The deglaciation history of Trondheimsfjorden and Trondheimsleia, Central Norway

Leif Rise, Reidulv Bøe, Harald Sveian, Astrid Lyså & Heidi A. Olsen


A dense grid of seismic data and core data from several boreholes up to 70 m deep, have been studied to determine the Quaternary stratigraphy in Trondheimsfjorden and Trondheimsleia. In the outer part of Trondheimsfjorden with water depths of 600 m, the basement rocks were glacially eroded to nearly 1300 m below sea level, and up to 750 m of sediments are present. Most of the sedimentary succession is acoustically stratified and was deposited during the last deglaciation when ice and water from a large sector of the Scandinavian ice sheet drained into the fjord. Chaotic seismic reflection patterns show that mass-wasting processes were common in some areas. At 13-12.5 ka ¹⁴C BP, the ice margin was located near the coastline west of Trondheimsfjorden, and up to 360 m of stratified sediments were deposited in the northern part of Trondheimsleia. The ice calved and receded rapidly in the deepest part of Trondheimsfjorden, and glaciomarine conditions were established near Trondheim around 12 ka ¹⁴C BP. The maximum sedimentation rate was probably 0.5-1 m/year both in Trondheimsleia and between Trondheim and Agdenes. During Allerød time the ice recession continued east- and southwards from Trondheim, and glaciomarine sediments were also trapped in the inner basin west of Skogn. These sediments were then eroded during the glacial re-advance to the line of the Tautra Moraines in the early part of the Younger Dryas (11-10.6 ka ¹⁴C BP) and partly re-deposited as tills and glaciofluvial deposits. Subsequent recession included minor re-advances, and at ca. 9.5 ka ¹⁴C BP the present catchment area was largely deglaciated. At this time, Trondheimsfjorden extended from Orkdalen to Snåsa, covering an area more than twice at the present time. In the second half of the Preboreal, the ice margin receded beyond the present water divide, and Trondheimsfjorden received meltwater run-off from glacial lakes between the ice and the water divide. Hemipelagic sedimentation, with generally decreasing sedimentation rates towards recent times, prevailed during the Holocene.

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Introduction and geological setting

Trondheimsleia follows along the trace of the Hitra-Snåsa Fault of the Møre-Trøndelag Fault Complex (MTFC) (Boe et al. 2005). Another major fault of the MTFC is interpreted to occur along Trondheimsfjorden from Orkdal to Verdal, and a third one from Rissa to Ver- ran. Trondheimsfjorden forms a deep fjord system with several main branches (Fig. 1) in the extension of the valleys Orkdalen, Gauldalen, Stjørdalen and Verdalen. Cambrian-Silurian metamorphic rocks predominate in the study area, with down-faulted Devonian sandstones and conglomerates locally present along the western side of Trondheimsleia (Wolff 1976; Boe et al. 2005). Compared to most other fjords in Norway, the central fjord is wider, with a shallow central part. The deepest basin (500-617 m b.s.l.) occurs between Trondheim and Agdenes. Pronounced thresholds occur at the entrance to Trondheimsfjorden at Agdenes (ca. 330 m b.s.l.) and at Tautra (ca. 50 m b.s.l.).

Directions of ice movement (Fig. 1b) became gradually more controlled by topography as the ice thinned and the ice margin receded (Reite 1994). Ice recessional lines for the Trondheimsfjorden area, spanning the time interval 12.5-9.5 ka ¹⁴C BP (Sveian 1997) show that the Tautra Moraines, formed in early Younger Dryas time, represent the most pronounced line. In the first half of the Preboreal (10-9.5 ka ¹⁴C BP), the glaciers retreated rapidly from the valleys, and Trondheimsfjorden emerged as a complex fjord system with long branches into the present day valleys (fjord-valleys). From its southernmost end in Orkdalen, the fjord extended ca. 200 km towards the northeast to Snåsa (Fig. 1c). At that time, a sound north of Beitstadfjorden connected Trondheimsfjorden to Namsfjorden, and the Fosen peninsula was one of the largest islands in Norway (Sveian & Solli 1997a).

During the deglaciation, the ice divide was located more than 100 kilometres east and southeast of the present water divide (Fig. 1a), and ice and water from a 50 000-60 000 km² area drained towards Trondheimsfjorden (Sollid & Kristiansen 1983; Borgstrøm 1989; Thoresen 1991). By comparison, the fjord presently receives precipitation from a 20 000 km² catchment area (Sakshaug & Killingtonveit 2000). At the end of the Preboreal, the ice margin had receded beyond the water divide, and for a short period the final meltwater drainage towards Trondheimsfjorden was via large ice-dammed lakes located between the ice sheet and the water divide (Sollid & Kristiansen 1983; Borgstrøm 1989; Reite 1997).

The first seismic investigation of Trondheimsfjorden, in 1971 and 1972, was in connection with a search for
Mesozoic sedimentary rocks (Sund 1973; Ofstedahl 1975). Based on these data, Ofstedahl (1978) recognised a basin with thick clay deposits northwest of Trondheim. Seismic data collected in 1988-1990 by the Geological Survey of Norway (NGU) led to the compilation of map-sheets Leksvik (Reite & Olsen 2002). Profiling along the southern fjord slopes in 1986-1987 focused on stability and erosional processes (Bjerkli & Olsen 1989). Beitstad-
Fiorden (Fig. 1) was mapped in 1986-1988 in a search for Mesozoic basins (Bøe & Bjerkli 1989). In 1999-2002 NGU, in cooperation with the Norwegian Geotechnical Institute (NGI), carried out detailed investigations of Trondheimsleia and Trondheimsfjorden for gas pipeline routes. An extensive seismic database and a number of 14C dating results on samples from deep boreholes strongly increased our understanding of the chronology and depositional processes, particularly in the Holocene succession (Lyså et al. 2002; Bøe et al. 2003a,b, 2004).

Dating results from the Late Weichselian succession are mainly obtained from the northern part of Trondheimsleia, west of Agdenes. However, the seismic stratigraphy and onshore data (Reite 1983, 1986a,b, 1987, 1990, 1994, 1995; Reite et al. 1982, 1999; Sveian & Bjerkli 1984; Sveian & Solli 1997a,b) provided a good basis for an improved understanding of the stratigraphy in Trondheimsfjorden. In this paper, we present a stratigraphic overview of the succession, and propose a geological model for the different phases of the deglaciation of the fjord area.

**Methods and database**

Complete swath bathymetric coverage, below the 20 m depth contour, was obtained during three cruises in different parts of the fjord: Norwegian Petroleum Directorate in 1997 (acquisition by Geoconsult); NGU and Industrikraft Midt-Norge in 1999 (acquisition by Norwegian Hydrographic Survey) and Naturgass Trøndelag (acquisition by Norwegian Defence Research Establishment) (Lyså et al. 2002; Bøe et al. 2003b). Multibeam bathymetry has been used for interpretation of sedimentary environment and slide history (Bøe et al. 2003b, 2004).

The shallow seismic database consists of various types of both analogue and digital seismic data (Fig. 2). Most of the data were acquired by NGUs research vessel FF Seisma in 1999-2002 in order to investigate sub-sea gas pipeline routes (Lyså et al. 2002; Bøe et al. 2003a, 2003b, 2004). Simultaneous recording by sleevegun (15 cubic inches) and boomer were acquired for 850 km, while 2000 km were collected for high-resolution studies (boomer and Topas). In addition, analogue shallow seismic sparker data were acquired in 1972-1981, of which ca. 1000 km have been interpreted. Six conventional seismic lines collected by the Norwegian Petroleum Directorate (NPD) in 1997 (recorded with a 700 m long streamer) have also been interpreted. The location of three of these lines is shown in Fig. 3. For calculation of sediment thickness, an average sound velocity of 1700 m/s was applied. Typical resolution (milliseconds two-way transit time; i.e. ms twt) and penetration (ms twt) in fine-grained sediments for various seismic sources are respectively: Topas (0.5, 40-120), boomer (4-6, 200-400), sleevegun/sparker (8-10, 500-600) and conventional seismic (14-18, >800).

During a cruise with the drilling ship M/S "Bucentaur" in 1999, 4 boreholes (16 to 69.9 m deep) were drilled for stratigraphic/sedimentological studies (S-cores) and 21 boreholes (up to 28 m deep) were drilled mainly for geotechnical evaluation of slopes (G-cores). Wireline operated push sampling equipment developed by Fugro Ltd. was applied to obtain ca. 80 cm long high quality cores (72 mm diameter) from the bottom of the borings at pre-defined levels. In the geotechnical boreholes, downhole cone penetration tests (CPTs) were performed,
commonly in the intervals between the cores. In addition, 20 gravity cores, up to 2.75 m long, were taken mainly for sedimentological studies (GC-cores). Some of the G-cores were described and analysed for index soil properties in the ships laboratory, but most of them were brought to NGI for index tests and advanced geo-
technical tests. The S- and GC-cores were X-rayed (XRI) in NGUs laboratory, and investigated by a non-destructive multi-sensor core logger (MSCL; P-wave velocity, gamma density and magnetic susceptibility). The MSCL measurements together with XRI, were of great importance in the decision-taking for the further laboratory

<table>
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Table 1. \(^{14}C\) ages were reported in conventional radiocarbon years BP (before present = 1950) in accordance with the international convention (Stuiver & Polach 1977). All calculated \(^{14}C\) ages have been corrected for fractionation so as to refer the results to be equivalent with the standard \(^{13}C\) value of -25‰ (wood). An ocean reservoir age of 400 years has been subtracted from the conventional \(^{14}C\) age to obtain the reservoir corrected age (not on wood fragments). AAR-samples: AMS Laboratory, University of Aarhus, Aarhus, Denmark. KIA samples: Leibnitz AMS Laboratory, Christian-Albrechts-Universität, Kiel, Germany.
program including sub-sampling for \(^{14}\)C dating. Unfortunately, the P-wave measurements gave reliable results for only a few cores. Only cores mentioned in the text are shown in Fig. 2. Material for radiocarbon dating was also obtained from the 31 m long core MD99-2292, taken by the research vessel "Marion Dufresne" (Bøe et al. 2003b).

A total of 42 samples were dated by the \(^{14}\)C AMS method. The main objective was to obtain ages of mass-movements in order to be able to calculate their frequency and erosive capacity (Bøe et al. 2003b), and to obtain better control of the age of the various strata. Sub-samples were carefully taken in order to avoid sediments from slides and turbidites. The material was prepared at Aarhus Universitet (Karen Luise Knudsen), before foraminifers were picked under a microscope. Where it was not possible to obtain enough material for dating by picking only one species of foraminifers, total benthic or total planktonic fauna had to be used. Benthic and planktonic foraminifers were not mixed in samples for dating. In some cases, benthic foraminifers had to be supplemented with ostracod shells and/or mollusk shells to obtain enough material for dating. If necessary, shell fragments with sharp edges were also used, however only shell fragments that apparently had not been transported. In borehole S2 three wood fragments were dated. The materials used and the dating results applied in this study are shown in Table 1.

The ages presented in this paper are all \(^{14}\)C-years before present (BP), and dating of shells/foraminifers have been corrected for a reservoir age of 400 years.

**Basement relief**

A bedrock relief map, based on all available seismic data (Figs. 2, 3), is shown in Fig. 4. As few seismic lines penetrate down to the crystalline basement in the deepest basins, contours are only drawn to 1100 ms twt below sea level (b.s.l.). The deepest fjord basin stretches from north of Trondheim to the Agdenes threshold. In the basin, the crystalline basement is generally deeper than 1100 ms twt b.s.l., reaching a maximum of nearly 1600 ms twt (ca. 1300 m b.s.l.). More than 500 m high mountains occur close to the fjord west of Trondheim, and the bedrock relief is thus ca. 1800 m over a distance of ca. 10 km. The topography of the fjord suggests that easily erodible Jurassic rocks were present in the central part of the fjord before the glaciations, along faults paralleling...
the MTFC (Bøe et al. 2005). Downfaulted Jurassic basins are present in Beitstadfjorden, Edøyfjorden and Frohavet (Fig. 1, Sommaruga & Bøe 2002).

The bedrock relief defines trenches in the extensions of Orkdalen, Gauldalen and Stjørdalen, all becoming gradually deeper towards the central and outer fjord. During the earliest Quaternary glaciations, the ice may have followed existing fluvial valleys, and the initial topography became increasingly developed through several tens of glaciations over the last 2-3 million years. The topography of the basement relief (Fig. 4) indicates that glacial erosion has mainly occurred along fractures and faults. The main trench along the northwestern side of the fjord gradually becomes deeper, southwest of Tautra. Seabed multiples complicate the interpretation, but the trench probably intersects the bedrock threshold below the Tautra Moraines before continuing northeastwards. At Ytterøy it splits, and the eastern branch can be followed to the embayment at the mouth of Verdalen (Sveian & Bjerkli 1984). Between the Frosta peninsula and Midtfjordsgrunnen (< 10 m b.s.l.) north of Trondheim, the bedrock relief is irregular and commonly shallower than 200 m (Fig. 4).

Seismic stratigraphy, borehole data and dating results

Northeastern Trondheimsleia

Two borings in Trondheimsleia (Fig. 3) give information on the upper part of the sedimentary succession. G11 (309 m water depth) is located southwest of Garten, at the northwestern shoulder of a narrow trench (Fig. 5). Seven push cores (each ca. 80 cm long) were taken at intervals 4 m apart. Between the sample intervals, cone penetration tests (CPTs) were performed, measuring the cone resistance and undrained shear strength to the termination of the borehole (28 m below the seabed). The uppermost core (0-0.8 m) comprises sandy clay with a high content of gravel, interpreted as ice rafted debris (IRD) from icebergs during the Younger Dryas. The rest of the borehole consists of silty clay, with an increasing amount of 2-4 mm thick silt and sand layers in the lower part (13-28 m). The cores show that some gravel fragments occur throughout, indicating deposition in a glaciomarine environment. The radiocarbon dating results gave 12 780 14C-years BP at 4.55 m depth and 12 670 14C-years BP at 24.3 m depth (Table 1). The results indicate some reworking, but as 40-50 m of stratified sediments...
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It is likely that the oldest deglaciation sediments in this area were deposited close to 13,000 \(^{14}\)C-years BP.

The thickest sediment succession in Trondheimsleia occurs between Agdenes and Garten (Figs. 3, 6), where a 1-3 km wide and more than 10 km long, northeast-trending basin contains up to 400 m of stratified sediments. This basin ends at a threshold south of Garten (Figs. 6, 7). Southwest of this threshold 50-200 m thick stratified sediments occur. An ice marginal deposit (till) has previously been suggested to be present at the threshold (Ottesen et al. 1995). New seismic data show that more than 50 m of stratified sediments drape parts of the ridge (Fig. 7), but seismic correlation of strata across the threshold has not been possible.

The 16 m long core S1 (408 m water depth) is located ca. 2.5 km northeast of the Garten threshold (Figs. 6, 7, 8). The upper 2.5-3 m consist of gravelly sand rich in shells and shell fragments, and two radiocarbon dates indicate that this layer was formed during the Younger Dryas/Early Holocene (Table 1). The layer can be resolved on Topas lines, and has been mapped over a large area (Boe et al. 2003a,b). At 3-10 m depth, laminated silty clay with varying content of sand and gravel is present. At 10-16 m, the sediments become coarser, and interbedded laminae/layers of silt, sand and gravel (occasionally with cross-lamination) occur. Dating of foraminifers in silty clay at 15.8 m below the seabed gave 12,230 \(^{14}\)C-years BP.

In the basin, between the thresholds in Stjønnefjorden and south of Garten, sub-parallel reflections occur below a reflector denoted X (ca. 40 m below the seafloor at the site of S1; Fig. 7). Above reflector X, several depositional sequences of variable thickness and acoustic character occur. It is not possible to trace reflector X confidently on the multichannel seismic line (Fig. 6), but the approximate level is indicated.

Outer Trondheimsfjorden between Agdenes and Korsfjorden

At the Agdenes threshold, the bedrock topography is irregular, and side echoes make interpretation of the seismic data difficult. Sediments interpreted as till occur locally (Boe et al. 2003a), but there are no seismic data to indicate that thick ice marginal deposits occur above the bedrock. No marginal moraines have been mapped in the adjacent onshore area. The deepest point of Trondheimsfjorden (617 m) is located ca. 4 km southeast of the Agdenes threshold.

Boring S2 (572 m water depth) west of Rissa reached 69.9 m below the seabed (Figs. 3, 9, 10b). A seismic line near the borehole location shows that five seismic units (A-E) can be distinguished in the upper section (Fig. 10a). Reliable sound velocities were logged only in a few cores, but 1550-1600 m/s appear to give a confident correlation between seismic units (A, B, C) and lithological logs (Fig. 10). Stable low mud pressure during drilling indicated that the depth interval 47.5-67 m is dominated by sand (Unit D2). The lithologies of the cores at 50 m and 55-56 m depth support this interpretation. A few intervals with increased mud pressure indicate fine-grained beds up to 0.5 m thick. Foraminifers and shells from 55.55 m depth yielded an age of 9730 \(^{14}\)C-years BP. Unit E is acoustically stratified, and as drilling parameters below 67 m indicate several clay layers in the sand, we infer that the boring...
Figure 6. Multichannel seismic line along the northernmost part of Trondheimsleia. Nearly 400 m of deglaciation sediments are deposited above the crystalline basement/till (black line) in the narrow basin between the Garten and Stjørnfjorden thresholds. An interval of this line deviates from the deepest trough, and side echoes from the flanks of the basin complicate the interpretation. The indicated 12.2 ka ¹⁴C time-line is supported by a radiocarbon dating at 15.8 m in boring S1. Horizon X represents a marked shift in the depositional environment. See Fig. 3 for location.

Figure 7. Boomer line crossing the threshold south of Garten in Trondheimsleia. Note the change from predominantly parallel-stratified sediments below horizon X, to a more variable acoustic signature above it. The levels of dated samples in the 15.8 m deep boring S1 are indicated. Note that glaciomarine sediments apparently drape till/bedrock ridge at the Garten threshold. See Fig. 3 for location.
terminated in the uppermost part of this unit (Fig. 10). If this is correct, the sound velocity in the sandy unit D2 is 1700-1750 m/s. The lowermost core (69.5-69.9 m) comprises cross-bedded and cross-laminated sand with some thin silty and clayey layers. Dating of foraminifers at 69.74 m gave 9990 \( ^{14} \text{C} \) years BP.

At site S2 (Fig. 3), the seismic data show a marked shift ca. 100 m below the seabed (Fig. 9). Seismic reflectors below unit E are mainly sub-parallel to parallel, while above, the seismic character is much more variable, with two major erosion surfaces and uneven thickness of units both across and along the fjord (Figs. 10a, 11). It appears that the composite thicknesses of the Holocene units A-D decreases towards Geitaneset-Rødberg, and increases again in the central fjord basin (Fig. 9). Unit E is very thick at Geitaneset-Rødberg, and particularly the upper part of this unit thins towards the northwest. Although uncertain, we postulate an age of 11 000 \( ^{14} \text{C} \) years BP for the base of Unit E (Fig. 9).

**Orkdalsfjorden, Gaulosen and the central fjord basin northwest of Trondheim**

More than 300 m of flat-lying, stratified sediments occur at the southern slope of Orkdalsfjorden, whereas the thickness is only 10-30 m at the northern slope. The sediments are truncated at the southern slope of the fjord, and up to 40 m of acoustically light and weakly stratified sediments drape the older succession. Up to 150 m of sediments occur in the deeper part of the fjord.
Figure 10. A) Boomer line along the fjord west of Rissa showing the different acoustic signatures of locally defined seismic units (A-E). The proposed lithological model is based on samples/drilling parameters in borehole S2, and the age model on the twelve $^{14}$C dates (Fig. 10b, Table 1). Sound velocity data for exact time-depth correlation do not exist. B) Stratigraphic log of the cores in borehole S2 with $^{14}$C dating results. See Fig. 3 for location.
In the outer part of Orkdalsfjorden and its extension Ytre Orkdalsfjorden, several sequences with chaotic seismic signature occur, indicating that mass movements were common during the deglaciation and the Holocene (Fig. 12) (Bøe et al. 2003b). These sequences thin northwards, and the internal seismic pattern becomes gradually more parallel-layered towards Korsfjorden. Between Ytre Orkdalsfjorden and Gaulosen, there is an abrupt change in acoustic character (Fig. 12). The more than 200 m thick, parallel-layered succession in Gaulosen indicates stable settling from suspension during the deglaciation. The variable acoustic pattern in the upper ca. 50 m (Fig. 12) reflects a depositional environment dominated by sediment waves and meandering sub-sea channels extending from Gaula (Bøe et al. 2004). The sediment waves have amplitudes up to 6 m and wavelengths of 200 m to several kilometres. In Ytre Orkdalsfjorden, the channel joins a channel from Orkdalsfjorden, and continues to Geitaneset. These channels were most likely important distribution routes for turbidity currents towards the deep fjord. In Gaulosen, the parallel reflections in the pre-Holocene succession are acoustically blanked, probably by shallow gas (Fig. 12, Gunleiksrud 1982).

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Central Trondheimsfjorden (Korsfjorden and Flakksfjorden) and the narrow outer Trondheimsfjorden (Fig. 3) contain up to 750 m of sediment, and were the main depositional areas during the deglaciation (Fig. 9). Only Holocene sediments have been sampled from the deep basins. In core MD99-2292 (Fig. 3), foraminifers in silty clay at 21 m below the seafloor gave an age of 7510 14C-years BP (Table 1).

**The southeastern fjord basin between Trondheim and Stjørdal**

The basement relief becomes gradually shallower along a trench from Trondheim to Stjørdal (Figs. 4, 9), evidently representing a continuation of Stjordalen. A wide depression, extending southwest from Åsenfjorden, joins this trench north of Ranheim (Figs. 3, 4). The thickest sedimentary succession (150–200 m) occurs along the axis of the trench. Several acoustically incoherent units of varying thickness are present. Some of these have been interpreted as slide deposits (Bøe et al. 2003b). In the northern part of the trench and north of it, the sediments are dominantly parallel-stratified.
Figure 13. a) Multichannel seismic line from Geitaneset to Ytterøy, crossing the Tautra threshold and boring S4 in the inner basin. The 9 ka $^{14}$C time-line is based on dating results, whereas the 10 ka $^{14}$C time-line is inferred. The thick, acoustically incoherent sediment succession between the inner basin and the Tautra Ridge represents till, much of it probably sourced from Allerød sediments deposited in the inner basin before the Younger Dryas readvance. b) Enlarged part of the seismic line showing the Younger Dryas glaciofluvial succession that makes up most of the Tautra Ridge. Note parallel-stratified Allerød sediments above the crystalline basement. See Fig. 3 for location.
A four km wide ice marginal ridge occurs across Stjørdalsfjorden between Skatval and Midtsand. The ridge has been correlated with the Tautra Moraines at Tautra (Reite et al. 1982; Reite 1994; Reite & Olsen 2002), and the new seismic data confirm the position of the Younger Dryas ice contact zone west of Tautra-Frosta, in the outer part of Åsenfjorden and across Stjørdalsfjorden. In Åsenfjorden, the ice marginal deposits have a thickness of nearly 100 m. Stratified sediments of assumed Allerød age occur below ice proximal Younger Dryas deposits in Åsenfjorden, Stjørdalsfjorden and west of Skatval.

**Midtfjordsgrunnen and the northern central fjord west of Tautra**

Midtfjordsgrunnen, with water depths locally less than 10 m, is the shallowest part of a 10x15 km plateau, extending from Frosta/Tautra (Fig. 4). Glaciomarine sediments commonly cover the irregular bedrock relief of the plateau and its slopes (Reite & Olsen 2002; Bøe et al. 2003b), but outcropping bedrock frequently occurs, especially along its slopes. The sediment thickness is generally less than 50 m, but may locally exceed 100 m.

A SW-NE trending bedrock trench along the northwestern side of the fjord extends from Korsfjorden towards Tautra (Figs. 4, 13). The water depth decreases from 470 m in the southwest to ca. 200 m where the Tautra Ridge starts to rise. Borehole S5, located at 360 m water depth in the trench northwest of Midtfjordsgrunnen (Fig. 3), was drilled to 17.8 m below seabed (Bøe et al. 2003b). Dating of foraminifers in silty clay at 16.8 m gave an age of 10 160^{14}C-years BP, and from the seismic data it was inferred that frequent mass movements occurred during the Younger Dryas and earliest Holocene (Bøe et al. 2003b).

**The Tautra area**

The ice marginal deposits at the threshold west of Tautra comprise a wide, complex formation, where the most pronounced, 3 km long, NW-SE trending crest is named the Tautra Ridge. This ridge is locally less than 50 m below sea level. Towards the SSE the Tautra Ridge disappears, but its steep western slope continues for ca. 2 km, marking the grounding line of the Younger Dryas ice front. The Tautra Ridge shows a complex internal architecture (Reite & Olsen 2002). Glaciofluvial deposits, dipping ca. 15 degrees towards the southwest, are up to 150 m thick (Fig. 13). They predominantly occur above the narrow bedrock trench, indicating mainly subglacial water discharge along this depression. Seismic data show pronounced glacial erosion on the proximal side of the ridge. In the trench northeast of the Tautra Ridge approximately 100 m of till occurs (Figs. 13, 14). Parallel-stratified sediments occur below the till (Fig. 14).

Shaded relief images from multibeam bathymetry reveal a fluted seafloor north and northwest of Tautra (Fig. 15). Seismic data show topographic features of varying size, including mega scale lineations and drumlin-like forms. The southwestern part of the Tautra island represents a similar ice-sculptured drumlin.

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*Figure 14. Seismic section (sleevegun) crossing the narrow trench northeast of Tautra. Note thick till units above stratified, Allerød, glaciomarine sediments. The postglacial sediment succession is up to 50 m thick. See Fig. 3 for location.*

*Figure 15. Shaded relief image showing megascale glacial lineations (arrows) formed during the early Younger Dryas readvance towards Tautra. Illuminated from the northeast. See Fig. 3 for location.*
The inner fjord basin southwest of Ytterøy

A narrow, elongated basin with a water depth of ca. 420 m (Fig. 13) occurs in the inner fjord south and southwest of Ytterøy, hosting flat-lying stratified sediments with a thickness up to 250 m. The basin continues as a narrow, deep trench towards Verdal (Figs. 4, 13).

Samples from the 30.8 m deep borehole S4 consist of homogeneous, bioturbated clay, with a few erosively based, upward fining silt and very fine sand turbidites (Bøe et al. 2003b, Figs. 13, 16). Seven samples dated in this borehole show a regular increase of age downwards, indicating none or a minor reworking of the dated materials (Table 1). A mixture of foraminifers/shell fragments in silty clay at 30.8 m gave an age of 8960 $^{14}$C-years BP. An acoustically chaotic unit with uneven thickness at 50-60 m depth is suggested to represent a large slide at the transition between the Younger Dryas and the Holocene. Small slides have been mapped along the slopes of the inner fjord; several of them are of fairly recent age (Bøe et al. 2003b).

Depositional environments

In northern Trondheimsleia, the thick parallel-layered sedimentary succession and the homogeneous, fine-grained sediments encountered in the upper part of borehole G11 indicate rapid suspension settling in the period 13-12.5 $^{14}$C ka BP. The shift in acoustic character at reflector X is interpreted to reflect a change in sedimentary environment as the ice margin retreated from the Agdenes threshold, introducing enhanced ocean circulation between Trondheimsfjorden and Trondheimsleia. One seismic line shows a 'wavy' layering above reflector X, possibly indicating strong current activity.

At site S2, the shift in seismic character at the base of unit E points to a change from a 'stable' to a more variable, current-influenced depositional regime. The shift may have occurred in the beginning of the early Younger Dryas climatic deterioration, or in the middle Younger Dryas, when the water volume of Trondheimsfjorden rapidly increased. The acoustic character and sedimentological changes of units A-E point to rapid changes in the depositional environment in this part of the fjord. The changes relate to changing current regimes along the narrow inlet fjord. High sand content and cross-bedding in the sand are indications of strong bottom currents and/or turbidity currents. In the period 9-10 ka $^{14}$C BP, when the sand was deposited, the palaeo-delta front of the river Skauga in Skaudalen was at least 10 km from the present shore line. We infer, however, that submarine channels from the river mouth brought sand to the deeper parts of the fjord. It is also possible that sand may have been transported along submarine channels from the river mouths of Gaula and Orkla (which drained large ice sheet areas) to be redistributed by bottom currents and/or turbidity currents along the axis of the narrow fjord towards Agdenes (Bøe et al. 2004).

In Trondheimsfjorden, few cores penetrate the base of the Holocene succession, and limited information about the deglaciation sediments exists. In large parts of the fjord, the pre-Holocene succession has a parallel-layered acoustic character indicating hemipelagic sediments, locally interbedded with turbidites in trenches and depressions. Particularly during the early deglaciation of the outer and central fjord, high meltwater discharge may have brought enormous amounts of suspended sediments into the deeper parts of the basin.
Slides and turbidites are common in Trondheimsfjorden (Boe et al. 2003b). During the deglaciation, slides most frequently occurred on slopes along the main trenches, where sedimentation rates were high; e.g. locally in Trondheimsleia, Orkdalsfjorden (Fig. 12), the fjord area between Stjørdal and Trondheim, and along the northern margin of Trondheimsfjorden. The sediments in the trench from Stjørdal to Trondheim were partly deposited when the ice margin was close to the southern shore of the fjord. Mass movements were directed northwards to the axis of the trench, and then followed the trench towards deeper water in the west. They were also common in the trench north of Midfjordsgrunnen, both during the deglaciation and after the ice margin retreated from the Tautra Ridge (Boe et al. 2003b). Acoustic blanking below the Holocene succession in Gaulosen makes the interpretation uncertain, but we infer that mass movements occurred also there. The mass-movement activity was highest in the first 1000 years of the Holocene (Boe et al. 2003b). Generally, sedimentation from suspension was dominant during the Holocene.

Sedimentation rates

It is not possible to trace the base Holocene horizon confidently everywhere, but some dating results (Table 1) have given important control points (borings G8, G11, S1, S2, S5). For MD 992292 and S4, dating of the early Holocene succession has given minimum values for the Holocene sediment thickness that provide a guide for interpretation. The acoustic signature of the upper strata of the fjord varies throughout the fjord, and the suggested 10 000 BP ‘time-line’ in Figs. 9 and 13 should be regarded as ‘the best estimate’. The lack of dating results makes the suggested older ‘time-lines’ speculative.

Horizon X in northern Trondheimsleia (Figs. 6, 7) is possibly related to ice retreat from the Agdenes threshold at ca. 12.5 14C BP. Up to 360 m of sediments occur below the X-horizon, indicating a maximum sedimentation rate of 50-100 cm/year. The sedimentation rate at site S1 was only 1 cm/year in the period 12 230-10 940 14C-years BP, and 0.03 cm/year in the last ca. 11 000 14C-years. This shows that most of the sediments were trapped in Trondheimsfjorden after the ice margin had retreated from the threshold at Agdenes (Fig. 17).

We infer that a similar model can be applied for the basins in Trondheimsfjorden, with very high sediment accumulation rates close to the retreating ice front. During the Late Allerød retreat, much of the sediments were deposited in the inner fjord basin, and adjacent to the ice margin in the outermost part of Stjørdalen, Orkdalen and Gauldalen valleys. Although sediments were deposited also in the deep outer basin, the retreat of the ice margin indicates decreasing sedimentation rates with younger ages (Figs. 9, 13, 17).

At site S2, the sedimentation rate shows a decreasing trend throughout the Holocene, from ca. 3 cm/year in the lowermost 1200 years of the core to ca. 0.15 cm/year over the last 2500 years (Table 1). The dating results at 20-21 m depth in both S2 and MD 992292 show a depositional rate of 0.3 cm/year for the last 7500 14C-years, indicating that Holocene sediments are fairly evenly distributed at the deep basin floor from north of Trondheim to the Agdenes threshold. The 12 dating results from S2 indicate that some intervals below 20 m depth comprise reworked sediments. In general, however, the age increases downwards, and the top of unit E appears to be close to base Holocene. Seismic tie from S2 indicates that base Holocene occurs at 50-80 m below the sea floor in the deep parts of the central and outer basins (Fig. 9). The maximum average sedimentation rate for the period 12.5-10 ka 14C BP was thus ca. 25 cm/year. During the first phase of the deglaciation, the sedimentation rate may periodically have been up to 100 cm/year.

Data from S4, in the inner fjord basin, give an average sedimentation rate of 0.34 cm/year for the last 9000 14C-years. In the first 1000 years of the Holocene, sedimentation rates were 2-3 cm/year (Fig. 16). In the late Younger Dryas, sedimentation rates may have reached 30-40 cm/year in the inner basin of Trondheimsfjorden.

The high sedimentation rates calculated for Trondheimsfjorden are comparable with rates recorded in temperate, meltwater-dominated glaciers in Alaska (Powel & Molnia 1989). The rates are two orders of magnitude higher than rates recorded from Andfjorden and Vågsfjorden (Plassen & Vorren 2002), and from modern, subpolar, glaciomarine fjord environments in Greenland, Spitsbergen and Baffin Island (Elverhøi et al. 1983; Stravers & Syvitski 1991; Andrews et al. 1994; Dowdeswell et al. 1994).

The extremely high sedimentation rates during the early phase of the deglaciation are related to the following main factors: (i) Ice and sediment-laden water from a large drainage area, flowing along several large valleys, confluened in the fjord, particularly in its deepest part. (ii) The Cambrian-Silurian metamorphic rocks in the drainage area had probably small resistance to glacial erosion, and the dominating fine-grained lithologies of these rocks were favourable for the production of silt and clay. (iii) The Agdenes and Garten thresholds were effective barriers, preventing dispersal of sediments to the outer coastal area.

Our data indicate that 10-15% of the sediments in the deepest fjord are of Holocene age. From an attempt to reconstruct the palaeo-seafloor in the valleys, Reite (1994) proposed that ca. 20% of the sediments in central Trondheimsfjorden were deposited after the deglaciation.
Figure 17. Geological section along Trondheimsleia and Trondheimsfjorden showing the location of the ice margin and sediments deposited during various time periods: A: 13-12.5 ka BP; B: 12.5-12 ka BP; C: 12-11 ka BP; D: 11-10.6 ka BP; E: 10.6-10 ka BP and 10-0 ka BP. Borings S1, S2 and S4 are indicated.
Deglaciation history

Earlier models for the deglaciation history of the Trondheimsfjorden area (Reite et al. 1982; Reite 1994; Reite et al. 1995; Sveian & Solli 1997a,b) have been included in the present model (Fig. 17). The model shows the ice margin and sediment sequences deposited at different time intervals. The suggested time lines in the fjord (Figs. 9, 13, 17) must be regarded as tentative, as few radiocarbon ages have been obtained from the pre-Holocene succession (Table 1).

The coastal areas (Fig. 17A)

The new radiocarbon ages of 12 780 and 12 670 14C-years BP in G11 correspond with ages reported by Kjemperud (1986), Follstad (1990), Holtedahl (1993) and Andersen et al. (1995), indicating that the ice margin was located along the coastline of More at 13-12.5 ka 14C BP, and at Fosen close to 12.5 ka 14C BP (Fig. 17A). In Trondheimsleia, up to 360 m of stratified sediments were deposited when the ice margin was located along the coast southwest of Agdenes (Fig. 17A). This interpretation is supported by the age of 12 230 14C-years BP at 15.8 m depth in S1 (Figs. 6, 7, 8). Farther north, the coastline of the Fosen peninsula was ice-free at 12.4-12.5 ka 14C BP (Andersen et al. 1995; Sveian & Solli 1997a,b).

Ottesen et al. (1995) suggested that the moraine at the ‘Garten Ridge’ and the deposits at the threshold to Stjørnfjorden were formed simultaneously as terminal deposits from a diverging ice stream in Trondheimsfjorden, spreading out west of the Agdenes threshold. The new seismic data show no convincing ice marginal deposits (Figs. 6, 7); stratified sediments appear to drape the bedrock relief at both thresholds. Our interpretation therefore does not support the proposed ice flow model of Ottesen et al. (1995), nor do glacial striae along the shore directly west of the Stjørnfjord threshold (H. Sveian, unpublished data).

Trondheimsfjorden prior to the Younger Dryas
(Figs. 17B and 17C)

The ice front probably halted and deposited a moraine at the Agdenes threshold, until the glacier became thin enough to float (height of ice sheet 30-40 m above the contemporary sea level). Before this halt, when the height of the ice sheet was ca. 150 m above the sea level, the ice lifted off the sea bottom in the outer Trondheimsfjorden basin, where the maximum depth of the basement relief is ca. 1300 m below the present sea level. At that time, the ice front was located many kms west of Agdenes. Parts of the stratified succession in the deepest basin were most likely deposited before open marine conditions were established (Fig. 17B).

At borehole S1, reflector X occurs 20-25 m below the sample with an age of 12 230 14C-years BP (Fig. 7). The sedimentation rate is unknown, but it is reasonable to assume an age close to 12.5 ka 14C BP for horizon X. We postulate that the ice margin started its retreat by calving from the Agdenes threshold at that time. At Rissa, the oldest age of a shell in glaciomarine clay is 12 080 14C-years BP (Reite 1994). A shell from 6.4 m depth in the Rissa quick clay slide gave an age of 11 780 14C-years BP (Lofaldli et al. 1981). The dated horizon is underlain by at least 15 m of glaciomarine clay. Dating of shells in clay from Ingdalen west of Orkdalsfjorden gave an age of 11 765 14C-years BP (L. Olsen, pers.comm. 2004). Although some of the ages might be slightly too old (Dyke et al. 2003), they indicate that the ice margin retreated from the Agdenes threshold before 12 ka 14C BP.

At ca. 12 ka 14C BP, an open fjord probably existed west of Trondheim, and the ice sheet was grounded on Midfjordsgrunnen (Fig. 17B). Marine limits and preliminary shoreline reconstructions indicate that Orkdalsfjorden was deglaciated at ca. 12 ka 14C BP (H. Sveian & L. Olsen, unpublished data).

Sub-till glaciomarine sediments on the Frosta and Skatval peninsulas indicate that the ice margin retreated to a position at least 15 km northeast of Tautra, in the Allerød (Reite 1994). In the fjord, up to 100 m thick tills overlying stratified sediments occur proximal to the Tautra Ridge (Figs. 13, 14). Although the innermost position of the ice front during the Allerød is unknown, we infer that Allerød clays were deposited over large parts of the inner basin, southwest of Ytterøy (Fig. 17C). The suggested time-line at 11 ka 14C BP is uncertain, but gives an idea of the approximate deposition in the fjord at that time.

Younger Dryas in Trondheimsfjorden (Figs. 17D and 17E)

The early Younger Dryas re-advance to the Tautra threshold (Fig. 1), including several minor oscillations of the ice front and deposition of the Tautra moraines in Central Norway, is previously well documented at Tautra (Reite & Olsen 2002), east and south of Trondheim (Reite 1994), in the Fosen mountains (Solid & Sorbel 1975; Reite 1990; Reite 1994; Sveian 1997) and at Forbordfjellet north of Stjordal (Sveian 1995, 1997). The new seismic and multibeam bathymetric data confirm the previous interpretations, give an improved picture of the great thickness and complexity of the submarine moraines and sediments in Trondheimsfjorden (Figs. 13, 14), and provide details on ice movements (Fig. 15).

The early Younger Dryas re-advance deposited nearly continuous ice marginal moraines north of Trondheim (Reite 1994; Sveian & Solli 1997a), reflecting a warm-based ice sheet. In contrast, large areas from Trondheim to Trollheimen (Fig. 1) have no early Younger Dryas moraines deposited above the marine limit (Reite 1990; Reite 1994; Sveian & Ro 2001). This probably reflects a
dominantly cold-based ice in the high mountains along the water divide south of Trondheim.

In early Younger Dryas, large volumes of glaciofluvial sand and gravel formed a large ice-contact sandur deposit in Skaudalen, between Verran and Rissa (Reite 1987), and the advancing ice margin deposited ca. 100 m of sediments in Åsenfjorden. The thick moraine complex forming a broad ridge across Stjørdalsfjorden (Fig. 9) reflects 4-5 minor oscillations in early Younger Dryas (Reite 1994). The seismic stratigraphy north and northwest of Tautra indicates at least two oscillations of the ice front during the early Younger Dryas. During the first phase of re-advance in latest Allerød-early Younger Dryas, till was deposited above stratified Allerød sediments in the trench northeast of Tautra (Figs. 13, 14). We infer that Allerød deposits in the deepest part of the inner basin were totally eroded, and incorporated in the till (Fig. 17D).

The Tautra Ridge was probably formed during a second phase, when the ice re-advanced slightly farther southwest. Glaciofluvial deposits appear to form the main part of the ridge (Fig. 13b). They predominantly occur above the narrow bedrock trench, indicating subglacial water discharge mainly along this depression. Because glaciomarine clays underlie the thick terminal deposits, slides were subsequently released distally to the ice front.

At 10.5-10.4 ka 14C BP the ice margin retreated 50-60 km towards the northeast in the main fjord (Sveian 1989), and 15-30 km in valleys entering the southern parts of Trondheimsfjorden (Reite 1994). This rapid retreat was of regional character, and has been described from e.g. Oslofjorden (Andersen et al. 1995). South of Trondheimsfjorden the recession was interrupted at least once, and during this period (10.5-10.4 ka BP) large glaciofluvial deltas were formed when the ice halted at Hovin and Kaldvelladalene in Gauldalen.

In the second half of the Younger Dryas another major re-advance to the Hoklingen Moraines occurred at ca. 10.3 ka 14C BP. The ice front advanced ca. 10 km and deposited a large terminal moraine at Straumen (Sveian 1989). Further south, the amplitude of this re-advance is unknown, but the ice front reached the lake Hoklingen south of Levanger, Hegra in Stjørdal and Støren in Gauldalen (Reite et al. 1982; Sveian 1997; Reite et al. 1999). In contrast to early Younger Dryas, continuous and very distinct marginal moraines were now deposited up to ca. 1000 m a.s.l. in the mountains south of Trondheim, probably reflecting a mid-Younger Dryas shift to more warm-based ice also there. The sedimentation rate in the inner fjord was high in the first 500 years after the ice retreated from Tautra (Fig. 17E), reflecting high meltwater discharge.

Conclusions

1) During the deglaciation of Trondheimsfjorden, there was a very high influx of sediment-laden meltwater from a large sector of the Scandinavian ice sheet. Hemipelagic sedimentation dominated, but slides, debris flows and turbidity currents occurred adjacent to the ice margin and along the fjord slopes. These processes were important for the distribution of sediments along trenches towards the deep basin. Sliding was particularly frequent in Orkdalsfjorden, Ytre Orkdalsfjorden, the fjord stretch between Stjørdalsfjorden and Trondheim, and southwest of Tautra.

2) The ice margin was located along the coast west of Trondheimsfjorden at 13-12.5 ka 14C BP (Fig. 17A). In this period, up to 360 m of stratified sediments were deposited in Trondheimsleia west of the Agdenes threshold, and the sedimentation rates were 50-100 cm/year. The sedimentation rate in the northern part of Trondheimsleia decreased abruptly after the ice margin retreated from the Agdenes threshold, being ca. 1 cm/year at 12 230-10 940 14C BP and 0.03 cm/year over the last 11 000 14C-years.

3) During numerous glaciations, glaciers eroded deeply into the bedrock, forming an 1100-1300 m deep basin between Trondheim and the Agdenes threshold. Up to 750 m of predominantly hemipelagic sediments occur...
in this fjord basin, of which 85-90% are of pre-Holocene age (Fig. 17B). The maximum sedimentation rate may have been 50-100 cm/year during the first 500 years of the deglaciation.

4) In Late Allerød, the ice margin was located at least 15 km northeast of Tautra. Most of the deglaciation sediments were deposited in the outer parts of the submerged valleys and in the inner fjord basin northeast of Tautra (Fig. 17C). During the early Younger Dryas re-advance, Allerød sediments in the inner fjord were eroded and re-deposited as till north-east of Tautra (Fig. 17D). During a late phase of this re-advance, up to 150 m thick of glaciofluvial sand and gravel deposits formed the Tautra Ridge, which is the most prominent part of the Tautra Moraines. The Tautra ice marginal zone continues southwards across the outer part of Åsenfjorden and Stjørdalsfjorden. Stratified Allerød clays underlie most of the marginal moraines.

5) At 10.5-10.4 ka 14C BP the ice margin retreated rapidly southwards in the Trondheim-Gauldal-Orkadal area, and northeastswards in the main fjord to the outermost part of Verdal and may be into Beistadsfjorden. A thick succession was deposited in the inner fjord basin southwest of Skogn (Fig. 17E). After another re-advance to the Hoklingen Moraines at ca. 10.3 ka 14C BP, the ice margin retreated rapidly (interrupted by several minor halts), and glaciomarine sediments were mostly deposited in the submerged parts of the valleys. The eastern (upper) parts of the valleys were mostly ice-free at 9.5 ka 14C BP, but meltwater runoff from extensive ice-dammed lakes east and south of the present watershed continued until ca. 9 ka 14C BP.

6) The Holocene succession in outer/central Trondheimsfjorden is up to 80 m thick, while it reaches 50 m in the inner fjord basin (Fig. 17E). Hemipelagic deposits predominate, but numerous turbidites, debris flow deposits and slides also occur. Sedimentation rates reached 3 cm/year in the earliest Holocene, but a marked decreasing trend is seen towards younger ages. At present it is less than 0.2 cm/year in most of the fjord area.

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