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# Large-scale development of the mid-Norwegian margin during the last 3 million years

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**Abstract**

During the last c. 2.7 My, large quantities of glacially derived material were transported westwards from the Norwegian mainland areas and inner shelf and deposited mainly as prograding sediment wedges into a basin of intermediate depth offshore Mid Norway. The deposits are more than 1000 m thick in extensive areas, and are defined as the Naust Formation. In the Haltenbanken–Trænabanken region, the shelf edge migrated 100–150 km westwards. The narrow Møre shelf was built out only in the order of 30–50 km, mainly due to a steeper pre-existing slope dipping towards a much deeper basin. In this area, the Holocene Storegga Slide, as well as older slides, displaced slope sediments towards the deeper part of the basin. In Early Naust time, the most extensive progradation occurred in the northern area, possibly due to the combined effect of land uplift and glaciations. The importance of glaciations for the progradation of the Møre shelf and areas farther south increased through the Pleistocene period. The Norwegian Channel Ice Stream became very important during the last three glaciations, and a thick succession of glacigenic debris flows was deposited on the North Sea Fan. More than 400 m of sediments accumulated during the Weichselian. All the last three glaciations supplied glacial debris beyond the shelf edge. The most extensive progradation in the north was in the Skjoldryggen region, particularly during the Elsterian glaciation. During 'ice-free' periods, hemipelagic and contouritic sediments were deposited on the slope. Such sediments are most common in the Storegga Slide area, where they hosted glide planes beneath the major slides.


*Keywords:* Continental shelf; Continental margin; Late Pliocene; Pleistocene

## 1. Introduction and applied methods

This paper is based on a regional study carried out for the Ormen Lange Project on behalf of Norsk Hydro (Rise et al., 2002). The main objective was to improve our understanding of the Late Pliocene and Pleistocene development of the shelf and margin between 62° and 68°N and to link this information to the area of the Storegga Slide where the Ormen Lange gas field is located (Fig. 1). During the last c. 3 million years, when the Naust Formation was deposited, several gigantic slides occurred in the Storegga area. One of the targets was to relate these slides to the geological development of the margin.

A total of 25,000 line kilometres of seismic data have been utilised, comprising most of the 2D high-resolution seismic data from the Seabed and Ormen Lange projects, in addition to conventional exploration 2D seismic lines on the shelf. Analogue shallow-seismic lines were also utilised on the shelf (Rise, 1988). Results from the study of several geotechnical boreholes, long stratigraphic cores and exploration wells (Eidvin et al., 1998; Haflidason et al., 1998, 2001; Berg et al., 2005) were incorporated into the seismo-stratigraphic framework.

## 2. Geological setting

The major postglacial Storegga and Trænadjupet slides occurred at the Møre and Lofoten margins, respectively,

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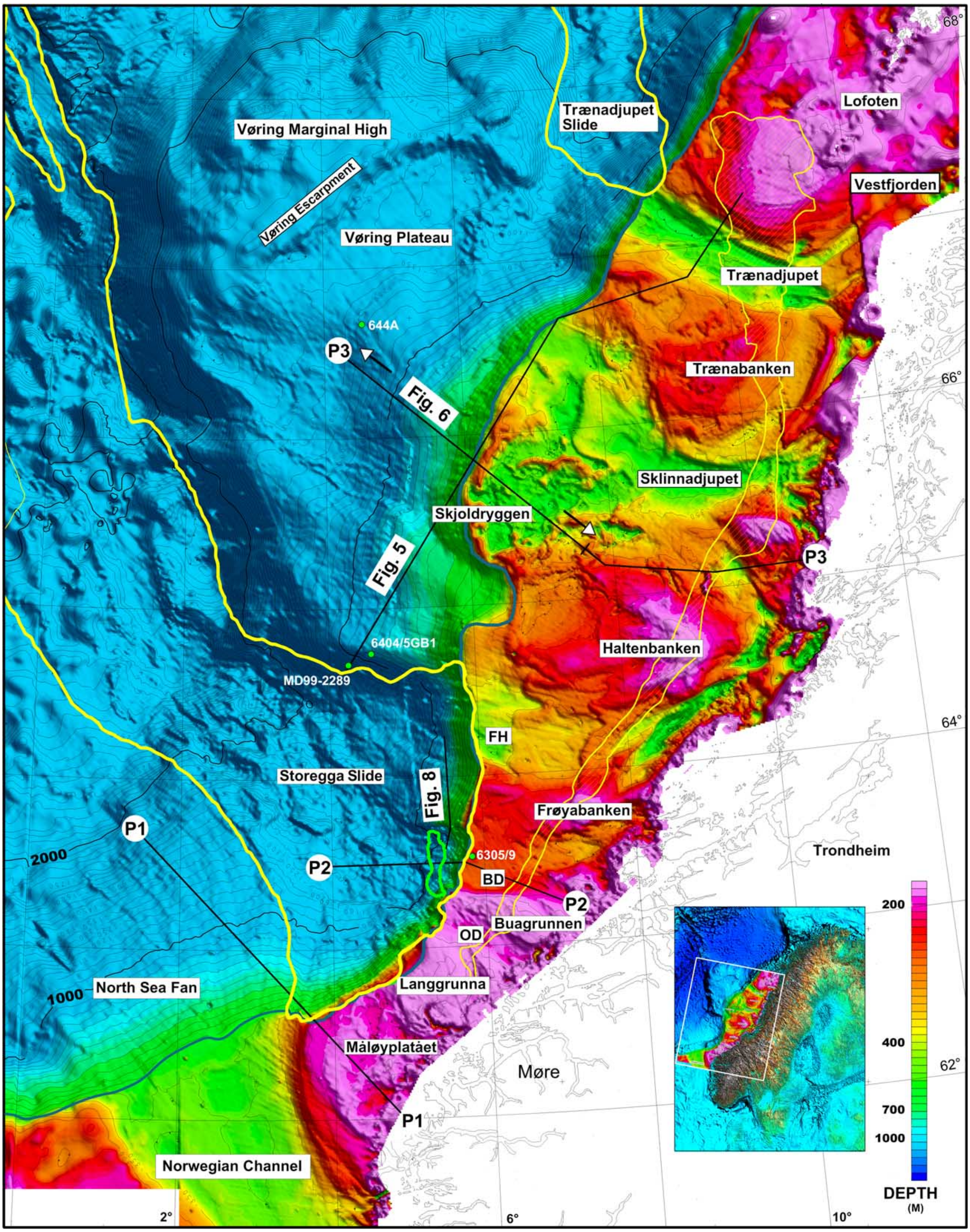


Fig. 1. Overview map of the Mid-Norwegian margin. The location of later figures is shown. P1, P2, P3, seismic profile lines; FH, Frøyabankhola; BD, Buadjupet; OD, Onadjupet; Ormen Lange Gas Field (green outline west of Buadjupet); subcrop of the Oligocene–Miocene Molo Formation (yellow hachures); Shelf break (blue line). Green dots are drillsites mentioned in the text.

(Fig. 1). The slopes towards the deep ocean in these areas are commonly only c. 1–2°, but are nevertheless steeper than the slope from the shelf edge towards the c. 1200–1400 m-deep Vøring Plateau. The water depth on the narrow Møre shelf is only 100–200 m, increasing northwards to 200–400 m in the very wide Halten- and Trænabanken shelf region (Fig. 1). Several troughs and depressions separate the shallower bank areas. Many of these troughs have been important for the margin development, as they represented paths for enhanced glacial transport by palaeo ice-streams during the Late Quaternary (Ottesen et al., 2001).

The erosional products from Mid Norway and the inner shelf were transported westwards, and a rapid construction of the continental shelf and margin took place during the last 2.6–2.7 Ma (Eidvin et al., 1998; McNeill et al., 1998). These deposits make up the Naust Formation (Dalland et al., 1988), comprising a thick succession of low-angle sediment wedges and sheet-like units (Figs. 2 and 3). Most of the sediments occur west of the subcropping 'deltaic sands' of the Molo Formation (Bugge et al., 1984; Henriksen and Weimer, 1996) (Fig. 1), inferred to be of Early Oligocene to Early Miocene age (Eidvin et al., 1998; T. Eidvin, pers. comm.).

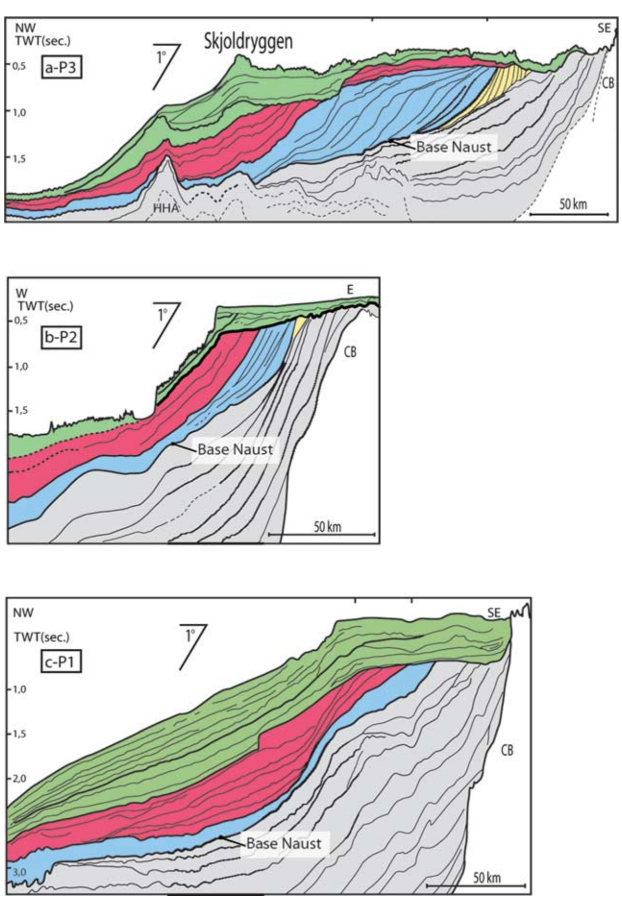


Fig. 2. Interpreted seismic profiles P3, P2, P1 (a–c) showing the main Late Pliocene-Pleistocene Naust sequences deposited west of the 'deltaic' Molo Formation (yellow). Naust W—blue; Naust U and S—red; Naust R and O—green; HHA, Helland Hansen Arch; CB, Crystalline bedrock. See Fig. 1 for location.

The timing of the Neogene uplift phases is uncertain (Stuevold and Eldholm, 1996), and the Norwegian mountain range may already have been uplifted to a level corresponding to the present when the first ice sheets covered Scandinavia at c. 2.7 Ma (Jansen et al., 2000). Glaciers generally followed pre-existing fluvial valleys to the coastal areas, and eroded weathered bedrock and unconsolidated Tertiary sediments. Moderate glacial conditions and rather small ice caps over mainland Scandinavia are inferred during the time period 2.7–1.1 Ma (Henrich and Baumann, 1994), causing a limited degree of ice flow towards the shelf according to Mangerud et al. (1996), Hjelstuen et al. (1999). The amount of ice-rafted detritus in deep-sea cores increased significantly at c. 1.1 Ma (Jansen and Sjøholm, 1991; Jansen et al., 2000). It has been suggested that the first ice-stream expansion to the shelf edge, within the Norwegian Channel, occurred at 1.1 Ma (Sejrup et al., 1995).

## 3. Description of sequences and time thickness maps

Below the present shelf north of Frøyabanken, the base of the Naust Formation is commonly seen as a down-lap surface, and it appears to represent an angular unconformity in the middle-eastern part of the area where it has been mapped (Fig. 3e). At the outermost shelf and beyond the shelf edge, the layers above and below base Naust are generally conformable.

The Naust Formation was subdivided into five seismic sequences (W, U, S, R, O), each comprising several units (Figs. 3e and 4). A sequence stratigraphic approach was applied in the Storegga Slide area in order to relate the geological development during the last c. 0.5 My to depositional cycles (Solheim et al., 2005). The sediment succession consists of several incoherent seismic units (till, glacigenic debris, slide deposits) interbedded with stratified units deposited in the periods between extensive glaciations. Stratified sediments are most common in the Storegga Slide area.

### *3.1. Sequence Naust W*

The upper boundary of Naust W (horizon TNW) is usually seen as a good regional seismic marker, but may locally be of variable character. The upper part of the sequence is commonly glacially eroded on the middle and eastern parts of the shelf (Figs. 2 and 3e).

North of Frøyabanken, where base Naust has a gentle dip towards the west, Naust W makes up a substantial part of the Naust Formation on the shelf (Figs. 2a, 3b and e). Extensive progradation occurred, and most of the present-day shelf was formed during the Naust W period. In the Haltenbanken region the palaeo-shelf edge of Naust W is only 30–50 km east of the present shelf break. The sequence comprises

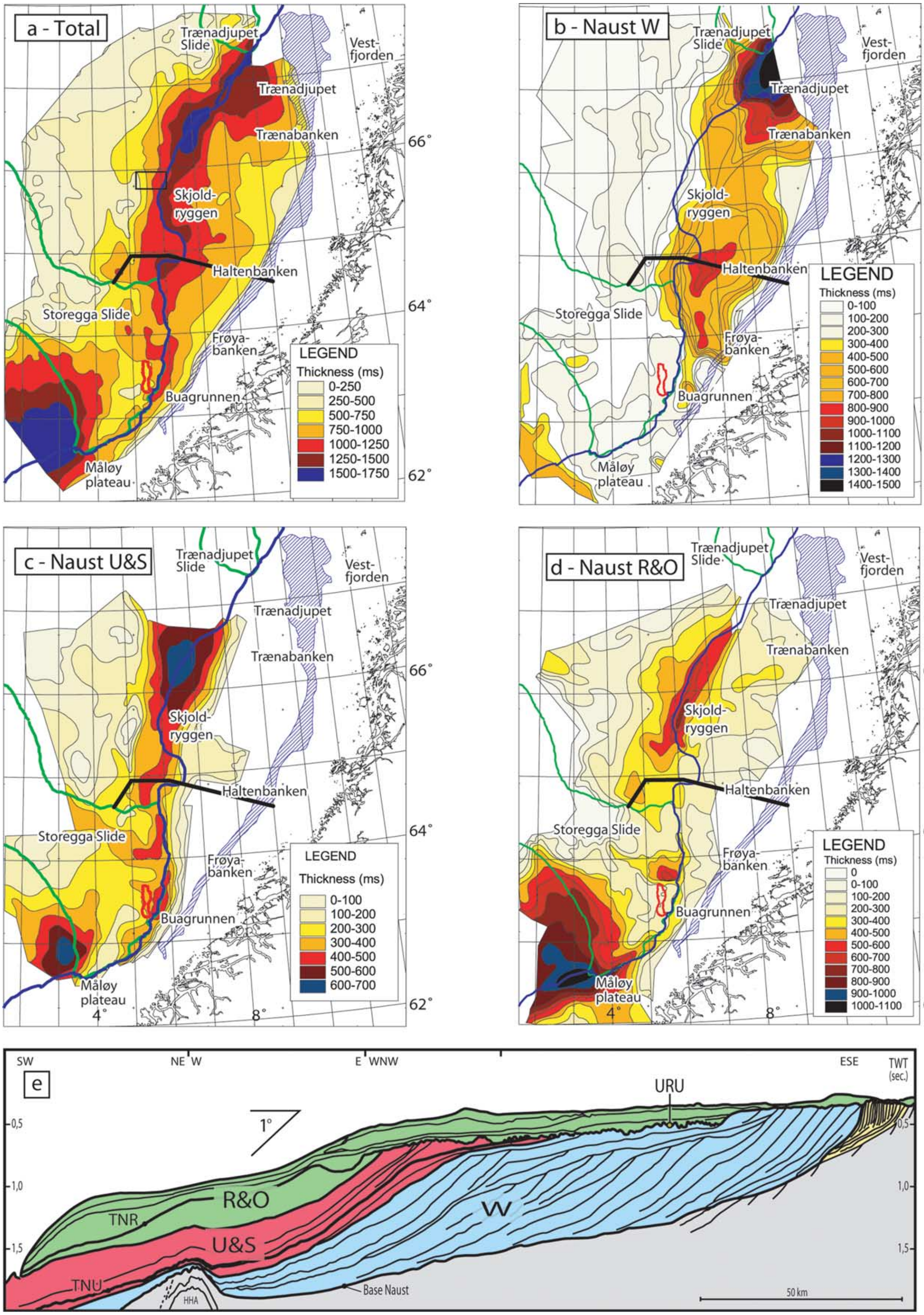


Fig. 3. Time thickness maps (two way travel time; twt) of: (a) Naust Formation; (b) Naust W; (c) Naust U and S; (d) Naust R and O. Note that the sediment thicknesses in the southern area increase towards younger ages. The blue line shows the present-day shelf break. The interpreted seismic line (e) illustrates the shelf to slope development at Haltenbanken through Naust time, west of the Molo Formation (yellow). URU, Upper regional unconformity.

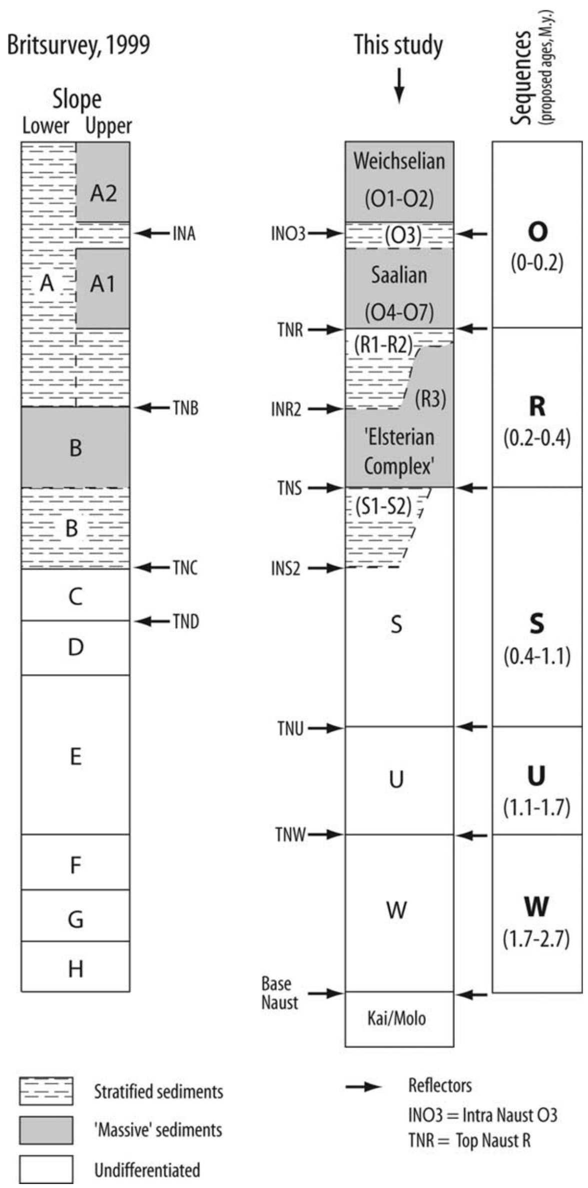


Fig. 4. Diagram of the defined sequences and horizons in the Naust Formation, mainly based on the stratigraphy applied in the Ormen Lange area (Berg et al., 2005). Correlation with a previously applied terminology and subdivision north of the Storegga Slide (Britsurvey, 1999) is shown. The proposed ages for Naust W, U and S are uncertain.

numerous low-angle, wedge-shaped prograding depositional units. Some angular unconformities occur within Naust W in the middle-eastern part of the shelf, showing cycles of strong erosion, and the seismic character indicates very active and possibly varying depositional systems (Rokoengen et al., 1995). The inferred palaeo-shelf surfaces have subsided more in the west than in the east through time, and thus show a decreasing westerly dip towards younger ages (Figs. 2a and 3e). Most of the units down-lap on the base Naust horizon. Naust W apparently pinches out against the eastern flank of the Helland Hansen Arch and other domes farther north, but reappears on the western side of these domes (Figs. 2a and 3e). The thickest sediments occur in the northernmost part (1400 ms twt), near outer Trænadjupet (Figs. 3b and 5).

West of Møre (Frøyabanken–Langgrunna), the basin is much deeper, resulting in steeper dips (Fig. 2b). The sheet-like units in this area commonly show an aggrading pattern as sediments were dispersed towards the deep part of the Møre Basin. The time thickness of Naust W is commonly less than 250 ms twt, showing a limited progradation of the Møre shelf and margin (Fig. 3b). In the northern part of the Storegga Slide area, thick slide deposits constitute the upper part of the sequence, showing that the area was slide-prone also in the early Naust period. Although the sequence reaches a time thickness of 400 ms twt at the North Sea Fan, it comprises only 20–30% of the Naust Formation in this area.

#### 3.1.1. Age of Naust W

A till unit sampled directly above the upper regional unconformity (URU) in the Norwegian Channel is interpreted to be 1.1 Ma (Sejrup et al., 1995). Since Naust W is truncated by URU farther north in the channel, we infer that the age of this sequence is older than 1.1 Ma.

Eidvin et al. (1998) studied several exploration wells located on the Mid-Norwegian shelf, and correlated planktonic fossil fauna with palaeomagnetically calibrated fossil zones from ODP/DSDP drillsites in the Norwegian Sea. Some of these wells are located along seismic profiles utilised in this study, and datings indicate that Naust W is older than 2.3 Ma.

### 3.2. Sequences Naust U and S

Sequences U and S comprise several aggrading or slope-building units, and the sediments probably represent several glacial–interglacial cycles. Maximum deposition occurred along the present shelf edge, and locally slightly west of it (Fig. 3c). The northern depocentre (>600 ms twt thickness) is located in the outermost Trænabanken and west of Sklinnadjupet. The units deposited on the slope of this area appear to be acoustically incoherent (Fig. 5), and many of them are fairly thick. Some units thin down-slope, and pinch out on the middle–lower slope. Other units are of fairly even thickness, or may thicken in the lower part of the slope. Hemipelagic or contouritic sediments in the northern area appear to be uncommon, but the amount of such sediments may have been underestimated due to the lack of a well-defined stratified acoustic pattern. The upper part of the combined sequences almost completely covers the Helland Hansen Arch (Figs. 2, 5 and 6) and other dome structures farther north.

On the middle–lower slope west of Haltenbanken, some units of stratified sediments occur between more acoustically incoherent units, one of them being up to 70 ms twt thick. North of the northeastern corner of the Storegga Slide, Sequence S comprises many thin

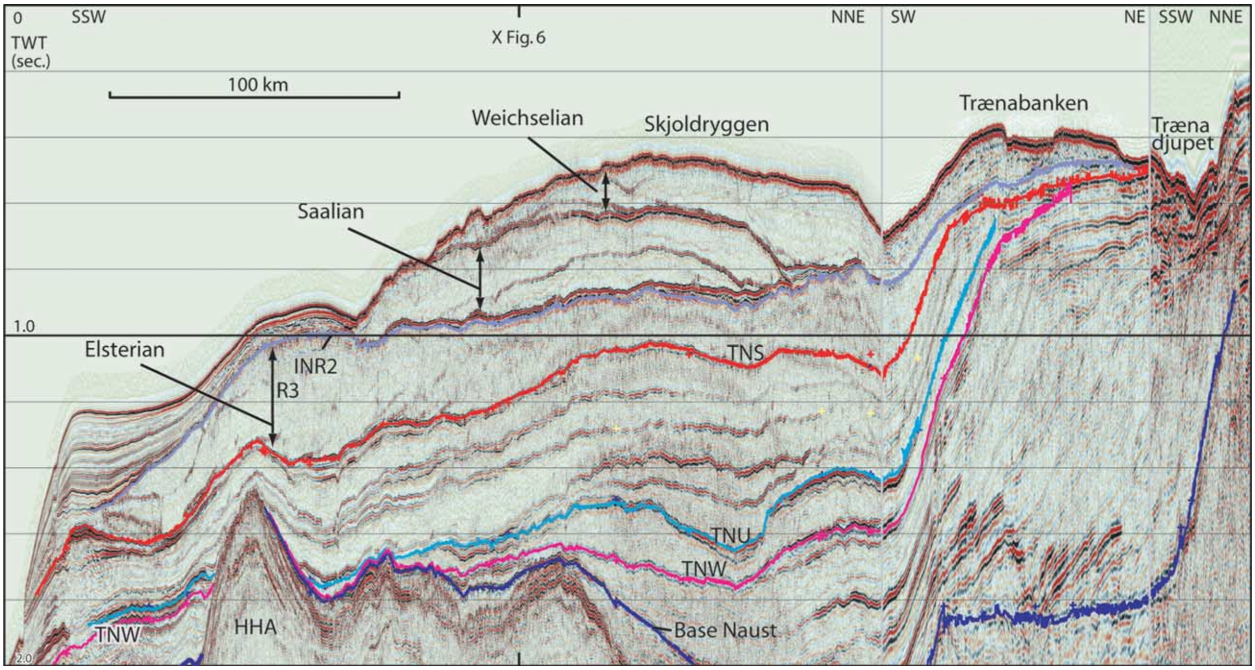


Fig. 5. Interpreted composite profile from Trænadjupet to the northern sidewall of the Storegga Slide. Note the thick stratified sediments at the 'shoulder' north of the slide, deposited above the thick Elsterian glacigenic debris (R3). The lobate progradation of Saalian deposits in the Skjoldryggen region is evident. The northern part of the line shows the extensive progradation of Naust W at northwestern Trænabanken. HHA, Helland Hansen Arch. See Fig. 1 for location.

sheet-like, acoustically incoherent units that commonly pinch out on the mid-slope and inter-finger with stratified sediments. The depositional environment in the Storegga Slide area is complex, with glacigenic debris, slide deposits and stratified sediments (Berg et al., 2005; Solheim et al., 2005). On the North Sea Fan, sediments up to 600 ms twt in thickness were deposited during the Naust U and S period (Fig. 3c).

### 3.2.1. Age of Naust S

Correlation to data presented by Eidvin et al. (1998) shows that the base of the Pleistocene fauna (1.7 Ma) is located close to the previously defined horizon TND (Britsurvey, 1999), now located within Sequence S (Fig. 4). Dated horizons in borehole ODP 644A have been seismically tied towards the shelf edge in the Skjoldryggen area, indicating that unit Naust D (Fig. 4) represents

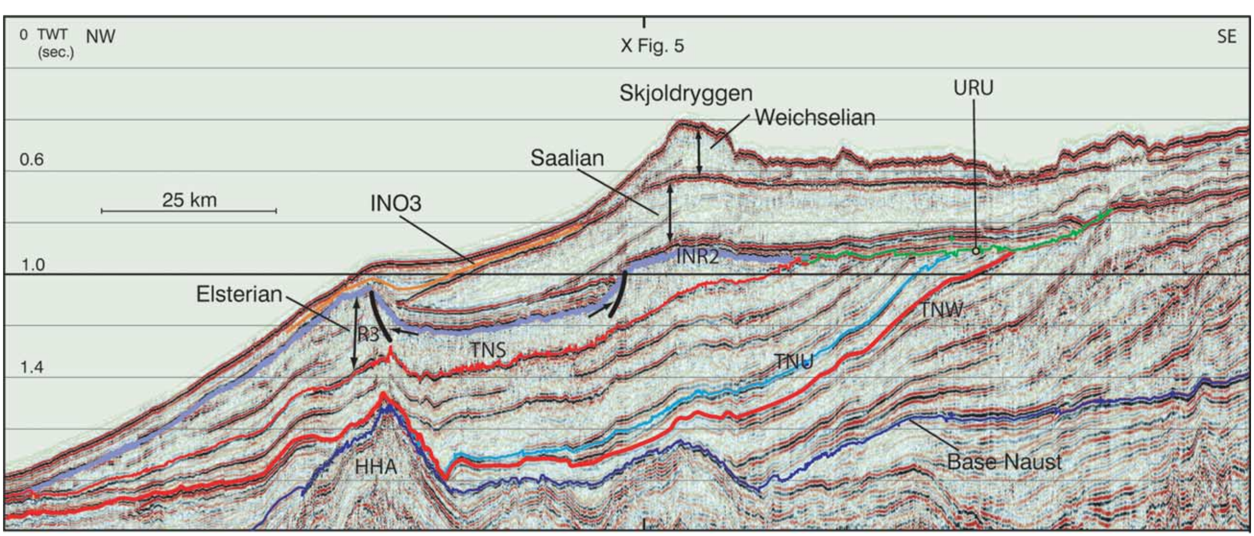


Fig. 6. Interpreted profile crossing the prominent Skjoldryggen ridge, which was formed as a terminal moraine during the Late Weichselian. Note the well-defined upper regional unconformity (URU), and that the Saalian Ice Sheet did not erode the stratified sediments deposited above the URU. Arrows mark slide scars of the Sklinnadjupet Slide. See Fig. 1 for location.

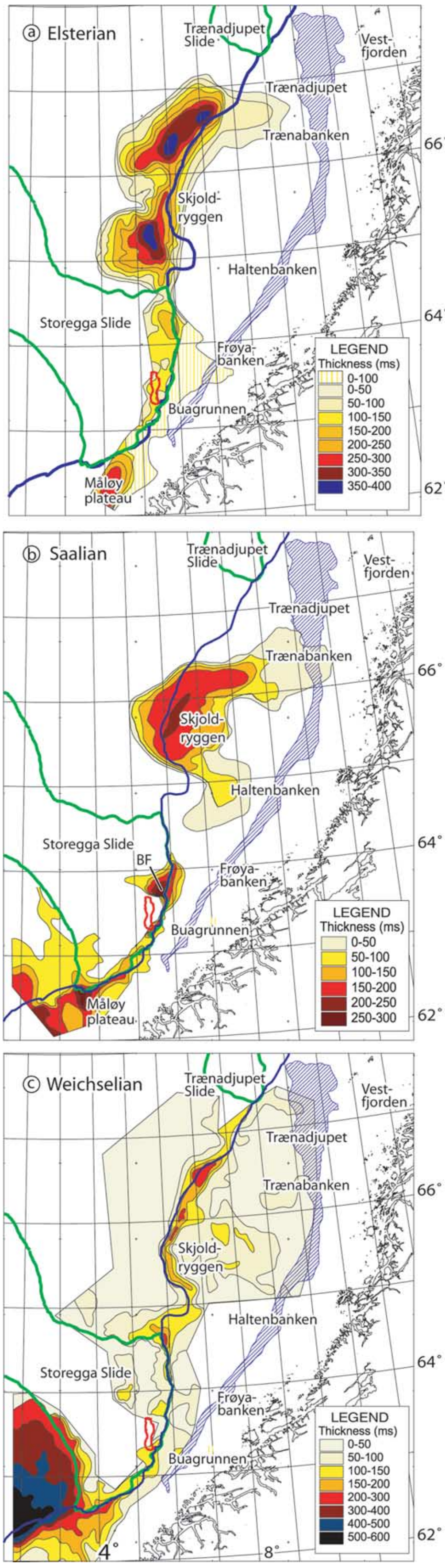


Fig. 7. Time thickness maps (ms twt) of glacigenic deposits from (a) the Elsterian; (b) the Saalian and (c) the Weichselian glaciations. The blue line shows the present-day shelf break. The ice sheets and ice streams supplied debris to nearly the entire upper slope during all the last three glaciations. BF=‘Buadjupet Fan’.

the oxygen isotope stage 14, inferred to be 500–600 ka (Dahlgren et al., 2002b). Boring 6404/5-GB1, located at the northern flank of the Storegga Slide, shows that the upper 70 m of Sequence S is within the Brunhes Normal Polarity Chron, i.e. $<0.78$ Ma (Haflidason et al., 1998).

### *3.3. Sequences Naust R and O—representing the last three to four climatic cycles*

During Naust R and O time, large quantities of glacigenic sediments and slide deposits, up to 1000 ms twt in thickness, were deposited on the North Sea Fan (Fig. 3d). Another prominent depocentre occurs in the Skjoldryggen region (c. 700 ms twt), comprising three well-defined units of glacial sediments (Figs. 5 and 6). The location of the depocentres shows that both the Norwegian Channel Ice Stream and the ice-stream flowing westwards between Haltenbanken and Trænabanken were very important for sediment supply to the margin. It is; however, evident that the ice sheet/ice streams also reached the shelf edge adjacent to the Storegga Slide at several times during the three to four last glaciations. During interglacials or periods with less extensive ice sheets, contour-parallel currents and hemi-pelagic processes deposited fine-grained stratified sediments on the mid-lower slope. These deposits are thickest in the area of the Storegga Slide, where they appear to be interbedded with glacigenic deposits or slide deposits.

#### *3.3.1. Chronostratigraphy and seismic correlation*

Although poorly constrained, it is likely that most of the Naust R and O sediments were deposited during the last 400,000 years (Berg et al., 2005). Eemian interglacial sediments were found at or close to horizon INO3 in core MD99- 2289 directly north of the Storegga Slide (Haflidason et al., 2003). INO3 separates the Middle and Upper Till (King et al., 1987, 1991) in the Skjoldryggen area, and the glacial units IKU-B and IKU-A in the northwestern Haltenbanken area (Rokoengen et al., 1995). Although the amino-acid values in borehole samples give no conclusive evidence of age (Haflidason et al., 1998, 2001), we infer that the Middle Till/unit IKU-B represents Saalian deposits (marine isotope stage 6; MIS 6). It is likely that the glacial unit below, Unit R3, represents deposits from the extensive Elsterian glaciation(s) (MIS 8–10), as also indicated by Dahlgren (2002b) based on a seismic tie from borehole ODP 644A. A possible Eemian fauna was detected close to INO3 in borehole 6305/9 (Site 20) south of Frøyabankhola (Haflidason et al., 2001), and this finding guided the differentiation of Saalian and Weichselian deposits farther south (Fig. 7).

*3.3.2. The Elsterian glacial deposits—and stratified sediments above*

Unit R3 composes most of Sequence R north of 65°N, and appears as a very thick (200–350 ms twt), seismically incoherent unit with an extensive distribution west of the shelf edge (Figs. 5–7a). Locally, the unit also occurs on the shelf (Fig. 7a). It is commonly acoustically transparent, and characterised by a rather abrupt distal pinch-out (Fig. 6). 3D-seismic data have revealed a large debris-flow lobe in the lower part of the unit (Britsurvey, 1999; Nygård et al., 2003), and stacked glacigenic debris-flow lenses have been identified in the distal parts. The deposition of Unit R3 appears to be related to strong glacial erosion on the shelf (Fig. 6). The Sklinnadjupet Slide removed parts of the unit west of Skjoldryggen (Fig. 6) (Dahlgren et al., 2002b), as also indicated by the time thickness map (Fig. 7a). Our interpretation indicates that this slide is related to collapse features on the Helland Hansen Arch.

At the margin adjacent to the Storegga Slide, large parts of the glacigenic deposits were subject to sliding (Solheim et al., 2005). After the glaciation, the slide scars of this palaeo-slide 'R' were filled with more than 100–150 m-thick, contouritic / hemipelagic sediments (units R1/R2) (Fig. 8). In the Skjoldryggen region (Fig. 6) and at Haltenbanken, these stratified sediments can be traced to the outer shelf area (Rokoengen et al., 1995). A substantial part of the sedimentation probably took place when the ice margin was located on the inner—mid part of the shelf.

*3.3.3. The Saalian–the second last glaciation*

The lobate shape of the up to 200 m-thick unit of Saalian glacigenic sediments (Figs. 5–7b) shows that the major ice-stream flowing out between Haltenbanken and Trænabannabanken became depositional at the outer part of the shelf. Numerous laterally stacked 'till tongues' were built out (King et al., 1987, 1991) as the grounding zone of the ice sheet successively migrated westwards (Dahlgren et al., 2002a). These grounding line wedges resemble bodies described in the literature as 'till delta' or 'subglacial delta' (Larter and Vanneste, 1995). The underlying stratified sediments on the outer shelf appear to be undisturbed, and the 'massive' unit shows a distinct 'pinch-out' on the upper slope (Fig. 6).

The Saalian Ice Sheet probably did not extend to the shelf edge in the outer Trænabanken and Haltenbanken regions (Figs. 5 and 7b), as previously proposed by King et al. (1987, 1991). Prograding 'till tongues' show evidence of an active ice front at mid–outer Haltenbanken, with deposition of hemipelagic sediments at the outer shelf and slope (unit IKU-B; Rokoengen et al., 1995). Saalian deposits are apparently absent in Frøyabankhola (Figs. 1 and 7b), but reappear at the shelf edge and upper slope off Møre and farther south. Although the Holocene Storegga Slide has removed much of these sediments, glacigenic sediments at least 200 m thick probably existed at the shelf edge/upper slope from outer Frøyabanken to Langgrunna. The sediments have the character of a trough mouth fan ('the Buadjupet Fan') (Figs. 7b and 8), showing that a major ice-stream between Frøyabanken and Buagrunnen supplied much of the material.

The amount of stratified sediments deposited on the slope during the period between the Saalian and Weichselian glaciations appears to be thin compared to the equivalent unit deposited after the Elsterian glaciation (R1/R2) (Fig. 8). At the outermost Haltenbanken, a c.15 m-thick layer of stratified sediments occurs beneath the Weichselian tills.

*3.3.4. The Weichselian–the last glaciation*

The Late Weichselian Ice Sheet extended to the shelf edge along the entire margin (Fig. 7c), with enhanced debris transport along ice-stream paths (Ottesen et al., 2001; Taylor et al., 2002; Sejrup et al., 2003). Glacigenic deposition beyond the shelf edge appears to have occurred mainly during the last glacial maximum. Correlation of radiocarbon dating results and high-resolution seismic lines (B. Hjelstuen, pers. comm. 2003) indicates that the supply of glacigenic debris beyond the shelf edge ceased at c. 16 ka BP. The prominent Skjoldryggen Ridge (Figs. 1, 6 and 7c)

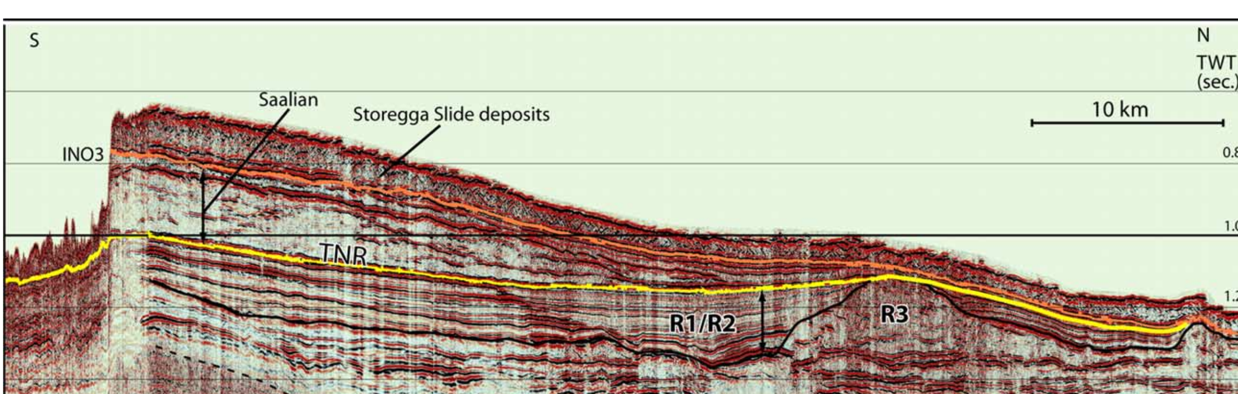


Fig. 8. Seismic profile along the slope north of the deep incision of the Storegga Slide. See Fig. 1 for location. The glacigenic unit R3 (Elsterian age) appears to be a remnant after the large palaeo-slide 'R', and this slide scar was infilled with stratified sediments (R1/R2). A thick sequence of Saalian debris flows was deposited above ('the Buadjupet Fan', see Fig. 7), but no major sliding occurred in this area after this glaciation. TNR, Top Naust R.

represents a terminal moraine, possibly push-shaped during a late re-advance. An ice-stream is inferred to have flowed along the northwestern branch of Sklinnadjupet, forming a depocentre at the shelf edge north of where the Saalian deposits terminate (Figs. 5 and 7c). Although evidence is lacking that Early-Mid Weichselian ice sheets reached the shelf edge, deposition may have occurred on the outer shelf.

In the northwestern part of Haltenbanken and on the adjacent upper slope, an up to 150 m-thick wedge comprising several 'till tongues' and debris flow lobes occurs above stratified sediments. Farther south, the Storegga Slide displaced and remoulded these glacigenic deposits, utilising the stratified sediments below as a glide plane. On the Møre shelf, there is a complex geology with several depositional and erosional cycles, indicating the former presence of a very dynamic ice sheet that possibly deposited more than 100 m of the glacial debris on the upper slope west of the main ice-drainage routes (Fig. 8). Glacigenic debris-flow lenses accumulated to a total thickness of c. 400 m on the North Sea Fan (Figs. 2c and 7c), showing the great importance of the Norwegian Channel Ice Stream during the last glaciation. The main supply of glacigenic debris appears to have occurred during the Late Weichselian (Sejrup et al., 2003).

## 4. Interpretation and discussion

### *4.1. Age of the sequences*

If the age suggested by Eidvin et al. (1998) for Naust W is correct (>2.3 My), the sediment supply to the northern shelf areas must have been extremely high in the period c. 2.7–2.3 Ma (Figs. 2a and 3b). Only a very strong Neogene uplift phase directly before and during this period, combined with frequent and large ice sheets eroding weathered bedrock and loose Tertiary sediments, could possibly explain this. In comparison, the accumulation rate in the period 0.4–2.3 Ma (Naust U and S) must have been very low. Similarly, it must also have been very low compared to the last 0.4 My (Naust R and O). Evaluation of the ages based on different datasets reveals a c. 1 My discrepancy with the previously defined horizon TND (located within Naust S) (Eidvin et al., 1998; Dahlgren et al., 2002b), and thus, at present, we cannot confidently assign ages, at least to the three oldest sequences. As previously mentioned, Naust W is likely to be much older than 1.1 My, and the uppermost part of Sequence S appears to be younger than 0.78 My.

### *4.2. Progradation of the margin and depositional environment*

The palaeo-shelf edge in the Haltenbanken–Trænabanken region prograded nearly 100 km westwards during Naust W time (Fig. 3). This corresponds poorly with the suggested environment in the period 2.7–1.1 Ma ('moderate glaciations/limited degree of ice flow onto the shelf') inferred by several authors (Henrich and Baumann, 1994; Mangerud et al., 1996; Hjelstuen et al., 1999). We disagree with this and postulate that a large portion of the huge, prograding sediment wedge was formed during numerous ice-sheet advances to the palaeo-shelf edge. In the Trænabanken/Trænadjupet area, Henriksen and Vorren (1996) concluded that the oldest part of the Naust sequence was deposited in a proximal position to grounded ice sheets on the shelf. A fairly high content of angular gravel fragments in lower Naust has been observed in exploration wells (T. Eidvin, pers. comm.), indicating that a glacial environment on the shelf was common in Late Pliocene time. Boreholes at Haltenbanken show till in the seismic unit IKU-I, which is a part of Sequence W (Rokoengen et al., 1995).

Some palaeo-shelf surfaces represent angular unconformities (Fig. 3e), which were formed either by glacial or marine/fluvial erosion. The Naust period was also characterised by sea-level fluctuations, and marine erosion, particularly of the inner shelf, was probably intermittently an important process in redistributing sediments westwards. Meltwater rivers may have supplied sediments directly to the shelf or shelf break, particularly in the period before the over-deepened fjords were formed. However, the dominant sediment matrix of the Naust Formation is clay/silt, and well logs show only some layers of sand (Rise and Rokoengen, 1991). It is, therefore, unlikely that rivers have contributed substantially to the extensive progradation during ice-free periods.

In the Møre region and farther south, Naust W is thin, possibly indicating that the glaciations were of lesser importance in southern Scandinavia during the early Naust period. During the next period (U and S time), the glacial processes in the southern region became more important than earlier, and the Norwegian Channel Ice Stream probably started to operate in this period. At the same time, the shelf edge was built out close to its present position (Figs. 2 and 3). Compared to the earlier Naust periods, the Norwegian Channel Ice Stream became very important during Naust R and O time (Fig. 3d). The ice sheets and ice streams extended out to the entire shelf edge at several times during the last three to four glaciations, and deposited significant volumes of sediment at the margin (Figs. 3, 5 and 6).

It is often difficult to decipher the depositional processes directly from the seismic pattern, but hemipelagic and contouritic sediments probably make up only a small portion of the total Naust sediment volume. Various down-slope processes appear to have dominated. In the Storegga Slide area and at the North Sea Fan, parts of the glacigenic debris deposited on the slope were displaced through several large slide events (King et al., 1996; Bryn et al., 2003; Nygård et al., 2005; Solheim et al., 2005).

*4.3. The large slides–relation to extensive glaciations*

The slide deposits in the northern part of the Storegga slide area are commonly interbedded with stratified sediments, and at least the last three large slides appear to be events related to processes controlled by climatic cycles (Bryn et al., 2003, 2005; Solheim et al., 2005). The preconditions for the third and second large slides (slides 'S' and 'R') appear to be similar to those for the Holocene Storegga Slide, and the cartoon in Fig. 9 illustrates that the sliding history is closely related to the Quaternary development of the Møre margin (Rise et al., 2002).

Although the large slides apparently occurred shortly after extensive shelf glaciations, it is important to note that there is no indication of major sliding in the northern part of the Storegga area after the Saalian. During this glaciation, glacigenic deposits up to 200 m thick were deposited above stratified sediments in the slope area where we, today, see the deepest incision of the Holocene Storegga Slide (Fig. 8). Weichselian glacigenic deposits accumulated above, and a total thickness of c. 300 m of glacigenic sediments occurred on the upper slope outside Buadjupet/Onadjupet after the last glaciation. This Saalian/Weichselian depocentre was possibly of great importance for the final development of the retrogressive Holocene Storegga Slide.

The seismic stratigraphy and inferred age of unit R3 indicate that the second last major slide in the Storegga area occurred at 200–300 ka BP. The major Tampen Slide on the North Sea Fan extended to the southern part of the Storegga Slide Complex (King et al., 1996). The age of this slide is inferred to be in the time interval Late Saalian–Early Weichselian (Nygård et al., 2005).

## 5. Conclusions

During the last c. 2.7 My, large quantities of glacially derived material were transported westwards from the onshore and inner shelf areas, gradually building out the current shelf. The maximum thickness of the Naust Formation is recorded along the present shelf edge, exceeding more than 1000 m over extensive areas (Fig. 3a).

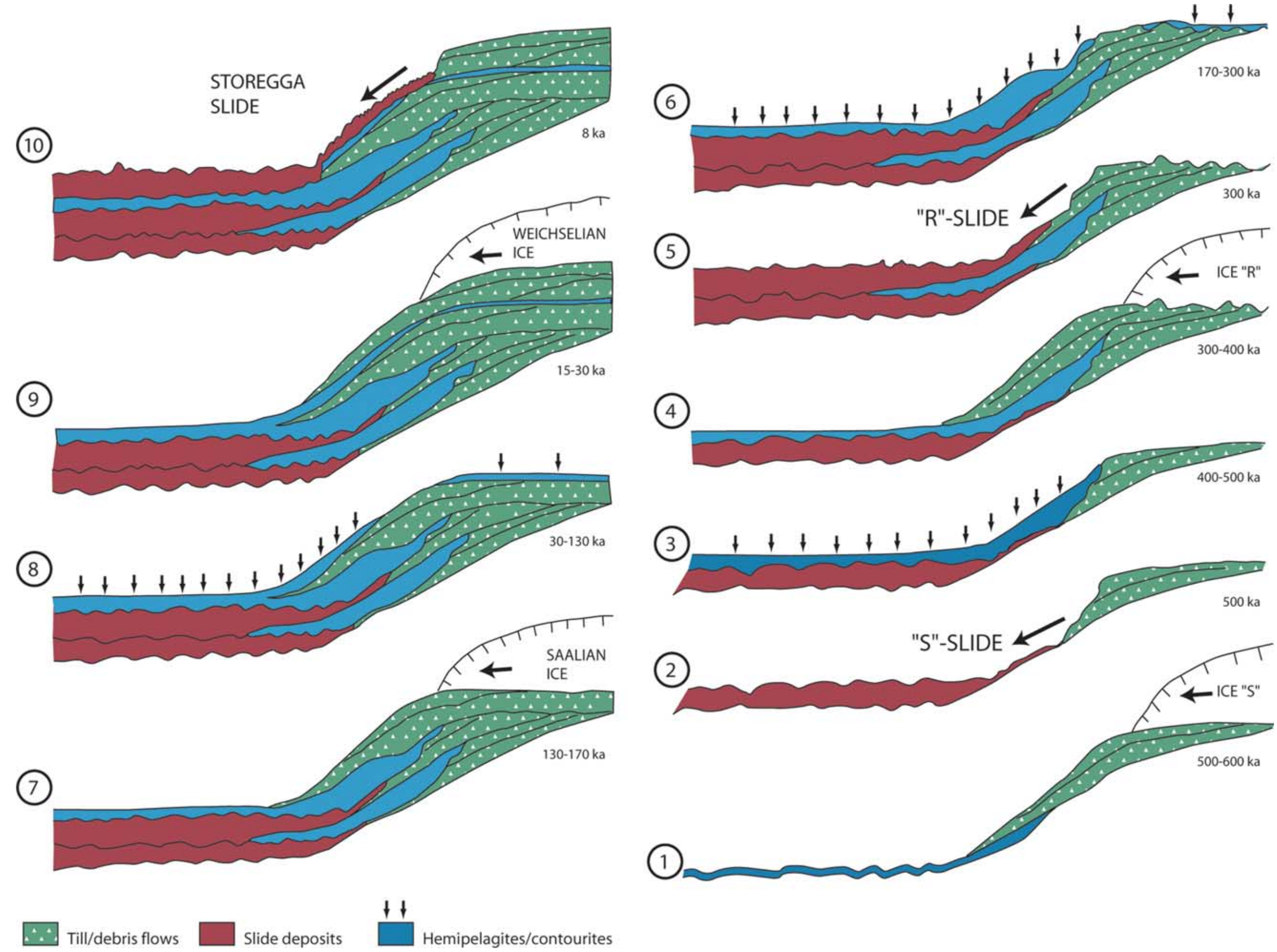


Fig. 9. Conceptual model illustrating the development of the Møre margin during the last c. 0.5 My. The last three gigantic slides seem to be cyclic events occurring after extensive glaciations. Note that weak layers in the fine-grained sediments infilling the slide scars acted as glide planes for younger slides.

The wide shelf in the Haltenbanken-Trænabanken region is mainly a result of an extensive progradation of sediment wedges into a basin of intermediate depth with a gentle seaward dip, expanding the shelf 100–150 km westwards (Fig. 2a). Less sedimentary material was supplied to the Møre shelf, but the narrow shelf in this area is mainly the result of a steeper dip of the pre-existing slope towards a much deeper basin, causing a larger proportion of sediments to be dispersed towards the deep ocean (Fig. 2b).

In early Naust time, the most extensive progradation occurred in the Lofoten–Haltenbanken area (Fig. 3b). The importance of glaciations at the Møre shelf and farther south increased through the Pleistocene period. The Norwegian Channel Ice Stream transported enormous amounts of glacigenic debris to the North Sea Fan during the last 3–4 glaciations (c. 400,000 years) (Fig. 3d).

The last three large slides in the Storegga area probably occurred shortly after extensive glaciations fed glacial debris beyond the shelf edge (Fig. 9). The fine-grained contouritic and hemipelagic sediments deposited on the slope during ‘ice-free’ periods hosted glide planes beneath the slides.

The chronostratigraphic data are partly inconsistent. Naust W is older than 1.1 My, and may be more than 2.3 My The two youngest sequences (R, O) probably represent the last c. 400,000 years.

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