Weichselian and Holocene geology of Sør-Trøndelag and adjacent parts of Nord-Trøndelag county, Central Norway

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In Sør-Trøndelag and adjacent parts of Nord-Trøndelag a clayey till (10-25 % in the clay fraction) is commonly found below 1-5 m of sandy till (1-5 % in the clay fraction). The clayey till is mostly found in drumlins, in stoss-side positions, in deep narrow valleys transverse to the dominent ice-flow direction during the Late Weichselian and in depressions in the terrain. Till fabric indicates a WNW ice flow both for the clayey till and for the sandy till. Such an ice flow is also indicated by drumlins, fluted surfaces and glacial striae. In general there is a 0.1-1 m thick transitional zone between the two till layers. It is concluded that the clayey till is older than Late Weichselian.

Radiocarbon dates of molluscs and gyttja indicate that the coastal areas were deglaciated at c. 12,500 years B.P. When the inland ice reached rock thresholds in the outer parts of the fjords the ice recession was temporarily halted. A steep glacier gradient caused by calving led to minor glacial readvances, and terminal moraines were formed. After a few hundred years the calving continued further inland, interupted by glacial readvances when the Tautra ice-marginal deposits (10,800-10,500 years B.P.), the Hoklingen ice-marginal deposits (c. 10,300 years B.P.) and the Vuku ice-marginal deposits (c. 9800 years B.P.) were formed. The rapid calving left isolated ice caps in mountainous areas along the fjords. The last remnants of the inland ice were situated in depressions in the terrain in the southern and eastern parts of the investigated area. As the ice culmination zone was situated to the east and south of the watershed, the drainage from a large area was directed toward Trondheimsfjorden.

During the deglaciation Trøndelag was deeply submerged by the sea. The subsequent shoreline displacement led to an intense fluvial erosion, and sediments deposited during glaciation and deglaciation were transported farther down the valleys or into the fjords. This erosion, together with leaching of saline pore water, reduced the stability of the remaining glaciomarine sediments, and numerous quick-clay slides have since occurred. These slides are characterised by an almost liquid clay as the disturbed shear strength is very low. The strong fluvial erosion also led to other types of clay slides and to slides in other superficial deposits.

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Introduction

During the last decades much information has been published on the Weichselian glaciation and deglaciation of Trøndelag (Richter 1957, Lasca 1969, Sollid & Sørbel 1975, 1979, Bugge 1980, Lien 1980, Løfaldli et al. 1981, Kjenstad & Sollid 1982, Reite et al. 1982, Sollid & Reite 1983, Reite 1983a, b, 1984, 1985, 1986a, b, c, 1987, 1988, 1989, 1990, 1991, 1992, 1993 and in press (1994a, b), Andersen & Karlsen 1986). The shoreline displacement and changes in vegetation have also been investigated (Kjemperud 1981, 1986, Selnes 1982, Sveian & Olsen 1984). Oftedahl (1977) studied the fjord sediments and the transport of suspended material into the fjord during postglacial fluvial erosion.

The purpose of this paper is to provide an account of our present knowledge of Weichselian and Holocene geology of Sør-Trøndelag and adjacent parts of Nord-Trøndelag county, Central Norway (Fig. 1), with special emphasis on:

- Tills and other sediments older than Late Weichselian.
- Late Weichselian and Early Holocene deglaciation; sediments and stratigraphy.
- Geological processes after the last deglaciation.

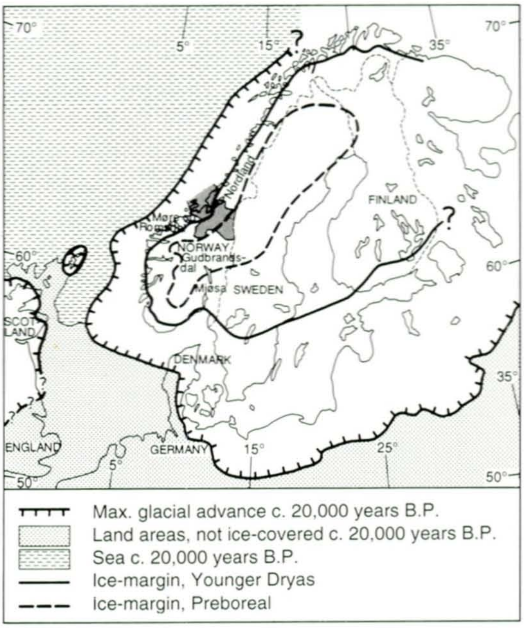

Fig. 1. Outlines of the Late Weichselian glaciation. The investigated area is shaded.

The work is based mainly on mapping projects on the superficial deposits, but additional studies have included the last deglaciation and till stratigraphy.

The stratigraphical terminology is in accordance with the proposals of Mangerud et al. (1974) and Mangerud & Berglund (1978). In the case of the ice-marginal deposits, informal names are used (Nystuen 1989).

Bedrock and geomorphology

Precambrian rocks predominate in the western part of the investigated area (Fig. 2), while metasedimentary and volcanic rocks from Late Precambrian to Silurian age are found in the central part of Trøndelag (Wolff 1979, Sigmond et al. 1984). Devonian sediments occur in small areas along the coast. Below the present sea-level even younger rocks, formed during the Late Mesozoic, have been found by seismic profiling (Bøe 1990).

The bedrock in Trøndelag is strongly influenced by the Caledonian orogeny (c. 500-400 Ma B.P.). The rocks have been metamorphosed at medium to high grade, and are strongly folded, faulted and fractured. The dominant strike trend (NE-SW) and the most common trend of faults and fractures (NNW-SSE) have to a large extent determined the orientation of the fjords and valleys.

During the Late Tertiary a marked uplift and faulting took place (Rundberg 1991). The uplift was greatest in the west, and led to a fast backward erosion by rivers that drained in this direction. The low-gradient east-directed rivers had less favourable conditions for erosion, and were partly captured by westerly drainage systems (Holtedahl 1950, 1953, 1960). A narrow, V-shaped valley incised in a broad, old valley is quite a common feature in this part of the country. Such narrow valleys are most likely formed by fluvial erosion triggered by the Tertiary uplift, but they have been slightly modified by glacial erosion. Other valleys in Trøndelag have been more strongly influenced by gla-

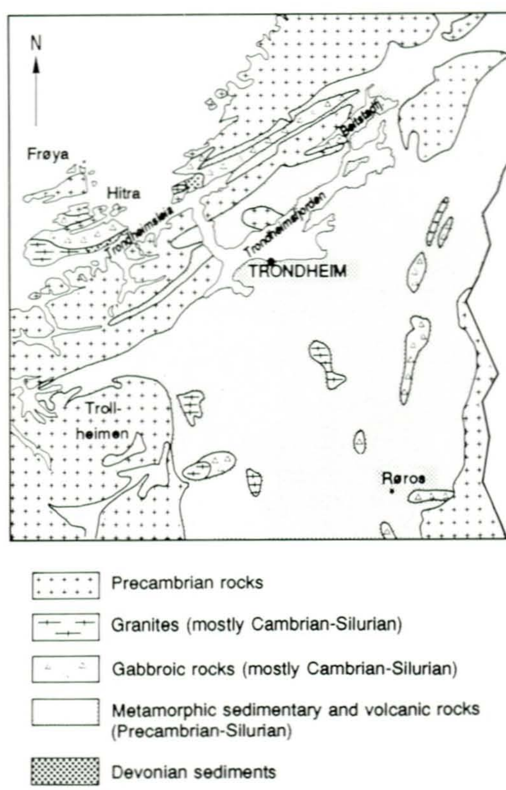

Fig. 2. Simplified bedrock map of Sør-Trøndelag and adjacent parts of Nord-Trøndelag. After Wolff (1979) and Sigmond (1985).

cial erosion. They are characterised by U-shaped transverse profiles and step-like longitudinal profiles, commonly with overdeepened rock basins, completely or partly filled by superficial deposits. The valleys in the easternmost parts of the counties are less marked. There the landscape is dominated by plateaux at altitudes of 700-1000 metres. These areas seem to be less affected by glacial erosion than the central and western parts of Trøndelag.

Most of the fjords and many lakes are overdeepened rock basins. They were moulded by glacial erosion, but pre-Quaternary valley systems may have existed along present valleys, fjords and lakes. Faulting may also have occurred, as in the Beitstadfjorden basin (Fig. 2) where down-faulted Mesozoic rocks have been protected from glacial erosion.

Trondheimsfjorden has a maximum water depth northwest of Trondheim of some 500 metres. In this part of the fjord up to 700 m of Late Weichselian and Holocene silt and clay have been reported (Oftedahl 1977). The bedrock surface is thus situated some 1200 m below the present sea-level. As the depth of a rock threshold at the mouth of the fjord is c. 500 m, the fjord has been overdeepened by some 700 metres.

At the coast a bedrock platform — the Strandflat — is situated a few metres above and below sea-level (Reusch 1894, Nansen 1922, Larsen & Holtedahl 1985, Holtedahl 1993). It was formed during the Quaternary by glacial erosion, frost weathering and marine abrasion.

Except for the lower parts of the valleys, where there is locally a very thick cover of Quaternary sediments, the topography is mostly dependent on the bedrock morphology.

Quaternary sediments, distribution and stratigraphy

During the Weichselian maximum, Trøndelag was completely covered by an inland ice sheet that moved in a WNW direction. Later, the glacier flow became more dependent on the topography.

The coastal areas and the highest mountains further east mostly consist of exposed bedrock. In the central parts of Sør-Trøndelag, discontinuous or thin till cover predominates. A thick till cover has a vide distribution in the southern and southeastern parts of the investigated area (Fig. 3). These tills generally have a smooth surface, but locally there are drumlins, fluted surfaces, hummocky moraines and Rogen moraines. Grain-size analyses indicate that most tills are sandy, with a clay content of 1-5 % (Fig. 7); and they have a medium boulder content which increases towards the surface. In some areas a clayey till with a clay content of 10-25 % is found below the sandy till. This has a low content of boulders and shows a high degree of compaction. Clay-rich tills are also found along the fjord, below the upper marine limit. These tills are underlain by glaciomarine sediments, and were formed by a glacier readvance across such sediments; and they are partly overlain by glaciomarine sediments deposited during and after the final deglaciation.

During the deglaciation, Trøndelag was deeply submerged by the sea. Where the meltwater streams reached sea-level, gravel and sand were deposited (Fig. 3) while suspended material was transported further out into the fjord. Glaciofluvial sediments are also found along the glaciofluvial drainage routes. During the deglaciation the ice culmination zone was situated to the south and east of the watershed, and a large area drained towards Trondheimsfjorden.

Because of the shoreline displacement, amounting to more than 175 metres in the eastern part of Trøndelag, marine sediments are now found high above the present sea-level. The lowered base level led to an intense fluvial erosion, and glacigenic sediments were brought farther down the valleys or into the present fjord. The fluvial erosion reduced the stability, and the remaining marine sediments have been strongly affected by slides. During the shoreline dis-

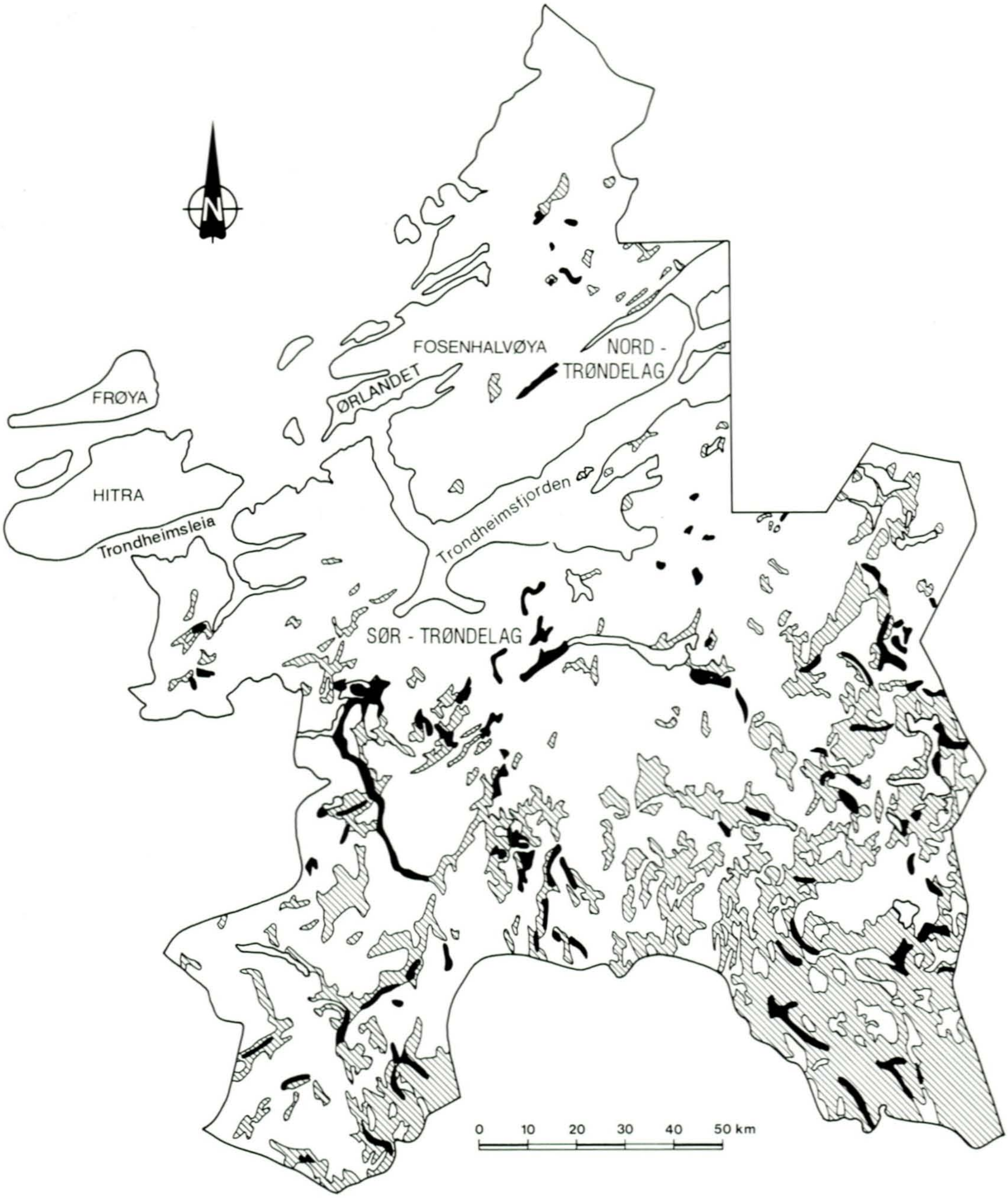

Fig. 3. Distribution of till, continuous cover (shaded) and glaciofluvial deposits (black).

placement, sediments below the upper marine limit were influenced by waves and currents. Some sediments, such as weathering material and peat, were formed in situ.

Quaternary sediments on the continental shelf and in the outer parts of the fjords

Bugge (1980) has mapped three till units on the continental shelf off the coast of Trøndelag. The Storegga moraine is situated close to the continental slope and is underlain by an older thick till unit. The middle unit, the Haltenbank moraine, marks the last ice advance on the shelf. The youngest unit, the Sula moraine, is less distinct; it is situated close to the outer islands along the coast. Based on radiocarbon datings, Bugge suggested that the inland ice reached the shelf edge some 13,000 years B.P. and retreated to Haltenbanken 12,300 - 12,400 years B.P. Andersen (1979) and Andersen & Karlsen (1986) are of the opinion that the deglaciation of the shelf took place earlier, and that the outer islands may have been deglaciated some 13,000 years B.P. (Fig. 1). Radiocarbon dates from the coast of Trøndelag (Kjemperud 1981, 1986, Reite 1987, 1988, 1990) are in favour of this conclusion. However, the age of the drift units on the shelf should be considered as unknown, since invesigations from Sunnmøre (Mangerud 1991, Larsen & Ward 1992) and Nordmøre (Follestad 1990) have indicated that sediments older than the last glacial advance to the shelf area may well be present.

In Trondheimsleia (Fig. 3), to the south of Hitra, Follestad & Andersen (1992) have described thick layers of diamicton below marine sediments. This diamicton represents both basal till and glaciomarine sediments strongly influenced by glacial erosion. The age of this diamicton is unknown.

To the west of Ørlandet (Fig. 3), D. Ottesen (pers. comm. 1992) found glaciomarine sediments with large erosion scars. Part of this erosion may have been caused by currents or slides; in other cases it can only be explained by glacial erosion. It can be concluded that some of the glaciomarine sediments in this area have been overrun by glaciers. The glaciomarine sediments may be older than the glacier advance to the edge of the shelf some 20,000 years B.P.

Interglacial and interstadial deposits in Central Norway

On the islands Frøya and Hitra, situated in the westernmost part of Sør-Trøndelag (Fig. 3), I. Aarseth (pers. comm. 1992) found fossiliferous marine deposits from the last interglacial (Eemian) and from one or more Weichelian interstadial. Deposits older than Late Weichselian have thus been protected from glacial erosion.

In Møre and Romsdal, studies of sediments in caves have proved the existence of alternating ice-free and ice-covered periods during the Weichselian (Mangerud 1981, 1991, Larsen et al. 1987). The end of the youngest of these ice free periods, the Ålesund interstadial, is dated to c. 30,000 years B.P. Larsen & Ward (1992) have described two glacial-deglacial sequences of Middle and Late Weichselian age at Skorgenes.

In the coastal areas of Nord-Trøndelag, interstadial sediments have been dated at Vikna (B. Bergstrøm, pers. comm. 1993) and Flatanger (L. Olsen, pers. comm. 1993). This part of the coast, too, was deglaciated during an interstadial, some 30,000-40,000 years B.P. In Lierne, situated in the northeasternmost part of Nord-Trøndelag, thin silt layers with organic remains in clayey till have been dated to c. 40,000 years B.P. (Olsen 1993).

Till older than the last deglaciation

In some areas in Trøndelag a clay-rich till is found below a sandy till at the surface (Fig. 4). This till is characterised by a clay content of 10-25 %, a high silt content and a low content of stones and boulders. Generally, no structures are visible and the till is highly compacted.

Stratigraphy, structures and textures were examined in several sections. Till fabric analyses were carried out for selected sections for the size fraction 20-64 mm (at least 50 clasts with distinct long axes). Striations on bedrock exposures below the clayey till

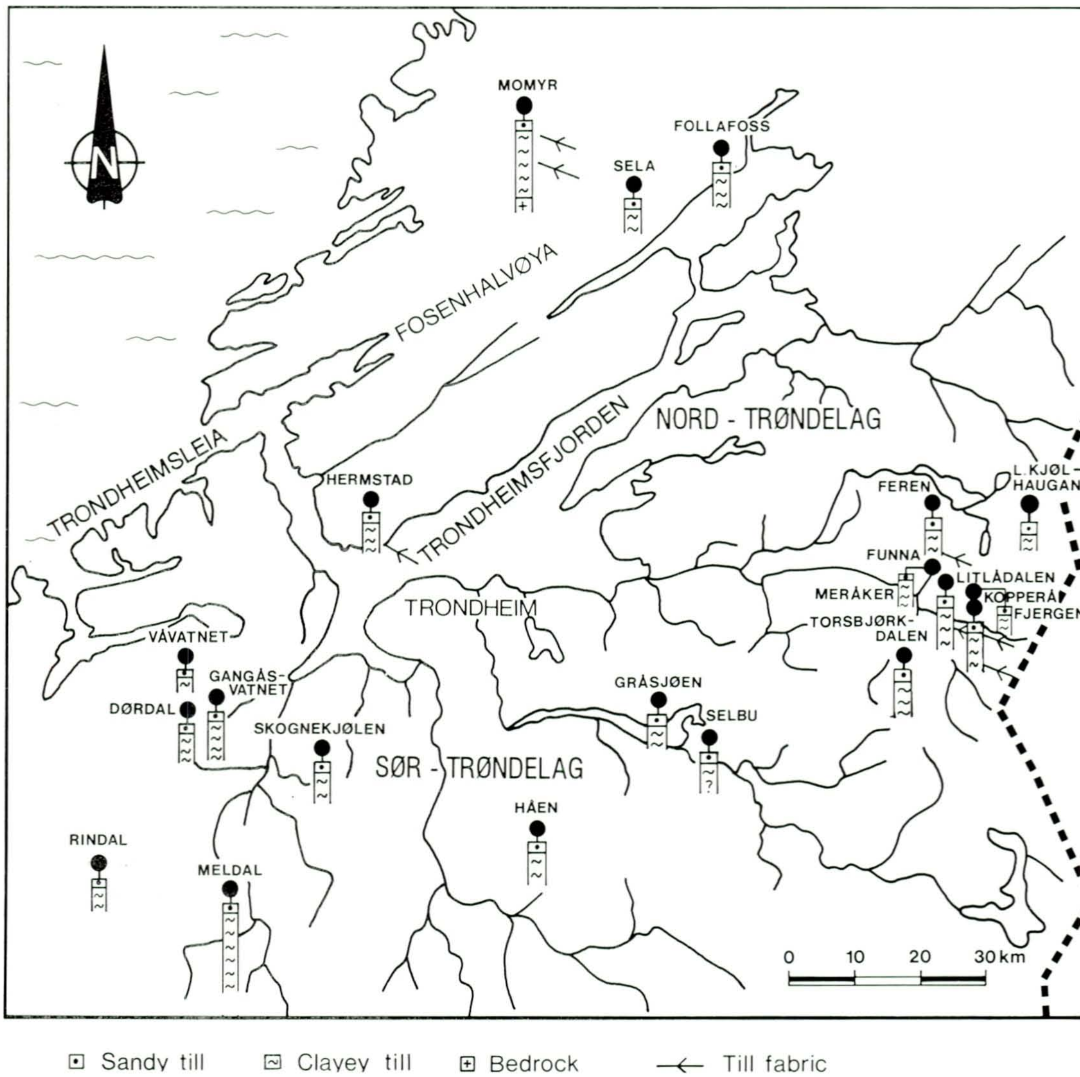

Fig. 4. Localities with clayey till below sandy till.

were measured, as were the orientations of drumlins.

Laboratory studies have included grain-size analyses of material finer than 19 mm, XRD-determinations of mineral content of the <2 micron fraction and pollen analyses. The samples for pollen analyses were prepared according to the procedures of Fægri & Iversen (1989). *Lycopodium* tablets were added, and 200 *Lycopodium* spores were counted (S. Selvik, pers. comm. 1993).

The Fosen Peninsula

At Momyr, close to the watershed, there are several large drumlins (Figs. 4, 5). The surrounding mountains consist of exposed bedrock or have a thin or discontinuous till cover. The drumlins have lengths of about 2 km, widths of 200-400 m and thicknesses of more than 25 m. Their longest axes indicate an ice movement toward the WNW. Several sections exposed during road constructions revealed clayey till resting on striated

Fig. 5. Large drumlin at Momyr. The drumlin has a length of 2 km.

bedrock. These striae have the same trend as the longest axes of the drumlins. All the sections show 1-3 m of sandy till towards the surface (Fig.6). The sandy till is homogeneous, and lumps of clayey till have not been observed. It is non-stratified and was probably deposited as a lodgement till. Between the two till layers is a 0.2-0.7 m thick transitional zone with a decreasing content of fines. In the sections along the road the clayey till is up to 5 m in thickness, but exposures along the river indicate that the

Fig. 6. Clayey till below sandy till in the distal part of the Momyr drumlins. The boundary between the two till beds is dashed. Glacial striae on bedrock below the clayey till indicate an ice flow toward the WNW.

thickness of this till is at least 20 metres, possibly even more. The clayey till has a clay content of 15-25 %, a high content of silt and a low content of stones and boulders. It shows no stratification, is highly compacted and was probably deposited as a lodgement till. Till fabric analyses indicate an ice movement toward the WNW, the same orientation as that in the overlying sandy till. These observations indicate about the same ice flow direction during an erosional phase prior to the drumlin formation, as during the deposition of the clayey till and the sandy till. No pollen grains were found in a sample from the clayey till; only a few, very small, unidentified plant fragments (S. Selvik, pers. comm. 1993).

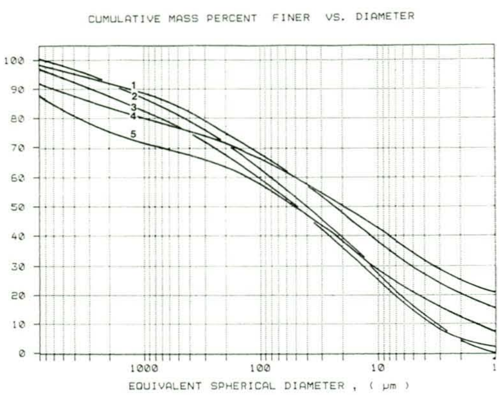

Fig. 7. Grain-size analyses of the < 19 mm fraction of clayey tills and sandy tills. 1 = Kopperå, 2 = Hermstad, 3 = Momyr, 4 = Feren and 5 = Torsbjørka. For location see Fig. 4.

At Hermstad, a couple of large drumlins of crag and tail type are situated in the lee of hills consisting of exposed bedrock (Fig. 8). A section in the distal part of one of these drumlins shows that it consists of clayey till below 2-4 m of sandy till (Fig. 7). There is a gradual transition between the two till layers. The clayey till consists of 15-20 % clay, and has a high silt content. It has a low content of boulders, and is highly compacted. Glacial striae on boulders in the clayey till indicate an ice movement towards WNW, the same direction as indicated by the long axes of the drumlins. No pollen grains were found in the clayey till, but a few, very small, unidentified plant fragments were observed (S. Selvik, pers. comm. 1993).

At Sela (Fig. 4), a road section shows that the sandy to gravelly till that dominates in this area is underlain by a very compact clayey till with a clay content of 20 %. The clayey till shows a clear resemblance to the Momyr and Hermstad localities. The Sela site is situated in a stoss side position to the dominent ice movement during Late Weichselian. It is overlain by a few metres of sandy till. One pollen grain from each of the species *Pinus*, *Betula* and *Artemisia*, one pollen grain from *Gramineae* and a few fragments of spores were found in a sample

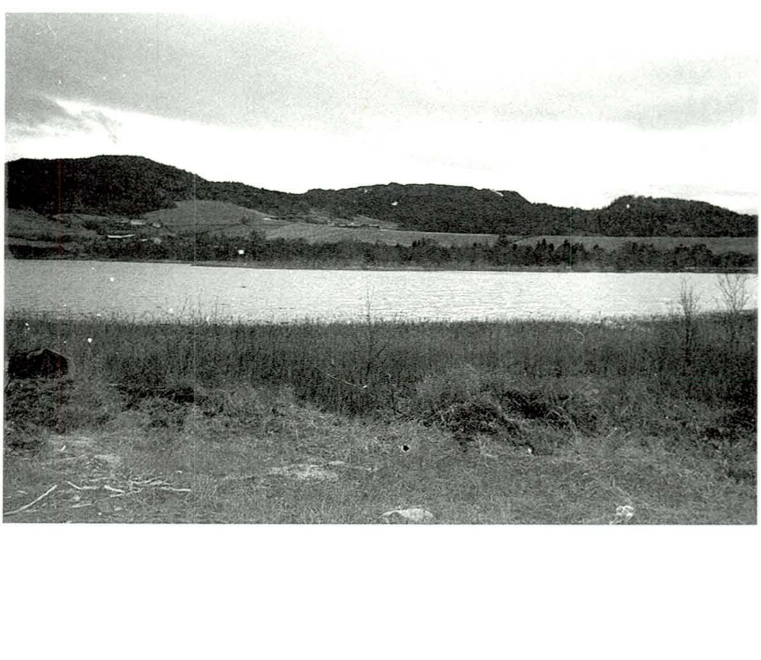

Fig. 8. The Hermstad drumlins, situated in lee positions to hills consisting of solid bedrock.

from the clayey till. The very low pollen content may be a result of contamination (S. Selvik, pers. comm. 1993).

To the north of Follafoss two large drumlins of crag and tail type are found (Fig. 4). Sections in one of these drumlins reveal silty/clayey till with a low content of stones and boulders. Toward the surface the till is more sandy. The till matrix resembles that described at Momyr, Hermstad and Sela, but it is not so compact. There are no sections through the second drumlin, and the till type is unknown.

Southwestern part of Sør-Trøndelag

At Våvatnet (Fig. 4), sandy till is underlain by clayey till with a thickness of more than 4 m. The site is situated in a stoss position to the dominant Late Weichselian ice flow. The clay content of the clayey till is c. 15 %, while the sandy till contains 4 % in the clay-size fraction. The clayey till has a low content of stones and boulders, it lacks clearly visible structures and is highly compacted.

At Gangåsvatnet (Fig. 4), clayey till is exposed below sandy till at the surface. The site is located on a till slope facing the direction of the Late Weichselian ice flow.

Dørdal (Fig. 4) is a deep, narrow, SW-NE-trending valley with a thick till cover. Several sections reveal that the sandy till at the surface (1-3 m in thickness) is underlain by thick clayey till. This till is very compact and lacks structures.

In Rindal (Fig. 4), tills with a clay content of 10-15 % are found at several localities. They are generally overlain by a thin cover of sandy till. The clay-rich till is mostly found in drumlins and in slopes facing the main direction of ice movement. It lacks clearly visible structures. Generally, there is a 0.5 m transitional zone between the two till layers.
Very thick clay-rich till is found in stoss side positions to the west of Meldal (Fig. 4). It is overlain by a thin cover of sandy till. The exposures of the contact between the two till layers is poor, so it is not clear if there is a sharp boundary or a gradual transition.

Central parts of Sør-Trøndelag

At Skognekjølen (Fig. 4), clayey till is found below more sandy till close to the surface. The clay content is c. 10 %. The till has a low content of boulders and resembles the clayey till at Fosenhalvøya and in the southwestern part of Sør-Trøndelag, although it is less compacted and the clay content is lower.

At Håen (Fig. 4), two distinct till layers are found in a drumlin. Below a 3 m thick sandy till at the surface is a clayey till, poor in boulders. The clay content of the clayey till is c. 10 %, which is somewhat lower than in the most clay-rich tills in Trøndelag. It is also less compacted, a feature which may be a result of the lower clay content.

In Selbu (Fig. 4) there are several large drumlins, indicating an ice movement towards NW to NNW. Only poor sections are available, but information from a farmer strongly suggests that at least the drumlin east of Flønes consists of clayey till with a low boulder content below a more sandy till at the surface.

Sections along the road at Gråsjøen (Fig. 4) show that a thin layer of sandy till at the surface is underlain by a thick clay-rich till, with a clay content of c. 10 %. This till is highly compacted, and resembles the clayey till found at Momyr, Hermstad and other localities, but the clay content is lower and the boulder content higher than at these localities. The clay-rich till at Gråsjøen may consist of redeposited clayey till that during erosion, transport and redeposition has been mixed with a sandy till.

Southeastern part of Nord-Trøndelag

River erosion to a depth of 15 metres at Feren (Fig. 4) has exposed 3 m of sandy till underlain by more than 10 m of blue-grey, clayey till. The till fabric in the clayey till indicates an ice flow towards the WNW. It lacks visible structures and is highly compacted. The clay content is 26 % (Fig. 7), and the till has a low content of boulders. The clay-size fraction is dominated by chlorite and illite, with some quartz and feldspar.

At Funna, 5 km to the north of Meråker, there is a till deposit more than 10 m in thickness (Fig. 4). Below 1-2 m of sandy till there is a highly compacted, blue-grey, clay-rich till with a low content of stones and boulders.

In Litlådalen (Fig. 4), the river has eroded deeply into tills deposited in a depression in the terrain. A sandy to gravelly till, 2-4 m in thickness, is underlain by more than 10 m of clayey till, exposed in several sections. The clay-rich till has a low content of stones and boulders and is highly compacted. The clay content is 23 %. Till fabric analyses indicate an ice movement towards the WNW for the glaciers that deposited the clayey till. The clay-size fraction is dominated by chlorite, illite, quartz and feldspar.

East of Lille Kjølhaugan (Fig. 4), a 5-10 m thick, very compact, till deposit is found in a stoss side position to the dominant ice flow direction. This area is othervice characterised by exposed bedrock. The deepest part of a 5 m section consists of clay-rich till with a low content of stones and boulders. The uppermost 2 metres is more sandy and has a higher content of coarse particles.

Excavations of till for a dam construction at Kopperå (Fig. 4) have provided excellent sections to a depth of 7 metres. Below 2-4 m of sandy till there is a highly compacted clayey till more than 5 m in thickness. The clay content in the clayey till is 22% (Fig. 7). Till fabric analyses both in the clayey till and in the sandy till indicate an ice movement towards the WNW. The clay-size fraction of the clayey till and the sandy till consists mostly of chlorite and illite, with some quartz and feldspar.

WNW-oriented drumlins to the west of Fjergen (Fig. 4) consist of compact, clay-rich till below 1-2 m of sandy till. The stratigraphy thus resembles that found at Kopperå, Feren and Litlådalen.

Sections along the road in Torsbjørkdalen (Fig. 4) reveal a sandy till at the surface, underlain by more than 4 m of clay-rich till. This till is highly compacted and lack structures. It has a low boulder content, and the clay-sized fraction makes up 14 % (Fig. 7). There is a 0.5 m thick transitional zone between the two till layers.

Discussion

All localities described above reveal the same general stratigraphy: a thin sandy till underlain by a thick, highly compacted clayey till devoid of structures and with a low boulder content. Fine-grained lacustrine or marine sediments have not been observed below the clayey till, and this till has no lenses or clasts of such sediments. In a few sections bedrock is reached below the clayey till. It is strongly sculptured by glacial erosion, with distinct glacial striae indicating a glacial flow towards WNW. This ice-flow direction is also indicated by the longest axes of the drumlins, the till fabric in the clayey and sandy till, and glacial striae on bedrock exposures situated just outside areas with clayey till.

Most sites where clayey till is found below an upper sandy till are situated 200-600 m above sea-level at localities that were well protected from glacial erosion during the Late Weichselian:
- Drumlins situated in depressions in the
- terrain
- Drumlins of crag-and-tail type
- Tills in stoss side positions to the Late
- Weichselian ice movement
- Tills in deep, narrow valleys transverse to the main ice movement

Outside areas with clayey till below sandy till, only the sandy till is found.

Tills in Trøndelag generally have a clay content of 1-5 % (Fig. 7), the same as is found for most Norwegian tills (Jørgensen 1977, Haldorsen 1981). Clayey till differs from the common till types. The clay content is generally 10-25 % (Fig. 7), the boulder content is low and the degree of compaction is very high. At Skognekjølen, Håen and Gråsjøen (Fig. 4) a transitional till type is found. This till may have been formed by glacial erosion of clayey till, and may represent a mixture of this till and the dominating till type (sandy till). Tills with a high clay content have been found on the North American continent (Dreimanis 1976), in Sweden (Lundqvist 1973) and in Denmark (Petersen 1973).

Clay-rich till with a clay content of 10-30 % is also found along Trondheimsfjorden. This till was formed during glacial readvances as the glaciers moved across glaciomarine sediments and eroded into these sediments. Glacitectonic structures and clastic dykes are often found in the subtill sediments. Lumps of clay in clay-rich tills have been observed in several sections. The stratigraphy, structures and textures clearly demonstrate the difference between the clayey till and the clay-rich till derived from glaciomarine sediments.

There is no connection between the content of fines and the underlying bedrock for the clayey tills in Trøndelag. They are found in areas with gneisses and granites as well as above greenstones, sandstones, phyllites and mica schists. This result is in contradiction to most till studies in Norway (Låg 1948, Jørgensen 1977, Haldorsen 1981), where a correlation has been reported between rock types in the source area and the content of fines.

The gravel fraction is mostly subrounded, indicating either a long glacial transport or a glaciofluvial/fluvial transport before the sediments were picked up by the glacier. A fairly long transport is also indicated by the bedrock content of the gravel fraction compared to the underlying bedrock.

The clayey till is generally dark blue-grey on fresh surfaces. When this till is exposed to weathering it becomes grey in colour. The dark colour can therefore be explained by redox conditions.

The mineral content of the clay fraction from sandy and clayey tills from Meråker has been analysed by XRD. The < 2 micron fraction is dominated by chlorite and illite, with smaller amounts of quartz and feldspar, as is found for marine clays deposited during the deglaciation (Sand 1986). These clays were mostly derived from Late Weichselian tills by glaciofluvial or fluvial erosion and transported as suspended material into the fjords. The mineralogy of the clay-sized fraction in the clayey tills indicates that these tills are derived from source rocks little influenced by weathering (Rundberg 1991). This accords well with the chemical reduction character (dark colour) of the tills. The high clay content found in clayey tills cannot be explained by glacial erosion in deeply weathered bedrock or fine-grained lacustrine or marine sediments, but must depend on differences in the glacier regime during erosion, transport and deposition of the clayey and sandy till.

The distribution of clayey tills, the stratigraphy of the sites and the marked difference in grain-size distribution and degree of compaction between sandy tills and clayey tills strongly suggest that they have not been deposited during the same glaciation phase. As most tills close to the surface were no doubt deposited during Late Weichselian and Early Holocene time, the clayey till must be older. Based on their distribution these tills may represent the erosional remnants of clayey tills that prior to the last glaciation phase had a wider distribution. This is supported by the fact that clayey tills have a very limited distribution compared to the total area covered by till. If this till has not been affected by later glacial erosion it should be expected that clayey till also occurred in areas where the till is less protected from glacial erosion. A transitional zone between the clayey till and the overlying sandy till could also be explained by glacial erosion in the clayey till. In the mountains to the northeast of Selbusjøen, clusters of drumlins are in a state of being partly destroyed by glacial erosion. Erosional remnants of a thick cover of clayey till are also found in a stoss side position at Kjølhaugan (Fig. 4) in an area dominated by exposed bedrock. Beside glacial erosion, snow avalanches, debris flows and fluvial erosion may have affected this deposit. If the clayey till has not been affected by later glacier erosion it must have been deposited during

a glacial phase when a strong erosion took place in most areas, contemporaneous with deposition of thick clayey tills within the very limited areas where this till type occurs.
Glacial striae, flutings and the orientation of drumlins indicate that most tills in Trøndelag were deposited during glaciations with the same directions of ice movement. As the inland ice became thinner, however, the direction of ice movement became highly dependent on the topography.

No pollen grains were found in three samples from clayey tills; in one sample four pollen grains were identified. The very low pollen content in the latter sample may have been caused by contamination. The lack of pollen in samples from clayey tills suggests that the clayey till was not derived from fine-grained lake sediments or marine sediments.

Radiocarbon dates of silt with organic material either underlying or reworked within a similar clayey till in southern Nordland and at Lierne, Nord-Trøndelag, gave ages ranging from c. 26,000 to c. 41,000 years B.P. (Olsen 1993). These dates indicate that the clayey till was deposited after an ice-free period at the transition Middle Weichselian/Late Weichselian. An ice-free period of this age has been reported from several localities along the coast and also from the Mjøsa/Gudbrandsdal area (Bergersen & Garnes 1981, Bergersen et al. 1991, Mangerud 1991, Rokoengen et al. 1993), and fine-grained bluish-grey tills in the latter area are radiocarbon-dated to ages younger than 31,000-37,000 years B.P. (L. Olsen, pers. comm. 1993). In Nordmøre and Romsdal, thick clay-rich tills have been found (Follestad 1990) which are assumed to be older than the last glacial advance to the continental shelf.

The clayey tills found in Sør-Trøndelag and adjacent parts of Nord-Trøndelag may be contemporaneous with the clayey tills in southern Nordland and at Lierne, Nord-Trøndelag, and the clay-rich tills in the Mjøsa/Gudbrandsdalen area and in Nordmøre and Romsdal. Possible correlative clayey tills have also been described from Central Sweden (Lundqvist 1973). Further investigations and search for buried organic material are needed in order to reach safer conclusions concerning the time of formation of the clayey till, but some of these tills do seem to be of Middle Weichselian age.

Late Weichselian deglaciation

During the Late Weichselian maximum, Trøndelag was most likely completely covered by glaciers that moved in a WNW direction (Fig. 9). This is indicated by glacial striae, fluted surfaces and drumlins. In the southwestern part of Sør-Trøndelag a northerly ice movement is found, probably from an ice culmination in Trollheimen.

In most valleys and fjords, glacial striae indicate an ice movement strongly dependent on topographical conditions. These striae were formed as the thickness of the inland ice diminished. They are not synchronous as the coastal areas were deglaciated c. 3000 years earlier than in the easternmost part of Trøndelag.

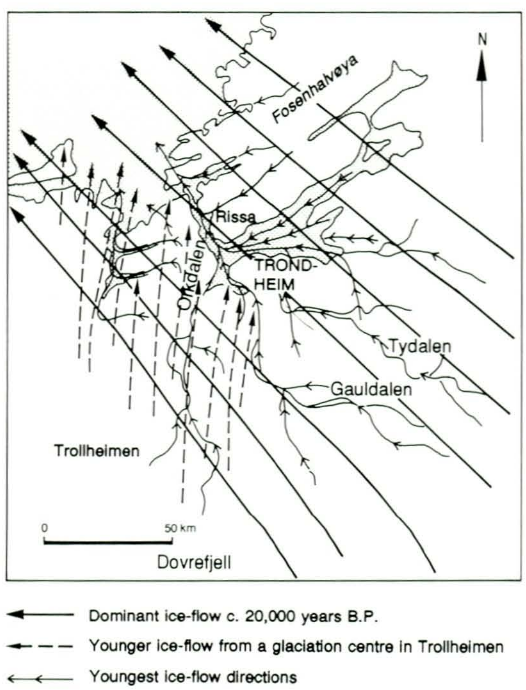

Fig. 9. Reconstruction of ice-flow directions during the Late Weichselian.

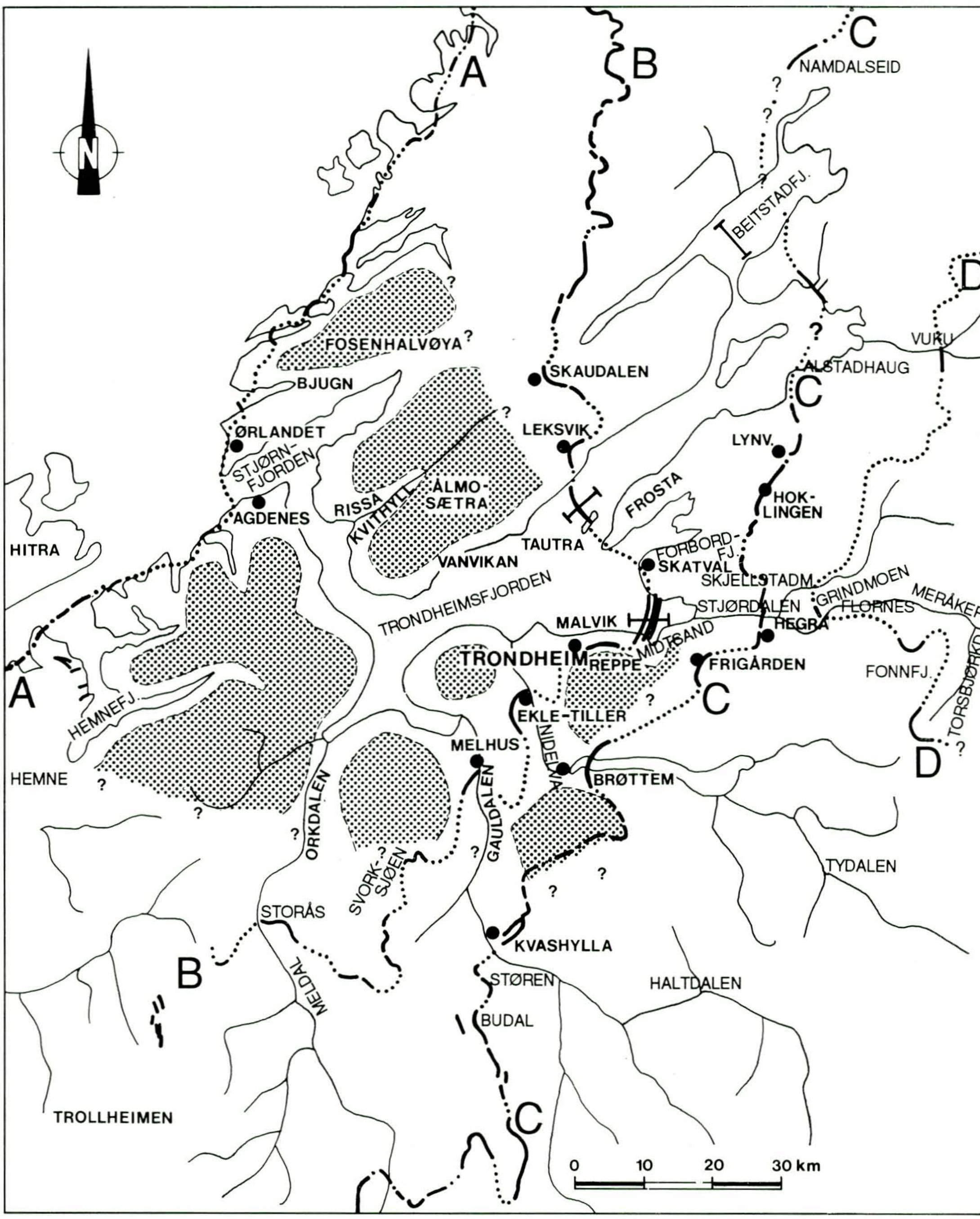

Fig. 10. Ice-marginal deposits in Sør-Trøndelag and adjacent parts of Nord-Trøndelag: A - A Ice-marginal deposits in the coastal areas. (c. 12,500 years B.P.) B - B The Tautra ice-marginal deposits (early Younger Dryas) C - C The Hoklingen ice-marginal deposits (late Younger Dryas) D - D The Vuku ice-marginal deposits (early Preboreal).

Local ice-caps left after calving in the fjords and the submerged parts of the present valleys are indicated (shaded areas), as are sites for stratigraphic correlation (filled circles) and seismic reflection profiles in the fjords.

Deglaciation of western parts of Trøndelag

During the Late Weichselian the inland ice had its maximum advance at some 20,000 years B.P. when it reached the outer parts of the shelf off Trøndelag (Fig. 1). The stratigraphy of the superficial deposits on the shelf strongly suggests the existence of several till units. Radiocarbon dates of molluscs and gyttja show that the outer part of the coast became ice free at c. 12,500 years B.P.

In the coastal areas terminal moraines are commonly found in the fjords and the lower parts of the valleys, but they cannot be traced in the mountainous areas between the fjords (Fig. 10). These moraines were deposited by an unstable ice front caused by calving (Kjenstad & Sollid 1982, Sollid & Reite 1983). They are not strictly synchronous as the glacier retreat by calving was highly dependent on water depth, exposure to wave activity and other topographical conditions. The halt in the deglaciation is also marked by a somewhat thicker till cover in the surroundings of the terminal moraines than elsewhere in the coastal areas. In the Hemnefjord, some of these terminal moraines are underlain by glaciomarine clays, and the till itself consists of reworked glaciomarine sediments, indicating a glacial readvance following a minor retreat. In a few terminal moraines glaciofluvial sediments are found below the till. Although some observations clearly indicate minor glacier readvances, these terminal moraines are characterised by a standstill of the ice front.

After a few hundred years a normal gradient of the inland ice was reestablished, and further thinning of the ice sheet led to an intense calving in Trondheimsfjorden and other fjords in Trøndelag. This calving was accelerated by the great depths of the central parts of most fjords in this region compared to the shallower threshold at their mouths. The ice front receded to lower parts of the valleys and shallow thresholds in the fjords. In the outer part of Trondheimsfjorden, Lien (1980) has described ice-marginal deposits in Stjørnfjorden and at Agdenes - Ørlandet (Fig. 10). These deposits may have been formed during minor halts or readvances of the fjord glacier.

Holtedahl (1929) and Løfaldli et al. (1981) have described a terminal moraine at Kvithyll, Rissa (Fig. 10). Several quick-clay slides in this moraine indicate that most of the sediments consist of glaciomarine clay. This clay has a high clast content toward the surface. The high shear strength found (Løfaldli et al. 1981) can, in my opinion, be explained by a weathering of the sediments rather than overconsolidation caused by the overburden of a glacier. The clasts were most likely transported by icebergs, as found elsewhere in the outer part of Trondheimsfjorden (Reite 1988). This process is discussed in more detail in the description of the Tautra ice-marginal deposits.

Radiocarbon dates of molluscs and gyttja (Reite et al. 1982, Selnes 1982, Kjemperud 1986) suggest that the deglaciation of the outer part of Trondheimsfjorden and the coastal fjords farther towards the north took place during Older Dryas/Allerød time, possibly as early as the transition Bølling/Older Dryas. Mollusc shells from glaciomarine clay at Bjugn and Ålmosætra, Rissa (Fig. 10) were radiocarbon-dated to 11,950 ± 150 years B.P. (T-6298) and 12,080 ± 150 years B.P. (T-6548), respectively (Reite 1987, 1988). Shells from a depth of 6.4 m in the Rissa quick-clay slide (Løfaldli et al. 1981) were dated to 11,780 ± 90 years B.P. (T-3034). The dated horizon is underlain by at least 15 m of silt and clay, deposited earlier during the deglaciation. Radiocarbon dates of molluscs from the Hemnefjord area (Lasca 1969) could suggest that this area was deglaciated later than the western part of the Fosen Peninsula. This may be expected as the Hemne area is protected against the open sea by several islands.

The intense calving in the fjords and the lower parts of the valleys which were submerged by the sea during the deglaciation, led to the existence of isolated ice caps in the mountainous areas between the fjords and the valleys (Figs. 10, 11). This conclusion is based on the existence of terminal

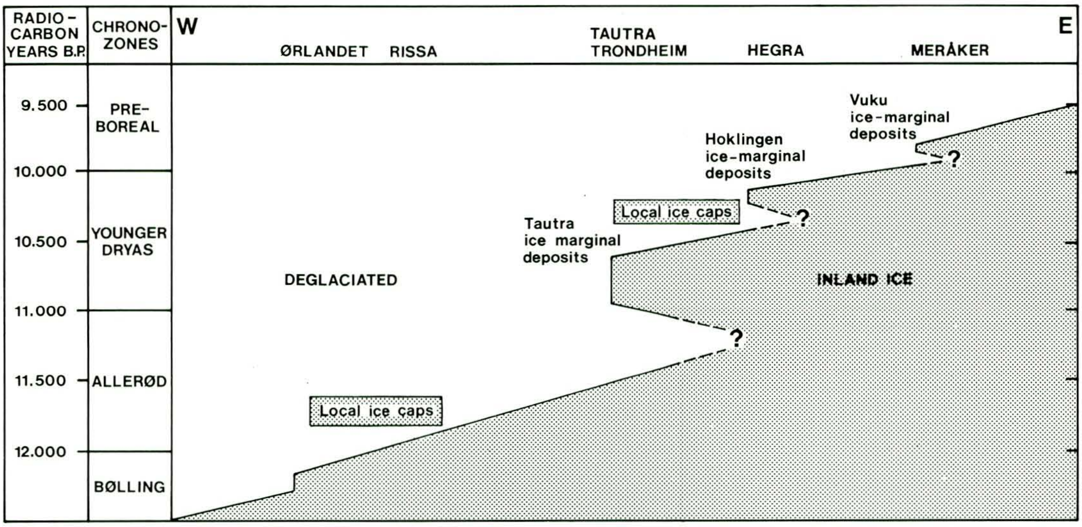

Fig. 11. Time-distance diagram for the deglaciation of the Trondheimsfjord area. Local ice caps left after fast calving in fjords and submerged valleys are also indicated. Modified from Reite et al. 1982.

moraines and glaciofluvial ice-contact deposits from these ice caps. Such deposits are quite common on the Fosen Peninsula (Reite 1990), in the Hemnefjord area (Lasca 1969) and in Gauldalen (Reite 1983a, 1984). Glacial striae that may have been formed beneath ice caps are also found. At Ålmosætra, Rissa (Fig. 10) and Vanvikan, glaciomarine sediments were tectonised by a glacial advance from a local ice cap, and at Ålmosætra parts of these sediments are overlain by till (Reite 1987). The radiocarbon dates suggest that this ice cap existed some 12,000 years B.P. As it was situated at least 500 metres below the glaciation limit and had no, or only limited, connection to the inland ice, this ice cap probably existed for less than two hundred years.

Radiocarbon dates from the Trondheim region (Reite 1990) indicate that this area was deglaciated no later than 11,500 years B.P. Ice caps situated to the west of Trondheim were almost contemporaneous as the calving in the fjord was so fast.

Ice caps existed on both sides of Gauldalen (Fig. 10) after the retreat from the Tautra ice-marginal deposits; and they are slightly younger than 10,500 years B.P. These ice caps, too, were situated far below the glaciation limit and had no, or only a limited, connection to the inland ice. They probably existed only for a short time.

The calving of the glaciers in Trondheimsfjorden proceeded to a position at least 15 km to the east of the Tautra ice-marginal deposits (Fig. 10). This is demonstrated by the occurrence of sub-till glaciomarine sediments on the Frosta and Skatval Peninsulas

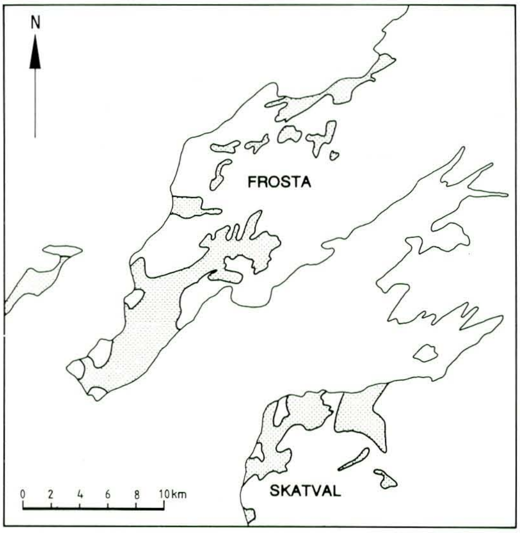

Fig. 12. The distribution of glaciomarine deposits (shaded areas) overlain by till in the Frosta - Skatval area. The same stratigraphy is found in submarine areas (see Fig. 13). After Reite 1986c.

and in the fjords to the north and south of Frosta (Figs. 12, 13). These sediments were deposited during the recession of the inland ice and the early Younger Dryas readvance towards Tautra from the easternmost position of the ice front during Allerød (Reite et al. 1982, Reite 1986a, c). The till was deposited during this readvance (Figs. 11, 12). In Beitstadfjorden, situated farther towards the north (Figs. 10, 13), glaciomarine sediments overlain by till are also found. If these sediments were deposited during the Allerød, the ice retreat must have been at least 35 km, judging by the position of the early Younger Dryas moraines in Skaudalen (Fig. 10). Sub-till sediments are also found to the south of Trondheimsfjorden, especially in Malvik, Trondheim and the lower part of Gauldalen. They were deposited during the Allerød ice recession and the glacial advance that took place during the Younger Dryas.

The sub-till glaciomarine sediments to the north of Tautra and in Beitstadfjorden have thicknesses of up to 200 m (Bjerkli & Olsen 1990, Reite in press 1994a, b). Such thicknesses indicate either a very rapid sedimentation of glaciomarine sediments during Allerød/early Younger Dryas, or that some of these sediments date from earlier interstadials or interglacials. If all the sediments were deposited during the deglaciation, this gives an average sedimentation rate of 0.1-0.3 m per year. This should not be dismissed, as high sedimentation rates have been found in the Trondheim region and in the lower parts of the valleys where most of the glaciofluvial drainage took place. It should be remembered that the ice-directed drainage from large areas to the south and east of the watershed was directed toward Trondheimsfjorden. The stratigraphies in the major valleys, where excellent sections are available to depths of more than 100 metres, do not indicate the existence of sediments older than the Allerød chronozone.

The Tautra ice-marginal deposits

The fast recession of the glaciers during the Allerød chronozone was followed by an early Younger Dryas glacial advance, caused by the marked Younger Dryas cooling. The Tautra ice-marginal deposits can be traced almost continuously from Melhus to Trondheim, Tautra, Leksvik, Skaudalen and along the border between Sør-Trøndelag and Nord-Trøndelag. In the mountains, one or two ridge-like terminal moraines are found, deposited during a marked glacial advance. In the lowland areas these deposits consist of terminal moraines and glaciofluvial ice-contact sediments.

The Fosen Peninsula

In the mountainous areas of the Fosen Peninsula (Fig. 10) there are distinct terminal moraines deposited by the inland ice (Sollid & Sørbel 1975, 1979, Sollid & Reite 1983). To the north of Skaudalen these ice-marginal deposits consist of one or two distinct ridges that appear to be push moraines. On the distal side of these moraines exposed bedrock is found almost everywhere, while the proximal side generally has a thin or discontinuous till cover, with thicker till deposits in depressions. During the early Younger Dryas glacial advance the inland ice therefore seems to have had a higher sediment load than during the ice recession in the Allerød chronozone.

The early Younger Dryas terminal moraines can be traced across Skaudalen towards Leksvik where they cross Trondheimsfjorden at Tautra (Fig. 13). In Skaudalen the terminal moraines rest on glaciofluvial sediments (Figs. 10, 14) which are underlain by 50 m of glaciomarine sediments (Kjærnes 1976). Molluscs from the uppermost 10 m of these sediments have been radio-carbon dated to 11,230 ± 120 years B.P. (T-6579). Most of the glaciomarine sediments were thus deposited earlier than Late Allerød (Reite 1993).

Between Skaudalen and Leksvik (Fig. 10) a few terminal moraines and sediments from ice-dammed lakes indicate the position of the ice front during the early Younger Dryas glacial advance. At Leksvik terminal moraines were deposited by a glacier in Trondheimsfjorden (Reite et al. 1982, Selnes 1982). In a basin distal to these moraines

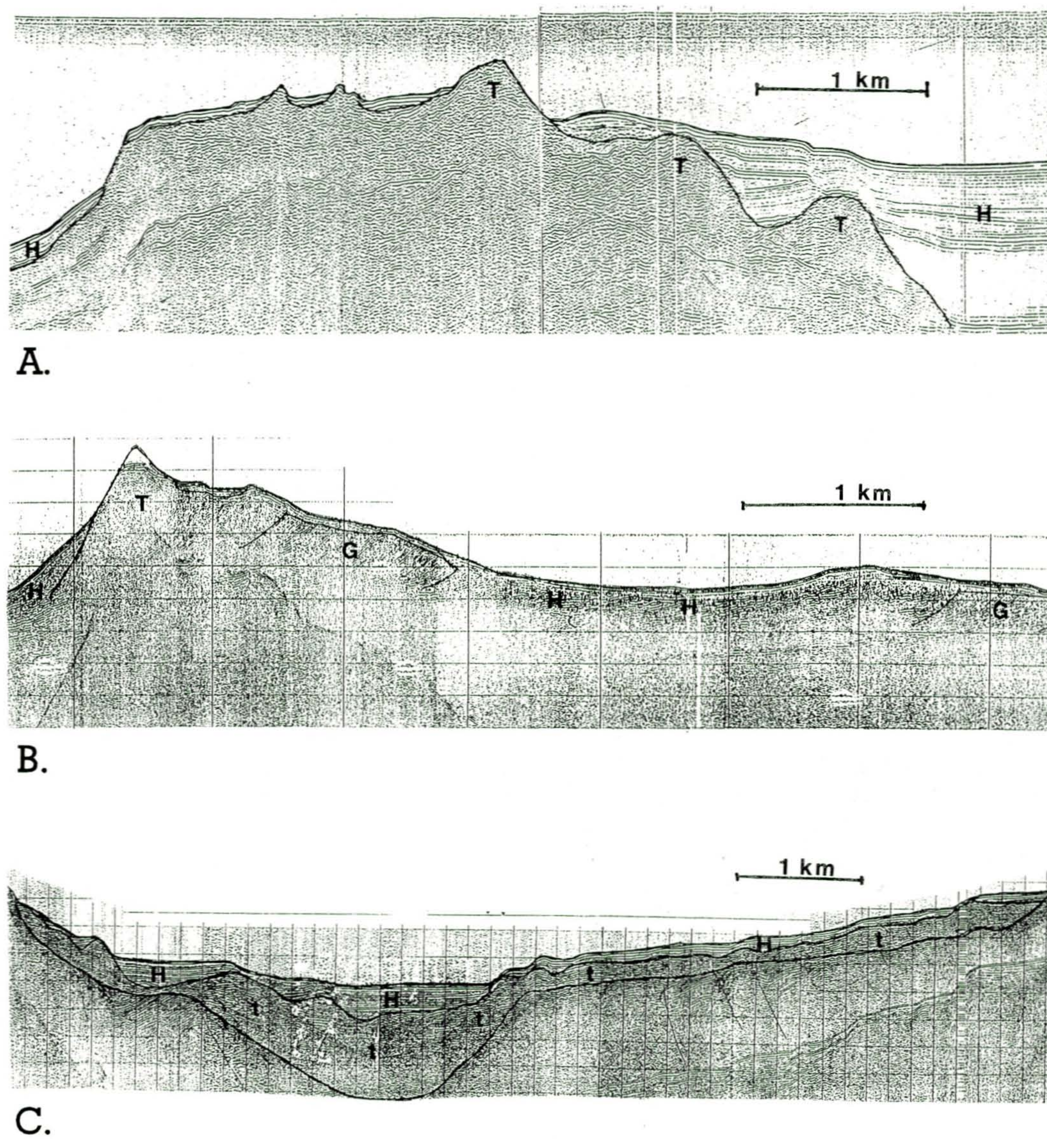

Fig. 13. Seismic reflection profiles through the Tautra ice-marginal deposits in Trondheimsfjorden. A. Along the fjord between Midtsand and Skatval. B. To the north of Tautra. C. Across Beitstadfjorden. The vertical scale is 4-7 times the horizonal one. For location, see Fig. 10. H - Glaciomarine/marine sediments. G - Glaciofluvial sediments. T - Terminal moraine. t - Till and glaciomarine/marine sediments strongly influenced by glaciotectonics.

gyttja was deposited during the Allerød. The advancing glacier dammed a lake in this area, and the gyttja was overlain by glaciolacustrine sediments. After the final deglaciation these sediments were overlain by gyttja. Radiocarbon dates of the two gyttja beds indicate that the ice-dammed lake existed during the first half of the Younger Dryas chronozone, approximately 10,800-10,500 years B.P.

Trondheimsfjorden and areas to the south

From Leksvik the terminal moraines can be traced to Tautra, Frosta, Skatval and Midtsand (Fig. 10). Seismic reflection profiles

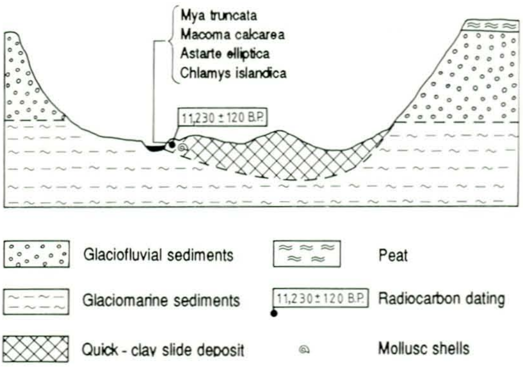

Fig. 14. Profile across Skaudalen 2 km distal to the early Younger Dryas terminal moraines.

(Fig. 13) along the fjord to the north of Tautra show a broad zone of ice-marginal deposits (Reite, in press 1994a). Distinctly dipping beds indicate that part of this deposit consists of glaciofluvial sediments with foreset beds. Between Frosta and Skatval the terminal moraines are less distinct (Reite 1986a). At Skatval, a terminal moraine is located along the lower slope of Forbordfjellet and a couple of moraines occur in the tidal zone in the southwestern part of the peninsula. At Skatval and Frosta, sub-till glaciomarine sediments are found over wide areas (Fig. 12). This till was no doubt deposited by an early Younger Dryas glacier readvance. From Skatval to Midtsand three terminal moraines are found in the fjord (Fig. 13). The westernmost moraine is not covered by younger sediments, whereas the other terminal moraines are covered by a few metres of silt and clay, deposited after the deglaciation (Reite 1986a). The terminal moraines crossing the fjord are underlain by thick Quaternary sediments, deposited during the Allerød glacial retreat. Older sediments may also be present. In Beitstadfjorden, sub-till glaciomarine sediments are found in the western part of the fjord. The till that covers these sediments was most likely deposited during the glacial readvance towards Skaudalen.

The early Younger Dryas terminal moraines rise above the present sea-level at Midtsand (Fig. 10). They can be traced towards Trondheim (Fig. 15), and less continuously to Melhus in Gauldalen (Reite 1983a). Sections at Vikhammer and Reppe, and a coring at Reppe (Fig. 16), clearly indicate that this part of the terminal moraine rests on glaciomarine sediments of great thickness. At Reppe, alternating layers of till and clay indicate that there were several minor oscillations of the ice front. The glaciomarine clay underlying this terminal moraine has not been dated, but was most likely deposited during the Allerød recession. At Vikåsen, 1.5 km to the south of Reppe, a 30 m long section revealed fossil-bearing glaciomarine clay overlain by a thin till layer and

Fig. 15. Terminal moraine at Åli, Malvik, deposited during the maximum glacial advance during Younger Dryas.

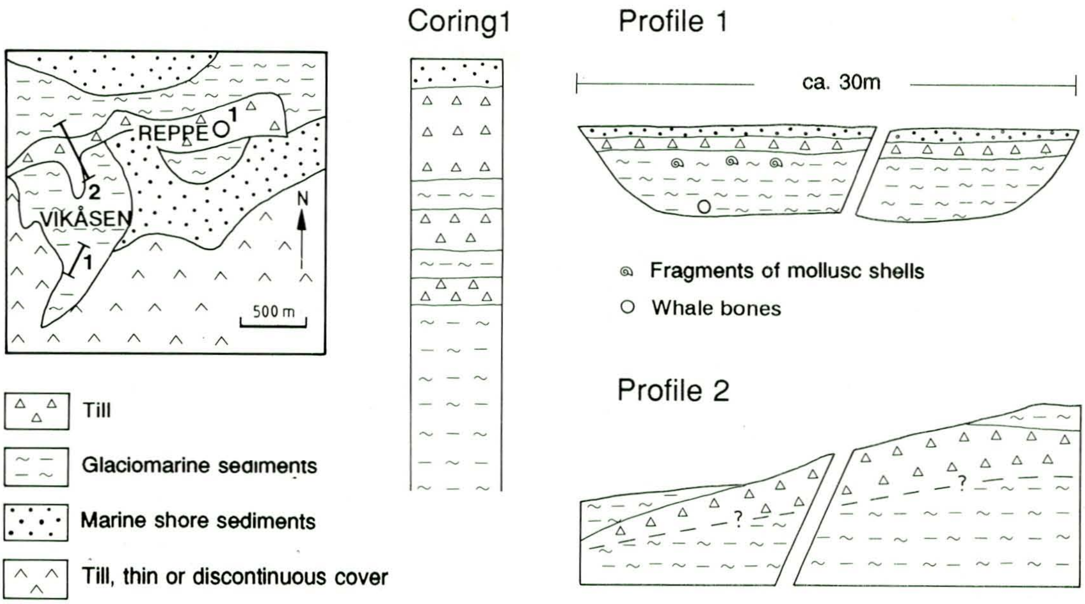

Fig. 16. Late Weichselian stratigraphy at Reppe - Vikåsen.

beach gravels. A fragment of a whale bone from this clay was radiocarbon-dated to 11,030 ± 150 years B.P. (T-11,100), indicating that this area was deglaciated at the transition Allerød/Younger Dryas followed by a glacial readvance after c. 11,000 years B.P, probably to the Tautra ice-marginal deposits.

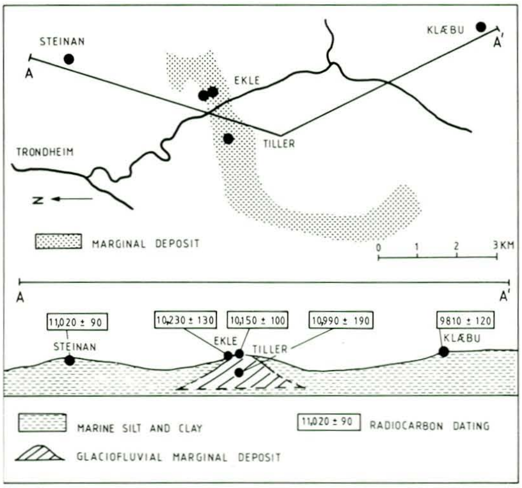

Fig. 17. Stratigraphy of the Ekle - Tiller ice-marginal deposit, with radiocarbon datings. After Reite (1983a).

At Ekle-Tiller, there is a large, arch-formed, glaciofluvial ice-contact deposit (Fig. 17). The meltwater drained both to Trondheim and to Gauldalen (Reite 1983a). Most of this deposit has not been built up to sea-level during the deposition, and it is partly covered by younger clay. The glaciofluvial deposit consists mostly of gravel and sand with marked foreset and bottomset beds. In the proximal part, till occurs together with large blocks of clay brought to the site by the glacier or by meltwater streams. Both the ice-marginal deposit and its feeding eskers are underlain by more than 20 m of older glaciomarine clay. This indicates a recession of the glaciers during the Allerød of at least 10 km in the Trondheim region, followed by a readvance when the glaciofluvial sediments were deposited.

No mollusc shells and very few foraminifera (K. Ofstad, pers. comm. 1978) have been found in the clays below the glaciofluvial sediments. Distal to the Ekle-Tiller ice-contact deposit, radiocarbon dates of molluscs from the uppermost part of the glaciomarine sediments clearly demonstrate that most of the clay was deposited during the Allerød chronozone (Reite et al. 1982). The foraminifera fauna in up to 17 m-long cores at Lade and Tyholt, 10 and 7 km distal to the Ekle-Tiller deposit, suggest arctic conditions. In the deepest parts of the cores, there were very few foraminifera, indicating high sedimentation rates. A dominent species throughout the cores is *Cassidulina crassa*, but *Elphidium excavatum, forma clavata*, is also quite common. An Allerød age is also likely for the clay beneath the glaciofluvial sediments.

A vertebrae of a big whale, found in the foreset beds of the Ekle-Tiller deposit, has been radiocarbon dated to 10,990 ± 190 years B.P. (T-787), indicating that the whale was buried at the transition Allerød/Younger Dryas (Fig. 17). The whale may also be derived from glaciomarine clay overrun by the Younger Dryas glacial readvance, or transported to the site by meltwater. Radiocarbon dates of molluscs (*Mya truncata*) from sandy silt overlying 4 m of silty clay which rests on the foreset beds gave ages of 10,230 ± 130 (T-786) and 10,150 ±100 years B.P. (T-854). The ice-marginal deposit may be considerably older as the shell locality is situated c. 20 m below the upper marine limit, and the sandy silt where the shells were found indicates shallower water than during the sedimentation of the underlying silty clay. This clay contains *Portlandia arctica*, indicating arctic conditions. The shells are few in number, and badly preserved.

The early Younger Dryas terminal moraines at Leksvik and Trondheim are fairly well radiocarbon dated. It can be concluded that this readvance took place during the first half of the Younger Dryas chronozone, and that the glaciers receded from this position at c. 10,500 years B.P. (Reite et al. 1982).

In Gauldalen (Fig. 10), the marginal deposits from the early Younger Dryas glacial advance are found in the Melhus district (Reite 1983a, b, 1984). As ice-contact deposits from the Allerød chronozone are found in the same region, and no radiocarbon dates exist, it is difficult to reconstruct the deglaciation of this area. The terminal moraine at Holem (Fig. 18) no doubt indicates a glacial readvance, as thick glaciofluvial deposits are overlain by 1-5 m of till; it should be correlated with the Tautra ice-marginal deposits.

From Melhus the early Younger Dryas ice front continues towards Storås in Meldal (Fig. 10), but as few terminal moraines are found the exact position of this ice front is not known. No radiocarbon dates exist, but a fossil ice vedge found in a sandur deposit at Svorksjøen (Reite 1984) suggests that this area was free of ice during the extremely cold climate that prevailed during the Younger Dryas chronozone. Arctic conditions during the early Younger Dryas are also indicated by the occurrence of marine shorelines in solid bedrock at Trondheim and at a

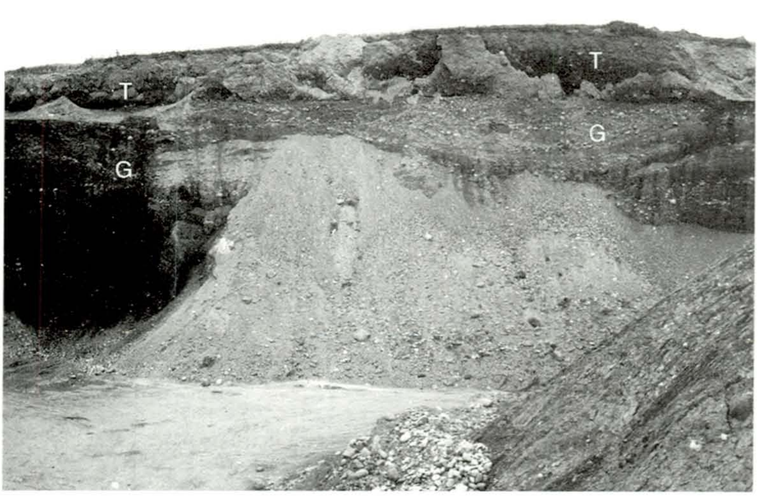

Fig. 18. Till (T) underlain by glaciofluvial sediments (G) at Holem, Melhus. The till was deposited during the glacial advance to the Tautra ice-marginal deposits.

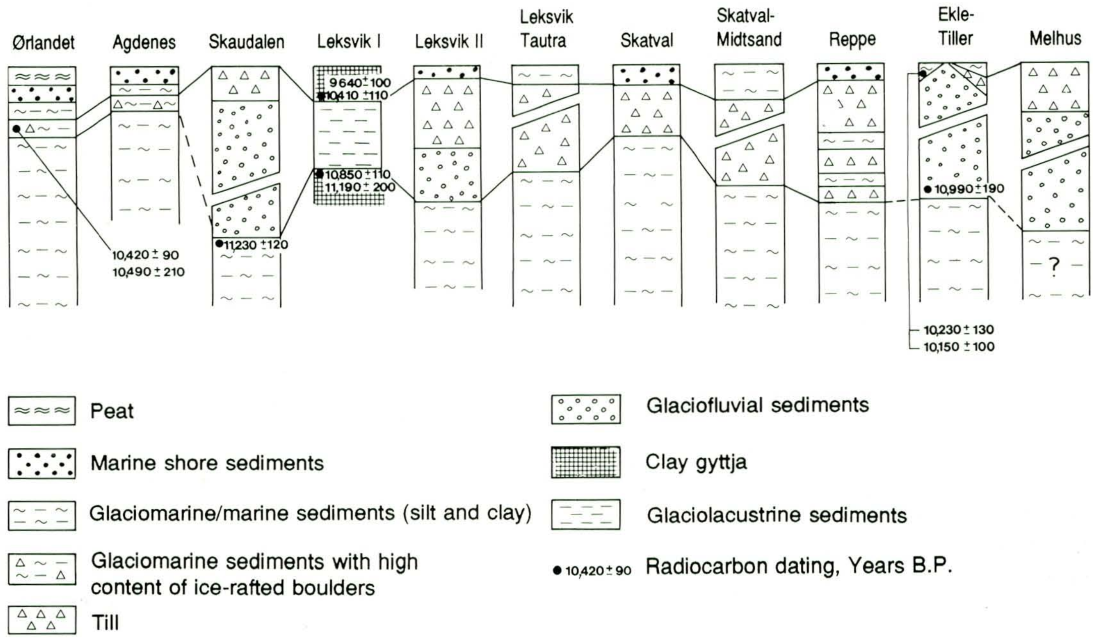

Fig. 19. Correlation diagram for early Younger Dryas (the Tautra ice-marginal deposits).

couple of other localities just outside the ice margin during early Younger Dryas, but not elsewhere in Trøndelag (Reite 1983a).

The correlation of the Tautra ice-marginal deposits is based on morpho-, litho- and chronostratigraphy and partly on biostratigraphy. The correlation should be reliable for Fosen, Leksvik, Tautra, Skatval, Stjørdal, Malvik, Trondheim and Melhus (Figs. 10, 19). The continuation of the ice front from Melhus towards Storås and Møre and Romsdal is more questionable. The shoreline displacement was slow during the Allerød and Younger Dryas chronozones, and correlations by shorelines alone are therefore not so strightforward.

During the glacial readvance to the Tautra ice-marginal deposits, the ice front terminated in Trondheimsfjorden for a distance of some 50 km. This led to an intense calving, and icebergs transported sediments far out into the fjord. Distal to the Tautra ice-marginal deposits the glaciomarine sediments commonly contain very many clasts close to the surface. At greater depths the content of stones and boulders is low. Radiocarbon dates of mollusc shells from this clast-rich bed at a depth of 0.7 and 1 m at Ørlandet (Reite 1988) indicate that it was deposited at c. 10,500 years B.P. It forms an important stratigraphic marker for the western part of Trondheimsfjorden. The very high clast content in this bed may be a result of low sedimentation rates of fines as the localities are situated rather far from where major meltwater streams drained into the fjord. Low sedimentation rates during Younger Dryas and Holocene have also been found at Rissa (Løfaldli et al. 1981), where only 3.7 and 6.4 m of clay were deposited after 10,920 ± 120 and 11,780 ± 90 years B.P., respectively, while c. 15 m of clay was deposted earlier during the deglaciation. In Trondheim, too, Allerød clay is found close to the surface in areas situated only 5-10 km distal to the Tautra ice-marginal deposits. These observations indicate that most glaciomarine clays were deposited within a very short distance from where the meltwater streams reached the sea.

The Hoklingen ice-marginal deposits

Radiocarbon dates of the Tautra ice-marginal deposits (Reite et al. 1982) and dates in areas situated to the east of these deposits indicate that the glaciers receded at c. 10,500 years B.P. to a position 20-50 km to the east of Tautra, followed by a readvance to the Hoklingen ice-marginal deposits.

The Hoklingen ice-marginal deposits are named from the type locality Hoklingen in Nord-Trøndelag (Fig. 10). Here, distinct terminal moraines and glaciofluvial ice-contact deposits are found in front of Movatnet and between Movatnet and Hoklingen. A slide depression into the terminal moraine at Lynvatnet strongly suggests that the Hoklingen ice-marginal deposits in this area are underlain by glaciomarine or marine sediments. This is also indicated by seismic refraction profiles, where seismic velocities could be explained by the occurrence of silt and clay below the till (Reite 1986c). The Hoklingen ice-marginal deposits can be traced to Beitstadfjorden and Hegra (Figs. 10, 20, 21), and less continuously towards Frigården, Brøttem and Kvashylla, Støren.

The heights of the reconstructed ice surface when distinct terminal moraines in Budal and to the northeast of Støren were deposited, suggest that these moraines were formed during the same glacial advance and can be correlated with the Hoklingen ice-marginal deposits (Fig. 10). The marked terminal moraines on Dovrefjell may also be correlated with this glacial advance. This correlation is based on the height of the inland ice, but as few terminal moraines are found between Budal and Dovrefjell the correlation is questionable.

Radiocarbon dates (Reite et al. 1982, Sveian 1989) indicate that the Hoklingen ice-marginal deposits were formed at about 10,300 years B.P. The stratigraphy at Hoklingen, Frigården, Brøttem and Støren could best be explained by a glacial readvance, as these deposits are underlain by glaciomarine clays (Fig. 21). At Frigården (Fig. 10) large slide scars from quick-clay slides show that this deposit is underlain by clay. At Brøttem the terminal moraine to a great extent consists of glaciomarine clay, reworked by a glacial readvance. At Støren most of Kvashylla consists of clay, even in the proximal part of the deposit. Only a few metres of glaciofluvial material were deposited during the readvance to the Hoklingen ice-marginal deposits. The size of this read vance is unknown for the investigated area, but observations from the inner part of Trondheimsfjorden (Sveian 1989) have indi-

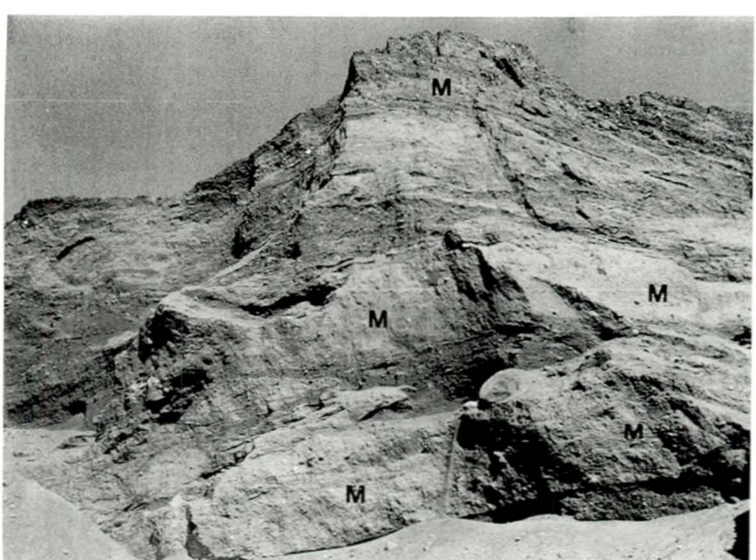

Fig. 20. Section across the ice-marginal deposit at Hegra. In the proximal part of this deposit layers of till (M) are commonly found. The distal part consists of glaciofluvial sediments with foreset beds. The height of the section is 15 metres.

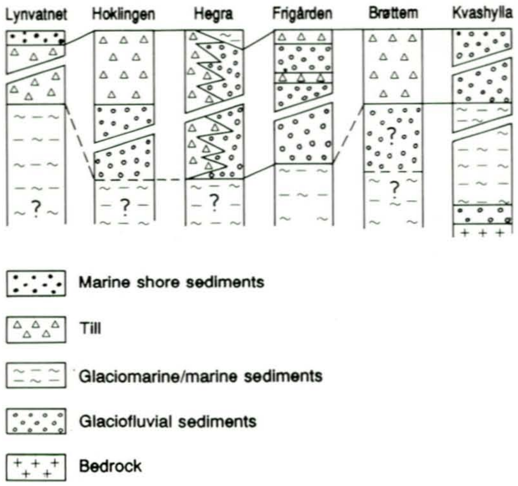

Fig. 21. Correlation diagram for late Younger Dryas (the Hoklingen ice-marginal deposits).

cated a glacial readvance of at least 20 km (Fig. 11).

The correlation of the Hoklingen ice-marginal deposits is above all based on morpho- and lithostratigraphy. Correlation based on the height of shorelines is not so very promising for this time interval, as the shoreline displacement during Younger Dryas was very slow (Kjemperud 1986).

The Vuku ice-marginal deposits

After the Hoklingen ice-marginal deposits were formed, the recession of the inland ice continued (Figs. 10, 11), interrupted by minor standstills or readvances (Sollid & Sørbel 1979, Reite et al. 1982, Sollid & Reite 1983).

At Meråker, terminal moraines are found which suggest an ice surface of 800-700 m a.s.l. (Fig. 10). The most distinct ice-marginal ridges occur in Torsbjørkdalen and to the west of Fonnfjellet. One of these terminal moraines can be traced for 4 km. The ice front in Stjørdalen may have been situated at Grindmoen, Flornes, where a small glaciofluvial ice-contact deposit is found (Fig. 10). The altitude of the inland ice strongly suggests that the terminal moraines in Meråker can be correlated with the Vuku ice-marginal deposits (Reite et al. 1982, Sveian 1989, H. Sveian, pers. comm. 1994).

A few, small, terminal moraines in Tydalen, situated 30-40 km to the east of Brøttem (Fig. 10), may also be correlated with the Vuku ice-marginal deposits. This correlation is based on the fact that these moraines are the only distinct terminal moraines formed after the ice recession from Brøttem, correlated with the Hoklingen ice-marginal deposits.

In valleys to the east of the terminal moraines in Meråker and Tydalen (Fig. 10), numerous glaciofluvial ice-contact deposits are found. Some of these deposits were formed in front of former valley glaciers, but they are too scattered to be used to reconstruct the deglaciation. The last remnants of the inland ice in Trøndelag were situated in the eastern and southern parts of the counties. To the south and east of the water-divide the inland ice still had a considerable thickness. This led to the development of ice-dammed lakes between the inland ice and the watershed; these lakes drained towards Trondheimsfjorden (Holtedahl 1960, Lundqvist 1969, Sollid & Reite 1983).

The deglaciation pattern of Sør-Trøndelag and adjacent parts of Nord-Trøndelag resembles that found in the Oslofjord region (Sørensen 1979) and in Nordland (Andersen et al. 1981). For western Norway, only one Younger Dryas glacial readvance from the inland ice has been found (Mangerud et al. 1979, Rye et al. 1987). Distal to the inland ice a local glaciation occurred. The mountains in Trøndelag were covered by the inland ice during the Younger Dryas; or they may have been situated below the glaciation limit during the Younger Dryas cooling.

Geological development after the deglaciation

The coastal areas were deglaciated at c. 12,500 years B.P., while the easternmost parts of the counties were covered by glaciers until some 9500 years B.P. Sediments depending on glaciers for their formation were thus deposited in the inland area 2000-3000 years after the coastal areas were deglaciated, and the sediments there became exposed to shoreline displacement, marine abrasion and fluvial erosion.

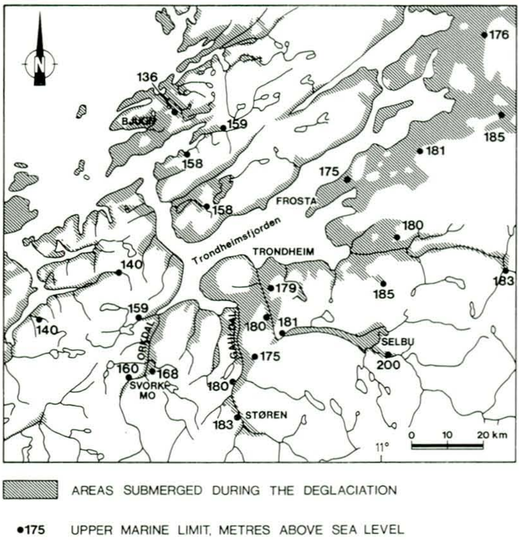

Fig. 22. Present land areas submerged by the sea during the deglaciation (shaded). Numbers show the upper marine limit at selected localities. Glaciomarine/marine sediments and marine shore sediments have a wide distribution in the shaded areas.

Shoreline displacement

During the deglaciation this part of Norway was deeply submerged by the sea (Fig. 22). In the coastal areas the sea reached some 120 m above the present sea-level, in the Trondheim region some 175 m (Kjemperud 1981, 1986, Reite et al. 1982).

Kjemperud (1986) has investigated the shoreline displacement in the coastal areas (Frøya, Hitra, Bjugn) and for the central part of Trondheimsfjorden (Fig. 23). The westernmost part of Trøndelag was deglaciated some 12,500 years B.P, while the central part of the fjord (the Tautra area) was deglaciated at the middle of the Younger Dryas chronozone.

During the Allerød and Younger Dryas chronozones a slow shoreline displacement took place, followed by a very fast displacement during Early Holocene (Fig. 23). At the outer coast a transgression or standstill took place at c. 8000-6500 years B.P. In the Verdal area (Sveian & Olsen 1984) a slow shoreline displacement occurred during the same time interval (Fig. 23). Otherwise there has been a gradually decreasing uplift after the deglaciation. An uplift of 2-5 mm a year still takes place (Sørensen et al. 1987), indicating that the isostatic readjustment has been rather slow.

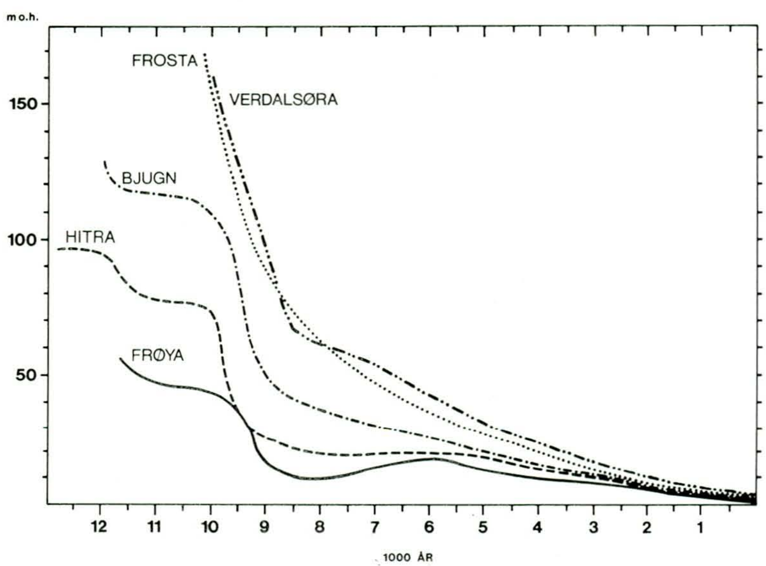

Fig. 23. Shoreline displacement diagram from Frosta, Bjugn, Hitra and Frøya (after Kjemperud 1986). The diagram from Verdalsøra is after Sveian & Olsen (1984).

Fluvial erosion

During the shoreline displacement (Fig. 23) the rivers have eroded heavily into sediments deposited during the glaciation and deglaciation, especially where these sediments consist of gravel, sand or finer particles. In areas with tills a considerable erosion has also taken place, but here a lag is formed which protects against further erosion. The sediments eroded were transported farther downstream or into the fjords.

Oftedahl (1977) has calculated that 6 km^3 of silt and clay was brought into Trondheimsfjorden from Orkdalen and 14.4 km^3 from Gauldalen. A considerable erosion also occurred along Nidelva and in Stjørdalen. Most of these sediments were deposited in the central part of the fjord. Of a total of 50 km^3 of Quaternary sediments in this fjord basin, Oftedahl claimed that about one half of these sediments were transported to the fjord during the shoreline displacement. Seismic reflection profiles of these sediments show horizonal lamination and a very smooth surface, indicating that turbidity currents have been a major transporting agent.

Newer calculations by the author of this paper indicate that Oftedahl had overestimated the fluvial erosion in these valleys, and that some 2.5 km^3 and 6 km^3 of silt and clay were brought into the fjord from Orkdalen and Gauldalen, respectively. Although the recalculated fluvial erosion is less than one half of that reported by Oftedahl, still some 20 % of the Quaternary sediments in the central part of Trondheimsfjorden were deposited after the deglaciation. The most intense fluvial erosion occurred during the first couple of thousand years after the deglaciation, when most of the shoreline displacement took place (Fig. 23). The new calculations of the extent of fluvial erosion should also be considered as approximati-

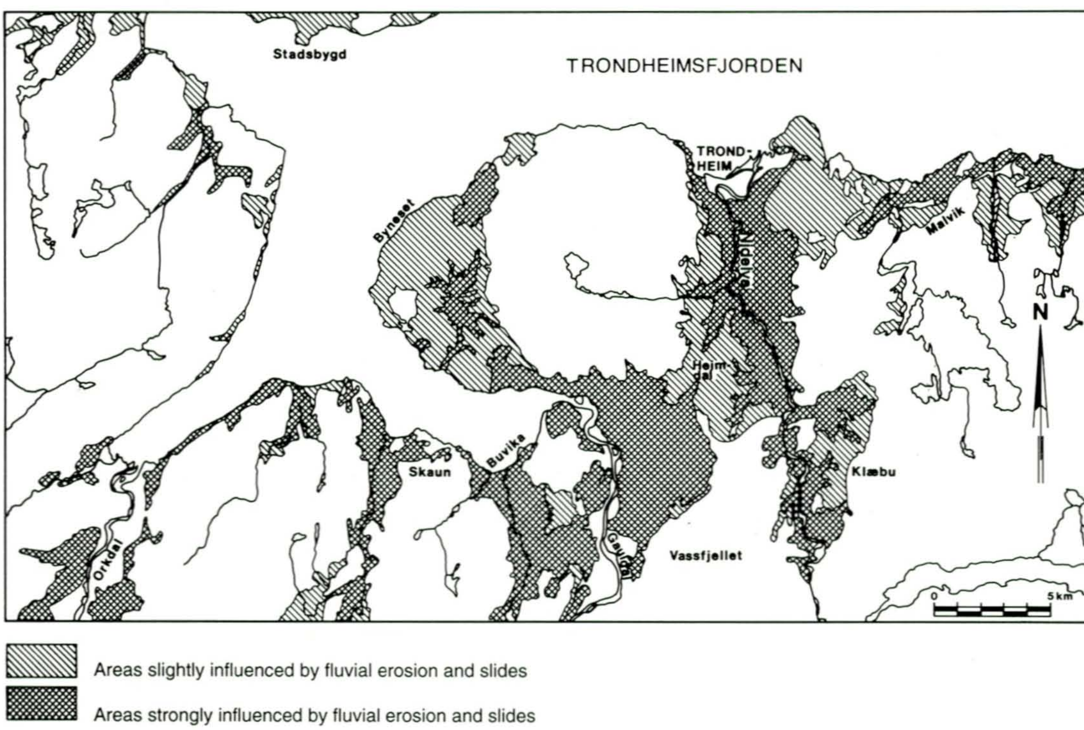

Fig 24. Fluvial erosion and slides in areas dominated by glaciomarine/marine sediments in the Trondheim - Orkanger area. Modified from Reite (1983a, 1983b).

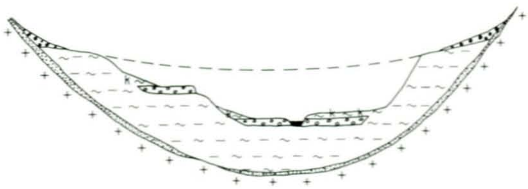

Fig. 25. Transverse profile of a valley situated below the upper marine limit. The sediments are strongly influenced by erosion during the shoreline displacement and transport of sediments to lower levels or into the present fjord.

ons, as it is very difficult to determine the upper surface of the eroded sediments. This is especially the case for the major valleys Orkdalen and Gauldalen, and along Nidelva, where only minor remnants are left along the valley sides (Figs. 24, 25). In the two first-mentioned valleys more than 80 % of the glaciomarine sediments are strongly affected by fluvial erosion and slides, and along Nidelva more than 60 %. Most of the remaining glaciomarine sediments are dissected by gullies, and commonly to depths of more than 20 metres. These gullies were formed during periods of heavy rain and snow melt. Small slides along the gully sides have accelerated the erosion. Bjerkli & Olsen (1990) have found that some gullies can be traced below sea-level to a water depth of more than 50 metres. In my opinion these submarine gullies may have been formed by sediment-loaded water from supramarine gullies that continued along the seafloor as a result of their high density, and eroded into sediments in the clay, silt and sand size fractions.

Slides

The shoreline displacement led to an intense fluvial erosion in glaciomarine clays and other sediments. In the main valleys Orkdalen, Gauldalen, Stjørdalen and along Nidelva, the base-level was lowered by some 175 metres. The rivers have eroded to a depth of more than 150 m, most of this erosion having taken place in glaciomarine sediments. During this land uplift, saline pore water was leached and replaced by fresh water. This process greatly increased the sensitivity of clays, and increased the risk for slides.

Quick-clay slides are characterised by an almost liquid clay, as the disturbed shear strengh is very low. Such slides are also found in areas where glaciomarine clays are overlain by tills, deposited during the Younger Dryas glacier advances to the Tautra and Hoklingen ice-marginal deposits. The overconsolidation caused by the overburden of the glaciers has been too small to exclude the possibility for quick-clay slides.

In areas with glaciomarine clays, numerous quick-clay slides have taken place, some of them during historical time. In 1978, a major quick-clay slide occurred at Rissa. Some 5 million m^3 of clay were involved, and the slide depression covered an area of 330,000 m^2. Several farms were destroyed and one person was killed (Gregersen 1981).

In 1962, a quick-clay slide took place in Skjelstadmarka, Stjørdal (Fig. 26), in an area strongly affected by slides. It was pro-

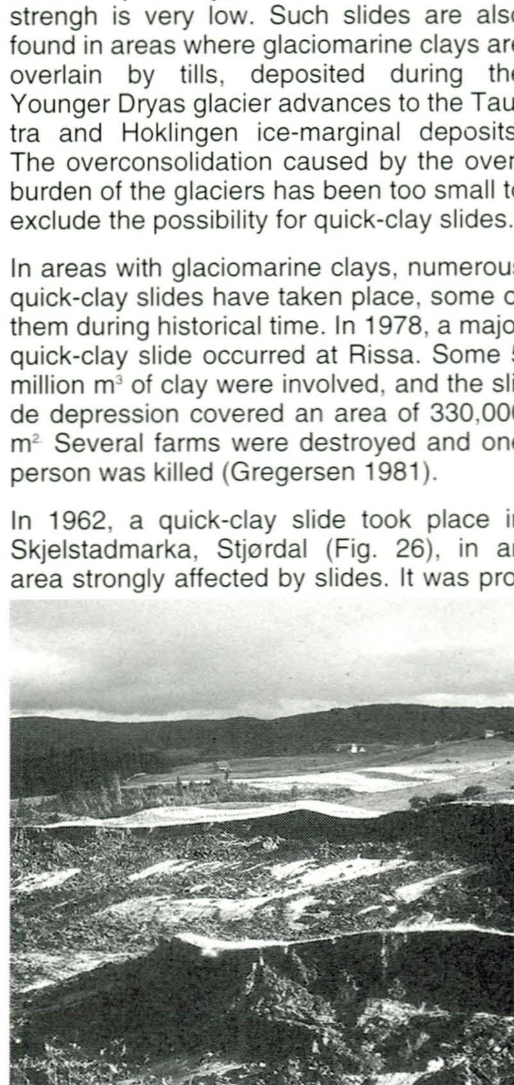

Fig. 26. Quick-clay slide in Skjelstadmarka, Stjørdal. The slide was triggered by fluvial erosion by the river Gråelva.

bably triggered by fluvial erosion from Gråelva.

In 1345, a large, catastrophic, quick-clay slide took place in Gauldalen (Holtedahl 1953). The slide blocked the river and a lake was formed further upstream. The greatest damage was caused by a gigantic flood when the river broke through the dam. 500 persons were killed, and many farms were destroyed.

Slide scars from quick-clay slides are quite common in Trøndelag. Most of these slides have occurred during pre-historical times, and few of them are dated. Dating is possible, however, as buried soil and vegetation are often found.

Recent investigations in Trondheimsfjorden at Trondheim and Malvik have demonstrated that slides in clay, silt and sand are also found in the fjord (Bjerkli & Olsen 1990). Some of the slide scars seem to be a part of quick-clay slides on land, while others are entirely submarine. During the last century several, mostly submarine, slides occurred in near-shore areas in the Trondheim region. Most of these slides were probably triggered by overloading in the tidal zone.

Fluvial erosion also led to numerous slides in non-sensitive clays. In areas strongly influenced by fluvial erosion it is often difficult to decide the relative importance of fluvial erosion and slides. Fluvial erosion has also reduced the stability of slopes in areas where the superficial deposits do not consist of clay. Slides in such areas generally involve smaller volumes than the quick-clay slides. They mostly occur after periods of heavy rain or snow melt or during the thawing of frozen ground.

Rock falls are common along steep cliffs, especially in areas distal to the maximum extent of the inland ice during the Younger Dryas. This difference may depend on the very cold climate that prevailed during Younger Dryas compared with the Holocene.

Conclusions

Thick Quaternary deposits, consisting partly of till, are found on the shelf and in the outer parts of the fjords. These deposits are not dated, but they may be older than the last Weichselian advance to the outer part of the shelf.

Clayey till below a sandy till layer is found in drumlins, in stoss-side positions to the dominent ice movement, in narrow valleys transverse to the main ice flow and in depressions in the terrain. The clayey till is most likely older than Late Weichselian, and may represent the erosional remnants of a more extensive, clayey till cover. Otherwise, the clayey till must have been deposited by an inland ice sheet where accumulation was restricted to the very limited areas where clayey till is found today.

The clayey till generally has a low clast content. It lacks structures, and is very compacted. The clayey till consists of 10-25 % of material in the clay-size fraction, while the sandy till deposited during later stages of the Late Weichselian generally contains 1-5% clay. Tills formed by glacial readvances across glaciomarine sediments have a clay content resembling that of the above-mentioned clayey till. Generally they can be distinguished from the clayey till by their stratigraphy, content of shell fragments and foraminifera.

The clay-size fraction of clayey tills consists of chlorite and illite, with some quartz and feldspar. The mineralogy resembles that found in the clay fraction of sandy tills and glaciomarine/marine sediments, which are mostly derived from tills deposited during the Late Weichselian.

The high clay content of clayey till compared with sandy till is not dependent on local bedrock or erosion in fine-grained waterlain sediments. The marked difference in clay content may depend on the distance of transport, and the temperature and pressure at the base of the inland ice.

The coastal areas were deglaciated at the transition Bølling/Older Dryas. Terminal moraines in the outer parts of the fjords were caused by the steep gradient of the inland ice, resulting from rapid calving and rock thresholds. These moraines are not strictly synchronous. They consist of till or poorly sorted glaciofluvial sediments, strongly reworked by waves and currents in the tidal zone.

After a readjustment of the gradient the ice recession continued into Trondheimsfjorden and other fjords along the coast by calving until more stable positions were reached. At such localities ice-marginal deposits were formed. In Trondheimsfjorden, this recession continued to a position at least 10-15 km to the east and south of Tautra. The calving was very fast, and local ice caps were formed along the fjords and in the lower parts of the present valleys. The ice caps on both sides of the western part of Trondheimsfjorden came into existence some 12,000 years B.P, while the ice caps on both sides of Gauldalen are slightly younger than 10,500 years B.P.

During early Younger Dryas the glaciers advanced across sediments deposited during the ice recession (Reite et al. 1982), and the marked Tautra ice-marginal deposits were formed at 10,800-10,500 years B.P. The very long calving front led to iceberg transport of clasts to the western part of Trondheimsfjorden, making an excellent chronostratigraphic marker for the Late Weichselian glaciomarine sediments. Shorelines in bedrock were formed just outside the ice margin, caused by the very cold climate that prevailed compared with earlier and later parts of the deglaciation.

At c. 10,500 years B.P. the glaciers retreated to positions 20-50 km to the east and south of the Tautra ice-marginal deposits, followed by a readvance to the Hoklingen ice-marginal deposits (Reite et al. 1982). These deposits were formed c. 10,300 years B.P. The marked terminal moraines in Budalen should be correlated with the Hoklingen ice-marginal deposits. The terminal moraines on Dovrefjell may also be contemporaneous with these moraines (Sollid & Reite 1983).

The ice recession from the Hoklingen ice-marginal deposits was interrupted by a small readvance to Meråker, Tydal and Haltdalen, where terminal moraines were formed. These moraines may be correlated with the Vuku ice-marginal deposits (Reite et al. 1982) as they indicate the same altitude of the inland ice. They were deposited at c. 9800 years B.P.

The last remnants of the inland ice in Trøndelag were situated in the eastern and southern parts of the counties. To the south and east of the water divide the inland ice still had a considerable thickness, and the glaciofluvial drainage from large areas was directed towards Trondheimsfjorden.

The shoreline displacement during the Holocene led to an intense fluvial erosion in the valleys, and the eroded sediments were transported farther downstream and eventually into the fjords. This erosion has reduced the stability of the remaining sediments and numerous slides have taken place. Some of these slides are caused by a leaching of saline pore water that reduced the disturbed shear strengh of silt and clay.

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