismic composite profile 3 from Buadjupet to the Storegga slide area. Blue – Naust W, red – Naust U & S, green – Naust R & O. See figure 5.2.1 for location and table 5.2.1 for reference to applied seismic lines.

Profile 4

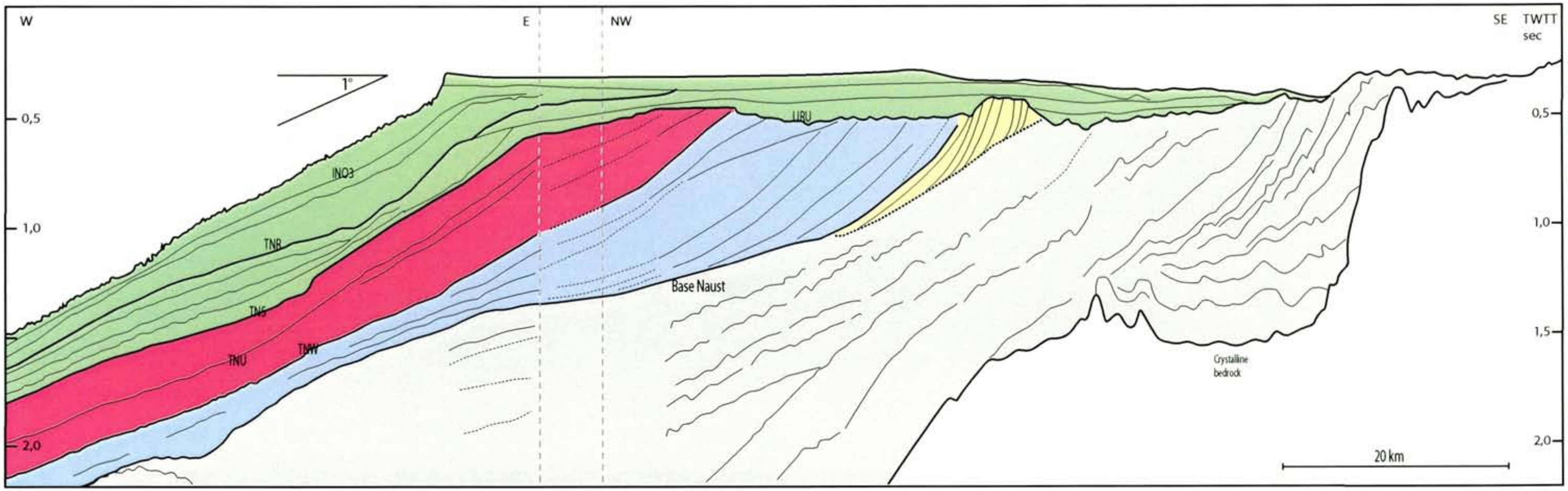


Figure 5.2.6 Line drawing of seismic composite profile 4 across Buadjupet and outer Frøyabanken and into the Storegga slide area. Yellow – Oligocene deltaic unit, Blue – Naust W, red – Naust U & S, green – Naust R & O. See figure 5.2.1 for location and table 5.2.1 for reference to applied seismic lines.

Profile 7

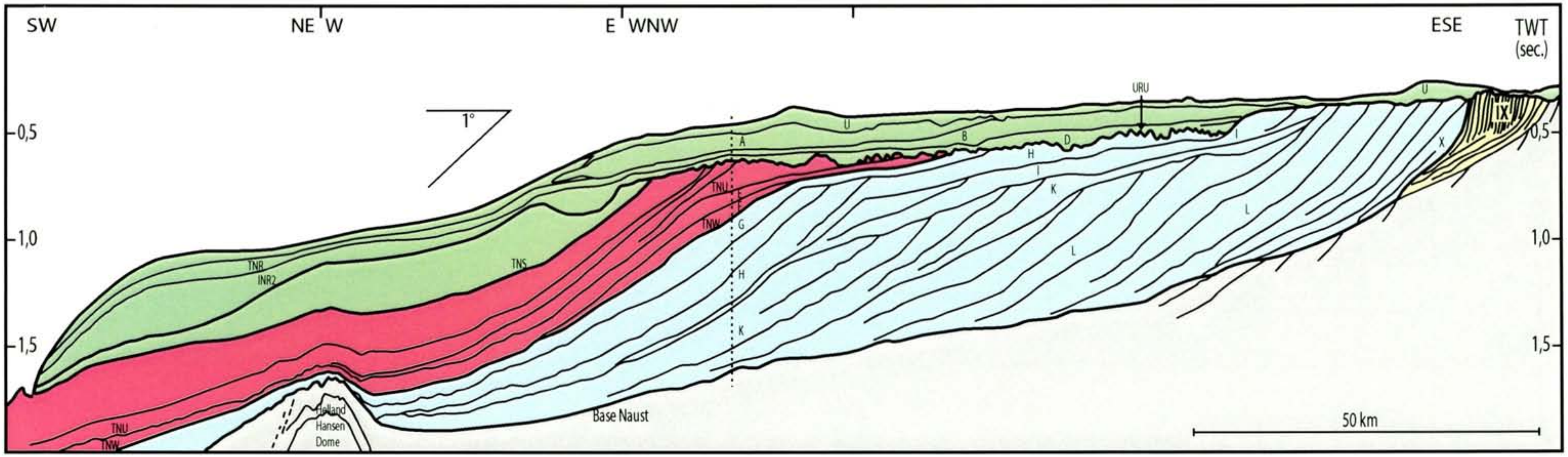


Figure 5.2.7 Line drawing of seismic composite profile 7 across Haltenbanken to the shelf edge, down the slope north of the Storegga slide and finally into the Storegga slide area. Yellow – Oligocene deltaic unit, Blue – Naust W, red – Naust U & S, green – Naust R & O. Letters to the right of stippled line refer to the stratigraphy by Rokoengen et al. (1995). Letters to the left of stippled line are reflectors defined by Norsk Hydro. See figure 5.2.1 for location and table 5.2.1 for reference to applied seismic lines.

Profile 8

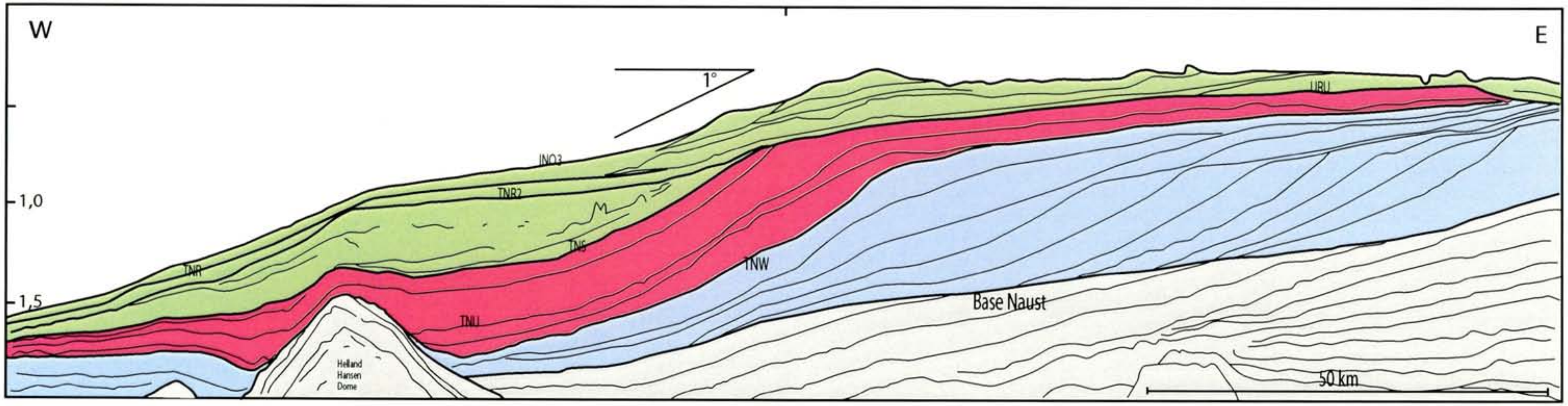


Figure 5.2.8 Line drawing of seismic composite profile 8 across northern part of Haltenbanken to the shelf edge and down the continental slope north of the Storegga slide area. Blue – Naust W, red – Naust U & S, green – Naust R & O. See figure 5.2.1 for location and table 5.2.1 for reference to applied seismic lines

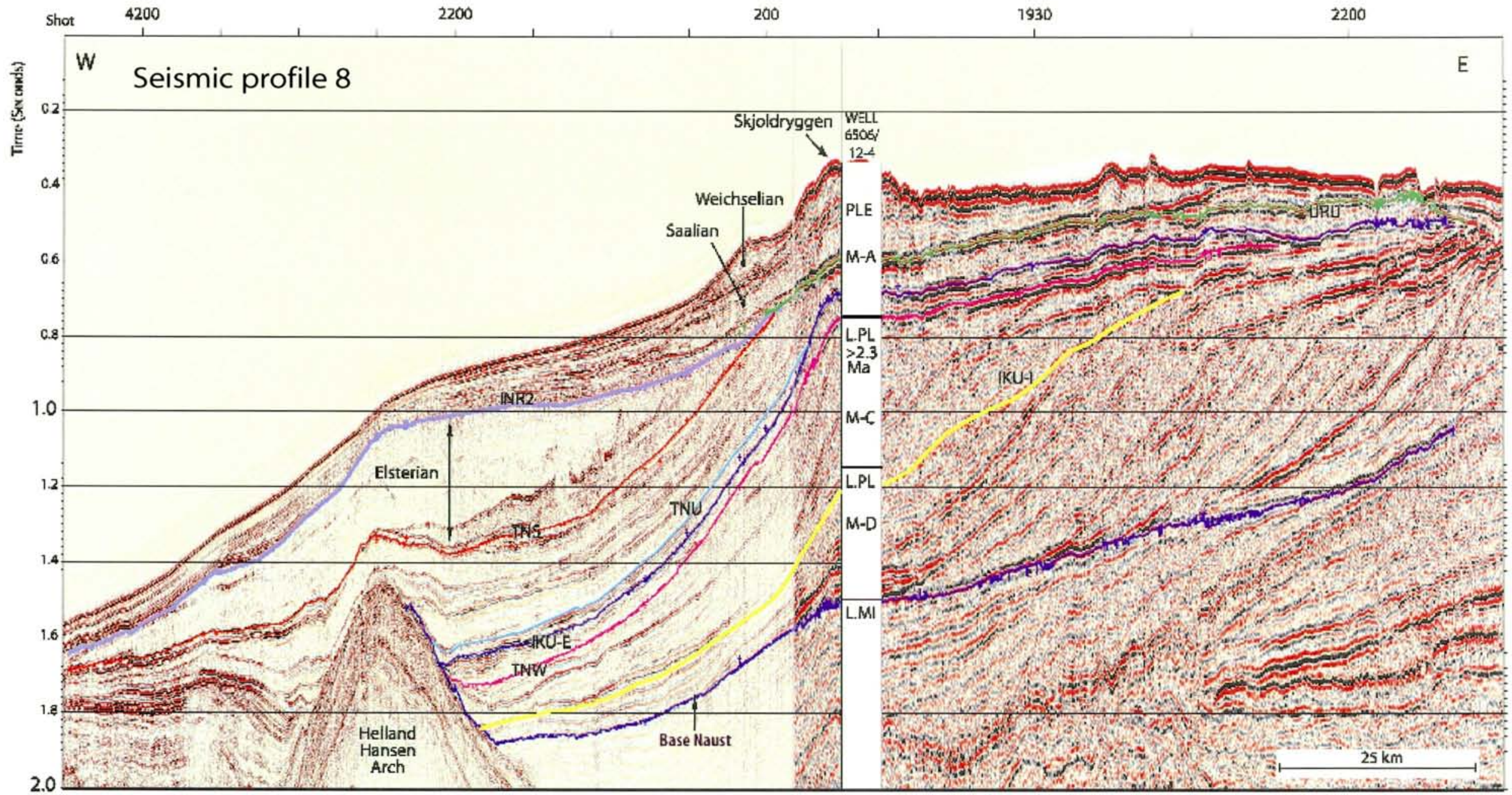


Figure 5.2.9 Interpreted seismic composite profile 8. Note that slightly westward dipping units of early Pleistocene age occur on the shelf, and that URU is poorly developed. The chronostratigraphy is based on investigations by Eidvin et al. 1998. PLE = Pleistocene, L.PL= Late Pliocene, L.MI = Late Miocene. M-A, M-C and M-D represent different fauna zones. See figure 5.2.1 for location and table 5.2.1 for reference to applied seismic lines.

Profile 9

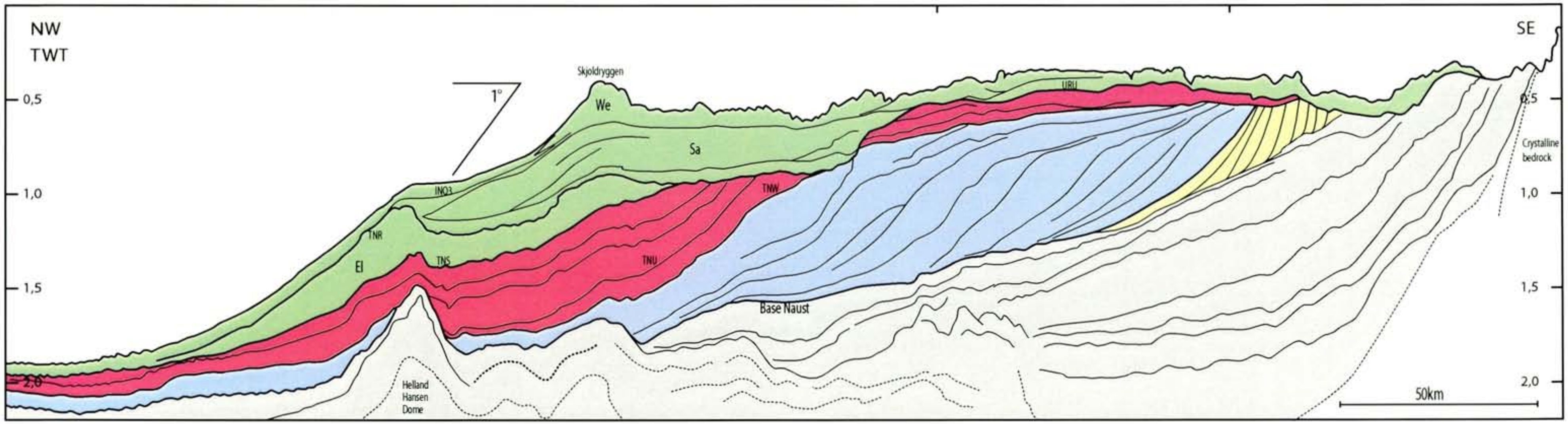


Figure 5.2.10 Line drawing of seismic composite profile 9 across Sklinnabanken and northern part of Haltenbanken to the shelf edge, across Skjoldryggen and down the slope onto the Vøring Plateau. Yellow – Oligocene deltaic unit. Blue – Naust W, red – Naust U & S, green – Naust R & O. We = Weichselian, Sa = Saalian, El = Elsterian. See figure 5.2.1 for location and table 5.2.1 for reference to applied seismic lines.

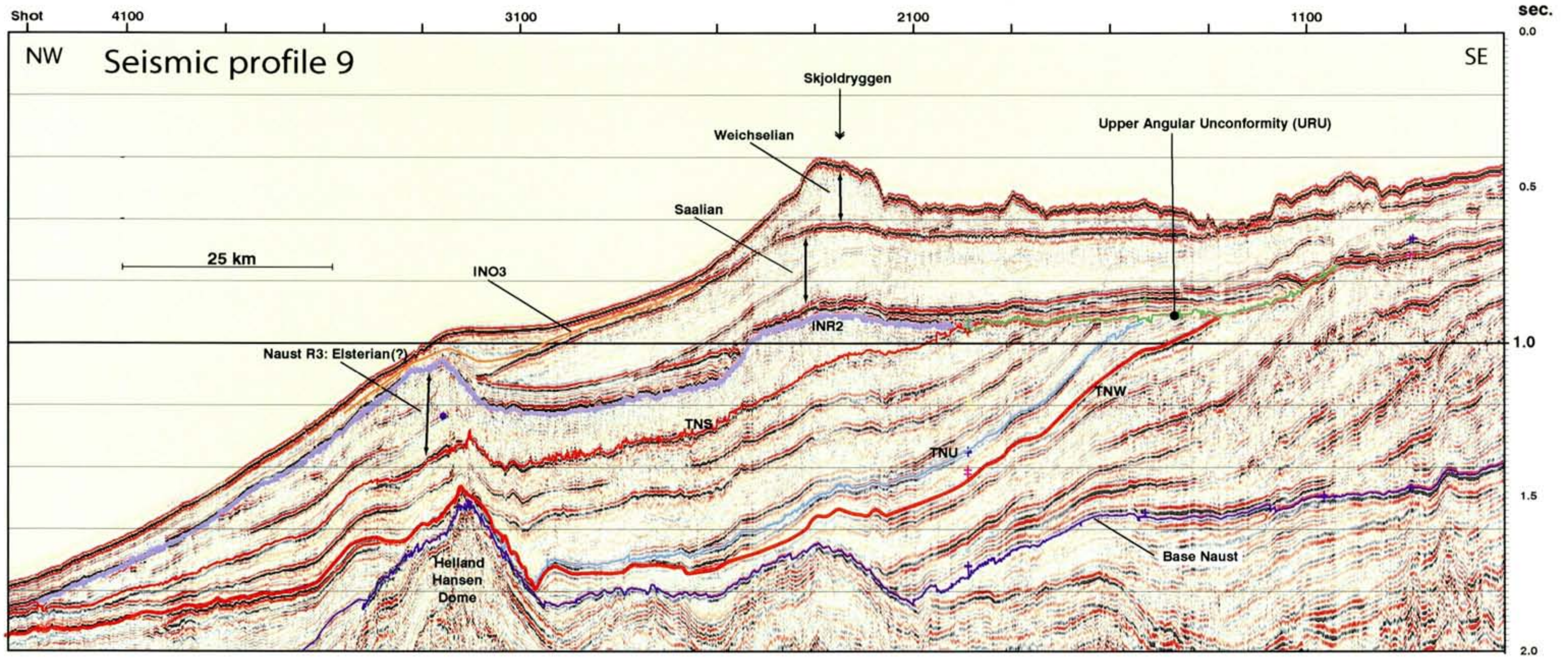


Figure 5.2.11 Interpretation of the western part of seismic composite profile 9 (Fig. 5.2.10). See figure 5.2.1 for location and table 5.2.1 for reference to applied seismic lines. Note the well defined regional angular unconformity (URU), and that the Saalian Ice Sheet did not erode the stratified sediments deposited above URU.

Profile 10

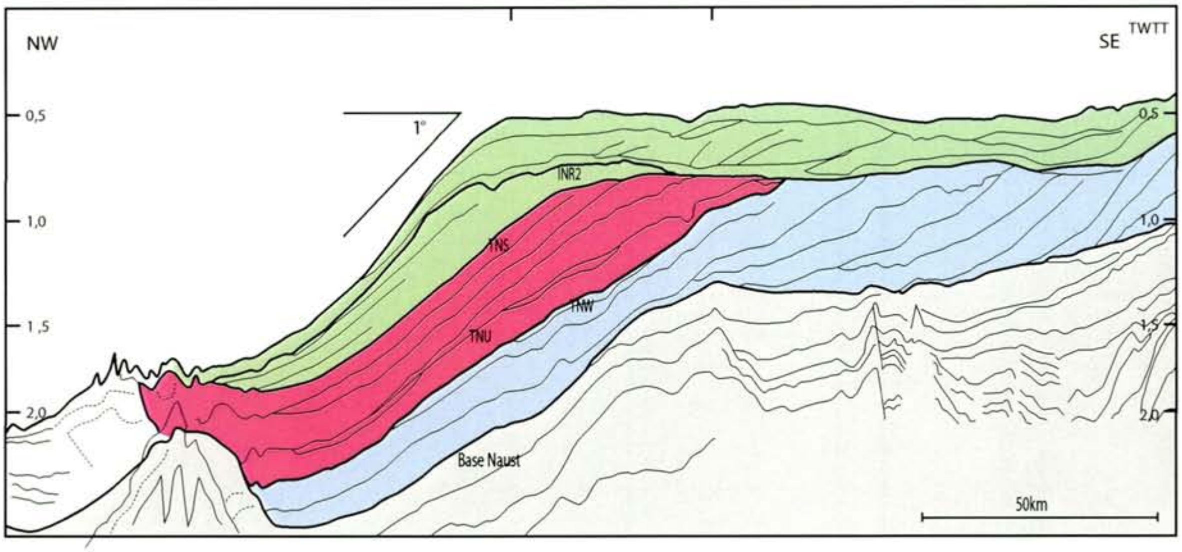


Figure 5.2.12 Line drawing of seismic composite profile 10 along outer Sklinnadjupet to the shelf edge and down the slope to the Vema Dome on the inner Vøring Plateau. Blue – Naust W, red – Naust U & S, green – Naust R & O. See figure 5.2.1 for location and table 5.2.1 for reference to applied seismic lines.

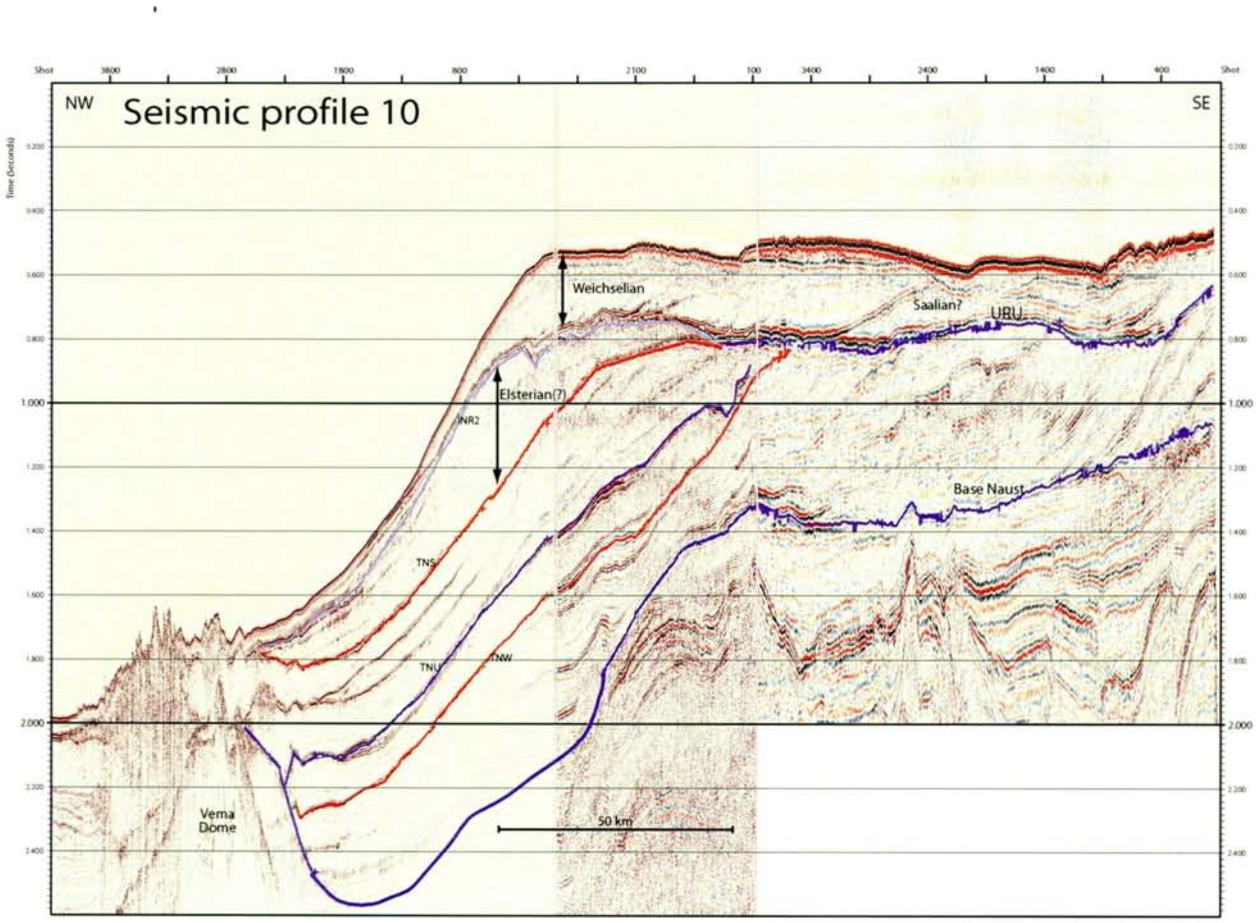


Figure 5.2.13 Interpreted seismic composite profile 10. Note that the angular unconformity (URU) is well defined, and that URU seems to be related to the deposition of unit R3 (Elsterian?). The Saalian Ice Sheet did not extend to the shelf edge west of Trænabanken. See figure 5.2.1 for location and table 5.2.1 for reference to applied seismic lines.

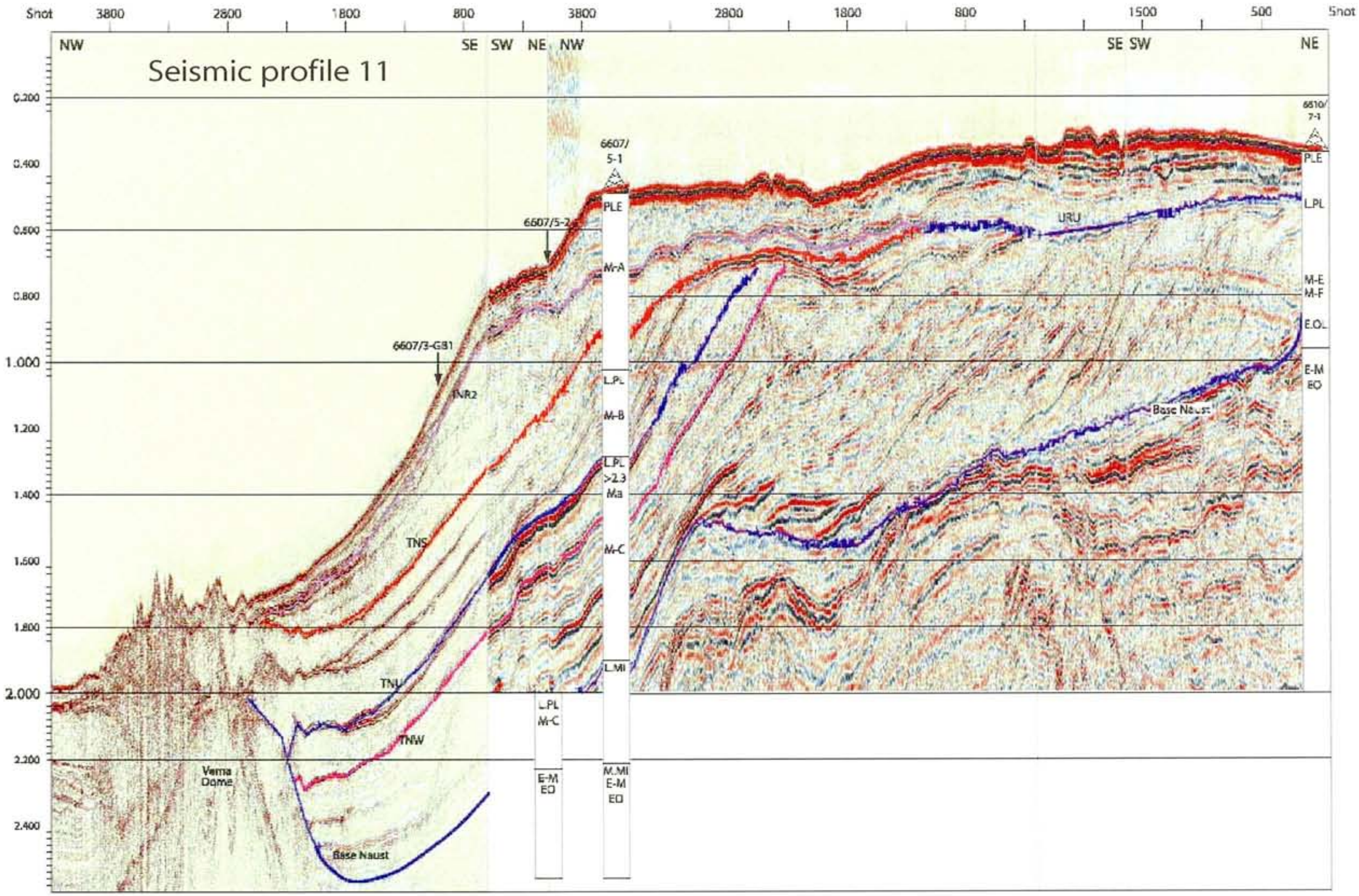


Figure 5.2.14 Interpreted seismic composite profile 11. The chronostratigraphy is based on investigations by Eidvin et al. 1998. PLE = Pleistocene, L.PL = Late Pliocene, L.MI = Late Miocene, M.MI = Mid Miocene, E.OL = Early Oligocene, E.-M.EO = Early-Mid Eocene. M-A, M-B, M-C, M-E and M-F represent different fauna zones. See figure 5.1.1 for location and table 5.2.1 for reference to applied seismic lines.

Profile 12

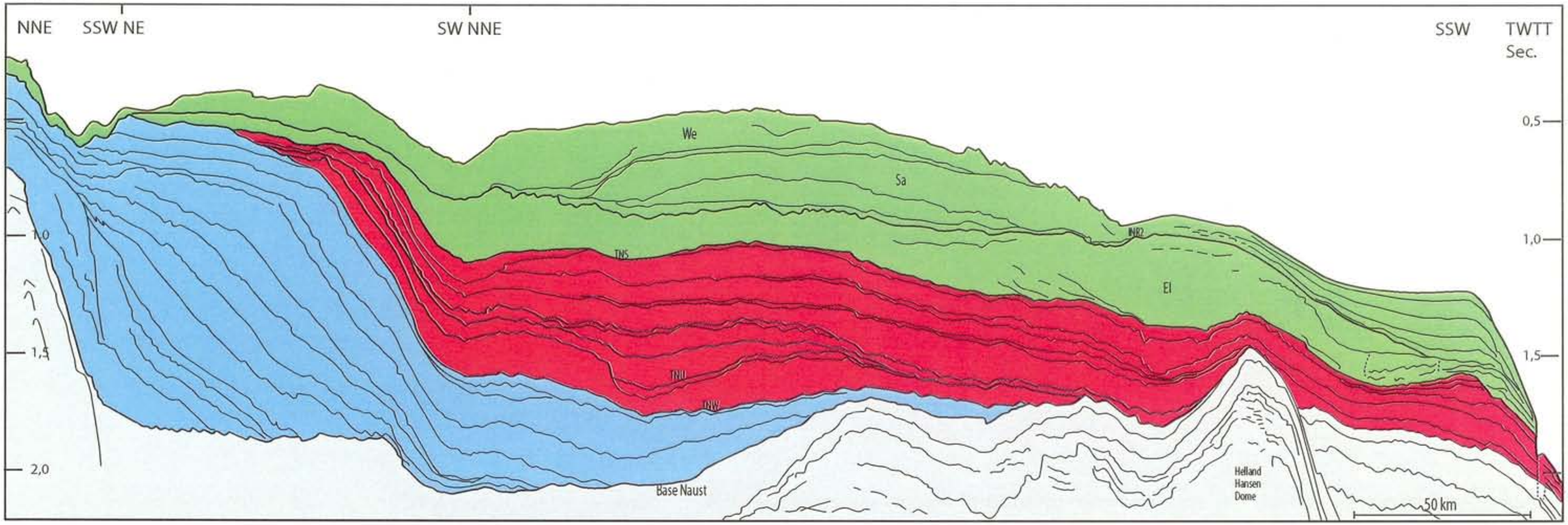


Figure 5.2.15 Line drawing of seismic composite profile 12 from the northern part of the Storegga slide across the outer shelf (Skjoldryggen) north-west of Haltenbanken and onto outer Trænabanken area, across Trænadjupet to Røstbanken. Blue – Naust W, red – Naust U & S, green – Naust R & O. We = Weichselian, Sa = Saalian, El = Elsterian. See figure 5.2.1 for location and table 5.2.1 for reference to applied seismic lines.

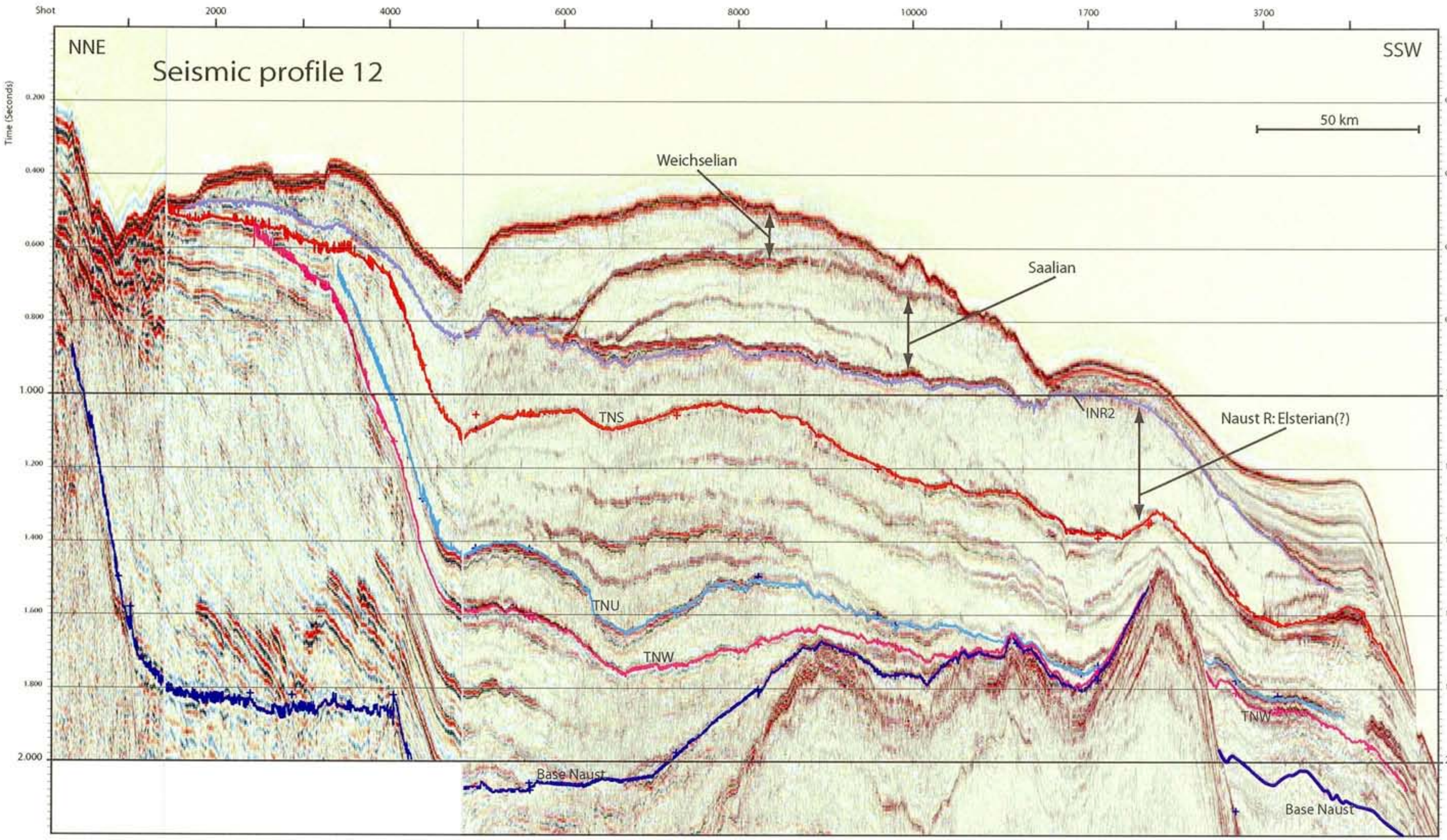
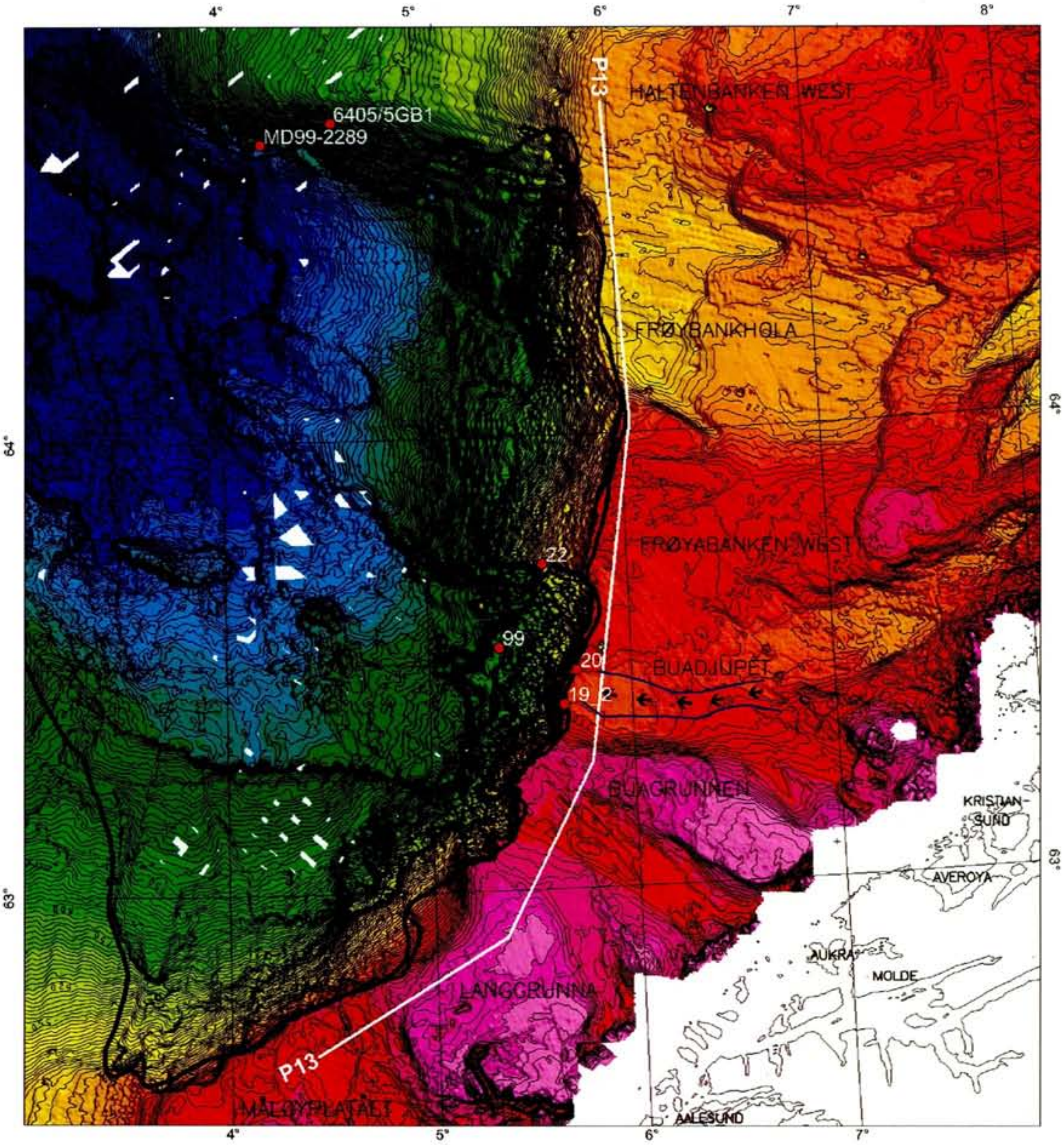


Figure 5.2.16 Interpreted seismic composite profile 12. Note the high amplitude reflections (sand/gas?) downlapping at Base Naust below Gamlembanken. The lobate shape of the Saalian deposits is evident. Note also the thick stratified sediments above Elsterian (?) glacigenic deposits north of the Storegga Slide. See figure 5.2.1 for location and table 5.2.1 for reference to applied seismic lines.



Profile 13

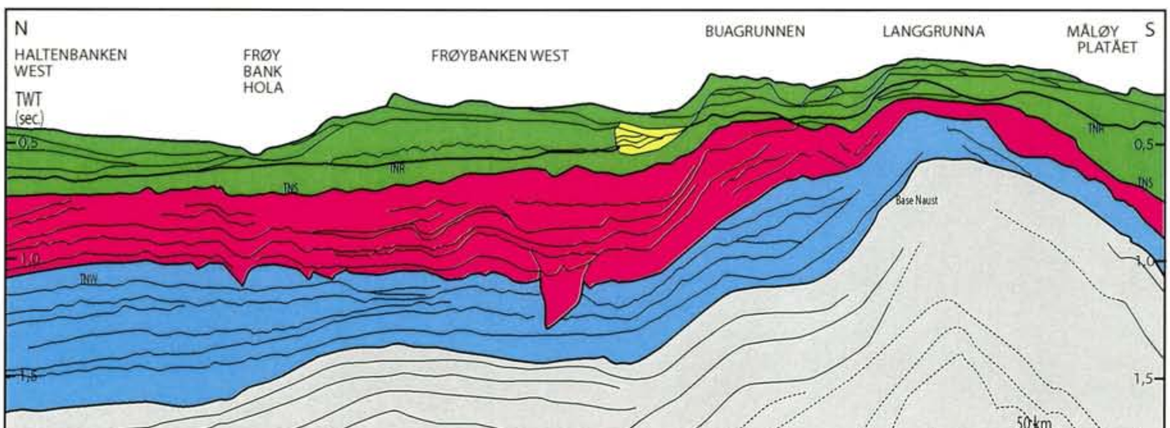


Figure 5.2.17A) Map of the shelf areas east of the Storegga slide area. The arrows show the location of a subglacial meltwater channel in Buadjupet.

Figure 5.2.17B) Line drawing of seismic composite profile 13. Blue – Naust W, red – Naust U & S, green – Naust R & O representing deposits from the three-four last glacial cycles. The stratified channel sediments (yellow) are interpreted to be of Late Saalian age. (See also figure 8.1.1.)

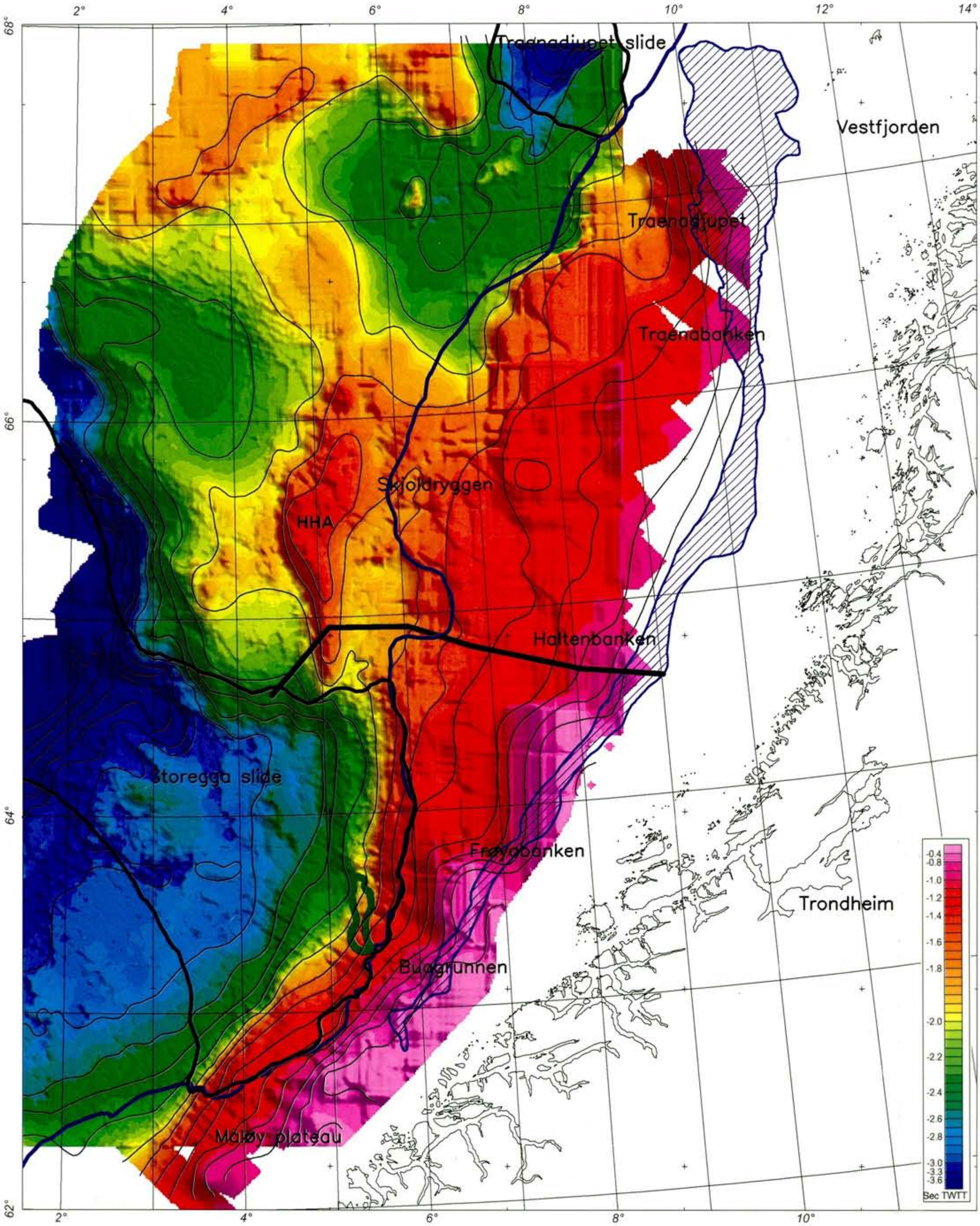


Figure 5.4.1 Time structure map of Base Naust. Note the Helland Hansen Arch (HHA) west of the present shelf edge (blue line), and the palaeo-topography of the Storegga area which is broadly similar to the present.

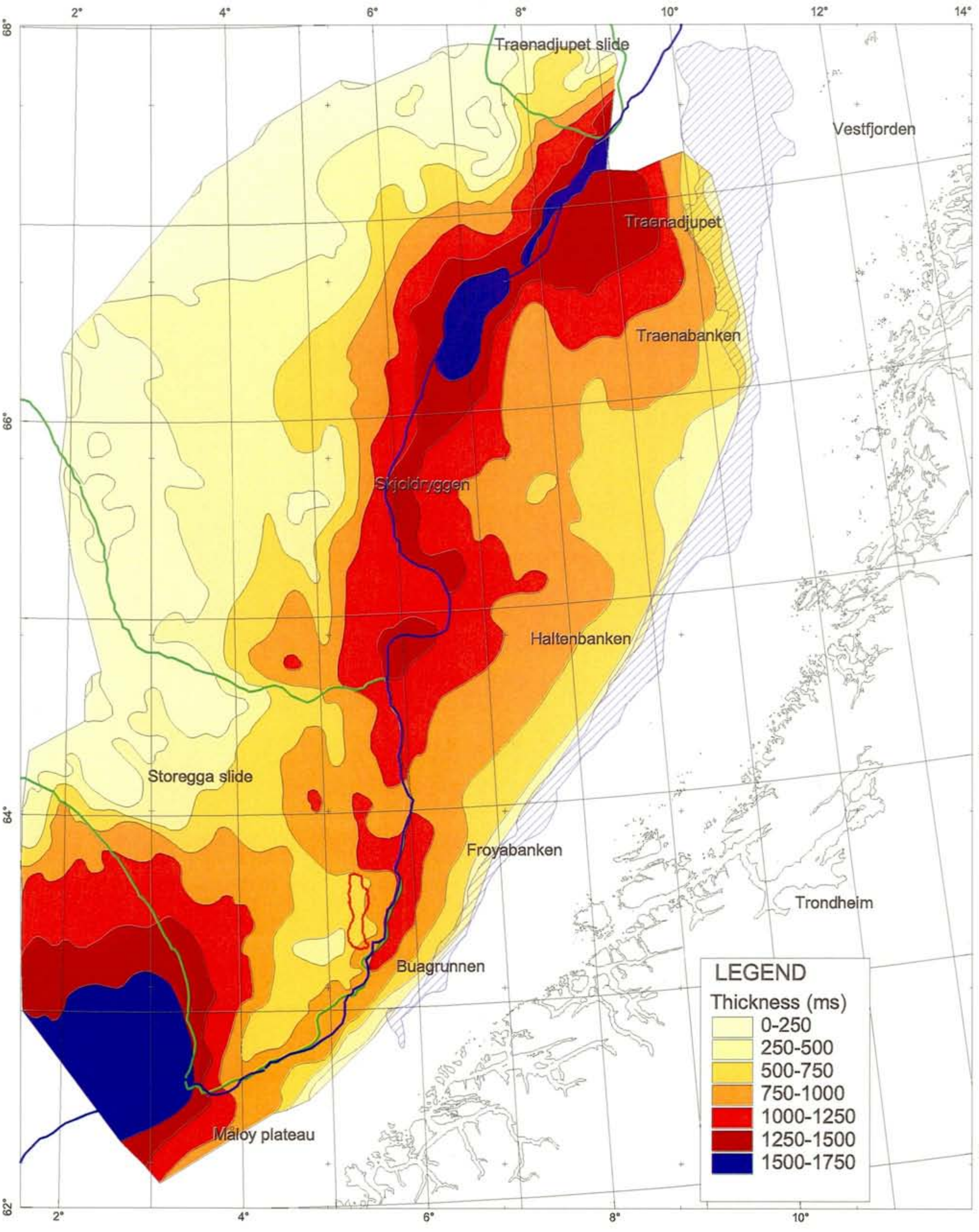
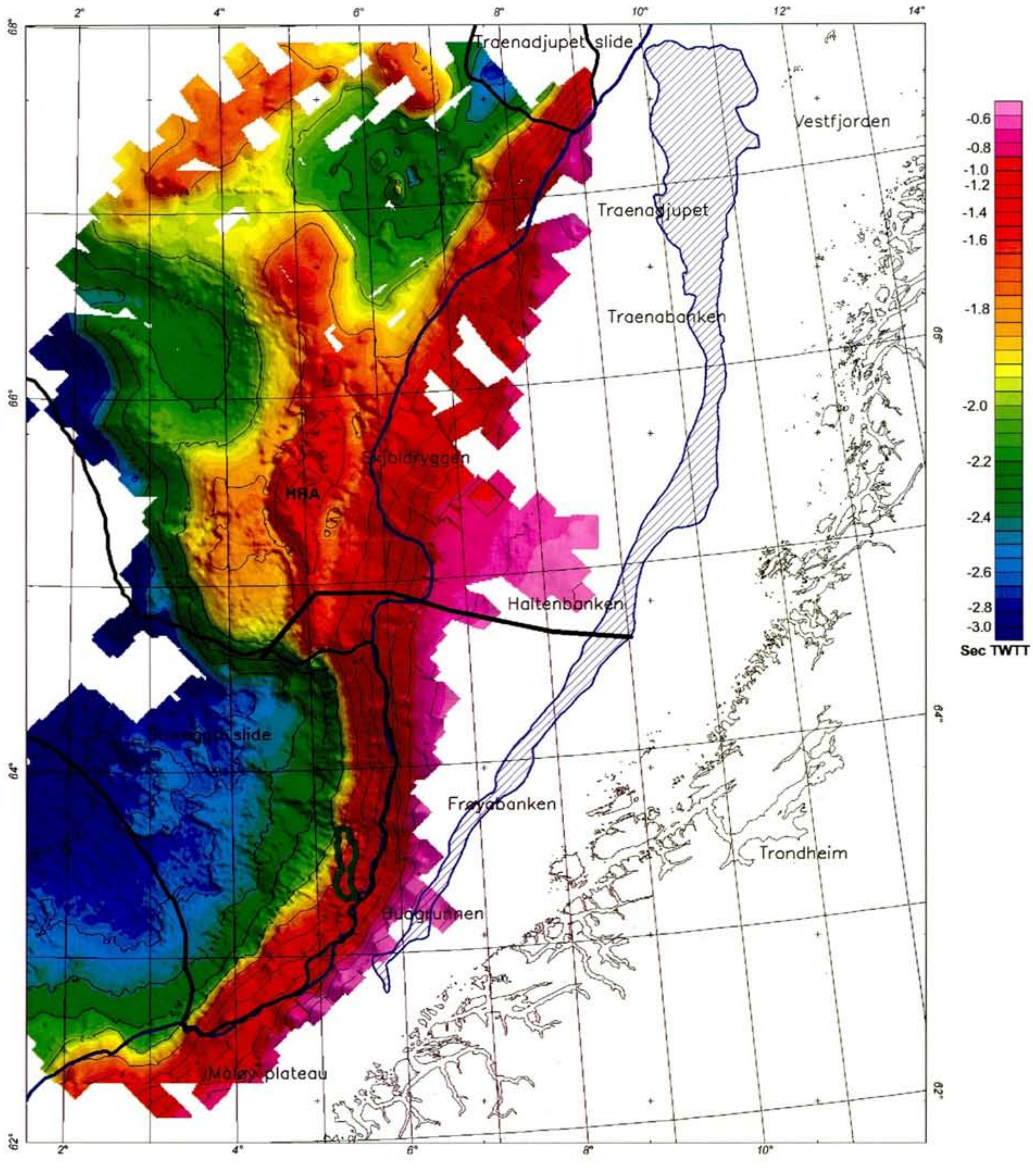


Figure 5.4.2 Isochron map of Naust Formation showing depocenters along the present shelf edge (blue line) from Haltenbanken to Trænadjupet, and at the North Sea Fan. The blue line marks the present shelf edge. Red outline - Ormen Lange field. Blue hatching - Oligocene deltaic unit.



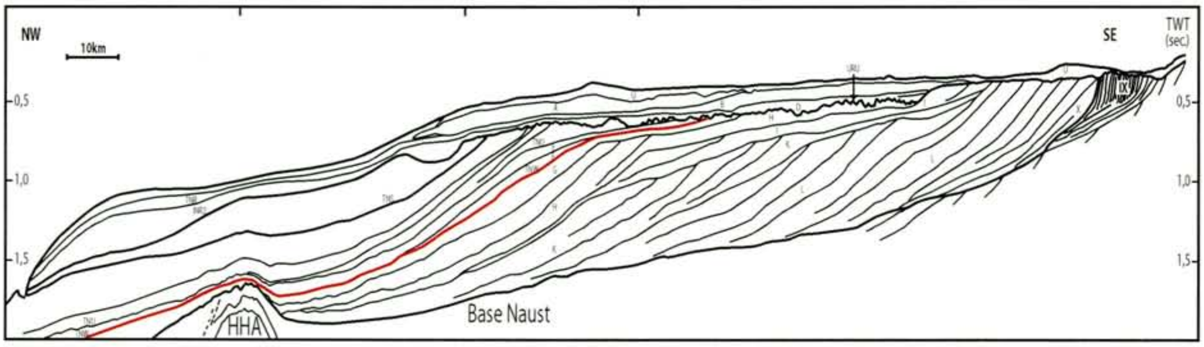


Figure 5.5.1 Time structure map of Top Naust W. Note the extensive progradation in the Haltenbanken-Trænabanken region, and that the depression east of the Helland Hansen Arch (HHA) nearly was 'filled up' during this period.

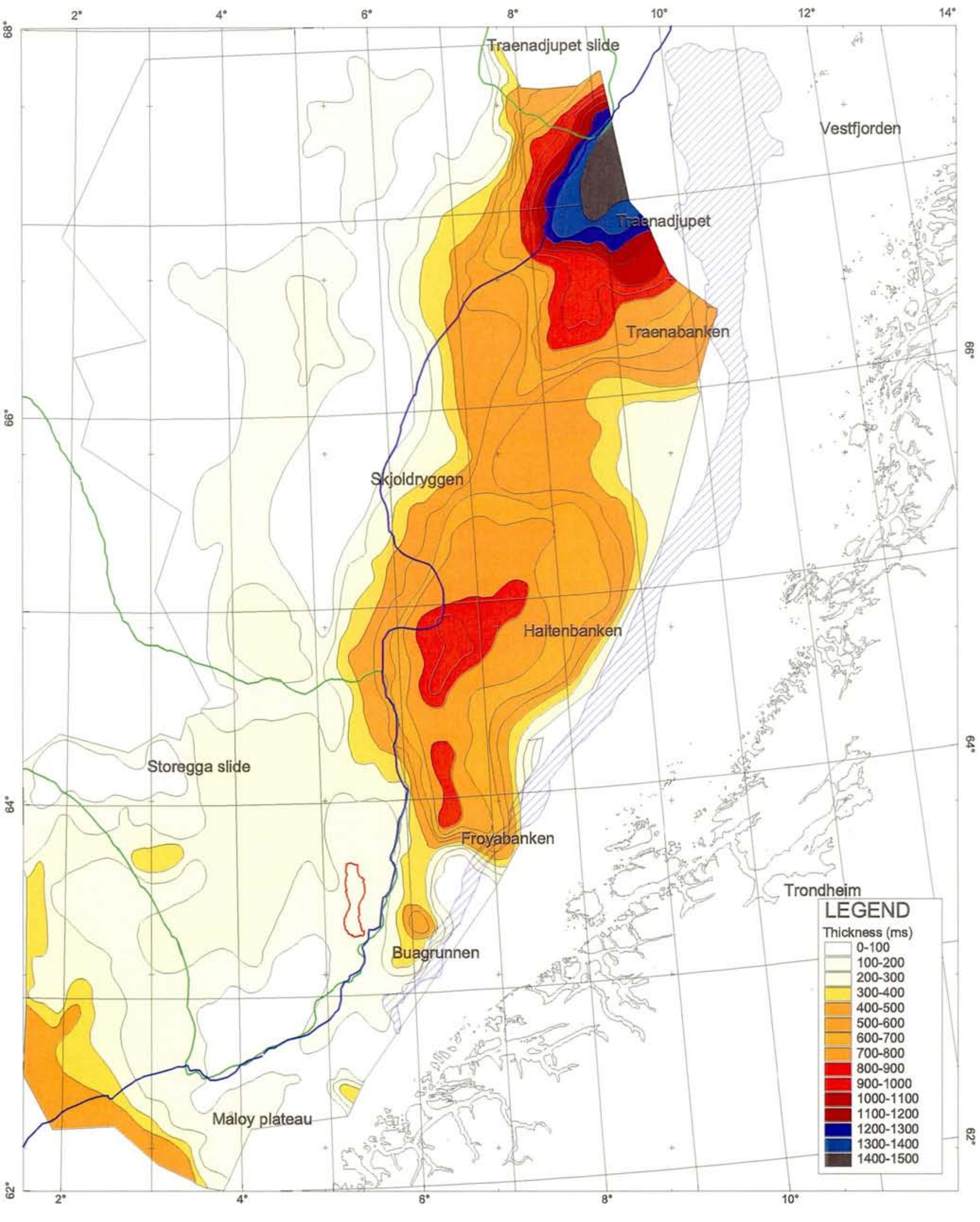


Figure 5.5.2 Isochron map of Naust W sequence showing that most of the Late Pliocene sediments were deposited north of Frøyabanken. The blue line shows the present shelf edge. The blue line marks the present shelf edge. Red outline - Ormen Lange field. Blue hatching. Oligocene deltaic unit.

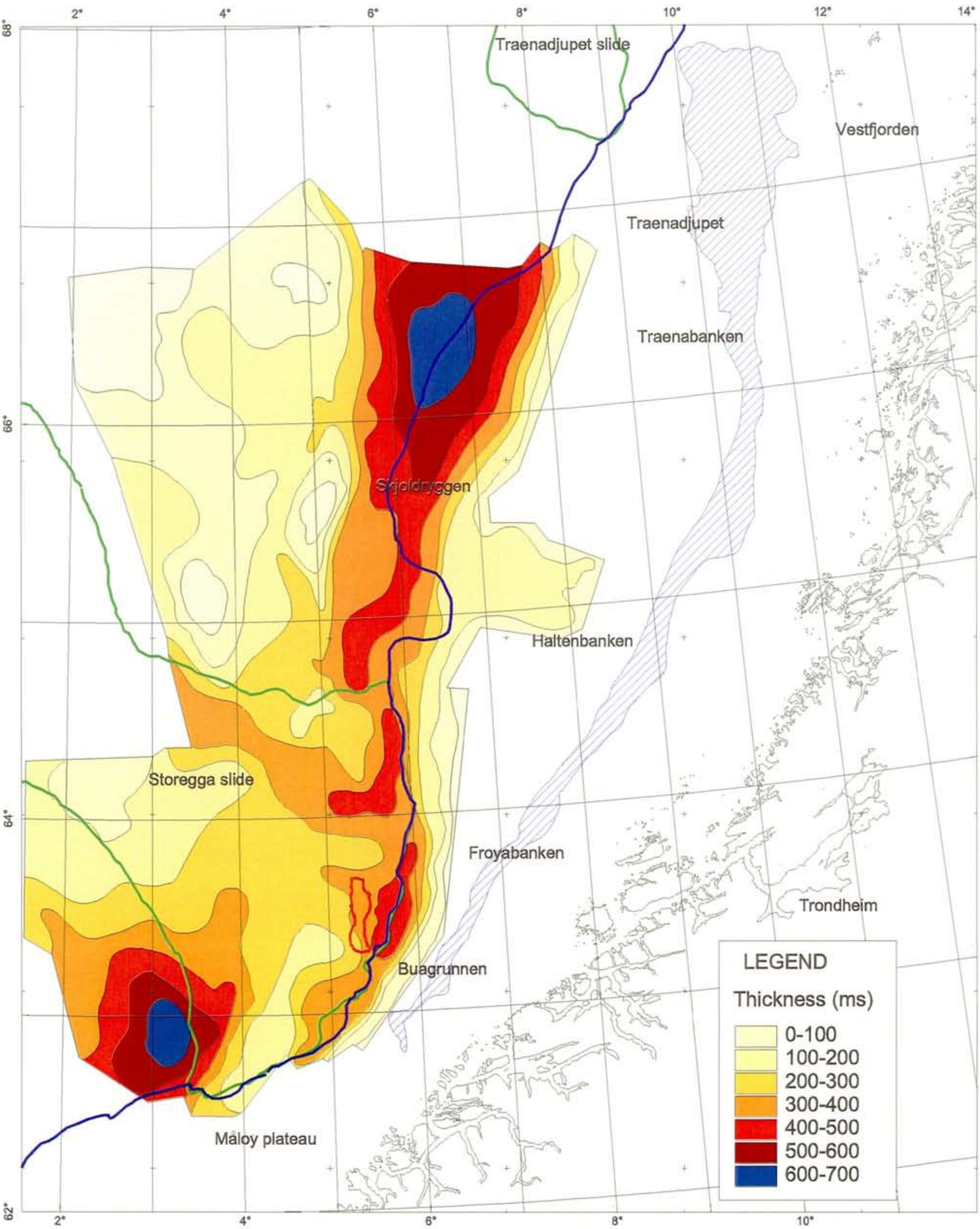


Figure 5.6.1 Isochron map of sequences Naust U & S. In this period (1.7-0.4 Ma) the shelf edge prograded farther westwards, close to its present position (blue line). The depocenter at the North Sea Fan shows that the Norwegian Channel Ice Stream started to operate. The blue line marks the present shelf edge. Red outline - Ormen Lange field. Blue hatching - Oligocene deltaic unit.

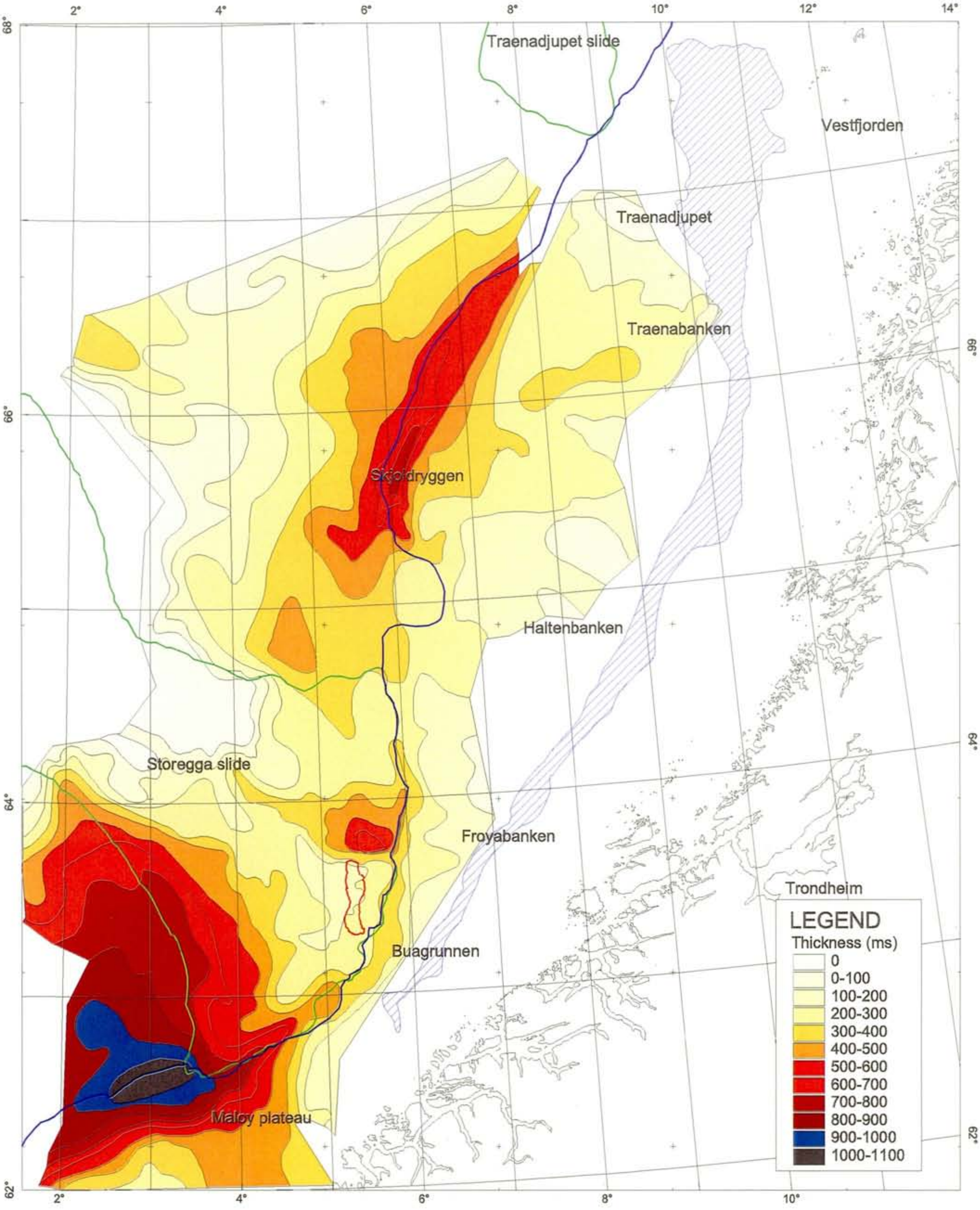


Figure 5.7.1 Isochron map of sequences Naust R & O. The huge depocenter at the North Sea Fan shows that the Norwegian Channel became an important ice drainage route during the last three-four glaciations. The blue line marks the present shelf edge. Red outline - Ormen Lange field. Blue hatching - Oligocene deltaic unit.

6. DEVELOPMENT OF THE SHELF AND MARGIN DURING THE THREE OR FOUR LAST GLACIAL-INTERGLACIAL CYCLES

6.1 'Elsterian' - the third last glaciation beyond the shelf edge

Ice sheets during the 'Elsterian' glaciation(s) seem to be have been very extensive and resulted in widely distributed debris-flow deposits west of the shelf edge (unit R3), particularly in the northern areas. Based on aminostratigraphic analyses of foraminifers collected in geotechnical boreholes, Haflidason et al. (1998) proposed that the unit was deposited during the Saalian glaciation (Marine Isotope Stage 6, i.e. MIS 6). New investigations of samples from boring 6405/2-GB1 indicate that the unit represents glacigenic debris-flows from an older glaciation (probably Elsterian, MIS 8; Haflidason et al. 2001). If the thick deposits of Lower Till (King et al. 1987) located in the middle-inner part of the shelf in the Trænabanken area represent the Elsterian glaciation, an even older age of Unit Naust R3 can be suggested (MIS 10). Thus, the age for these 'Elsterian' deposits may therefore range between 200 and 400 ka (MIS 7-10), as proposed by Norsk Hydro (2001).

Unit R3 (previous Unit Naust B) is readily distinguished by its particularly thick, seismically massive and commonly transparent nature (Figs. 5.2.9, 5.2.16). In the Helland Hansen license area (PL 210) the lower part of the unit is marked by a higher degree of chaotic reflections, and 3D time slices document that the unit consists of large debris-flow lobes (Britsurvey 1999). Individual debris-flow lenses, typical of glacigenic debris-flow deposits, are also observed in the northern area.

Beyond the present shelf edge north of 65°N the unit is 200-350 ms twt thick in extensive areas, representing the consistently thickest unit within the Naust Formation in this area (Fig. 6.1.1). The unit commonly is characterized by a rather abrupt distal pinch-out (Fig. 5.2.11), but locally a gradual distal transition to stratified sediments is also seen. On Gamlembanken and outer Trænabanken the unit also occurs on the shelf (Fig.6.1.1).

Previous interpretations indicated that a large slide removed the unit over a considerable area north and northwest of the Helland Hansen licence area (Britsurvey 1999). Studies by Laberg et al. (in press) also favour interpretation of a slide (proposed name 'Sklinnadjupet Slide'). Our database comprises few lines in this area, and a large collapse feature in the Helland Hansen Arch is evident. As indicated by the isochron map, unit R3 becomes thinner or is locally absent above the collapse feature, which could be related to a slide event (Fig. 6.1.1).

In most of the shelf area east of where the thickest 'Elsterian' glacigenic deposits occur, a very pronounced erosional unconformity is present. In large areas this surface is developed as an angular unconformity (URU), showing strong glacial erosion of westerly dipping sediments (Figs. 5.2.11, 5.2.13). This glacial surface was previously thought to be the base Quaternary, and to mark the interface to underlying Tertiary and Mesozoic sediments. Mapping by King et al. (1987) revealed that URU is a fairly smooth surface north of Haltenbanken. In the outer Haltenbanken region the erosional surface is commonly very uneven (Rokoengen et al. 1995; Amaliksen et al. 1989), possibly similar to the irregular present seafloor east of Skjoldryggen.

Our interpretation demonstrates that the thick 'Elsterian' deposits west of the shelf edge are the products of this strong glacial erosion on the shelf, related to the last shaping of URU. The deposits may indicate that several ice sheets extended to the shelf edge in this period. Truncation of weak internal reflectors in unit R3 indicates that the last glacial advance eroded parts of the older deposits, and that this ice sheet in some areas was erosive beyond the present shelf edge. It seems that the main ice drainage during this period was directed westward between Haltenbanken and Trænabanken. Two separate depocenters indicate that two ice streams were active (Fig. 6.1.1). Although the topography of the regional angular unconformity as mapped by King et al. (1987) reveals two palaeo-troughs towards the central part of the depositional area, no direct correlation to the depocenters is found. Therefore, we believe that the ice was active on a wide front in the region, although the ice drainage was focused along these palaeo-troughs (Fig. 6.1.2).

Unit R3 thins abruptly towards north just southwest of Trænadjupet, but the unit may reappear as a trough mouth fan directly west of this trough. Our database in this area is limited, but we suggest that Trænadjupet was poorly developed at this time. Much of the ice drainage out Vestfjorden could therefore have been directed in the northernmost palaeo-trough, which is located in the southwestern extension of Vestfjorden (between Gamlembanken and Trænabanken). In the area where the 'Vestfjorden ice stream' coalesced with the huge 'ice drainage' system between Haltenbanken and Trænabanken, the flow direction was possibly forced northwestward toward the northernmost depocenter (Fig. 6.1.2).

The glacigenic unit R3 also shows a distinct southerly termination, below the upper part of the slope north of the Storegga Slide (Fig. 6.1.1). At c. 64°40'N the unit becomes very thin, and its southward continuation was previously found uncertain (Britsurvey 1999). Britsurvey (1999) suggested, that their Unit Naust B was equivalent to Unit Naust R in the southern part. Our interpretation, supported by seismic data in the outermost part of the shelf, supports Britsurvey's interpretation (Fig. 5.2.17). The unit is much thinner and less evident than farther south because part of the unit has been removed by a huge slide ('R-slide', Norsk Hydro 2001). Therefore the thickness of the unit has been greater than indicated by the map in figure 6.1.1. The positive bathymetric shape of the upper slope west of Frøyabankhola possibly relates to thick glacigenic debris deposits in this area (see Fig. 8.1).

In the outer Frøyabanken region the 'Elsterian' deposits are also present on the shelf. They are up to 100 ms twt thick and are mainly interpreted as tills. A large portion of these deposits were removed by glacial erosion, particularly in the eastern part of the shelf. Along the outer part of the Møre shelf unit R3 is fairly thin, but 'reappears' as an up to 300 ms twt thick unit in the northwestern part of the Måløy Plateau (Fig. 6.1.3). As our database comprise few lines at the North Sea Fan, the interpretation is fairly uncertain in this area.

6.2 Stratified sediments deposited during a period with limited ice cover on the shelf

A continuous cover of stratified sediments has been mapped above URU in the central and outer part of the shelf south of Trænabanken. King et al. (1987) interpreted this layer as glaciomarine sediments related to the formation of till tongues. The thickness varies mainly between 10 and 50 ms twt, and since the layer partly exists below the Lower Till, we believe that there was a period of hemipelagic sedimentation on the shelf before the till-tongues of the Lower Till were formed. Glacial erosion removed parts of these sediments in the central shelf area, and most of the sediments in the inner shelf. The thickness of the stratified sediments commonly increases west of the Lower Till, indicating deposition related to a period with less extensive ice sheets. The Saalian glaciation depositing Middle Till does not seem to have caused any marked erosion of the underlying stratified sediments east of Skjoldryggen (Fig. 5.2.11).

Stratified sediments also occur in the Haltenbanken region (north of 64°15'N) above URU (horizon at the base of unit IKU-D), but these sediments cannot be mapped as a continuous layer. In the deepest depressions of the unconformity, stratified sediments up to 100 ms twt thick are reported (Rokoengen et al. 1995). The stratification becomes less evident where the unit thins, and above paleo-highs where the unit IKU-D has a more chaotic seismic appearance.

In the eastern slope of the Storegga Slide the stratified sediments representing units R1/R2 commonly show a convex upward or mounded geometry (see Fig. 8.2.3). The deposits often display a moat channel where they terminate upslope, and contour parallel currents have probably dominated the deposition. Detailed mapping of the contourite above the INR2-slide surface, shows that the sediments preferentially infill slide-scars and other depressions (Norsk Hydro 2001). The stratified sediments in the upper part of Sequence R, are commonly 50-150 ms twt thick (Fig. 6.2.1). In some areas they reach nearly 200 ms twt, but the thickness is small where ridges occur on the INR2 slide surface.

Thick stratified sediments also exist directly north of the Storegga Slide, particularly in the area where the glacigenic debris-flows of Unit R3 pinch out southward (Fig. 6.2.1, 5.2.16). Farther north the thickness is commonly much less than 50 ms twt, although it reaches up to 100 ms twt in some areas. In the area where a collapse feature in the Helland Hansen Arch occurs, up to 150 ms twt thick-mounded bodies of stratified sediments are found. These sediments can be followed towards north as a 50-100 ms twt thick layer along the middle-lower slope (Fig. 6.2.1). In the slope adjacent to the northwestern Skjoldryggen region the stratified sediments are thin, but northwest of outer Trænabanken a more than 50 ms twt thick sequence of stratified sediments reappears. Few lines were available in the northern area but these sediments possibly correspond to the stratified Nyk drift, which can be followed to the Nyk Slide and the Trænadjupet Slide farther north (Laberg et al. in press).

The commonly thick sequence of stratified sediments in units R1/R2 seen both on the shelf and on the slope in the southern part of the study area, may either indicate;

(i) a long time interval between the 'Elsterian' glaciation and the next extensive glaciation (Saalian) or,
(ii) a very high sediment supply in the period between these peak glaciations. The catchments of thick stratified sediments on the shelf possibly indicate that the ice sheet(s) was located in the inner part of the shelf during fairly long periods.

6.3 Saalian - the second last glaciation at the shelf edge

The isochron map of the Saalian deposits (horizon INO3 to horizon TNR) reveal three depocenters comprised mainly of tills (shelf) and glacigenic debris-flows (slope) (Fig. 6.3.1). The detection of Eemian sediments combined with interpretation of all available seismic data have given a new understanding of the Saalian glaciation on the shelf, which apparently was more variable and dynamic than previously imagined (Fig. 6.3.2).

Haltenbanken – Trænabanken region

The depocenter located in the Skjoldryggen region is the largest, with a thickness of up to c. 250 ms twt of sediments adjacent to the present shelf edge. In most of this area, the Saalian deposits coincide with the Middle Till as described King et al. (1987). In the area directly north and south of Skjoldryggen, new data available during this project indicated that a reinterpretation of 'the Middle Till' was necessary. This reinterpretation (Ottesen et al. 2001b) describes in more detail the correlation to previous mapping.

Mapping of the westward prograding clinoforms in this acoustically incoherent unit shows that numerous 'till tongues' are developed indicating several ice sheet oscillations. Some of these oscillations may represent different main ice sheet advances, with ice free conditions on the shelf in the period between ice advances (interstadials). The palaeo water depth in the outer part of the shelf was probably fairly large, with enough accommodation space for deposition of the extensive and up to 260 ms twt thick unit (Fig. 5.2.11). The outer part of the till tongues probably represents debris-flows deposited west of the respective grounding lines of the ice sheet, and may explain the limited extent of erosion of underlying stratified sediments. Glacial erosion occurred in the inner part of the shelf (Sklinnadjupet), particularly along the path of ice streams that fed this huge depositional system.

The westernmost termination of the Saalian glacigenic deposits is c. 50 km west of the shelf edge in central part of Skjoldryggen, at a depth of c. 1100 m below the present sea level (Fig. 6.3.2). Glacigenic deposits did not extend to the shelf edge immediately north and south of Skjoldryggen, indicating that a huge ice-lobate depositional system was repeatedly active in the central-outer part of the shelf. The ice masses responsible for the progradation of stacked till-tongues flowed out between Haltenbanken and Trænabanken, with a focused ice drainage towards the palaeo-trough extending westwards below the present Sklinnadjupet (Fig. 6.3.2). West of this confluence zone, where the 'ice stream' had more space and 'spread out', the ice sheet started to deposit its load at the respective grounding lines. The lobate shape of the deposits and several of the 'till tongues' within the Saalian deposits, shows that the ice advanced slowly in the outer part of the shelf, and did not have the character of an ice stream feeding a trough mouth fan (Vorren and Laberg 1997).

We indicate that the Saalian tills are thin at Trænabanken, but several alternative interpretations may be suggested. The interpretation is uncertain, and parts of what King et al. (1987) interpreted as the 'Lower Till' in the northwestern Trænabanken region may be Saalian deposits. A Weichselian ice stream in Trænadjupet made the last shaping of URU here (King et al. 1987; Ottesen et al. 2001a), and only a thin layer of Weichselian deposits is found above the erosional surface. As input of glacigenic debris-flows to the slope region off Trænadjupet is evident (Dahlgren et al. in press), we propose that an ice stream out Trændjupet also was active during Saalian time (Fig. 6.3.2). This ice stream possibly caused the main initial shaping of the Trænadjupet transverse trough.

In the outer Haltenbanken region Saalian deposits did not extend to the shelf edge. Our interpretation indicates that most of Unit IKU-B (Rokoengen et al. 1995) represents Saalian deposits. The unit comprises several till units and is best developed in the northern part of Haltenbanken. The complexity associated with several events of glacial erosion has made it difficult to map sub-units. Parts of the unit may represent deposits equivalent to the Lower Till of King et al. (1987), and may be older than Saalian. The unit is eroded by the Weichselian ice sheet(s) to a variable extent, and the thickness of the unit varies frequently (ranging between 40 and 120 ms twt).

In the depression between Haltenbanken and Frøyabanken at c. 64°– 64°30'N (Frøyabankhola), Saalian deposits are apparently absent. This was first thought to indicate that 'a Saalian ice stream' flowed out between Haltenbanken and Frøyabanken, but seismic data off the shelf edge do not suggest any glacigenic debris-flow deposits on the slope. The Saalian ice sheet(s) probably only extended to a limited degree west of Frøyryggen, and an ice shelf may have occurred between Frøyabanken and Haltenbanken. Possibly, this area may periodically also have acted as a calving bay for a more passive Saalian ice drainage from the coast.

Møre region

South of Frøyabankhola the Saalian deposits reappear in the outermost part of the shelf, and in slope areas where the Storegga Slide did not remove sediments. A Saalian age of the deposits is supported by Eemian sediments preserved in a very thin layer located close to the interpreted INO3 horizon (Boring 20 at Buadjupet, Haflidason et al. 2001).

The thickest Saalian deposits occur between Frøyabankhola and Buagrunnen on the outer shelf, and in the upper part of the adjacent slope, where the sub-units O4-O7 is up to 270 ms twt thick. Sub-unit O5 makes up most of this deposit, which consists of numerous lenses of glacigenic debris-flows west of the shelf edge, deposited above a thick sequence of stratified sediments (see Fig. 8.3.1). The thickness decreases downslope, and the westernmost part of the debris-flow deposits pinch out (downlap) where the slope angle decreases. Although the southern part of the glacigenic sequence is removed by the Storegga Slide on the slope, it is evident that an active ice drainage system in the outer Frøyabanken – Buagrunnen region must have been responsible for these thick deposits on the outer shelf and slope. Several ice streams from the onshore area probably coalesced between Buagrunnen and Frøyabanken, and advanced as a major ice stream to the shelf edge were the tills and glacigenic debris-flows where deposited. Pronounced glacial erosion on the shelf indicates a rapid ice flow and/or a steep gradient of the ice surface. Both the geometry and the seismic appearance of this unit resemble that of a glacial fed trough mouth fan. The Saalian ice advanced to the shelf edge at least twice in this region, although the deposits are dominated by Unit O5.

The strong erosion seen below the present Buadjupet may be a late Saalian event, resulting from subglacial meltwater discharge (see Figs. 8.1, 8.1.1). An east-trending 'channel' can be followed c. 50 km in the central part of Buadjupet. The slightly over-deepened channel is 5-10 km wide and up to 80 ms twt deep and is filled with stratified sediments. The channel's largest depth (530 ms twt) occurs 20-25 km east of the shelf edge, and becomes slightly shallower westwards. Glacial erosion during the Weichselian removed parts of the channel sediments (see Fig. 8.1.1), but erosion alone cannot explain the absence of the channel near the shelf break, as displayed by seismic line NH9651-302. The channel seems to end just east of the shelf break, suggesting that it was formed subglacially by meltwater erosion. Close to the shelf break, open fractures in the ice will reduce water pressure, and thus the erosional capacity of the water. Such channels are well known in the North Sea, but this is the only example known to us on the mid-Norwegian shelf.

Boring 20 (6305/9-GB1) is located close to the channel, but it appears that the channel sediments were not sampled. These sediments are interpreted to be older than the Eemian sediments found in boring 20, and we suggest that the channel was formed during a late phase of the Saalian glaciation.

The Saalian deposits occur as a wedge at the shelf edge from Buagrunnen to south of the Måløy Plateau, and are commonly 100-150 ms twt thick along the shelf edge. In some areas two or more sub-units occur, and we believe that the ice sheet reached the shelf edge east of the central Storegga slide at least twice. The bathymetric map reveals a 'high' morphological segment of the upper slope outside Onadjupet/Buagrunnen (see Fig. 8.1). This segment consists of c.170 ms twt thick Saalian glacigenic debris-flow deposits, undisturbed by the Storegga Slide. An ice stream that was a part of the dynamic 'Møre ice sheet', flowed out Onadjupet and may have deposited much of these sediments. Reconstruction of the Saalian debris-flow deposits on the slope is difficult. However the location of transverse troughs pointing towards the deep incision of the Storegga Slide, combined with the measured thickness of the deposits, indicate that between 150 and 250 ms twt of Saalian debris-flows were deposited on the upper slope. There is no indication of sliding in the Storegga Slide area after the last Saalian peak glaciation, and we believe that these deposits remained undisturbed on the slope until the Storegga Slide occurred. We infer that these deposits may have been an important element for the Storegga Slide development.

Måløy Plateau and North Sea Fan

Thick Saalian deposits occur in the outermost part of the Måløy Plateau, commonly being c. 150 ms twt thick (Fig. 6.3.1). The deposits comprise several glacigenic wedges that built out the shelf edge (Fig. 6.1.3), indicating that the ice sheet advanced across the plateau several times during this period. The wedges resemble till tongues in the outer Skjoldryggen region, and they rapidly pinch out in the upper slope. Typical glacigenic debris-flow lenses are not observed, but a thin layer of related sediments may occur in the slope.

The open seismic grid together with the complex geology with several cycles of deposition and erosion, opens for alternative interpretations in the border zone between the Norwegian Channel and the Måløy Plateau. Our interpretation indicates a local depocenter with up to 250 ms twt thick sediments, located adjacent to the southern corner of the Storegga Slide (Fig. 6.3.1). While tentative, this depocenter may be related to a Saalian ice stream in the Norwegian Channel, causing strong glacial erosion of the western flank of the Måløy Plateau.

Saalian glacigenic debris-flows in the order of 200 ms twt in thickness have been deposited at the mouth of the Norwegian Channel, but the sediments apparantly thins rapidly towards north. Although parts of these deposits were removed during the Tampen Slide, suggested to be an early Weichselian event (Britsurvey 1999), the amount of Saalian material deposited in the North Sea Fan is much smaller than during the Weichselian. This indicates that the ice stream in the Norwegian Channel was only moderately active during the Saalian.

6.4 Weichselian - the last glaciation

The Weichselian deposits mapped in this study correspond to different units mapped in previous studies. Improved chronostratigraphic control together with new high quality seismic profiles permit an improved correlation between slope and shelf, and forms the basis for relatively consistent mapping of the entire area (Fig. 6.4.1). The unit comprises mainly till in the shelf areas, till tongues/debris-flow in the upper slope and a thin layer of stratified sediments in the slope. An ice flow model during Late Weichselian is shown in figure 6.4.2 (Ottesen et al. 2001a).

An important result of the interpretation is that the Weichselian ice sheet extended to the shelf edge at least twice along the entire shelf margin. Possibly, several advances to the shelf edge occurred in the Møre area. Thick Weichselian glacigenic debris-flows at the North Sea Fan show that Norwegian Channel Ice Stream also was very active in this period (Fig. 6.4.3). Interpretation of the seismic stratigraphy in the Norwegian Channel indicates that three or four main periods of ice streaming occurred during the Weichselian (King et al. in prep.). The glacial palaeo-environment in the Norwegian Channel was probably similar to some of the ice streams in Antarctica today (Fig. 6.4.4).

Digital bathymetric data off Mid-Norway, provides an unique regional view into glacial processes and ice-sheet dynamics during the Weichselian glaciation (Ottesen et al. 2000; 2001a). In the following we will comment on the main topographic features and relate them to observations in this study.

Haltenbanken and Trænabanken region

The shelf includes the large bank areas (Røstbanken, Trænabanken and Haltenbanken), separated by depressions (Trænadjupet and Sklinnadjupet), which have acted as major ice drainage routes.

The bathymetric expression of the wide Trænadjupet trough, located between Trænabanken and Røstbanken, contains linear features parallel to the trough axis, reflecting the flow direction of ice streams. Swath bathymetric data and 3D images of the sea floor show linear flutes and megascale lineations, verifying that an ice stream flowed out Trænadjupet. In the eastern part, at least two different glacial drainage systems coalesced; ice flow from the northeast (Vestfjorden) and southeast joined to become one major ice stream along Trænadjupet. Older sediments along the flanks of Trænadjupet are strongly eroded, and above the angular unconformity only a thin layer of Weichselian deposits occur. We have no seismic data at the mouth of Trændjupet, but according to Dahlgren et al. (in press), Weichselian debris-flows are located here.

The most spectacular Weichselian deposit is the c. 150 km long and 10 km wide Skjoldryggen ridge at the shelf edge (Fig. 5.2.1). The ridge is up to 150 m high and represents a terminal moraine formed along the grounding line of the Weichselian ice sheet. Active drainage of ice out Sklinnadjupet fed debris to the outer-grounding zone. The Weichselian till tongues terminates at a water depth of 500-600 m below the present sea level, and do not extend as far west as the Saalian deposits in this area (Figs. 5.2.11, 6.3.2, 6.4.3). During the gradual build-up of Skjoldryggen, the ridge may have supported the ice and reduced the supply of debris to the slope.

The map of the acoustically massive sediments demonstrates deposition beyond the present shelf edge, but the westward extension of such sediments is greater south and north of Skjoldryggen. The complex morphology east of Skjoldryggen is likely resulted from glaciotectonic deformation during a late stage (Fig. 6.4.5). A cold-based ice-sheet probably existed for some time east of Skjoldryggen. Both the rough topography and the evident final push of Skjoldryggen, may relate to an ice advance once the ice had become wet-based again.

Weichselian till tongues east of Skjoldryggen are few and much less developed than the Saalian till tongue deposits. This may indicate shallower water depths than during deposition of the Saalian tills. Flat-lying internal reflectors, as well as erosional reflectors, indicate that accommodation space (i.e. water depth) was much less than during the Saalian. We therefore infer that the subsidence of the area between peak Saalian and Weichselian glaciations was relatively limited.

Due to a combination of several factors, i.e. terminal moraine ridge/frozen or stagnant ice, the ice drainage towards west was reduced. The easiest path for the ice masses to move was in the northwestward extension of Sklinnadjupet. The largest depo-center related to the Weichselian ice occurs at the shelf edge just north of where the lobate Saalian deposits pinch out (Figs. 5.2.16, 6.3.1, 6.4.1). The location of this depo-center, as well as observation of stacked debris-flow lenses in the middle-lower slope, indicates that an ice stream flowed in the northwest continuation of Sklinnadjupet (Fig. 6.4.3). Based on radiocarbon dates of sediments in the slope, the ice sheet is interpreted to have reached the shelf edge of the northern region between 21 and 17 ka. At c. 16.5 ka the outer shelf was deglaciated (Dahlgren and Vorren 2001).

The Weichselian deposits correlates to units IKU-U and –A in the Haltenbanken region, mapped by Rokoengen et al. (1995). In the northwesternmost part of Haltenbanken, including the 'embayment' south of Skjoldryggen, the deposits consist of several till-tongues deposited above a 15-20 ms twt thick layer of fine-grained sediments. These stratified sediments occur west of the Saalian till tongues, which did not extend to the shelf edge in this area, and the Eemian INO3 horizon is correlated with the upper part of this layer. The Weichselian deposits are commonly in the order of 150 ms twt thick, and several till tongues occur in the upper slope, indicating deposition during different phases.

The isochron map of the Weichselian sediments (Fig. 6.4.1) reveals large deposition in the western part of Haltenbanken, and indicates an active flow of ice across or south of the bank. Deposition occurred where accommodation space was available in the outer part of the shelf, just west of where the youngest Saalian till tongue was deposited.

A late advance of the Weichselian ice sheet is commonly observed to have been very erosive, also in the outer shelf. This strong erosion indicates a major late advance, and possibly correlates to the last phase of the Weichselian maximum glacial advance (LGM 2). Most of the eroded material was deposited as till tongues/debris-flow deposits beyond the shelf edge (see Fig. 8.2.3).

Several radiocarbon dates in samples from the IMAGES core 2291 and Boring 6405/2-GB1 located just west of the pinch out of three separate till tongues (deep towed boomer line NH9651-109 used for correlation), demonstrate that the glacigenic debris is deposited within the period 16-27 ka (Haflidason et al. 2001; H. Haflidason, pers. comm. 2001). The oldest till tongue unit is interpreted to have an age between 19 ka and 27 ka, and the two youngest units seem to have been deposited between 16 ka and 19 ka. Although it is not possible to confidently correlate the two youngest till tongues to an erosional reflector on the shelf, we believe they represent deposition during LGM 2.

In this area we have no indications of an earlier Weichselian ice sheet reaching the shelf edge. It seems that the two major Late Weichselian advances deposited most of the up to 200 ms twt thick glacigenic debris at the shelf edge.

South of Haltenbanken

Along the shelf edge just east of the Storegga Slide the maximum thickness of Weichselian deposits commonly is slightly more than 100 ms twt. There are no indications of increased deposition off Frøyabankhola where an ice stream between Haltenbanken and Frøyabanken can be inferred from the bathymetry. It is clear, however, that the ice sheet extended to the shelf edge in the entire region.

At the shallow Møre shelf the thickness of the Weichselian deposits is commonly 50-100 ms twt, often comprising several thin till units. Several erosional surfaces indicate a dynamic ice sheet in this region, and the short distance to the mainland (see Fig. 8.1) containing high mountains suggest that the ice sheet reached the shelf edge several times during the Weichselian. The seismic data reveal that ice streams periodically flowed out Buadjupet and Onadjupet. Significant volumes of debris were possibly deposited beyond the shelf edge and later removed by the deep incision of the Storegga Slide. It is possible that up to 150 ms twt thick sediments were deposited in the slope outside Buadjupet/Onadjupet.

At the North Sea Fan stacked debris-flow lenses being in the order of 500 ms twt thick in extensive areas, show that the Norwegian Channel Ice Stream was very active during the Weichselian. The deposits occur above the Tampen Slide (Figs. 5.2.2, 5.2.3). Three or four periods of ice streaming in the Norwegian Channel are proposed by King et al. (in prep.). The northeastern part of the fan deposits was removed by the Storegga Slide.

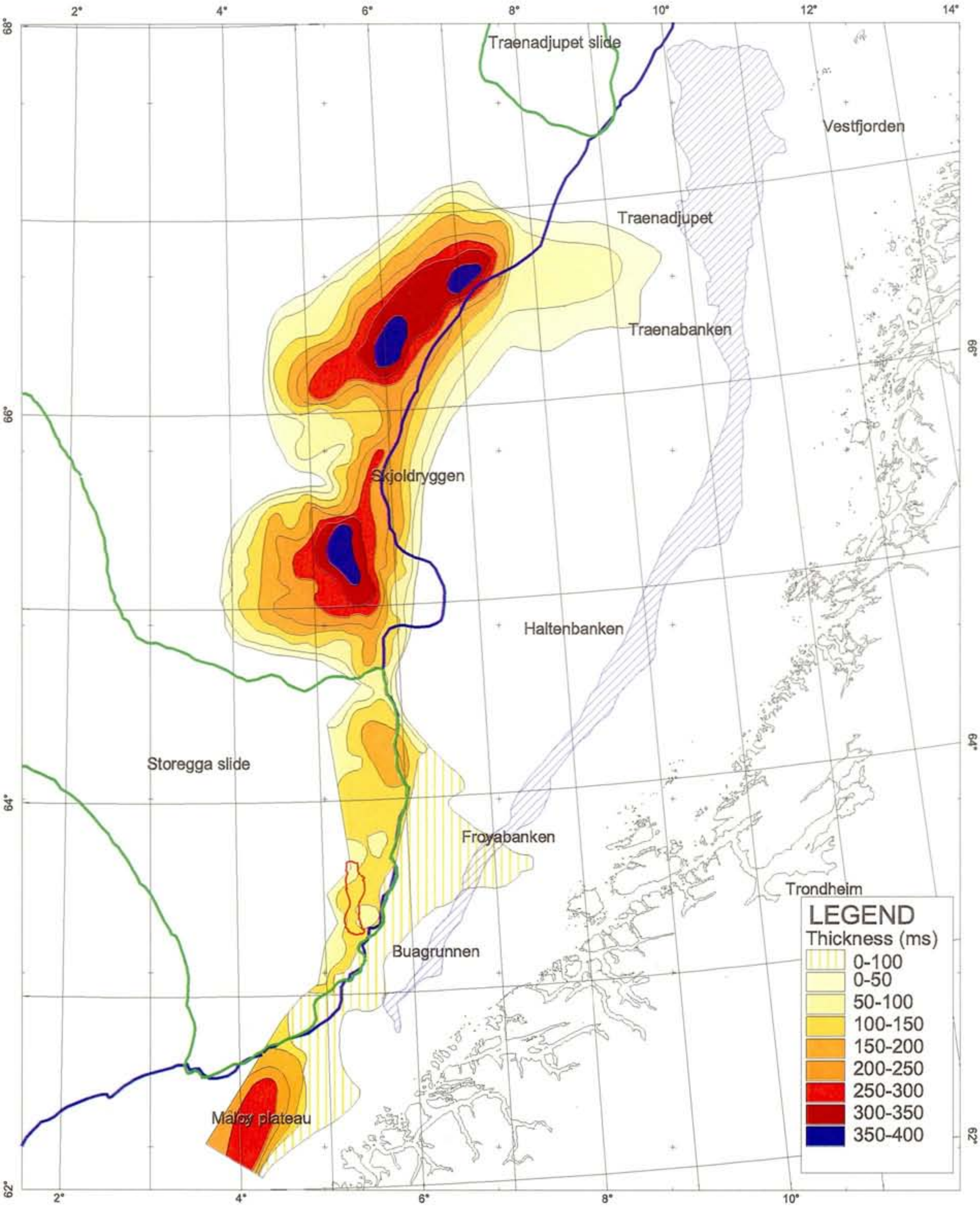


Figure 6.1.1 The isochron map of Sequence Naust R shows that the Elsterian glaciation(s) reached the shelf edge along the entire mid-Norwegian margin. More than 300 m thick glacigenic debrites were deposited on the slope west of Haltenbanken-Trænabanken. The blue line marks the present shelf edge.

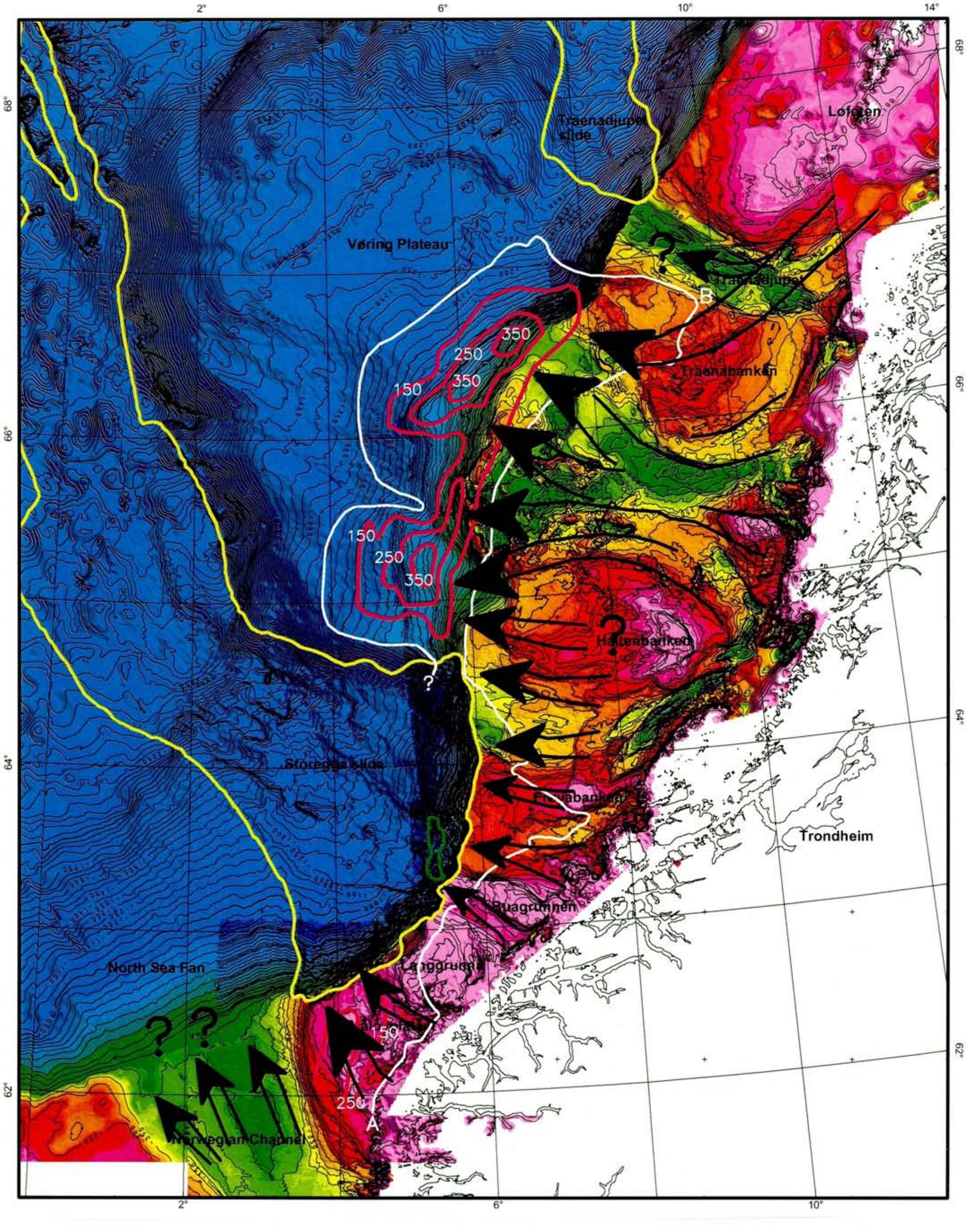


Figure 6.1.2 Major depocenters of Sequence Naust R (red contours) with inferred ice flow pattern during peak Elsterian glaciation(s). Elsterian sediments occur west of the white line (A-B). The western limit of the debris flow deposits is shown north of the Storegga slide.

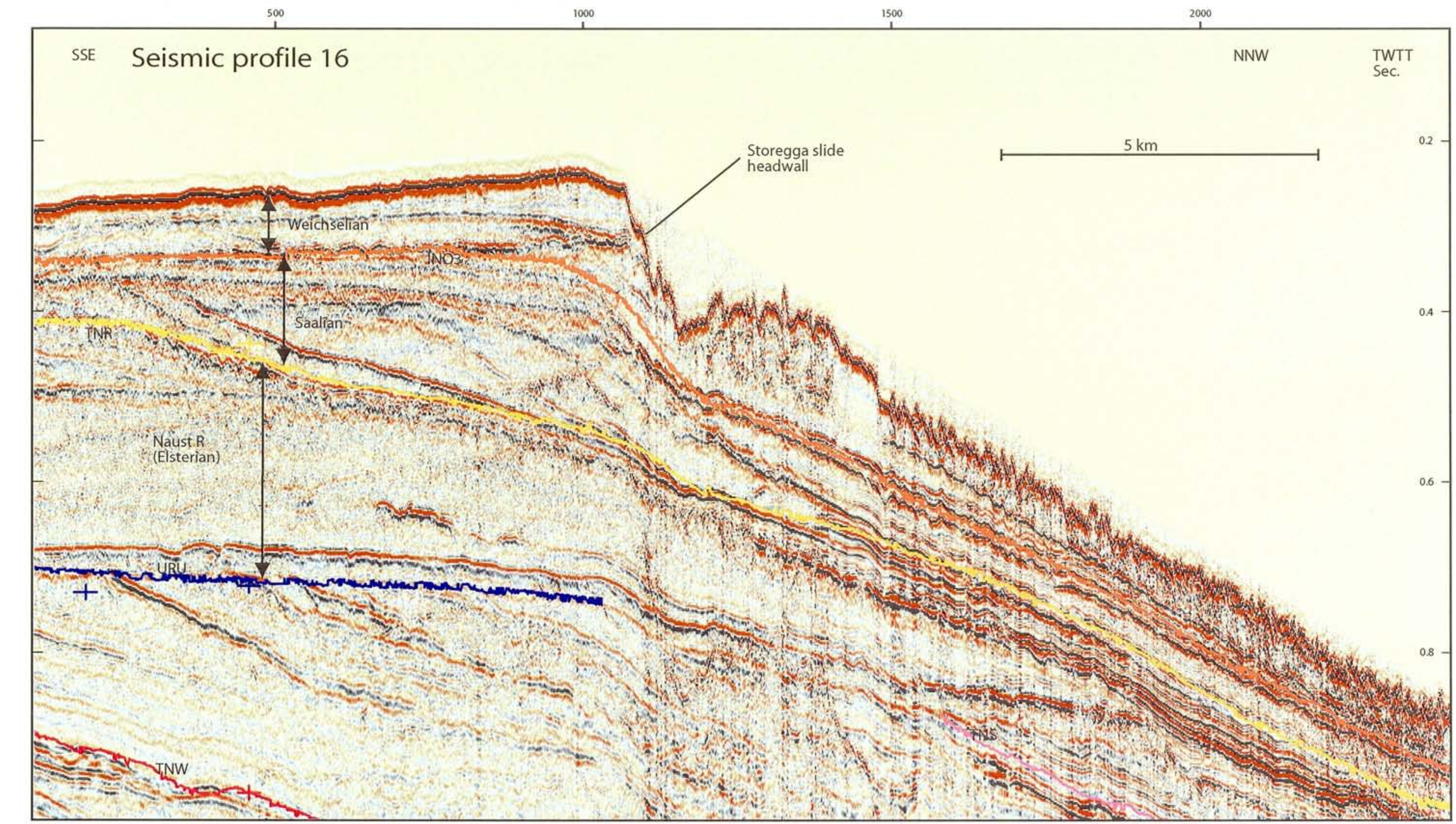


Figure 6.1.3 Very thick Elsterian and Saalian glacigenic deposits occur at the outer part of the Måløy Plateau. For location of profile NH0169-301, see figure 8.1.

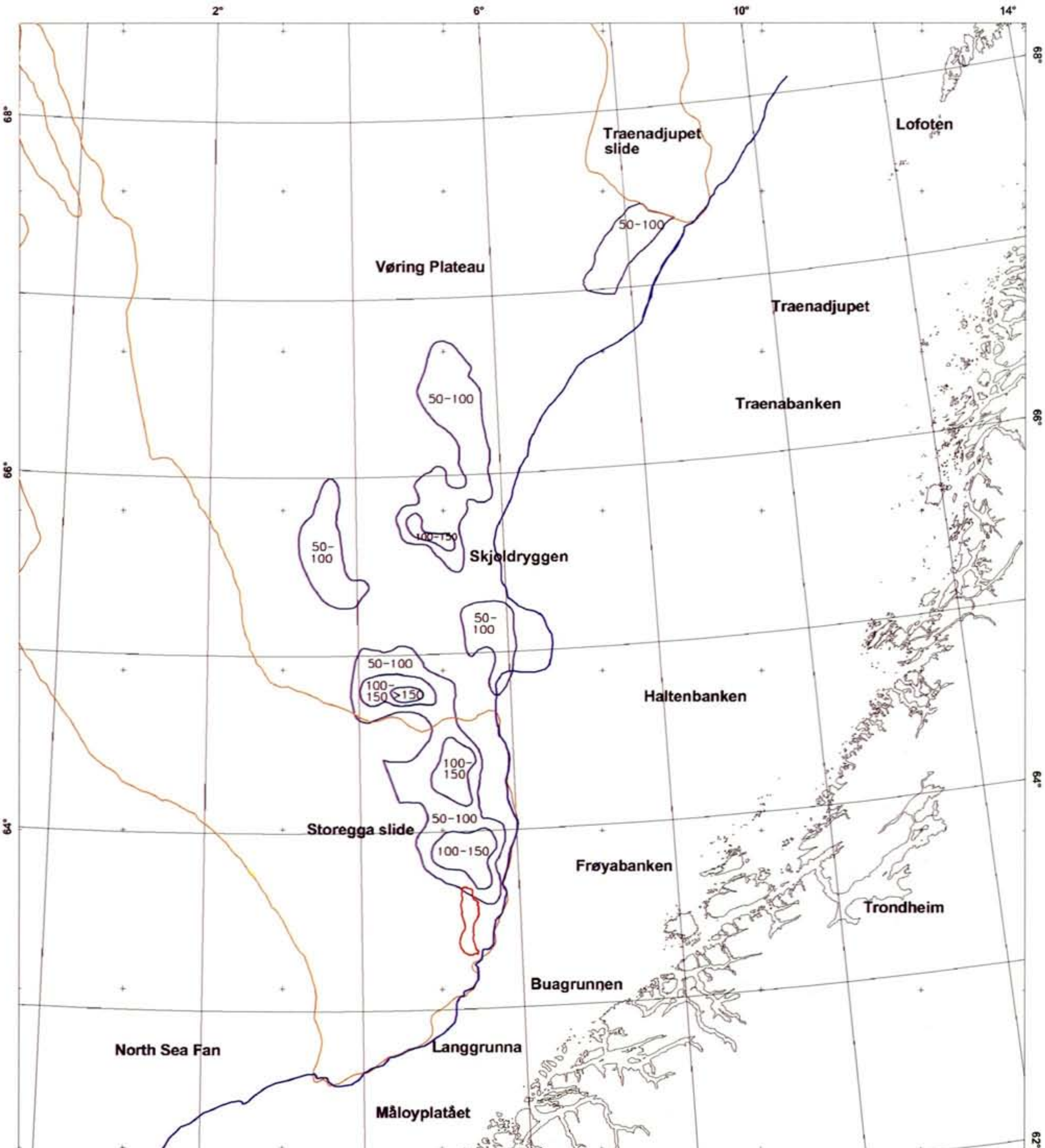


Figure 6.2.1 Distribution and thickness (ms twt) of stratified contouritic sediments (units R1/R2), deposited after the Elsterian glaciation(s). Orange line - outline of Storegga and Trænadjupet slides. Red line - Ormen Lange field.

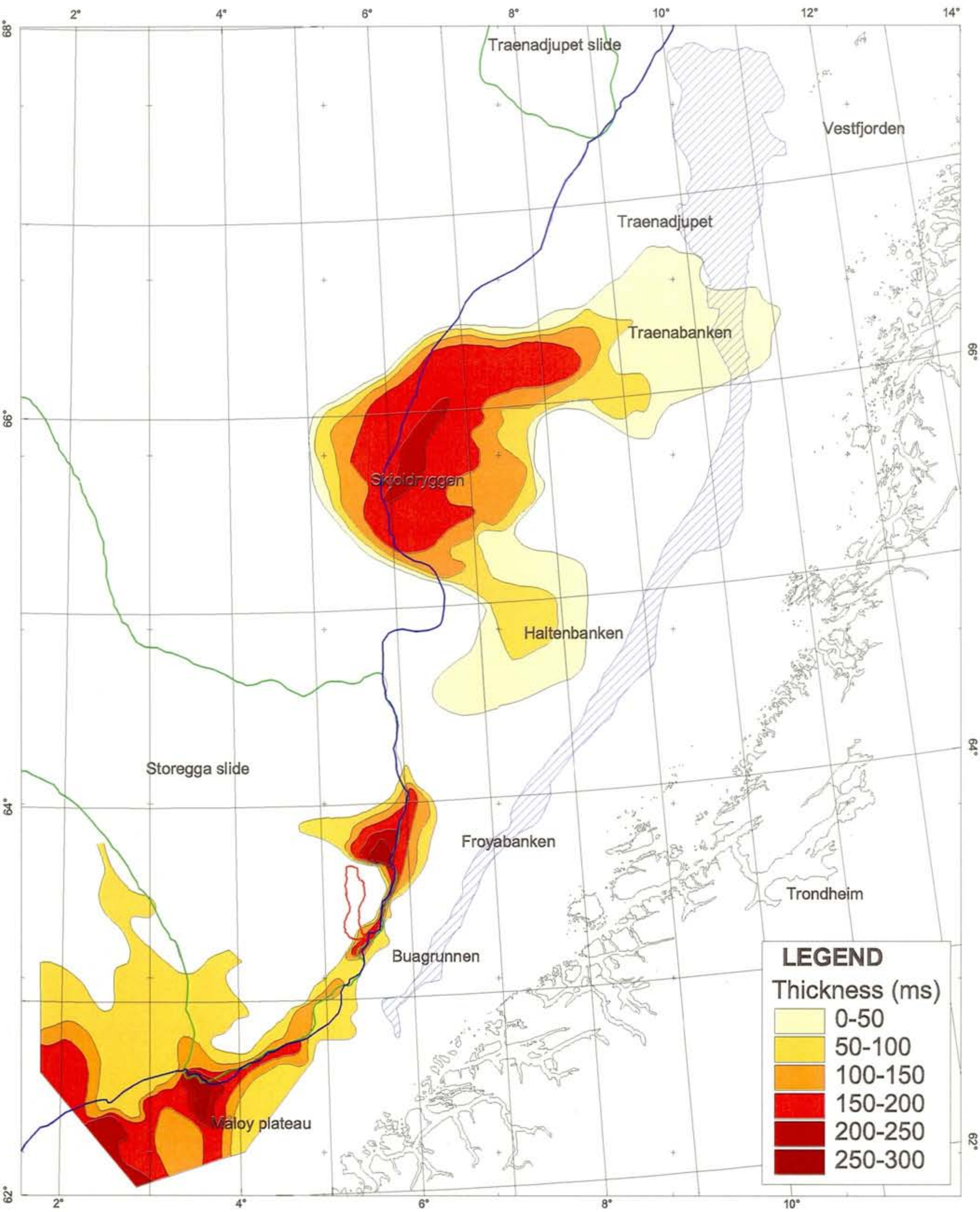


Figure 6.3.1 Isochron map of Saalian glacigenic sediments (tills, debris flows). Note the lobate shape of the deposits in the Skjoldryggen region related to a focused ice drainage out Sklinnadjupet. The blue line marks the present shelf edge. Red outline - Ormen Lange field. Blue hatching - Oligocene deltaic unit.

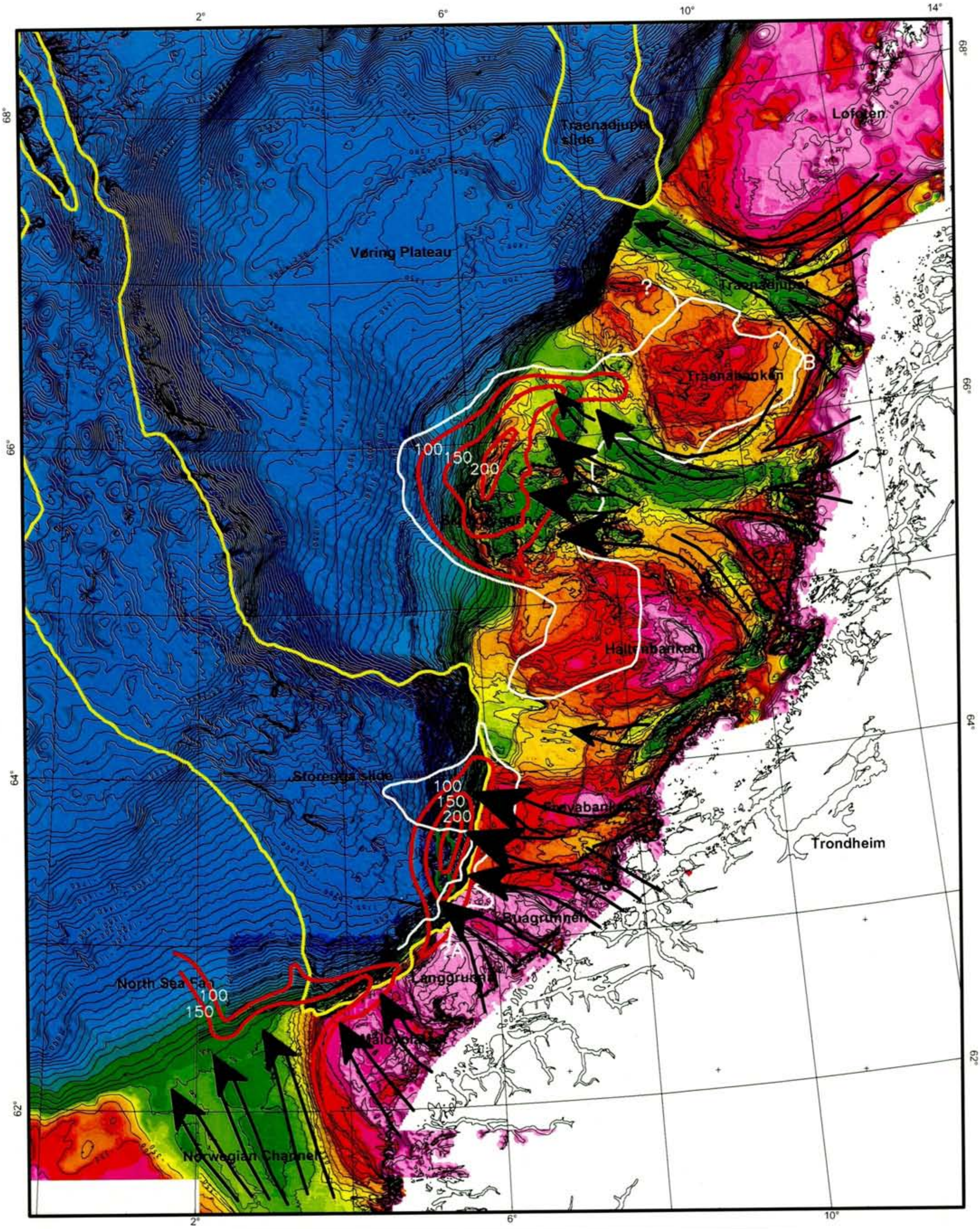


Figure 6.3.2 Major depocenters of Saalian sediments (red contours) with inferred ice flow pattern during peak glaciation. Saalian sediments are found west of the white line (A-B). The western limit of glacigenic deposits is shown in the Haltenbanken-Trænabanken area, and where the "Buadjupet Fan" occurs west of the focused ice drainage between Buagrunnen and Frøyabanken. Inferred thickness of Saalian sediments (ms twt) is marked where the fan was removed by the Storegga slide.

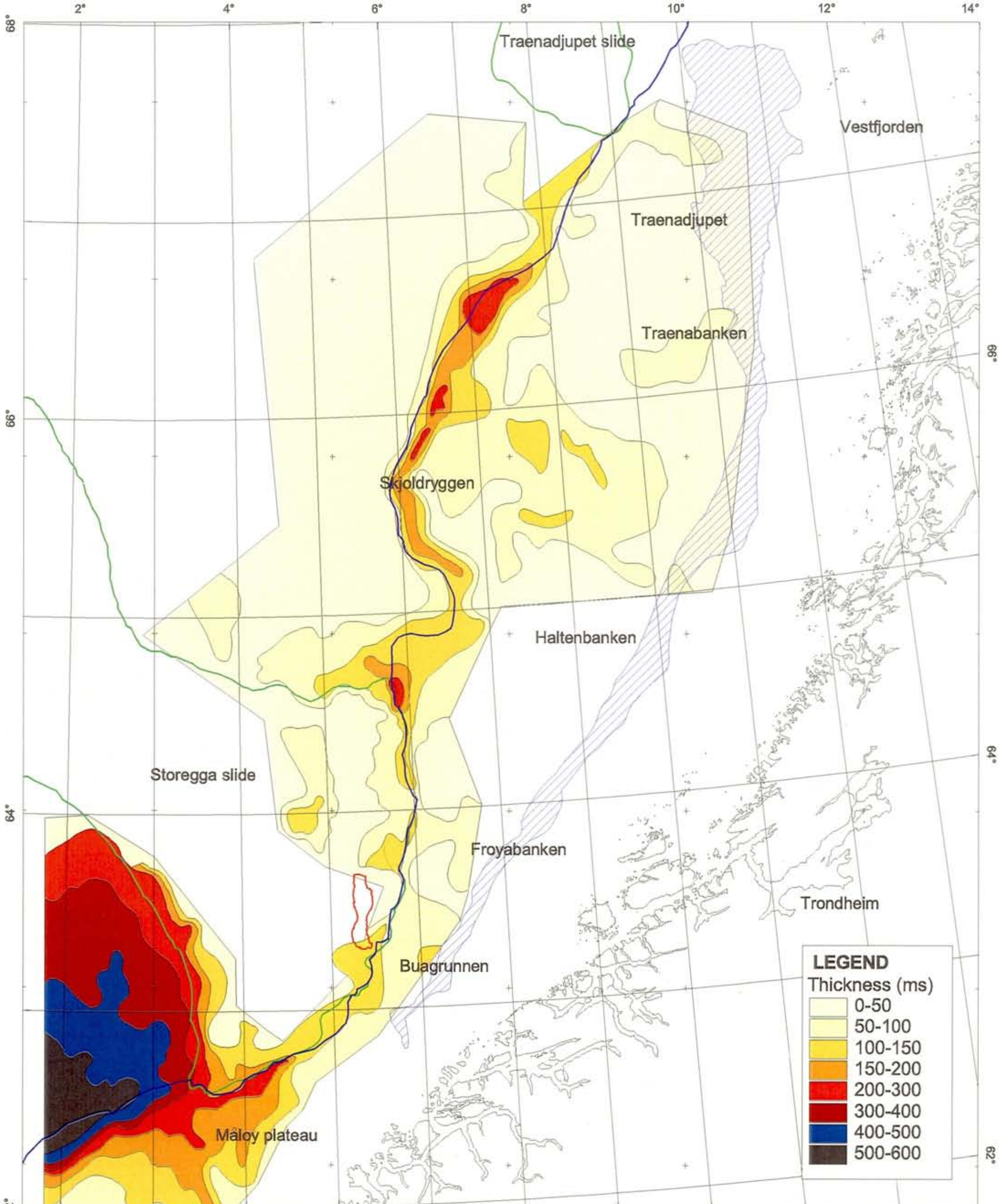


Figure 6.4.1 Isochron map of Weichselian sediments. The map represents sediments above the INO3-horizon (Eemian age). The Norwegian Channel Ice Stream was active in three-four periods during Weichselian, and deposited more than 400 m thick glacigenic debris flows at the North Sea Fan. Red outline - Ormen Lange field. Blue hatching - Oligocene deltaic unit.

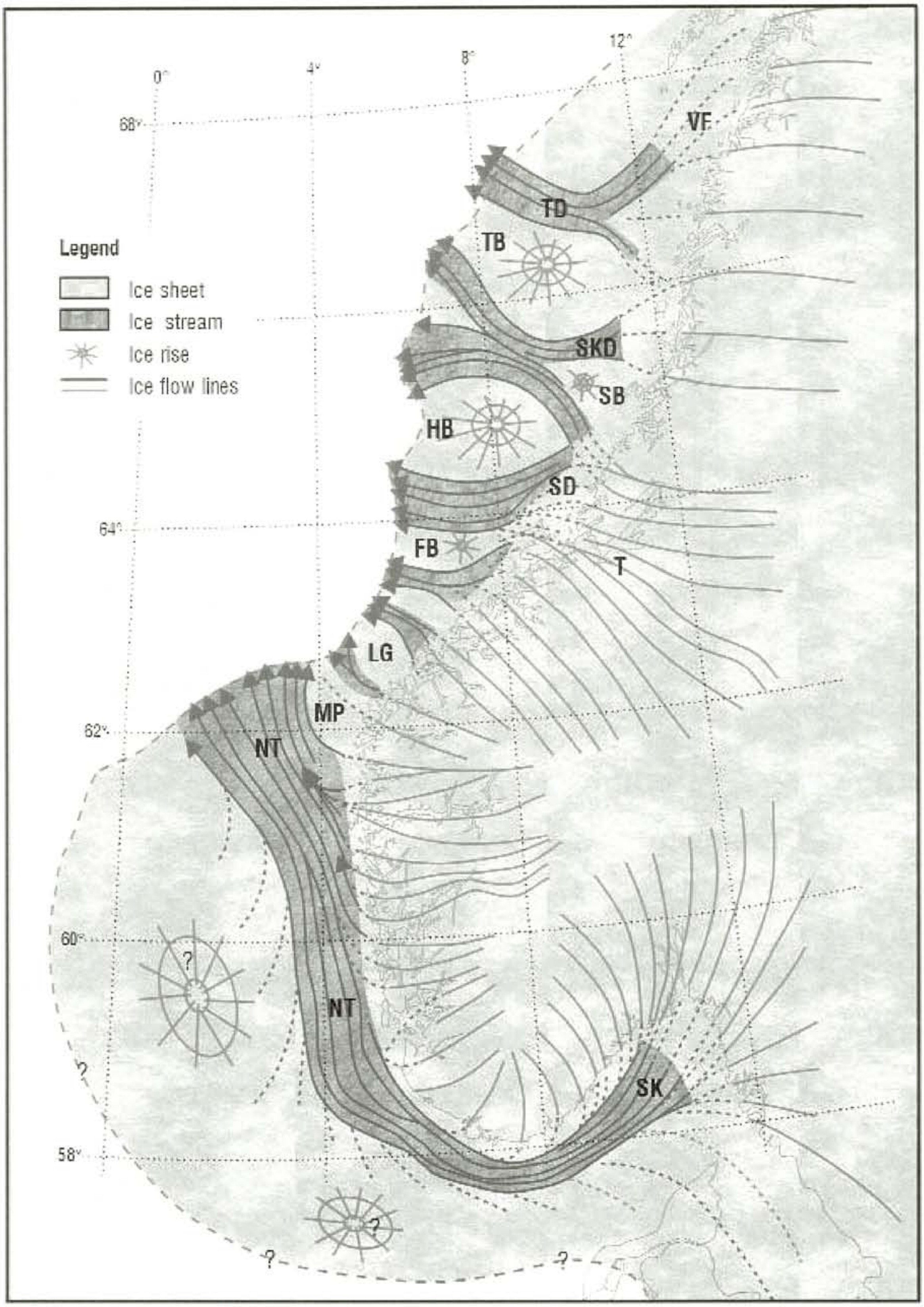


Figure 6.4.2 Interpreted ice-flow model during the Late Weichselian (after Ottesen et al. 2001a).

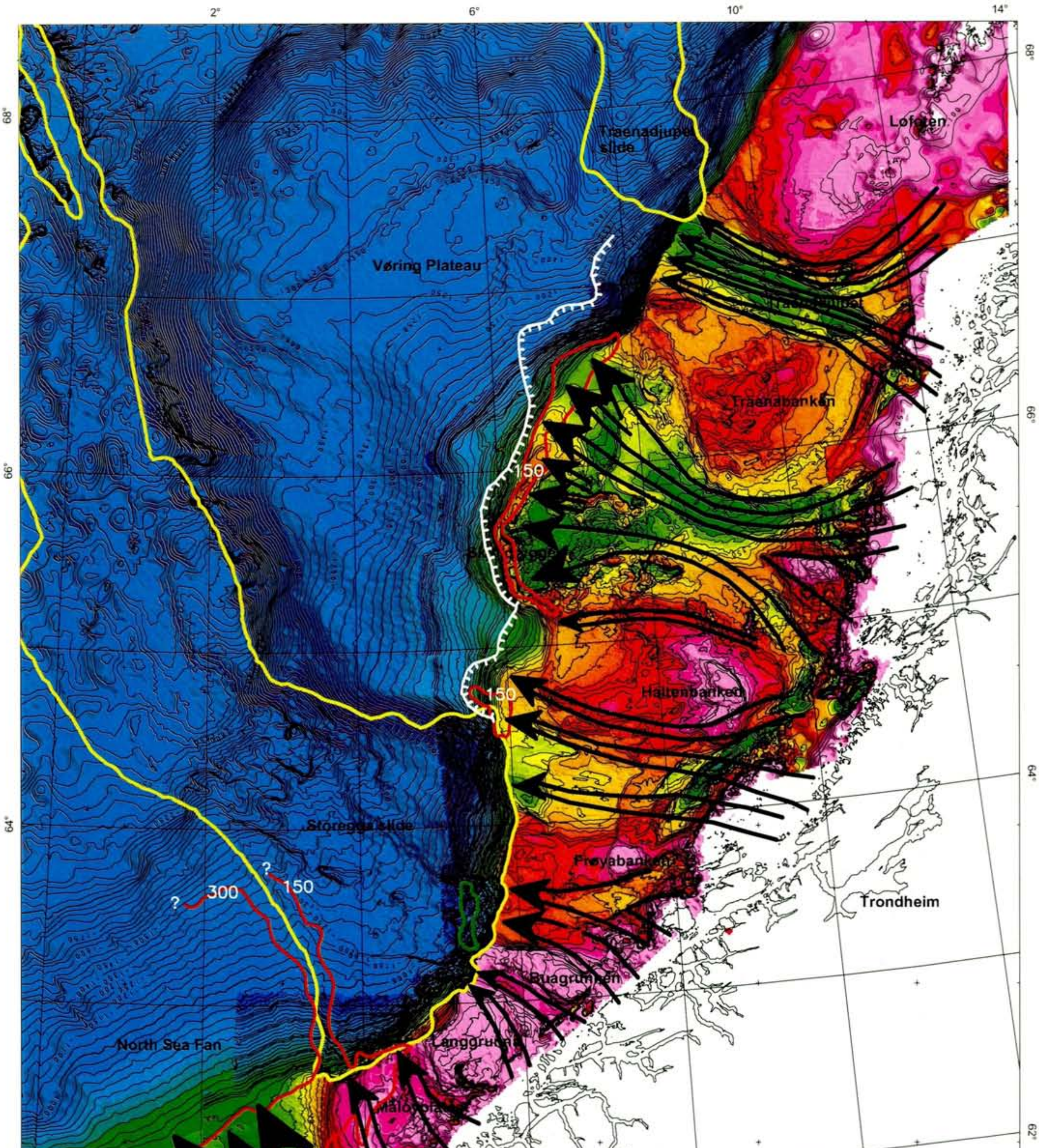


Figure 6.4.3 Major depocenter of Weichselian sediments (red contours) with inferred ice flow pattern during the last glacial maximum. The Late Weichselian Ice Sheet reached the shelf edge along the entire margin. The white line shows the western limit of the glacigenic debris flows north of the Storegga Slide.

Figure 6.4.4 The Jutulstraumen Ice Stream, Dronning Maud Land, Antarctica. (Photo Kjetil Melvold, UiO.)

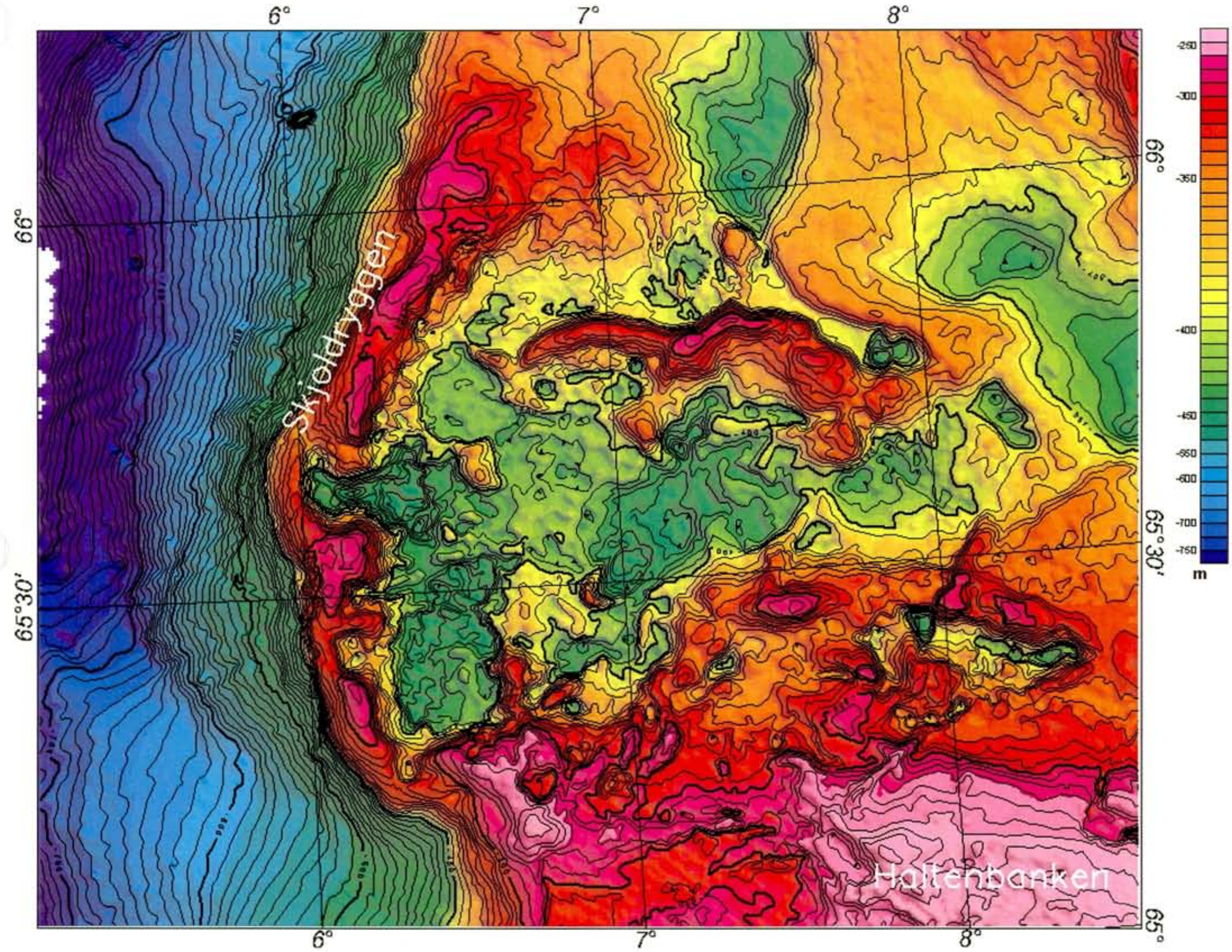


Figure 6.4.5 The irregular morphology in the Skjoldryggen area is probably due to glacio-tectonic processes during a late stage of the Late Weichselian glaciation.

7. CHRONOSTRATIGRAPHIC INFORMATION AND CORRELATION WITH THE ESTABLISHED SEISMOSTRATIGRAPHY

Information from cores / geotechnical boreholes and exploration wells, which are not a part of the Seabed Project and other studies related to the Ormen Lange Field, is summarized in sections 7.2 and 7.3. In Section 7.1 we present an overview of various chronostratigraphic data, and discuss information that seem to be incompatible with the data.

7.1 Overview and discussion

Weichselian (Naust O, upper part)

In spite of comprehensive surveys, the timing and even the extent of the last glacial maximum on the Mid-Norwegian shelf have remained uncertain (Holtedahl 1993). The prevailing view has been that the ice reached the shelf edge at its maximum and remained there until 18 ka, followed by a gradual retreat, reaching the coastal areas at about 13 ka (Andersen 1981). Conventional radiocarbon dating of one sample from the outer shelf indicated, however, that the ice reached the shelf edge there as late as 13 ka (Rokoengen 1979; Bugge 1980). New accelerator mass spectrometer (AMS) radiocarbon dates indicate that the outermost till unit near the shelf edge south of Haltenbanken (till tongue 23) was deposited at about 15 ka, and that till tongue 24, pinching out c. 20-30 km east of the shelf break, was deposited at about 13.5 ka (Rokoengen and Frengstad 1999).

The oldest till tongue unit in the slope south of Skjoldryggen is interpreted to have been deposited during the period 16-27 ka BP (see Section 6.4). As thick till tongues also occur in the outer part of the adjacent shelf (in seismic unit IKU-A), we cannot exclude the possibility for an Early or Mid-Weichselian glaciation on the mid-Norwegian shelf. The youngest till tongues on the upper slope seem to have been deposited in the period 16-19 ka. AMS dates of foraminifera from stratified sediments located in the upper slope (IMAGES core MD99-2291, Fig. 5.2.1), show a very high sedimentation rate in the period 15-16 ka, possibly related to initial deglaciation of the shelf edge (Hjelstuen et al. in prep., see Section 8.3). By comparison, the sedimentation rate at this location has been low after 15 ka. Unpublished AMS dates in glaciomarine sediments close to the mainland (Trondheimsleia) indicate that the ice margin had retreated to the coastal area at c. 13 ka or even earlier (R. Bøe, pers. comm. 2001). Stratified glaciomarine sediments were deposited in the Norwegian Channel from c.15 ka, indicating an earlier deglaciation of the shelf in this area (Sejrup et al. 1995).

Eemian/Saalian (Naust O, lower part)

The detection of an Eemian fauna in the IMAGES core MD99-2289 was an important finding for the present project, as this level (reflector INO3, previously INA) could be traced towards the upper slope where till tongues pinch out. As our seismic database did not contain the deep tow boomer line NH9753-205 run across the location of the IMAGES core, we applied an indirect tie for the Eemian horizon at the intersection between lines NH9753-205 and NH9651-109 (Atle Nygård, UiB, pers. comm., 2001). New high-resolution seismic data improved the regional understanding of the margin development, and made it possible to differentiate between Weichselian and older sediments. The tie of the Eemian horizon (INO3) indicates that most of what King et al. (1991) interpreted as the Upper Till in the central Skjoldryggen region represents Weichselian sediments (Naust A2, Britsurvey 1999). This interpretation is also supported by possible Eemian sediments at 11 m depth in the Gjallar Ridge boring 6704/12 (Haflidason et al. 1998), and by the seismic tie from ODP 644A (Dahlgren et al. in press, Svitzer 2002). Reflector INO3 seems to correspond closely to the level where Eemian fauna were found in interglacial sediments in the Smørbukk South Field (Sættem et al. 1996). Borehole 6305/9 (site 20) at the outer shelf east of the Storegga Slide, where an Eemian fauna was found in a thin layer close to the interpreted INO3-horizon, yielded another check-point for the interpretation (Haflidason et al. 2001).

The interpreted INO3 horizon has been the 'guideline' for defining the glacial deposits below as Saalian (Naust A1 and corresponding seismic units south of Skjoldryggen). Our interpretation of Saalian deposits in the Skjoldryggen region agrees with that of Dahlgren et al. (in press) who, by means of a high-resolution boomer line, tied MIS 6 in ODP 644A to the Naust Unit A1 (Middle Till).

Elsterian (Naust R)

Both the Saalian and the Elsterian were extensive glaciations in Europe. The thick glacigenic debris flows in Unit R3 seem to be related to a very erosive shelf glaciation, and we have therefore tentatively related Unit R3 to the Elsterian. Unit R3 comprises several sub-units, which may indicate that it represents more than one glaciation (Elsterian complex).

The boundary between the Saalian (lower Sequence O) and 'Elsterian' (Sequence R) deposits is mainly based on the regional seismic interpretation, and in most of the studied area it is evident that they represent different glaciations. The amino acid ratios measured in borehole samples commonly show a fairly high scatter (Haflidason et al. 1998, 2001). Normal marine/glaciomarine clays (Unit R1, site 19-2 and site 20) give, for example, ratios typical for Eemian sediments, c. 150 m below the INO3-reflector. If these values are correct, a Saalian age of unit R3 may be inferred, indicating that the Eemian horizon is incorrectly tied from the IMAGES core MD99-2289. Although the age of Sequence R is somewhat uncertain, we have chosen to rely on the Eemian fauna detected in site 20 and suggest that the sequence may represent two glacial/interglacial cycles (Marine Isotop Stage 7-10; proposed age window 0.2-0.4 Ma).

Naust W, U and S

Seismic correlation shows that dating results from a geotechnical core at the Draugen Field (Haflidason et al. 1991) are incompatible with results from a detailed biostratigraphic study of several exploration wells (Eidvin et al. 1998). The fauna in these wells were correlated with faunal zones from ODP/DSDP drillings in the Norwegian Sea, as these zones are paleomagnetically calibrated. These dating results and ages from some other cores are shown relative to the applied stratigraphy in table 7.1.1.

The study of Eidvin et al. (1998) indicates that Sequence Naust W is older than 2.3 Ma and does not correspond to the results at Draugen, indicating that the uppermost part of Naust W is younger than the Brunhes/ Matuyama boundary (0.78 Ma). Sequence Naust W comprises approximately half of the Naust Formation in the northern areas, and if the suggested age is correct, the depositional rate must have been extremely high in the period 2.8-2.3 Ma.
Both the amino acid ratios and the general seismic stratigraphy indicate that Sequences O and R are younger than 0.4 Ma. This implies that the accumulation rate in the period 0.4-2.3 Ma (Sequences U+S) must have been very small compared to the last 0.4 million years.

Based on a combination of aminostratigraphy and palaeomagnetic data, Haflidason et al. (1991) suggested that the Brunhes/Matuyama (B/M) boundary was at 90 m in the investigated Draugen core. Re-evaluation of the magnetic data shows that the B/M-boundary is between 35 m and 113 m (Haflidason, UiB, pers. comm. 2002). If the B/M-boundary is located in the upper part of this section, above IKU unit I, the age discrepancy between the Draugen borehole and the wells investigated by Eidvin et al. (1998) is much less. The lack of good tie lines from the area of soil borings (Rise and Rokoengen 1991) make the correlation to the regional seismostratigraphic framework uncertain.

The chronostratigraphy in borehole ODP 644A has been seismically tied towards the shelf edge in the Skjoldryggen area, applying a high-resolution boomer line (Svitzer 2002), based on work by Dahlgren et al., (in press). This correlation indicates that unit Naust D (now a sub-unit within Sequence S) represents the oxygen isotope stage 14 (MIS 14, inferred to be 500-600 ka). The base of the Pleistocene fauna zone M-A in well 6607/5-1 (Eidvin et al. 1998) corresponds to horizon Top Naust D (TND), indicating an age of c. 1.7 Ma. Well 6607/5-1 is located at the shelf edge north of Skjoldryggen, and from our database we have not been able to evaluate this large age discrepancy. The upper 70 m of Naust S at boring 6404/5-GB1 seems to be within the Brunhes Normal Polarity Chron, i.e. < 0.78 Ma, Haflidason et al. (1998), (Table 7.1.1).

A fairly high content of angular gravel fragments in cuttings and sidewall cores in the lower Naust Formation (T. Eidvin, pers. comm. 2001) indicates that a glacial environment on the shelf commonly occurred in Late Pliocene time. It is inferred, however, that the first glaciations were small and did not supply glacial debris directly to the shelf edge (Thiede et al. 1989, Heinrich and Baumann 1994, Mangerud et al. 1996).

Deep sea cores show that the input of ice-rafted detritus increased significantly at c. 1 Ma, and that more distinct interglacial-glacial shifts were introduced following 100 ka cycles (Jansen and Sjøholm 1991, Heinrich and Baumann 1994). These observations have commonly been interpreted to correspond to the first major shelf glaciations. If the dates of Eidvin et al. (1998) are correct, this implies that the glacial environment in the Late Pliocene must have been much more severe than earlier inferred from deep-sea cores, and that glaciers frequently brought debris to the shelf edge.

The till found directly above the regional angular unconformity (URU) in boring 8903 in the Troll Field is suggested to be 1.1 Ma (Sejrup et al. 1995). As Naust W is truncated by URU in the northern part of the Norwegian Channel, this sequence is inferred to be older than 1.1 Ma (Fig. 5.2.2B).

Due to the apparent discrepancy of datings relative to the seismic stratigraphy, the proposed ages of Sequences Naust S, U and W in this study (Tab. 7.1.1) are very uncertain. Our age model is illustrated on a vertical section in figure 7.1.1. For comparision, we have outlined age models based mainly on ages given in Haflidason et al. (1991), Eidvin et al. (1998) and Svitzer (2002). Svitzer (2002) based their younger ages on the study by Dahlgren et al., (in press), but we do not know the background for the ages of TNW and TNU.

Table 7.1.1 Proposed ages of sequences defined in this study. Results from various chronostratigraphic investigations are marked with arrows. *1) Eidvin et al. 1998, *2) Haflidason et al. 1998, *3) Haflidason et al. 1991, *4) Dahlgren et al., in press.

Reflectors	Stratigraphy/ proposed age (Ma)	Age (Ma) (from various chronostratigraphic investigations, reference to cores/boreholes)
		c. 0.015 Retreat of ice margin from shelf break
	Weichselian (O) 0.010-0.115	
INO3		c. 0.12 Eemian (MD99-2289, site 20, Smørbukk South)
	Saalian (O) 0.13-0.2	
TNR		
	R1/R2	Ages poorly constrained; indicated from aminostratigraphy in geotechnical boreholes; and interpretation of seismic stratigraphy
INR2		
	Elsterian (R3) 0.2-0.4	
TNS		
	S1&S2	
INS2		< 0.78 (*2) 6404/5-GB1, c. 70 m below TNS
	Naust S 0.4-1.1	1.7 (*1) 6607/5-1, at reflector TND defined by Britsurvey 1999 0.5(*4) Tie from ODP 644A (reflector TND)
TNU		
	Naust U 1.1-1.7	2.3 (*1) 6607/5-1, 150 ms twt above TNW
TNW		2.3 (*1) 6506/12-4
	Naust W 1.7-2.8	0.78 (*3) 6407/5, Draugen
Base Naust		2.6-2.8 (*1) Based on fauna correlation to deep-sea cores
	Kai Fm.	

7.2 Age and soil properties of sediments; summary of information from previous geotechnical boreholes

Smørbukk South Field (Block 6506/12)

The Quaternary geological history and resulting soil conditions of the upper c. 250 ms twt of the Smørbukk South Field on the westernmost part of Haltenbanken was evaluated by Sættem et al. (1996). The study was based on the existing shallow geological framework in the region (King et al. 1987, Mogensen and Rise 1988, Rise and Rokoengen 1991, Rokoengen et al. 1995), including site data and cores from soil investigation boreholes.

The deepest boreholes penetrated c. 100 m below the sea bed, and a high recovery of good quality core was obtained. The uppermost 78 m comprises medium to hard, clayey till with varying shear strength, and has a sharp boundary to underlying, possibly under-consolidated, glaciomarine and marine sediments. A summary of the soil conditions is shown in figure 7.2.2, including a correlation with the established IKU seismic stratigraphy. To explain the varying shear strength of the cored sediments in Smørbukk South, Sættem et al. (1996) proposed a new model for sediment consolidation by freezing of pore water onto the base of the ice sheet.

The amino-acid ratio of 0.087 measured in the warm fauna at 93.5 m below the sea bed (Sejrup and Bratten 1991) corresponded closely to ratios in Eemian sediments in the western Barents Sea and in the North Sea (Knudsen and Sejrup 1988, Sættem et al. 1992). This sample of silty clay was therefore correlated with the Eemian Interglacial. The Eemian level was interpreted to be within the seismically layered part of unit IKU-B, mapped on the outer part of Haltenbanken (Rokoengen et al. 1995). The lithology together with the amino-acid ratios indicate that the units IKU-A (+A1) and -U consist dominantly of tills of late Mid or Late Weichselian age. Sættem et al. (1996) suggested that deposition during Late Weichselian (30-13 ka) was most likely, and that earlier Weichselian ice expansions did not reach across the Smørbukk South area.

The correlation of the Eemian, to lie within the stratified sequence of IKU-B in the present study of Sættem et al. (1992), is consistent with the data from the present project. The detection of Eemian sediments at 19 m depth in the IMAGES core MD99-2289 in the middle slope has been correlated with the regional Intra Naust O3-reflector (previously the Intra Naust A reflector). This reflector can be followed towards the upper slope/outer shelf northwest of Haltenbanken, where it lies within the stratified part of the IKU-B unit.

The seismically massive sub-unit Naust O1/O2 (previously Naust A2, Britsurvey 1999), which is above the Intra Naust O3-reflector in the upper part of the slope, is equivalent to the 'Upper Till' mapped by King et al. (1987) in Skjoldryggen-Trænabanken area, as well as units IKU-A and –U defined in the Haltenbanken area (Rokoengen et al. 1995).

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The deepest boreholes penetrated c. 100 m below the sea bed, and a high recovery of good quality core was obtained. The uppermost 78 m comprises medium to hard, clayey till with varying shear strength, and has a sharp boundary to underlying, possibly under-consolidated, glaciomarine and marine sediments. A summary of the soil conditions is shown in figure 7.2.2, including a correlation with the established IKU seismic stratigraphy. To explain the varying shear strength of the cored sediments in Smørbukk South, Sættem et al. (1996) proposed a new model for sediment consolidation by freezing of pore water onto the base of the ice sheet.

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The correlation of the Eemian, to lie within the stratified sequence of IKU-B in the present study of Sættem et al. (1992), is consistent with the data from the present project. The detection of Eemian sediments at 19 m depth in the IMAGES core MD99-2289 in the middle slope has been correlated with the regional Intra Naust O3-reflector (previously the Intra Naust A reflector). This reflector can be followed towards the upper slope/outer shelf northwest of Haltenbanken, where it lies within the stratified part of the IKU-B unit.

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Smørbukk (alpha) Field (Block 6506/12)

Several soil investigation boreholes have been drilled in the northern part of Block 6506/12, 15-20 km NNW of the Smørbukk Sør boreholes. These boreholes are located at the south-western part of Skjoldryggen, in an area where there are many till tongues. Due to a high content of stones and boulders in a hard matrix, drilling and sampling were found to be very difficult (Mogensen and Rise 1988). Several of the soil units contain boulders larger than 0.5 m.

The undrained shear strength is commonly much higher, shows even larger variations, than at Smørbukk South. The lowest values are found in the upper c. 8 m of unit IKU-U (10-70 kPa), increasing to 150-650 kPa in the lower part of the unit (overconsolidation ratio, OCR, up to 17). The base of unit IKU-U corresponds to a slightly softer layer c. 20-25 m below the sea-bed. In unit IKU-A the undrained shear strength varies mainly in the order of 400-750 kPa, and a decrease in shear strength at c. 60-65 m probably correlates with the base of the Weichselian tills. The sampled upper part of the underlying unit IKU-B shows somewhat higher values (600-950 kPa, OCR 2.5-4).

The University of Bergen has carried out 5 amino acid ratios of foraminifera picked from samples in the longest core 1001A. Table 7.2.1 shows the results and correlations with the established seismostratigraphy (Mogensen and Rise 1988).

Table 7.2.1 Amino-acid values in geotechnical boring 1001A at Smørbukk Alfa, and correlation with the seismostratigraphy.

Depth in core	**Alle/Ile-ratio**	**NGI soil unit**	**IKU-unit**	**Seabed Project unit**
c. 20 m	0.05	II	U (lowest part)	Naust O1 (previous NaustA2)
c. 35 m	0.08	III	A (upper half)	Naust O2 (previous Naust A2)
c. 60 m	0.06	IV	A (lowermost part)	Naust O2 (previous Naust A2)
c. 95 m	0.11	VI	B (middle to upper part)	Naust O4-O7 (previous Naust A1)
c. 100 m	0.17	VII	B (middle to upper part)	Naust O4-O7 (previous Naust A1)

The results confirm the data from Smørbukk South, supporting a Weichselian age of the seismically massive units IKU-U and –A (i.e. tills in Naust unit O1-O2). An indicated Saalian age of the sediments at 95-100 m may be due to glacial reworking of older sediments, but the general seismostratigraphy also supports the suggestion that the thick till wedges in unit IKU-B (or Middle Till) were deposited during the second last glaciation. The results correspond to the interpretation in this project.

Heidrun Field (6507/7)

A summary of the soil conditions of the Heidrun and Midgard Fields have been presented by Mogensen and Rise (1988). The upper 5-10 m at Heidrun (Unit IKU-U) is soft to stiff clay. The undrained shear strength is in the range 50-150 kPa, increasing to 300-800 kPa in the underlying seismically massive unit IKU-A. The Saalian unit IKU-B below is strongly overconsolidated in the upper part where the undrained shear strength is in the range 1000-2000 kPa. In the lower part of the unit the overconsolidation decreases, with undrained shear strengths in the range 300 to 400 kPa. All the units have similar grain-size distributions with poor sorting typical for tills or glaciomarine clays deposited close to the grounding line. Cobbles exist throughout all units. No chronostatigraphic investigations were carried out at Heidrun.

Draugen Field (6407/9)

A number of CPTs and soil borings have been carried out at the platform site at Draugen. The deepest boring is 130 m below the seabed, and has been divided into 8 soil layers (Rise and Rokoengen 1991). A summary of the soil information (NGI-report) and proposed correlation to IKU's regional seismostratigraphy is shown in table 7.2.2. The correlation is uncertain due to a lack of good tie lines from the area with soil borings.

All soil units contain gravel size clasts in a fine-grained matrix, and cobbles occur in several of the layers. Deposition in a dominantly glacial and glaciomarine environment is therefore inferred. In the extremely hard soil unit II, large cobbles and boulders stopped the drilling progress on several occasions.

After the geotechnical testing was completed, the University in Bergen carried out detailed bio- and chronostratigraphic investigations of the remaining sub-samples from the deepest Draugen core (Haflidason et al. 1991). Although the total material available represented only 1.5% of the total length of the core, the detailed analysis contributed important results (Fig. 7.2.2). Based on the interpretation of Haflidason et al. (1991), and comparison with IKU's seismic interpretation close to the borehole, the following conclusions can be made:

1. Except for the upper c. 6 m, the core represents deposits older than the Eemian. The amino-acid ratios indicate that unit IKU-U in some areas in the middle/eastern part of the shelf may include sediments older than Weichselian.

2. Unit IKU-B comprises sediments older than Saalian in the Draugen area. The base of unit IKU-B (at c. 50 m) correlates with an interglacial period.

3. Paleomagnetic investigations indicate that the Brunhes/Matuyama boundary (780 ka) occurs at c. 90 m depth in the core within unit IKU-I. The transition from normal to reversed polarity, combined with a marked step in amino acid values from about 0.3 to 0.4, seems to correlate with an internal reflector in unit IKU-I (Rise and Rokoengen 1991). The resolution of the strontium isotope data is low in the time period studied, but Haflidason et al. (1991) indicate that the interpreted till at the base of the core may be as old as 1.1 Ma. Recent correlation with 3D seismic data shows that the borehole probably did not penetrate the base

of unit IKU-I, which is a pronounced angular unconformity in the Draugen-Njord area (F. Riis, DPD, pers. comm. 2001). According to F. Riis, the angular unconformity has been eroded into a local small depression where the geotechnical borehole was located.

4. The sampled section of unit IKU-I (within Sequence Naust W) contains both till, glaciomarine and normal marine sediments. Two interglacial periods were interpreted within the cored part of this unit. Unit IKU-I pinches out below the outer part of the shelf, but the diachronous reflector at the base continues beyond the present shelf edge. The reflector is about 1000 ms twt below the sea bed at the shelf edge (Fig. 3.2.2, profile 1).

The high-resolution seismic line close to the investigated borehole between Draugen, Njord and the exploration well 6406/8-1 shows that the Draugen area is within the easternmost (lower) part of the Upper Pliocene/Pleistocene prograding clinoforms (Fig. 3.2.2, profile 1). It also shows that an incomplete stratigraphy is preserved compared to locations farther west (Rise and Rokoengen 1991). The prominent angular unconformity at the base of unit IKU-I in the Njord - Draugen area is older than the Upper Regional Unconformity (URU), which is shallow and difficult to interpret in this area.

As horizon TNW is at a higher stratigraphic level than unit IKU-I, the chronostratigraphic data from Draugen indicate that the upper part of Sequence Naust W is of Quaternary age (< 1.7 Ma). These results contradict chronostratigraphic investigations in wells, indicating that Sequence Naust W is older than 2.3 Ma (see Section 7.3).

The Brunhes/Matuyama (B/M) boundary is an important chronostratigraphic marker, and before the revision we asked the University of Bergen to re-evaluate the data. Based only on the magnetic data, the B/M-boundary is located somewhere between 35 m and 113 m (Haflidason, UiB, pers. comm. 2002). The aminostratigraphy does not, however, indicate that the boundary is in the upper part of the section. If it is above IKU Unit I, the apparent age discrepancy to other data would be much less.

Table 7.2.2 Soil conditions at Draugen and proposed correlation with IKU-units.

Average depth interval (m)	Soil unit	Soil unit description	S_u (kPa)	Possible correlation with IKU units
0 to 6	I	Clay, silty, sandy, very soft to medium	10-50	U
6 to 15 (2)	II	Clay, silty sandy, very hard	500-1000	
15 to 17 (2)	III	Clay, silty sandy, very stiff to hard	~200	B
17 to 30	IV	Clay, silty sandy, very hard	400-500	
30 to 48	V	Clay, silty sandy, very stiff	200-500	
48 to 59	VI	Clay, silty very stiff, partly laminated	200-250	I
59 to 94	VII	Clay, silty sandy, very hard	500-1000	
94 to 130 (TD)	VIII	Clay, slilty very hard	450	

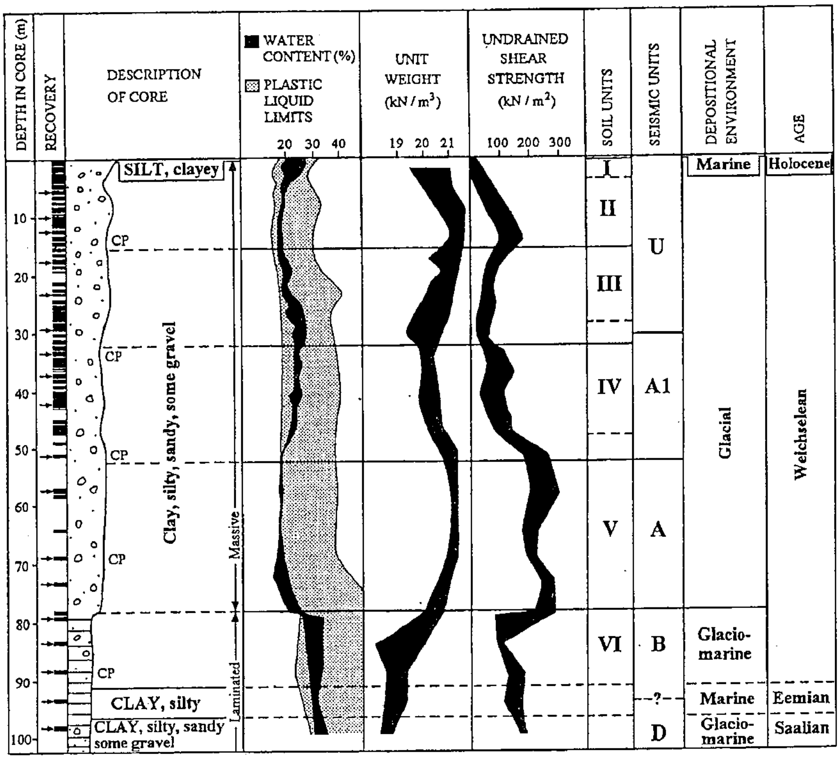


Figure 7.2.1 Summary of geotechnical boreholes in the Smørbukk South Platform area. Seismic units IKU-U, -A1 and A represent Weichselian deposits. Eemian sediments are found within unit IKU-B, corresponding to horizon INO3 in the present report (after Sættem et al. 1996).

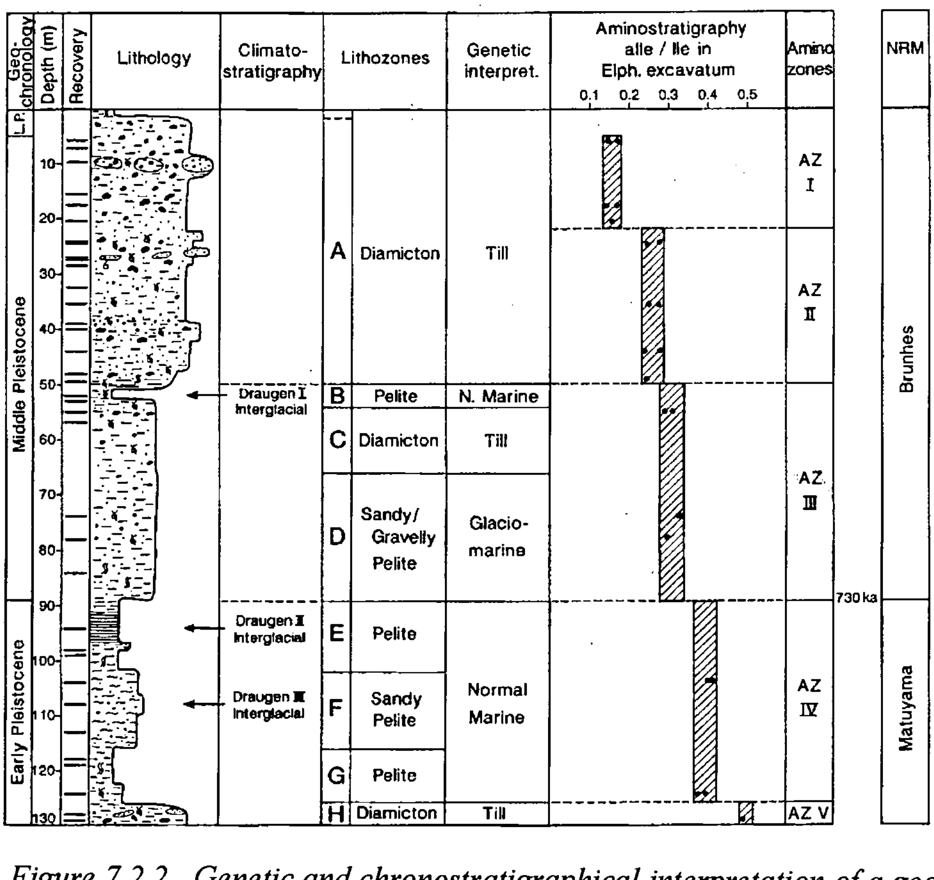


Figure 7.2.2 Genetic and chronostratigraphical interpretation of a geotechnical core at the Draugen platform site (after Haflidason et al. 1991). Lithozones B to H corresponds to unit IKU-I, which in this study is a part of Sequence Naust W.

7.3 Evaluation of age based on biostratigraphic analyses, and correlation with the established seismostratigraphy

In routine biostratigraphic investigations of wells, the upper parts have not been given a high priority, and consequently the dating of Cenozoic sediments is of variable quality. In order to improve the dating of the sediments and interpret the depositional environment based on the microfaunal content, Eidvin et al. (1998) made a detailed study of six exploration wells from the Mid-Norwegian shelf. Emphasis was placed on correlating planktonic fossil fauna with fossil zones from ODP/DSDP drillings in the Norwegian Sea, as these zones are paleomagnetically calibrated. The analyses were based largely on ditch cuttings, but available side-wall cores were also used. Biostratigraphic interpretation and correlation were based mainly on last appearance data (LADs) of the various taxa, but existing side-wall cores have, in some instances, made it possible to record first appearance data (FADs).

Four of the wells are located at or very near seismic lines interpreted in this project, and a summary of the study by Eidvin et al. (1998) is presented below in order to correlate faunal zones and inferred ages with the established seismostratigraphy.

Well 6506/12-4 (Smørbukk Field, 65°12'N, 6°43'E, 256 m below sea level)

This well, located on the Halten Terrace, is situated relatively close to the present shelf edge, and to the Neogene depocenter. An E-W composite seismic line through the well gives a good picture of the geological development (Fig. 5.2.9), and illustrates where the defined faunal zones are located relative to the interpreted reflectors. The interval velocities applied for calculation of depth to the base of the faunal zones in milliseconds twt (Tab. 7.3.1), seem to correspond fairly well to the interpretation of Eidvin et al. (1998).

Table 7.3.1 Correlation of defined faunal zones and interpreted reflectors in well 6506/12-4.

Horizon / defined faunal zone(s)	**Depth below RKB to base of zone (m)**	**Depth interval below sea level (m)**	**Applied velocities (m/s)**	**Calculated interval below sea level (ms twt)**	**Indicated age of defined zone(s)**	**Reflector at or close to base of faunal zone**
Seabed		256	1485	345		
M-A	660	256 – 635	1900	345 - 743	Pleistocene	Top Naust W
M-C	1040	635 – 1015	2000	743 - 1123	L. Pliocene (>2.3 Ma)	
M-D	1480	1115 – 1455	2100	1123 - 1542	L. Pliocene	Base Naust
M-G/-H/-I	1920	1455 – 1895	2200	1542 - 1942	L. Miocene	Mid Miocene unconformity at c. 1800 ms twt
M-L	1960	1895 – 1935		1942 -	L. Oligocene – E. Miocene	

The base of the faunal zone M-D was interpreted to represent the base of the Late Pliocene sediments (Eidvin et al. 1998). With the applied velocities, this level correlates with our interpretation of the Base Naust.

The faunal zone M-C has a characteristic assemblage of foraminifera (*C. grossus*, *N. atlantica* (sinestral), *G. bulloides*) indicating a Late Pliocene age, but older than 2.3 Ma. As the faunal zone M-B is not present, the youngest part of the Late Pliocene is not recorded in well 6506/12-4. The top of the Upper Pliocene sediments in this well correlates with the regional reflector Top Naust W, which in this area is developed as an apparent angular unconformity just east of the palaeo-shelf break (see Fig. 5.2.9). The erosional character of the reflector may explain that the uppermost part of the Upper Pliocene sediments has been removed.

The uppermost faunal zone M-A has been recorded from c. 340 m (uppermost investigated sample) to c. 630 m below sea level. The zone contains an assemblage indicating a Pleistocene age (younger than 1.7 Ma).

Well 6607/5-1 (66°38′N, 7°32′E, 368 m below sea level)

This well on the Utgard High is also situated close to the Neogene depocenter. A composite seismic line from the Vema Dome, through the wells 6607/5-2 and -1 near the present shelf edge, and the well 6610/7-1 at the eastern part of Trænabanken, illustrates the geological development (Fig. 5.2.14). In some intervals, check shot data and sonic logs were applied for calculation of the depth (ms twt) to the base of the faunal zones (see * in Tab. 7.3.2).

Table 7.3.2 Correlation of defined faunal zones and interpreted reflectors in well 6607/5-1.

Horizon / defined faunal zone(s)	**Depth below RKB to base of zone (m)**	**Depth interval below sea level (m)**	**Applied velocities (m/s)**	**Calculated interval below sea level (ms twt)**	**Indicated age of defined zone(s)**	**Reflector at or close to base of faunal zone**
Seabed		368	1485	496		
M-A	960	368 – 933	2000	496 - 1061	Pleistocene	Top Naust D
M-B	1220	933 - 1193	2175	1061- 1300*	L. Pliocene	Base IKU-E
M-C	2020	1193 - 1993	2540	1300- 1930*	L. Pliocene (>2.3 Ma)	Base Naust
M-H/-I/-J	2382	1993 - 2355	2400	1930 - 2232	L. Miocene	M. Miocene Unc. ('base Kai Formation')
M-K	2448	2355 - 2421			M. Miocene	
M-N	2520	2421 - 2493			E. – M. Eocene	

Our interpretation of Base Naust corresponds with the base of the Late Pliocene faunal zone M-C at 1.93 s. twt. The boundary between the Late Pliocene faunal zones M-C and M-B corresponds to 1.30 s. twt, correlating with reflector Base IKU-E (Rokoengen et al. 1995). Base IKU-E is within Sequence Naust U. According to Eidvin et al. (1998) all sediments deposited below this reflector should therefore be older than 2.3 Ma. It should be noted that horizon TNW occurs c. 150 ms twt below this reflector. Although no velocity survey has been carried out in the upper part of the well, the base of the Pleistocene faunal zone M-A (younger than 1.7 Ma) seems to correspond or be close to reflector Top Naust D (Britsurvey 1999).

Well 6607/5-2 (66°41'N, 7°21'E, 523 m below sea level)

This well, on the Utgard High, is located some kilometres WNW of well 6607/5-1 (Fig. 5.2.14). Only a few samples were taken in the upper part of the well, but the faunal zone M-C (Late Pliocene) was recorded above a level corresponding to 2.25 s. twt (2295 m below sea level).

The interval 2295-2345 m below sea level was of Early to Mid Eocene age, indicating that the Upper Miocene Kai Formation pinches rapidly out west of well 6607/5-1.

Well 6610/7-1 (66°17'N, 10°16'E, 265 m below sea level)

Well 6610/7-1, on the Nordland ridge, was analysed because it penetrated the proximal and oldest parts of the Upper Pliocene deposits. This well also penetrates the underlying Lower Oligocene deposits. In some intervals, check shot data and sonic logs were used for calculation of the depth (ms twt) to the base of the faunal zones (see in * in Tab. 7.3.3). Comparison of the well data and the seismics is illustrated in Fig. 5.2.14.

Table 7.3.3 Correlation of defined faunal zones and interpreted reflectors in well 6610/7-1.

Horizon / defined faunal zone(s)	**Depth below RKB to base of zone (m)**	**Depth interval below sea level (m)**	**Applied velocities (m/s)**	**Calculated interval below sea level (ms twt)**	**Indicated age of defined zone(s)**	**Reflector at or close to base of faunal zone**
Seabed		265		357		
M-E	<710-830	<685 - 805			L. Pliocene	
M-F	830-890	805 - 865		– 874*	L. Pliocene	Base Naust
No defined zone	890-970	865 - 945		874 – 943*	E. Oligocene	
M-N	970->1090	945 - >1065		943 -	E.-M. Eocene	

The interpretation of the Base Naust coincides closely to the top of the Lower Oligocene sands in the Molo Formation.

The occurrence of *C. grossus*, *E. hannai*, *G. bulloides* and *N. atlantica* (sinestral) in the faunal zone M-E indicates that this zone is of Late Pliocene age, but older than 2.3 Ma (Eidvin et al. 1998). The base of Zone M-F coincides with Base Naust.

8. MASS-WASTING PROCESSES

The Storegga Slide was identified by Bugge (1983) as one of the world's largest slides (Fig. 8.1), and described as a result of three slide events (Bugge et al. 1987, 1988). Slide I was the largest, and interpreted to have taken place more than 30,000 years ago. Slides II was approximately half the size of Slide I and occurred c. 7200 ^{14}C years ago, while Slide III was a smaller event that took place soon after Slide II. Recent studies show, however, that the Storegga Slide, most likely took place in one event c. 8000 calendar years ago, creating three slide scarps 1, 2 and 3 (Norsk Hydro 2001). The slide probably initiated in the deeper parts, perhaps beyond scarp 3, and developed retrogressively, forming scarps 2 and 1. The various scarps show shifts between different detachment levels, indicating that various weak layers acted as slip planes during the development of the slide. In general the slide stepped up to higher stratigraphic horizons (slip planes) towards east. The inclination map of the mid-Norwegian margin shows that the slopes in the Storegga area in general are steeper than in the adjacent areas (Fig. 8.2).

The central parts of the Storegga Slide display an extremely rough topography (Fig. 8.1, Encl. 2), and since much of the older deposits have been removed or are strongly disturbed, only parts of the geological history before sliding can be portrayed. North of the central and deeply incised slide area, where stratified sediments in sub-unit O3 (including Eemian sediments) commonly acted as the main slip plane, it is possible to put the Storegga Slide in a large-scale geological context. It is evident that the Storegga Slide is the last of several major slide events in the region. Although mapping of previous slides is not a topic of this report, we will try to relate some of the observations to the general development of the shelf margin in this area.

8.1 Outer shelf topography and relation to the stratigraphy

A composite high resolution seismic line located slightly east of the present shelf edge illustrates the stratigraphy on the outer part of the shelf (Fig. 5.2.17). The line runs from east of the northeast corner of the Storegga Slide and southwards, crossing the shallow banks of Buagrunnen and Langgrunna. The outer part of the shelf is deepest from Frøybankhola and towards the northern end of the profile, and in this area Late Weichselian tills in the order of 130-200 ms twt thick occur. These deposits become thinner west of the shelf edge and were partly displaced by the Storegga Slide. Frøybankhola seems mainly to relate to strong glacial erosion during a late Weichselian ice advance. Saalian glacigenic deposits are absent in the northern part of the profile, as the ice sheet did not extend to the shelf edge between Skjoldryggen and Frøyabankhola.

The outermost part of Frøyabanken (between Frøyabankhola and Buagrunnen) is shallower, mainly due to deposition of thick Saalian tills on the outer shelf (Figs. 8.1, 8.1.1). The Weichselian deposits above are much thinner than in the western Haltenbanken area. The Saalian deposits are up to 270 ms twt thick also west of the shelf break, and comprise numerous lenses of glacigenic debris-flow deposits. Most of the deposits are made up of unit O5, or the 'Buadjupet Fan'. The thickness decreases downslope, and the unit pinches out in the middle – lower part of the slope. It seems likely that an active ice-drainage system between Frøyabanken – Buagrunnen region supplied glacigenic debris to the outer shelf and slope (Figs. 6.3.2, 6.4.3). In Buadjupet, the Saalian deposits are locally eroded (Fig. 8.1.1), but reappear as a wedge at the outer shelf at Buagrunnen and farther south (Fig. 5.2.17).

Buagrunnen has been a shallow bank during a long period, and Langgrunna seems to have been shallow throughout the entire Naust time (Fig. 5.2.17). The geology of the area from Buagrunnen and southwards is complex, and several strong glacial erosion events on the shelf make it difficult to map units and outline the glacial history. The sediments above the angular unconformity are thinner than further north (Figs. 5.2.4, 5.2.15), but interpretation along the shelf break indicates that the shallow Møre shelf was glaciated many times during the last three-four glaciations. Several erosional reflectors show that the transverse shelf trough Onadjupet (between Buadjupet and Langgrunna) acted as a path for ice streams during several glaciations. Strong glacial erosion at the shelf edge during the Weichselian indicates that the ice sheet possibly was much thicker in the outer part of the Møre shelf, than further north where the shelf is much wider.

8.2 Mass wasting in the Storegga Slide Complex

Early work in the Seabed Project as well as other studies indicated a complex and longer-term slide history in the vicinity of the Storegga Slide (Evans et al. 1996; King et al. 1996; McNeill et al. 1998). New seismic data confirmed and provided support for this view of a long-term history of sliding events, and the term 'Storegga Slide Complex' was introduced by Britsurvey (1999). The data showed that several Naust units at depth within the Storegga Slide scar were at least partly formed of slide/slump deposits. The history of sliding dates back to Naust Unit W times, and possibly back to Kai Formation times (Britsurvey 1999).

Britsurvey (1999) mapped two large palaeo-slides beneath the northeastern part of the Storegga Slide and close to its northern flank (Pslide_2 and Pslide_3). The slide scarps are close to the head-/sidewall of the Storegga slide, and the slide events were regarded as early movements of the Storegga Slide Complex. On some seismic profiles at the northern flank of the Storegga slide, the slide scarps can be seen c. 7 km to the north of the Storegga Slide (Figs. 8.2.1, 8.2.2). In this area, another younger and smaller slide event was recognized (Pslide_1). This palaeoslide is located approximately 10 kilometers north-east of a similar feature identified by Evans et al. (1996). The data coverage did not allow checking of the relative age of these events (Britsurvey 1999).

The time structure map of the base of thick stratified sediments in Sequence R (horizon INR2) shows an uneven surface (Norsk Hydro, 2001). The Storegga slide has cut a large area of the central part of the INR2-surface, but the surface was inferred to represent a major slide event. Norsk Hydro (2001) did not make any attempt to correlate to Britsurvey's slide events, but the present study indicates that the 'Naust R-slide' correlates with Pslide_2 (Britsurvey 1999).

A time structure map of horizon INS2, at the base an older thick contouritic deposit in the eastern slope, shows several slide scars along the slope (Norsk Hydro 2001). The width of each slide scar is in the order of 25 km and the cut depth in the order of 200 m. This Intra Naust S slide ('Naust S-slide') covers an area similar to the present Storegga Slide, but the slide(s) were not correlated to previous observed slides.

Several seismic lines of very high resolution collected in 2001 made it possible to obtain an improved large-scale view of the sliding history in the northern part of the Storegga Slide, and to relate the slides to other depositional processes on the slopes. A profile from the northern flank of the Storegga Slide to the basin (Fig. 8.2.1) convincingly shows that four major slides have accumulated in this part of the basin after Naust W times. Thick slide deposits probably also accumulated earlier in the basin. Like the Storegga Slide, all the slide deposits apparently thicken in the basin, being 50-200 ms twt thick. Some units in the central part of the basin may be remnants of slide deposits, eroded by younger slides. The interpretation is uncertain however, and the sediments could also be remnants of debris-flows. Stratified sediments in the slopes, can partly be followed into the basin where they thins or are totally eroded by slides. Only the stratified sediments of Unit R1/R2 can with confidence be followed from the eastern slope to the northern flank of the Storegga Slide.

Slide scarps in the eastern slope

The headwall of the Storegga Slide is commonly easily recognised on the E-W seismic profiles (Fig. 8.3.2). Although the quality of several of the seismic lines is high, it is often difficult to interpret the headwall and slide scarps of the older slides in the eastern slope. To distinguish between glacigenic debris-flow deposits and slide deposits is therefore often difficult. The distribution of the contourites which preferentially infill the depressions has been a guide to recognize the slide scars and the different slide deposits. Below Sequence Naust S, stratified sediments are commonly thin or absent, and we have not been able to relate the inferred slide deposits in the basin to evident slide scars. These sediments may therefore represent low-density debris-flows accumulating in the deep part of the basin. As the units appear as thick massive sediment bodies nearly without internal layering, similar to the units above which are related to slide scars, we believe that this interpretation is more unlikely.

Slide scarps in the northern slope

Several slide scars are seen in the northern flank of the Storegga Slide (Fig. 8.2.1). In this area, apparently continuous hemipelagic/contouritic sedimentation through the entire Naust period has only been interrupted by some sliding events. Three slide scars corresponding to slides of different age occur at nearly the same location, c. 10 km north of the Storegga Slide (Fig. 8.2.2). It should be noted that pronounced bright spot reflections are evident beneath the oldest of these slide scars, and that a bottom simulating reflector (BSR) is present within the stratified sediments between this slide and the slide above.

The youngest event is a very small slide (previous denoted as Pslide_1), probably a local event only affecting a small area on the northern flank. The slide scar below is the northernmost evidence of a regional major slide event; its slide deposits can be followed across the basin to the eastern slope. This slide has been mapped as Pslide_2 by Britsurvey (1999), and corresponds to the 'R-Slide' (Norsk Hydro 2001). The slide deposits are up to 200 ms twt thick in the northern part of the basin, and three slide scarps illustrate that the sequence of sliding stepped up to shallower stratigraphic horizons (slip planes) towards the north where the slide terminated. An older slide also represents a major sliding event, probably correlating to Pslide_3 (Britsurvey 1999). We have not been able to follow this slide confidently to the eastern slope, but the apparent stratigraphic position indicates that it may correspond to the 'S-Slide' (Norsk Hydro 2001). Slide escarpments in the central part of the basin, as well as deformation features, indicate that the slide had a significant impact on the subsurface and removed parts of older slide sediments or debris-flow deposits in the basin (Fig. 8.2.1).

Directly south of an old slide scarp (Fig. 8.2.1), massive sediments in the order of 30-100 ms twt thick are found above Top Naust W (TNW). In the basin TNW seems to represent the surface of very thick and extensive slide deposits. As described below, several slide scars have been formed (close to TNW time) into dipping strata below the outer shelf east of the Storegga Slide.

8.3 Stratified sediments ('contourites')

The main controls on sedimentation in the slope area have been extensive glaciations, mass wasting processes, and deep-water circulation. Warm Atlantic water moving northward as the Norwegian Current, is important for the slope-parallel processes on the Norwegian Margin. This current is influenced by the climatic cycles, with reduced flow in glacial periods as the oceanic polar front moved southwards. The warm northward-flowing Norwegian Current consequently had an increased flow during interglacials (Heinrich and Baumann 1994).

Three or four sub-units of stratified sediments are found beneath the middle-lower slope in the northeastern part of the Storegga Slide (Fig. 8.2.3). The sediments commonly have a convex or mounded geometry, often showing both onlapping and downlapping termination of reflections. The deposits often display a moat channel where they terminate upslope, and resemble contouritic sediment bodies as described by Faugères et al. (1993). The currents in the upper slope probably were strong enough to erode, or to transport sediment particles, probably over long distances. Deposition occurred in areas where the current velocity decreased, but as some of the stratified sediments can be followed in the deep part of the basin, hemipelagic sedimentation also had a certain importance.

Particularly during early deglaciation phases plume glaciomarine sedimentation possibly occurred. This is documented by radiocarbon dates in sediments lying stratigraphically above the youngest till-tongue in the upper slope just north of the Storegga Slide (Hjelstuen et al. in prep.). A very high sedimentation rate between c. 15,000 and 16,000 ^{14}C-years ago is indicated by the IMAGES core MD99-2291 at 575 m water depth (Fig. 8.3.1A). The grain size distribution shows a marked upward shift to more fine-grained sediments at c. 15,500 BP. A corresponding change in the seismic character from stratified to homogeneous/transparent is evident on the deep towed boomer records. An isochron map representing the early deglaciation period (15.0-15.7 ka) shows a depo-center in the upper slope (Fig. 8.3.1B).

Also during some periods when the ice sheet did not expand to the shelf edge, a high flux of suspended glaciomarine material could have resulted in a fairly large hemipelagic input of sediments to the slope. The so-called contourites may therefore represent sediments of a 'mixed' source origin, but mainly deposited in the long periods between the most extensive glaciations.

Detailed mapping of the two thickest contourites, above the INS2- and INR2-slide surfaces, has shown that the sediments preferentially infill slide scars and other depressions (Norsk Hydro, 2001). This is best illustrated in seismic lines run parallel to the slope contours (Fig. 8.3.2). Borings show that the contouritic sediments have much higher water contents and are more fine-grained than the debris-flow deposits. The distinct seismic character of horizon TNR at the interface between debris-flow deposits in Sequence O and the contourites in Sequence R below, is caused by a sharp decrease in density and velocity. No distinct change, however, can be detected in the undrained shear-strength values.

8.4 Old slide features beneath the outer shelf

All the shelf profiles in this project have been examined for evidence of major sliding events. As most of these profiles are of limited resolution and the grid is very open, we suggest that some major slide events may remain undetected.

At least two candidates for slide events, close to reflector TNW, were found on the N-S composite high-resolution profile on the outer shelf (Fig. 5.2.17). Just north of the present Buadjupet, a 10 km-wide slide scar cuts at least 200 ms twt into the existing slope sediments (Fig. 8.1.1). Alternative interpretations of the continuation of this deep slide scar are possible. It may represent a local slide event, but tentatively we suggest that it correlates with a slide farther north beneath Frøyabankhola. If correct, this slide scar may be part of a regional slide event. Although the slide scars beneath Frøyabankhola are fairly small, this slide appears to erode older units. The erosional surface can be tied to an uneven reflector slightly above TNW seen on the parallel line NH 9753-302B in the upper part of the slope, and we suggest that this uneven surface may represent a major slide event that occurred close to TNW time.

At outer Frøyabanken, a possible palaeo slide has been observed in Sequence Naust W. On seismic profile MB 15-84 (Fig. 8.4.1A), an approximately 25-30 km-wide and 200 ms twt-deep channel-like depression occurs. The strong reflector at the base of the 'channel' dips towards west/northwest, and reaches a depth of c. 1.4 s twt near the present shelf edge. It is truncated by the Upper Regional Unconformity (URU) c. 10 km east of MB 15-84 (Fig. 8.4.1B). The extent of the possible slide scar is poorly constrained due to the width of the seismic grid.

8.5 Age estimate of slides (eastern slope) and relation to peak glaciations

The slide scars of 'Slide S' have been mapped by Norsk Hydro (2001). Although the side walls of this slide are clearly seen, it is difficult to recognize the back walls. The relationship between the last glaciation in Sequence S and the 'S-slide' is therefore somewhat uncertain, although it seems likely that the slide occurred some time after the last extensive glaciation in

Sequence Naust S. Up to 60-70 m-thick contourites infilling the slide scars indicate that a long ice-free period occurred after the sliding. As the age of the sediments is uncertain, the age estimation of the S-slide is also speculative.

The glacigenic debris-flow deposits in unit R3 above (Fig. 8.3.2) are, in this report, tentatively assigned to the third last glaciation ('Elsterian'), but some data indicate that the sediments may also represent an even older glaciation. The 'dating' methods are uncertain, however, and an age range of 200-400 ka is proposed (Norsk Hydro 2001). Although the slide scars in the eastern slope are vague compared to the Storegga slide, it is evident that these glacigenic sediments were subject to a major sliding event ('R-slide', Pslide_2). The seismic interpretation indicates that the slide occurred some time after the last 'Elsterian' glaciation, but it is impossible to be specific about the timing. After the slide event, stratified sediments (unit R1/R2) were deposited on the slope, preferentially infilling slide scars (Norsk Hydro 2001). It seems likely that a fairly long period was necessary in order to deposit the up to 200 ms twt-thick sequence, and the sediments may represent two glacial-interglacial cycles. There are no signs of instability features in these sediments, and we believe that no major slide event occurred in the basin during this period.

On the slope west of Frøyabankhola – Buagrunnen, glacigenic debris-flow deposits up to 270 ms twt thick of Saalian age were deposited above the stratified sediments (subunits R1/R2). A Saalian age for these sediments is supported by the general seismic stratigraphy, and a verified Eemian age of sediments directly above (corresponding to reflector INO3 in boreholes 20 and 22, Haflidason et al. 2001). We do not know when exactly during the Saalian period (c. 130-200 ka) the most extensive glaciation(s) occurred, but although this glaciation was large, there is no evidence of major sliding after it ended.

The inferred ages of Sequence Naust R, together with the thick unit R1/R2, indicate that the 'R-slide' is older than 250 000 years. Before the Storegga Slide there may, thus, have been a period of 250 000-350 000 years without major slide events in this region. However, the Tampen slide located at the North Sea Fan (Figs. 5.2.2, 5.2.3) is interpreted to be an early Weichselian event (Britsurvey 1999).

Thick stratified sediments separating the slide deposits, both at the base of the northern slope and in the eastern slope, show that at least the last three major slides were cyclic events. Although the large slides most likely were related to peak glaciations or processes connected to the deglaciation, the frequency of major slides seems to be much lower than the frequency of glaciations. The general seismic stratigraphy, with the evidence of thick contourites filling in the deep slide scars, indicates that sliding occurred some time after a peak glaciation. An important observation supporting this view is that no slides are found within the thick contourites in the eastern slope.

8.6 Age estimates of slides and reflectors north of the Storegga Slide

The very high resolution of the seismic lines acquired in 2001 permits an indirect age estimate to be made for horizons and slides north of the Storegga Slide. As mentioned earlier the slides Pslide_1, Pslide_2 and Pslide_3 are located in the same area on line NH0163-301, c. 7 km to the north of the Storegga Slide. The slides are sharply defined as they occur where stratified sediments apparently have been deposited throughout the entire Naust period. The location is close to where Eemian sediments were found in the IMAGES core MD99-2289 (horizon INO3), and we have applied the interpreted horizon INO3 as a reference level for esimation of ages. We did not have deep towed boomer data available for tie of the INO3-horizon, and these data should be utilized for an improved correlation. The depositional rate has probably varied frequently, but due to lack of data, we applied a constant depositional rate throughout the entire Naust period in order to estimate 'age 1' in table 8.6.1 (equal to the depositional rate during the last 125,000 years, i.e. Eemian to recent).

The reference point for measurements was chosen where profiles NH0163-301 and NH9651-202 intersect being close to the three northernmost slide scars. The geotechnical boring 6404/5-GB1 (terminated 309 m below the seabed) is located at the intersection, and permits comparison with previous chronostratigraphic investigations. Table 8.6.1 illustrates the depth to different interpreted horizons, as well as the depth to the first reflector that apparently continues 'unbroken' above each of the slide scars or slides.

The described approximate age determination approach, results in 'ages 1' are probably too high in the upper part and too low in the lower part. Palaeomagnetic investigations revealed that all tested samples in the boring fall within the Brunhes Chron, indicating an age younger than 780 ka (Haflidason et al. 1998). The age of the Naust Formation is c. 2.8 Ma, indicating that the average depositional rate applied is too high, and that lower depositional rates should have been used for the lower part of the stratigraphy.

The results from the IMAGES core, on the other hand, show that the ages suggested by Haflidason et al. (1998) for core 6404/5-GB1 are too young. Amino-acid values in the 'Saalian window' (0.17-0.25) were found in the interval 140-210 m in the core, but this interval must represent Elsterian or older sediments.

Depositional rates have varied, and the 'ages' listed in table 8.6.1 only represent speculative ages. If one assumes that the depositional rate in the period between Eemian and the time of Pslide_3 was 50% higher than during Eemian to Recent, an interval of c. 80 000 years exists between the small Pslide_1 and the Pslide_2 ('age 2'). Similarly, the period between the two major slide events, Pslide_2 and Pslide_3, will be c. 300,000 years. In order to achieve an age of 2.8 Ma at Base Naust, we reduced the depositional rate for the period between Pslide_3 and Base Naust to only 50% of that of the period following the Eemian.

Although the absolute age is uncertain, this simple approach for age estimation at the northern flank indicates that there was a period of at least 300,000 years between the Storegga Slide and the second last major slide in the Storegga Slide Complex. The period between the Pslide_2 and Pslide_3 was probably similar.

Table 8.6.1 Calculation of tentative 'ages' based on two different assumptions of depositional rate

Horizon/level	Depth twtt (ms)	Interval velocity (m/s)	Calculated depth below seabed (m)	Age 1 * (years)	Age 2 ** (years)
Seabed	1307		0	0	0
		1530			
INO3	1366		45	125 000	125 000
		1580			
TNR	1452		113	315 000	250 000
		1600			
Top Pslide_1	1474		131	365 000	285 000
		1600			
Top Pslide_2	1531		176	485 000	365 000
		1620			
TNS	1609		238	660 000	480 000
		1620			
TD 6404/5-GB1	1700		312 (309)	860 000	615 000
		1650			
Top Pslide_3	1740		345	960 000	680 000
		1750			
TNW	2034		602	1 670 000	2 100,000
		1800			
Base Naust	2184		737	2 050 000	2 850 000

* Age 1: Accumulation rate constant, equal to the last c. 125,000 years (post Eemian)
** Age 2: Accumulation rate in the period between Eemian and the time of Pslide_3 assumed to be 50% higher than for the post Eemian period. The rate before Pslide_3 was set to half of the post Eemian period, in order to obtain a 'correct' age of base Naust.

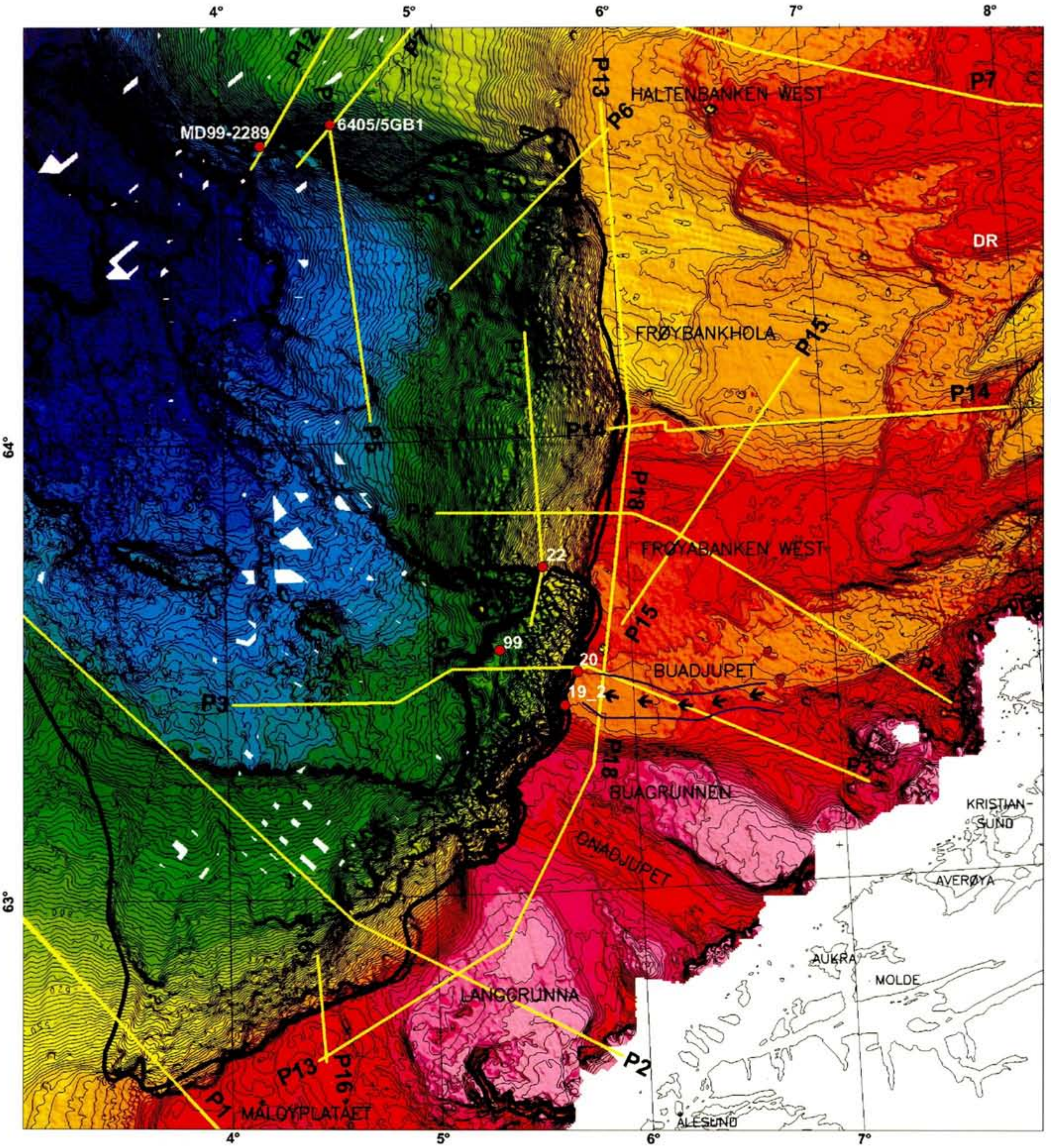


Figure 8.1 Bathymetric map of the eastern part of the Storegga Slide area. Presented seismic profiles and geotechnical boring sites are shown. The arrows mark a burried channel (see Fig. 8.1.1). See table 5.2.1 for reference to the seismic lines applied.

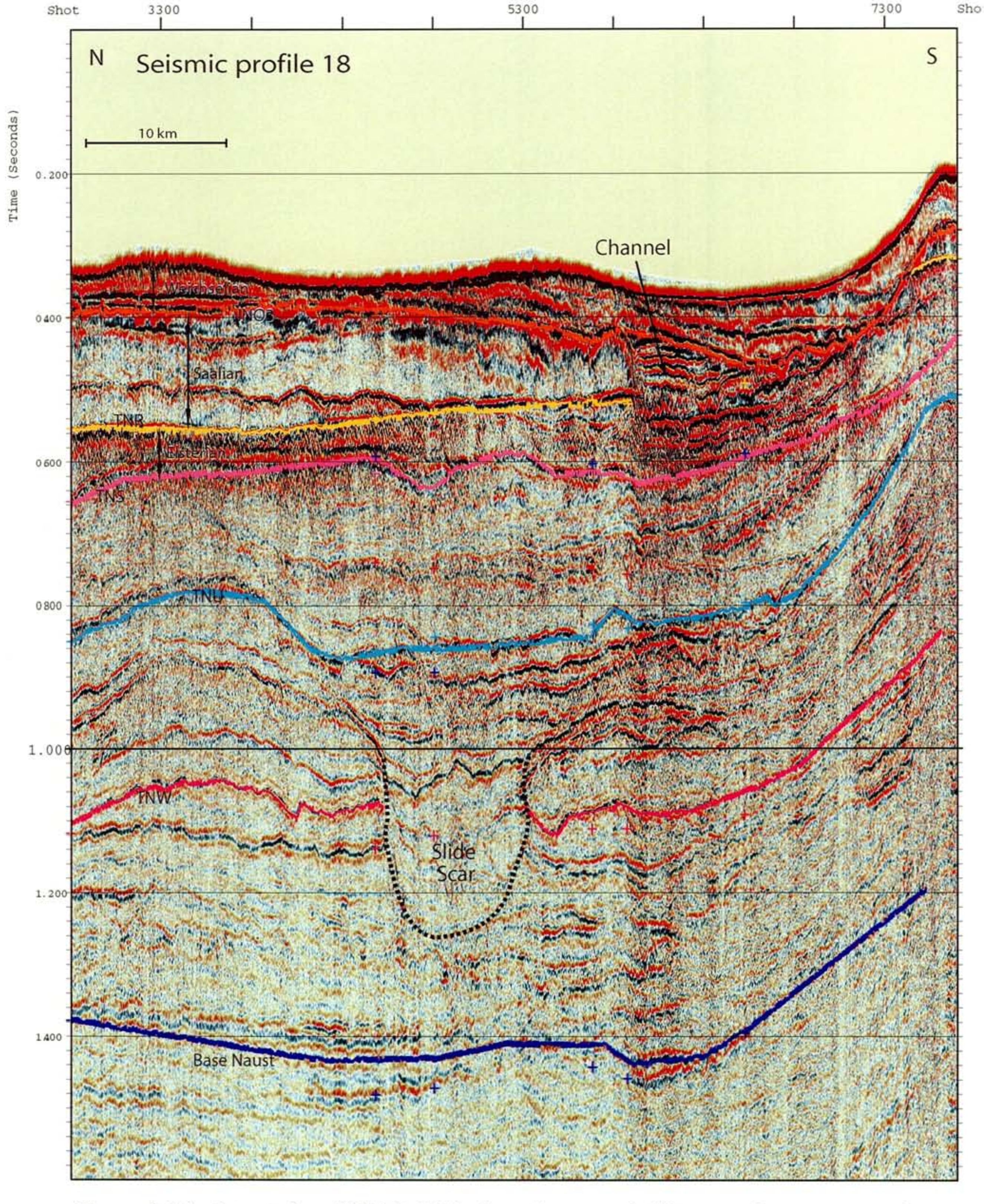


Figure 8.1.1 Seismic line NH0163-1303 along the outer shelf between Buagrunnen and Frøyabanken west (northern end). Note the infilled subglacial channel of Late Saalian age and the slide scar near the TNW horizon. The line segment is a part of profile 13 (Fig. 5.2.17B). See figure 8.1 for location.

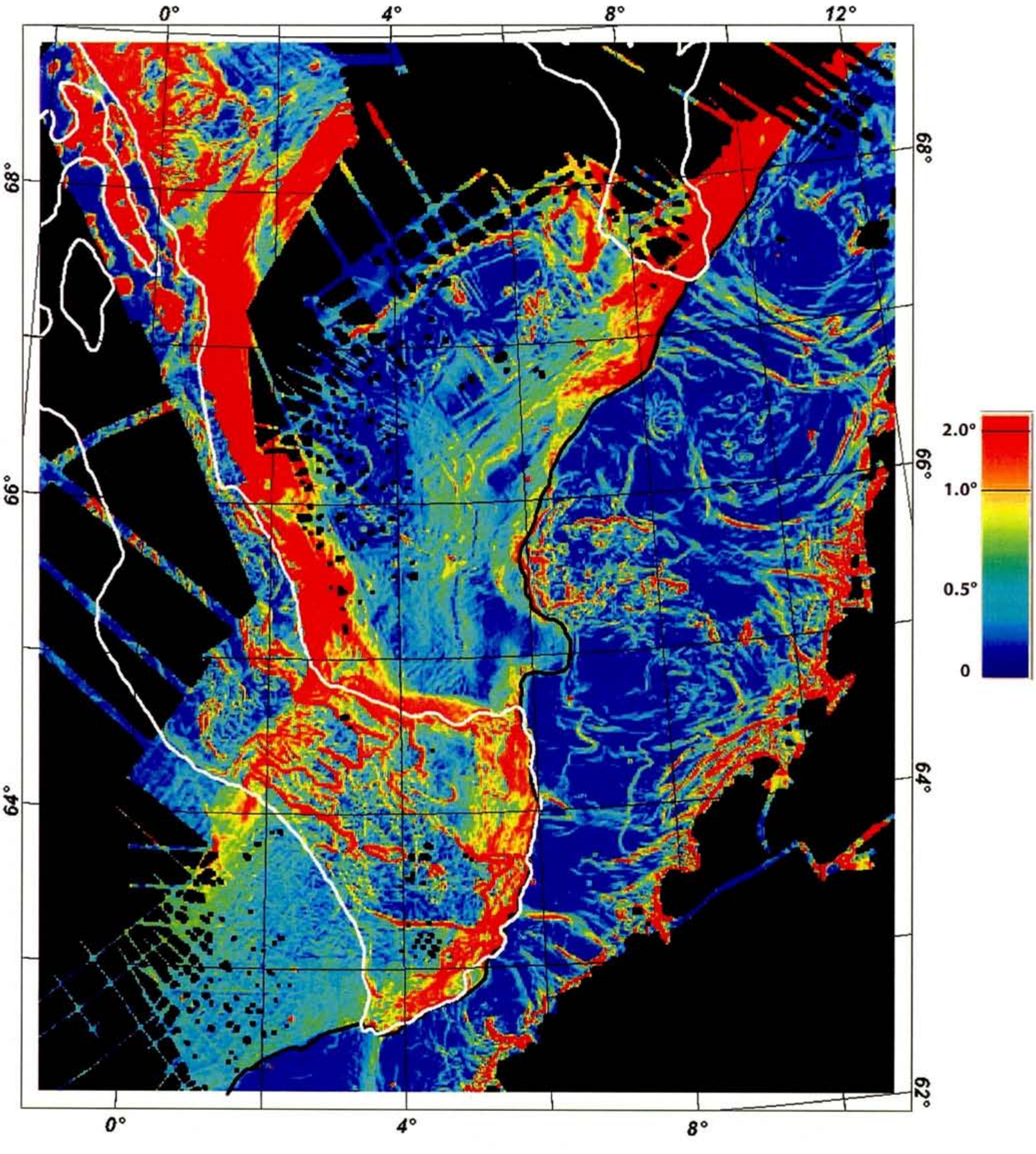


Figure 8.2 Slope inclination map of the mid-Norwegian margin.

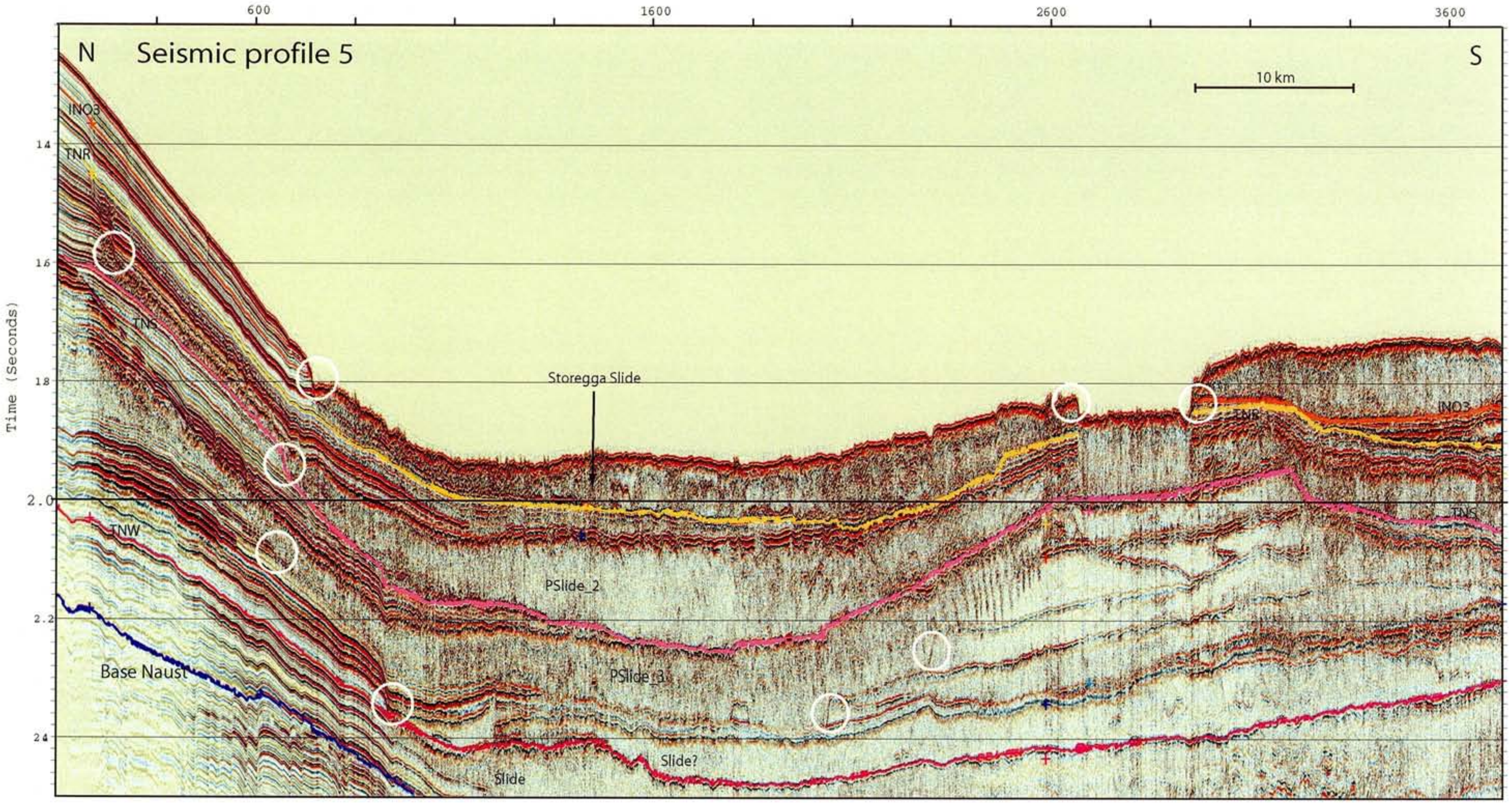


Figure 8.2.1 Seismic profile NH0163-301 from the northern flank of the Storegga Slide and southwards, showing that deposits from several major slides accumulated in the basin. In the northern part of the basin, the slide deposits are interbedded with stratified sediments, indicating that the slides represent cyclic events. Slide scars are shown with circles. See figure 8.1 for location.

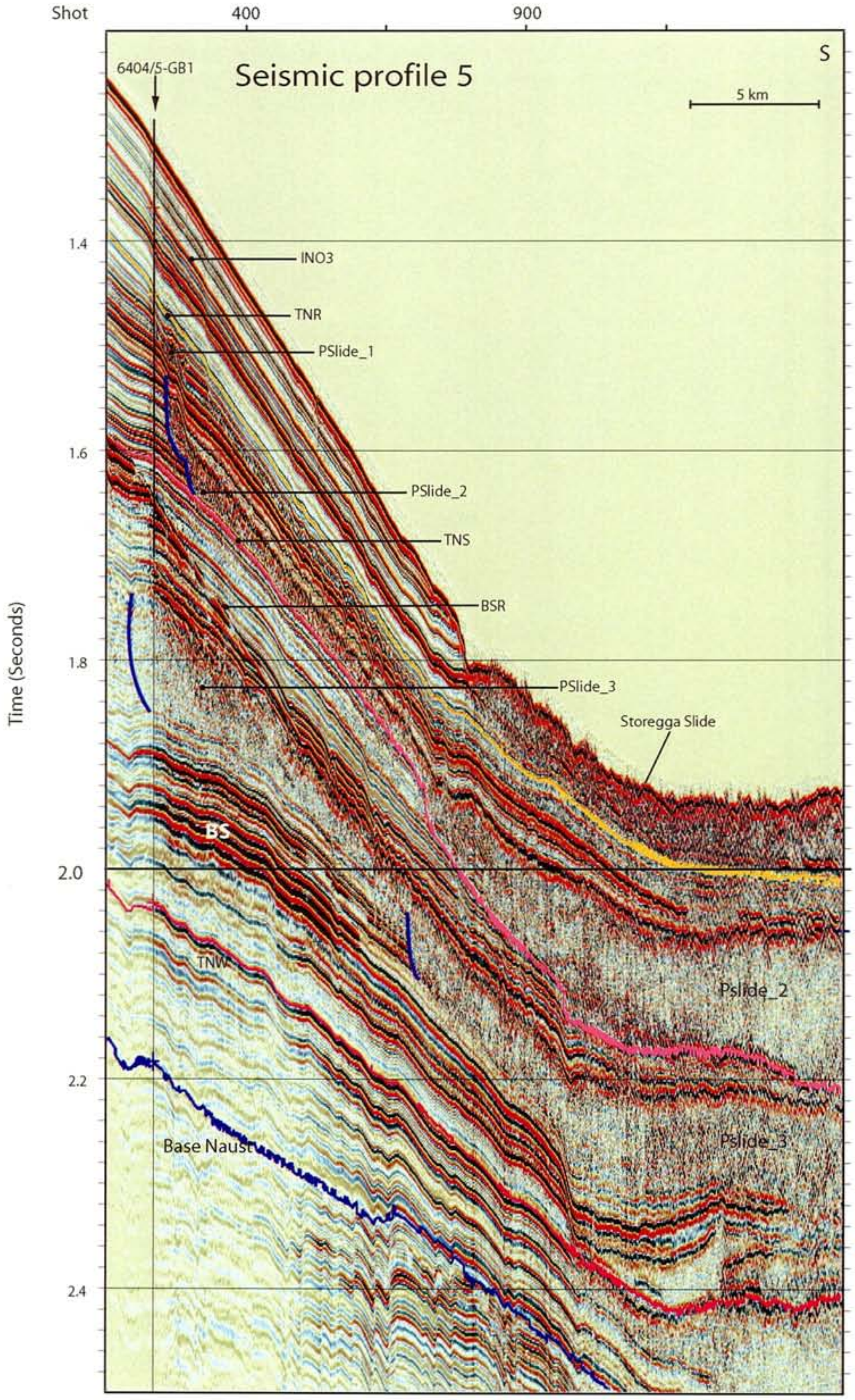


Figure 8.2.2 Seismic profile NH0163-301 at the northern flank of the Storegga area, showing that two major slides extended farther north than the Storegga Slide. The northernmost slide scars of three separate slides are located close to each other, in an area where a Bottom Simulating Reflector (BSR) and bright spot reflections (BS) occur. An indirect age approach using the INO3-horison (Eemian, i.e. c. 125,000 years) as a reference level, indicate an age interval of at least 300,000 years between major slide events. See figure 8.1 for location, and table 8.6.1 for calculation of 'ages'.

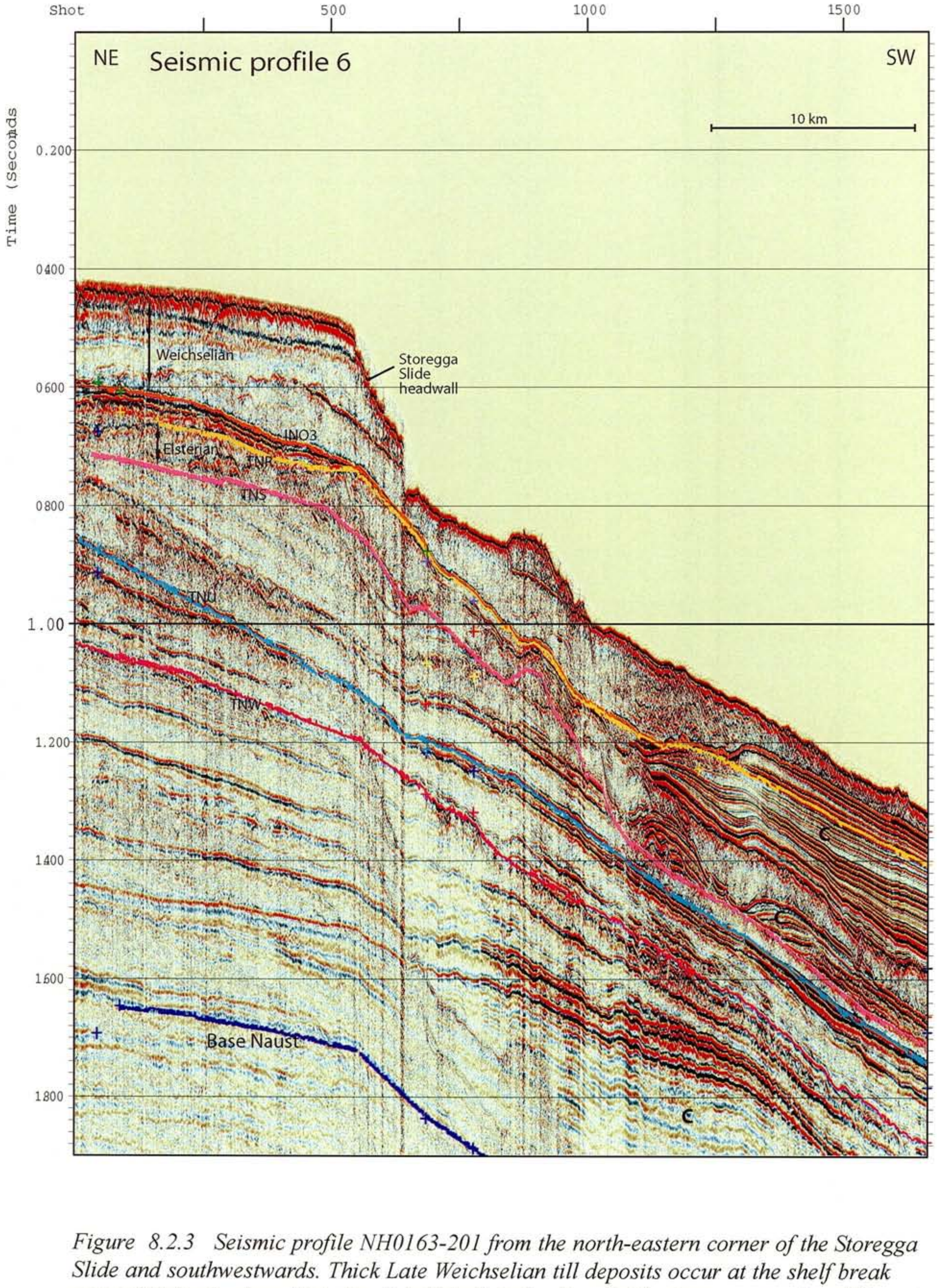


Figure 8.2.3 Seismic profile NH0163-201 from the north-eastern corner of the Storegga Slide and southwestwards. Thick Late Weichselian till deposits occur at the shelf break west of Haltenbanken. Note the slided block, indicating that horizons separating different till tongues may act as glide planes. The mounded contourites (C) occur at different intervals. See figure 8.1 for location.

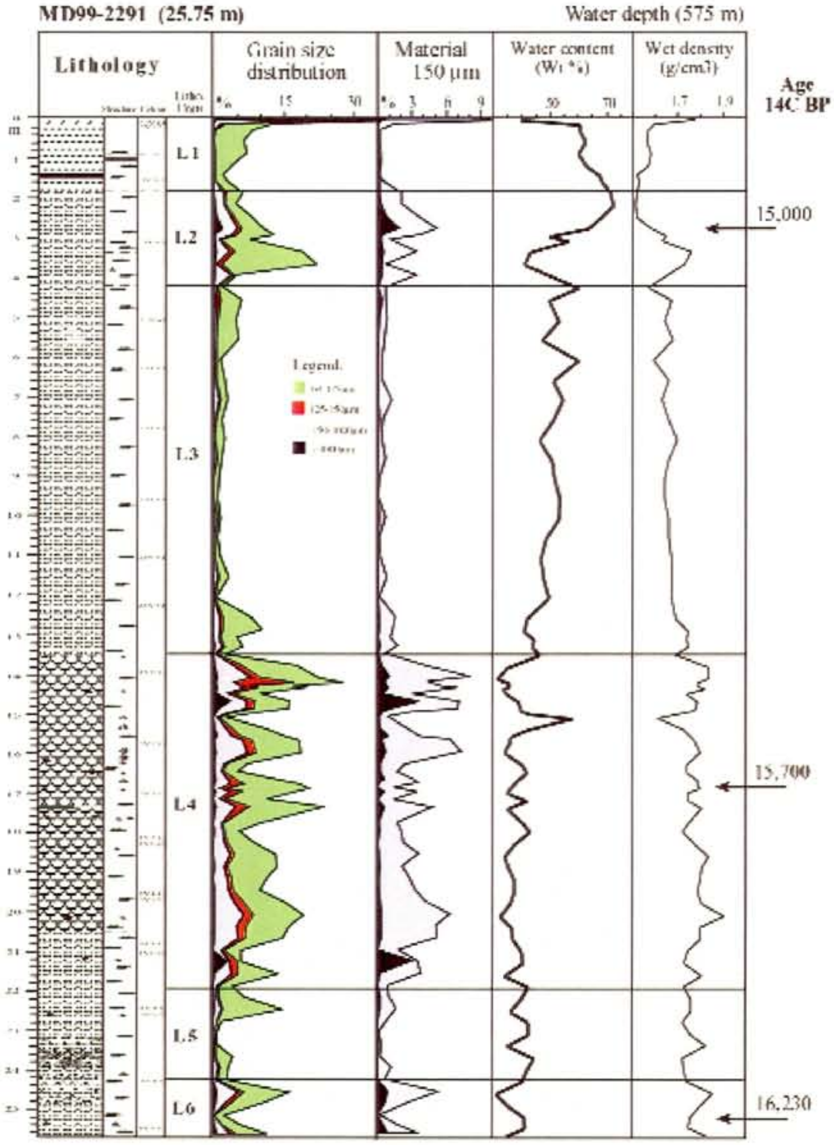


Figure 8.3.1A The litho- and chronostratigraphy of Images core MD99-2291. The location of the core is shown in Fig. 5.2.1 (after Hjelstuen et al. in prep.).

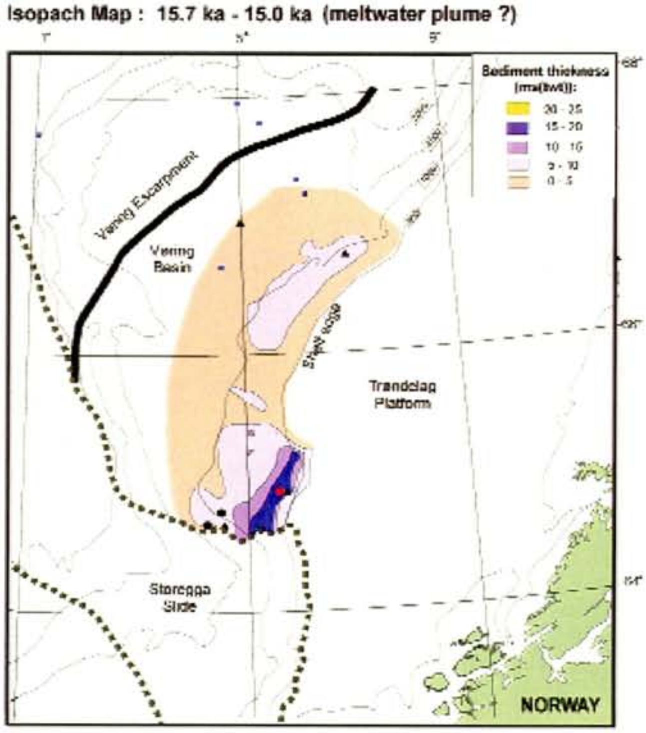


Figure 8.3.1B Isochron map of stratified sediments covering the early deglaciation period 15.7-15.0 ka BP. The map is based on deep-towed boomer data. Images boring MD99-2291 is labelled red (after Hjelstuen et al. in prep.).

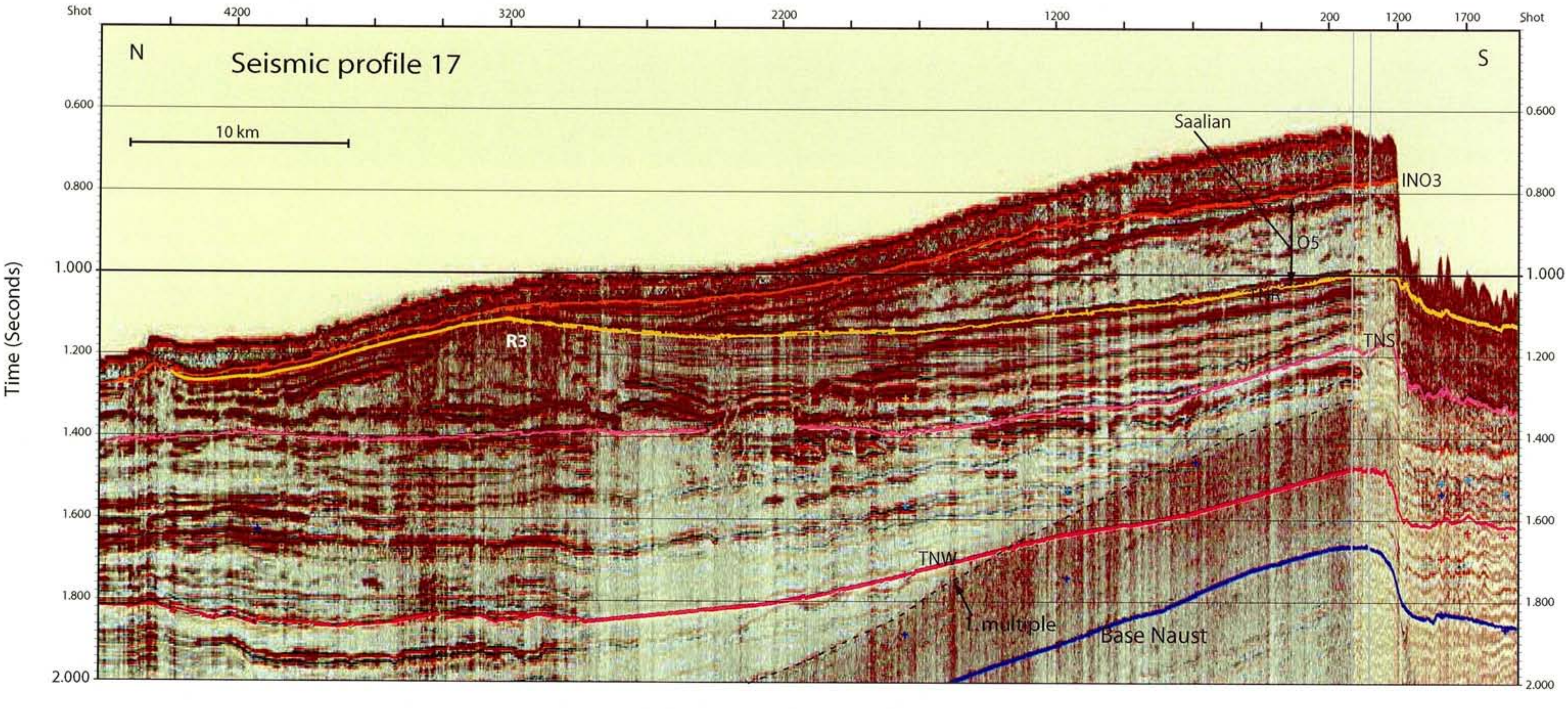
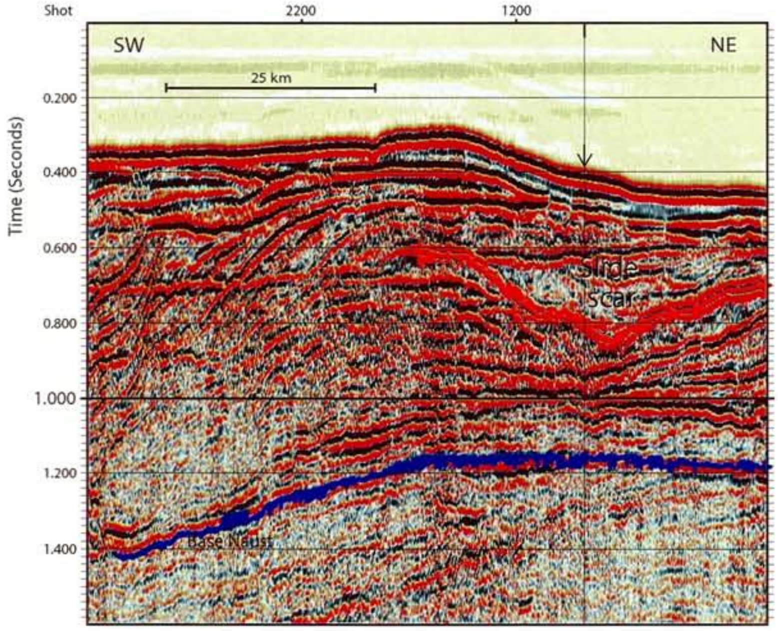


Figure 8.3.2 Seismic profile along the slope north of the deep incision of the Storegga Slide. The debris flows in unit R3 appears to be a remnant after a large slide ('R-slide'), and this slide scar was infilled with stratified sediments. A thick sequence of Saalian debris flows was deposited above the stratified sediments, but no sliding occurred after the Saalian glaciation. For location of lines NH0163-302 / NH9956-202, see figure 8.1.

Seismic profile 15



Seismic profile 14

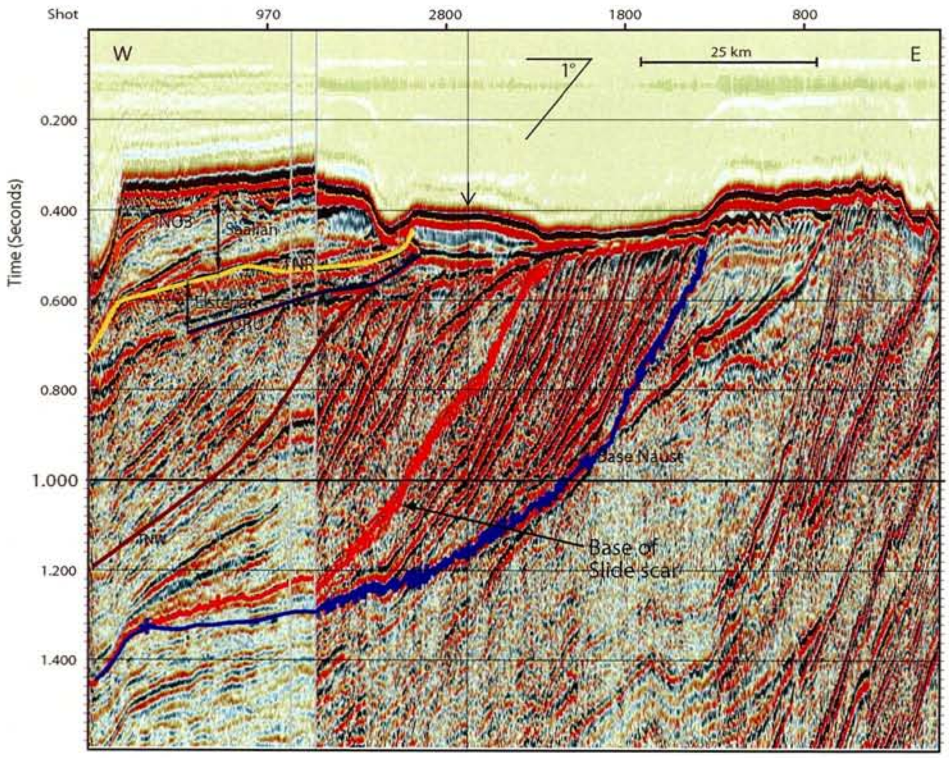


Figure 8.4.1A Seismic line MB 15-84 across a possible paleo-slide scar. The scar is approximately 25-30 km wide and 200 ms deep. The arrow marks the intersection between profiles 14 and 15. See figure 8.1 for location.

Figure 8.4.1B Seismic composite profile ST8501-303 and MB 84-2. The red reflector marks the base of the slide scar. The vertical line on the profile marks the intersection between the lines. The arrow marks the intersection between profiles 14 and 15. See figure 8.1 for location.

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Appendix 1

SINTEF review report STF-NH-OL-26/1

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<tr><td colspan="2" rowspan="3">SINTEF

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Doc.: 37-00-NN-G15-00108</td></tr>
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Martyn Stoker</td><td>CHECKED BY
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ABSTRACT:

SINTEF is performing a verification study on Norsk Hydro's activities related to seabed stability at Ormen Lange.

Contract No.: NHT-B44-5110651-01
Contract Name: Verification Seabed Stability Ormen Lange Phase III

The present report contains comments from the verification group to report:

Large scale development of the mid-Norwegian shelf and margin with emphasis on the last 3 million years.
Doc.: 37-00-NN-G15-00108
NGU-report, May 2002

The review has been performed by:

- Martyn Stoker, BGS

FINDINGS

The overall purpose of this study was to better understand the evolution of the Mid-Norwegian continental margin, with emphasis on the last 3 million years, spanning the deposition of the Naust Formation. Emphasis was placed on the large-scale development of sedimentary systems on the margin, and to integrate this information with areas where detailed risk analyses have been undertaken. The report was structured as follows:

- Cenozoic development of the margin – the tectonic processes that have shaped the margin.
- Summary of glacial history – a comprehensive literature review providing an onshore–offshore linkage.
- Database and work approach.
- Seismic stratigraphy and subdivision of sequences – the stratigraphic methodology and rationale for Naust subdivision.
- Development of the shelf and margin during the three or four last glacial-interglacial cycles – a comprehensive reconstruction of repeated glaciation offshore Mid-Norway.
- Chronostratigraphic information and correlation to the established seismostratigraphy – an open and honest reporting of the stratigraphic problems within the proposed framework.
- Mass wasting processes – a summary of the history of sliding

A key objective of the report was the development of a common stratigraphic framework for the Naust Formation, along the entire mid-Norwegian margin, using ALL available data.

GENERAL COMMENT

On the whole, this is a well-written report that addresses a wide range of processes and factors that have influenced the shaping of the Mid-Norwegian margin. The *Executive Summary* and *Summary & Conclusions* sections that precede the main text are especially useful, providing a concise summation of the main points. An important aspect in the production of the report has been the opportunity to review not only existing published data, but also to integrate the growing library of information generated by both the Seabed and Ormen Lange projects. All of these data have been fully utilised and discussed in this study. Overall, we think that this report is excellent and helps to consolidate the Ormen Lange geomodel by providing the best regional context that could be expected from the available evidence.

In the following text, we have highlighted a number of key points that stand out from the report that we believe are important aspects to consider in the development of the Ormen Lange geomodel, as well as several critical comments that address some of the stratigraphic problems.

KEY POINTS FOR THE GEOMODEL

Detailed information supporting the following key points, which are here regarded as being of importance to the Ormen Lange project work, are provided by this report.

- Cenozoic tectonism and volcanism have played a major role in shaping the Mid-Norwegian margin. Understanding this structural framework provides a regional context for slide distribution.

- A unified stratigraphic framework that is accessible both to academic and industrial institutions is being established. The Naust W–O succession represents a set of composite sequences that can be identified throughout the area of study.

- Glacigenic strata form an important component of the upper Pliocene–lower Pleistocene prograding wedges. Thus, glaciation—and its interface with the marine environment—has had a major, direct, impact on margin architecture throughout the accumulation of the Naust Formation.

- A significant regional change in the general style of margin architecture—from prograding to aggrading—takes place at about 0.4Ma. This is probably linked to the development of the Upper Regional Unconformity (URU), which is discussed in more detail below, and may have implications for the post-Naust S stratigraphy.

- Ice-stream activity, particularly the Norwegian Channel ice stream, was enhanced in the mid- to late Pleistocene interval, along the length of the Mid-Norwegian margin. In addition to debris-flow material, the ice streams also transported finer-grained sediment that sourced significant plume deposits.

- The duration of peak glacial periods—ice reaching the shelf edge—was short, and characterised by the rapid deposition of debris-flow dominated sequences. In contrast, the intervening intervals of more restricted glaciation were relatively long enabling the accumulation of normal marine/glacimarine sediments. This interplay of processes dominates the post-Naust S succession in the Ormen Lange region resulting in an overlapping slope-apron–sediment-drift system.

- On the outer shelf and slope, thick stratified sediments of units R1/R2 are predominantly of glacimarine origin deposited under the influence of contour currents, when ice sheets did not extend beyond the inner shelf. The interglacial component of this section is regarded as negligible. The physical properties of these strata are weaker than the debris flows.

- The last 3 major slides—the ‘S’, ‘R’ and Storegga slides—seem to be cyclic events (about every 300ka), following extensive glaciation. However, the frequency of major sliding events is less than the frequency of extensive glaciation.

CRITICAL COMMENTS, QUESTIONS AND RECOMMENDATIONS

We do have several critical comments on this report that we hope will improve aspects of the communication of this information, as well as a better general clarification of some of the outstanding stratigraphic issues. Questions and recommendations are given in bold type. we consider that all of these comments are important to the project, and would like to see some refinement of the report. We have also included a key recommendation that is not only addressed to the workers at NGU, but also to the members of the Ormen Lange project.

1. The layout of the report is generally good, however, we do feel that the *Stratigraphy* could be better organised. Section 7, which outlines some of the problems of stratigraphic correlation and age dating, should be an integral part section 5, which presents the stratigraphic subdivisions. The presentation of the main sequences, Naust W–O, should be preceded by a definition of the key surfaces (TNW, TNU, TNS, and TNR), the problems associated with the dating of these surfaces, and the reasons why NGU have chosen to accept some dates and not others[1]. We spent some time addressing these problems before we reached section 7, just to find a very good summary of the unresolved problems in Table 7.1.1 that arise largely from the conflict between the interpretation of commercial wells and the Draugen (DR88/30) borehole. We have summarised the main areas of conflict in Table 1 (below). This table also includes the problematic recognition of Eemian strata at site 20, as pointed out by Kåre Rokoengen at the June seminar in Trondheim. **QUESTIONS: 1) Why are the commercial well data preferred? 2) Why is there conflict between the commercial wells and the stratigraphic age model that has been adopted, especially in the assignment of ages to Naust U and W? RECOMMENDATION: We strongly recommend reorganisation of the stratigraphic information, such that the reader can conclude—from an open and honest reporting— that the framework established is the best that can be developed on available data.** The timing of events affects the entire geomodel, especially with regard to postulated ages and frequency of pre-Holocene slides. This, in turn, impacts on the proposed *Slide Explanation Model* that is being developed.

UNIT / SITE	20	Draugen	6607/5-1	6506/12-4	MODEL AGE
Lower 03 (INO3)	Eemian				MIS stage 5
RI	Eemian				MIS stage 7
S			Late Plio-early Pleist. 1.7Ma		0.4-1.1Ma
U			Late Pliocene >2.3Ma		1.1-1.7Ma
W (IKU-1 sub-unit)		Early-mid Pleistocene		Late Pliocene >2.3Ma	1.7-2.8Ma

Table 1. Conflicting age dates. Model ages represent the scheme proposed by the Ormen Lange project.

2. The origin and dating of the Upper Regional Unconformity (URU) is a problem of very general interest. Originally defined as an angular unconformity that separates underlying sedimentary rocks from overlying glacial deposits, it has in the past been assigned ages ranging from 1.7Ma in the Barents Sea, 1.1Ma in the Norwegian Channel, to 0.4Ma on the Mid-Norwegian Shelf. What is clear from the NGU report is that the URU lacks a proper definition. It is not stratigraphically sensible to have one term for a potentially diachronous surface or, worse still, that covers unrelated surfaces. However, from reading the NGU report it is our perception that the URU as defined on the Mid-Norwegian margin is probably the correct definition, i.e. an angular unconformity that marks a significant change in sedimentation style from prograding to aggrading. This change is manifest in the expansion of ice sheets across the shelf at about 0.4Ma thereby removing a large part of the Naust W–

[1] Whilst reference to previous reporting concerning definition of reflectors is made in the NGU report, we are asking for a more comprehensive definition of each of the key reflectors, including age dating in the light of new and reappraised information.

S succession. This is very comparable to the architecture of the prograding wedge offshore Britain, where a distinct angular unconformity, dated at about 0.44Ma, marks ice-sheet expansion. We would agree with the NGU interpretation that the R3 debris flows (calibrated as Elsterian) preserved on the slope were deposited immediately in front of the ice sheet responsible for the cutting of the URU. Thus, the earlier phases of erosion preserved in the Norwegian Channel and on the Barents margin should be regarded as different surfaces. There appears to be clear evidence (from the Draugen borehole) that pre-URU (on the Mid-Norwegian Shelf) sediments include glacigenic strata, e.g. preserved in unit IKU-I, which is now incorporated as part of Naust W. Thus, the previous concept of the URU separating pre-glacial from glacial strata no longer holds true. <u>RECOMMENDATION</u>: **It is necessary to define and clarify what you mean by the URU. This should also be incorporated into the stratigraphic definitions section discussed in point 1.**

3. As noted in point 1, there are significant discrepancies between the Draugen borehole and commercial wells. This is a serious conflict both in terms of academic understanding of the margin, and the implications for the timing of events in the Ormen Lange region. <u>RECOMMENDATION:</u> **As an extension to point 1, we would like to see a more considered appraisal of the problem presented in the NGU report. This would be best accomplished by clearer presentation of the local and regional seismic-stratigraphic setting of the Draugen borehole.**

4. On page 91, in the introduction to section 5—Seismic Stratigraphy—the NGU report states that 'a sequence stratigraphic approach was applied for definition of Sequences S and R', and they referenced Norsk Hydro (2001 – report 37-00-NH-G15-00058). However, according to Svitzer (2002 – report SP2-05-SV-02D-00000-02; their page 6 & Fig. 7), the cyclicity model is restricted to post INS2 deposition, which is essentially Naust R and O. <u>RECOMMENDATION:</u> **This requires clarification.**

5. On page 160, there seems to be some uncertainty to the recognition of Slide 'S'. <u>QUESTION:</u> **This poses the general question as to what degree of confidence is there in palaeoslide recognition?**

6. The clarity of many of the figures could be greatly improved!

KEY RECOMMENDATION

- **The conflict in age dates for the Naust sequences S, U and W, and the confusion over whether or not the lower part of O3 (INO3) or R1 is Eemian, should be addressed by communication and discussion between all parties involved, i.e. the Bergen group and the Ormen Lange project team, and perhaps include Tor Eidvin at NPD. Understanding slide chronology and frequency throughout the entire Naust succession is dependent upon a stratigraphic framework where all issues of conflict have been resolved as far as is possible within the realms of the available data. From a verification point of view, we are not convinced that these issues have been addressed.**

Appendix 2

Reply to SINTEFs review report STF-NH-OL-26/1.

NGU
Norges geologiske undersøkelse
Geological Survey of Norway

MEMO

To: **NORSK HYDRO ASA,**
Att. Petter Bryn, Kjell Berg

Date: 20. november 2002

REPLY TO SINTEF's REVIEW REPORT STF-NH-OL-26/1

ORMEN LANGE PHASE III

NGU report 2002.015 " Large scale development of the mid-Norwegian shelf and margin with emphasis on the last 3 million years" was delivered to Norsk Hydro in May 2002.

The report has been reviewed by Norsk Hydro's verification team, coordinated by Sintef Civil and Environmental Engeenering, Rock and Soil Mechanics.

As a result of the review, some general remarks, critical comments, questions and recommendations have been presented.

This memo is a reply to the six points given in the review report STF-NH-OL-26/1.

Terje Thorsnes
Program manager

Dag Ottesen
Project leader

Comment on the review report of "Large scale development of the mid-Norwegian shelf and margin with emphasis on the last 3 million years" (Doc.: 37-00-NN-G15-00108)

The review report lists six points with critical comments, including some questions and recommendations. Several of the comments given by the verification group are relevant, and will be used as a 'guideline' for the revision of the report. In this reply we will discuss the critical comments and recommendations, and outline what we intend to improve in the revised report.

1. Refinement of Chapter 5 - Stratigraphy

We agree that the presentation of the main sequences should have been preceded by a definition of the key surfaces. Looking into the report again, we see that TNW and TNU may be better described. One reason is that the reflector TNW is of variable character throughout the large area, representing a horizon that has been possible to follow throughout the area. Sequence Naust U is mainly mapped in the Storegga area, and becomes very thin to the north. In the northern area, TNU is of variable character and is, in part, difficult to follow confidently. This is probably of lesser importance as sequences U+S are treated as a composite sequence in our report. TNS is well described in section 5.6, but we have forgotten to define TNR in section 5.7, probably because sequences R+O in this section are described as a composite sequence. In our revision of the report we will improve the definitions of the key surfaces, and harmonize the descriptions of the sequences with those in the Seabed Phase IV report (Svitzer 2002).

In Ch. 5 we outlined the seismic stratigraphy, together with a general description of the geometry and seismic character throughout the area. We also made some suggestions for the depositional environment. In sections 5.5, 5.6 and 5.7 we noted proposed ages for the Naust sequences in the headings, and we understand that the reader would expect to know more about the background for these ages. The problems of stratigraphic correlation and age dating are presented in Ch. 7, and we don't agree that this 'confusing topic' should be an integral part of Ch. 5. In the introduction to Ch. 5 we will include a paragraph briefly discussing the age uncertainties, and make a reference to the age discussion given in Ch. 7.

Two questions about age are raised by the verification group:

1- Why is there a preference for the commercial well data? It is easy to note that the proposed age model is very uncertain (Table 7.1.1), representing something between the investigation of commercial wells (Eidvin 1998) and borehole data from Draugen (Haflidason et al. 1991). From Eidvin`s investigations, it seems that c.70% of the Plio-Pleistocene wedge was deposited prior to 2.3 Ma. If it is correct that TNS (i.e. base of R3 - 'Elsterian') is 0.4 Ma, this will imply that deposition during the period 0.4-2.3 Ma was limited and of the same magnitude as after 0.4 Ma. Haflidason`s data combined with the established seismic stratigraphy indicate the opposite, a low rate of deposition in the period 0.8-2.8 Ma, and a very high rate in the period 0.4-0.8 Ma.

In the revised report we will include a vertical section from shelf to slope in order to elucidate our age model, and illustrate this together with other possible models (Haflidason 1991; Eidvin 1998; Svitzer 2002). We will comment on suggested ties from well ODP 644 (Svitzer 2002), which apparently gives a large age discrepancy compared to Eidvin (1998).

2- Why is there an age conflict .....? It is not possible to answer this question satisfactorily. As there are conflicting ages in the literature, we have simply made a proposal based on the various data. We agree that the timing of events affects the entire geomodel, and further work should be carried out in order to obtain a better understanding of the chronology. Topics that should be addressed in such a study should include the various dating methods, the quality of the seismic data and the confidence of seismic ties.

3. Local and regional seismic-stratigraphic setting of the Draugen borehole.

We agree that a more considered appraisal of the problem could possibly be obtained by reviewing all the existing relevant data. More than 10 years ago, IKU (now SINTEF Petroleum Research) looked into the same problem, and concluded that correlation with the regional seismic framework was uncertain due to a lack of good tie lines from the area of soil borings (Rise and Rokoengen 1991). IKU suggested, however, that the 130 m-long borehole possibly did not penetrate the pronounced angular unconformity in the Draugen-Njord area (base of unit IKU-I), and that the inferred Brunhes/Matuyama boundary at c. 90 m depth could be correlated with an internal reflector in unit IKU-I.

During the project period, the conflicting age issue was discussed with T. Eidvin and F. Riis in NPD. Eidvin has re-studied forams from the Draugen borehole, finding that Quaternary sediments occur in the lower part, thus supporting Haflidason`s interpretation. Riis kindly studied 3D data at Draugen, and found that the angular unconformity (base IKU unit I) had been eroded into a local small 'hole' in the area where the geotechnical borehole was located. He also concluded that the borehole had been terminated above the angular unconformity. In the revised version of this report we will make a reference to the work done by NPD.

No 2D seismic lines of high resolution in the actual shelf area were included in the NGU project, and only a poor seismic tie to the wells studied by Eidvin exists. The seismic interpretation by Rise and Rokoengen (1991) indicates, however, that base IKU-I as well as the Brunhes/Matuyama boundary is at a much deeper stratigraphic level than the levels suggested to define 2.3 Ma. We do not deny that a seismic explanation for this apparent discrepancy may exist, and it might be an idea to make a separate study together with NPD, including all relevant data of good quality (3D, 2D, digital version of 2.5 s site survey tie-lines Draugen- Njord and Njord-Smørbukk, other long 2.5 s. tie-lines). Before finishing the next version of the report, we will ask the geoscientists at the University of Bergen to re-examine the paleomagnetic data from Draugen. To which degree of confidence can we say that the Brunhes/Mauyama boundary is encountered in boreholde DR88/30?

2. Interpretation, origin and dating of URU

We agree that the Upper Regional Unconformity (URU) lacks a proper definition, but from our 2D database with partly poor resolution on the shelf areas, we have not been able to do this for such a large area. It is also clear that URU is variably developed and of varying age in different regions, and that it is difficult to correlate these surfaces. In some areas, URU is well defined, whereas in adjacent areas the same horizon seems to be a reflector within a flat-lying sequence, and is often difficult to interpret satisfactorily. The irregular surface at the base of unit IKU-D, recognized as URU at northern Haltenbanken, is, for instance, a very shallow and poorly defined reflector at southern Haltenbanken (Draugen-Njord). The apparent URU in this area (base IKU unit I) is much older. The nature of URU is probably controlled by several factors. The impact of glacial erosion is important, as is very well illustrated in the Norwegian Channel south of Norway. In most of this area URU is of Late Weichselian age, but in adjacent areas (south of Arendal / Jæren), the URU was developed during an Early or Mid Pleistocene glacial event (like what we see in the Troll area).

This study has shown that we are still far from a proper understanding of URU or the different angular unconformities, and this is hopefully reflected in descriptions in various sections of the report. Although we are not able to give a stratigraphic definition, we will, in the revised report, add a section about URU (in Ch. 5). Here, we will summarize observations carried out in this study and discuss some of the problems related to this term. Hopefully, this will clarify what we mean by the URU, and at the same time elucidate some of the factors of importance for its formation.

4. Sequence stratigraphic approach

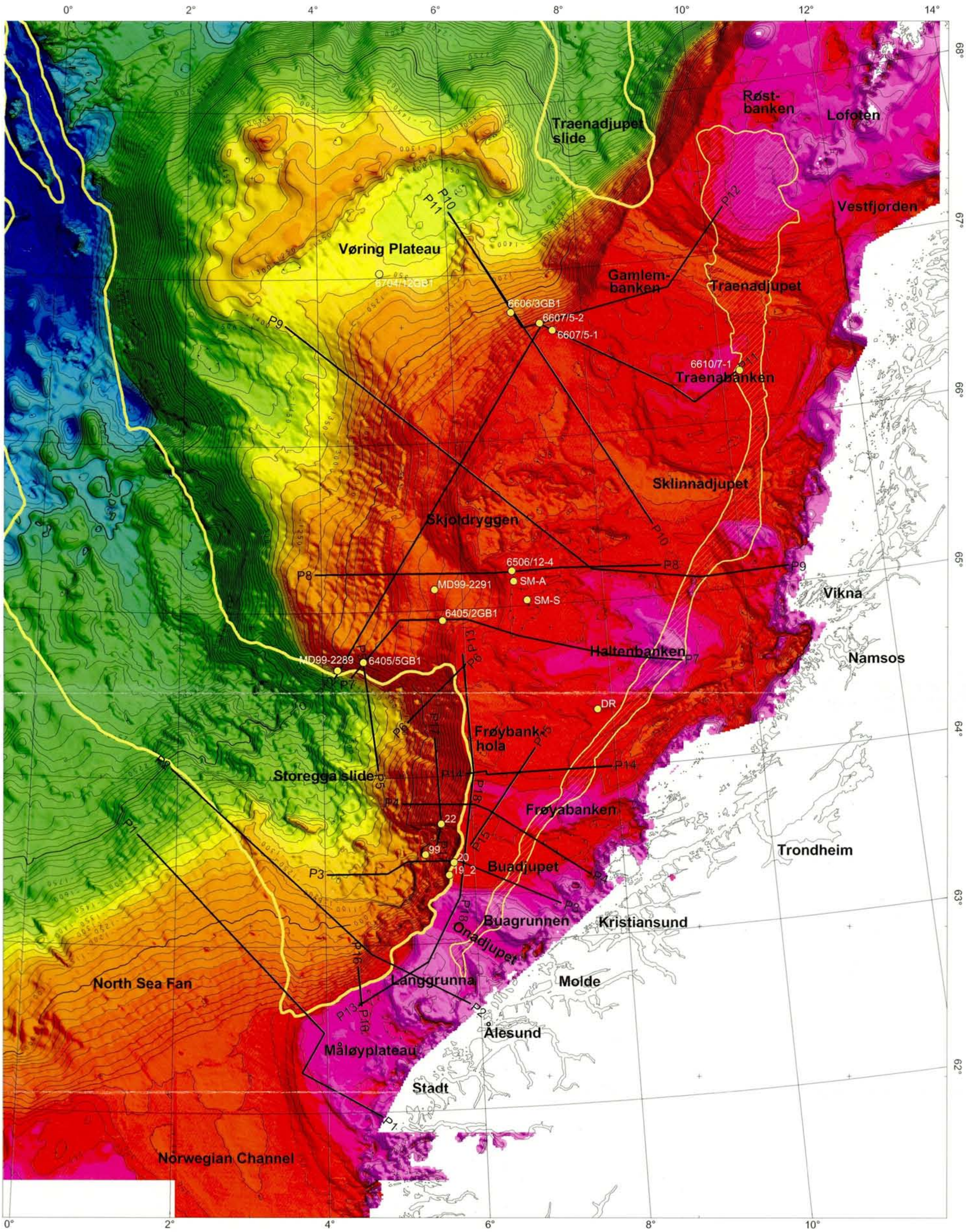
We agree that this should be clarified. We make here a reference to Norsk Hydro 2001–report 37-00-NH-G15-00058, and it is clear that Sequence O has fallen out by mistake. The correct sentence should be: ' a sequence stratigraphic approach was applied for definition of the upper part of Sequence S, and sequences R and O'. This will be corrected in the final text.

5. Recognition of Slide 'S'

We wrote that recognition of defined slide scars in Slide 'S' was difficult, but we did not mean to express a doubt about the actual recognition of the paleoslide. Our intention was to say that a poorly defined backwall of this slide made the relationship between the last glaciation in Sequence S and Slide 'S' uncertain. The study by Norsk Hydro 2001 involved much more data (also 3 D), and the mapping of the stratified sediments showed clearly that different slide scars had been filled in with contouritic sediments. We will correct the text in order to avoid a misunderstanding about the confidence of Slide S.

6. Clarity of figures

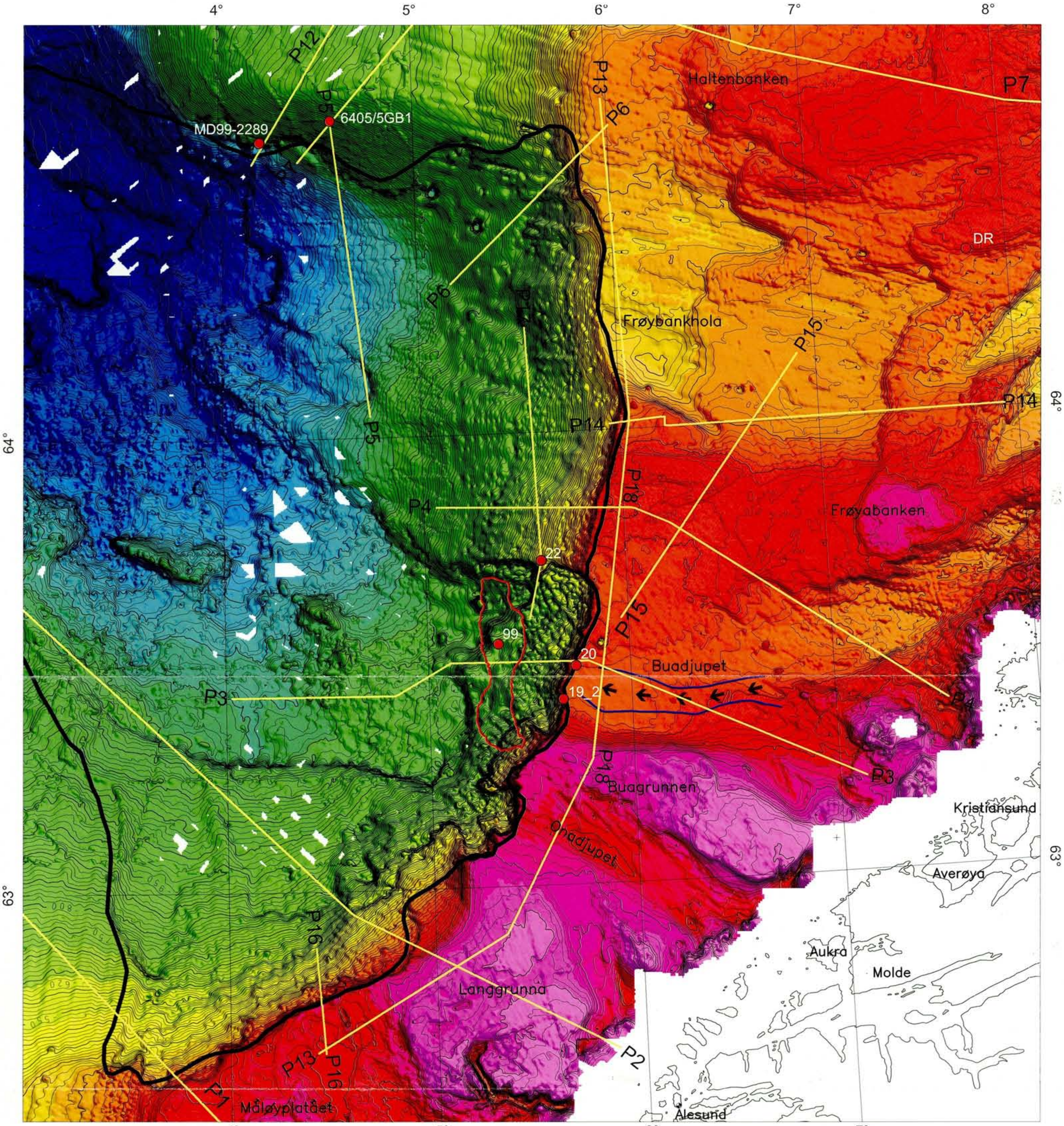
So far, we have received only positive comments on the Figures, also from Norsk Hydro. Improvements may include a lot of work.



ENCLOSURE 1

NGU-report 2002.015

Bathymetric map of the study area, showing presented seismic profiles, exploration wells and geotechnical drilling sites.



ENCLOSURE 2

NGU-report 2002.015

Bathymetric map of the eastern part of the Storegga slide area. Presented seismic profiles and geotechnical drilling sites are shown.