Quaternary geological mapping of Central Fennoscandia and Nordland: Deglaciation, deposition, stratigraphy and applications

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Growing older has the inherent possibility of spending more time doing what we *want* to do and not being so tied to what we *need* to do.

(Common wisdom)

Abstract

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The thesis describes firstly the development of Quaternary geological mapping in Norway with special emphasis on different scales and the use of the maps for engineering purposes. Maps at small scales (1:50,000-1:1,000,000) have the disadvantages that they show general information and few details. However, these maps are not intended for showing details but to indicate where to find areas suited for production of minerogenic resources, ground water, cleaning of waste water, earth heating systems, buffering of acid rain, plant production, recreation, geo-hazards such as clay slides and construction. Most of these activities/uses are located to areas with thick surficial deposits. As less than 10 % of the area of Norway has such qualities, it is important to use the areas optimally, and the maps may be helpful in planning such use.

Regional Quaternary geological maps at small scales from Central Fennoscandia (1:1,000,000 and 1:2,000,000) that show the distribution of the surficial deposits, glacial geomorphology, ice-flow indicators and stratigraphy onshore and on the shelf areas, and a map of the surficial deposits of the County of Nordland (1:250,000) are described. These enclosed maps are fundamental parts of this thesis, and they demonstrate clearly the importance of the Caledonian mountain chain for the distribution of the surficial deposits left by the Fennoscandian ice sheet. Most of the surficial deposits are located to the east of the mountain chain, which shows a conservational or even a depositional regime in this area, probably because of long periods where a cold-based ice situation prevailed. On the western side of the mountain chain the temperate glaciers ("warm-based" ice) had a tremendous erosive effect during several glaciations that have produced the dissected Norwegian coast and left sparse surficial deposits.

As the glaciation centre was located east of the mountain chain during the Late Weichselian glaciation, the ice flow to the west was most intense where the lowest pass points were situated. Consequently, the ice flow in these areas was probably very sensitive to changes in the glacier volume as the ice was temperate and quite mobile. Surges and fast flowing ice streams could have been common phenomena. This can probably explain the rapid changes in the position of the glacier margin that are reported along the coast of Norway where, e.g. up to ten glacial stadials are recorded during Late- and Postglacial times. The ice flow probably also had its greatest endurance along these lowest areas. Another consequence of the concentrated ice flow was probably that the marginal zone of the glacier during the latest phases of the deglaciation had a substantially more lobe-like appearance than presented in earlier glacial models.

Two areas of Northern Norway where pronounced ice lobes probably existed have been studied in this thesis, the Lofoten and the Bindal-Tosen areas. In Lofoten, ice lobes from the huge Vestfjorden glacier that was flowing towards southwest and the local glaciers in the Lofoten mountains coalesced and ice lobes were directed northwards through the north-south-trending sounds towards the shelf edge at the last glacial maximum. At the end of the deglaciation of this area, an ice readvance probably deposited a few end moraines in the sounds in the western part of Lofoten, the *Lofoten event*. This readvance is tentatively dated to c. 13.5 ka BP or may be younger, but is definitely older than 11 ka BP.

In the Bindal-Tosen area three main glacier readvances are recorded, namely the *Heilhornet event* in two episodes that are older than 10.6 ka BP and c. 10.4-10.3 ka BP, respectively; the *Breidvika event* at c. 10.2-10.1 ka BP and the *Vassås event* at c. 9.8 ka BP. Based on moraine morphology and stratigraphic evidence, strong topographic deviations of the ice flow and a dynamic active ice margin are recorded. The ice supply to the area changed markedly from the northeast and east to the southeast as the ice flow across the high-altitude easterly pass points ceased. The latest ice flow was channeled through the lowermost part of the mountain chain, the Namsvatnet area, which is situated at only c. 350-400 m a.s.l.

Acknowledgements

The present work has been carried out in the Quaternary Geological Section, Geological Survey of Norway (NGU) where I have been fully employed since 1976. The thesis is based on four Quaternary geological maps, the compilation of which was financed by NGU, the Geological Surveys of Finland (GTK) and Sweden (SGU) and Nordland County. I have financed the detailed fieldwork reported in this thesis myself. As a doctoral student at the Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology (NTNU), I have benefited from the Department's resources, a support that is greatly acknowledged.

This thesis would hardly have been realized without the inspiration and belief imparted by Professor Kåre Rokoengen at the Department of Geology and Mineral Resources Engineering at the NTNU, to whom I address my sincere thanks.

I also want to express my thanks to all my co-operative partners during the Mid-Norden Project, namely Kalevi Mäkinen and Keijo Nenonen and their co-workers at the Geological Survey of Finland (GTK), and Robert Lagerbäck and his co-workers at the Geological Survey of Sweden (SGU) who performed most of the geological work in the Finnish and Swedish areas, respectively, of the Maps of Central Fennoscandia and to the Norwegian leader of the Mid-Norden Project, Ron Boyd, who also corrected the English language in most of the thesis. David Roberts kindly improved the English language in parts of the thesis. Thanks also to the staff of the GIS Section at NGU for digitising the Norwegian material and to Per Larsson, SGU who compiled the Central Fennoscandian maps and made them printable. Thoughts are also sent to the "father" of the Mid-Norden Project, the late Gunnar Kautsky who unfortunately died last October.

The compilation of the Quaternary Geological map of the County of Nordland was possible thanks to the former director of the Geological Survey of Norway (NGU) Knut S. Heier. The GIS Section at NGU also performed all the digitising of this map.

Thanks also to colleagues in the Quaternary Geology Section at NGU for inspiration and support. After fourteen years in an administrative career path, I was allowed to concentrate fully on the thesis without interference. Special thanks are addressed to Louise Hansen for introducing me to the magic world of Adobe Illustrator and to Lars Olsen for co-operation in the Mid-Norden Project and for unfailing encouragement when discussing problems and commenting on drafts as an external adviser.

Finally, special thanks to Helen for love and patience, to Renée and Kari for understanding and belief and to Monica, Joakim, Malin and Kristian who have shown me the real meaning of life.

Trondheim, May 2003

Contents

1. Maps of Quaternary geology in Central Fennoscandia, sheet 1: Quaternary Deposits, scale 1:1,000,000 (small-scale reproduction).

2. Maps of Quaternary geology in Central Fennoscandia, sheet 2: Glacial Geomorphology and Palaeohydrography, scale 1:1,000,000 (small-scale reproduction).

3. Maps of Quaternary geology in Central Fennoscandia, sheet 3: Ice-flow Indicators, scale 1:1,000,000, and Quaternary stratigraphy, scale 1: 2,000,000 (small-scale reproduction).

4. Quaternary geology in the County of Nordland, scale 1:400,000 (small-scale reproduction).

5. End moraines etc. in the Norwegian part of the Central Fennoscandia and Nordland.

6. Correlation chart for the Weichselian in Central Norway.

7. Map of geographical names (the Norwegian part of the Central Fennoscandia and Nordland).

8. CD-ROM with printable PDF-files of maps 1-4.

9. Map of geographical names (Central Fennoscandia).

The Quaternary geological maps of Central Fennoscandia and the County of Nordland are enclosed in full scale versions in the copies of the thesis submitted to the doctoral committee. Other copies contain the maps at reduced scales only.

Notes on the contributions to the different parts of the thesis

I was introduced to the Quaternary geological mapping activity at the Geological Survey of Norway (NGU) in 1978, and since then I have published more than 40 maps at different scales, with accompanying descriptions, from most parts of Norway. I have also produced several reports on mineral resources (sand and gravel), and as a result of that activity, I have had co-operation with local authorities in several municipalities and learnt about their problems and needs for geological information. In addition, I was in charge of Quaternary geological mapping activity at NGU for a period of fourteen years (1986-1999). **Part I** of the thesis, in which the Quaternary geological maps are thoroughly discussed, can therefore be looked upon as a "mapping memoir" as it is mostly based on my own experience.

Part II of the thesis is based mainly on the results from two of the latest - and largest - mapping activities that were performed under my supervision. The mapping projects were called **the Mid-Norden Project,** which produced geological maps of Central Fennoscandia, and **the Nordland Project**. Both projects were multidisciplinary projects, and more information on them is found in Chapter 4.

My contribution to the Central Fennoscandian Quaternary geological map sheets was to compile the Norwegian map area, to perform additional aerial photo interpretations and field control and to write the text concerning the Norwegian areas. The stratigraphy map was not compiled by me, but is included in the thesis since it was printed on the same sheet as the map of Ice Flow Indicators and, more importantly, because stratigraphical information is a necessary supplement for understanding and describing the Quaternary geological history of the region. Most of the text that is included on the maps is used in Part II of the thesis, but I have added much new text on deglaciation and in the discussion. However, most of the deglaciation chapter is based on the work of other scientists. The text concerning the Nordland map is written by myself including an extensive review of earlier investigations.

The Quaternary geological maps produced during the Mid-Norden and Nordland projects (Bargel et al. 1999a, b, c, Bargel 2001), are fundamental parts of this thesis. In addition to the prints in reduced scales (Enclosures 1-4), digital versions are accessible on the attached CD-ROM (Enclosure 8) as ***printable files (PDF, TIF and JPG-formats)***. Prints in full scale are also available from the Geological Survey of Norway (NGU). The maps of Central Fennoscandia are also available at the Geological Survey of Finland (GTK) and the Geological Survey of Sweden (SGU).

Part III of the thesis, which is completely written by myself, is based on information that was elucidated during the preparation of the maps and review of the literature. It was clearly demonstrated to me that there was a striking connection between the concentrated location of the many sets of Preboreal end moraines in Norway and the east-west oriented corridors in the mountain chain. No direct evidence of this phenomenon was found in the literature, even though several scientists have indeed worked on the east-west migration of the ice divide.

It is also a striking fact that little detailed work on deglaciation chronology based on the moraines had previously been performed on the Lofoten islands and in the Bindal area in Nordland. For these reasons, I decided to give a short account of the east-west migration of the Scandinavian ice sheet, to perform some reconnaissance work on the Lofoten islands and to work thoroughly on the deglaciation of the Bindal area.

Summary and conclusions

Quaternary geological mapping is performed by geological surveys in most countries. At the Geological Survey of Norway (NGU), mapping of the surficial deposits has been one of the main tasks from the establishment of the institution in 1858, in the beginning mainly as an aid for agriculture and forestry. During recent decades, society's needs for information on the Quaternary deposits has increased, particularly within the fields of environment and health, physical planning, economy and supply of natural resources.

Geological mapping is not looked upon as a science by everyone, but its results have often proved to be valuable in a scientific context as the extensive database the maps represent give valuable information, useful in, e.g. the study of regional trends. Geological mapping can, however, be regarded as a journey of discovery, which is the basis for most scientific research on the development of the earth's crust and which provides a framework with which all laboratory-based research must be compatible.

Much detail information is also recorded (analog or digital), for example the location of exposed sections in distant areas and details beyond the reach of aerial photo interpretation, e.g. in heavily forested areas or of objects too small to be identified on aerial photos or maps. In addition, much sedimentological and stratigraphical work has to be performed during the fieldwork in order to understand the genesis of the deposits. Creation of geological models of the areas is an important part of the mapping activity that is necessary for attainment of an understanding of the Quaternary geological history on a regional scale.

What could be criticized is the fact that the many mapping geologists involved have not used, or have had the opportunity to use, the enormous data at hand to do more science and to tell the layman what the results of the geological mapping mean.

This thesis is a contribution to understanding of the Quaternary geology of Central Fennoscandia with special emphasis on the Nordland area. The thesis has the following aims:

A. To compile four Quaternary geological maps of Central Fennoscandia (showing surficial deposits, geomorphology and paleohydrography, ice flow indicators and stratigraphy) and a Quaternary geological map of the surficial deposits of Nordland.

B. To create a link between the Quaternary geological maps, applications of the map-data and studies of Quaternary geological history (Part I).

C. To present a coordinated description of the five Quaternary geological maps and compile a review of the Late Weichselian and Early Holocene deglaciation history of the mapped area (Part II).

D. To identify areas for in-depth investigation of the deglaciation and to perform these studies (Part III).

A. COMPILATION OF QUATERNARY GEOLOGICAL MAPS

This thesis is based on the data included in five maps of Quaternary Geology (Fig. A1):

1. Quaternary Deposits of Central Fennoscandia (scale 1:1,000,000) (Fig. A2)
2. Glacial Geomorphology and Palaeohydrography of Central Fennoscandia (scale 1:1,000,000) (Fig. A3)
3. Ice-flow Indicators of Central Fennoscandia (scale 1:1,000,000) (Fig. A4)
4. Quaternary Stratigraphy of Central Fennoscandia (scale 1:2,000,000) (Fig. A4)
5. Quaternary Deposits in Nordland County (scale 1:400,000) (Fig. A5)

The maps (Figs. A1-A5) are shown in small-scale reproductions. Larger scale maps are shown in the Enclosures 1-4 and as printable PDF-files on the attached CD-ROM (Enclosure 8). Prints in full scale are available from the Information Centre at the Geological Survey of Norway (NGU). The maps of Central Fennoscandia are also available at the Geological Survey of Finland (GTK) and the Geological Survey of Sweden (SGU).

The data presented on these maps are partly compiled from earlier maps at various scales, but extensive additional aerial photo interpretation and fieldwork has also been performed in selected areas. Representative data are shown with the objective of highlighting the dominant features of the areas.

Even though much of the information presented is well known, the maps are unique, as no attempt has been made before to compile data from the whole area including the Norwegian shelf and the Gulf of Bothnia. The distribution of the surficial deposits, the morphological elements and the directions of the ice movements are striking, and can mostly be explained by the localization of the mountain chain and the direction of moisture-bearing winds.

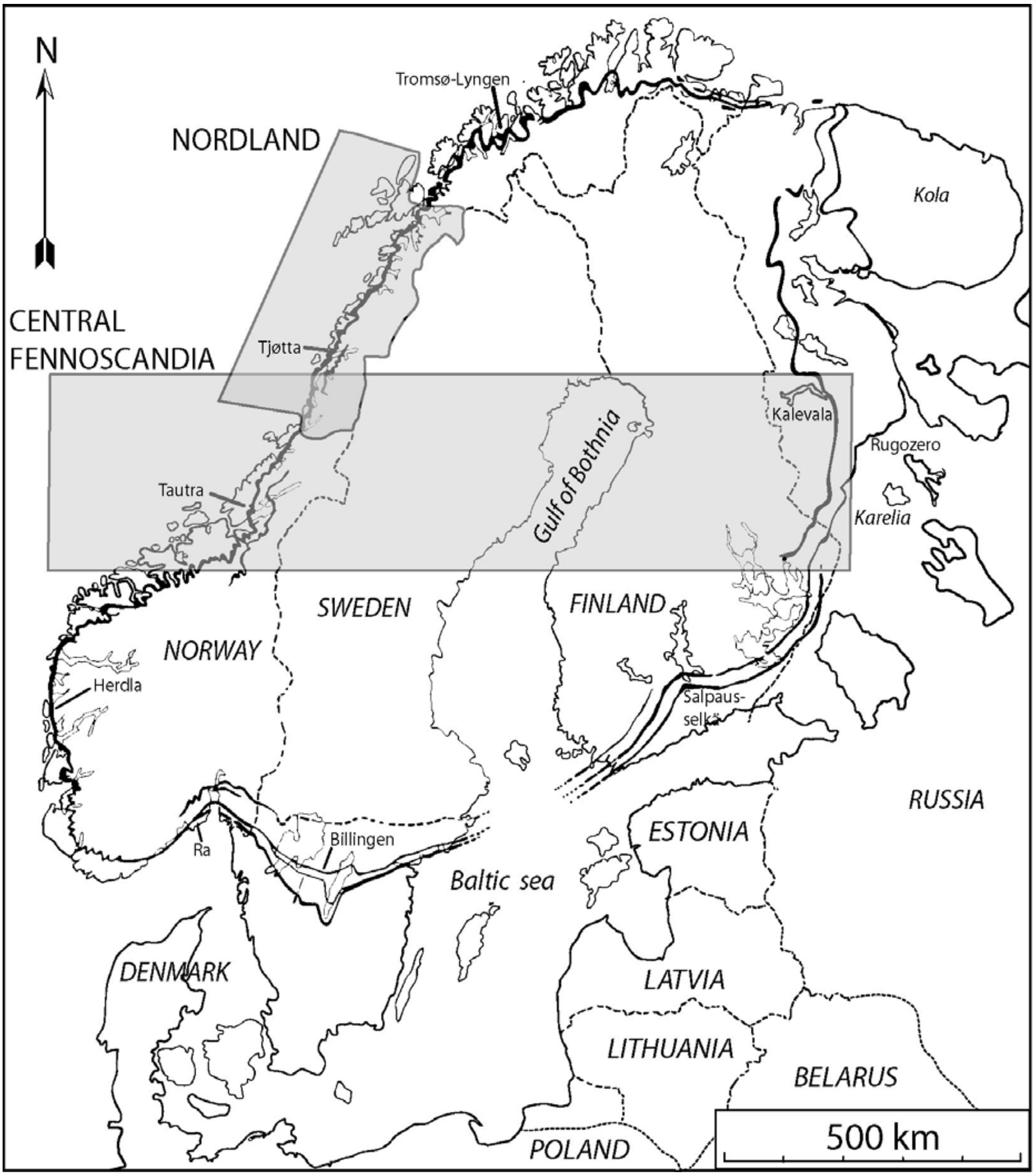


Fig. A1
Key map of North-Western Europe with the Central Fennoscandian and Nordland map sheet areas framed and shaded. The heavy lines represent the Younger Dryas ice marginal deposits. Selected names of the ice-marginal lines are shown. The map is slightly modified after Andersen et al. (1995).

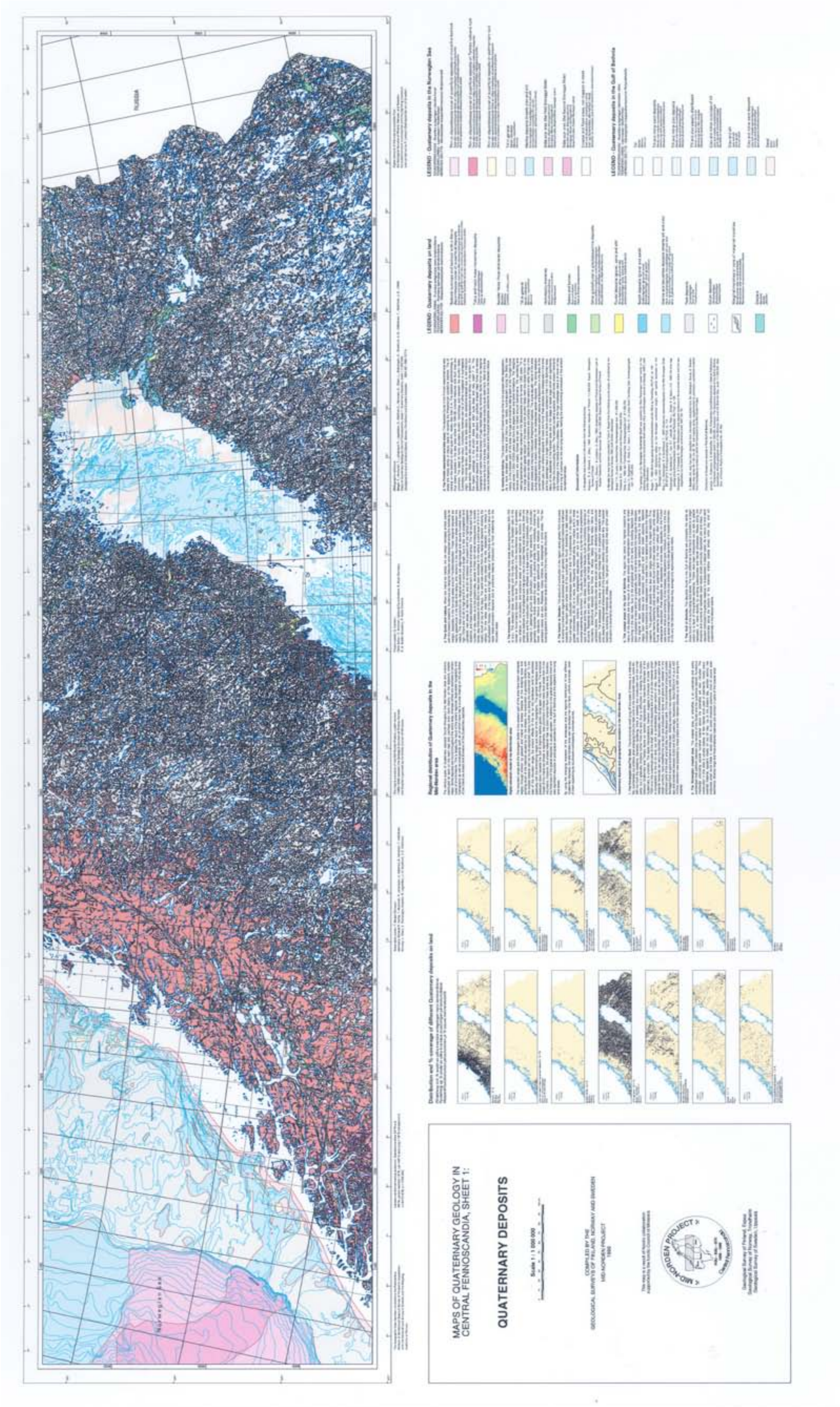


Fig. A2
Small-scale reproduction of the *Maps of Quaternary geology in Central Fennoscandia, sheet 1: Quaternary Deposits*, scale 1:1,000,000 that shows the general arrangement of the map (Bargel et al. 1999a).

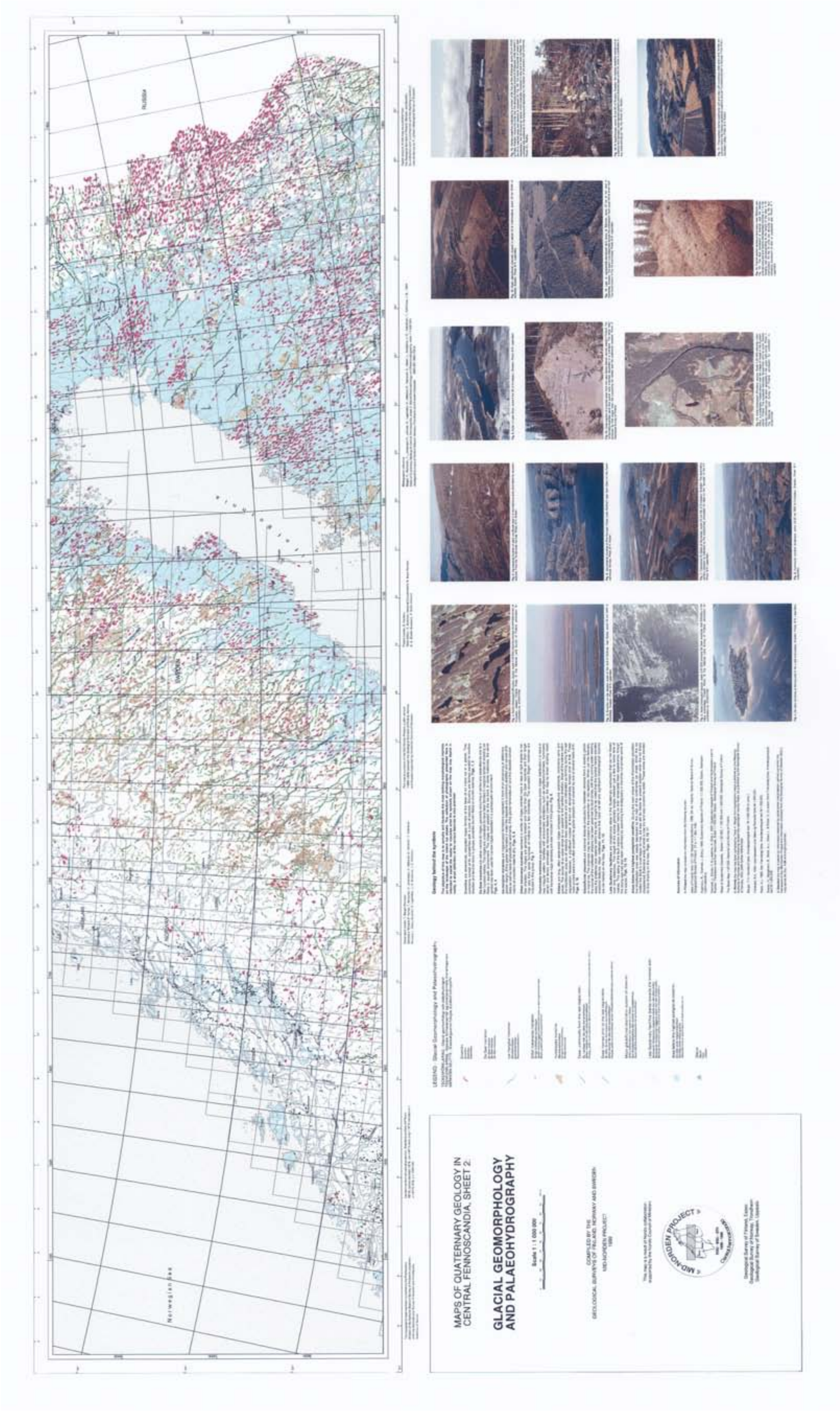


Fig. A3
Small-scale reproduction of the *Maps of Quaternary geology in Central Fennoscandia, sheet 2: Glacial Geomorphology and Palaeohydrography*, scale 1: 1:1,000,000 that shows the general arrangement of the map (Bargel et al. 1999b).

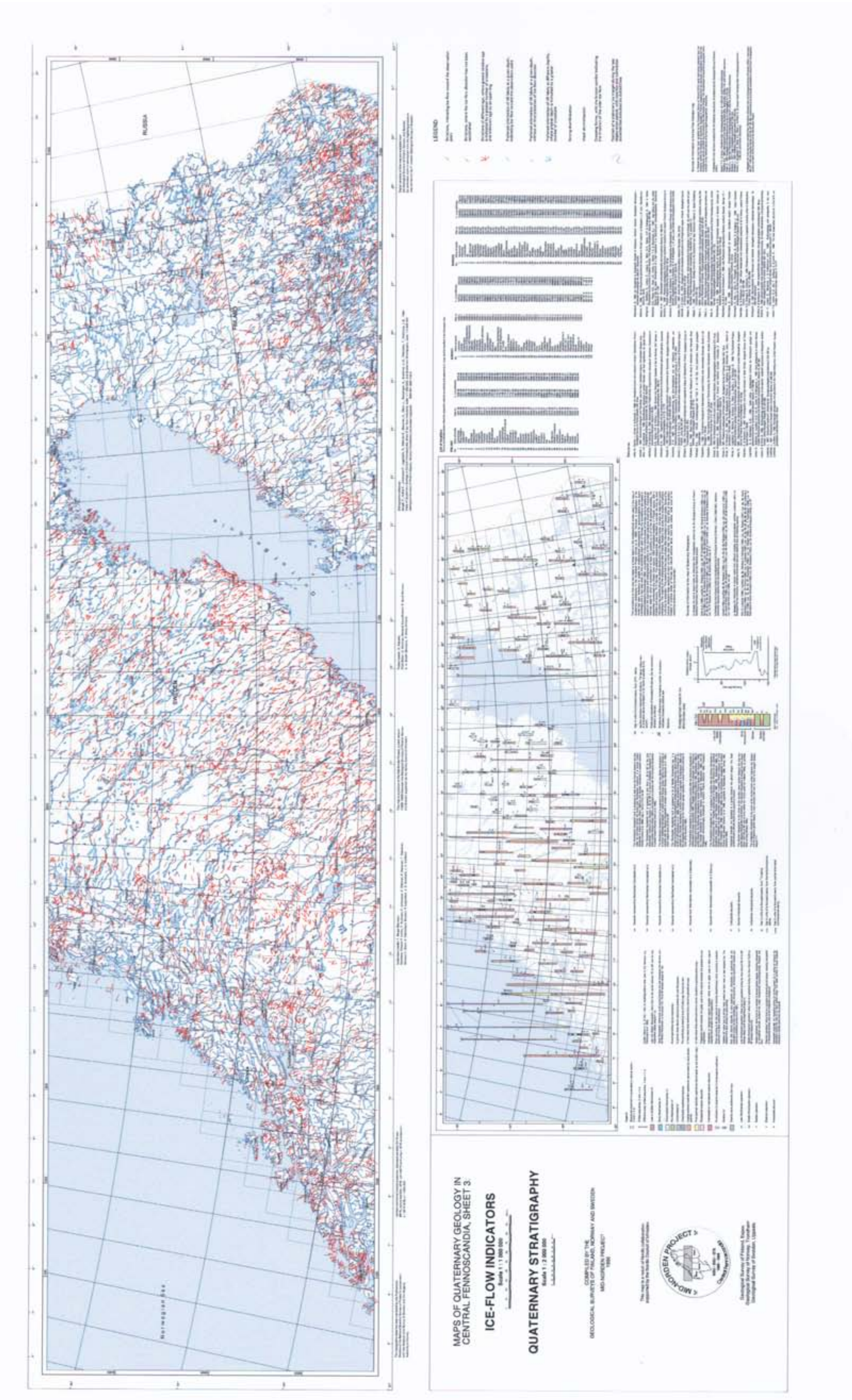


Fig. A4
Small-scale reproduction of the *Maps of Quaternary geology in Central Fennoscandia, sheet 3: Ice-flow Indicators*, scale 1:1,000,000, and *Quaternary stratigraphy*, scale 1: 2,000,000 that shows the general arrangement of the map (Bargel et al. 1999c).

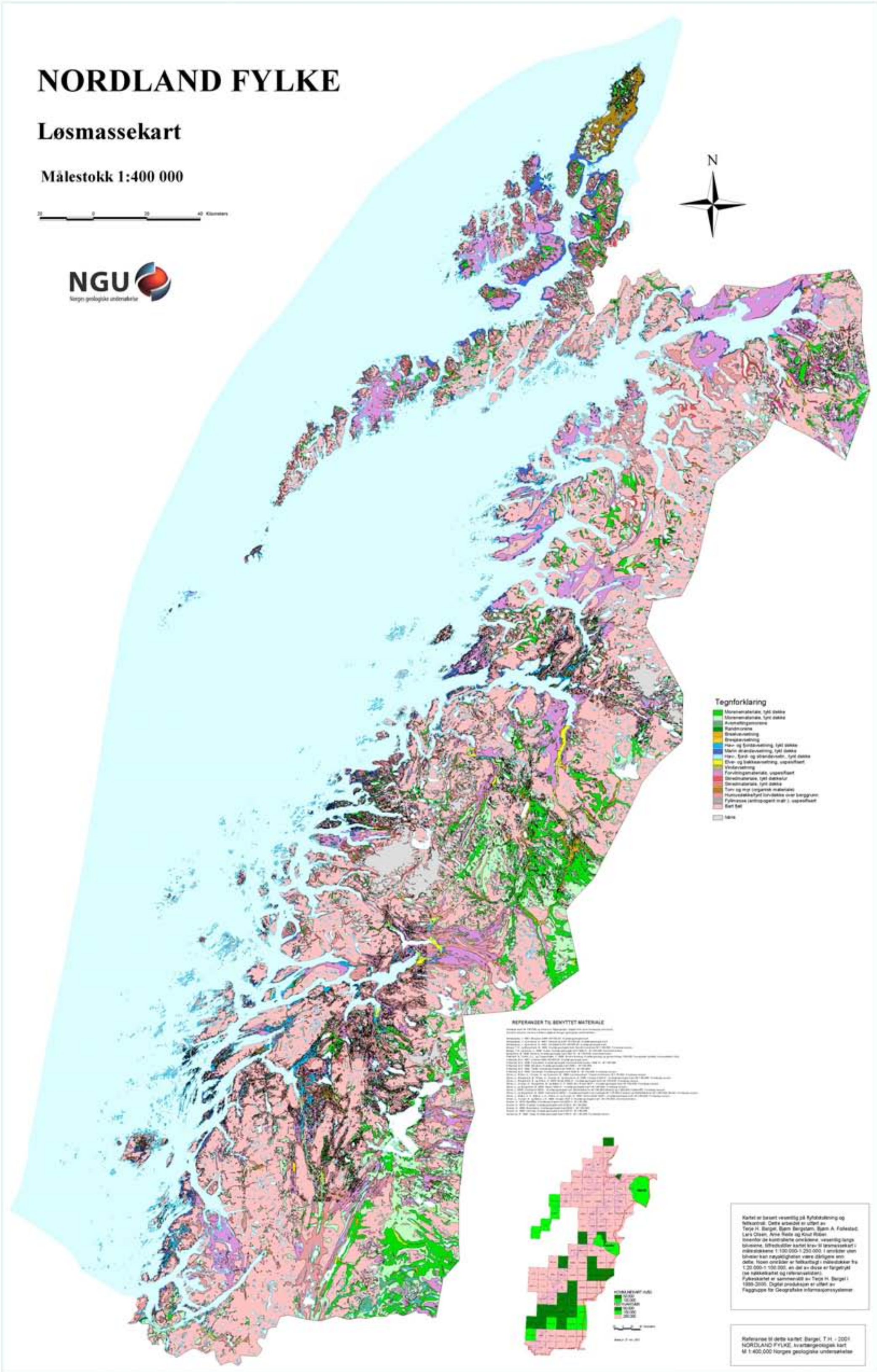


Fig. A5
Small-scale reproduction of the map *Quaternary geology in the Nordland County*, scale 1:400,000, that shows the general arrangement of the map (Bargel 2001).

B. QUATERNARY GEOLOGICAL MAPPING: HISTORY, MAP CONTENTS AND APPLICATION

In the first part of the thesis a review of the history of Quaternary geological mapping in Norway is presented. Before the foundation of NGU in 1858, only scattered projects involving Quaternary geological mapping were performed. One of the main tasks allotted to NGU was the geological mapping of the heaviest populated areas of the country.

An extensive mapping of the surficial deposits was carried out, and a colour map at a scale of 1:400,000 from the southern and the southeastern parts of Norway was compiled and published in 1866. During the following decades most of the published maps were combined bedrock and surficial deposit maps, mostly at the scales of 1:1,000,000 and 1:250,000.

The first series of Quaternary Geological maps was published in the years 1951-1960. These maps too were at a scale of 1:250,000, but only parts of the southeastern Norway were mapped. The trend to specialize maps was further developed, and in the late 1960s the mapping strategy was changed from the production of overview maps to semi-detailed maps at a scale of 1:50,000.

The first 1:50,000-map was published in 1972, and up to nine maps were published each year during the "golden era", 1979-1988. More than 140 maps have been produced from many parts of Norway as priority has been given to the densely populated areas (Fig. B1).

Additionally, a map series at a scale of 1:20,000 was published during the years 1976-1993 when conflicting forms of land use was an emerging problem, mostly in the Oslofjord and Trondheimsfjord areas (Fig. B1).

A few maps at a scale of 1:10,000 were also published. Several municipality maps at varying scales (1:80,000-1:250,000) have been printed and county maps at the scales of 1:125,000-1:1,000,000 will be finished by 2004. Several overview maps of the surficial deposits on the continental shelf have also been produced.

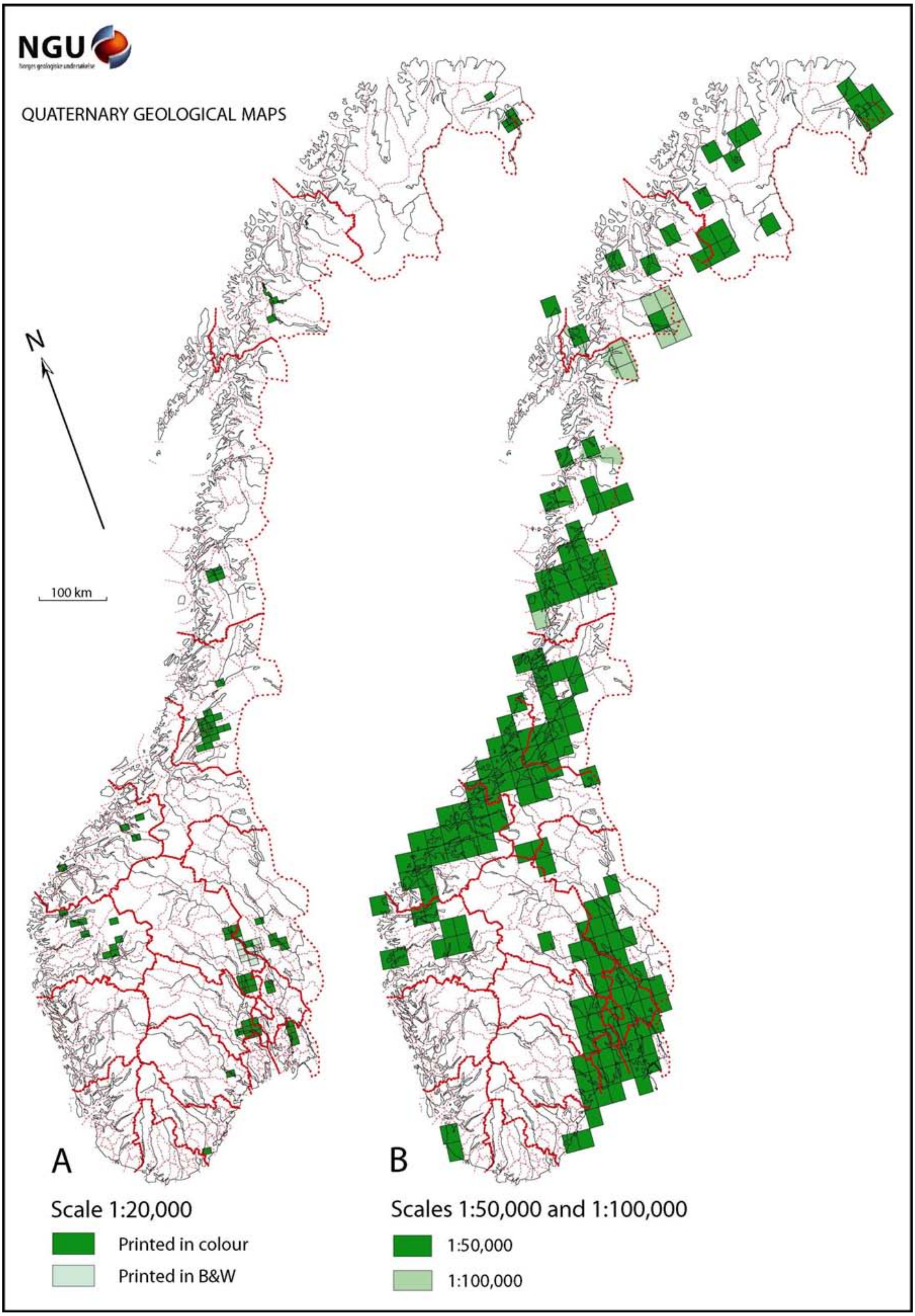


Fig. B1
Maps of Norway showing the coverage of modern Quaternary geological maps scales of **A**: 1:20,000 and **B**: 1:50,000 and 1:100,000 produced by NGU. The unmarked (white) areas on B are mostly mapped at 1:250,000. Modified from the map catalogue available on the web site http://www.ngu.no/.

The main reasons for mapping the surficial deposits are:

1. Proper use of the land areas, initially for agricultural purposes, later for more differentiated land-use like construction, infrastructure etc.
2. Localization of resources for exploitation: groundwater, peat, sand and gravel.
3. A scientific and educational interest in identifying deposits such as, e.g. sub-till sediments and moraines, valuable for deglaciation studies.

During all the years in which Quaternary Geological maps have been produced, it is the genesis of the deposits that has been shown. This is due to the fact that there is a strong relationship between the genesis and the general properties of the deposits. The legend that is used is based on the basic agencies acting on the earths crust, and often detailed geological descriptions and terms have been employed.

Many users that are not geologists feel that the maps are difficult to read. The maps at a scale 1:50,000 are often too general for planning purposes. These maps are, however, not intended to show details but to indicate where to find areas suited for production of ground water, cleaning of waste water, earth heat production, buffering of acidic rain, plant production, recreation, geo-hazards such as clay slides, construction and minerogenic resources. Most of these activities/uses are located to areas with thick surficial deposits. As less than 10 % of the area of Norway has the appropriate qualities it is important to use them optimally. Geologists in general have to be better to communicate this message to the planners and to the public.

The latest trend is to map smaller areas in great detail for specific purposes as listed above. The focus on the third dimension is improved by drillhole information, geophysical measurements and stratigraphical studies. Production of thematic maps that are intended to increase the accessibility of the data have high priority and all the maps have been, or are going to be digitised.

Most of the facets of Quaternary geological mapping are analysed in the main text, and this has resulted in the following conclusions:

1. Quaternary geological maps at a scale of 1:50,000 are overview maps to be used for primary planning and orientation only.
2. Traditional (genetic) overview mapping in Norway should be continued until the proposals in the NOU 1974:10 are fulfilled (populated areas with thick deposits in 1:50,000, the remaining areas in 1:250,000).
3. The mapping policy summarized in 2) is the best in relation to cost, area coverage and quality of the information obtained.
4. The general area information given on the properties of the deposits is not satisfactory for modern requirements related to land use. Chemical and physical parameters and stratigraphic information are necessary in order to evaluate the technical properties of the lithologies found.
5. Quaternary geological maps at scales of 1:5,000-1:20,000 have extended utility for practical purposes due to the detailed base maps, which allow more geological data to be presented.
6. New map projects intended for practical applications should concentrate on combining mapping at larger scales and on solving specific problems in limited areas.
7. All mapping results should be registered on high-quality base maps.
8. All data must be digitised.
9. Geologists should learn to communicate better with users and the public.

C. DESCRIPTION OF THE QUATERNARY GEOLOGICAL MAPS, THE DEGLACIATION HISTORY AND THE ANALYSIS OF REGIONAL TRENDS

The second part of the thesis is allocated to the enclosed Quaternary geological maps of Central Fennoscandia and the County of Nordland (Figs. A2-A5, Enclosures 1-4). The maps and their content are described and commented upon with special emphasis on the great east-west differences of the distribution of the surficial deposits, the changes in the ice-flow directions during the last glaciation and the variation in deglaciation pattern, that is all a result of the geographical location of the north-south-oriented Caledonian mountain chain with its steep, narrow western flank and broad, low-lying eastern margin, and the effect this situation has had on precipitation, ice growth and the distribution of the glaciers.

The onshore map area is compiled with data from databases at the Geological Surveys of Finland, Norway and Sweden, based on Quaternary geological maps of various scales and quality, supplemented with interpretation of aerial photographs. The data on the western shelf are interpreted from seismic registrations and sediment samples collected by the Continental Shelf and Petroleum Technology Research Institute (IKU) (Rise 1988, Rokoengen & Rise 1989). The data in the Gulf of Bothnia is compiled from Ignatius et al (1980).

C.1 Map descriptions

The map of Quaternary Deposits in the Central Fennoscandia at a scale of 1:1,000,000 (Bargel et al. 1999a) (Fig. A2, Enclosure 1) shows the regional distribution and genetic variation of the uppermost part of the Quaternary deposits on land and on the continental shelf off Norway and in the Gulf of Bothnia.

The genetic mapping methods used were developed by the national Geological Surveys, and presented in Sweden by, e.g. Granlund (1943), G. Lundqvist (1951) and J. Lundqvist (1969, 1987), in Norway by Follestad (1972, 1973) and in Finland in Atlas of Finland (1990), and have undergone continuous development up to recent times. The colours used on the map are a compromise between the different standards commonly used on the national map series in the three countries, as defined in the Nordkalott Project (Hirvas et al. 1988).

It is well known that the various types of Quaternary deposits found throughout Central Fennoscandia are unevenly distributed (e.g., Thoresen 1991, Fredén 1994, Kujansuu & Niemelä 1984). Some deposits are found throughout the entire area, whereas others are restricted to certain types of environment. The distribution of till, which covers 43 % of the land area, is a striking example of this phenomenon (Fig. C1). The uneven distribution of the deposits is largely the result of the area's regional, large-scale topography and hydro-graphy as well as the glacioisostatic changes, all of which have had a crucial bearing on the dynamics of the inland ice-sheets and formation of the Quaternary deposits through time.

By using the changing character of the landscape and the regional distribution of the different Quaternary deposits, Central Fennoscandia is divided into nine fairly uniform sub-areas on the Quaternary deposits map (Fig. C2).

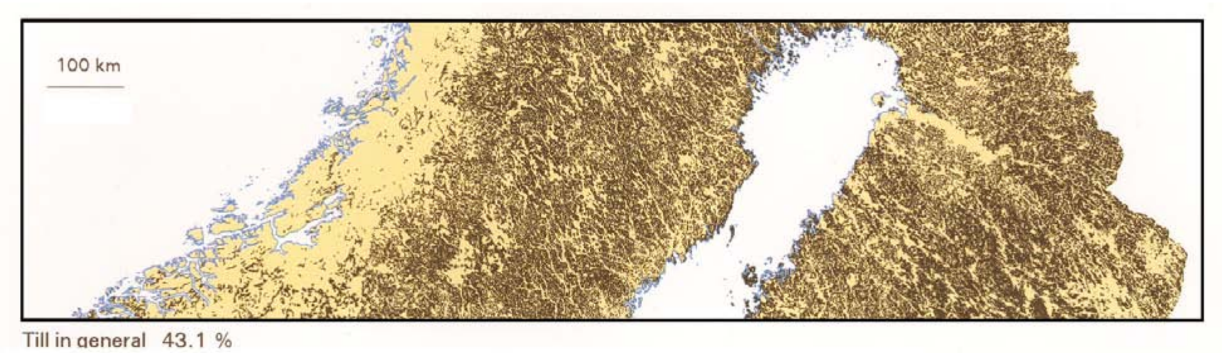


Fig. C1
Map showing the onshore distribution of till (black) in Central Fennoscandia. Reproduced from Bargel et al. (1999a).

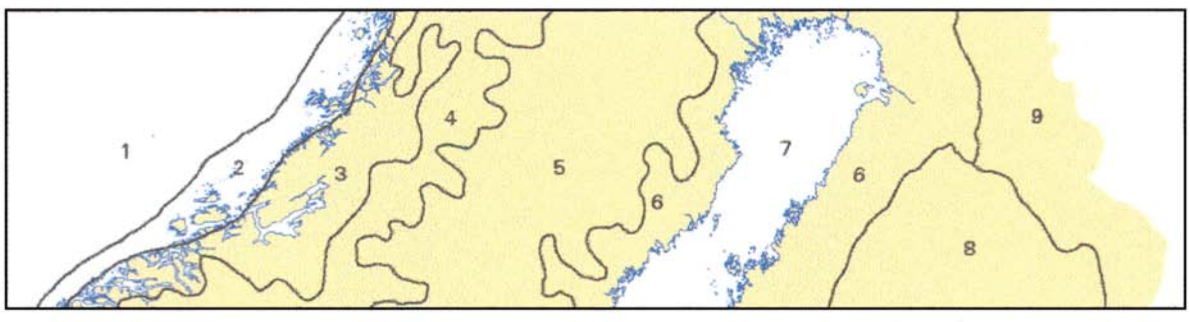


Fig. C2
The nine sub-areas of Central Fennoscandia as shown on the Quaternary deposits map. Reproduced from Bargel et al. (1999a).

Most of the areas are southwest-northeast oriented zones, trending parallel to main topographical features such as the Caledonian mountain range and the general trend of the coastlines. The described sub-areas are (Fig. C2):

1. The continental shelf off Norway
2. The coastal area of Norway
3. The fjords and valleys in Norway
4. The mountain chain
5. The interior of Sweden
6. The coastal areas of the Gulf of Bothnia
7. The Gulf of Bothnia
8. The Finnish watershed and lake areas
9. Karelia and Kainuu, eastern Finland

The Map of Glacial Geomorphology and Palaeohydrography at a scale of 1:1,000,000 (Bargel et al. 1999b) (Fig. A3, Enclosure 2) shows the most striking morphological imprints of the inland ice sheets and melt-water on the landscape. The drumlins, De Geer moraines, ice-marginal- and other transverse moraines, hummocky moraines, eskers and glaciofluvial erosion systems are visualised. Late Quaternary fault lines, areas below the highest postglacial coastline and modern glaciers are also shown. The main features of these formations are described.

The Map of Ice-flow Indicators at a scale of 1:1,000,000 (Bargel et al. 1999c) (Fig. A4, Enclosure 3) shows a representative selection of glacial striations, drumlins and till fabric measurements. The age relationships of striations with different directions at the same locality are indicated. Included on this map are also ice-marginal features and the inferred positions of the different stationary ice margins during the last deglaciation period as interpreted mainly from ice-marginal deposits.

The map of Quaternary stratigraphy at a scale of 1:2,000,000 (Bargel et al. 1999c) (Fig. A4, Enclosure 3) shows, in columns, the stratigraphy of 162 excavated, drilled or natural sections including 4 on the Norwegian continental shelf. The sequences represented are chosen from c. 1500 investigated localities in Finland, c. 800 in Sweden and c. 70 in Norway. On the continental shelf the number of available drilled sections is limited, and the correlations are mainly based on seismostratigraphy. The selected sequences were intended to provide not only as much information as possible about the glacial development in the different areas, but also to give an idea about the typical stratigraphy.

A new stratigraphical model for the Weichselian in Central Fennoscandia, is proposed (Fig. C3). This model is also applied to the county of Nordland, and it indicates rapid shifts in the western ice-margin extent during the Late Weichselian.

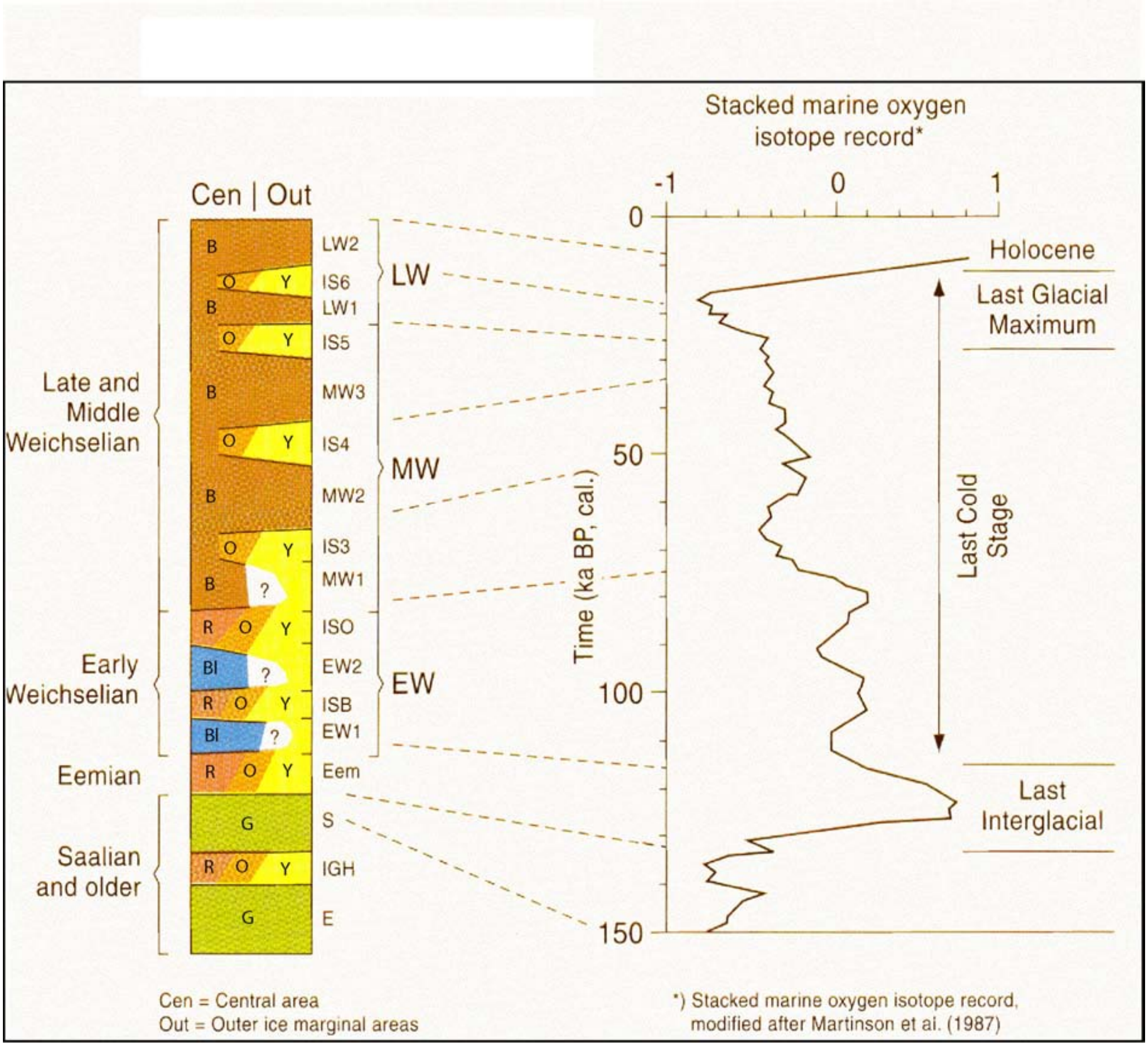


Fig. C3
The stratigraphical model of Central Fennoscandia and Nordland.
B: Late or Middle Weichselian till. **Bl**: Early Weichselian till. **G**: Pre-Weichselian till.
O: Coarse-grained water-lain sediments (dominated by sand and/or gravel). **Y**: Fine-grained water-lain sediments (dominated by silt and/or clay). **R**: Interstadial or interglacial organic deposits.
LW: Late Weichselian glaciation (LW1 and LW2 or LGM 1 and LGM 2).
IS3-IS6: Weichselian Interstadials (no. 3-6)
MW: Middle Weichselian glaciation (MW1-MW3).
ISO: Weichselian Interstadial no. 2 (Odderade)
ISB: Weichselian Interstadial no. 1 (Brørup)
EW: Early Weichselian glaciation (EW1 and EW2).
S: Saalian Glaciation
IGH: Holsteinian Interglacial
E: Elsterian Glaciation
Reproduced and slightly modified from Bargel et al. (1999c).

The Quaternary geological map of the county of Nordland (Bargel 2001) (Fig. A5, Enclosure 4) is the most detailed map of its kind produced so far from this area. The map data are at a scale of 1:250,000 or better, but as the county is more than 500 km long from north to south, the map is presented at a scale of 1:400,000 for practical reasons.

The county map has been compiled by using earlier published maps at scales of 1:50,000-1:100,000, by aerial-photo interpretation and supplementary field checking. The morphology and the sediments are described using the same criteria as on the Central Fennoscandia Map of Quaternary deposits (Bargel et al. 1999a). Three geographically different areas were defined:

1. The coastal area, including the strandflat.
2. The fjords, valleys and the island archipelago in the north.
3. The mountains.

Generally, the Quaternary deposits are extremely sparse and exposed bedrock is the most dominant feature.

C.2 The last deglaciation of Central Fennoscandia and Nordland - conclusions

A relatively detailed review of the deglaciation history of the area based on the extensive literature is presented in the thesis. The main glacial, interglacial and interstadial episodes in the Central Fennoscandia and Nordland areas was summarized in a figure on the Central Fennoscandian stratigraphy map (Bargel et al. 1999c), which also includes data from Nordland (Fig. C3).

The ages used are based on:

1. Varve chronology on deglaciation features in the Gulf of Bothnia (expressed in absolute ages up to c. 12,000-15,000 clay varve years BP; also denoted 12-15 *cal ka ago*) (e.g., Brunnberg 1995).

2. Radiocarbon age determination for objects up to c. 40,000 years old. Most of the ages that are mentioned in the thesis are determined by this method; the dates are not calibrated and are denoted *^{14}C ka BP,* or only *ka BP* (e.g., Olsen et al. 1996c).

3. Amino acids, oxygen isotopes, OSL (TL) and U/Th for determinations within and out of reach of the radiocarbon method (> c. 40,000 years old), are given in absolute ages and denoted *cal ka BP*; or these dates may have been converted to the ^{14}C-yr

timescale (and denoted ka BP) using particular calibration methods (see, e.g., Olsen et al. 2001a).

The following conclusions can be presented based on the Central Fennoscandian and Nordland mapping (Bargel et al. 1999c, Bargel 2001):

1. Strata representing both the Pleistocene and older units have been described from the continental shelf off Central Norway.
2. Saalian deposits, which correlate with oxygen isotope stage 6, and Holsteinian and Elsterian deposits, which may correlate with one or more of the oxygen isotope stages 7-11, are relatively common in Central Finland.
3. Eemian sediments have been described from one locality in Central Norway in the coastal area and in seismic profiles on the continental shelf off Norway. In Finland, Eemian sediments have been described from several localities.
4. The Weichselian interstadial no. 1 is considered to correlate with the Brørup interstadial in Denmark at c. 110-80 cal ka BP, with the Jämtland interstadial (older part) in central Sweden, the Oulainen interstadial and the Horonkylä interstadial in central Finland and the Peräpohjola interstadial in northern Finland and Sweden.
5. The Weichselian interstadial no. 2 is considered to correlate with the Odderade interstadial in northwestern Germany at 85-75 cal ka BP, the younger part of the Jämtland interstadial in central Sweden, the Mertuanoja interstadial in central Finland, the Tärendö interstadial in northern Sweden and the Peräpohjola interstadial in northern Finland.
6. The Weichselian interstadial no. 3 is considered to be of Middle Weichselian age. It is inferred to correlate with the Bø interstadial in coastal southwestern Norway (50-55 cal ka BP). Possible correlatives are, e.g. the Tärendö interstadial in northern Sweden and the interstadial represented by the Horonpa sponge deposits in central Finland.
7. The Weichselian interstadial no. 4 is considered to date from the late Middle Weichselian. It is named Hattfjelldal interstadial I in the inland region of central Norway and is inferred to correlate with the Ålesund interstadial which existed some 28-39 ka BP in southwestern coastal Norway. The continental shelf off Norway probably remained ice-free for a long period until after 30 ka BP.

8. The following ice expansion was limited. Sediments in coastal caves show that the outer coastline of Møre was ice-covered c. 28 ka BP. Rapid shifts in the extent of the ice are recorded on the shelf, and the coast of Helgeland could have been ice-free or glaciated during a very short interval at this time.
9. The Weichselian interstadial no. 5 is supposed to date from c. 27 ka to the Late Weichselian maximum ice advance c. 24 ka BP. It is named Hattfjelldal interstadial II in inland central Norway and is thought to correlate with the Hamnsund interstadial in coastal western Norway.
10. At 24-21 ka BP the inland ice reached its maximum extension in the Weichsel (LGM 1). The continental shelf off Norway and most of the coastal areas were completely glaciated, but the possibly existence of nunataks in Møre and on Andøya in Nordland is hypothesised.
11. The Weichselian interstadial no. 6 is supposed to date from the interval between the two major ice advances during the broad Late Weichselian maximum. It is named Trofors interstadial in the inland region of Norway and Andøya interstadial in coastal northern Norway. The coast and the valleys were possibly ice-free, but the higher ground was probably partly glaciated. The age of this interstadial is c. 17-21 ka BP.
12. The second ice advance of the Late Weichselian maximum, LGM 2, occurred at c. 17-15 ka BP (Fig. C4). The ice extension in the west was of about the same size during LGM 1 and LGM 2, and it ended abruptly in both events at the shelf edge, but the highest coastal mountains and the outer parts of the shelf were perhaps not ice-covered everywhere during LGM 2.
13. The main deglaciation started c. 15-14 ka BP, but ice-lobes deposited till tongues on the western shelf at c. 15 ka BP and c. 13.5 ka BP. The shelf deglaciated rapidly thereafter (Fig. C4).
14. A small ice advance reached the outer coastal districts and deposited the Tingvoll moraine, the Outer coastal moraines and the Vega moraine at c. 12.4-12.0 ka BP (denoted 12,200 on Fig. C4).
15. The deglaciation in the Allerød interstadial led to intense calving of the fjord glaciers in the west, especially in the Trondheimsfjorden district, and many valleys were ice-free. In the east, the southeastern part of Finland including eastern Karelia (Fig. A1), was deglaciated during the Heinola-deglaciation.

16. In the period Late Allerød and Early to Middle Younger Dryas a nearly continuous set of end moraines was deposited in the west, the Tautra moraines and the Tjøtta moraines (YD, Fig. C4). Two separate glacial phases may be represented: 10.8-10.6 ka BP and 10.4-10.3 ka BP, respectively. The greatest end formations are situated in the mouths of the valleys. In the northern part of the Trøndelag area the ice advance in Younger Dryas was more extensive than during the Outer coastal Substage. In the late Younger Dryas the Hoklingen moraines were deposited in Trøndelag and the correlative Nordli moraines were deposited in Nordland (10.2-10.1 ka BP). In the east (Fig. A1) the Salpausselkä I and Tuupovaara end moraines (11.3-11.1 cal ka ago), the Salpausselkä II and the Koitere end moraines (10.8-10.6 cal ka ago) and the Pielisjärvi end moraines (10.5-10.4 ka ago) were deposited. The latter is correlated with the Salpausselkä III end moraine in south-western Finland.
17. In the Preboreal, end moraines were deposited in the inner part of the Trondheimsfjorden (Fig. C4), the Vuku moraines (9.9-9.8 ka BP), the Grong-Snåsa moraines (probably c. 9.7 ka BP) and a set of tentatively correlated discontinuous end moraines with a possible age of c. 9.5 ka BP. In the east, the end moraines in Liperi are tentatively correlated with the Vuku moraines.

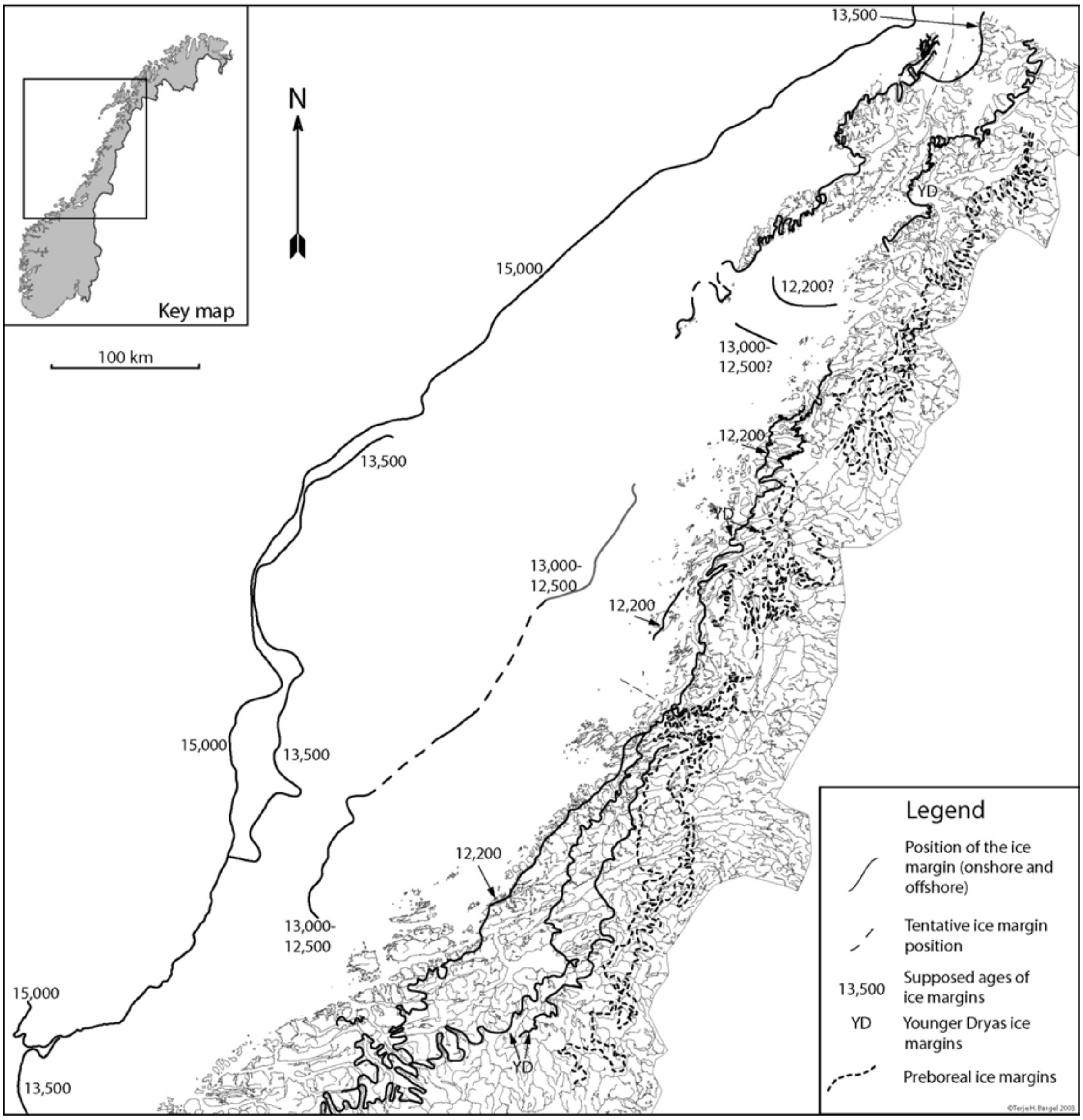


Fig. C4
Ice marginal lines in Norway and on the Norwegian Continental shelf. Supposed ages (figures in ^{14}C y BP) of the offshore moraines are indicated. The 15,000 line is located to the shelf edge. Some of the ages and correlations are based on relatively sparse data. References and details on the onshore moraines are found in Enclosure 5.

D. THE TOPOGRAPHIC INFLUENCE ON THE GLACIAL DYNAMICS, THE EAST-WEST BALANCE AND THE DISTRIBUTION OF MORAINES IN LOFOTEN AND BINDAL

D.1 Glacial dynamics, the east-west balance and the distribution of the Preboreal moraines

To the east of the Caledonian mountain chain, the erosive effects of the ice on the landscape tend to diminish gradually with reduction in the height and relief of the topography. The general landscape slopes gradually down to the Gulf of Bothnia before gently rising again into Finland. The erosional impact of the inland ice-sheets is significantly less prominent in these more level areas than in the mountains. As a consequence of this, the thickness of the glacial deposits is usually greater and gradually becomes thicker towards the east. Surficial deposits from several glacial epochs have accumulated, and numerous stratigraphical localities with at least two glacials and one interglacial have been reported (Fig. C3), which shows a conservational or even a depositional regime, probably because of cold-based ice (e.g., Sollid & Sørbel 1988, Andersen & Nesje 1992). In addition to the glacial deposits there are also significant deposits of post-glacial sediments in the Gulf of Bothnia and the adjacent low-lying land areas.

On the western side of the mountain chain the dominant temperate glaciers ("warm-based" ice) had a tremendous erosive effect that has, during several glacials, produced the dissected Norwegian coast. The erosion was concentrated to the depressions in the landscape, the lakes, the valleys, the fjords and depressions and troughs on the shelf where the major ice-flows were channelled (Andersen & Nesje 1992, Ottesen et al. 2001). The eroded material from the massive erosion of the bedrock caused by the ice sheets can be found deposited in the fjords (Oftedahl 1977), but mainly on the continental shelf (e.g., Holtedahl 1993, Rokoengen et al. 1995).

As the glaciation centre was localized east of the mountain chain (e.g., Ljugner 1949), the ice flow to the west must have been most intense where the lowest passageways were situated. The lowest, and even the broadest pass point of the mountain chain are located to the lake area between the Lierne and Børgefjell mountains, where the elevations are less than 400 m a.s.l. (Fig. D1). All the other pass points along the mountain chain are narrower and seldom lower than 500 m a.s.l. Consequently, the ice flow in these areas was probably more sensitive to changes in the glacier volume than in higher areas, as the ice was temperate and readily moveable. Surges could have been a common phenomenon.

A glacier-dynamic model like this could probably explain the rapid changes in the position of the glacier margin that are reported along the coast of Norway where, e.g. up to ten glacial stadials (end moraines) are recorded from the Late- and Postglacial. These moraines are mostly located to valleys and fjords that communicate with the pass points. This fact indicates that the ice flow probably had its greatest endurance along the lowest passageways just described. In the areas that are located away from the zones of the main ice flows, almost no end moraines of Preboreal age are found, and the reconstructions shown (Fig. C4) are highly tentative in these areas.

Another consequence of the concentration of ice flow in zones was probably that the glacier during the latest phases of the deglaciation had a substantially more lobe-like appearance than presented in earlier glaciation models. This situation became most pronounced as the glacier thinned, and the lobes existed as long as the glacier was dynamically active.

Two areas in Nordland (the Lofoten and the Bindal-Tosen areas, Fig. D1) where application of the glacier lobe model has had a vital importance to the understanding of the features observed, are studied in more detail.

D.2 Moraine studies in Lofoten

Mountainous areas that are heavily dissected by cirques characterize the Lofoten islands, which are also separated by north-south-oriented sounds. Some of the mountains reach more than 1000 m a.s.l. from which steep cliffs fall to the sea. End moraines that are mostly located in the short Lofoten cirque valleys and have clearly been formed by local glaciers, are present in large numbers. However, several moraines have a position relative to the topography that probably disqualifies deposition by local glaciers.

Five types of moraines or diamictic material are identified on the Lofoten islands, the L_1-L_5-moraines (the $Lofoten_1$-$Lofoten_5$-moraines) (Fig. D2). The classification is based mainly on geographical and morphological criteria and on the supposed genesis and age of the moraines.

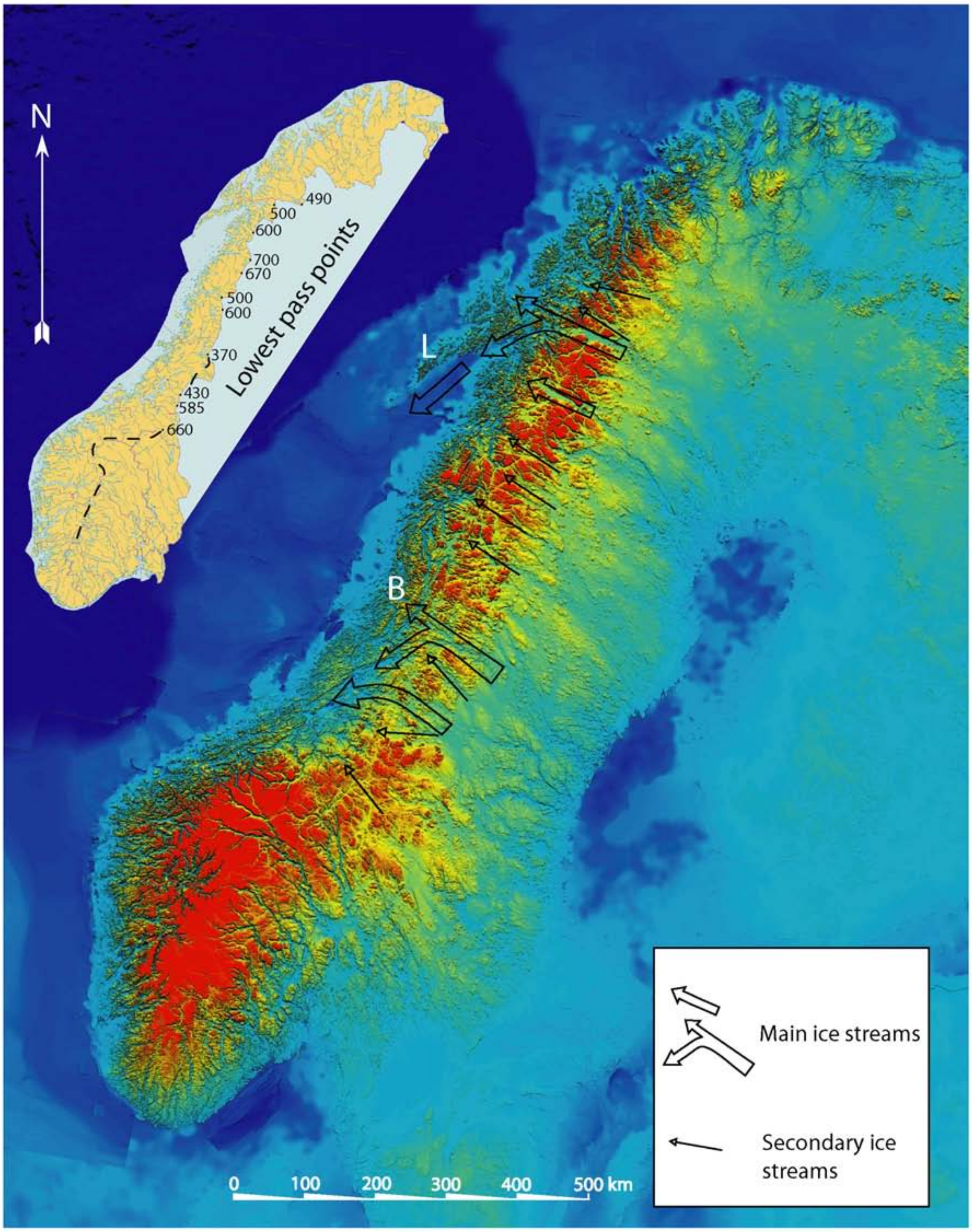


Fig. D1
Digital shadow relief map of Fennoscandia that shows the dominant passageways of the ice streams during the last phase of the deglaciation. The *Main ice streams* followed the lowest pass points along the mountain chain and they are probably responsible for the youngest (Preboreal) moraines in the Norwegian valleys. On the inset map the main watershed in southern Norway is indicated (broken line). In northern Norway the watershed mostly follows the Norwegian / Swedish border, and here the lowest pass points are shown (figures in m a.s.l.). B=Bindal, L=Lofoten.

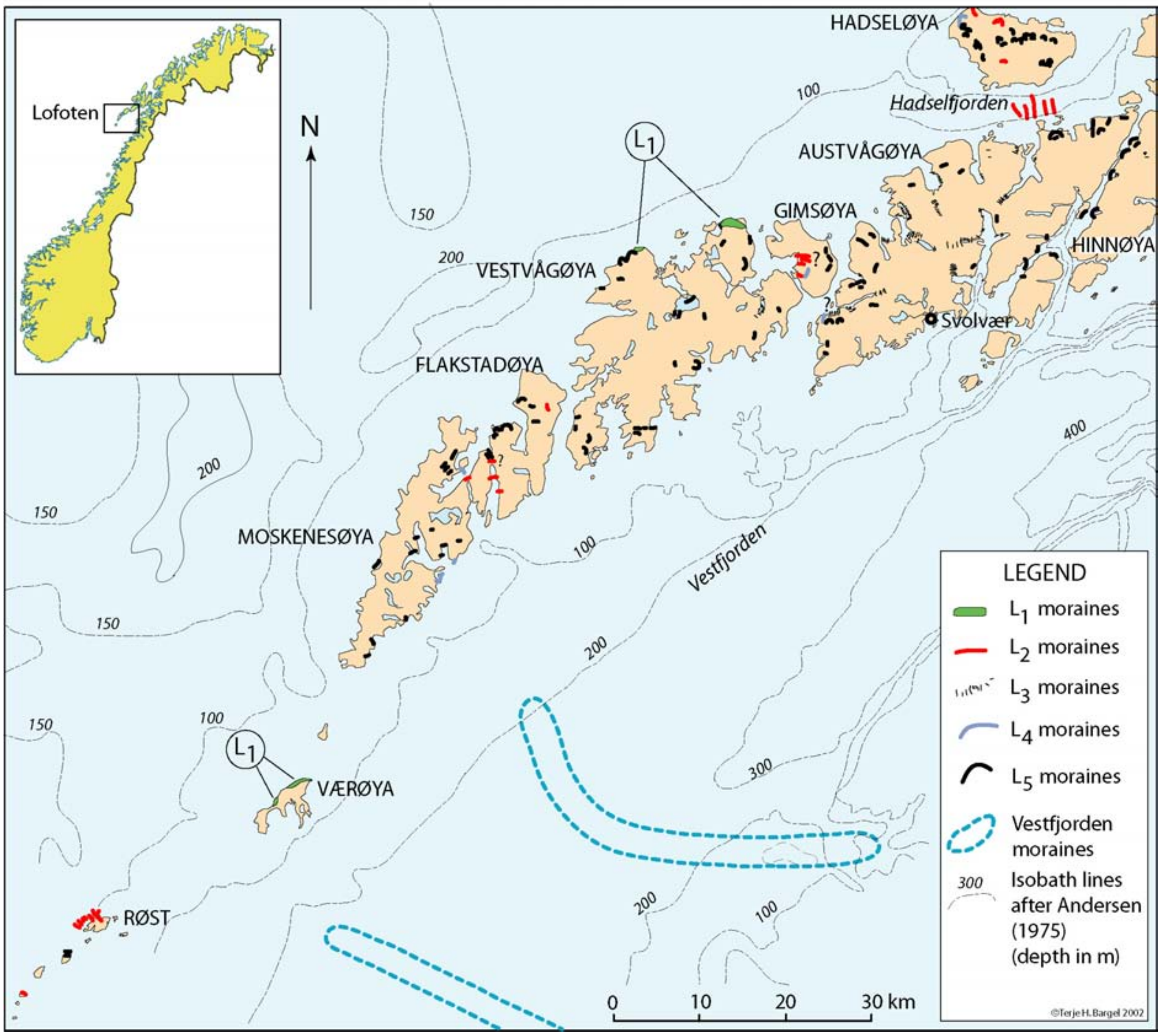


Fig. D2
Sketch map of the Lofoten islands that shows the location of the L_1-L_5 moraines. The two youngest Vestfjorden moraines are also indicated.

L_1-moraines are hummocky accumulations of diamictic material situated on the northwest side of high, steep cliffs facing northwest. The material could either be lee-side accumulations deposited during the last glaciation/deglaciation cycle, or the diamicton could have a local provenance, originally deposited as talus or local moraines produced on the nearest mountains and then re-sedimented by the sea or by glaciers. In any case, the diamictic material was most probably deposited or remoulded by a regional glacier, and they are consequently the oldest moraines.

L_2-moraines are single transverse moraines mostly localised to the north-south-oriented sounds that separate the Lofoten islands and on Røst. The positions of the moraines indicate that at least some of them were deposited in the sea by a regional ice flow from the Vestfjorden area towards the continental shelf outside the Lofoten islands. Based on this interpretation, a tentative correlation of the ice margin during the deposition of the L_2-moraines is proposed (Fig. D3). The correlation supposes that a northwest-directed ice advance, which is here named the *Lofoten event*, has deposited the L_2-moraines. The Lofoten event is tentatively correlated with the smaller ice readvance recorded on the shelf and in the coastal areas in Northern Norway at c. 13.5 ka BP. Alternatively, correlation with the Skarpnes-Vega moraines at c. 12.2 ka BP could also be possible. The fact that moraines of the Lofoten event are traced only in the southwestern parts of the Lofoten islands could be a result of the local glaciation centred on Austvågøya that hampered accumulation.

L_3-moraines or moraines of De Geer type frequently occur in low-lying valleys, often partly submerged. They are normally interpreted as end moraines or as moraines deposited submarginally in cracks in the glacier sole during the deglaciation, and which show a stepwise recession of the glacier towards the glaciation centre. The L_3-moraines are concentrated to the eastern parts of Austvågøya, which has the highest mountains in Lofoten. The glaciation centre in question was probably located in these mountains. The time of deposition of the L_3-moraines was probably during the deglaciation after the Lofoten event.

L_4- and L_5-moraines are cirque moraines that are located in the cirques, the cirque valleys or in areas just outside the cirques. The moraines most often have a C-shape with the concave side facing the cirque, strongly indicating the direction of deposition. The L_4-moraines and the L_5-moraines are often located in the same valley-/fjord system, clearly demonstrating their age difference. The L_5-moraines are located inside or just outside the cirque. The L_4-moraines are associated with a more significant lowering of the glaciation limit than the L_5-moraines and represent a relatively massive expansion of the local glaciers as they occupied several small fjords. The glacier advance that deposited the L_4-moraines is tentatively correlated with the Lofoten event.

Based on studies of the moraines on the Lofoten islands, a deglaciation chronology is proposed (Fig. D3). As a result of the recession of the glacier margin from the LGM I-position on the continental shelf, most of the area was deglaciated, but local glaciers may have existed. The readvance to the LGM II-position was probably almost as extensive as the LGM I. The main deglaciation started at c. 15-14 ka BP, but ice-lobes deposited till tongues on the western shelf and small moraines in the sounds in the western part of the Lofoten area before the final recession of the continental glacier, the *Lofoten event*. The local glaciation during the Lofoten event was intense, and the local glaciers coalesced with the main ice sheet. Most of the ice probably vanished during the following deglaciation, leaving many sets of De Geer moraines in the fjords. During the climatic deteriorations in the Older Dryas, the Younger Dryas and probably the Preboreal chronozones, the local glaciers expanded causing cirque moraine deposition.

Conclusion

1. During the Late Glacial Maximum (LGM I) the Vestfjorden glacier expanded northwards through the sounds between the islands, coalesced with the Hadselfjorden glacier from northeast and ended at the shelf break. Local glaciation on the islands was very active and the highest mountains could have been ice covered.
2. During the following deglaciation, the continental glacier withdraws from most of the area, but local glaciers have most probably existed.
3. The readvance to the LGM II position at c. 15 ka BP was probably almost as extensive as the LGM I.
4. The main deglaciation started at c. 15-14 ka BP, but ice-lobes deposited till tongues on the western shelf and small moraines in the sounds in the western part of the Lofoten area at c. 13.5 ka BP, the *Lofoten event*. The local glaciation during the Lofoten event was intense, and the local glaciers coalesced with the main ice sheet.
5. Most of the ice probably vanished during the following deglaciation leaving many sets of De Geer moraines in the fjords.
6. During the climatic deteriorations in the Older Dryas, the Younger Dryas and probably the Preboreal chronozones, the local glaciers expanded causing cirque moraine deposition.

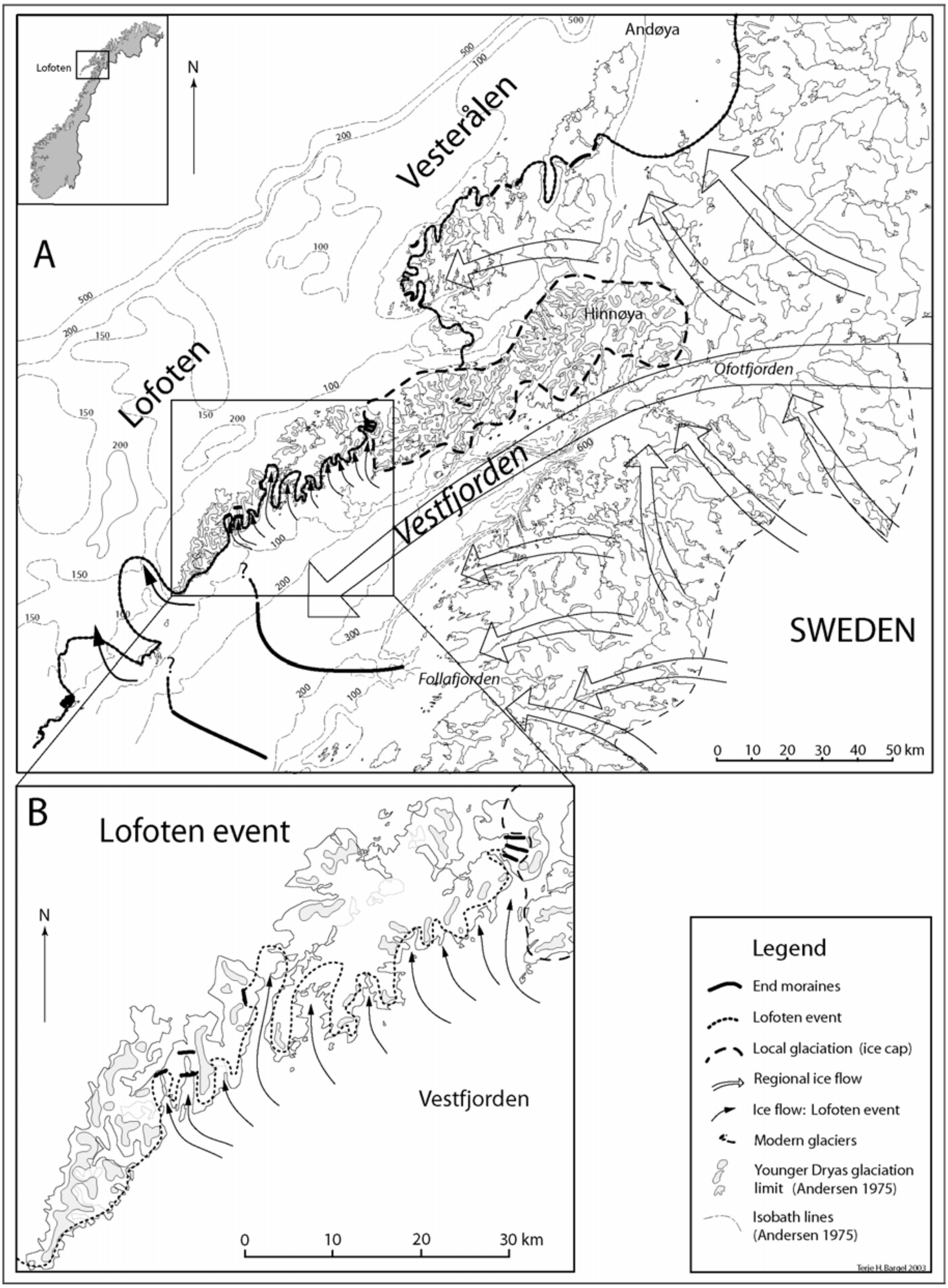


Fig. D3
Map of northern Nordland showing a reconstruction of the Lofoten event, accompanying regional ice flows, the local glaciation on Austvågøya and Hinnøya and the coalescing zone of the regional and the local glaciers. The correlative moraines in Lofoten, Vesterålen and Vestfjorden are also shown. Based on data published by Andersen (1975), Rasmussen (1984), Fjalstad (1997), Vorren & Plassen (2002) and on observations by the present writer.

D.3 Moraine studies in Bindal

Deep fjords that are encircled by high mountains characterize the Bindal area (Fig. D4). No valleys connect the inner part of the north-northeast-trending Tosenfjord to the interior region due to a long north-south trending chain of mountains. The ice flow in the southwestern direction along this overdeepened fjord, or from the east towards this fjord, must have ended at a relatively early phase of the deglaciation because of high-altitude pass points. An ice flow from the southeast along the lowest pass point of the mountain chain dominated the area during the latest deglaciation phase (Fig. D1).

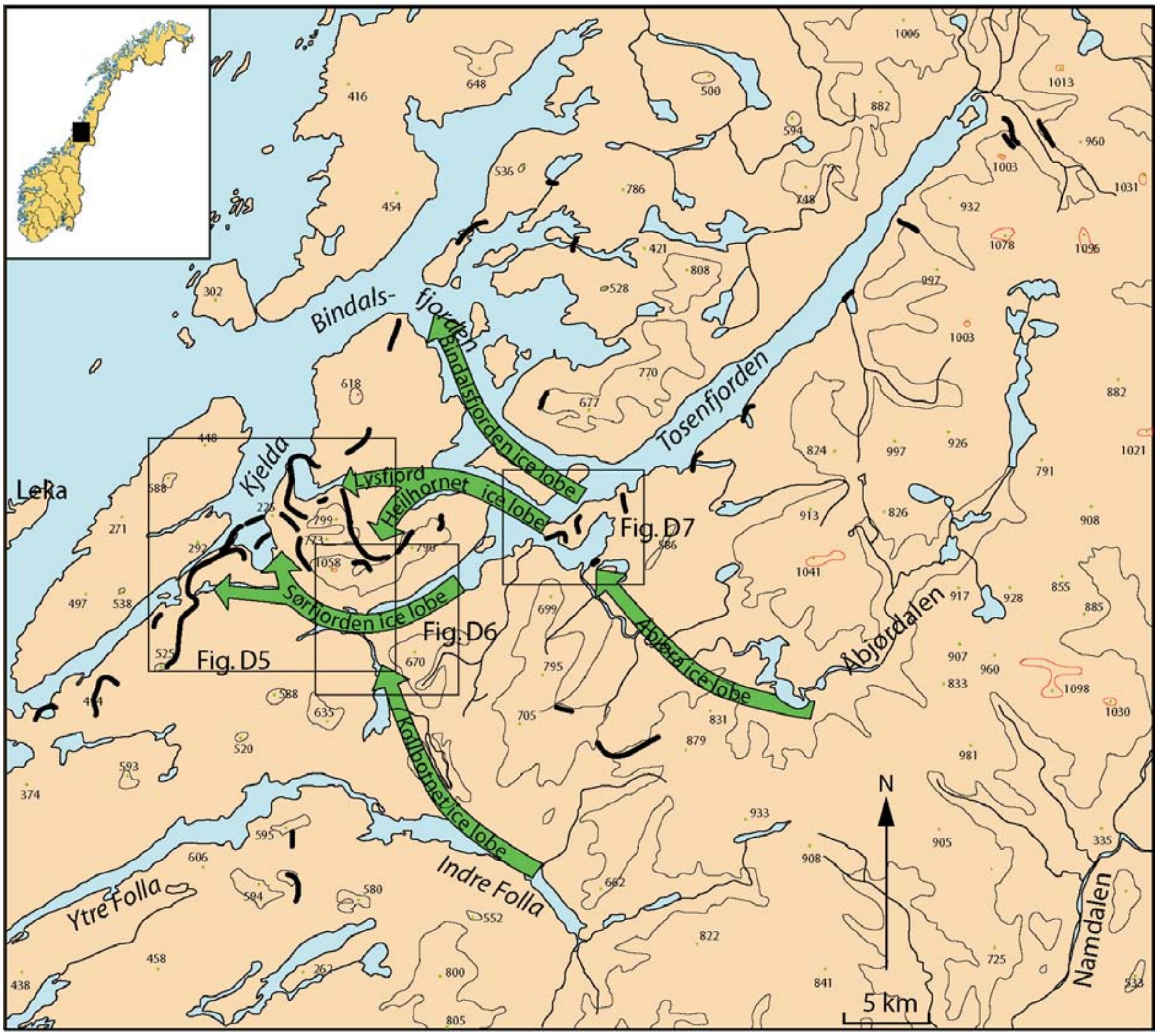


Fig. D4
Overview map of the Bindal area and surroundings showing the moraines (black), the inferred ice lobes (green arrows) and the location of detailed maps

Younger Dryas and Preboreal end moraines are present (Andersen et al. 1981). The area has been remapped as part of the present thesis. Based on ice-flow indicators, moraines and the area's morphology, three ice lobes representing the Younger Dryas main ice advance and two younger ice lobes are defined and discussed (Fig. D4). A relatively detailed reconstruction of the ice margins during the Younger Dryas and the Preboreal Stadials recorded in the Bindal area is proposed (Fig. D5-D8).

Younger Dryas regional ice advances (c. 11-10 ka BP) in the Bindal area

The main ice advance event in the Bindal area during this interval is recorded and named the *Heilhornet event*, a two-fold event that is dated to be older than 10.6 ka BP and c. 10.4-10.3 ka BP, respectively (Fig. D5). The oldest part of this event is correlated with the youngest phase of the Tjøtta Substage in central Nordland, which occurred at c.10.9-10.8 and 10.6-10.5 ka BP (Andersen et al. 1982, 1995), and the Tautra Substage in Trøndelag, which also occurred in two phases called the Tautra moraines during c. 10.8-10.5 ka (Reite et al. 1982, Reite 1994, Andersen et al. 1995, Sveian 1997). The new data makes it necessary to slightly modify the earlier reconstructed position of the ice margin in the Heilhornet area (Marthinussen 1962, Sollid & Sørbel 1979, Sollid & Reite 1983, Andersen et al. 1981).

The second main ice advance documented in the Bindal area during Younger Dryas is called the *Breidvika event* (Fig. D6). The event is tentatively correlated with the Nordli substage in central Nordland at 10.2-10.1 ka BP (Andersen et al. 1995) and the Hoklingen substage in Trøndelag at 10.4-10.3 ka BP (Reite et al. 1982, Reite 1994, Andersen et al. 1995, Sveian 1997). This correlation implies a confirmation of ice flow from the southeast as the last active ice in the western Bindal area and that the Tosenfjorden glacier had ceased to be of importance. Based on glacioisostatic and topographical considerations, the moraines in the Tosenfjorden area are correlated with the Breidvika event (Fig. D8).

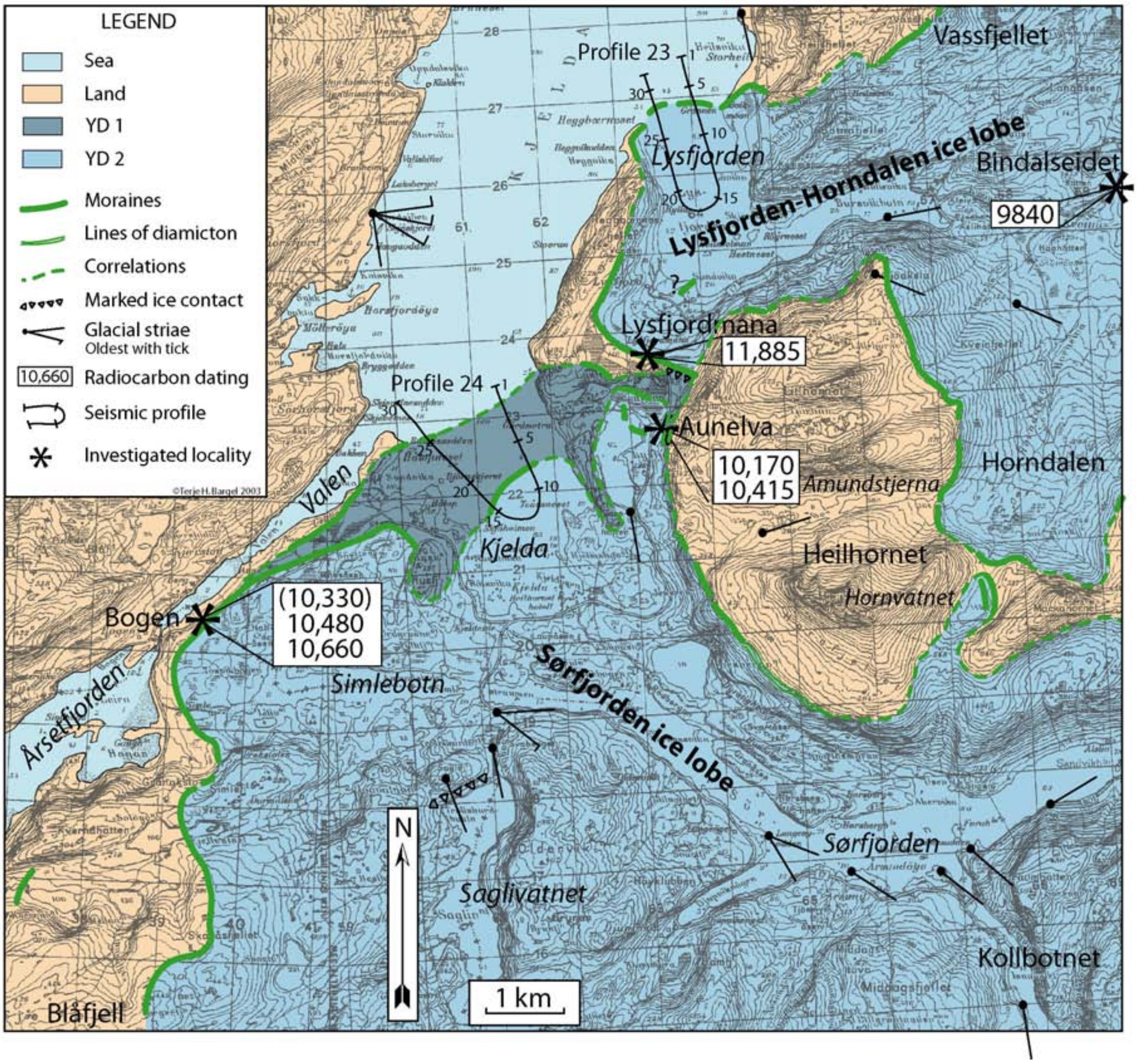


Fig. D5
Map of the Heilhornet area showing a reconstruction of the Lysfjorden-Heilhornet ice lobe and the Sørfjorden ice lobe during the Heilhornet event. The radiocarbon age in brackets is according to Andersen et al. (1981).

Preboreal ice advances (c. 10-9 ka BP) in the Bindal area

An early Preboreal ice advance at 9.9-9.8 ka BP is documented in the Terråk-Vassås area and named the *Vassås event*. This event is correlated with the Narvik I substage in northern Nordland at c. 10.1-9.7 ka BP (Andersen et al. 1995) and the Vuku substage in Trøndelag at c. 10.0-9.8 ka BP (Reite et al. 1982, Reite 1994, Andersen et al. 1995, Sveian 1997). Based on glacial-dynamic considerations and topographic limitations, the new interpretation requires substantial refinement in the reconstructed position of the ice margin during the Vassås event as proposed by Andersen et al. (1981).

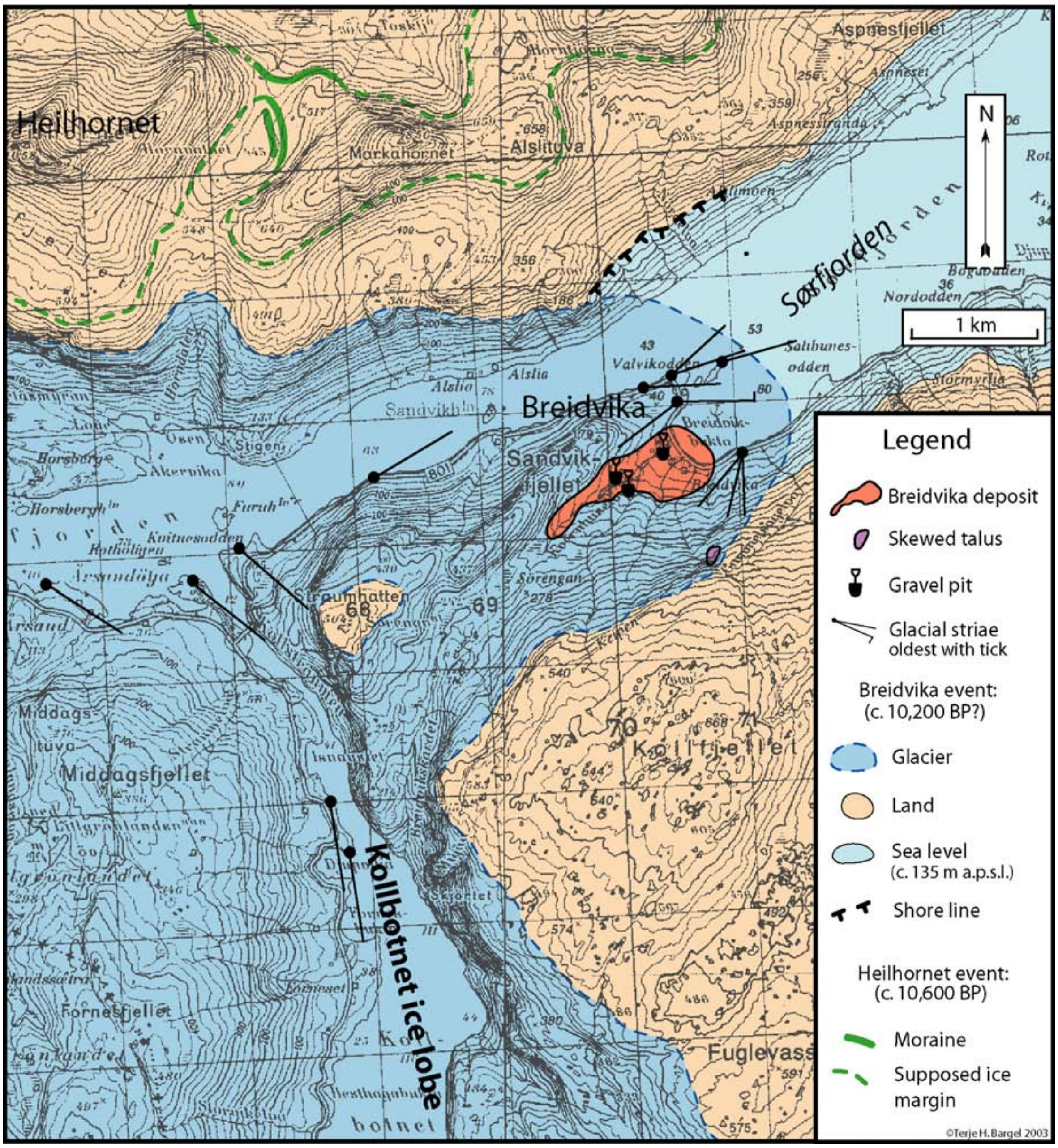


Fig. D6
Map of the Breivika-Kollbotnet area showing a reconstruction of the Kollbotnet ice lobe during the Breidvika event. The southwest-oriented striae are supposed to be the oldest striae on this map.

The ice supply to the area changed markedly from the northeast and east to the southeast after the Heilhornet event as the ice flow across the high-altitude easterly pass points ceased. The latest ice flow was channelled in the Follafjorden area via the lowermost part of the mountain chain, which is the area between the Lierne and the Børgefjell area (Fig. D1).

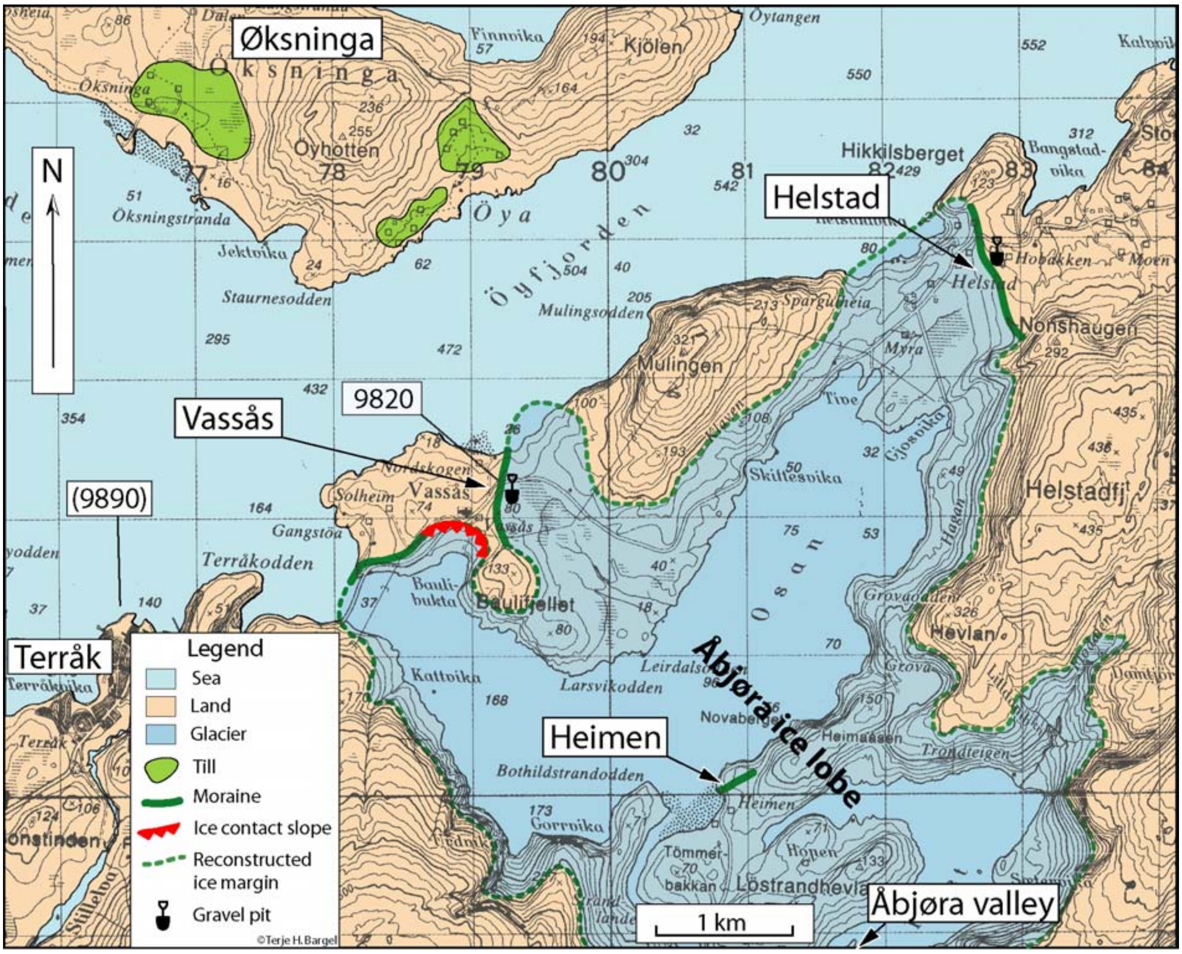


Fig. D7
Map of the Terråk area showing the terminal moraines at Vassås, Helstad and Heimen. The supposed stoss-side till on the island Øksninga, gravel pits (spades), radiocarbon dates and the reconstruction of the Vassås event are also shown. The age at Terråk (in brackets) is according to Andersen et al. (1981).

Conclusions (Fig. D8)

1. In the Bindal-Tosen area, three ice-lobe readvances are recorded, namely the *Heilhornet event* at c. > 10.6 ka BP, the *Breidvika event* at c. 10.2-10.1 ka BP and the *Vassås event* at c. 9.8 ka BP. The events are correlated with the Tjøtta/Tautra substages, the Nordli/Hoklingen substages and the Narvik I/Vuku substages, respectively.

2. Strong topographic deviations of the ice flow and a dynamically active ice margin in the Bindal area are recorded. The ice supply to the area changed markedly from the northeast and east to the southeast as the ice flow across the high-altitude easterly pass points ceased.

3. The latest ice flow was channelled through the lowermost part of the mountain chain, between the Lierne and the Børgefjell mountains, where the elevations are less than 400 m a.s.l.

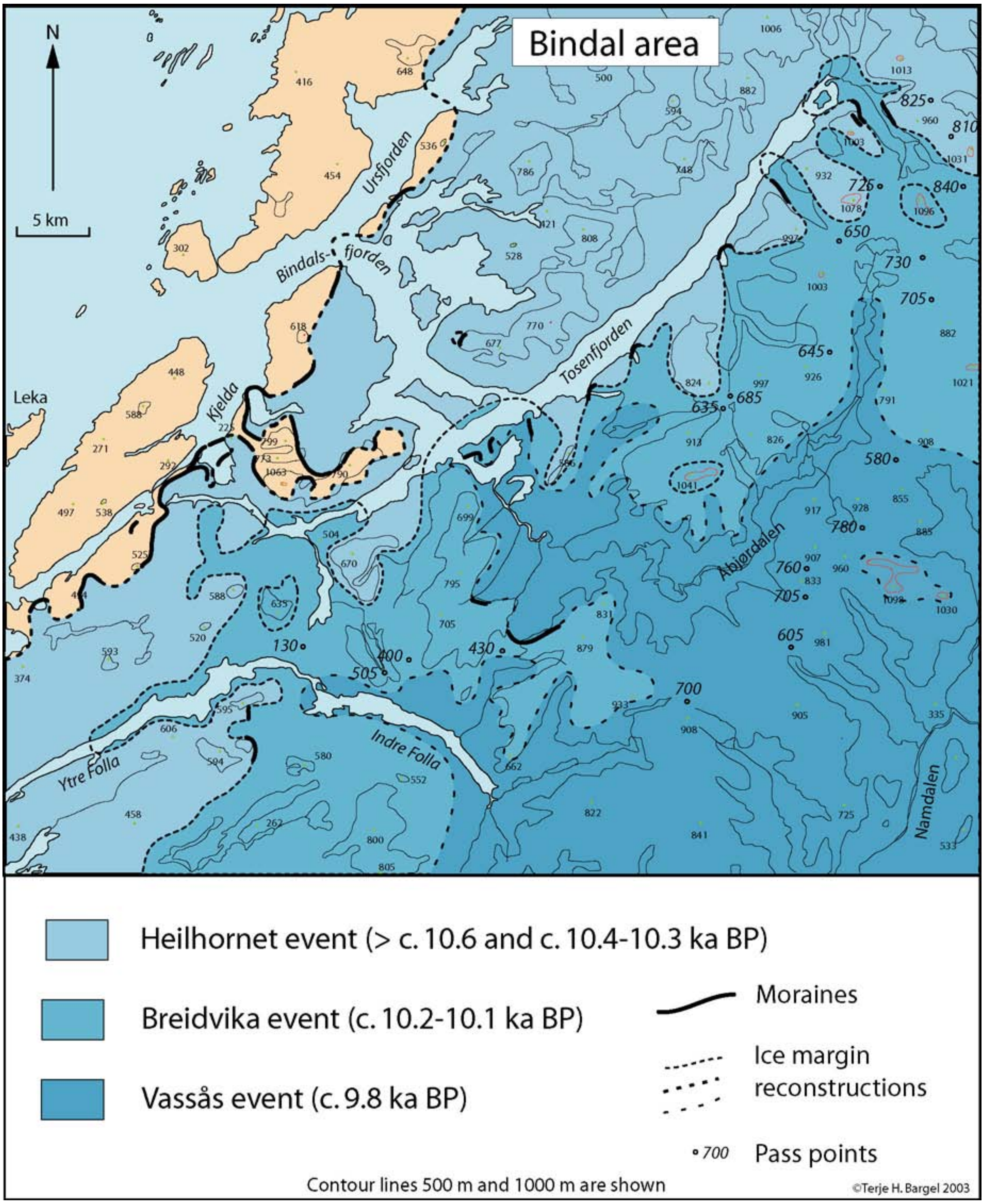
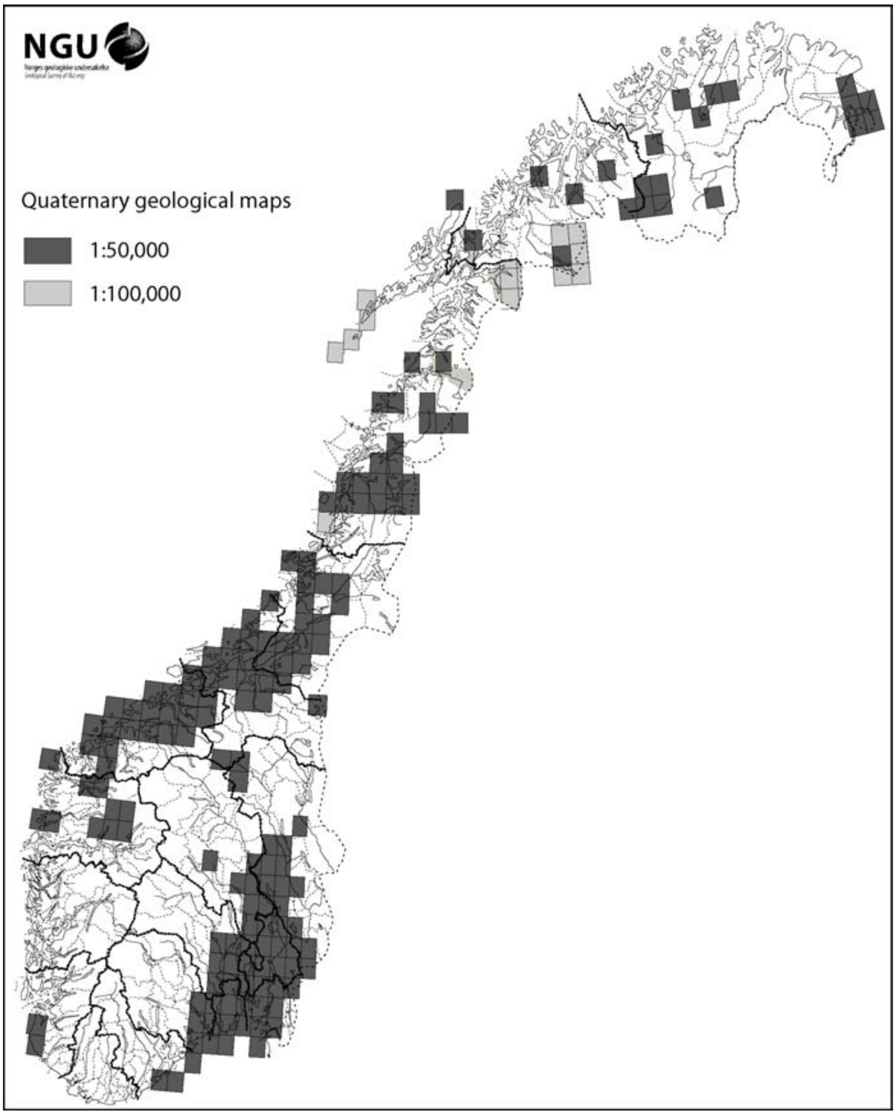


Fig. D8
Map of the Bindal area and surroundings showing a reconstruction of the ice margins during the Heilhornet event (early/middle Younger Dryas), the Breidvika event (late Younger Dryas) and the Vassås event (early Preboreal).

PART I BACKGROUND FOR THE THESIS



Chapter 1 Quaternary geological mapping and science

1.1 Introduction

Quaternary geological mapping is performed by most geological surveys. In addition, in many other countries, research on unconsolidated sediments has priority for, e.g. land-use, resource investigations and for scientific reasons. At the Geological Survey of Norway (NGU), mapping of Quaternary deposits has been one of the Survey's main tasks from the establishment of the institution in 1858. During recent decades, society's needs for information of the Quaternary deposits have increased, particularly within the fields of environment and health, physical planning, economy and supply of natural resources, agriculture and forestry. The geological surveys in, e.g. Finland and Sweden have defined similar objectives for their activities.

Many scientists look upon mapping activity with scepticism. They consider it to be simply registration and routine work, with little to do with science. It is true that much of the work is routine as policy has always been to complete whole map sheets with information in order to produce a tool for, e.g. land use planning. By doing so, much time has to be spent on mapping deposits that are not so interesting in a scientific context. On the other hand, the detailed scanning of the terrain implicit in the mapping has often revealed exposed sections of scientific interest in remote areas, in addition to morphologic features in forested areas that are difficult to interpret correctly on aerial photographs. Much sedimentological and stratigraphical work has been performed during the fieldwork in order to understand the genesis of the deposits. The creation of geological models of the areas is an important part of the mapping activity, which is necessary in order to understand the Quaternary geological history on a regional basis. The very large database of ice-flow indicators such as glacial striae, at NGU, could not have been achieved without much fieldwork. The criticism of the mapping is, for these reasons and others, misplaced. What could be criticized is the fact that the many mapping geologists involved have not used, or have had the opportunity to use, the enormous data at hand to do more science and to tell the layman what the results of the geological mapping mean.

1.2 Objectives and organization of the thesis

The Quaternary geological maps of Central Fennoscandia and the County of Nordland form an area of c. 450,000 km^2 (Fig. 1.1), a tremendous area of land with a huge potential for geological studies - much more than can be interpreted within the frame of a single thesis. During the compilation of the maps and the obligatory review of the existing literature, several very interesting areas and themes for further study have been identified. On this basis the thesis has aimed to:

A. Compile four Quaternary geological maps of Central Fennoscandia: surficial deposits, geomorphology and palaeohydrography, ice flow indicators (scale 1:1,000,000) and stratigraphy (scale 1:2,000,000) (Enclosures 1-3) and the Quaternary geological map of Nordland at a scale of 1:400.000 (surficial deposits) (Enclosure 4).

B. Create a link between the Quaternary geological maps, the practical applications of the map data and the study of Quaternary geological history (Part I).

C. Present a coordinated description of the five Quaternary geological maps and compile the Late Weichselian and Early Holocene deglaciation history of the mapped area (Part II).

D. Identify areas for in-depth investigations and perform these studies (Part III).

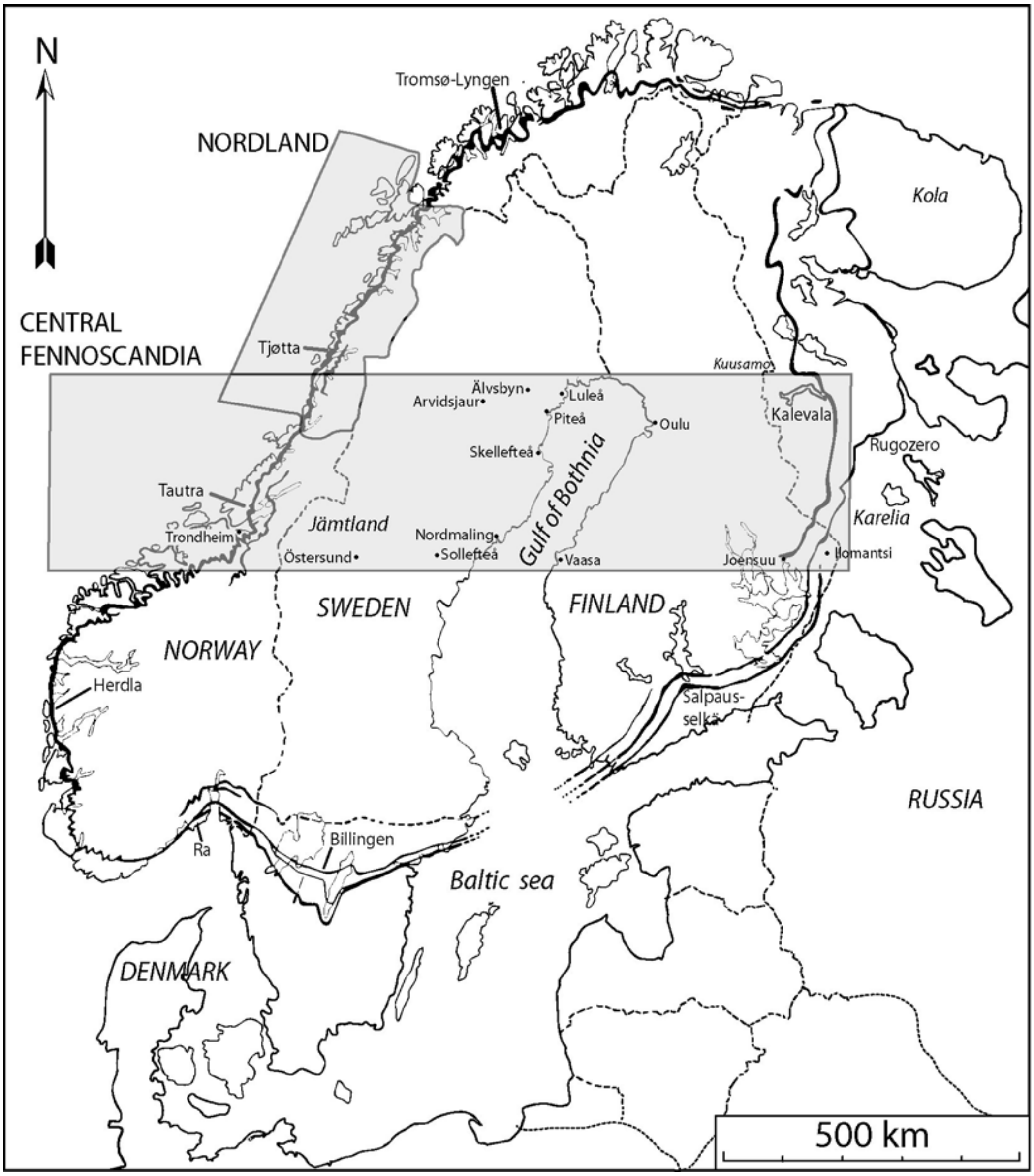


Fig. 1.1
Key map of Northwestern Europe with the Central Fennoscandian and the Nordland map sheet areas framed and shaded. The heavy lines represent the Younger Dryas ice marginal deposits. Selected geographical names in Sweden and Finland and selected names of the ice-marginal lines are shown. Slightly modified after Andersen et al. (1995).

A. Compilation of Quaternary geological maps

The five Quaternary geological maps that are fundamental to this thesis are printed or plotted on four separate sheets. The maps sheets are large pieces of paper, the size of the Central Fennoscandian sheets is c. 150 x 90 cm, and the Nordland sheet is c. 90 x 130 cm. The maps are not enclosed in the thesis in these dimensions, but in reduced versions, for practical reasons. The maps are also included on the enclosed CD-ROM in PDF-format, which can be used for screen viewing or printing in the preferred scale. Prints in full scale are available from the Information Centre at the Geological Survey of Norway (NGU). The maps of Central Fennoscandia are also available at the Geological Survey of Finland (GTK) and the Geological Survey of Sweden (SGU).

B. The Quaternary geological maps as links for understanding the optimal use of the natural resources and for the study of recent geological history

As this thesis has much to do with Quaternary geological mapping, Part I is focused on Norwegian Quaternary geological maps in general. The history of Quaternary geological mapping at NGU is reviewed and its main periods are described. From the start in the 1850s there has been a change from overview maps to maps with greater detail. During the last 20-30 years, compilation of overview maps containing more detail than earlier has returned to the agenda in order to complete a database of the whole country.

The usefulness of the maps and their descriptions has been the theme of several governmental committee reports, which have all concluded in favour of high quality maps. The level of detail in the maps, founded on a genetic classification of the surficial deposits, is determined on that basis. Arguments for the scientific use of the map data have been summarized in the introduction to this chapter. These will be considered again at the end of Chapter 2.

Part I concludes with a short introduction to older literature from Central Fennoscandia and the Nordland area, Chapter 3. The main focus is on literature concerning the Norwegian areas, and more than 600 references are listed at the end of the thesis.

C. Description of the Quaternary geological maps, the deglaciation history and analysis of regional trends

The Quaternary geological maps of Central Fennoscandia are described in Part II of the thesis. Details are given on the topography, the regional distribution of the deposits (Chapter 4), their morphological imprints (in mega and macro scales) on the landscape (Chapter 5), the ice flow indicators and the stratigraphy (Chapter 6). The same information is also given for the Nordland area (Chapter 7). At the end of Part II a comprehensive review of the deglaciation of the Central Fennoscandia and Nordland is presented. This presentation is based on literature study, and since most of the literature concerning the Norwegian area is included, this chapter could be of special interest to other scientists (Chapter 8).

D. Regional trends and detailed studies in selected areas

Part III of the thesis is dedicated to the new insight, which can be derived from the overview maps across the international borderlines. Because very little scientific work has been performed in many areas, a painful selection had to be made, as several topics of interest have been revealed.

The detailed information on the bathymetry of the continental shelf that has newly become available, has prompted ideas on concentrated ice streams along bathymetrical depressions that do not always have known direct continuations onshore. The detailed information on the moraines that is presented on maps at small scales shows that the moraines are located in specific areas along the Norwegian coast. In combination with topographic information and knowledge of the migration of the glaciation centres on the eastern side of the mountain chain, this has led to the idea of concentrated ice streams from the east (Chapter 9).

The lobe configuration of the glacier margin has probably been more accentuated along the coast and valleys in Norway during the deglaciation than has been understood earlier. This idea, in combination with studies of moraines and radiocarbon dates (Table 1.1), is used to propose new deglaciation chronologies for the Lofoten islands (Chapter 10) and the Bindal area (Chapter 11).

1.3 Age determination results

The ages used in the thesis are based on age determination by:

4. Varve chronology on deglaciation features in the Gulf of Bothnia (expressed in absolute ages up to c. 12,000-15,000 clay varve years BP; also denoted 12-15 *cal ka ago*) (e.g., Brunnberg 1995).
5. Radiocarbon age determination for objects up to c. 40,000 years old. Most of the ages that are mentioned in the thesis are determined by this method; the dates are not calibrated and are denoted *^{14}C ka BP,* or only *ka BP* (e.g., Olsen et al. 1996c).

6. Amino acids, oxygen isotopes, OSL (TL) and U/Th for determinations within and out of reach of the radiocarbon method (> c. 40,000 years old), are given in absolute ages and denoted *cal ka BP*; or these dates may have been converted to the ^{14}C-yr timescale (and denoted ka BP) using particular calibration methods (see, e.g. Olsen et al. 2001a).

Table 1.1 shows the radiocarbon dates that have been acquired especially for the thesis, and all of them are published here for the first time. Except for the last two localities, all are situated in the Bindal area.

Locality, municipality	**Lab. no.**	**Species**	**Age ka BP**	**Site**
Fuglvatnet, Velfjord, Brønnøy	T-8617	Mya truncata	9650 ± 110	Littoral
Lysfjordmana, Bindal	TUa-3433	Shell fragment	8065 ± 50	Moraine
Lysfjordmana, Bindal	TUa-3677	Shell fragments	11,885 ± 75	Moraine
Aunelva, Bindal	TUa-3014	Macoma baltica	10,415 ± 85	Littoral
Aunelva, Bindal	T-15636	Mya truncata	10,170 ± 90	Littoral
Bogen, Bindal	T-15324	Hiatella arctica	10,660 ± 180	Marin
Bogen, Bindal	TUa-3676	Portlandia arctica	10,480 ± 70	Marin
Vassås, Bindal	TUa-3013	Portlandia? fragm.	9820 ± 90	Marin
Bindalseidet, Bindal	T-15323	Mya truncata	9840 ± 65	Littoral
Straumøya, Frøya	T-15071	Mya truncata	10,355 ± 65	Till/littoral
Nerdvika, Smøla	TUa-3012	Shell fragments	38,950 ± 780	Till

Table 1.1
Radiocarbon dates from central Norway, carried out for this thesis.

Chapter 2 Quaternary geological maps

2.1 Introduction

A Quaternary geological map is principally a map with information on the geological processes that acted during the Quaternary, and on the results of these processes. This includes erosion and sedimentation, glacial sculpting of the surficial deposits and the bedrock, the geometry of the deposits, their chemical, physical and technical characteristics, structures and textures, neotectonics and volcanic activity. The most common maps show the situation at present, but maps showing the development of various features and maps showing paleoreconstructions have also been produced.

Maps containing many topics are difficult to read and will not be helpful to many users. The most frequent presentation form of printed maps is to present one or very few themes. Digitised maps and databases produced for use in a Geographical Information System (GIS) simplify the process of choice of themes in the first place, as one can easily make a range of compilations using the digital databases.

In this chapter the Quaternary geological thematic maps containing information on the surficial (unconsolidated) deposits will be described and discussed. First a short review of the development of Norwegian Quaternary geological maps is presented. It will be shown that the principle of genetic classification of the deposits that was established more than 150 years ago is still valid today. The genetic classification gives information, albeit indirectly, on the physical characteristics of the deposits, and with that in mind, an account of the practical applications of the maps in regional planning and resource management is given. The various map types and map scales are also given attention.

2.2 The history of Quaternary geological mapping in Norway

Some milestones from among the many Norwegian Quaternary geological maps will be described below. It has not been the intention to make a complete historical presentation of the earliest years, and for the most part only maps published by NGU will be mentioned. The information is compiled from Ingvaldsen (1983) and also based on my own experience in charge of the Quaternary mapping activity for fourteen years.

2.2.1 The earliest maps

During the years 1840-1845 the well known Norwegian geologist B. M. Keilhau published the voluminous "*Gæa Norvegica*" that included a geological map of Norway, probably the first one (Keilhau 1840-1845). When the Geological Survey of Norway was established in 1858, geological mapping was its primary task (Fig. 2.1) in addition to prospecting for mineral resources. The first maps published by the new institution were combined maps of the bedrock and the surficial deposits. Later an extensive mapping of the surficial deposits was carried out, and a colour map at a scale of 1:400,000 from the southern and southeastern part of Norway was compiled (Kjerulf & Dahll 1866). This map showed the general trends of distribution of marine clays, sand- and gravel deposits, tills and the greatest ice-contact deposits.

Fig. 2.1
W.C. Brøgger and H.H. Reusch as young mapping geologists at Corsica in 1876 properly equipped to perform fieldwork. Reusch was the director of NGU during the years 1888-1921. From NGU´s archives.

A geological map of the Trondheim area at a scale of 1:800,000 was compiled by K. Hauan and Th. Kjerulf (Kjerulf 1875). The map covers most of the Norwegian part of Central Fennoscandia (Fig. 1.1). On this map we can find information on marine clay and sand, sand in general, fluvial sand and till ("erratic deposits in the inland").

The first geological map from Northern Norway was at a scale of 1:1,000,000. This was primarily a bedrock map, but with some scattered indications of glacial and postglacial deposits (Dahll 1879).

From the end of the 1870s up to c. 1960, several maps at scales of 1:100,000 and 1:250,000 were published from all parts of Norway. These map series were bedrock maps with additional information on the surficial deposits in areas where these dominated. The surficial deposits and other traces of the glaciation were mapped and little changed for several decades. The genetic classification was the same, but more details were introduced on the newer maps (Fig. 2.2).

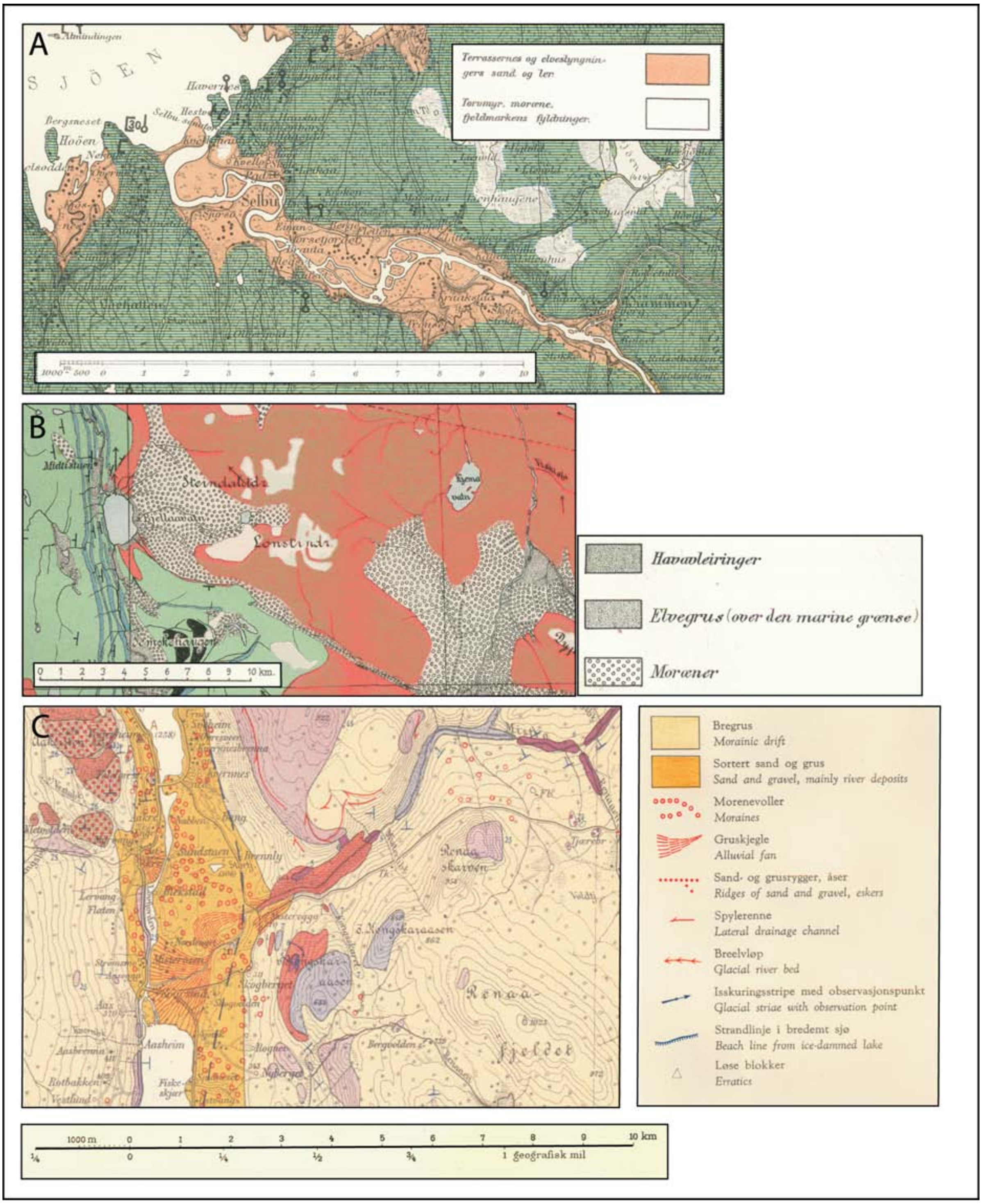


Fig. 2.2
Older geological maps published by NGU that show how Quaternary geological information was presented: **A**: Selbu, central Norway (Homan 1890), **B**: Saltdalen and Dunderlandsdalen, northern Norway (Rekstad 1913c), **C**: Ytre Rendal, southern Norway (Holmsen & Oftedahl 1956). Colours used on the maps that are not represented on the legends, show bedrock units.

2.2.2 The era of Quaternary geological maps

Probably the first Quaternary geological map published by NGU from central Norway was a map at a scale of 1:50,000 of the Trondheim area compiled by W. Blakstad in 1891 (Fig. 2.3 A) and published by Reusch (1901a), including a short description. The deposits were classified mainly as we do today. The first Quaternary geological map series was published in the period 1951-1960. The fieldwork had started as early as 1936, and by 1960 six map had been printed. The maps were at a scale of 1:250,000 and the area between Oslofjorden and Røros was mapped (G. Holmsen 1951, 1954, 1955, 1956, 1958, 1960) (Fig. 2.3 B). Several years later a map of the Jotunheimen mountain district was printed at the same scale (P. Holmsen 1982). With these maps a new way of thinking of Quaternary geology and of the practical usage of the surficial deposits and maps was introduced. Two new elements were used: thin and discontinuous deposits and the highest mountains were mapped for the first time, and the traditional genetic classification of the deposits was supplemented with a technical parameter: the dominant grain size. A simplified map of Southern Norway at a scale of 1:1,000,000 was also compiled (G. Holmsen 1971a, Fig. 2.3 C) and this map was the first to be printed in the colours now used as standard (Fig. 2.6, Ch. 2.5.2).

Thematic maps of the deposits were, for a long time, the main Quaternary geological maps that were produced in colour. However, several other thematic regional maps had been printed as figures in scientific papers, for example the interpretation of ice movement in Tanner (1915, Fig. 3.4), ice margins in Holtedahl (1929, Fig. 3.7), Grønlie (1940, Fig. 3.9), Undås (1942, Fig. 3.6) and shoreline isobases in Rekstad (1922, Fig. 3.3). A Glacial Map of Norway at a scale of 1:1,000,000 was compiled by O. Holtedahl and B.G. Andersen and published as an enclosure to the Norwegian edition of Geology of Norway (O. Holtedahl 1953). A revised version at a scale of 1:2,000,000 was published as an enclosure to the English edition of Geology of Norway (O. Holtedahl 1960). These maps show glacial striae, end moraines, glaciofluvial drainage marks, ice divides and marine limits. Thematic maps of exploited or potentially exploitable sand and gravel deposits in southern Norway at a scale of 1:1,000,000 was compiled by G. Holmsen (1965, 1971b). These maps are very schematic and include no quality parameters, and are not very useful for practical purposes.

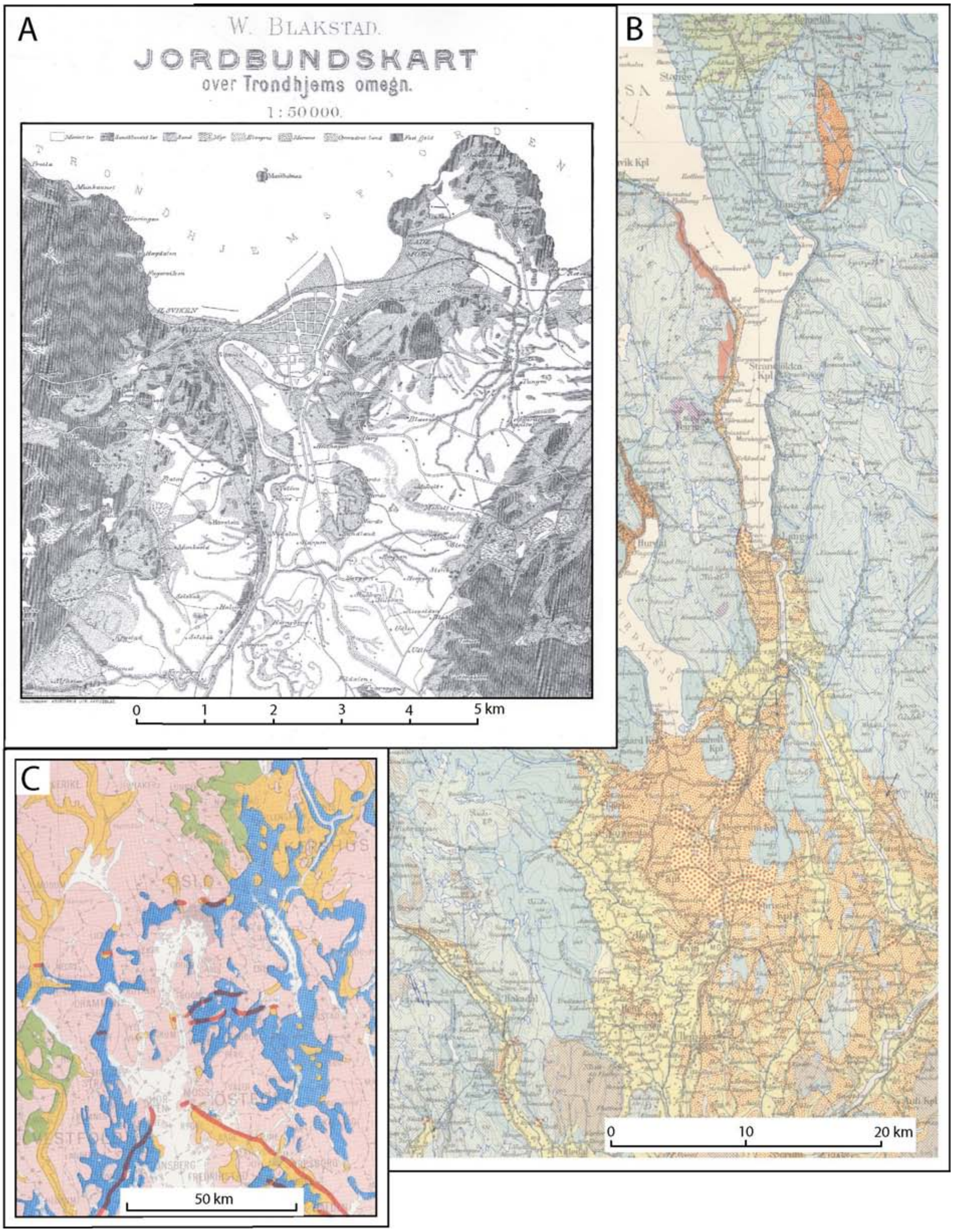


Fig. 2.3
Quaternary geological maps published by NGU. **A**: Trondheim 1:50,000 (W. Blakstad 1891, published by Reusch 1901a), **B**: Part of Oppland 1:250,000 (G. Holmsen 1954), **C**: Part of the simplified map of Southern Norway 1:1,000,000 (G. Holmsen 1971a). The extensive legends are omitted as the intention is to show what the maps look like, not to show the geology in detail.

As part of the National Atlas of Norway, the National Map Authority (Statens kartverk) published several thematic maps at scales of 1:1,000,000-1:5,000,000 of the glacial geology (Sollid & Torp 1984), the glacial chronology (Andersen & Karlsen 1986), land uplift (Sørensen et al. 1987) and the surficial deposits (Thoresen 1991).

As a result of the Nordkalott project, five Quaternary geological maps at a scale of 1:1,000,000 were printed. They covered the parts of Norway, Sweden and Finland north of 66^{o}N. The maps presented data on the deposits, glacial geomorphology and palaeohydrography, ice-flow indicators, ice flow directions and stratigraphy of Northern Fennoscandia (Hirvas et al. 1988). The Mid-Norden project (Part II of this thesis) was a follow-up project that compiled the same type of maps for Central Fennoscandia (Bargel et al. 1999a, b, c).

2.2.3 Modern Quaternary geological map series

Quaternary geological maps at a scale of 1:50,000 were developed in the early 1970s, and the first map was published in 1972. A description with focus on the technical properties of the deposits, in addition to the traditional deglaciation history, was also published (Follestad 1972, 1973). Inspiration from the more voluminous description of the Quaternary geology of, e.g. Jämtlands län of J. Lundqvist (1969) is clearly recognizable. The first 1:50,000 maps have been supplemented with new sheets up to the present day with small changes, and the most densely populated areas have now been covered (Fig. 2.4 B).

A parallel series of Quaternary geological maps at 1:20,000 was published during the years 1976-1993 (Fig. 2.4 A). A few maps at 1:10,000 and 1:5,000 have also been printed. An overview map of Norway at 1:1,000,000 has also been compiled. County maps at scales of 1:125,000 - 1:500,000 have been published too. All these maps are described below (Ch. 2.5.1).

When the production line for digital maps was introduced in 1994, the development of new map types accelerated. Combination of themes such as modern versions of combined maps with bedrock and surficial deposits, and maps with derived themes such as, e.g. ground water utility, infiltration utility and others based on the databases, are now easy to produce. A few of these map types are described in Ch. 2.5.1.

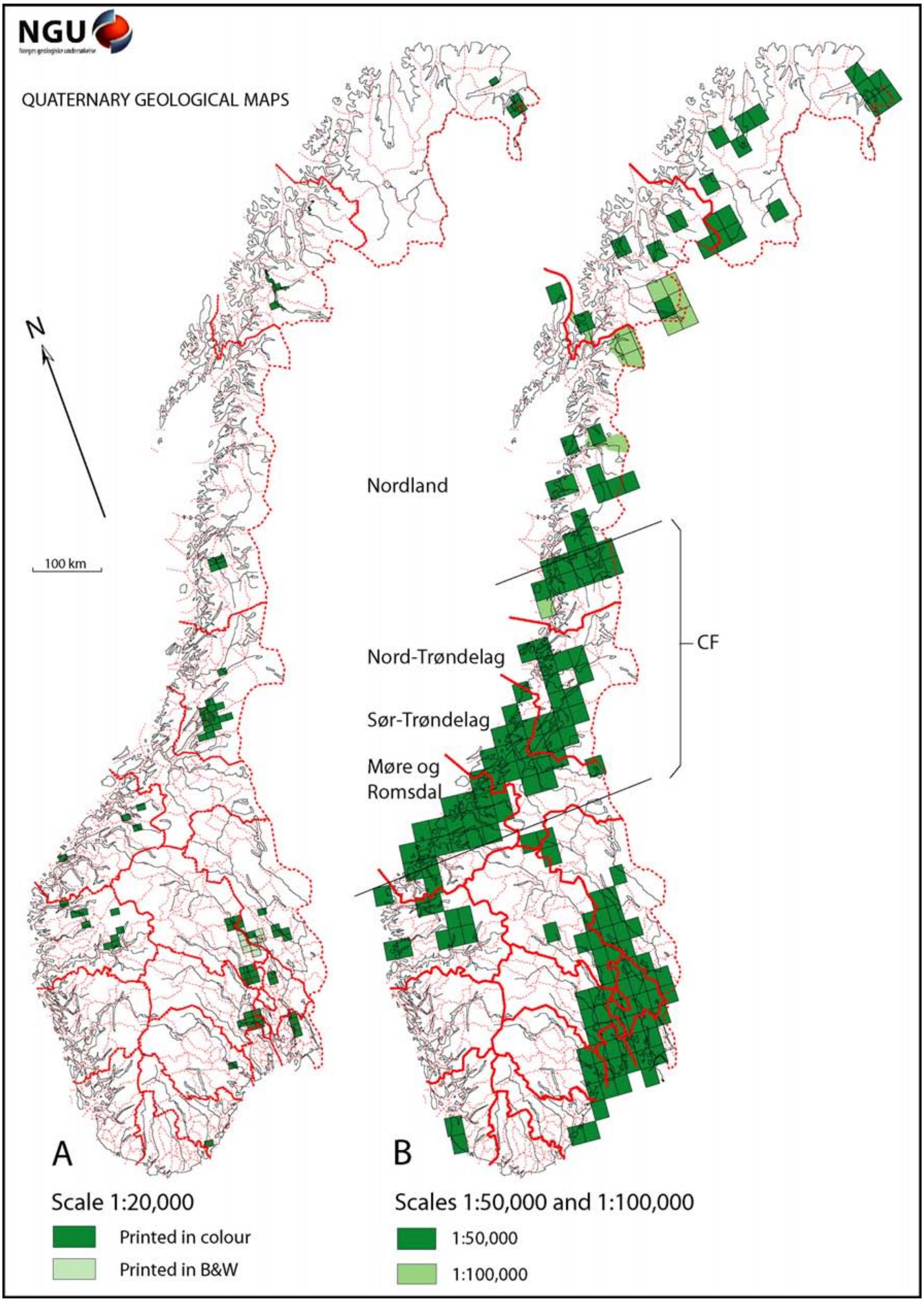


Fig. 2.4
Maps of Norway showing the coverage of modern Quaternary geological maps at scales **A**: 1:20,000 and **B**: 1:50,000 and 1:100,000 produced by NGU. The unmarked (white) areas on B are mostly mapped at scale 1:250,000. The Norwegian part of Central Fennoscandia is indicated with two parallel lines (CF) on B. Modified from the map catalogue available on the web site http://www.ngu.no/.

The former *Continental Shelf Institute (IKU)* performed regional mapping of the Quaternary deposits on the continental shelf off Norway as a government-funded project to get background data for the petroleum industry. Several maps at different scales were produced (e.g., Gunleiksrud & Rokoengen 1980, Rokoengen et al. 1980, Maisey & Wøien 1983, Bugge & Wøien 1984, Rise et al. 1984, 1988). The project funding gradually decreased and the responsibility for the geological mapping of the surficial sediments on the continental shelf down to was eventually given to NGU in 1987.

2.3 Map applications and regional priorities

The case for performing investigations of the surficial deposits was summarized in the Governmental proposition from 1856 (Ingvaldsen 1983). The main value in this work was thought to be related to agriculture as more knowledge of the distribution of clay, sand and carbonate sand would be valuable when new areas were to be cultivated. Organic material from peat bogs was also of interest as a source of energy. Road engineers´ need for geological information was also considered, and even scientific interests. Today c. 3 % of the total area of Norway is cultivated, and an additional 3 % of the area is physically and climatically suited for cultivation, but these areas are occupied by productive forests (Statistisk årbok 2000)

For more than 20 years, NGU has argued that surficial deposits, including the soil cover, are fundamental natural resources comparable with water and air (Bargel et al. 1981). They are, together, the main basis for plant- and animal life, and thus for agriculture and habitation. The use of surficial deposits as, e.g. building material, areas for construction and communication, sources of ground water and areas for waste disposal, binds areas with these utilities for a very long time. Due to potential conflicts the use of land for such purposes is regulated in many national laws.

2.3.1 NOU 1974:10

A Governmental report that assessed Quaternary geological mapping in Norway (NOU 1974:10) argued that the main objective of these maps is to acquire data considered relevant, at the time of map production, for achieving optimal utilisation of the appropriate areas. This must be considered as an acceptance of the view that the work has not been done once and for all, but rather that the data have to be supplied with new maps and parameters in parallel with the development of new technology and the continually changing needs of modern society. The digitisation of the maps is just one example of the upgrading of the data.

Quite interesting, but not surprising, is the fact that was underlined in the same report (NOU 1974:10), that, in order to be serviceable to many users, a variety of data is needed, and the suitability in relation to a variety of applications listed, was estimated in the range of "useful" to "necessary".

The data needed for **farming** includes information on the thickness of the soil, its physical and chemical properties, and production potential.
In **forestry** the maps are very useful in the evaluation and exploitation of the forests, for construction of forestry roads and in relation to drainage.
In **road construction** information on the distribution and properties of the deposits is helpful in the choice of routes and in finding readily accessible construction materials.
In **hydropower projects** the maps present valuable information relative to dam sites, accessible construction materials and to the consequences of dams for the development of the watercourses.
In **geotechnical investigations** the maps present necessary information, at a general level, on the endurance and stability of the deposits in relation to landslides and prevention of erosion.
For **water supply** from ground water in sand- and gravel deposits it is necessary to know the stratigraphy of the deposits in order to localise, exploit and protect the water.
The porosity of the deposits is an important consideration in use of sorted deposits for **waste disposal,** as it is used actively in the decomposition of organic wastes in the spill water.
Knowledge of the quality and volume of the **sand- and gravel deposits** is most important in optimal use of the resources as building material.
A selected group of active and potential users of the maps was asked for their opinions on map scales and regional priority. Most of the respondents preferred the scales 1:10,000 and 1:50,000 in areas where

- construction and building activity are concentrated
- communication lines are planned
- hydro power constructions are planned
- agricultural and forestry activity are located
- exploitable resources are situated
- landslides could happen

In addition to these well-known priorities, a new element was introduced as several users wanted data from mountain areas where recreation centres are situated. The argument was to get information from the maps on the potential for water supply from groundwater and on possible locations for sites for infiltration of waste water.

The conclusions in NOU 1974:10 were therefore, not surprising, that maps should be available at scales of 1:10,000 and 1:50,000 in areas below the highest marine shore line where clays are situated, and elsewhere where essential areas of thick deposits are located. The document concluded that about 25 % of the total area should be mapped during the following 20 years (Fig. 2.5).

2.3.2 The Quaternary geological test project

The Quaternary geological test project (Kvartærgeologisk forprosjekt, Reite 1981) was a follow-up of NOU 1974:10. In this new project, the same issues as in the 1974-project had priority, but now in greater detail, as several test mapping-projects were performed and the users were more thoroughly questioned. Not surprisingly, the conclusions from this test project were about the same as in NOU 1974:10 as regards the mapping scales and the map contents, and an increased mapping activity was highly recommended (Fig. 2.5). The really new issue, however, was the recommendation of data registration in computerized databases.

2.3.3 The situation after the test projects

Today, most, but not all of the recommendations in NOU 1974:10 and from the Quaternary geological test project have been fulfilled. The Norwegian Institute of Land Inventory (NIJOS) performs detailed mapping in the agriculturally interesting areas (Grønlund & Solbakken 1982). The largest quick-clay slide in Norway in recent decades, in Rissa in Trøndelag in 1978 (Gregersen 1981, Løfaldli et al. 1981), initiated greatly increased mapping activity at scales of 1:50,000 and 1:20,000 below the highest Postglacial sea level in the areas of Norway where most of the marine clays are situated, the area north of Oslofjorden and the area around Trondheimsfjorden (Bargel 1988).

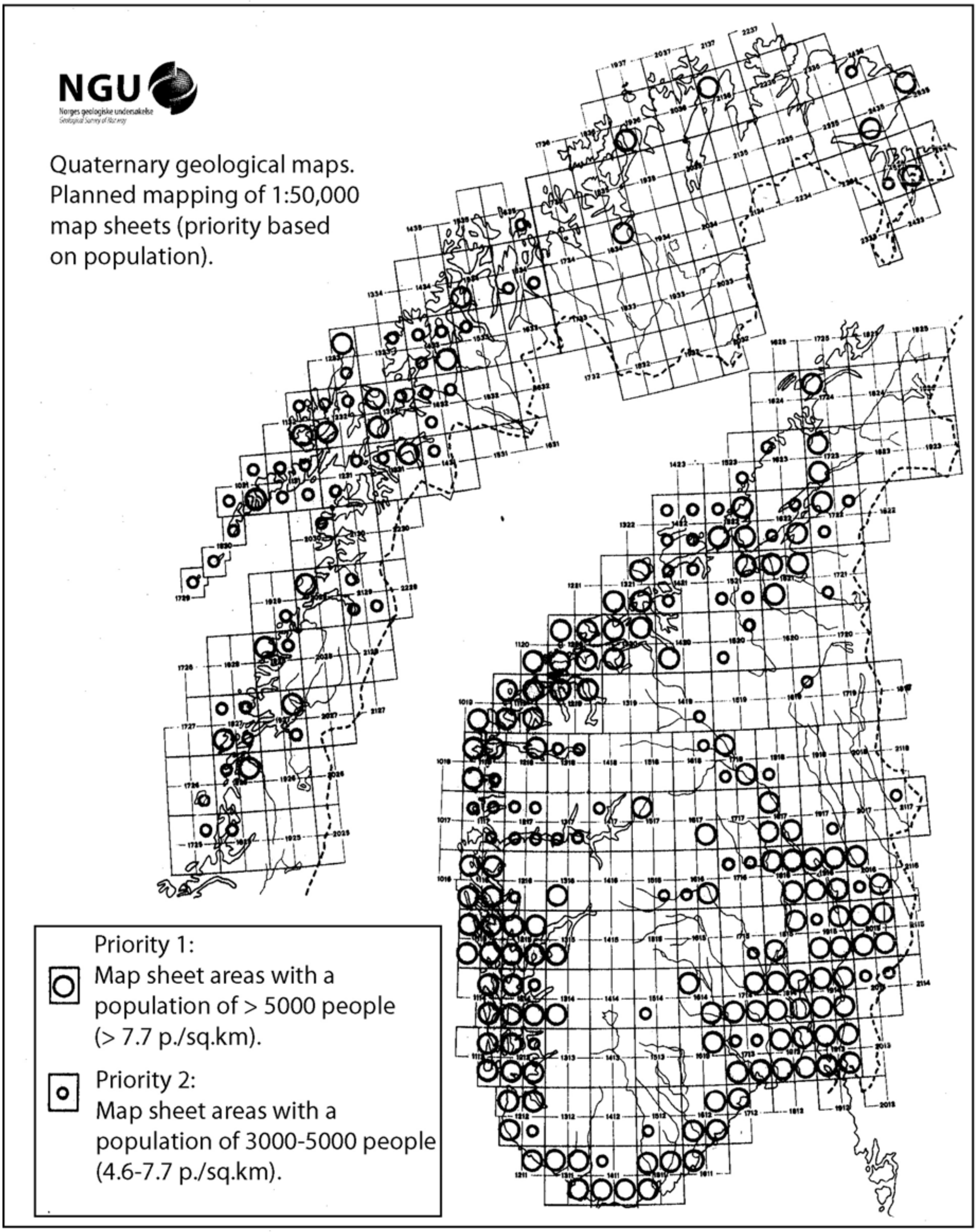


Fig. 2.5
The planned coverage of Quaternary geological maps at 1:50,000 according to the Quaternary geological test project (Reite 1981). Cf. the actual situation shown in Fig. 2.4 B.

NGU has now finished most of the planned Quaternary geological mapping at 1:50,000 in Norway, and the development of the databases for this data is proceeding. However, no maps in these scales exist in the upper parts of the great valleys in southeastern Norway and along the southern and southwestern coasts of Norway (Fig. 2.4 B). Areas where mapping at these scales has had low priority will be mapped at 1:250,000 by 2004 as recommended in the revised mapping plan of Norway (NOU 1983:46). The sand- and gravel deposits are mapped and classified in the Sand- and Gravel Database (Stokke 1986, Neeb 1987, 2000, http://grusogpukk.ngu.no/).

2.3.4 Economic considerations

It has been pointed out, in several evaluations, that funding of Quaternary geological mapping is thought to be a good investment in regions of high human activity. This is based on the fact that the information on a map is valuable over an extended period of time (e.g., Jansen 1984). The two Governmental reports discussed above (NOU 1974:10 and NOU 1983:46) concluded that the benefit was considerable to all the users (see Ch. 2.7.2).

Similar discussions about Quaternary geological mapping have also taken place in other regions, e.g. in the USA. In a project description in *The National Geologic Map Database of the United States Geological Survey* it is stated: "Geologic maps, derivative maps, and related information serve a vital role in supporting public and private decision-making, general education, and advances in scientific research" (USGS 1995). Even stronger formulations are found in the preceding *National Geologic Mapping Act of 1992* manifested in Public Law 102-285, which says, amongst many other statements (http://ncgmp.usgs.gov/info/ngmact.html):

> "(2) geologic maps are the primary data base for virtually all applied and basic earth-science applications, including--
> (A) exploration for and development of mineral, energy, and water resources;
> (B) screening and characterizing sites for toxic and nuclear waste disposal;
> (C) land use evaluation and planning for environmental protection;
> (D) earthquake hazards reduction;
> (E) predicting volcanic hazards;
> (F) design and construction of infrastructure requirements such as utility lifelines, transportation corridors, and surface-water impoundments;
> (G) reducing losses from landslides and other ground failures;
> (H) mitigating effects of coastal and stream erosion;
> (I) siting of critical facilities; and
> (J) basic earth-science research;..."

Most of these arguments may be used to promote Quaternary geological maps and data.

The direct benefit in monetary savings is, however, difficult to calculate, despite the many positive declarations. This problem may partly be due to the fact that the input and output (benefit) values are difficult to compare, and that, because of that, probably nobody has bothered to try,

As an approximation it could be relevant to start with a real example from a user response (Lie et al. 1987). A consultant evaluated the utility of a good(?) Quaternary geological map as saving 1-8 hours work on small jobs, and up to 1-2 weeks on more complex missions. If the map is useful in, e.g. 10-20 commissions in an urban district over a period of several years, the investment must have been of great value. Arguing with some economists is difficult, however, as they have learnt that an investment has to give a profit within a few years.

The first modern Quaternary geological maps were produced more than thirty years ago, and they have about the same quality as the maps produced today. Even though claims for additional parameters are accelerating, the genetic information and the general properties of the deposits have always been the basis for more detailed studies. With this in mind, it is a plausible conclusions that the maps at either scale (1:10,000-1:50,000) are valuable over an extended period of time; say 30-40 years as they give important information on, e.g. non-renewable resources.

2.4 Classification of the surficial deposits

As mentioned in the previous sections, a genetic classification of the deposits is most often used on maps in Fennoscandia. The main argument for doing so is the close relationship between the genesis and the general properties of the deposits (e.g., Bargel et al. 1981).

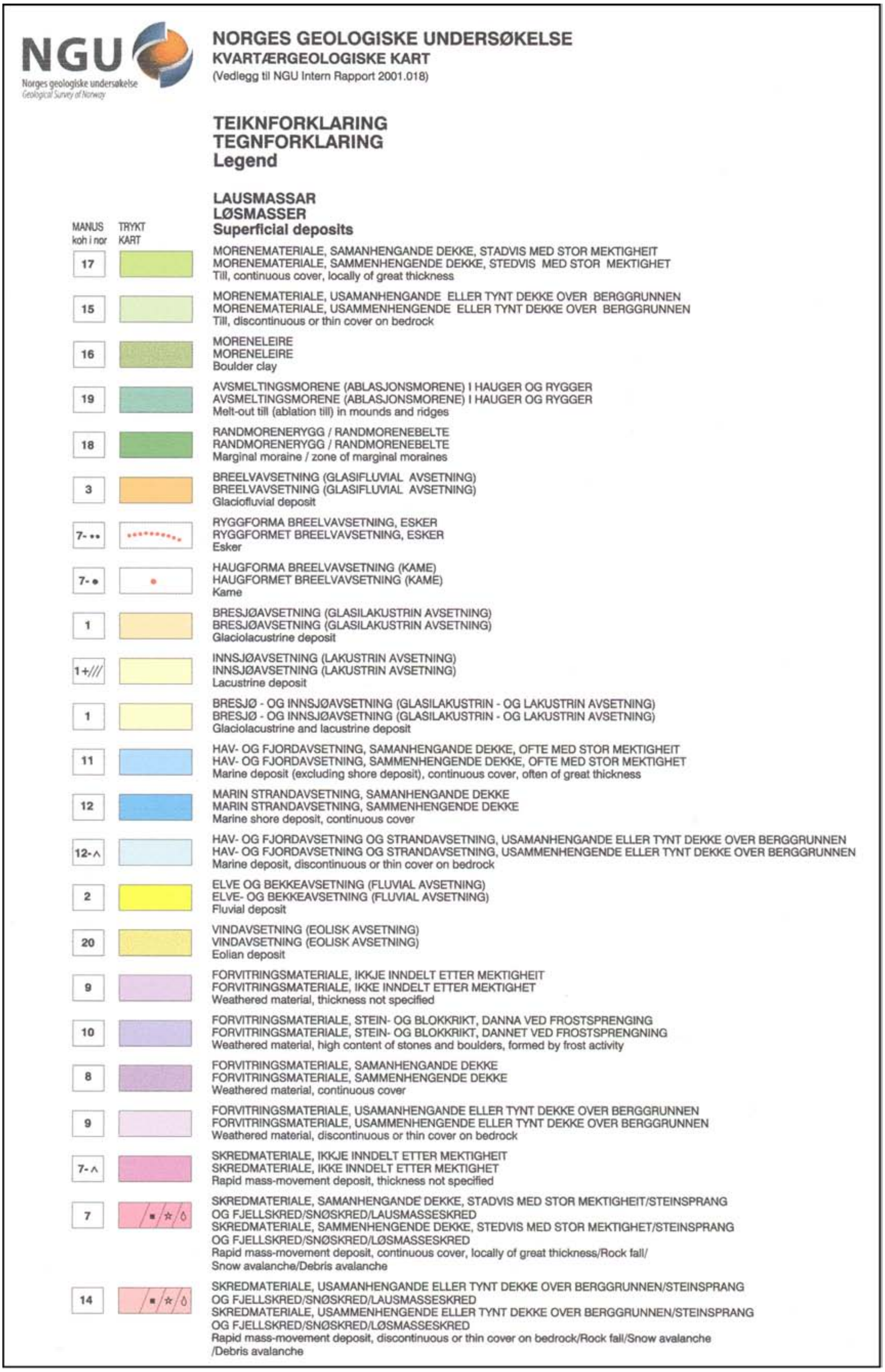
The physical, chemical and technical properties of the deposits are the combined result of the source rocks (provenance), the transport agencies and the transport distance (dispersal), the depositional environments and post-depositional alteration (lithification and diagenesis). On the Norwegian Quaternary geological maps the deposits are classified with the main focus on the transport agencies and depositional environments into: Till, glaciofluvial-, glaciolacustrine-, fluvial-, marine-, eolian-, weathering-, mass-movement deposits and bogs. Details on these parameters and the definitions used are mostly in accordance with the generally accepted criteria discussed in most textbooks in sedimentology, e.g. Reading

(1996), Leeder (1999) and Boggs (2001), and will be summarized below with special emphasis on the Nordland map. Several maps at larger scales have a more detailed classification of the deposits, but the main units are unchanged (Fig. 2.6). The complete legend used (in Norwegian and English) is available at NGU (Bergstrøm et al. 2001a).

Till. On the maps, the till is divided into *till* (*basal till*), *ablation till* and *unspecified till* in ice-marginal moraines. *Basal till* is transported and deposited beneath glaciers and has been subject to tremendous crushing and abrasion that has led to the content of all grain sizes from clay to boulders in varying proportions. The variation in grain sizes is determined by the provenance and the strength relationship between the crushing and abrasion processes and the transport distance (Låg 1948, Jørgensen 1977, Haldorsen 1981). The transport distance of Norwegian basal tills is generally short, most often less than 5 km (Haldorsen 1983).

During the comminution process the mineral grains tend to accumulate in the same sizes as those of the source rocks, which is a phenomenon called *Terminal Grades* by Dreimanis & Vagners (1969), and later used by other authors (e.g., Haldorsen 1977, Olsen 1979). The mineral content and the grain crystal size in the source rocks are therefore the determining factors for the variation of grain sizes in the tills. For example, a fine-grained, hard rock such as gabbro will tend to produce a till with a high content of sand and gravel, very little clay and great physical strength. These properties are desirable in gravels used as aggregates in concrete and in road construction (e.g., Neeb 1992). On the other hand, fine-grained, soft rocks such as, e.g. many types of shale, will produce tills with a high clay content, little gravel and with low physical strength. Such tills will, however, give good soils for farming and forestry due to their more ready decomposition.

The lowermost part of the basal till, called *lodgement till* by, e.g. Boulton (1976) and Dreimanis (1976), is often strongly consolidated due to ice-pressure, which is a result of the combined effects of the weight and motion of the ice. The consolidation of sediments beneath tills has been used to evaluate the thickness of the ice that was responsible for the consolidation (Rokoengen et al. 1979, Larsen et al. 1995), but as demonstrated by, e.g. Sættem et al. (1996), the process is dependent on several other factors in addition to the ice thickness. At many localities situated in positions sheltered from the ice erosion, a strongly consolidated dark grey till, rich in clay, is observed beneath a sandy till (e.g., Reite 1994c).



NGU
Norges geologiske undersøkelse
Geological Survey of Norway

NORGES GEOLOGISKE UNDERSØKELSE
KVARTÆRGEOLOGISKE KART
(Vedlegg til NGU Intern Rapport 2001.018)

TEIKNFORKLARING
TEGNFORKLARING
Legend

LAUSMASSAR
LØSMASSER
Superficial deposits

MANUS koh i nor	TRYKT KART	
17		MORENEMATERIALE, SAMANHENGANDE DEKKE, STADVIS MED STOR MEKTIGHEIT MORENEMATERIALE, SAMMENHENGENDE DEKKE, STEDVIS MED STOR MEKTIGHET Till, continuous cover, locally of great thickness
15		MORENEMATERIALE, USAMANHENGANDE ELLER TYNT DEKKE OVER BERGGRUNNEN MORENEMATERIALE, USAMMENHENGENDE ELLER TYNT DEKKE OVER BERGGRUNNEN Till, discontinuous or thin cover on bedrock
16		MORENELEIRE MORENELEIRE Boulder clay
19		AVSMELTINGSMORENE (ABLASJONSMORENE) I HAUGER OG RYGGER AVSMELTINGSMORENE (ABLASJONSMORENE) I HAUGER OG RYGGER Melt-out till (ablation till) in mounds and ridges
18		RANDMORENERYGG / RANDMORENEBELTE RANDMORENERYGG / RANDMORENEBELTE Marginal moraine / zone of marginal moraines
3		BREELVAVSETNING (GLASIFLUVIAL AVSETNING) BREELVAVSETNING (GLASIFLUVIAL AVSETNING) Glaciofluvial deposit
7- ••		RYGGFORMA BREELVAVSETNING, ESKER RYGGFORMET BREELVAVSETNING, ESKER Esker
7- •		HAUGFORMA BREELVAVSETNING (KAME) HAUGFORMET BREELVAVSETNING (KAME) Kame
1		BRESJØAVSETNING (GLASILAKUSTRIN AVSETNING) BRESJØAVSETNING (GLASILAKUSTRIN AVSETNING) Glaciolacustrine deposit
1+///		INNSJØAVSETNING (LAKUSTRIN AVSETNING) INNSJØAVSETNING (LAKUSTRIN AVSETNING) Lacustrine deposit
1		BRESJØ - OG INNSJØAVSETNING (GLASILAKUSTRIN - OG LAKUSTRIN AVSETNING) BRESJØ - OG INNSJØAVSETNING (GLASILAKUSTRIN - OG LAKUSTRIN AVSETNING) Glaciolacustrine and lacustrine deposit
11		HAV- OG FJORDAVSETNING, SAMANHENGANDE DEKKE, OFTE MED STOR MEKTIGHEIT HAV- OG FJORDAVSETNING, SAMMENHENGENDE DEKKE, OFTE MED STOR MEKTIGHET Marine deposit (excluding shore deposit), continuous cover, often of great thickness
12		MARIN STRANDAVSETNING, SAMANHENGANDE DEKKE MARIN STRANDAVSETNING, SAMMENHENGENDE DEKKE Marine shore deposit, continuous cover
12-∧		HAV- OG FJORDAVSETNING OG STRANDAVSETNING, USAMANHENGANDE ELLER TYNT DEKKE OVER BERGGRUNNEN HAV- OG FJORDAVSETNING OG STRANDAVSETNING, USAMMENHENGENDE ELLER TYNT DEKKE OVER BERGGRUNNEN Marine deposit, discontinuous or thin cover on bedrock
2		ELVE OG BEKKEAVSETNING (FLUVIAL AVSETNING) ELVE- OG BEKKEAVSETNING (FLUVIAL AVSETNING) Fluvial deposit
20		VINDAVSETNING (EOLISK AVSETNING) VINDAVSETNING (EOLISK AVSETNING) Eolian deposit
9		FORVITRINGSMATERIALE, IKKJE INNDELT ETTER MEKTIGHEIT FORVITRINGSMATERIALE, IKKE INNDELT ETTER MEKTIGHET Weathered material, thickness not specified
10		FORVITRINGSMATERIALE, STEIN- OG BLOKKRIKT, DANNA VED FROSTSPRENGING FORVITRINGSMATERIALE, STEIN- OG BLOKKRIKT, DANNET VED FROSTSPRENGNING Weathered material, high content of stones and boulders, formed by frost activity
8		FORVITRINGSMATERIALE, SAMANHENGANDE DEKKE FORVITRINGSMATERIALE, SAMMENHENGENDE DEKKE Weathered material, continuous cover
9		FORVITRINGSMATERIALE, USAMANHENGANDE ELLER TYNT DEKKE OVER BERGGRUNNEN FORVITRINGSMATERIALE, USAMMENHENGENDE ELLER TYNT DEKKE OVER BERGGRUNNEN Weathered material, discontinuous or thin cover on bedrock
7-∧		SKREDMATERIALE, IKKJE INNDELT ETTER MEKTIGHEIT SKREDMATERIALE, IKKE INNDELT ETTER MEKTIGHET Rapid mass-movement deposit, thickness not specified
7		SKREDMATERIALE, SAMANHENGANDE DEKKE, STADVIS MED STOR MEKTIGHEIT/STEINSPRANG OG FJELLSKRED/SNØSKRED/LAUSMASSESKRED SKREDMATERIALE, SAMMENHENGENDE DEKKE, STEDVIS MED STOR MEKTIGHET/STEINSPRANG OG FJELLSKRED/SNØSKRED/LØSMASSESKRED Rapid mass-movement deposit, continuous cover, locally of great thickness/Rock fall/ Snow avalanche/Debris avalanche
14		SKREDMATERIALE, USAMANHENGANDE ELLER TYNT DEKKE OVER BERGGRUNNEN/STEINSPRANG OG FJELLSKRED/SNØSKRED/LAUSMASSESKRED SKREDMATERIALE, USAMMENHENGENDE ELLER TYNT DEKKE OVER BERGGRUNNEN/STEINSPRANG OG FJELLSKRED/SNØSKRED/LØSMASSESKRED Rapid mass-movement deposit, discontinuous or thin cover on bedrock/Rock fall/Snow avalanche /Debris avalanche

Fig. 2.6
Part of the standard legend used on the Quaternary geological maps that are currently being published by NGU. From Bergstrøm et al. (2001a).

The topmost part of the basal till (called *basal melt-out till* by Dreimanis 1976) is most often not as compact as, and contains less fine material than the deeper parts because of washing during the deglaciation or later. Below the highest late- and postglacial marine level, the top layer of the till has almost always been washed by the sea, and in exposed areas the till may be completely converted to shore deposits, and is consequently mapped as such. At higher levels frost heaving has often led to concentration of boulders on the surface.

Morphological elements in the basal till, such as drumlins and various types of hummocky moraines are described in Ch. 5.2.

On the Quaternary geological maps basal till is grouped according to its thickness. *Thick till* is, by definition, more than 0.5-1 m in thickness. Bedrock outcrops may be present, but normally the till hides the bedrock morphology. In many valley sides and in low-relief areas a thickness of 5-10 m may be registered. Occasionally up to 20 m thick basal till is observed. *Thin till* is, by definition, less than 1 m in thickness. The bedrock morphology is mostly visible and exposures of the bedrock are common. Occasionally the till thickness may exceed 1 m, but only in limited areas. In Norway thin tills are important in, e.g. forestry because areas with thick deposits are restricted. The transition between thick and thin till is gradual, and the boundary on the map is most often based on interpretation, not on observations.

In tills the grain shapes are often angular or sub-angular due to intense crushing beneath the ice. The great variation in the textural and structural parameters of the basal till are most often not expressed on the maps, which is a serious deficiency. This is best demonstrated on overview maps at small scales where not even additional symbols (Ch. 2.5.2) are used.

Ablation till is till which has had an englacial or supraglacial transport and is deposited on top of the basal till. During deposition the ablation till is often washed and re-transported by the melt-water, and has therefore been sorted and occasionally stratified as a glaciofluvial deposit. The content of fines is therefore very low in such cases, and sand, gravel and cobbles often dominate. Boulders are often situated on the surface. Huge blocks with a volume of many tens of cubic meters are also often observed. During deposition ablation till may occasionally be influenced by debris flow processes called till-flow (e.g., Boulton 1968, Marcussen 1975), which may produce flow till with the same grain-size distribution as the englacially/supraglacially transported debris, without much washing and removal of the fines. Ablation till in general is most often found concentrated in depressions in the landscape where dynamically dead ice was located during the final deglaciation phases. The surface morphology has often, under such circumstances, small hills and depressions (dead-ice terrain), and the thickness of the ablation till shows great variation. Ablation till without these morphological variations is difficult to distinguish from washed basal tills.

Ice marginal moraines are ridges made by the pushing of a normally expanding ice (push moraines). Depending on their position relative to the ice front, the moraines are called end moraines or lateral moraines. The size of the ridges varies significantly from very small, sometimes only boulder strings in the mountains (Fig. 4.8), via broad zones of lateral moraines along valley sides to huge end moraines a few hundred meters high in the fjords and valleys (Fig. 4.5, Fig. 4.7, Fig. 11.5). The inland ice deposited most of the huge end moraines during the deglaciation. A considerable number of mainly small moraines deposited by present glaciers are found in the mountains.

The moraines are generally composed of till, but moraines that are deposited in a submarine position, and situated today in the fjords and the valleys, may contain a considerable proportion of sorted material and fines, and may sometimes have a glaciofluvial composition. The younger moraines in the mountains are often rich in boulders that are angular due to the high content of frost-cracked material. The boulder material in the older moraines is most often sub-angular and sub-rounded due to grinding activity in the marginal zone of the depositional glaciers.

Glaciofluvial deposits. Glaciofluvial deposits are transported by melt-water from glaciers and are deposited in direct contact with a glacier or close to it. The deposits are characterised by their morphological features and by their sorted appearance. Sand, gravel and pebbles are often the dominating grain-sizes, while fines are missing. The clasts are often rounded. The petrography is often close to that of the surrounding till, which shows that the glacier rivers eroded the till and that the transport distance has been short. Many glaciofluvial deposits are very large both in extent and volume and they are valuable resources as ground water aquifers and for exploitation of sand and gravel.

Glaciofluvial material is the main constituent in ice contact deposits, which are deposited in the sea and found today in valleys (Fig. 8.13, Fig. 11.21). Ice contact *deltas* have been levelled on the top by the sea, while deposits that have not reached sea level may have a ridge-like and rounded appearance (*randås*) (Fig. 4.7). Glaciofluvial outwash that has filled the complete width of a valley above sea level is called a *sandur.* During regression, the rivers eroded terraces in the glaciofluvial deposits at lower levels and created deltas, classified as fluvial deposits further downstream. Sinusoidal ridges such as *eskers* are mostly found in the valleys near the watershed (Fig. 4.13, Fig. 4.17), and are locally associated with *kames,* glaciofluvial material in mounds.

Glaciolacustrine deposits. Glaciolacustrine deposits are sedimented in temporary lakes dammed by a glacier (Fig. 3.2) or in lakes situated close to an ice front. Deposition ended when the ice melted and the lake drained. The sediment is most often characterised by fine sand and silt in subhorizontal beds. Cross-bedded sand and gravel may occur too, and in several localities beaches and strandlines are developed. In Norway glacial lake sediments are mainly found on the eastern and southern sides of the main watershed and in some tributary valleys where melt-water was dammed by the glacier in the main valley during the deglaciation, e.g. on the northern side of Saltfjellet, central Nordland (Ch. 3.3.5).

Fluvial deposits. Fluvial deposits are transported and deposited by rivers and creeks. In Norway, where the relief is high, the fluvial deposits are often very coarse (Fig. 7.4), and in that sense their similarity to glaciofluvial deposits is striking. The missing characteristic morphology of ice-contact deposits and localization relative to modern rivers are, however, helpful criteria for interpretation of their genesis. In the valleys, as mentioned above, rivers have dissected the huge ice-contact glaciofluvial deposits, and eroded material is deposited more distally as fluvial terraces and fluvial deltas at gradually lower levels. The fluvial terraces have mostly the same provenance as the eroded deposits, but the fluvial sediments are more mature. This is accentuated in some broad valleys with meandering rivers. At these locations fine-grained overbank sediments containing modern organic material may also be present. More commonly the fluvial material consists of gravel, stones and even boulders due to the steeply inclined riverbeds and high water discharges. Below the highest Late- and Postglacial sea level, extensive marine clays (see below) are often located beneath several meters of fluvial deposits. In steep valley sides containing till, tributary rivers may erode and deposit alluvial fans on the valley floor/valley side area. These fans may contain well-sorted sediments or diamictons or an admixture of these sediments.

Marine deposits. Marine deposits are fine-grained sediments - silt and clay - sedimented in salt- or brackish water in the sea and in the fjords. Due to isostatic depression from the ice and the delayed rebound, the sea level was higher than today during deglaciation, and marine sediments are now located on dry land (Fig. 4.9). The greatest volumes are, however, still situated below sea level, mainly in the fjords, but also on the continental shelf and on the deep-sea bottom. In the valleys and in the fjords these deposits may occasionally exceed 700 m in thickness, e.g. in Trondheimsfjorden (Oftedahl 1977). A thin bed of shore-washed material is often located on the top of the clay in the valleys, most commonly close to the valley sides and protruding hills. In the valleys thin beds of fluvial deposits often cover the marine clay. The clays are subject to ravination and frequent quick-clay slides.

Glaciomarine deposits are clays that are deposited in the sea, close to a calving ice front, or beneath a floating glacier (e.g., a shelf-ice) (Fig. 11.11). Coarse material, from sand to boulders, which was released from the ice or from icebergs during the melting, is found, unevenly dispersed, in the clay.

Marine shore deposits. Marin shore deposits are washed by sea waves and/or by near-shore currents and are typically located from the highest Late- and Postglacial sea level down to somewhat below the present sea level. Generally the washed material is till, but all sediments that have been, or are available to the waves are possible sources, e.g. the ice-contact deposits are easy washable and, in many cases, have extensive shore deposits. The shore deposits are generally situated on top of other deposits (Fig. 10.4), but may also be located on the bedrock. The wave-washed deposits may occasionally be up to five or six meters in thickness. Shorelines, ridges and bars are often present.

Their grain size varies tremendously, from fine sand to boulders, due to differences in exposure to the waves. The fines are normally removed, while the residue is washed back and forth, and will eventually become very well rounded. Due to variation in the wave activity during the seasons, a bimodal grain size distribution (coarse gravel and fine sand only) is occasionally present. The shore deposits have a high content of carbonate shell remains that are washed in from higher elevations, and at many localities the thickness of these deposits may exceed 10 m, e.g. at the outer part of the Trondheimsfjord area (Ottesen et al. 1995) (Fig. 4.6). Along the coast there are many observations of peat zones beneath the shore deposits. These are remnants of bogs that were submerged and buried during the *Tapes transgression* (e.g., Holtedahl 1953, Fjalstad 1997). Wave-washing of glaciomarine clays containing quantities of coarse sediments will leave the stones and boulders free, on top of the remaining clay, a phenomenon occasionally observed along the coast, e.g. at Ørland (Reite 1990) and in the Narvik area (Bargel et al. 1995a).

Eolian deposits. Eolian deposits are composed of fine sand, predominantly in the size range 0.2-0.5 mm (Selmer-Olsen 1954) that is transported along the surface by strong winds. Even finer particles may occasionally be airborne. The deposit may act as a blanket on top of other deposits, or as dunes oriented transversely to the prevailing wind direction. Active barchans are almost non-existent in Norway (Klemsdal 1969). Eolian deposits are often associated with large glaciofluvial deposits in inland areas where fossil dunes may be present, e.g. on the Gardermoen ice-front delta (Østmo 1976, Longva 1987, Bargel 1997) and in the Elverum area in Østerdalen (Bargel 1982). Active dunes are found at a few inland localities, e.g. in the Røros area (Reite 1997). On the coast eolian deposits are often situated in the vicinity of shore deposits with a high sand-content. Both active and fossil dunes are situated along the coastline, and most of them are small, e.g. in the Ålesund area (Hamborg 1983) and at Andøya (Flakstad et al. 1985). Relatively large fields of this kind are known from the Varanger Peninsula in Finnmark (Olsen et al. 1996c).

Weathered material. Chemical and/or mechanical decomposition of the bedrock produces weathered material. Most often both kinds of weathering act together in Norway, which makes their differentiation sometimes problematic. A simplified classification is presented here, bearing in mind that this is not correct in all cases. The criteria used are based on the grain size of the residue; fine-grained residue (mostly sand) is a result of chemical weathering; coarse material (stones and boulders) is produced by mechanical weathering.

The products of *chemical weathering* in Norway are rich in sand and there is sometimes, in areas with deep-weathering profiles (see below), a gradual transition from the bedrock to loose material. The rock material is locally derived, but chemical alteration has produced new minerals. Sometimes a few cm of the surface of the bedrock is weathered and eroded, but most often only a few mm is removed. Rock surfaces are often accessible to water, and frost action in pores accelerates the weathering process, and the original ice-polished rock surface will become rugged. Near the sea, salt will act as a chemical agent accelerating the weathering. The weathering products are eroded and concentrated by, e.g. rain-wash into the nearest depression where several meters of sediment may be deposited (Fig. 10.2).

Chemical weathering as far north as in Norway is normally a very slow process. However, certain minerals such as, e.g. the feldspars may easily decompose when they are exposed to the action of humic acids and carbon dioxide. For example, in the Hamarøya area the Tysfjord Granite is granulated down to as much as 10-12 m below the surface. Solution has taken place along grain boundaries between Ca-plagioclase grains and the rock has completely lost its cohesion. Nevertheless, as can be seen in sections, the rock structure is still intact (Brattli 1985). In the Hamarøya area unweathered residual boulders can be observed inside deeply weathered sections (Peulvast 1985). Similar kinds of weathering are observed at other localities, e.g. in acid intrusive complexes in the Oslo area (Bastiansen et al. 1957). Heavy weathered areas with deep weathering profiles are situated, e.g. on the Stad Peninsula in Møre (Roaldset et al. 1982) and in Vesterålen (Peulvast 1985).

Mechanical weathering in Norway is mainly due to the freezing of water in pores and cracks in the bedrock. Due to the c. 9 % expansion when water converts from a liquid to a solid phase, the rock is split with tremendous power. This process is most easily recognizable in the mountains where extensive block-fields are located, but this type of mechanical weathering is active wherever freezing happens.

Rapid mass-movement deposits. Rapid mass-movement deposits include material from rock-falls, landslides, earth-flows, debris-flows, mud-flows and snow avalanches. *Falling rocks* that are loosened from the hillsides by mechanical weathering produce talus. *Giant rock-falls* or *landslides* as a single event also produce talus. At the surface, the talus consists of angular boulders and has an open structure. Beneath this top layer the structure is closed by infill of fallen rock fragments. Talus is mostly located at the foot of steep valley sides as fans and aprons, and is very common in all mountainous parts of Norway (Fig. 4.10, Fig. 7.5, Fig. 10.5, Fig. 10.8)

Deposits from *earth-flows, debris-flows, mudflows* and *snow avalanches* may consist of a mixture of weathering material and till, but also bigger rock fragments and organic debris (Fig. 7.6). The material is angular and unsorted and is normally concentrated at the bottom of steep hills or valley sides as fans or aprons. Unusually large fans may be located in front of narrow gorges in the valley sides. When performing detailed mapping the type of mass-movement is indicated on the maps by symbols (Bergstrøm et al. 2001a).

Peat and bog. Peat and bog (organic material) is used to describe all kinds of natural accumulations of plant remnants where the production of new material is faster than the decomposition of the old. The different kinds of bogs are not differentiated. Bogs are very common in most of Norway (Moen 1998).

Exposed bedrock. Areas mapped as exposed bedrock may look quite different in nature due to the great weathering difference of the rocks. Rocks with very little content of nutritient minerals such as, e.g. some granites and ultramafic bodies, are often completely exposed, and no mapping problems exist. On the other hand, some calcareous rocks and shales rich in mica may be vegetated, even though the weathering products are sparse.

2.5 Modern Quaternary geological maps: Scales and content

2.5.1 Mapping and map scales

A mapping project is comparable to any scientific investigation as regards planning the fieldwork. All accessible geological information from the area is reviewed as preparation. A thorough aerial photo interpretation is commonly performed, and a preliminary map is produced. The aerial photo interpretation is normally based on panchromatic vertical images at scales of c. 1:35,000 and c. 1:15,000. These images are standard products from the Norwegian aerial photography companies, which normally produce images for base-map construction. Colour photographs, IR-images, orthophotos and orthophoto maps were tested several years ago, but the results then were not convincing. Because of limitations inherent in the photographs and in their interpretation (e.g., Fromm et al. 1962), supplementary field control is obligatory in most cases. If an overview map is to be produced, the preliminary map is used to decide where detailed fieldwork has to be done, thereby reducing the costs.

Before 1994, all map production at NGU was manual. For practical reasons it was decided not to reproduce areas smaller than c. 1 mm^2 on the printed map, mainly because of the difficulty in recognising some colours within smaller areas without magnification. An area of 1 mm^2 on a map at a scale of 1:50,000 corresponds to an area of 2,500 m^2 in the field. Comparable figures on other scales are presented in Table 2.1. The geologist uses a 0.2 mm black ink pen for drawing on maps and aerial photographs in the field. The second row in Table 2.1 shows what this line means in the field.

Table 2.1
The table show the size in the field of an area of 1 mm^2 and the width of a 0.2 mm pen line on maps in the most used scales (1 mm^2 is the lower practical reproduction area on maps produced using manual methods).

Scale	**1:5,000**	**1:10,000**	**1:20,000**	**1:50,000**	**1:100,000**	**1:250,000**	**1:1,000,000**
A 1mm^2 square on the map	25 m^2	100 m^2	400 m^2	2,500 m^2	10,000 m^2	62,500 m^2	1,000,000 m^2
A 0.2 mm pen line on the map is in the field	1 m	2 m	4 m	10 m	20 m	50 m	200 m

Before the days of unscrambled GPS-signals, one of the most obvious sources of error in mapping was the transformation of data from field observation to the aerial photograph and finally to the map, all of them at different scales and varying projection, especially considering that the work were done manually! The errors could be up to many hundred metres during small-scale mapping in areas with low relief.

All thematic mapping before the days of unscrambled GPS signals, was dependent on base maps to localise the information geographically. In Norway, the base maps are produced by the Norwegian mapping authority (Statens kartverk), and the printed versions are at scales of 1:50,000 and 1:250,000 with contour intervals of 20 m and 100 m, respectively. Detailed topographical maps are produced at 1:5,000 with a contour interval of 5 m (Økonomisk kartverk). Maps at 1:10,000 and 1:20,000 are compiled by photographic reduction of four or sixteen 1:5,000 maps, respectively. The maps at 1:20,000 give a good combination of a detailed base map and a regional overview. All these base maps have been used in the production of Quaternary geological maps (Fig. 2.7). Digital base maps have been available for more than ten years, and in present-day mapping, the scale can easily be changed digitally and one can also produce derived maps for specific purposes. However, one problem the user has to face, is that the original data is always qualitatively associated with a particular maximum map-scale. Computer scaling and production of adjusted maps at larger scales therefore implies a reduction in the quality of the data, relative to the scale and assumed purpose of the maps.

Maps at 1:5,000 are only used when small areas are to be mapped, mainly as documentation and limitation of exploitable resources and as a planning tool for construction work. The mapping is costly due to the need for much fieldwork, geophysics, drilling, excavations and analyses in order to achieve the necessary information on the sedimentology and stratigraphy, ground water level and bedrock morphology of the area. Very few maps sheets have been produced at this scale, but this kind of inventory work has been performed in several smaller areas.

Maps at 1:10,000 were produced as a part of *the Quaternary geological test project* (Kvartærgeologisk forprosjekt, Reite 1981, Bergstrøm 1981) and the Kongsvinger project (Bargel 1983, 1984a, b, c). The maps include an area of 30 km^2 each, four times the area of a 1:5,000 map, but the costs are generally lower because the detailed investigations are not normally so extensive throughout the map sheet area.

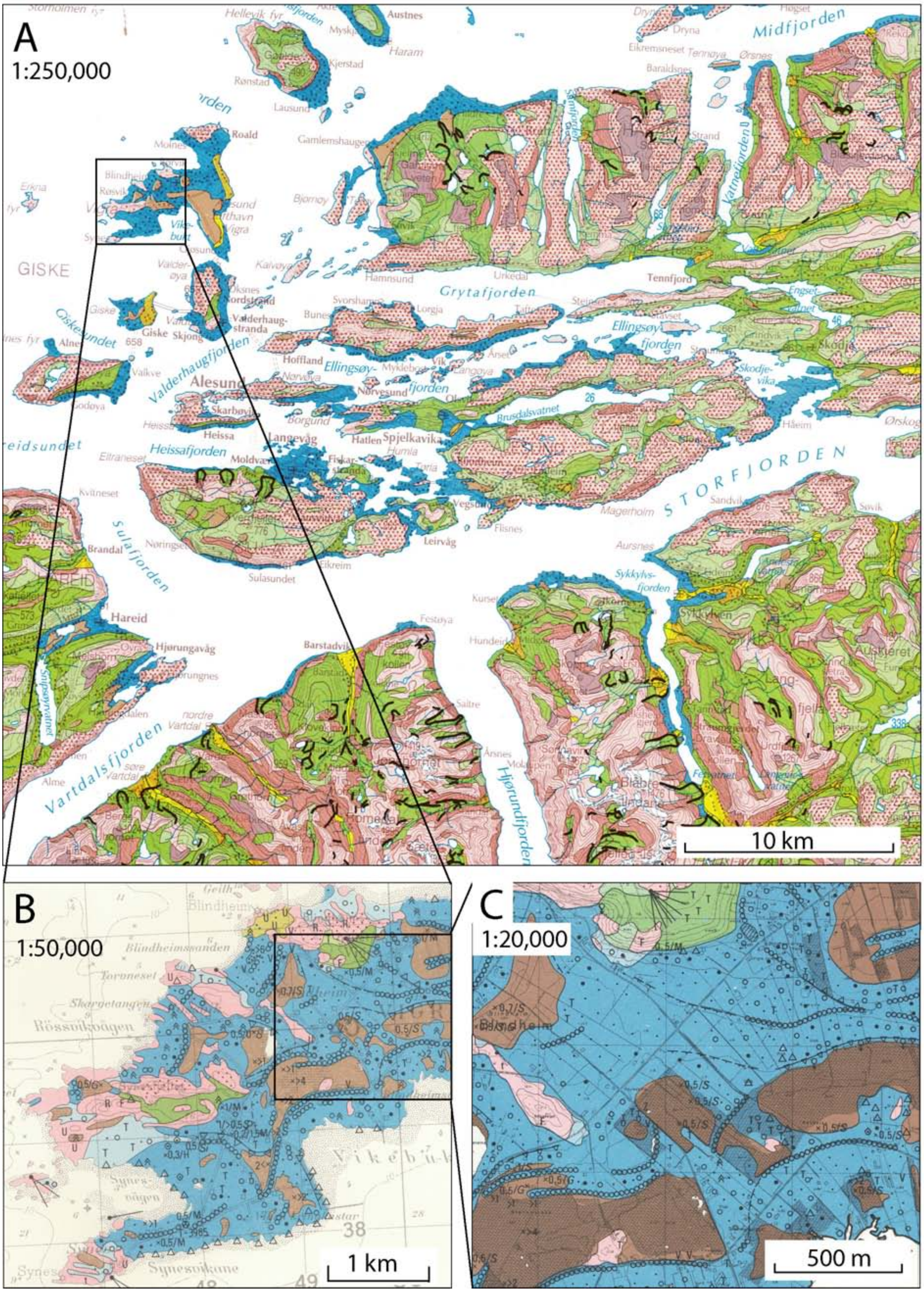


Fig. 2.7
Illustrations of Quaternary geological maps published by NGU at the most used scales. **A**: 1:250,000 (Follestad 1995a), **B**: 1:50,000 (Hamborg 1983) and **C**: 1:20,000 (Hamborg & Lien 1984). The areas shown are from the Ålesund district, the south-westernmost part of the Central Fennoscandian area.

Maps at 1:20,000 are considered as the optimal map scale as far as regional coverage and details are concerned, mainly because of the good-quality base map. The mapping is costly as the time spent is, on average, 175 days/map sheet of 120 km^2. NGU has produced 80 sheets (70 are printed in colour, 10 in black and white) at 1:20,000 during the years 1976-1993. Priority has been given to areas where conflicting land use might emerge, mainly in the Oslofjord and Trondheimsfjord areas (Fig. 2.4 A). Evaluations of the usefulness and economics of these maps have been performed (e.g., NOU 1974:10, Bergstrøm 1980, Bargel 1985).

Maps at 1:50,000 are the main map series at NGU as they are thought to give the optimal relationship between the resource used and the area covered. The mapped areas are c. 600 km^2 each, and the time spent is c. 210 days field work on average on each map sheet. More than 140 maps have been produced (Fig. 2.4). The mapped areas are geographically large, which gives good opportunities for a regional understanding of the Quaternary geological history of the area. The maps show, in addition to the distribution and genesis of the deposits, the grain-size distribution, morphology, active erosion and slides, stratigraphy and direction of ice movements. Representative samples of the deposits are collected and analysed, and occasionally drilling and geophysical measurements are performed. Even though the maps contain much information, they are still overview maps.

Municipality maps at scales of 1:50,000-1:250,000 are used as popular presentations for the public, but also as planning maps for the municipalities. A popular description may be attached to the map (Follestad 1994d, Nordgulen et al. 1997, Reite 1997, Bargel 1999, Reite et al. 1999b, Thoresen & Follestad 1999). Combined bedrock and Quaternary deposit maps have also been produced (Thorsnes & Reite 1991, Bargel et al. 1995b).

County maps. Quaternary geological county maps at scales of 1:125,000-1:500,000 are overview maps that show the distribution and genesis of the deposits and the deglaciation history. The preferred scale is 1:250,000, but other scales have been used in some areas for practical and economic reasons (e.g., the size and shape of the county in relation to an acceptable form for the map product). The maps are compiled by aerial photo interpretation and field control along the roads. Published maps at larger scales are, of course, used as control, but their information is reduced to the 1:250,000-level. NGU has produced nine county maps so far (Klakegg et al. 1989, Reite 1990, Riiber & Bergstrøm 1990, Follestad 1995a, Thoresen et al. 1995, Olsen et al. 1996d, Bargel 1997, Bargel 2001, Sveian et al. in prep.). Other institutions have also produced county maps (Sollid 1976, Jansen 1983, Sollid

& Kristiansen 1983, Kristiansen & Sollid 1985, 1988, Sollid & Trollvik 1991). The production of such maps will be completed for all counties during 2004. The Nordland map (Bargel 2001) is one of the basic elements in this thesis, see Enclosure 4.

National map. As a part of the National Atlas of Norway, a Quaternary geological map was produced at a scale of 1:1,000,000, accompanied by a simplified description (Thoresen 1991). The map was compiled using aerial photo interpretation and short field trips, as well as use of pre-existing map material. The map presents an overview of the distribution and genesis of the most important deposits.

Maps of Quaternary Geology in Northern and Central Fennoscandia. Five maps from Northern Fennoscandia (Hirvas et al. 1988) and four maps from Central Fennoscandia (Bargel et al. 1999a, b, c) have been produced at scales of 1:1,000,000 and 1:2,000,000. The maps show the deposits, the geomorphology and the palaeohydrography, the ice movements and the stratigraphy. The maps are simplified overviews and are based on existing maps supplemented with interpretation of aerial photographs and some additional fieldwork. The deposits maps are identical with other maps of this kind except that the thin deposits are combined with exposed bedrock. The maps of Central Fennoscandia are a basic part of this thesis (Enclosures 1-3).

Maps of the continental shelf. The very few regional maps from the Norwegian shelf, are at scales of 1:250,000-1:1,000,000 (Bugge & Wøien 1984, Gunleiksrud & Rokoengen 1980, Rokoengen et al. 1980, Rise et al. 1984, 1988). The maps were produced on the basis of shallow seismic profiling, supplemented with bottom sampling, and the main content is sea bottom sediment and sediment thicknesses. Mapping of the sea floor provides information about, or relevant to marine deposits and resources including bioresources, alternative routes for cables and oil- and gas pipelines and localisation of installations for petroleum production.

2.5.2 Colours and symbols

A geological map may be very complicated and difficult to read. For that reason, colours have been used to represent the different geological units on most of the maps produced by NGU from as early as the 1860s. The style of the earlier Quaternary geological maps was almost unchanged until c. 1970. The new strategy was to produce maps at 1:50,000 and new colours and categories of deposit were introduced.

The colours used as a standard on the modern Quaternary geological maps were introduced in the early 1970s and later revised (NGU 1972, NOU 1974:10, Bargel et al. 1981, NGU 1987, Bergstrøm et al. 2001). This standard is used on almost all maps produced by NGU, at all scales (Fig. 2.6). Other mapping institutions in Norway use the same standard. The colours chosen are meant to give the reader certain associations, and then be a parameter that is easier to remember.

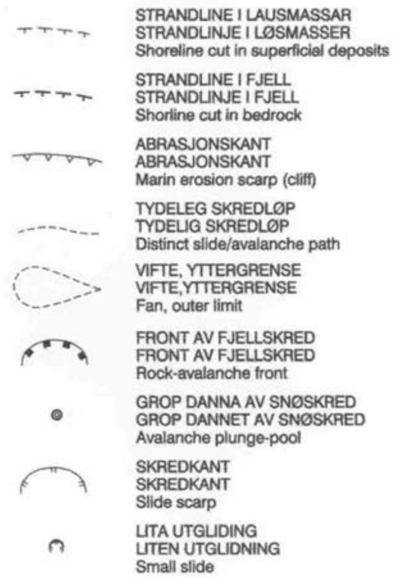


Fig. 2.8
A few of the standard symbols used on the modern Quaternary geological maps produced by NGU. About 100 symbols that are printed in black and red colours are used. From Bergstrøm et al. (2001).

The colour chosen to represent till is green, as the dominant deposit-type in Norway by area is till, and most of the plant material is found on till. Marine deposits are, of course, blue, while orange and yellow colours are used for glaciofluvial and fluvial deposits, respectively, as the dominant Norwegian rocks often produce sand and gravels with these colours. Several deposits, e.g. till and marine deposits, are differentiated into thick and thin deposits with the use of dark and light colour tones. Deposits that have characteristic morphology such as, e.g. end moraine, ablation till and esker have their own colour tone. Exposed bedrock should have had a grey colour according to the association principle, and a few maps were printed in that way. These maps were visually unbalanced, and a light red colour is used today. Bogs are printed with a brown colour.

In addition to the colours, several letters and symbols are used on maps at scales of 1:50,000 and larger, occasionally on maps at smaller scales, for additional information on the deposits. Letters are used for small or scattered occurrences of essential deposits. Symbols are used to express grain size, morphological features on the surface, stratigraphy and other elements (Fig. 2.8). Detailed information on the colours and symbols is available from NGU (Bergstrøm et al. 2001).

Maps of Quaternary Deposits in Northern and Central Fennoscandia. The use of colour in these two maps is different from the Norwegian standard. The reason is that these maps were produced in cooperation with the Geological Surveys in Finland and Sweden, and the three institutions use different colours on their national maps. The compromise shown (Fig. 4.1, Enclosure 1) is based on elements from map standards from all the three Surveys, as decided during the Northern Fennoscandia project (Hirvas et al. 1988).

2.6 Quaternary geological mapping in Finland, Sweden and Denmark

The geological surveys in many countries perform Quaternary geological mapping in a way comparable to NGU. The regional maps show the topmost meter of the deposits. Application of the genetic principle in classifying the deposits is basic in all countries. Coloured areas on the maps give the genetic information. Additional information such as grain size, block content, morphological details, etc. are widely given by use of symbols. Most of the maps are digitised. Detailed information on the maps and the map content is available on the respective web sites:

(Finland)	http://www.gtk.fi/quater.htm
(Denmark)	http://www.geus.dk/
(Sweden)	http://www.lm.se/kartplan/sgu/index.htm
(Norway)	http://www.ngu.no/

The method for performing the fieldwork is somewhat different, especially if Norway and Denmark are compared. The Norwegian way is to use geological deglaciation models to analyse the areas and then to use the observed grain size, morphology and detailed location of the deposits in relation to the topographical units. The genetic classification and regional limitations are therefore performed partly by interpretation. In contrast, the Danish method is to study samples in the field every 100-200 m and plot the observations on the map. The interpretation and regional limitations are drawn on that basis. In Finland and Sweden a combination of these methods is used, dependent on the nature of the areas to be mapped.

The intended map scales are of course important factors, which decide the smallest details to be visualized and the intensity of the fieldwork. Maps at scales from c. 1:20,000-1:300,000 are being, or have been produced by the surveys in all the countries. Country maps at scales from 1:400,000-1:1,000,000 have also been produced.

The arguments for spending money to produce Quaternary geological maps and associated databases are similar in all countries. The maps are applied to land use planning, construction activity, the search for surficial resources, agricultural and forestry purposes, to groundwater studies and planning of environmental aspects. For that reason, the most detailed mapping is carried out in populated areas in all the countries. In Denmark, c. 80 % of the total area is mapped at 1:25,000, while in Norway maps at 1:20,000 cover c. 3 % of the total area (Fig. 2.4 A). The previously mentioned web sites may be visited for references and further details.

To get a real impression of the task and the need for information, we have to remember the differences in the Quaternary geological history, topography and coverage of deposits and use of the areas in the four countries. In Norway, about 6 % of the land area is covered with thick deposits (> 1 m), while in Denmark Quaternary deposits or soft rocks cover almost the entire mainland.

2.7 Discussion and conclusions

During more than 150 years of Quaternary geological mapping in Norway the main arguments for this work have been:

4. Proper use of land areas, initially for agricultural purposes, later for more differentiated land-use such as construction, infrastructure etc.
5. Localization of resources for exploitation: groundwater, peat, sand and gravel.
6. A scientific and educational interest in identifying deposits such as, e.g. sub-till sediments and moraines valuable for deglaciation studies.

Before analysing these arguments it is useful to examine how, and which data are achieved by the mapping process. To pinpoint the problems only mapping at 1:50,000 will be discussed, as it has been the most generally used map scale when producing Quaternary maps in Norway.

The map data are, by tradition, acquired by first interpreting the depositional conditions using geological models combined with morphologic observations. As the genetic picture is interpreted in this way, the general properties of the deposits are established; only a few additional parameters are given. Sorted deposits are given a general grain-size distribution of the top layer while tills, moraines, mass-movement deposits and weathering material are not. Deeper strata are more or less neglected, but natural cuttings on riverbanks, ravines, gravel pits and excavations made for construction purposes are of course studied. In some instances drillholes and seismic profiling are accessible, which will give sporadic information on the stratigraphy of the deeper parts of the deposits. If not measured by drilling or geophysical methods, the thickness of the deposits is estimated. Scattered samples may be collected, and most generally only grain-size analyses are performed.

2.7.1 Society's need for information about the surficial deposits

The former need for maps to localise potential areas for *agricultural purposes* is not a prioritised theme in today's Norway as almost all profitable areas are already being exploited and marginal fields and farms are now disused. Farmers of today want chemical data, which influence their fertilizing needs; data on porosity and permeability related to watering or ditching requirements and the problem of erosion, all are summarized in the aim of higher productivity (NOU 1974:10, 1983:46, Reite 1981). These kinds of data are now achieved with the aid of the detailed topographical maps (Økonomisk kartverk), by the soil investigations performed by Norwegian Institute of Land Inventory (NIJOS) and, in greater detail, by municipal agricultural advisers. The existing Quaternary geological maps, whatever their scale, will occasionally be helpful as an introduction to the problems, but for most practical modern agricultural purposes this sort of data is not sufficient.

The regional mapping of the clay deposits in the *Quick Clay Mapping Project* (Leirprosjektet, Bargel 1988) was more successful. During this project NGU mapped the clay deposits and Norwegian Geotechnical Institute (NGI) investigated the clay slide hazard in the Oslofjord and Trøndelag areas.

Localization of resources for exploitation is among the uses of the Quaternary geological maps. Groundwater is mainly found in the fluvial and glaciofluvial deposits in Norway, and where maps are available, a primary localisation of potential resources can be done based on the maps, e.g. in the Fauske area, Nordland (Erichsen 1993-1996). Localisation of peat resources is mainly of historical interest, and an almost complete data set is available from other institutions, e.g. on the detailed topographical maps (Økonomisk kartverk). Sand and gravel occur in remote areas and below the highest marine level, where sand- and gravels may be covered by clays; the maps have been used to localise deposits for road-construction and dam building. In populated areas, however, most of the deposits of interest have been known and exploited for many years before any mapping was performed. Proper use of high-quality gravels has, for the last fifteen years or so, been a specialised thematic mapping activity, namely creation of the Sand- and Gravel database, which is localised at NGU (Neeb 1987, Stokke 1988). When this database was constructed, the Quaternary geological maps were of great value in localising deposits of interest.

Scientific and educational interests are mainly focused on information on deposits to be used for studies on glacier variations and the last deglaciation. For example, regional location of dateable sub-till sediments has given much new information on rapid changes in the inland ice during the Mid- and Late Weichselian (Reite 1994c, Olsen 1997a, Olsen et al. 2001a, b, c). Detailed mapping of moraines in, e.g. the Trøndelag area, has given much new information on the late Weichselian deglaciation of the area (Reite et al. 1982, Sveian 1997).

Realistic views on the usefulness of the maps are necessary when arguing for funding of further mapping. The benefits argued in NOU 1974:10 (Ch. 2.3.1) seem however to be too optimistic in relation to the claims of today. In spite of this, geological mapping is an investment in the future. It is very well documented in all the countries that have performed Quaternary geological mapping, that its usefulness is indisputable. The arguments for continuing the mapping are easy to find as the maps are tools for managing land areas and their resources in an optimal manner.

Modern use of the surficial deposits, e.g. for construction, communication, groundwater, infiltration, disposal of waste water, environmental and health aspects, requires more knowledge of the deposits than before. The need for new parameters, including stratigraphy, makes it necessary to change the way of mapping to satisfy new requirements set by the users of the data.

2.7.2 Who are the users?

Communication with the users is very important as they have varying geological competence and specific needs. A planner in a small municipality may know some geology, if he happens to have, e.g. a higher agricultural education. An architect, a technician, an economist or a lawyer may not. In a planning situation there are many factors that have to be considered, and we have to accept that geology is not important at all in some situations. In any case, the data presented by the geologist has to be used in order to be profitable, but too often this is not so, as demonstrated in several investigations.

Several geologists have tried to explain the maps and to simplify the information, e.g. Bargel et al. (1981), Augedahl & Olsen (1982), Lie et al. (1987), but many users feel that the maps and the descriptions are complicated and not as specific as wanted. The users will probably not make the effort needed to learn geology just to understand these maps. It is therefore the responsibility of the data producers to present the data in a more useable way.

Information activity must not be neglected (Lie et al. 1987); as stated by Rowley et al. (1997): "Thus the geosciences are among the most practical of the sciences, but like all others have been under increasing criticism for not saying so to the layman taxpayer."

In my opinion the criticism is correctly addressed, not because we explain how clever geologists are or how important the geologists' work is, but because we do not communicate properly with the users of our data and knowledge. The scientific manner of presenting several possible conclusions is not necessarily preferable when reporting to a layman. We have to be specific and to find the best solution to the problems, possibly only one solution. If this feels difficult, geologists have to learn more practical geology and how planners work. This is necessary if we want to improve communication, because, as we know, planners do not learn much geology in their training.

2.7.3 Why produce overview maps?

In this chapter focus has been placed on the utility of Quaternary geological maps in varying scales. As inquiries have shown, most users prefer maps at scales of 1:5,000-1:10,000; why then produce maps in smaller scales? To try to find some answers, it could be useful to describe the two principal ways of compiling small-scale maps.

1. In areas where no maps exist, an overview map is normally the best way of acquiring primary information rapid and in an economically acceptable way. This has been done all over the world in relation to all mappable topics from the beginning of mapping activity. The Quaternary geology of Norway is mapped in this way for most of the country, but there are still areas that have not been mapped at proper scales (e.g., 1:250,000 or better). The quality of overview maps is not always satisfactory, but a bad map is better than no map and upgrading is normally done if required.
2. In areas where highly detailed mapping has been performed, a simplified presentation at a small scale is often compiled just to get an overview. Overview maps of the Quaternary geology of several areas of Norway have been compiled in this way, e.g. the county map of Oslo and Akershus (Bargel 1997). The map quality achieved using this method is often very good.

An overview map will give the general trends and show, from a larger area than the detailed maps, where, e.g. resources and areas with various properties are located. It is necessary to have this information in order to manage the resources in a sensible manner on a regional scale. This is one of the arguments used in many countries that have produced a National Atlas.

In science, new ideas on regional trends may emerge when huge data sets are analysed and presented in a simplified form, as lots of detail may camouflage the main trends. The glacialdynamic work of, e.g. Kleman & Borgström (1996) is just one example of this use of data. This fact is the bearing idea in Part III of this thesis.

2.7.4 Conclusions

10. Quaternary geological maps at a scale of 1:50,000 are overview maps, to be used for primary planning and orientation only.
11. Traditional (genetic) overview mapping in Norway should be continued until the proposals in NOU 1974:10 are fulfilled (populated areas with thick deposits at 1:50,000, the remaining areas at 1:250,000).
12. The mapping policy summarized in 2) is the optimum in relation to costs, coverage and quality of the achieved information.
13. The general regional information given on properties of the deposits is not satisfactory for modern usages of the areas covered. Chemical and physical parameters and knowledge of stratigraphy are necessary in order to evaluate the technical properties of the deposits.
14. Quaternary geological maps at scales of 1:5,000-1:20,000 have extended applicability due to their more detailed base maps.
15. New map projects intended for practical purposes should concentrate on combining mapping at greater scales and on solving specific problems in limited areas.
16. All mapping results should be registered on high-quality base maps.
17. All data must be digitised.
18. Geologists should learn to communicate better with their users.

Chapter 3 Earlier investigations in Central Fennoscandia and Nordland

3.1 Introduction

The literature concerning Quaternary geological issues in the Central Fennoscandia is relatively extensive. The area under consideration is extensive too (Fig. 1.1), and for that reason the Finnish and Swedish areas are treated with much less focus on the historical retrospect than the Norwegian areas. Most of the literature concerning the Norwegian part is cited, but the Finnish and Swedish areas are looked upon through the eyes of earlier reviewers. Nevertheless, the reference list, which exceeds 600 publications, shows that activity on Quaternary geological studies has been quite impressive.

About 25 % of the cited publications are of "pre-^{14}C" age. Modern geologists are very much focused on ages, relative and absolute, as a framework for their investigations. Scientific work performed before reliable age determinations of organic matter was at hand, is probably not considered today as much as is deserved. One should not misjudge the oldest literature because of its lack of sophisticated instrumental measurements, detailed stratigraphical logs and intricate theoretical interpretations. The older scientists were experts on the *Art of Observation*, and the missing details were counter-balanced by the ability to think regionally and to create brilliant ideas. Several of the problems geologists are still trying to solve today were formulated more than one hundred years ago. The question of possible ice-free areas during the ice age, which will not be treated here, is one example.

3.2 Sweden and Finland

The Swedish and Finnish Quaternary geological literature is at least as voluminous as the Norwegian, and an in-depth review of this huge amount of papers is far beyond the scope of this thesis. For that reason, several earlier review works have been essential in the writing process, first of all the Geology volume of the National Atlas of Sweden (Fredén 1994), The Atlas of Finland (1990), a comprehensive work on Swedish geology (Lindström et al. 2000) and the descriptions of the Quaternary county maps from central north Sweden (Granlund 1943, Fromm 1965, Lundqvist 1969, 1987). Several review articles have also been used, e.g.

Ignatius et al. (1980), Lundqvist (1974, 1980, 1981, 1983), Hirvas et al. (1981). The description of the Central Fennoscandian area presented as Part II of this thesis is, thanks to co-operation with Finnish and Swedish colleagues in the Mid-Norden Project (see Introduction to Part II), based on the latest investigation results.

A few publications that are concerned with special problems should also be mentioned as they have had a vital influence on the interpretation of some aspects of the deglaciation of Fennoscandia: the east-west balance of the continental ice sheet, varve chronology, the problem of the De Geer moraines and the glacial lakes.

The position of the ice divide along the mountain chain has been thoroughly studied by, e.g. Ljugner (1945, 1949) (Fig. 3.1). During the first glaciation recognised by him, the Prime Glaciation, the ice divide moved away from the mountains towards the east. Then the ice disappeared, leading to the Interval, and new ice growth fed by westerly winds took place, the Posterior Glaciation. According to Ljugner (op. cit.) the wet winds changed to a southeasterly direction, and the ice divide then emerged towards the east, as far east as the Gulf of Bothnia. These surprising conclusions were based on relatively few striae observations, and have been strongly criticized, but later investigations have verified the main lines of Ljugner's theories (e.g., J. Lundqvist 1971, J. Lundqvist 1974). A similar migration of the ice divide towards the southeast took place in southern Norway (e.g., G. Holmsen 1915, P. Holmsen 1951).

In the central part of Sweden the problem of ice recession has preoccupied many scientists. Due to a complete lack of end moraines in the area, as can be seen on the Central Fennoscandian maps (Bargel et al. 1999a, b, c), the problem of ice recession has been solved in another way than in, e.g. Norway. By applying **varve chronology,** the use of annually deposited clay/silt laminae in non-saline water, it has been possible to reconstruct the recession of the ice front in much more detail than has been possible in Norway (e.g., De Geer 1940, Cato 1987, Strömberg 1990, 1994, Wohlfarth et al. 1997) (Fig. 8.4). In Finland too, varve chronology has been used with profit in many areas (e.g., Sauramo 1923, Niemelä 1971). As the glacial varves can be linked to the varves deposited by modern rivers, varve chronology can also be used as an absolute age determination method (e.g., Cato 1985) even though some problems in doing so have been discovered (Wohlfarth & Possnert 2000). There is a divergence of several hundred years in the ages obtained by the varve method and the radiocarbon age determination method.

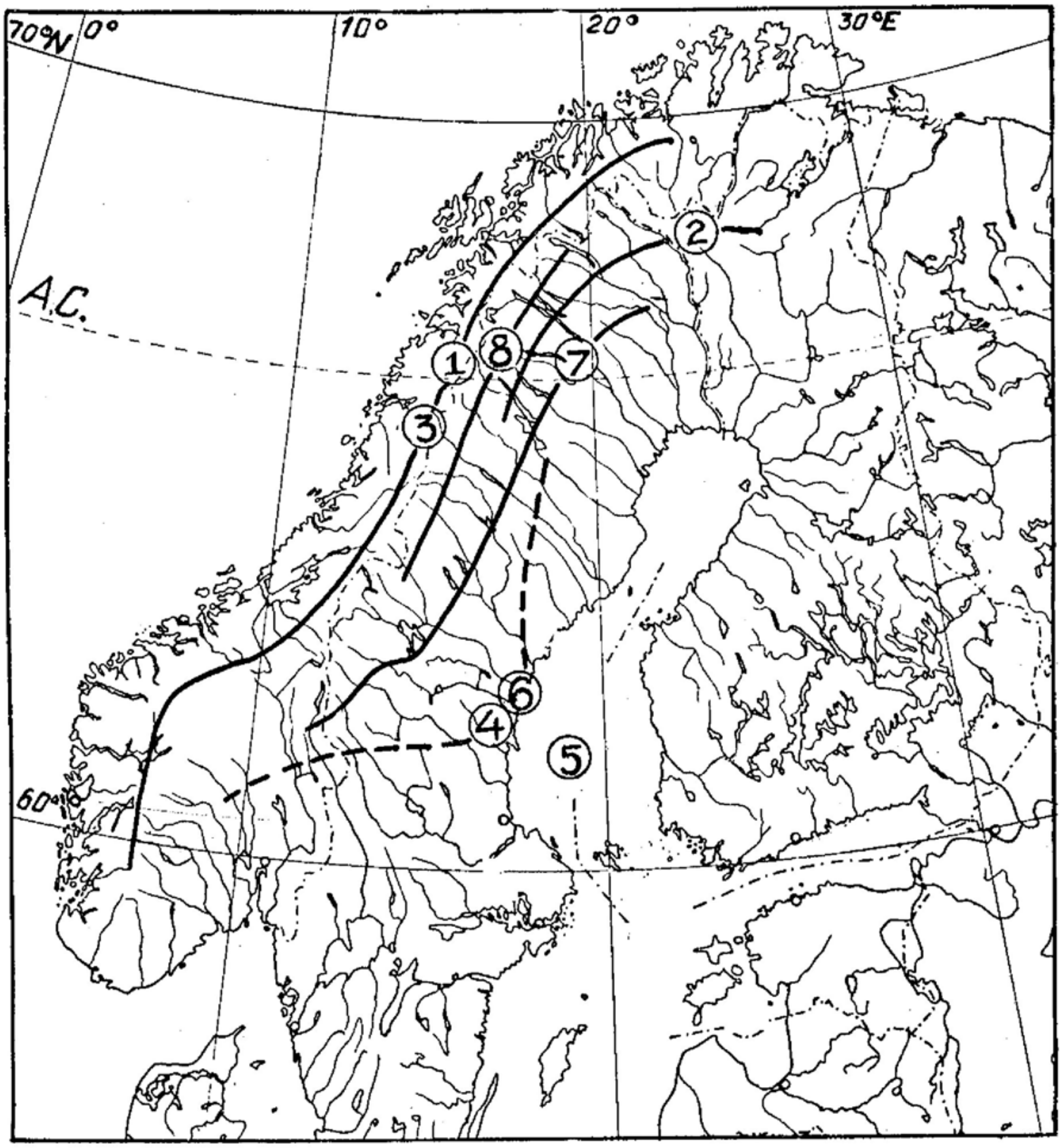


Fig. 3.1
The migration of the ice divide along the Scandinavian mountain range during the last ice age as proposed by Ljugner (1949). The two glaciations of the last ice age were called the Prime Glaciation (ice divide positions 1-2) and the Posterior Glaciation (ice divide positions 3-8), respectively, separated by a period of deglaciation, the Interval.

De Geer moraines, which are mainly found below the highest postglacial coastline, have earlier been regarded as annual moraines, deposited at the ice margin during the winter standstill in the recession (Fig. 5.3, Fig. 5.4, Fig. 10.14). Varve chronology has shown, however, that the annually ice recession in the Gulf of Bothnia was relatively fast, 200-500 m/a. The De Geer moraines are separated by less than 100 m, which shows that more than one moraine was deposited each year (Zilliacus 1987, Aartolahti et al. 1995). When correlated, the De Geer moraines show the direction of ice recession and correlative positions of the ice front. De Geer moraines are described in Ch. 5.5.2.

During the deglaciation, many **glacial lakes** were dammed between the mountain chain and the shrinking ice divide (Fig. 3.2). The nature of the lakes has been much debated (e.g., Holmsen 1915, Lundqvist 1972), but it seems to be true that most of the lakes drained for some time across the lowest pass points along the mountain chain, into the Norwegian Sea. Subhorizontally bedded silt deposits and shorelines prove that water tables have existed. Most of the lakes probably drained slowly beneath the vanishing ice during the last phases of their existence. However, the lake Lower Glåmsjø in Østerdal, southern Norway, drained catastrophically. This event is dated to c. 9.2 ka BP (Longva & Thoresen 1991) and indicates when the last ice remnants disappeared from the area.

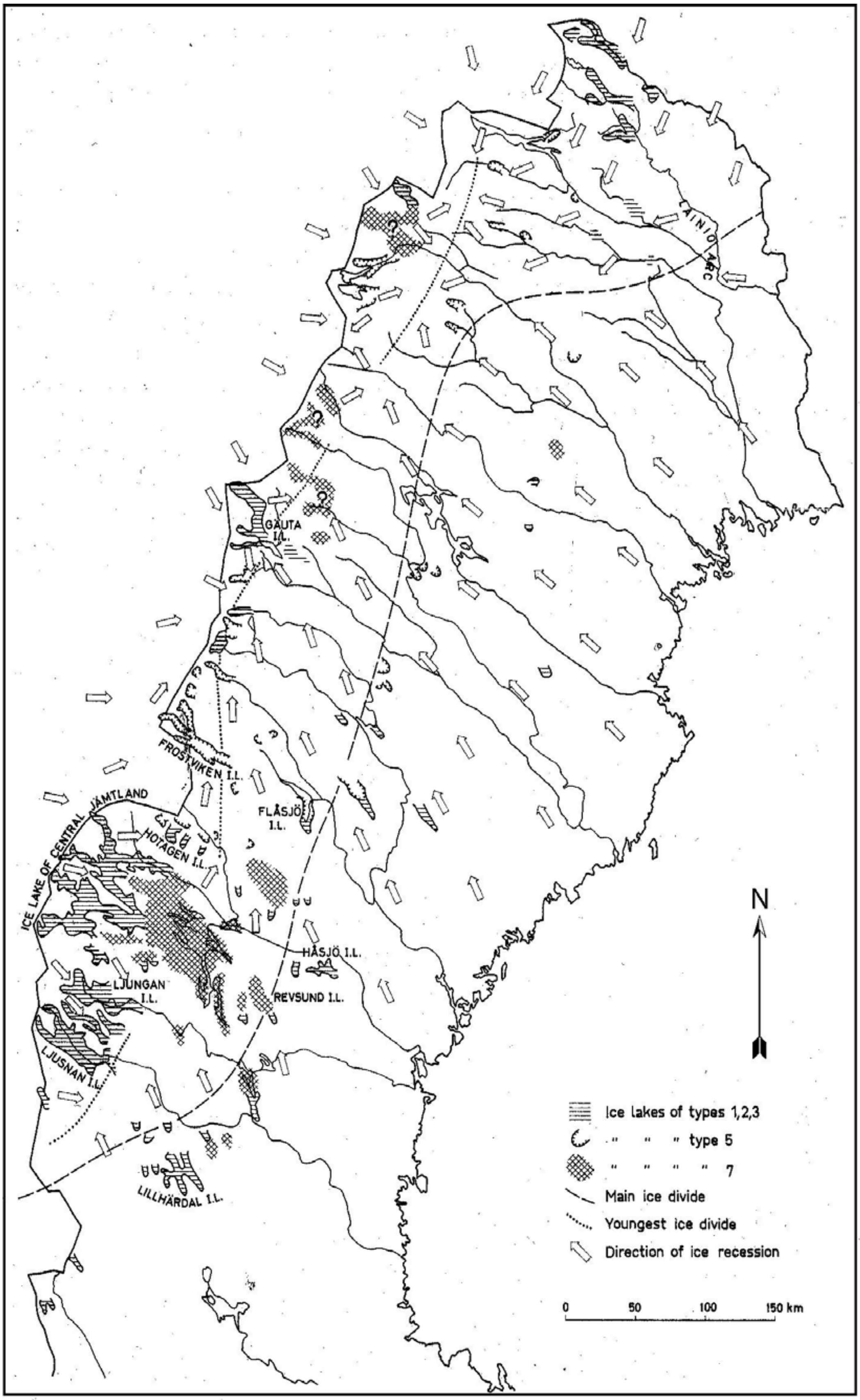


Fig. 3.2
Glacial lakes along the Scandinavian mountain chain during the last epoch of the deglaciation according to Lundqvist (1972).

3.3 Norway

3.3.1 Regional investigations

Investigation of Quaternary geology in Norway has a long tradition; one of the oldest reports is more than 200 years old, written by I.C. Fabricius. In his *Reise nach Norwegen* (Travel to Norway), published in Hamburg in 1779 (cited by Keilhau 1838), he made some remarks on "reduction of the water", which tells us that Fabricius had observed raised shore marks. Keilhau (op. cit.) made several observations on raised shorelines along the coast of southwestern Norway, but only scattered observations were done farther north. He focused on erratics, shorelines and fossil seashells, and recognized that the land upheaval has been greatest in the southeastern and central parts of Norway, which, as we know today, is correct (e.g., R. Sørensen et al. 1987).

The new ideas on an earlier raised sea level were generally accepted, and collection of new data accelerated. Most of the work in Norway in the middle of the 19th century was accomplished in the area around Oslofjord. This was quite natural since the first Norwegian university was situated in Oslo, and so was the Geological Survey of Norway (NGU), which was established in 1858 (Ch. 2.2.1). However, a limited activity was also performed in Northern Norway, and a geological map of this area was printed in colour (Dahll 1879).

At the end of the 19th century geoscientific work was going on in most of the country. One of the pioneers, Hans Reusch (Fig. 2.1), made geomorphological studies concerning the strandflat, fjord and valley formation (Reusch 1894, 1901b). Nansen (1922) made a thorough study of the Norwegian strandflat. Helland (1893) presented a detailed description on the soils in most of Norway. The points of interest in those times were fossil shell localities, raised shorelines, erratics and moraines. Helland (1900) and Hansen (1900) described erratics, moraines, glacial striae and raised shorelines along the Norwegian coast. Rekstad & J.H.L. Vogt (1900), J.H.L. Vogt (1907a) and Rekstad (1922) made maps of isolines of raised shorelines from most of the coast north of Sognefjord (Fig. 3.3). Rekstad (1925a) presented a study of erratics, from the Oslo area along the Norwegian coast as far north as the island of Andøya, far north of the Arctic Circle. The erratics are found on the coast and in some fjords below the Late Glacial marine level. Rekstad (op cit.) concluded that icebergs transported the erratics, and that this transport was older than the Ra-time (Younger Dryas). He tentatively associated the highest marine level with the Ra-time. He also noticed glacier transport by the Baltic glacier (Wennberg 1943) that had deposited chert on Jæren. Later, the geologists came aware of erratics of red sandstone along the coast of Trøndelag and Nordland (e.g., Dahl et al. 1997). As the source rock was traced to the Swedish mountain chain, erratic transport by ice streams across the watershed towards the west coast was indicated.

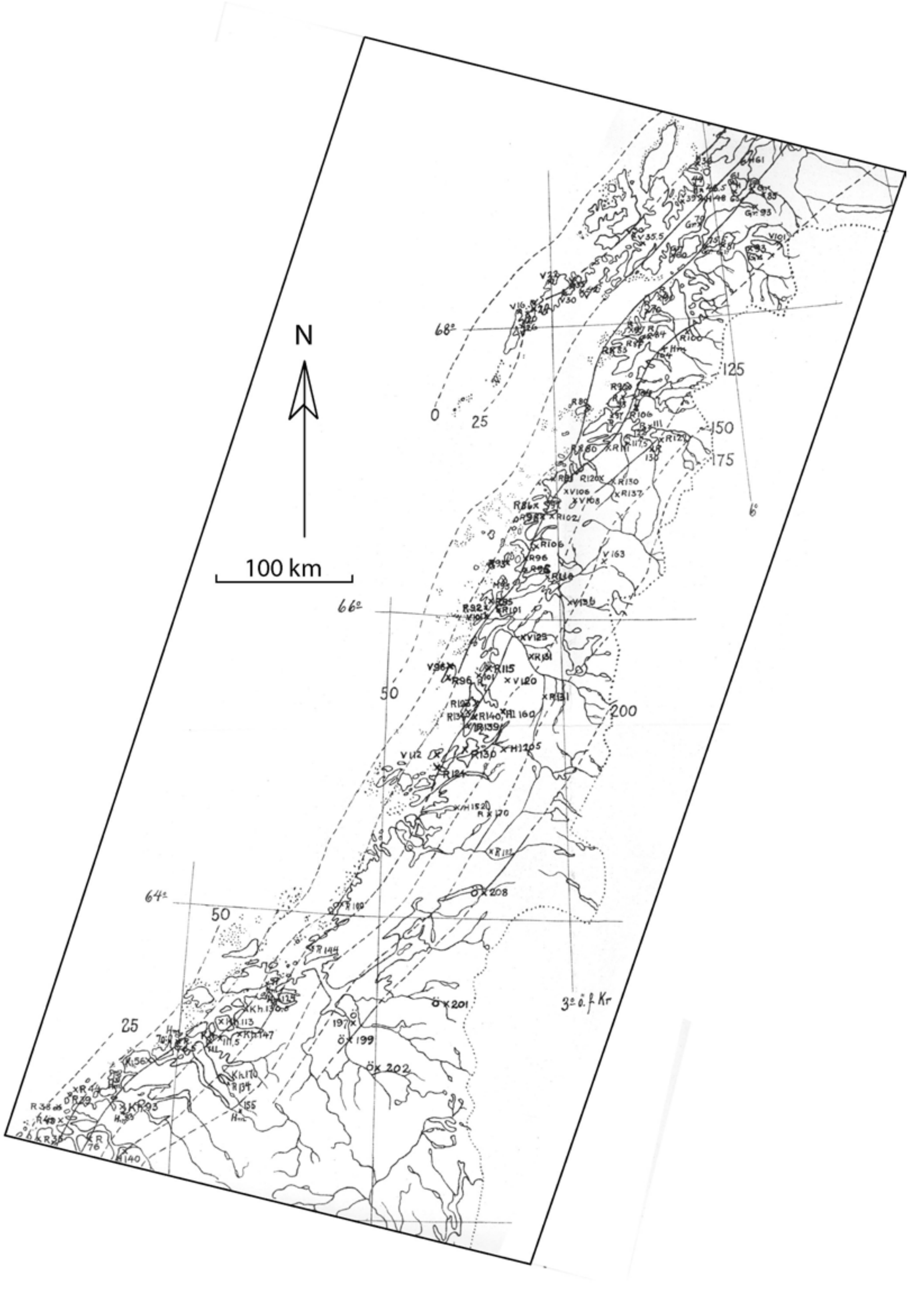


Fig. 3.3
The central part of Norway including the areas covered by the Central Fennoscandian and the Nordland map sheets. This map shows the isolines of the highest raised shorelines in Norway. The measured localities and the isolines in m. above present sea level are shown. The original map covered all of Norway at a scale of 1:1,000,000 (Rekstad 1922), cf. Fig. 3.8.

Several review works published during the last century should also be mentioned as they summarise the current knowledge. Tanner (1915) presented an overview of possible ice flow directions in Northern Fennoscandia (Fig. 3.4) and proposed that the most pronounced moraines in northern Norway were of Ra-age. The works of O. Holtedahl (1953, 1960) are classical, giving a comprehensive presentation of both the bedrock and the glacial geology of Norway. The work of Oftedahl (1980) is less complete on the Quaternary. Andersen (1965a) described the Quaternary of Norway and reviewed Quaternary research in Norway (Andersen 1987), and Mangerud (1991) summarized the last ice age in Scandinavia.

As knowledge developed enormously during recent decades, works concerning shorter time intervals of the Weichselian have been given special attention, e.g. the period 15-10 ka BP (Mangerud et al. 1979), the Early and Middle Weichselian (Mangerud 1981) and the Late- and Postglacial deglaciation (Andersen 1979, 1980, 1981, Andersen et al. 1995). Andersen & Borns (1994) wrote a popularised presentation of the Quaternary, and Andersen (2000) presented a follow-up version in Norwegian with focus on the Norwegian areas. A comprehensive description of the Quaternary geology of Norway was also given by (Jørgensen et al. 1997).

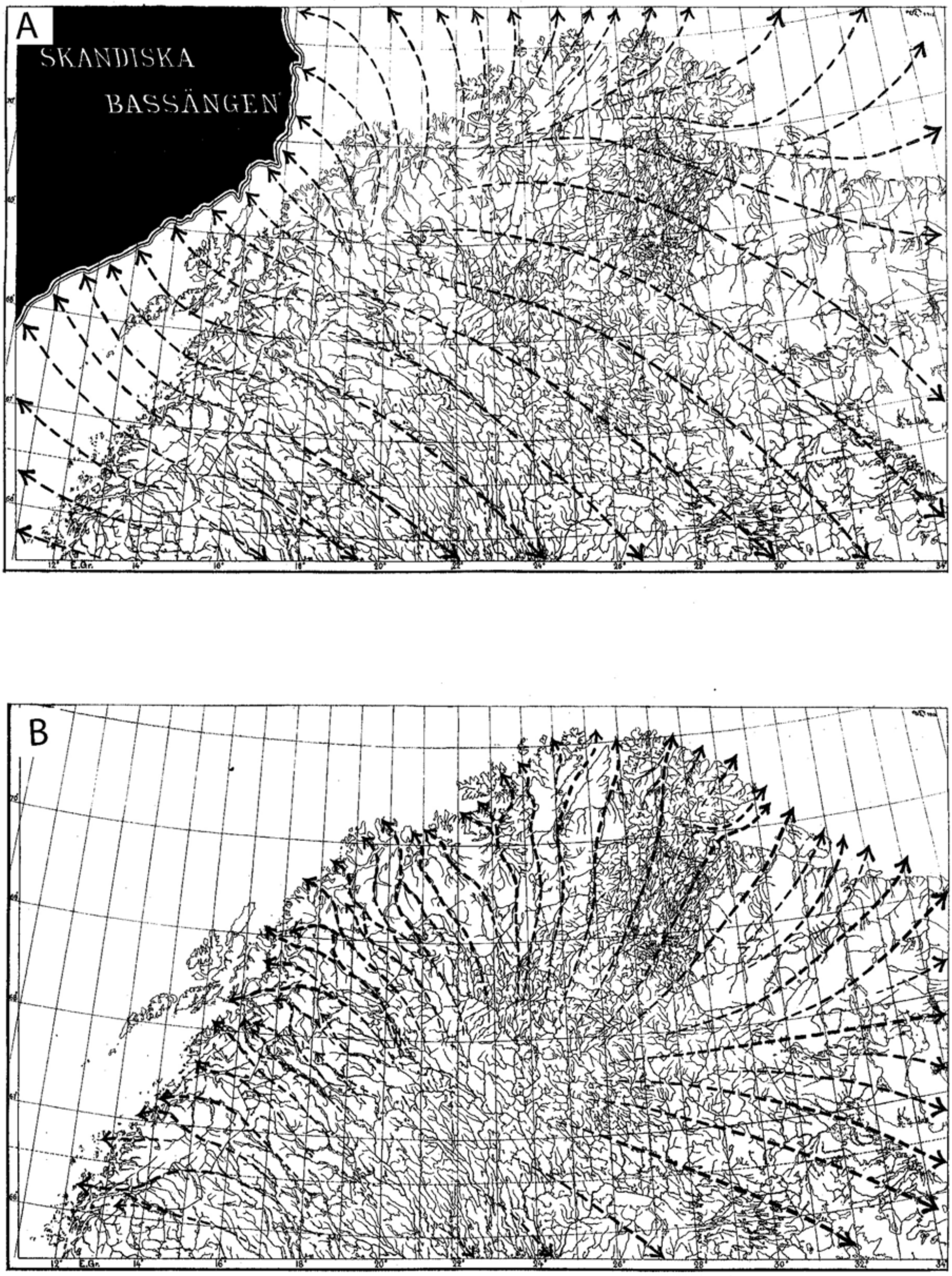


Fig. 3.4
Ice flow directions of the northern Fennoscandian area during **A**: an early phase of the last *glaciation*, and **B**: during an early phase of the last *deglaciation*. Note the proposed positions of the ice divide and that little attention has been given to the topography in **A**. From Tanner (1915).

3.3.2 The Continental Shelf

No complete review of the geological investigations of the Norwegian continental margin will be given here as this was thoroughly treated by H. Holtedahl (1993). He noticed the marked change in knowledge of the Quaternary stratigraphy on the shelf that happened from the mid-1970s, of course accelerated due to the development of the petroleum industry in the area. Based on continuous seismic profiling, the glacial nature of the proposed moraine ridges on the shelf was demonstrated, and publications dealing with glaciations and deglaciation of the shelf increased in number.

The earliest activity concerning the shelf was bathymetry, which gave an impression of the morphology of the sea bottom. J.H.L. Vogt (1900) reported thick gravel deposits on the shelf outside Helgeland based on scattered, small sea-bottom samples acquired together with the depth data. Based on this knowledge it was widely agreed during the first half of the 20th century that the special submarine topography could only be explained by glacial erosion and deposition. O. Holtedahl (1940, 1960) described ice-marginal features and terminal moraines along the shelf edge (Fig. 3.5). Undås (1942, 1963) used bathymetric data to propose the position of the Ra off the coast of central Norway, which includes Møre and Trøndelag (Fig. 3.6).

Fig. 3.5
Proposed ice margins on the continental shelf off the coast of central Norway based on bathymetric data. Marginal fault lines are dotted. T = glacial troughs (Holtedahl 1940).

Andersen (1965a, b, 1968) indicated several moraines on the shelf outside Troms and Nordland based on bathymetric data. The morainic composition of the ridges on the shelf off Central Norway and Troms was shown by seismic registrations (Bugge et al. 1974, 1976, 1978, Lien 1976, Rokoengen & Bugge 1976, Rokoengen et al. 1977, 1979, Bugge 1980, Vorren et al. 1983). Andersen (1979) compiled a map of supposed submarine moraine ridges along the Norwegian coast (Fig. 8.5). Vorren et al. (1983, 1988) and Vorren & Plassen (2002) studied moraines in Andfjorden and defined several stadials, which they proposed were deposited in the time range Middle to Late Weichselian. Bugge (1983) and Bryn et al. (2002) studied submarine slides on the Norwegian continental margin, especially the Storegga slide west of the Møre/Trøndelag area. Rise et al. (1984, 1988), Rokoengen 1979, 1980, Rokoengen et al. (1980, 1982, 1995) and Rokoengen & Frengstad (1999) have studied the sea bottom features and the stratigraphy of the sediments of the mid-Norwegian shelf.

King (1980) and King & Fader (1986) developed the *till tongue model* which predicts a way to distinguish between till and intervening glaciomarine sediments. This model was used to identify several till tongues outside the mid-Norwegian shelf (King 1993, King et al. 1987, 1991). Ottesen et al. (2001) studied glacial processes and large-scale morphology and proposed that the ice flow was concentrated to several well-defined pathways on the shelf.

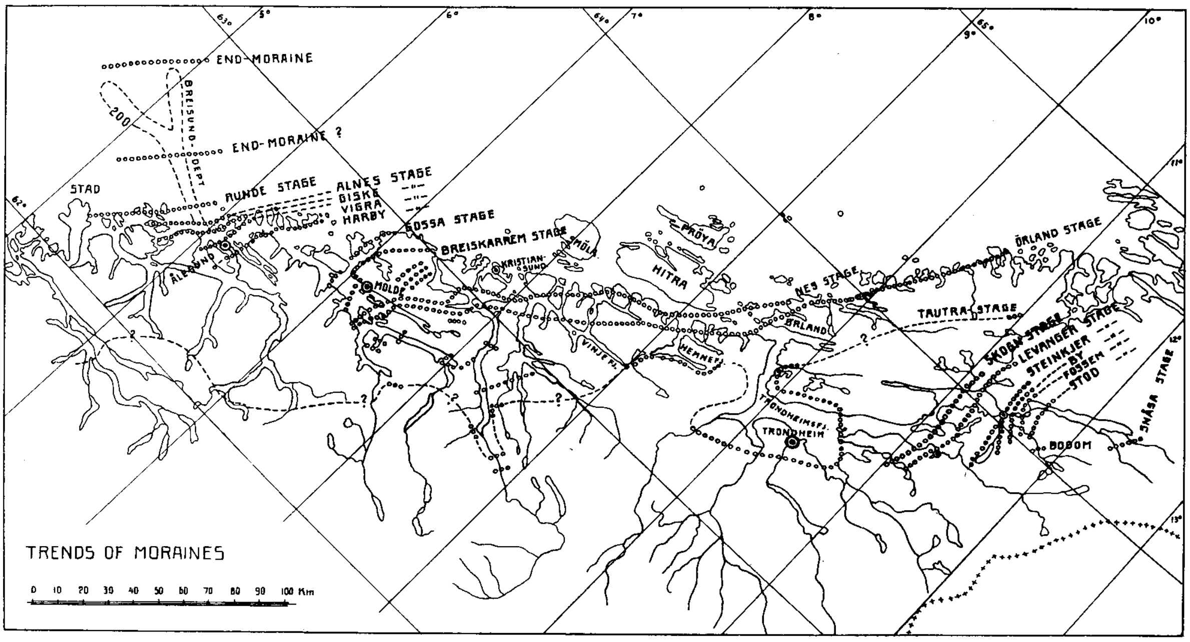


Fig. 3.6
Moraine lines in the Møre- and Trøndelag areas as proposed by Undås (1942).

3.3.3 The Møre district

Extensive work in Møre was very sparse before c. 1975. Several geologists visited the district at the end of the 18th and at the beginning of the 19th century, mainly performing studies on raised shorelines, coastal caves and the strandflat (e.g., Kjerulf 1871, Reusch 1894, Hansen 1890, 1891, 1900, Rekstad 1906, 1909, G. Holmsen 1922, Nansen 1922, Undås 1942).

Kaldhol (1916, 1922, 1925, 1930, 1946) observed raised shorelines, but he also studied shell localities and moraines. On that basis he constructed three glacial stadials on the coast and fjord districts, which he called the First-, the Second- and the Third Glacial, respectively. The outermost of these stadials was correlated intuitively with "the great glacial in Northern Europe", probably meaning the Weichselian maximum. Parts of some islands were not ice-covered in this reconstruction. The innermost of his glacial stadials was correlated with the Ra in the Oslofjorden area (Younger Dryas). Undås (1942, 1963) studied raised shorelines and moraines and proposed several moraine lines (Fig. 3.6).

Marine geological studies on the Møre shelf were pioneered by H. Holtedahl (1955). Regional deglaciation studies during recent decades were performed by Reite (1968), Sollid & Sørbel (1979) and Sollid & Reite (1983) (Fig. 8.13). Detailed studies were executed by Mangerud et al. (1984), Follestad (1984a, b, 1985, 1986, 1987, 1988b, 1989, 1990b, 1992b, 1994a, b, c, d, 1995b), Johansen et al. (1985), Follestad & Lebesby (1986), Larsen et al. (1988, 1991), Follestad & Andersen (1992), Follestad & Ottesen (1996), Follestad & Anda (2002).

Nesje et al. (1987, 1988), Follestad (1990c), McCarroll & Nesje (1993) and Larsen et al. (1995) carried out studies of mountain block fields and of the thickness of the ice sheet in the Møre area. Interstadial sediments were investigated by Mangerud et al. (1981), Miller et al. 1983, Hamborg & Lien 1984, Landvik & Mangerud (1985), Landvik & Hamborg (1987), Larsen et al. (1987), Valen et al. (1996) and modern studies of the strandflat by Holtedahl (1960), Larsen & H. Holtedahl (1985) and H. Holtedahl (1998).

The Geological Survey of Norway (NGU) has published several Quaternary geological maps from the area. The maps are at scales of 1:20,000 to 1:250,000 (Follestad 1982, 1983, 1984a, b, 1985, 1986, 1987, 1988b, 1989, 1990b, 1992b, 1994a, b, d, 1995b, Follestad & Andersen 1992, Follestad & Ottesen 1996, Follestad & Anda 2002, Bargel in prep.) (Fig. 2.4).

3.3.4 The Trøndelag Counties

Hörbye (1857) studied the evidence of the ice age in Trøndelag, and reported observations of glacial striae in the mountains. His registrations are printed on a coloured map, and the results are supported by modern studies. Reusch (1889) found erratics on the highest mountains in the Sylane massif, and concluded that the ice had covered the mountains. Friis (1898) drilled at many localities in soil around Trondheimsfjorden as a result of the large quick clay slide in Verdalen in 1893, as a result of which 116 people were killed. Øyen (1908, 1909, 1910, 1914) made many observations on shorelines, on the stratigraphy of marine clays and on fossil seashells. He also defined several moraine lines, and made correlations with other localities in Southern Norway, Sweden and Denmark. Øyen (1914) named his moraine lines the Ørland-, Agdenes-, Rissa-, Statsbygd-, Heimdal-, Gauldal-, Ekne-, Beitstad-, Steinkjer- and the Sunnan-lines, from the oldest to the youngest, respectively. As Øyen presented no map, the course of the respective ice fronts cannot be visualized. His observations of the moraines were quite good, but the correlations were relatively imaginative.

O. Holtedahl (1929) too, identified several moraines and presented correlations on a map. He too meant, with Øyen (1914), that the moraine at Ørlandet was the oldest one (Fig. 3.7). The "Ra-time" ice margin was located not far from the position regarded as probable today, but he correlated the clay ridge at Rissa with the Tautra moraine.

Undås (1942, 1963) studied raised shorelines and moraines and proposed a lot of moraine lines, mainly on the islands and the coast of Møre and Trøndelag, but also at the inner end of the Trondheimsfjorden area (Fig. 3.6). The Ra was located in the sea outside the islands.

During recent decades several studies on the deglaciation of Trøndelag have been published (Lasca 1969, Reite 1972, publ. in: Oftedahl 1974, Sollid & Sørbel 1975, 1979, Oftedahl 1977, Kjemperud 1981, 1986, Kjenstad & Sollid 1982, Reite et al. 1982, Selnes 1982, Sveian & Olsen 1984, Aarseth 1990, 1995, Reite 1994c, Andersen et al. 1995, Sveian 1997, Sveian & Solli 1997, Sveian & Rø 2001). Most of the studies are based on detailed mapping of the deposits, including an almost complete registration of the moraines on maps at a scale of 1:50,000 (Reite 1983a, b, 1984, 1985, 1986a, b, c, 1987, 1988, 1990, 1991, 1992, 1993, 1994a, b, Sveian 1988, 1989, 1991, 1992, Sveian et al. 1993, Follestad 1995b, Follestad & Ottesen 1996) (Fig. 2.4). Thanks to detailed mapping and a number of radiocarbon age determinations, the deglaciation chronology is relatively well established.

3.3.5 Nordland County

Nordland in general

Rekstad & J.H.L. Vogt (1900) presented many observations on moraines, raised shorelines and terraces and marine fauna on Southern Helgeland. Rekstad (1906, 1910a, b, 1912, 1913a, b, c, 1915, 1917a, b, c, 1919, 1922, 1924, 1925 a, b, 1929), performed investigations in most

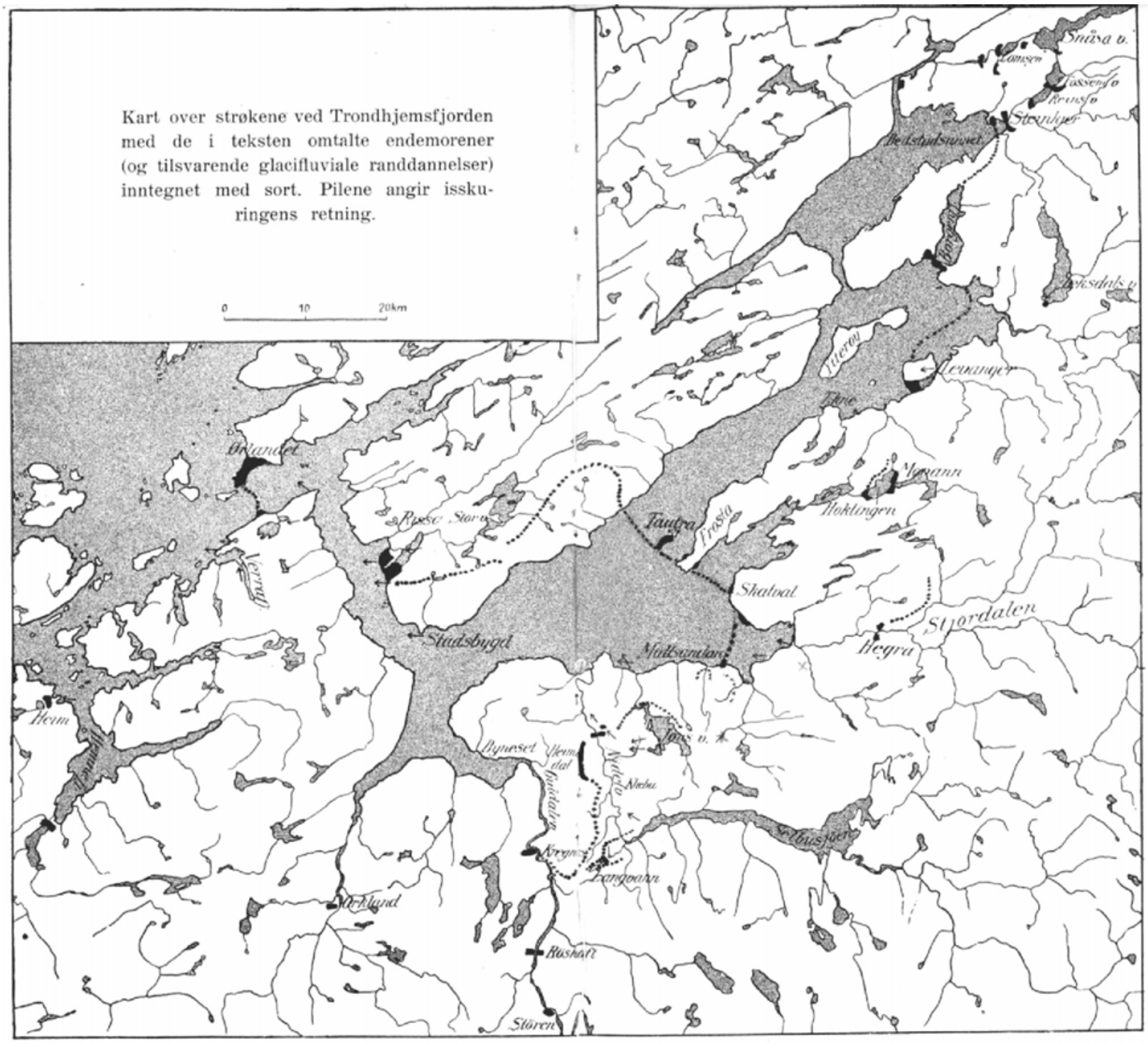


Fig. 3.7
Moraines and correlations in the Trondheimsfjorden area, according to Holtedahl (1929).

of Nordland, except Lofoten and Vesterålen. He mapped the bedrock and the Quaternary deposits and observed numerous moraines, raised shorelines and terraces, marine fauna and glacial striae. The results are documented in articles and on several maps printed in colour. In Rekstad's articles we can find the beginning of a chronological system in his description of moraines in the valleys, as he noticed that the outermost moraines must be older than the inner ones. Not so sensational as we see it today, but Rekstad was one of the first geologists in Norway who noticed that point. On Helgeland Rekstad observed erratics of red sandstone, which he believed must have been transported from Sweden.

Grønlie (1909, 1910, 1927, 1940, 1951) is best known for his work on raised shore levels. He worked out precise measurements and thorough analyses of Late- and Postglacial shorelines along the coast from Hammerfest to Bindal and constructed isobases for the Post Glacial Tapes shoreline (Fig. 3.8), and a shoreline diagram for Northern Norway. On this basis, he concluded that the outer parts of Lofoten and Vesterålen were ice-free during the Weichselian maximum. He introduced the name Tromsø-Lyngen moraines for the most marked moraines in Troms (Grønlie 1940), and agreed with J.H.L. Vogt and Tanner in correlating them with the Ra in southern Norway. According to Grønlie (1940, 1951) the Tromsø-Lyngen ice-margin was situated partly along, partly distally to the outer coastal districts in Nordland. Based on the shorelines he indicated five ice margins in Northern Nordland and Troms (Fig. 3.9).

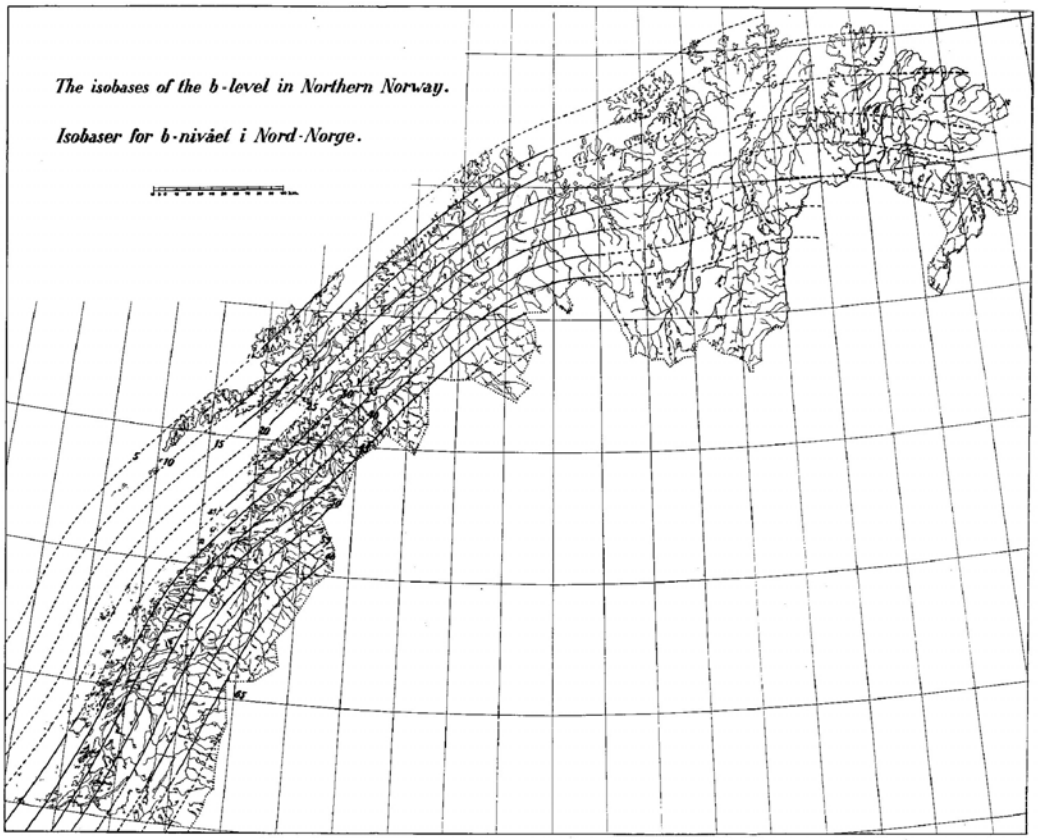


Fig. 3.8
Isobases for the Late-Glacial Tapes shoreline in Northern Norway (Grønlie 1940). Cf. Fig. 3.3.

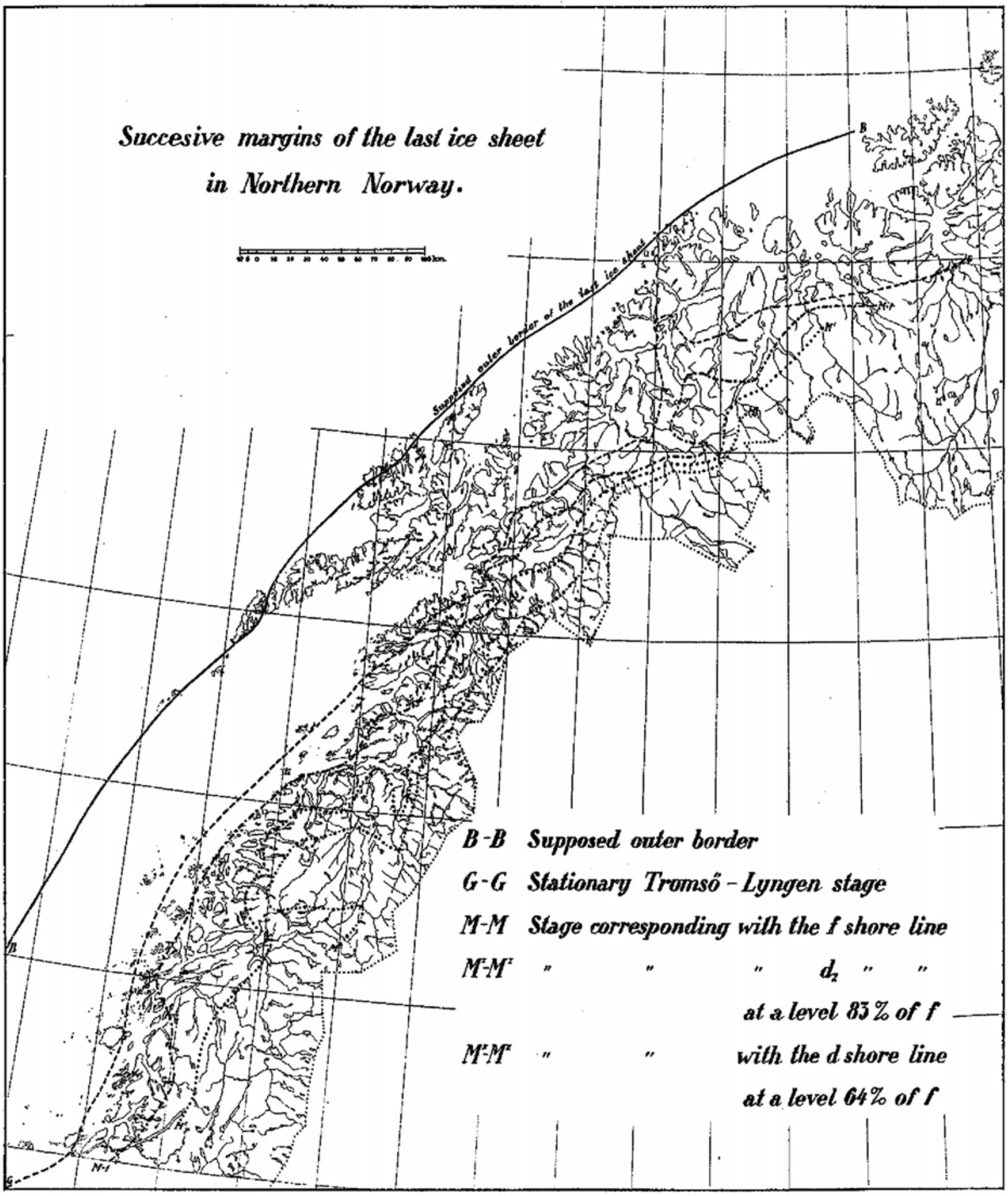


Fig. 3.9
Ice marginal lines in Nordland and Troms as proposed by Grønlie (1940).

Marthinussen (1960, 1962) constructed isobases for the Main (Younger Dryas) Shoreline in Finnmark, Troms and Ofoten in Nordland. He correlated several end moraines along the coast of Northern Norway with the Tromsø-Lyngen event and claimed that most of the coastline was ice-free then. He also advocated that most of Northern Norway, except the outer part of Lofoten, was ice-covered during the Last Glacial Maximum (LGM).

Marthinussen's conclusions were based mainly on raised shorelines, but he also used radiocarbon age determinations from moraines, and he was probably the first geologist who published age determination of shell from Northern Norway.

Andersen et al. (1981, 1995) published reviews of the deglaciation chronology in Nordland (Fig. 8.12).

The oldest indications of climatic variations in Nordland were achieved by speleothem stratigraphy (Lauritzen 1984, Lauritzen et al. 1980, 1990). More than 100 uranium series age determinations of speleothems from some of the numerous karst caves in Nordland have been performed. The method reaches far beyond the Weichselian, and the ages obtained indicate speleothem formation, and consequently ice-free conditions, during several periods in the Late Quaternary, c. 500, 400, 340-300, 240-200, 200-190, 140-90, 70, 50, 30 and less than 10 ka BP (Lauritzen 1991). According to Lauritzen (op. cit.) this fits fairy well with the deep-sea oxygen-isotope record (Imbrie et al. 1984) and the climatic fluctuations recorded in Fennoscandia (e.g., Andersen & Mangerud 1990).

NGU has, since 1979, published several Quaternary geological maps from the Nordland area. The maps are at scales of 1:20,000 to 1:2,000,000. Most of the maps present a lot of information on the Quaternary deposits, and are useful for both regional and/or local planning and geological research (Alstadsæter 1981, Alstadsæter & Hollund 1981a, b, Bargel & Bergstrøm 1993, Bargel & Olsen 1995, Bergstrøm 1994, 1995, Follestad 1981, 1988a, 1990a, 1992a, in prep. a, b, c, d, e, Olsen et al. 1996a, b, 2000a, b, c, d, 2001e, Sveian 1979a, 1979b, 1980a, b, 1984a, b, Sveian et al. 1979, Sveian & Vallevik 1983, Olsen & Riiber in prep, Sørensen in prep. (Fig. 2.4).

The Helgeland district

Rekstad & J.H.L. Vogt (1900) observed glacial striae in the southern part of Helgeland, and noticed that the general direction of the ice movement had been towards the NW. They found erratics from the Oslo area, and thought that they had been transported along the coast by icebergs. They also reported some observations on moraines.

Holmsen (1913, 1932) reported numerous observations on glacial striae and glacial deposits in Hattfjelldalen and Rana. Granlund & Lundqvist (1936) reported some observations on the till, weathering limits and the size of the ice sheet in Rana. They concluded that the outer islands on the coast were not glaciated, even though Rekstad (1925b) had documented glacial striae on the Træna islands.

Svensson (1957, 1959) mapped moraines in the Bindal-Tosenfjorden area (Fig. 11.2). Marthinussen (1962) presented many observations on moraines and shorelines in Bindal and Sømna, and performed the first radiocarbon age determination from the area. Andersen et al. (1979, 1982) and Rasmussen (1979, 1981, 1984a) performed deglaciation studies along the coast of Nordland south of Saltenfjorden. They mapped shorelines and moraines, and proposed a moraine chronology (Fig. 8.12).

Rekstad & Vogt (1900) described numerous coastal caves in southern Helgeland, and the wave-eroded hole in the mountain of Torghatten was thoroughly studied. Rekstad (1912, 1913b), Oxaal (1915), Møller (1985) and Sjoberg (1988) also described coastal caves in Nordland.

Shorelines and shore terraces from small glacial lakes in the Børgefjellet area are described by Rekstad (1924), Strand (1956), Grønhaug & Gustavson (1960), Gustavson (1973) and Sivertsen (1973). R. Dahl (1968) and Lundqvist (1972) described glacial lakes in Sweden that drained across the watershed to the Norwegian fjords.

The Salten-Ofoten districts

J.H.L. Vogt (1907a, 1913) observed raised shorelines and end moraines and constructed the isolines for the highest shore levels in northern Nordland. He correlated the moraines with the Ra moraines in southern Norway, and so did Sjøgren (1909) and Tanner (1915). Tanner (1915) also presented a map showing a possible regional ice-movement pattern in Northern Fennoscandia (Fig. 3.4).

The glacial lake, Nordre Bjøllåvatn, on the mountain Saltfjellet was discovered by Rekstad (1913c) as he noted well-developed, high-lying shore terraces. In Rekstad's opinion, the glacial lake could have been up to 60 km long, but Oxaal (1919) found it to be only about 35 km long. G. Holmsen (1932) and Nordnes & Sund (1953) also described the glacial lakes on Saltfjellet. Sveian (1979a, 1980a, 1984a) and Sveian & Vallevik (1983) mapped the shore phenomena of the glacial lake in detail, and concluded that its size must have been as proposed by Oxaal (1919). Sveian (1979b, 1980b, 1984b) and Sveian et al. (1979) also mapped glacial lakes in several other valleys on the northern part of the Saltfjellet. Sveian et al. (1979) mapped and defined the Preboreal Ølfjell event on Saltfjellet.

G. Holmsen (1917a, b, 1919) reported numerous observations on glacial striae, glacial- and marine deposits in Sørfold and Sulitjelma, as did Grønlie (1927) in the Folda area and Foslie (1941, 1942) in Tysfjorden. Donner (1969) supposed that the Finneid moraine was correlative with the Tromsø-Lyngen moraines. R. Dahl (1967, 1968) performed detailed mapping of the deposits in the fjords and valleys in the inner part of the Ofoten area and described moraines and other glaciogenic deposits. Of special interest is his description of lateral moraines on the southern side of Skjomenfjorden, which he correlated with the Tromsø-Lyngen moraines. He believed that the correlative end moraine was situated on a threshold in the inner part of Ofotfjorden (Fig. 8.15).

Andersen (1975) mapped the end moraines and proposed a moraine chronology for Nordland north of Saltfjellet. The correlation was mainly based on radiocarbon dates of moraines and studies of shorelines. In the Ofotfjorden-Hinnøya area Bergstrøm et al. (2001) proposed a revised deglaciation chronology based on detailed studies of moraines.

Lofoten and Vesterålen

Late Glacial moraines and raised beach phenomena are very common in this area and were reported from the Lofoten islands by, e.g. Helland (1897), J.H.L. Vogt (1907b), Bergström (1973), Møller & Sollid (1972, 1973), Møller (1982), Møller et al. (1992) and Andersen (1975). J.H.L. Vogt (1907b) was probably inspired by the strandflat studies of Reusch (1894), and performed some elevation measurements on the strandflat in Lofoten.

From the Vesterålen area, Helland (1897), Reusch (1896, 1903), Enquist (1918), G. Holmsen (1924) and Undås (1938, 1967) reported some observations of shorelines and moraines on Andøya. On Hinnøya and Andøya islands shorelines and moraines were observed by Grønlie (1940, 1951), and Marthinussen (1960, 1962) constructed equidistant shoreline diagrams from these areas. Møller & Sollid (1972, 1973) and Møller (1982) mapped shorelines and moraines, constructed an equidistant shoreline diagram and correlated the moraines with the shorelines (Fig. 8.10). Five events older than the Younger Dryas were proposed in Lofoten and Vesterålen; the oldest one was thought to be of Weichsel maximum age. They believed that the highest mountains were nunataks during the maximum glaciation. Bergström (1973) studied cirques, cirque moraines, raised shore levels, end moraines etc., and he too tried to date the moraines by correlative shorelines. He was of the opinion that all these westerly islands were completely ice-covered during the last ice age. Rasmussen (1984a, 1984b) mapped the marginal moraines older than Younger Dryas on Langøya and proposed a revised deglaciation chronology.

During recent decades, several investigations on Andøya have revealed much new information on the Weichsel maximum ice margin and on the deglaciation (K.D. Vorren 1978, Flakstad et al. 1985, T.O. Vorren et al. 1988, Møller et al. 1992, Alm 1993, 1994, Fjalstad 1997, Vorren & Plassen 2002). This is discussed in more detail in Chapter 8.3.

3.4 Areas for further study

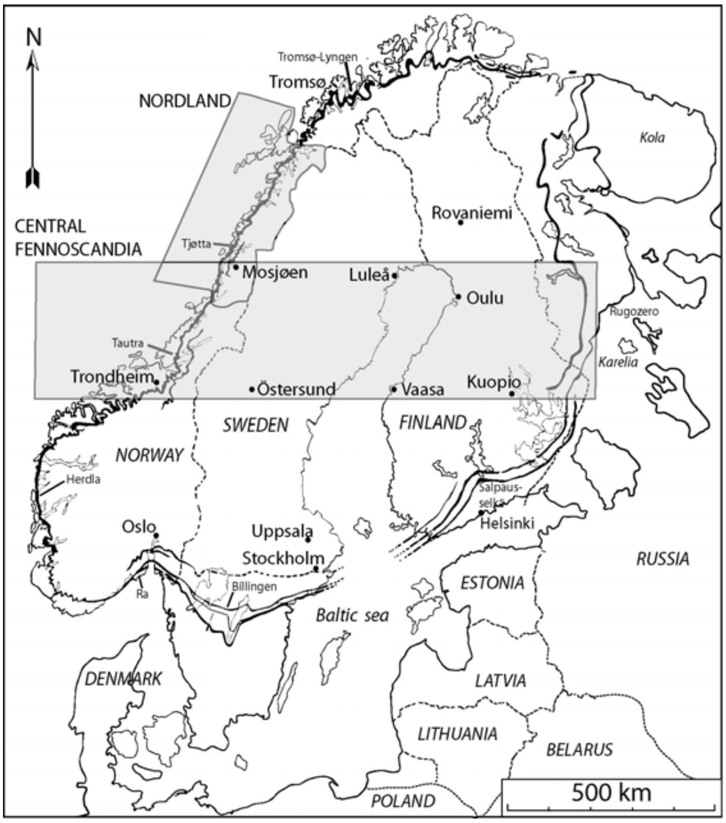
The Quaternary geological mapping of Central Fennoscandia and Nordland (Bargel et al. 1999a, b, c, Bargel 2001) has revealed several problems that deserves further attention. Even though much work has been done as documented in Part IV, it is an amazing fact that several aspects of the Quaternary geological history in the area are still more or less unknown, or needs more work to be resolved. Examples of unsolved problems are:

- The deglaciation of several areas are little known
- Ice free areas during the glaciation(s)
- Early-middle Weichselian history
- Pre-Weichselian history
- Correlation between the shelf and the mainland areas
- Sea-level changes

One of the most striking facts, however, is that no efforts have been made to put forward a deglaciation chronology of the Lofoten islands in northern Nordland, except the work of Møller & Sollid (1972, 1973) and Møller (1982) that has to be revised. An attempt to solve this problem is presented in Chapter 10 of this thesis.

The deglaciation of the Bindal area in southern Nordland is sparsely documented in the literature. A contribution to understand details of the deglaciation of this area is presented in Chapter 11 of the thesis.

PART II QUATERNARY GEOLOGICAL MAPPING OF CENTRAL FENNOSCANDIA AND NORDLAND



Introduction to Part II

In this part of the thesis five Quaternary geological maps that were produced as parts of two large, multidisciplinary projects, the Mid-Norden Project and the Nordland Project are described and the Quaternary geological history of the areas covered is reviewed. The text and illustrations in this part of the thesis are partly adapted from the four printed Quaternary geological maps of Central Fennoscandia (Bargel et al. 1999a, b, c, Enclosure 1-3) and from the map of Nordland (Bargel 2001, Enclosure 4). Geographical names used in Part II are included in Enclosure 9 (Central Fennoscandia) and Enclosure 7 (The Norwegian part of Central Fennoscandia and Nordland).

The Mid-Norden Project that produced maps of Central Fennoscandia was a joint venture between the Geological Surveys of Finland, Norway and Sweden, in the years 1989-1996. The first results of the Quaternary geological subproject (three of the enclosed map sheets) were printed in the first half of 2000 (even though the official printing year is 1999). Additional material is planned to be published in 2003-2004 (Bargel et al. in prep. a, b). The project was a continuation of the Nordkalott Project (1980-1986) (Hirvas et al. 1988), and aimed to produce a modern geoscientific atlas and databank to be used in prospecting for mineral resources and in the evaluation of environmental issues within an area in Central Fennoscandia from the western coast of Norway to the eastern border of Finland between the tangents to the latitudes 62°45'N and 66°N (Fig. 1.1). The maps are the first to include Quaternary geological information from the Norwegian Continental Shelf, the Gulf of Bothnia and the continental areas together.

Seven subprojects were accomplished within the Mid-Norden project: Data, Bedrock geology, Quaternary geology, Geophysics, Metallogeny, Industrial minerals and Environmental geology. The project resulted in the compilation of 9 maps and several reports and publications.

The objective of the Quaternary geological subproject was to produce and present data on the Quaternary deposits for use in regional planning, exploitation of resources and regional geological studies. Four Quaternary geological maps at scales of 1:1,000,000 and 1:2,000,000 of Central Fennoscandia were compiled (Bargel et al. 1999a, b, c, Enclosures 1, 2 and 3), a popular report and a scientific article are in preparation (Bargel et al. in prep. a, b). The products are mainly based on previous mapping, but additional fieldwork has been performed in selected areas.

The Nordland Project (Nordlandsprogrammet, 1992-1999) was carried out by the Geological Survey of Norway (NGU), supported by the County authorities of Nordland (NFK), and aimed to produce digital geological data in order to support the mineral industry, prospecting for new mineral resources and to produce data to achieve better regional and local planning within the County of Nordland. The county is situated between latitudes $64^o55´$N and $69^o20´$N. The areas of the Mid-Norden and the Nordland projects overlap in the southern Helgeland district of Nordland (Fig. 1.1).

The same subprojects as in the Mid-Norden project were carried out in the Nordland project, but also projects on geochemistry, hydrogeology, marine geology and geology for the layman ("Geotourism") were carried out in Nordland. Much fieldwork was carried out during the project, leading to considerable new knowledge. Several databases and many maps, reports and articles were produced (see Bargel et al. 2000 for an overview of these). A Quaternary geological map of the county of Nordland was made at a scale of 1:250,000, but was printed at a scale of 1:400,000 for practical reasons (Bargel 2001, Enclosure 4).

Chapter 4 Central Fennoscandian Quaternary Deposits map (Enclosure 1)

4.1 The map compilation

The map of Quaternary Deposits at a scale of 1:1,000,000 (Bargel et al. 1999a) shows the distribution and genetic variation of the uppermost part of the Quaternary deposits on land, on the continental shelf off Norway and in the Gulf of Bothnia (Fig. 1.1).

The onshore map area was compiled using data from Quaternary geological maps at various scales and of varying quality, supplemented with interpretation of aerial photographs. The Norwegian part was compiled using data from four county maps at a scale of 1:250,000: Sør-Trøndelag (Reite 1990), the northern part of Møre og Romsdal (Follestad 1995a), the southern part of Nordland called the Helgeland district (Bargel 2001) and Nord-Trøndelag (Sveian et al. in prep.) (Fig. 2.4 B). The Swedish part was compiled using data extracted from the SGU map series Ak (N^{os} 1-24) and from county maps at a scale of 1:200,000 (Lundqvist 1969, 1987). The Finnish part was based on maps at a scale of 1:1,000,000 (Kujansuu & Niemelä 1984, Niemelä et al. 1993).

The genetic mapping methods used onshore were developed by the national geological surveys, and presented in Sweden by, e.g. Granlund (1943), G. Lundqvist (1951) and J. Lundqvist (1969, 1987), in Norway by Follestad (1972, 1973) and in Finland in the Atlas of Finland (1990), and have undergone continuous development up to the present.

These maps were redrawn with simplification, and digitised. The simplification process, primarily aimed at removing certain details, was performed with a geological mind as it was focused on conserving deglaciation information, such as moraines and glaciofluvial deposits at the expense of, e.g. till in general.

The colours used on the map to represent the different geneses of the onshore surficial deposits are a compromise between the different standards commonly used in the national map series in the three countries, as defined in the Nordkalott Project (Hirvas et al. 1988) (Fig. 4.1). The classification and the general properties of the surficial deposits are described in Chapter 2.4.

The offshore data are interpreted from seismic registrations and bottom sediment samples. The map of the continental shelf area off Norway is based on maps and seismic profiles produced by the then-existing Continental Shelf Institute (IKU) and published by Bugge (1980, 1983), King et al. (1987), Rokoengen et al. (1980, 1995), Rokoengen & Frengstad (1999). The map of the Gulf of Bothnia is based on a map at a scale of 1:1,000,000 compiled by Ignatius et al. (1980).

The offshore sediments are classified partly lithologically, and partly genetically as till and marine clay are differentiated. However, the lithological units used are not the same on the Norwegian Continental Shelf and in the Gulf of Bothnia. Consequently, three separate legends are used on the map: Quaternary deposits on land, Quaternary deposits in the Norwegian Sea (the Norwegian Continental Shelf) and Quaternary deposits in the Gulf of Bothnia, respectively (Fig. 4.1).

4.2 Regional distribution of the deposits

By using the changing character of the landscape and the regional distribution of the different Quaternary deposits, the Central Fennoscandian area is divided into nine fairly uniform sub-areas on the Quaternary deposits map (Bargel et al. 1999a). Most of the areas are southwest-northeasterly oriented zones (Fig. 4.2), trending parallel to main topographical features such as the Caledonian mountain range and the general trend of the coastlines. The described sub-areas are (Fig. 4.2):

10. The continental shelf off Norway
11. The coastal area of Norway
12. The fjords and valleys in Norway
13. The mountain chain
14. The interior of Sweden
15. The coastal areas of the Gulf of Bothnia
16. The Gulf of Bothnia
17. The Finnish watershed and lake areas
18. Karelia and Kainuu, eastern Finland

The implications of the topography for the Scandinavian ice sheet, its distribution and movements, is the subject of discussion in Chapter 9.

Fig. 4.1
The three map legends used on the Quaternary deposits map of Central Fennoscandia. Reproduced from Bargel et al. (1999b).

4.2.1 The continental shelf off Norway

The continental shelf lying off the coast of Norway is a relatively flat, shallow area (< 400-500 m water depth) emerging from the tidal zone to the continental break, some 60-260 km from the coastline (Holtedahl 1993). Generally speaking, there are little Quaternary deposits on the inner parts, which are underlain by crystalline rocks except in the depressions, but the unconsolidated sediments gradually thicken away from the littoral zone (Rokoengen et al. 1995). Due to difficulties in locating the Quaternary/Tertiary boundary on seismic registrations, the maximum thickness of the Quaternary sediments is uncertain. The latest interpretations, however, suggest a thickness of some 1,000-1,500 m on the outermost parts of the shelf (Rokoengen et al. 1995) (Fig. 4.3).

Most of the deposits on the shelf are of till or till-like material (glaciomarine deposits included) which is comparable to the till on land, but with a considerably higher content of clay (Bugge et al. 1978, Bugge 1980, Rokoengen 1980). Several huge marginal moraines have also been identified, e.g. Skjoldryggen (Fig. 8.5 A), a very extensive moraine ridge which is present along the greater part of the Nordland shelf edge (e.g., H.Holtedahl 1993). Secondary marine processes, such as wave action and ocean currents, have modified the top layer and produced a sand- and gravel-rich seabed on the shallower parts of the shelf, and soft clay on the deeper parts.

On the continental slope just outside Storegga there is a giant submarine slide scar (Enclosure 1). The original surface slope is less than 1^{o} in the offshore direction. The slide was interpreted to have occurred in three episodes some 30 and 8-6 cal ka ago, respectively (Bugge 1983). Investigations on the slide scar for the Ormen Lange gas project have shown that the slide occurred as one major event 8,2 cal ka ago followed by several smaller slides (Bryn et al. 2002). Around 5,600 km^3 of up to 450 m-thick sediment was displaced by these slides, and the masses travelled up to 800 km along the seabed. Earthquakes probably triggered the slides (Bugge 1983, Bryn et al. 2002).

Fig. 4.2
The nine sub-areas within Central Fennoscandia as found on the Quaternary deposits map. Reproduced from Bargel et al. (1999b).

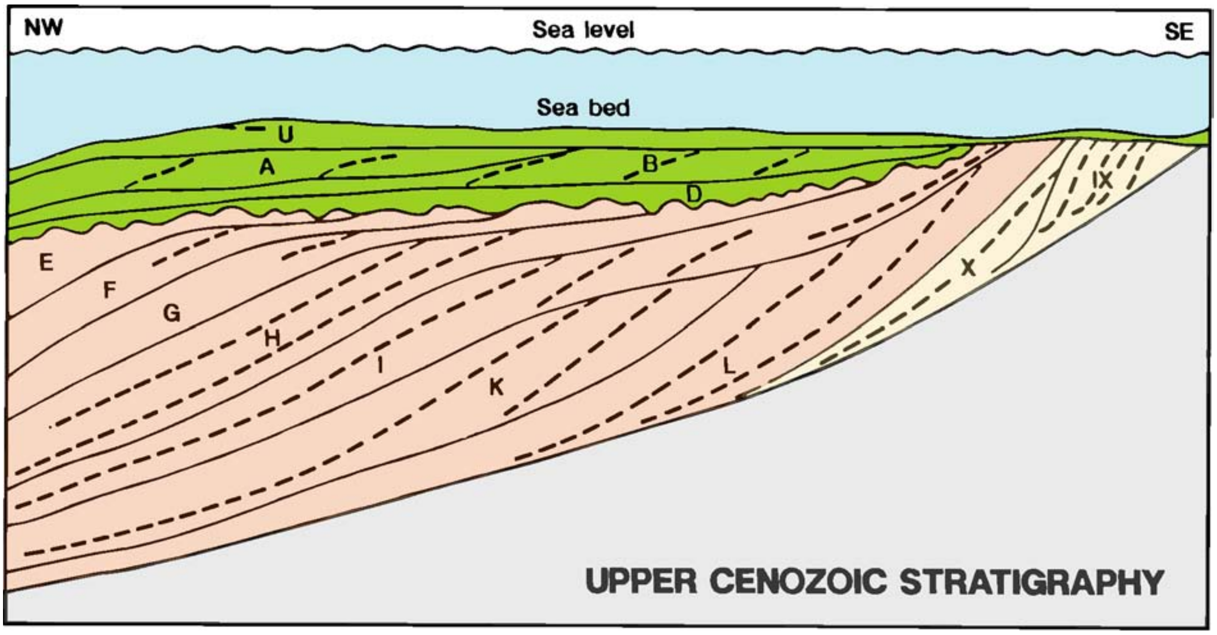


Fig. 4.3
Composite geoseismic profile showing the upper Cenozoic stratigraphy across the mid-Norwegian shelf. Unit IX (and X?) probably represent the upper Oligocene, units L-E are thought to represent upper Pliocene/Pleistocene sediments, while units D, B, A and U above the angular unconformity probably represent the last interglacial/glacial cycle. The latest interpretations suggest a thickness of some 1,000-1,500 m on the outermost (northwestern) parts of the shelf (Modified from Rokoengen et al. 1995).

4.2.2 The coastal area of Norway

The low-lying part of the coastal area, which was named *the strandflat* by Reusch (1894) and was thoroughly treated by Nansen (1922), is an undulating and partly submerged rock platform between the mouths of the fjords and the outermost islands (Fig. 4.4). Numerous monadnocks protruding several hundred meters above the strandflat are also included (Holtedahl 1998).

The deposits in this area are usually sparse. Scattered end moraines that were heavily washed during the regression are found in some fjord mouths (Fig. 4.5). A few metres-thick package of sediments, mostly wave-washed material, both minerogenic and organic, appears locally on top of clay in the coastal zone (e.g., Reite 1994). Occasionally the organic carbonate accumulation may exceed 10 m in thickness (Fig. 4.6), and the sedimentation started before 10 ka BP (Ottesen et al. 1995a). Up to the present day, eolian activity has produced small local dune fields (e.g., Klemsdal 1969). In some sheltered positions interstadial and interglacial sediments are found (e.g., Mangerud 1981, Mangerud et al. 1981, Larsen et al. 1987, Larsen & Ward 1992, Olsen 1993, 1997a, Olsen et al. 2001a, b, c, Aarseth 1990, 1995). In addition, the present writer have achieved an AMS-date at 38,950 ± 780 (Table 1.1) of a shell fragment collected from an overconsolidated basal till at the island Smøla. Shallow bogs and frost-shattered bedrock are common in parts of the coastal area.

Fig. 4.4
View from Lurøyfjellet (685 m a.s.l.) towards the SW showing the numerous low and small islands, islets and skerries that are typical of the strandflat. The archipelago Solvær is seen in the top centre, and to the far right the monadnock Lovunda (623 m a.s.l.) is seen. Photo: Svein Gjelle.

Fig. 4.5
Ice-marginal moraine of pre-Younger Dryas (Late Bølling?) age near Osen on the Fosen peninsula, Norway. Photo: Harald Sveian.

Fig. 4.6
Littoral deposit, nearly 100 % carbonate sand, consisting of shell- and coralline fragments. The deposit is c. 11 m in thickness and the production of organic material started c. 10,000 years ago. From Lysøya on the Fosen peninsula, central Norway. Photo: Terje H. Bargel.

Fig. 4.7
Ice-marginal moraine of early Preboreal age in a valley area in Trøndelag. From the Melhus area, Gauldalen, Norway, looking at the distal slope. The moraine is mostly composed of glaciofluvial material and is partly covered by marine clay, which shows a submarine deposition (randås). Photo: Terje H. Bargel.

4.2.3 The fjords and valleys in Norway

When the inland ice melted, the ice margin retreated almost parallel to the present coastline (Fig. 8.4). Numerous ice-marginal features were deposited along the retreating ice margin, especially in the low-lying areas around Trondheimsfjorden (Reite 1994c, Sveian 1997) (Fig. 4.7). These marginal deposits are mainly glaciofluvial in the fjords and in the valleys below the highest postglacial coastline, and diamictic in the higher regions. The most prominent ice marginal deposits situated in the fjords and in the valleys are transversal, ridge-shaped and several hundred metres high. Between the valleys the ridges are much smaller, 10-30 m high and in places up to 6-8 km in unbroken length (Fig. 4.8).

Due to the Late- and Postglacial rebound, vast areas of marine clay and silt lie between the present and the highest Late-/Postglacial coastline, and these deposits are often dominant in the fjords and valleys. This has caused a large number of clay slides up to the present day, several of them resulting in loss of life (Bjørlykke 1893, Løfaldli et al. 1981, Gregersen 1981, Bargel 1988) (Fig. 4.9). In several fjords, a clay thickness of 400-600 m has been recorded (e.g., Oftedahl 1977). In the valleys, a sand layer of 2-4 m is locally found on top of the clays. The sand was eroded from the marginal deposits crossing the valleys. On the valley sides there are, in some places, thick tills, especially in the valleys in southwestern Norway. On the steep, high valley-sides in Møre there are numerous talus and rapid mass-movement deposits due to extensive material production by frost shattering on the mountainsides (Fig. 4.10).

4.2.4 The mountain chain

The mountains are here defined as areas that are generally above c. 600-700 m a.s.l. This elevation does not correlate with the tree line, which, on the Swedish side of the border, is found mainly above this level. The deposits in the mountainous region are generally very thin, or non-existent, and extensive areas of exposed bedrock are common. In many areas the bedrock is frost shattered and has given rise to boulder fields and talus slopes (Fig. 4.10).

Both the bedrock and the deposits have been affected to a large extent by frost processes, which have resulted in patterned ground and solifluction, especially at higher elevations. The deposits generally become thicker towards the east, and in several areas forms hummocky moraines at lower elevations (Fig. 4.11). Various types of smaller glaciofluvial deposits are relatively common, but persistent eskers are rare. Peatlands, mostly shallow, are widespread

Fig. 4.8
Ice-marginal moraine of early Preboreal age in a mountainous area dominated by exposed bedrock. From the Terråk area, Norway. Cf. Fig. 11.23). Photo: Harald Sveian. Reproduced from Bargel et al. (1999b).

Fig. 4.9
Fine-grained marine sediments (silt and clay) with numerous slide scars and ravines are common below the highest Postglacial coastline around Trondheimsfjorden in Norway. From Kvål in Gauldalen, central Norway. Photo: Harald Sveian. Reproduced from Bargel et al. (1999b).

in some areas. The few existing glaciers in Central Fennoscandia are situated in the very highest mountains (more than c. 1800 m a.s.l., NVE 1973, 1988).

4.2.5 The interior of Sweden

The extent of deposits in this region varies greatly locally, but there are regional diversities as well. The deposits become thinner toward the mountain peaks where most of the outcrops are found. According to data obtained from drilled wells, deposits thicknesses between 5 and 15 m predominate in the region, but greater thicknesses, 20-30 m or more, are frequently recorded along river valleys and in areas with hummocky moraine (Fig. 4.11).

Complex stratigraphic sequences, with two or more till beds or till-covered sediments, are common (Bargel et al. 1999c). Till, usually of sandy composition, is by far the most dominant type of deposit and has, in many areas, formed surface features such as Rogen moraines, hummocky moraines or drumlins (Fig. 4.12), see Ch. 5.2. Peatlands are also very extensive with bogs generally being deeper here than in the mountains. Glaciofluvial deposits mainly follow the valleys, largely forming valley trains and persistent eskers (Fig. 4.13). The Cambro-Silurian area around the lake Storsjön near Östersund in Jämtland holds a particular position. The landscape in this area is more gently formed than the crystalline basement areas and bedrock outcrops are rare, despite the modest thickness of the Quaternary deposits. The special bedrock, consisting of limestones, shales etc., has given rise to fertile soils that are either under cultivation or covered by dense forests.

Fig. 4.10
Post-glacial talus cone underlying the 1000 m high Trollveggen escarpment in Romsdalen, central Norway. Photo: Terje H. Bargel.

Fig. 4.11
Hummocky moraine landscape, some 15-20 km SSE of Arvidsjaur, Sweden. Photo: Robert Lagerbäck. Reproduced from Bargel et al. (1999b).

Fig. 4.12
Transverse ridges at Myrberget, some 25 km NE of Arvidsjaur, Sweden, are the most common morphologic units on this photograph. The dominant ice-flow direction (towards the SE shown by the arrow) is indicated by the streamlined, elongated till ridge on the "lee-side" of the hill in the background. Photo: Robert Lagerbäck. Reproduced from Bargel et al. (1999b).

Fig. 4.13
Esker in Lake Kilver, some 8 km SE of Arvidsjaur, Sweden. Photo: Robert Lagerbäck. Reproduced from Bargel et al. (1999b).

4.2.6 The coastal areas of the Gulf of Bothnia

The region lies below the highest coastline and many of the deposits are the result of the same erosion and sedimentation processes as those occurring in the sea today. Due to the post-glacial uplift of the land, the existing deposits have been subjected to wave action at a gradually lower level and reworked into new types of deposits. The original till layer, especially if deposited in higher locations exposed to the sea, has largely been washed away and reworked into gravelly and sandy beach deposits (Fig. 4.14). Bedrock outcrops are therefore more widespread in this area than in the adjacent areas above the highest coastline (Fig. 4.15). The glaciofluvial deposits have also largely been reworked into beach deposits. Fine-grained marine sediments (silts and clays) are found in the lower areas in the terrain, while sandy fluvial sediments generally make up the uppermost layer in the river valleys' often impressive stratigraphic sequences. Peat deposits are widespread in some areas, especially on the Finnish side, where the bogs are commonly of the treeless, flat *aapamire* type (Atlas of Finland 1990). However, the mires in the low-lying areas that have emerged from the sea relatively recently are generally of a modest thickness. In the very flat Finnish area they average only approximately one metre in thickness.

Fig. 4.14
At Asplövberget, some 10 km SE of Älvsbyn, Sweden, the highest coastline stands out as a distinct limit between wave-washed bedrock and a forested layer of thin till, which is unaffected by any wave activity (cf. Fig. 4.15). Photo: Robert Lagerbäck. Reproduced from Bargel et al. (1999b).

Fig. 4.15
Highest coastline (indicated by a broken white line) at Stor-Snöberget, some 25 km WNW of Piteå, Sweden. Above the white line, the densely-forested summit is till-capped, while beneath it, the till is washed away and bedrock is exposed (cf. Fig. 4.14). Photo: Lars Rohde. Reproduced from Bargel et al. (1999b).

4.2.8 The Gulf of Bothnia

The deposits found in the Gulf of Bothnia are principally the same as those found in the surrounding land areas. The main difference is that the till is covered to a larger extent by a layer of fine-grained sediments. These have been transported out to sea by glacial meltwater, or more recently by existing watercourses and shore processes. Waves along the shoreline and currents at moderate depths erode previously deposited silts and clays. The resultant mobilized fine-grained material is re-deposited in deeper water. As a result, till and sand predominate along the bottom of the relatively shallow coastal areas, while clay and silt predominate in the deeper basins (Ignatius et al. 1980).

4.2.8 The Finnish watershed and lake areas

The deposits found in the Finnish watershed and lake areas are mostly sandy or clayey basal till covering the Precambrian crystalline bedrock. The till blanket on the bedrock is often quite thin, mostly less than 5 m. The bedrock geomorphology is thus clearly exposed in the lake area where NW-SE oriented fractures and fault lines are prominent. The basal till forms abundant drumlin morphology and between the drumlin fields, hummocky moraine fields occur. The whole terrain, as well as the lake basins, is streamlined due to the intensive glacial activity (Fig. 4.16). The peat areas also cover the streamlined depressions and valleys in the terrain. For this reason, peat bogs in the drumlin areas are often relatively deep and may reach 7 m. The glaciofluvial deposits in the area commonly include eskers with perfectly shaped ridge forms and kame topography with kettle holes as traces of huge melted dead ice remnants. Some minor ice-marginal moraines are found in the area, but the ice retreat was evidently quite rapid here. The Baltic waters (Ch. 8.2.1) submerged most of the area and fine-grained glacial sediments cover the deepest valleys.

4.2.9 Karelia and Kainuu, eastern Finland

This area in Eastern Finland was the first to be exposed after the deglaciation. As a more elevated area, Karelia and Kainuu was mostly supra-aquatic during the development of the Baltic Sea. In the Karelian part of the area, the huge end moraine complex dating back to the Younger Dryas period some 10-11 ka BP also includes the largest esker and kame formations (Fig. 4.17). The marginal-moraine chains are distinctly formed and can be traced around Fennoscandia. The oscillating and melting ice margin remained in the Salpausselkä zone for some 1,300 years.

Till is the most abundant glacial deposit in the area and drumlin fields mark the lobate form of the ancient active ice lobes. Glaciofluvial formations are represented as perfectly formed eskers or valley fillings in the deeply eroded and intensively fractured Precambrian bedrock. The supra-aquatic nature of the area during deglaciation is clearly indicated by the widespread eolian deposits. The strong katabatic winds from the melting ice-sheet caused intensive eolian activity and deposition in the area. In the Karelian part, even thin deposits of loess are found. Peat deposits are widespread in the area and the peat bogs have a longer history and more complex succession than in the Bothnian area. Many of the peatlands in the Karelian area have developed raised bogs that are significantly higher than the surrounding terrain. The bedrock contains quartzite, which forms erosional remnants and monadnocks in the Karelia-Kainuu plateau. Many of the high monadnocks have till cover on top and a ring of outcrops on the low-lying slopes, marking the shore-forming processes around the ancient ice-dammed lakes (cf. Ch. 4.2.6 and Ch. 8.2.1).

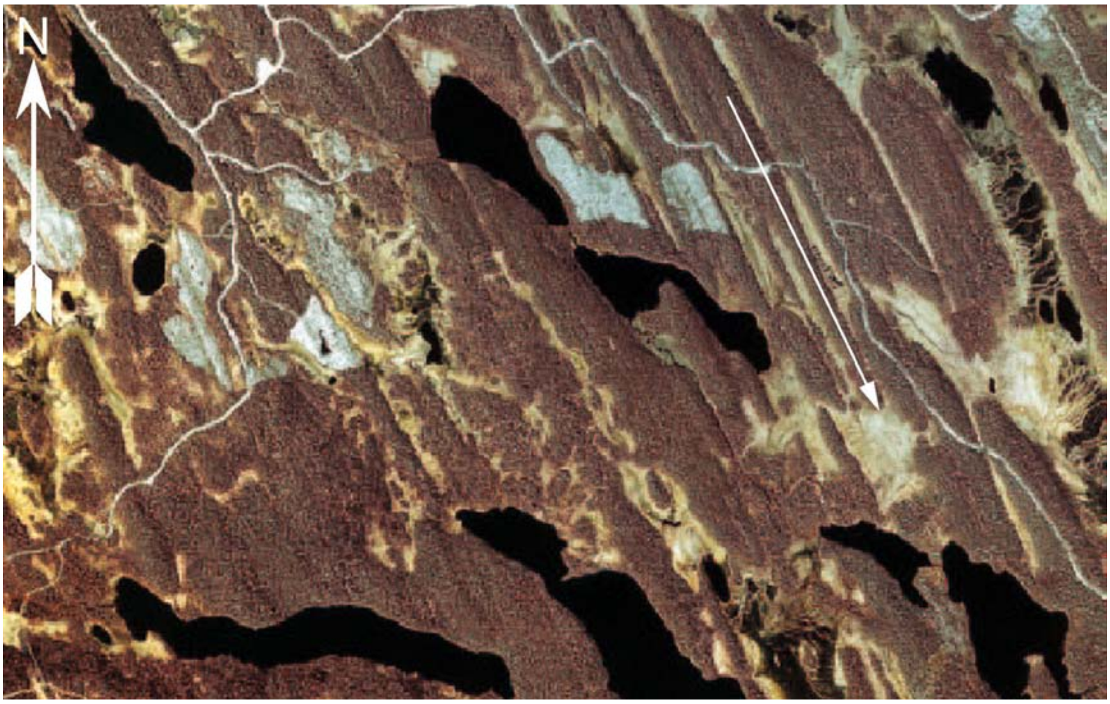


Fig. 4.16
Aerial photograph showing strongly drumlinized terrain at Kuusamo, eastern Finland. The arrow shows the direction of the ice flow. Photo: The National Land Survey of Finland. Reproduced from Bargel et al. (1999b).

Fig. 4.17
Cross section of a typical esker from the Lake Saima district, central eastern Finland. The horizontally stratified sand and gravel were originally deposited in a crevasse. The esker itself achieved its final shape when the supporting ice melted and the sediments were remained. Photo: Geological Survey of Finland. Reproduced from Bargel et al. (1999b).

4.3 Distribution of the Quaternary deposits

It is well known that the various types of Quaternary deposits and deglaciation features found throughout Central Fennoscandia are unevenly distributed (Thoresen 1991, Fredén 1994, Kujansuu & Niemelä 1984). This phenomenon is clearly shown on the enclosed maps as well (Bargel 1999a, b, c, 2001, Enclosure 1-4). Some types of deposit are found throughout the entire area, whereas others are restricted to certain types of environments. The distribution of till, which covers 43 % of the Central Fennoscandian area, is a striking example of this phenomenon (Fig. 4.18).

The uneven distribution of the deposits is largely the result of the area's regional, large-scale topography and hydrography (Fig. 4.19) and of the glacioisostatic changes, all of which have

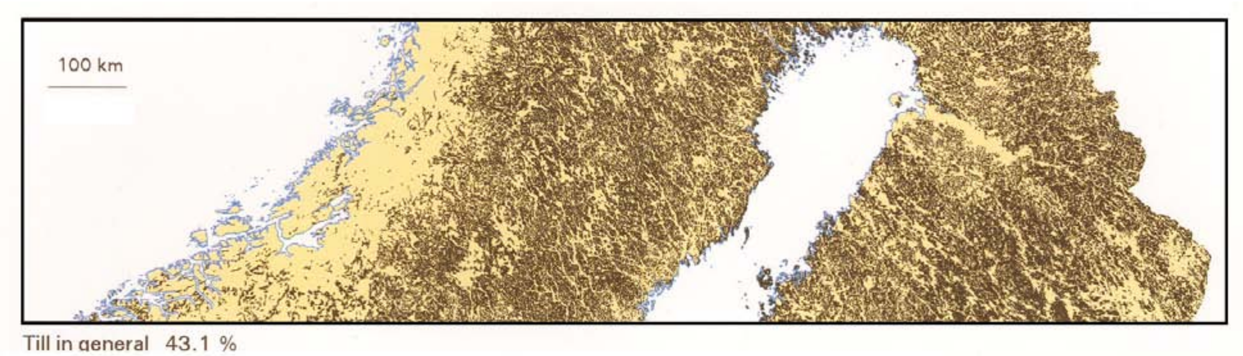


Fig. 4.18
Map showing the onshore distribution of till (in general) in Central Fennoscandia. Reproduced from Bargel et al. (1999a).

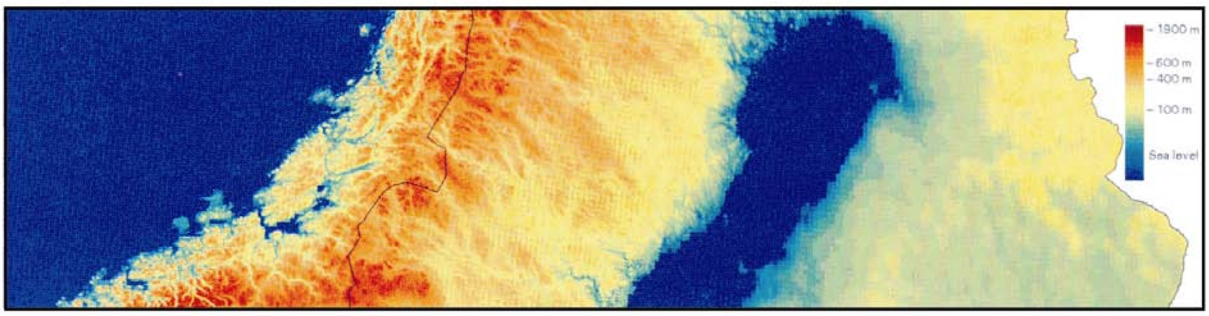


Fig. 4.19
Digital elevation model of Central Fennoscandia that shows the level lowland of Finland and eastern Sweden (greenish and yellow colours) and the contrasting highland in a broad zone along the Swedish-Norwegian international border and in most of Norway (orange and red colours). Reproduced from Bargel et al. (1999a).

had a crucial bearing on the dynamics of the inland ice-sheets and formation of the Quaternary deposits through time.

The mountain range and the fjords in the western part of the area (Fig. 9.3) have been reshaped largely through erosion by glaciers and inland ice-sheets (e.g., Holtedahl 1967). Despite the massive erosion of the bedrock caused by the ice sheets, the deposits are generally thin, and the bedrock is frequently exposed. The eroded material can be found deposited in the fjords (Oftedahl 1977), but lies mainly on the continental shelf (e.g., Holtedahl 1993, Rokoengen et al. 1995).

To the east of the mountain range, the erosive effects of the ice on the landscape tend to diminish gradually with the diminishing height and relief of the topography. The general landscape slopes gradually down towards the Gulf of Bothnia before gently rising again in Finland (Fig. 4.19). The erosional impact of the inland ice-sheets is significantly less prominent in these more level areas than in the mountains. However, the eroded material has not been removed from these areas and, therefore, the thickness of the glacial deposits is usually greater and becomes gradually thicker in an easterly direction.

This distribution of the surficial deposits is in accordance to the general glaciological models for ice-sheet erosion and deposition (e.g., Sugden & John 1976, Hughes 1981). The models predict that little or no erosion takes place in the central parts of the ice sheet because the ice sheet is frozen to the substratum (cold-based ice). In the peripheral parts of the ice sheet, the ice is warm-based and erodes the substratum.

Numerous, small end moraines that were deposited during the period c. 13,0-9,5 ka BP characterize the Norwegian part of the area. All these end moraines show an unstable ice margin at the time of deposition; the margin reacts relative rapidly to small changes in the ice volume. This is probably because of the sliding effect of the warm-based glacier sole. On the eastern side of the ice sheet, in Finland, there are few, but huge, end moraines that were deposited in less than 1 ka. This shows a stable, and steadily melting ice margin that was not able to react much to smaller variations of the ice masses. The existence of very long esker trains above, and numerous De Geer moraines below the highest marine shore level, leads to the same conclusion. The situation in Sweden is partly comparable with the Finnish one.

The problem of east-west migration of the ice divide and glacier dynamics is further discussed in Chapter 9.

Chapter 5 The Central Fennoscandian Glacial Geomorphology and Palaeohydrography map (Enclosure 2)

5.1 The map compilation

The Map of Glacial Geomorphology and Palaeohydrography at a scale of 1:1,000,000 (Bargel et al. 1999b) shows the most striking morphological imprints of the inland ice sheet and the melt-water on the landscape. The drumlins, De Geer moraines, ice-marginal and other transverse moraines, hummocky moraines, eskers and glaciofluvial erosion systems are visualised. Late Quaternary fault lines, areas below the highest postglacial coastline and modern glaciers are also shown (Fig. 5.1). The main features of these formations are described below.

The Norwegian part of the map was compiled using data from four Quaternary geological county maps (Reite 1990, Follestad 1994, Bargel 2001, Sveian et al. in prep.). The Swedish part is based on information obtained by interpretation of aerial photographs and carried out within the framework of the Mid-Norden project (see Introduction to Part II) and on information extracted from the Geological Survey of Sweden map series Ak (N^{os} 1-24). The Finnish part is based on the Atlas of Finland (1986, 1990), Kujansuu & Niemelä (1984), Niemelä et al. (1993), and on various maps published by the Geological Survey of Finland.

5.2 Geomorphological features

5.2.1 Drumlins

Drumlins are streamlined, elongated ridges formed at the base of an inland ice sheet or a glacier. They commonly consist of till, sometimes with a core of bedrock. Drumlins form parallel to the ice-flow direction and tend to occur in groups, so-called drumlin fields or drumlin swarms. The drumlins may be up to 50-60 m thick, 200-300 m broad and several km long. The most prominent drumlins and drumlin fields are situated in Finland where the topography, in large areas, is dominated by these ridges (Fig. 4.16).

Fig. 5.1
The legend of the Central Fennoscandian Glacial Geomorphology and Palaeohydrography map. Reproduced from Bargel et al. (1999b).

Drumlins, albeit less prominently on the map, are common along the coast of Sweden between Nordmaling and Luleå (Fig. 1.1, Fig. 5.2). A glacier that was moving towards the southeast formed most of the drumlins in Sweden, but in the Östersund area some drumlins indicate a northeastly-moving glacier (Lundqvist 1969) and a more southerly flow is registrated in the Umeå area (Granlund 1943, Lundqvist 1987). Very few drumlins are situated in the Norwegian part of the area. They are normally small and seldom occur in swarms. A west-northwest moving glacier deposited most of these drumlins (Reite 1990, 1994c).

5.2.2 De Geer moraines

De Geer moraines are rather narrow till ridges, generally occurring in series and separated by one hundred to a few hundred metres. The ridges are thought to have formed in cracks in the ice within the marginal zone of receding ice in an aquatic environment. Blake (2000) advocates formation at the grounding line of a tidewater glacier, and that the glacier may also have advanced and included marine sediments with shells in the moraines. De Geer moraines are deposited parallel to the ice front and are usually from less than one hundred to a few hundred metres long and up to 5 m high. The moraines are mostly located in the Vaasa area in Finland (Zilliacus 1987) (Fig. 5.3) and the Luleå area in Sweden (Fig. 5.4). In Norway, a few localities are found in Møre where several ridges are also located in fjords (Larsen et al. 1991).

5.2.3 Ice-marginal moraines

Ice-marginal moraines are ridge-shaped formations deposited in front of an advancing or stationary glacier margin. If the glacier terminates in water, the deposits are commonly stratified and consist of till beds as well as beds of glaciofluvial sediments. If the glacier terminates on land, the deposits consist mainly of unsorted material (till) (Fig. 4.8). By far the most numerous ice-marginal moraines are located in the coastal areas of Norway (Fig. 4.5). The ridges are mostly small, but tentative correlation is relatively easy as they are often situated close to each other (Sollid & Reite 1983, Sveian 1997). The largest ridges are normally situated in the valleys; they were deposited during the Older Dryas-Preboreal time interval (Fig. 4.7).

Fig. 5.2
Drumlins on the western coast of the Gulf of Bothnia, near Byske, north of Skellefteå, Sweden. Photo: Robert Lagerbäck. Reproduced from Bargel et al. (1999b).

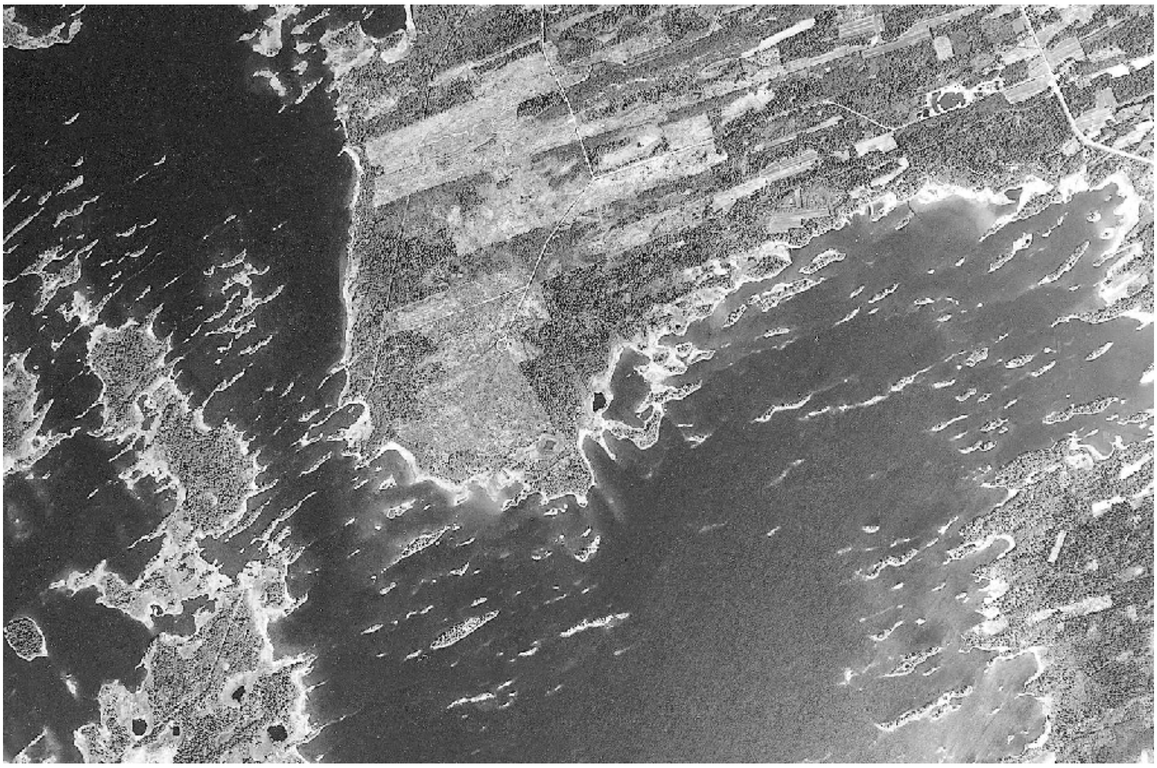


Fig. 5.3
Aerial photograph showing the De Geer moraines near Björköby in the Vaasa archipelago, Finland. Photo: The National Land Survey of Finland. Reproduced from Bargel et al. (1999b).

Fig. 5.4
De Geer moraines at Storgrundet in the Luleå archipelago, Sweden. Photo: Robert Lagerbäck. Reproduced from Bargel et al. (1999b).

Small, and often discontinuous moraines are often located in the mountains (Fig. 4.8). In Møre there are numerous small cirque moraines in the mountains that were deposited by local glaciers during the Younger Dryas. In Finland there are relatively few ice-marginal moraines, but most of them are huge and very long. The oldest ones are situated in the Oulu area in northwest and were probably deposited during the Weichsel I glaciation (e.g., Atlas of Finland 1990). An end moraine zone, with moraine capped by till, is interpreted as the southern end of the prime Weichselian glaciation (Sutinen 1992). The most impressive ice-marginal moraines are situated in the easternmost part of the Finnish part of Central Fennoscandia, and belong to the Salpausselkä formation that was deposited during the Younger Dryas. These ridges are mostly composed of sorted material due to their aquatic deposition in the Baltic ice lake, but till is often found on the surface of the ridges. Several huge ice-marginal moraines of Preboreal age are situated in the central and the northern part of the Finnish map area. In the Swedish part there are no ice-marginal moraines, indicating fluctuating ice margins during the last deglaciation.

5.2.4 Other transverse moraines

These moraines represent a variety of ridges oriented more or less at right angles to the ice-flow direction. The ridges are generally broader and higher than De Geer moraines and their length may vary from some hundreds of metres to a few kilometres. The so-called Rogen moraines are included in this group. All these moraines generally occur in valleys or in flat-lying areas. Numerous transverse moraines occur in much of the Swedish area, (Fig. 4.12), and they are often associated with the hummocky moraines. In Finland these moraines are principally found in the southwestern part. In Norway no moraines of this category are mapped.

5.2.5 Hummocky moraines

Hummocky moraines are generally characterised by hummocks and/or ridges that are distributed in a more or less irregular pattern, generally denoted as ablation moraine. Varieties with pronounced orientations, such as slightly drumlinized, hummocky terrain and terrain dominated by transverse features (denoted on the map by brown shading mixed with transverse ridge symbols) are also included in this group. Geographically these morphological elements have a slightly wider distribution than, and are often associated with "other transverse moraines". Hummocky moraines are therefore found in all the three countries, but most frequently in Sweden, (Fig. 4.11).

5.2.6 Eskers

Eskers are long, often steep-sided ridges composed of glaciofluvial sediments (Fig. 4.17), commonly sand and gravel that was deposited in tunnels or open cracks in the inland ice. The course of an esker tends to run parallel to the ice-flow direction. Most of the eskers within Central Fennoscandia are of relatively fresh appearance and are interpreted as having formed during the last deglaciation. However, a significant number of them were demonstrably formed prior to that (e.g., Lagerbäck & Robertsson 1988). These more ancient eskers are often smoothed by glacial abrasion and covered by one or several beds of till. In Sweden and Finland eskers can be followed more or less continuously for several hundred kilometres, (Fig. 4.13), and they are common in the valleys in most of the mapped area. In the Norwegian part of Central Fennoscandia the eskers are normally less than one km long and are situated in flat-lying areas above the postglacial marine limit.

5.2.7 Glaciofluvial channels

Glaciofluvial channels are erosional features produced by meltwater streams from a wasting glacier or inland ice. The channels may be incised in the deposits or into bedrock. When cut into bedrock, fault zones have governed the course of the meltwater streams with the running water wearing away the shattered rock material within the fault zone. It ought to be noted that the symbol on the map merely denotes erosional features. Major meltwater streams that have not left any significant morphological imprints are not marked on the map. These channels are most pronounced in Sweden and Finland, probably due to the more common, thick deposits, (Fig. 5.5, Fig, 5.6). In Norway most of the glaciofluvial drainage was directed to the deep valleys, and they are not mapped as glaciofluvial channels.

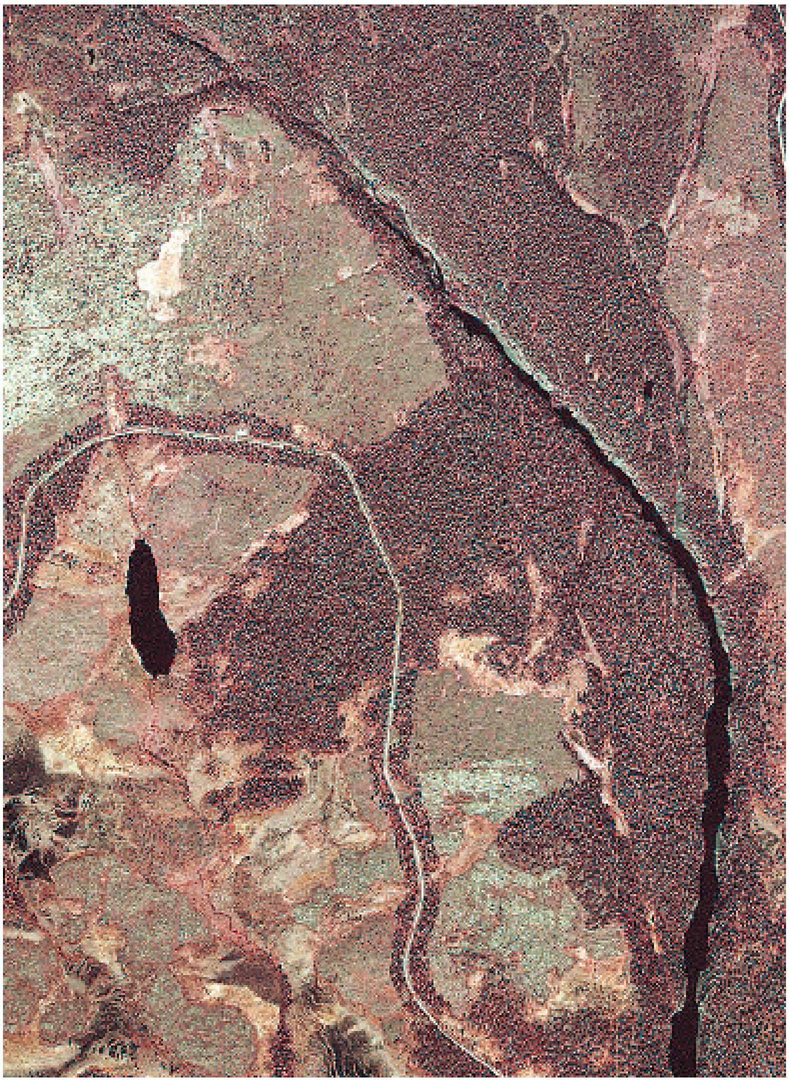


Fig. 5.5
Aerial photograph showing Julma-Ôlkky, a subglacially incised canyon near the village of Hossa in the Kuusamo district, Finland. The subglacial meltwater flowed from north to south (from top to bottom of the photo). Several tributary channels can be seen, especially in the upper right corner. Photo: The National Land Survey of Finland. Reproduced from Bargel et al. (1999b).

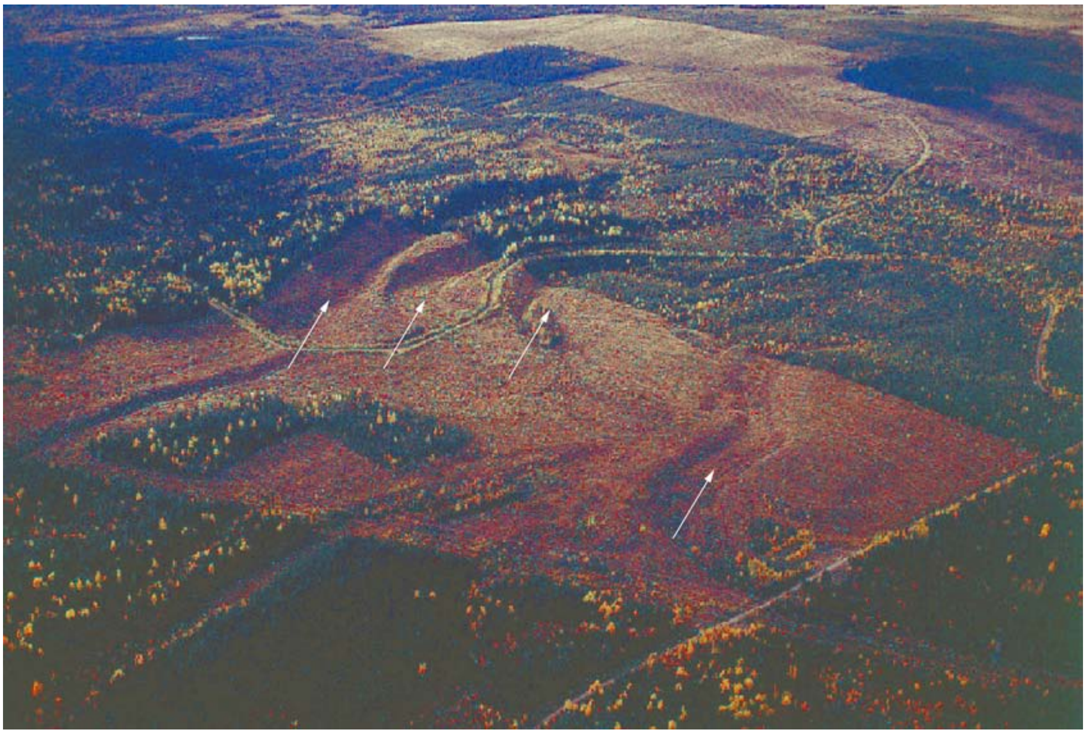


Fig. 5.6
Major glaciofluvial channels (arrows) incised in glacial till at Ytterbodarna, some 35 km WNW of Sollefteå, Sweden. Photo: Robert Lagerbäck. Reproduced from Bargel et al. (1999b).

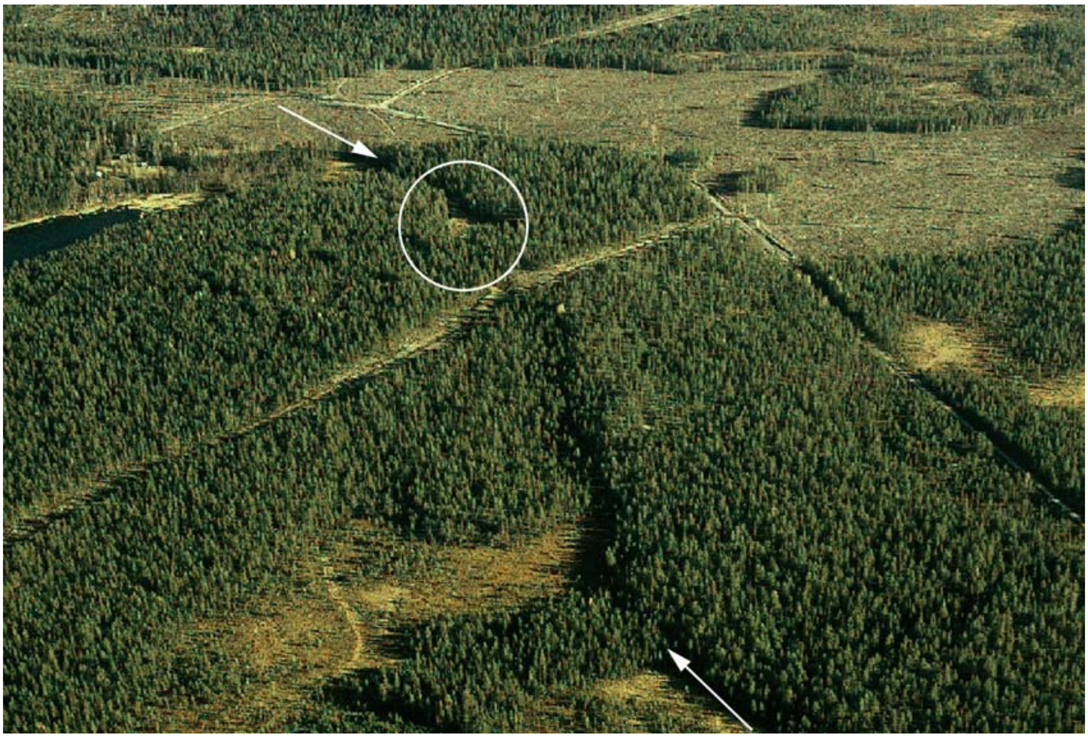


Fig. 5.7
Late- or postglacially developed fault scarp at Röjnoret, some 40 km to the west of Skellefteå, Sweden. The scarp runs diagonally across the photograph, from upper left to lower right, as indicated. The trench shown in Fig. 5.8 is encircled. Photo: Robert Lagerbäck. Reproduced from Bargel et al. (1999b).

5.2.8 Late Quaternary faultlines

Faultlines are conspicuous steps in the Quaternary deposits that can be traced over long distances. The faults are probably due to the isostatic uplift. The height of the scarps generally ranges between just a few to some tens of metres. The dating of the fault scarps is based mainly on their remarkably fresh appearance, though their young age has also been confirmed by examining the stratigraphy in trenches cut across some of the scarps. Faultlines are documented in the coastal areas of Sweden (Svedlund 1985, Rohde et al. 1990, Lagerbäck 1990) (Fig. 5.7, Fig. 5.8).

Fig. 5.8
Trench section across a fault scarp near Röjnoret (see Fig. 5.7). The fault movement is reverse, and the bedrock (orange coloured and heavy disintegrated) exhibits a 7 m high hanging wall (corresponding to the height of the step in the overburden). All the till units are abruptly cut by the fault, indicating movement of late- or postglacial age. Photo: Robert Lagerbäck. Reproduced from Bargel et al. (1999b).

5.2.9 Areas below the highest postglacial coastline

During the main phase of the Weichselian glaciation the Mid-Norden area was deeply depressed by the load of the continental ice sheet. When the ice melted the Earth's crust began to rise, but was still far below its present position when the ice finally disappeared. Extensive areas of what is now dry land were covered by water. These areas are denoted by blue shading on the map (Fig. 4.9, Fig. 4.14, Fig. 4.15). The ice-sheet was thickest in the Gulf of Bothnia district, and the crustal depression was greatest in this area, about 800 m below the present level. The highest shoreline is c. 285 m above the present sea level, and is situated near Kramfors at the southernmost part of the Swedish Central Fennoscandia (Fredén 1994). In Finland the highest shoreline is situated northeast of the Gulf of Bothnia at c. 220 m above the present sea level (Atlas of Finland 1990). In Norway the uppermost limit is at 200 m located at the eastern end of the lake Selbusjøen east of Trondheim (e.g., Reite 1994c).

5.2.10 Glacier

A few glaciers are found in Central Fennoscandia (Østrem et al. 1973, 1988). All of the glaciers are very small and are mostly of the cirque type. These glaciers are situated in the highest mountains in Møre and in the Røsvatnet-Børgefjellet area in Norway. Some very small glaciers are found in Sweden. Only the glaciers in Møre are presented on the map, and because of their small sizes they are hardly visible.

Chapter 6 The Central Fennoscandian Ice-flow Indicators and Quaternary stratigraphy maps (Enclosure 3)

6.1 Compilation of the map of Ice-flow Indicators

The Map of Ice-flow Indicators at a scale of 1:1,000,000 (Bargel et al. 1999c) shows a representative selection of glacial striations, drumlins and till fabric measurements. The age relations of striations with different directions at the same locality are indicated. Included on this map are also ice-marginal features and the inferred positions of the different stationary ice margins during the last deglaciation period as interpreted mainly from ice-marginal deposits (Fig. 6.1).

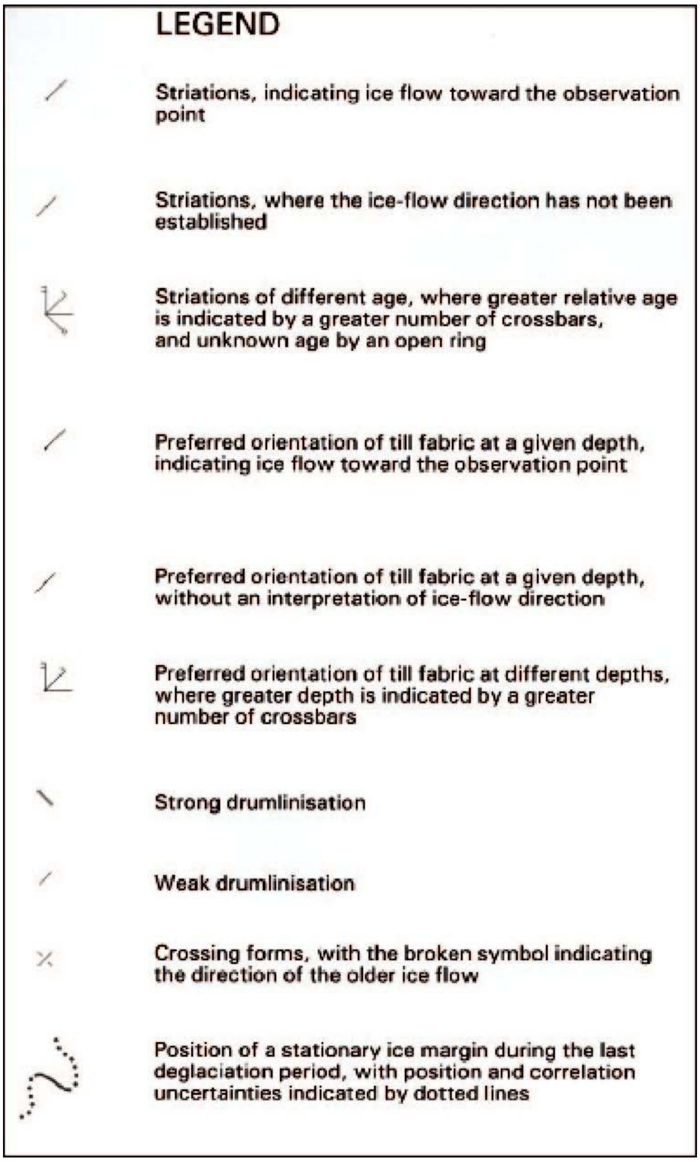


Fig. 6.1
The legend of the Central Fennoscandian stratigraphy map. The legend is in colour, but is shown here in black and white. Reproduced from Bargel et al. (1999c).

The *Norwegian* part of the map is compiled using data from Rekstad (1917b, 1924), Foslie (1957), Reite (1990), Follestad (1994c), Bargel (2001), Sveian et al. (in prep.), and various detailed maps published by the Geological Survey of Norway. The *Swedish* part is based on information extracted from the Geological Survey of Sweden map series Ak (N^{os} 1-24) and Ca (N^{os} 45, 55). The *Finnish* part is compiled from information extracted from the database for Mapping of Quaternary

Deposits in Finland. The interpretation of streamlined glacigenic forms in Finland is based on the National Board of Survey's digital topographic information. All the national datasets have been supplemented with previously unpublished material from investigations carried out within the framework of the Mid-Norden Project.

6.2 The ice flow in Central Fennoscandia

6.2.1 Ice flow indicators and age

Glacial striae on bedrock surfaces are the most common ice flow indicators in Central Fennoscandia. When the correct direction is determined (the one of the two possible), exact information of the direction of movement of the bottom of the ice is at hand. If many coinciding striae observations are obtained from an area, we can conclude that the ice masses that transported the erosive objects were moving in a certain direction. The problem is, however, that the "age" of the directions observed is not easy to obtain. When crossing striae are observed, the relative age relationship may often be determined. In areas with long-lasting erosive conditions such as found in the Norwegian area, the striae are most probably a result of the latest flow direction, which in many areas could also have been the most dominant flow direction (Fig. 6.2). In Sweden and Finland, where less erosive glaciers acted, the situation is sometimes more complex.

Till fabric, measuring of the orientation of elongated clasts in tills, has in many situations revealed a till stratigraphy with strong variations in the ice movements, dating back to pre-Eem glaciations (e.g., Olsen et al. 1996c). *Drumlins* and the transverse till ridges of the *Rogen* type were probably deposited at the base of the ice 200-700 km inside the ice margin during the end of the deglaciation (Fig. 4.12, Fig. 4.16). Even though some information on ice flows older than the last glacial maximum can be seen on the map, the following discussion deals only with the deglaciation period.

6.2.2 The ice flow during the last deglaciation

The general pattern of the ice flow is from the highest part of the ice sheet (ice divide or ice domes) towards the lower and more peripheral areas, which normally would mean flow perpendicular to the ice margin. Even though the map shows glacial striae in many different directions, well developed glacial sculpturing like, e.g. roche moutonnées indicates that the general directions were maintained for an extended period of time.

Fig. 6.2
The oldest dominant ice-flow direction towards the west and northwest in most parts of western Central Fennoscandia was not only confined to the valleys that were oriented parallel to that direction, but is found in the mountain areas as well. This photograph shows the sculpturing of the bedrock at Mellingsfjellet, in the Majavatnet area, southern Nordland, at c. 670 m a.s.l. The ice-flow direction (NW) is indicated (arrow). Photo: Terje H. Bargel.

Many of the glaciations probably started in the Scandinavian mountain chain, and as the ice volume and thickness increased, the ice flowed towards the coastal areas in the west and the inland areas in the east, from an ice divide that was located parallel to the mountain chain. Simultaneously with the ice growth, the elongated ice divide migrated to the east. The ice flow was directed from the ice divide towards the southeast in most of the Swedish inland and coastal areas and in most of Finland, and towards the west and northwest in the mountains and in most of Norway. This situation is well documented in Sweden where striae with a westerly direction are found relatively far to the east, and this direction is more common closer to the mountain chain. Not all the glaciations followed this pattern. Several older glaciations probably didn't grow into huge ice sheets like the Late Weichselian ice sheet.

The detailed pattern of the ice flow in Central Fennoscandia area was mostly determined by:

a) the bedrock relief
b) the changing position of the culmination area or the ice domes, and
c) the production of ice lobes.

In areas of low *bedrock relief*, or when the ice is considerable thicker than the amplitude of the topography beneath, the ice flow is independent of the topography and will tend to flow in the direction of the inclination of the ice surface (e.g., Paterson 1981). Otherwise, the ice flows tend to follow depressions in the landscape, which are mostly excavated by the ice itself, like fjords, valleys and mountain passes. This phenomenon is dependent on the magnitude of the relief, and is consequently most accentuated in the mountainous areas in the western part of Central Fennoscandia (e.g., Andersen & Nesje 1992). Ice streams in bathymetric depressions on the Norwegian shelf have been discussed by, e.g. Ottesen et al. (2001) (Fig. 6.3).

The oldest registered ice flow in the western part of Central Fennoscandia is towards the northwest or west and is not only documented by glacial striae but also by till fabric (Follestad 1990c, Reite 1994c). Most of the valleys and fjords along the Norwegian coast are oriented parallel to this direction, and hence the ice flow has been almost unchanged in these areas during the time interval under consideration. Several fjords and valleys, however, are oriented at oblique angles, or even perpendicular to the oldest ice movements. In such situations, the ice flow, as long as the ice was thick enough, has crossed the deep valleys and fjords as is demonstrated in most of the SW-NE - oriented structural fjords and valleys in Møre, in the northeastern part of Trondheimsfjorden and in several smaller fjords farther north. In the last phase of the deglaciation Trondheimsfjorden acted as a confluence basin for ice flow from the north, east and south. The ice sheet has also crossed the Namdalen valley perpendicularly. In Sweden, confluent striae show that huge ice masses were probably channeled through the Storsjö basin across Storlien to Trondheimsfjorden in the west for a long period of time (Lundqvist 1969), across the relatively low pass point in this area (430 m a.s.l., Fig. 9.3). It has also been demonstrated, that huge ice masses were channeled through the Limingen-Namsvatnet basin (370 m a.s.l.) to Trondheimsfjorden, Namdalen and Follafjorden.

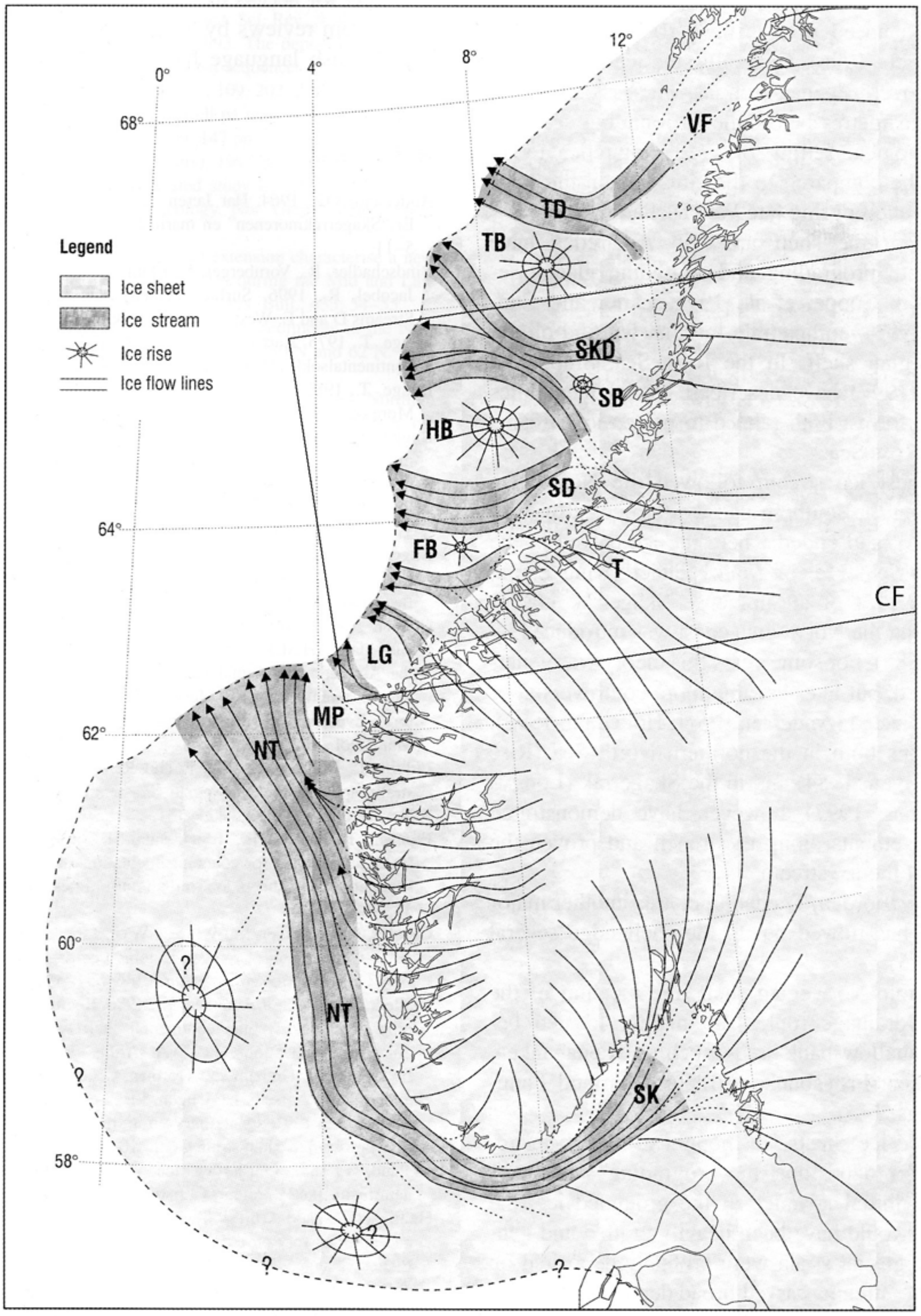


Fig. 6.3
Simplified late Weichselian ice-flow model showing ice streams flowing along the main offshore depressions on the Norwegian Continental Shelf. The onshore ice flow directions indicated apply only to the topmost part of the ice sheet during the glacial maximum. The Central Fennoscandian map sheet area is indicated (CF). From Ottesen et al. (2001).

The *ice culmination area* could be elongated, as along a mountain chain, or could consist of several separate domes. Radial, more or less independent ice flows can be generated from each dome, and opposing flows from different ice domes will be deflected and coincide, as demonstrated in the area south and southeast of Trondheimsfjorden where the ice flow in the northeastern direction from the Trollheimen-Jotunheimen mountains (located in Norway south of the Central Fennoscandian map sheet area) is deflected towards the north by the northwestern ice flow from the border zone (e.g., Sollid & Reite 1983, Nesje et al. 1987). The ice dome or domes are normally not stationary during a glaciation, and changing positions will lead to changing ice flows, sometimes even to complete reversal of the ice flow directions. This was demonstrated from, e.g. inland Sweden by Ljugner (1949) who mapped the east-west movements of the elongated Fennoscandian ice sheet during the Weichselian, based on analyses of age relationships of glacial striae.

During the deglaciation, ice masses could be dynamically isolated from the main ice sheet and act as separate glaciation centres for a limited period of time. Great deviations from the regional ice flow could also then be the result, as discussed in Chapter 9.

During the Younger Dryas ice margin readvance in Finland, the ice flow was separated into several *ice lobes* in which the ice movement directions at the ends of the lobes took varying directions, perpendicular to the curved ice margin (Ch. 8.2). The greatest lobes within the Central Fennoscandian map sheet area are the Kuusamo lobe in the north, and the North Karelian ice lobe or the Oulu lobe in the south (e.g., Punkari 1980, Aario & Forsström 1979). These great lobes were divided into several smaller lobes, as shown by attached esker systems. Different activity in the lobes was responsible for variations in the structure and size of the Salpausselkä end moraines. The northernmost lobe moved in an easterly direction into Russia and deposited the Rugozero and the Kalevala end moraines and the Kuusamo drumlin field. The southernmost lobe moved towards the southeast into Russia and deposited the southern part of the Rugozero and the Pielisjärvi end moraines and the Kuhmo drumlin field (Fig. 8.1).

In the Salpausselkä zone there are groups of striae formed by two or three ice lobes of different ages. The borders between the lobes are well marked. Based on the striae, the oldest ice flow in this area was to the southeast (Repo 1957). The morphology of the Salpausselkä end moraines morphology shows that the inland ice was moving in a different manner from before, when the Salpausselkä I was deposited. This fact is in accordance with the proposed ice-free period during the Heinola-deglaciation.

The youngest striae are orientated perpendicularly to the ice margin, and the direction consequently changes as the ice margin changes, e.g. along the semicircular front of the ice lobes. Inside the great interlobate zones the striae show that the ice flow was forced towards the interlobate area, even though other interpretations have also been given (Repo 1957). The last ice movements may be grouped geographically: In the eastern part of the area the flow was in a south-southeasterly direction, and in the Joensuu area towards the south. The direction of the latest ice movements is also mostly shown by the orientation of the drumlins. In the Ilomantsi-Lieksa area the striae show an ice flow towards the east. This is in accordance with the orientation of the end moraines on the Russian area (Fig. 8.1).

6.3 Compilation of the map of Quaternary stratigraphy

The map of Quaternary stratigraphy at a scale of 1:2,000,000 (Bargel et al. 1999c) (Enclosure 3), shows, in columns, the stratigraphy of 162 excavated, drilled or natural sections, including 4 on the Norwegian Continental Shelf. The sequences represented were chosen from c. 1,500 investigated localities in Finland, c. 800 in Sweden and c. 70 in Norway. On the continental shelf the number of available drilled sections is limited, and the correlations are mainly based on seismostratigraphy. The selected sequences were intended to provide not only as much information as possible about the glacial development in the different areas, but also to give an idea of the typical stratigraphy. A new stratigraphical model for the Mid-Norden area is proposed, including rapid shifts in the western ice-margin extent during the Late Weichselian, as predicted by Olsen (1997a), and described in detail by Olsen et al. (2001a, b, c, d).

6.4 The stratigraphical data

The correlations on the Quaternary stratigraphical map (Bargel et al. 1999c) are based to a large extent on the stratigraphical model used in the map of Quaternary stratigraphy in the Nordkalott Project (Hirvas et al. 1988). However, a modification of the model has been necessary to update the stratigraphical interpretations, accommodating more recent knowledge and a new map area. The newest data from continental Norway, which are used in the model, are first summarized (Ch. 6.4.1). On the continental shelf west of Norway the correlations are based on seismostratigraphy (Rokoengen 1996). Otherwise, the data are mostly sub-till sediments or alternating till/sediment/till sequences Fig. 6.4).

In the onshore areas of Norway most correlations are related to the occurrence and stratigraphical position of the youngest extensive bluish-grey, fine-grained, regional, basal till (e.g., Låg 1948), which is represented in at least 32, possibly up to 41 of the 48 selected localities and is possibly of Late Glacial Maximum age (LGM, Olsen et al. 2001a, b, c). About 60 % of the sections located in onshore areas of Norway are natural sections along rivers and creeks, while most of the remaining sections were dug using excavators. On the map, 47 sequences are chosen to represent Finland, whereas 63 sequences represent Sweden. The majority of the stratigraphical data in these countries has come from studies of sections in pits dug by excavators. This means that the map provides little information on deeper strata as only a few of the columns represent large sections in quarries or high river sections.

6.4.1 Middle- and Late Weichselian events in Nordland

From inland localities in Norway, Olsen (1997a) and Olsen et al. (2001a, b, c) have obtained more than 100 ^{14}C-AMS age determinations from sediment layers between till beds with total organic carbon contents of 0.2-1.5 %. Determinations performed on low-organic samples like this should be looked upon with great scepticism, but the results presented are consistent throughout most of Norway, accounting for the validity of the data. These data indicate that in the interval 40-13 ka BP there were many rapid shifts in the glacial extent (Fig. 6.4 A, B), and based on these results a new conceptual model for the glacial variations during the Middle and Late Weichselian is proposed (Fig. 6.4 C). According to these age determinations, an ice free situation existed in the inland areas of southern Nordland, and a warm period at c. 39-30 ka BP led to rapid deglaciation, possibly leaving most of Norway ice-free, the *Hattfjelldal I interstadial*. The subsequent colder period resulted in an ice readvance to the coastal areas, which was succeeded by a new deglaciation, the *Hattfjelldal II interstadial* at c. 28-24 ka BP. Another climatic deterioration initiated the Weichsel maximum or the *Late Glacial Maximum* (LGM) at 24-21 ka BP, during which the ice margin was located at the outer margin of the continental shelf.

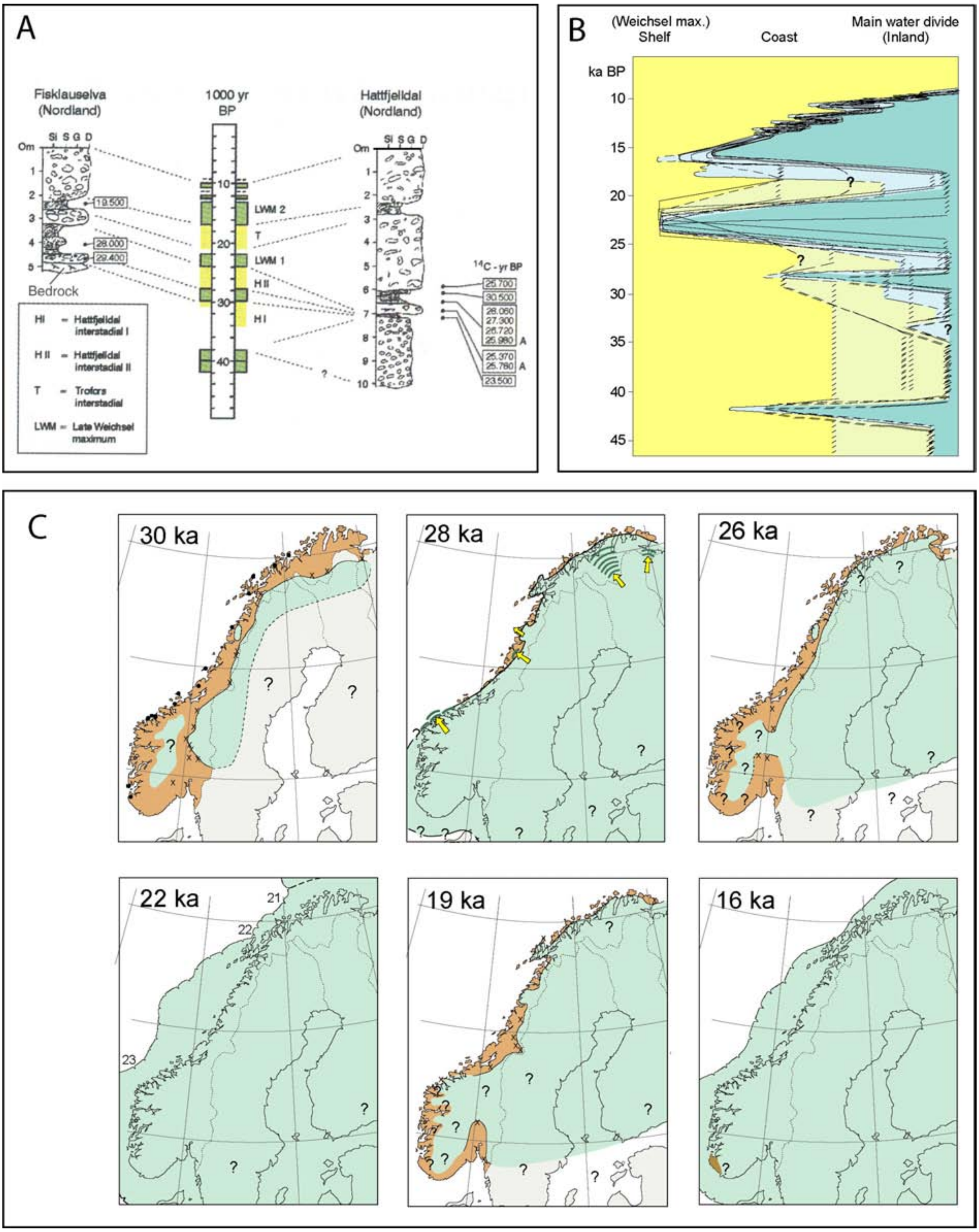


Fig. 6.4

A: The stratigraphy with dates (yr BP) at two inland sites in Nordland. These sites include sedimentary units, which represent all the main episodes shown in Fig. 6.4 B and Fig. 6.4 C. (Olsen 1997a).

B: Composite glaciation curve for Norway during the last glaciation (c. 40-10 ka BP). The curves constructed along nine profiles in most parts of Norway are all plotted on the same diagram with all profile lines defined to be of equal length (Olsen 1997a).

C: Maps showing the glacial extension and ice-free areas during six major episodes in the period 30-16 ka BP (Olsen 1997a).

The LGM has earlier been indirectly dated to c. 21-17 ka BP according to Hughes et al. (1981) and at c. 22-17 ka BP according to Andersen & Borns (1994). Newer data, as just mentioned, seems to indicate that the LGM occurred somewhat earlier, at 24-21 ka BP, followed by a partial deglaciation of the coastal parts of Norway, the *Andøya* and *Trofors interstadials* (Vorren et al. 1988, Olsen 1997a). New ice growth at 17-15 ka BP was almost as extensive as the LGM. The two stadials are called LGM 1 and LGM 2, respectively (Olsen 1997a, Bargel et al. 1999c, Olsen et al. 2001a, b, c). The main deglaciation started c. 15-14 ka BP, but small, short-lived readvances occurred at c. 15 ka BP, 13.5 ka BP, 12.2 ka BP, 10.8 ka BP and 10.3 ka BP (Enclosure 6).

6.5 The stratigraphical model for Central Fennoscandia

(Fig. 6.5, Enclosure 6)

The different units are briefly described below, from the oldest to the youngest, respectively.

On the continental shelf off Norway strata representing most of the Pleistocene and possibly even older units, have been described (Rokoengen et al. 1995). All ages are still rather uncertain. Bedrock unit IX (Fig. 4.3) was assigned an Early Oligocene age by Edvin et al. (1998), but it may be younger. The units K-E represent Upper Pliocene or Pleistocene sediments, while units D, B, A and U probably represent the last interglacial/glacial cycle. The angular inconformity beneath unit D was interpreted as a result of strong glacial sculpturing in late Saalian time, but could also be Elsterian.

The Holsteinian interglacial is the ice-free period between the Saalian and the Elsterian glacial stages. It may correlate with one or more of the oxygen isotope stages 7-11. Saalian, Holsteinian and Elsterian deposits are relatively common in Finland (e.g., Hirvas & Nenonen 1987).

The Eemian interglacial is the name of the ice-free period between the last two glacial stages (Weichselian and Saalian). The Eemian interglacial is thought to have begun about 135-125 cal ka BP and lasted for 10,000 years (cf. Nilsson 1983), or perhaps twice as long (Nielsen 1994). Eemian sediments have been described from one locality in the coastal area of Mid-Norway (Aarseth 1990, 1995) and in seismic profiles and borings on the continental shelf off Norway (Rokoengen et al. 1995, Sættem et al. 1996). In Finland Eemian sediments have been described in several localities (e.g., Hirvas & Nenonen 1987). No Eemian sediments are known in the Swedish Central Fennoscandian area so far.

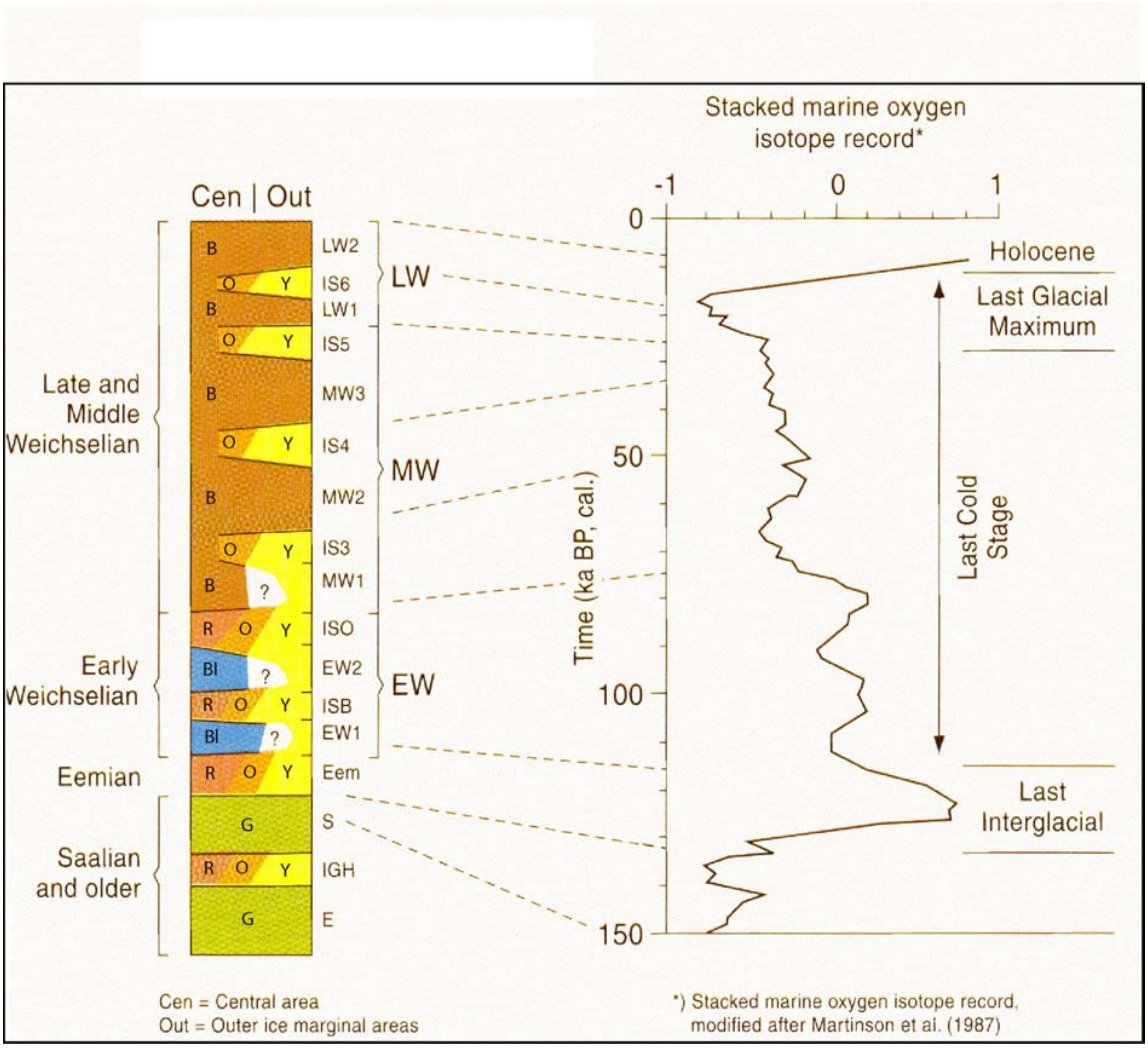


Fig. 6.5
The stratigraphical model of Central Fennoscandia and Nordland.
B: Late or Middle Weichselian till. **Bl**: Early Weichselian till. **G**: Pre-Weichselian till.
O: Coarse-grained water-lain sediments (dominated by sand and/or gravel). **Y**: Fine-grained water-lain sediments (dominated by silt and/or clay). **R**: Interstadial or interglacial organic deposits.
LW: Late Weichselian glaciation (LW1 and LW2 or LGM 1 and LGM 2).
IS3-IS6: Weichselian Interstadials (no. 3-6)
MW: Middle Weichselian glaciation (MW1-MW3).
ISO: Weichselian Interstadial no. 2 (Odderade)
ISB: Weichselian Interstadial no. 1 (Brørup)
EW: Early Weichselian glaciation (EW1 and EW2).
S: Saalian Glaciation
IGH: Holsteinian Interglacial
E: Elsterian Glaciation
Reproduced and slightly modified from Bargel et al. (1999c).

The Weichselian interstadial no. 1 is thought to correlate with the Brørup interstadial in Denmark at c. 110-80 cal ka BP (S. Th. Andersen 1961). Possible counterparts in Sweden and Finland are the Jämtland interstadial (older part) in central Sweden (Lundqvist 1967, 1981, Robertsson 1988), the Oulainen interstadial and the Horonkylä interstadial in central Finland (Niemela & Tynni 1979, Forsström 1982, 1988, Nenonen 1995) and the Peräpohjola interstadial in northern Finland and Sweden (Donner et al. 1986, Lagerbäck & Robertsson 1988, Hirvas 1991, Nenonen 1995).

The Weichselian interstadial no. 2 is thought to correlate with the Odderade interstadial in northwestern Germany at 85-75 cal ka BP (Averdieck 1967). Possible counterparts in Sweden and Finland are the younger part of the Jämtland interstadial (Vålbacken) (Mörner 1981,

Robertsson 1988) in central Sweden, the Mertuanoja interstadial in central Finland (Iisalo 1992, Nenonen 1995), the Tärendö interstadial in northern Sweden (Lagerbäck & Robertsson 1988) and the Peräpohjola (Kauvonkangas) interstadial in northern Finland (Mäkinen 1985, Forsström 1988).

The Weichselian interstadial no. 3 is thought to be of Middle Weichselian age. It is inferred to correlate with the Bø interstadial in coastal southwestern Norway, which existed c. 50-55 cal ka BP (Andersen et al. 1983). Possible correlatives in Sweden and Finland are, e.g. the Tärendö interstadial in northern Sweden (Lagerbäck & Robertsson 1988) and the interstadial represented by the Horonpa sponge deposits in central Finland (Niemela & Tynni 1979, Nenonen 1995).

The Weichselian interstadial no. 4 is thought to date from the late Middle Weichselian. It is named *Hattfjelldal interstadial I* in inland central Norway (Olsen 1997a, Olsen et al. 2001b, c) and is inferred to correlate with the Ålesund interstadial in southwestern coastal Norway (Mangerud et al. 1981) which existed some 28-39 ka BP. Rokoengen & Frengstad (1999) find that the continental shelf off Norway probably remained ice-free for a long period until after 30 ka BP.

The subsequent ice expansion was limited. Sediments in coastal caves show that the outer coastline of Møre was ice-covered c. 28 ka BP (Larsen et al. 1987). Rapid shifts in the glacial extent are recorded on the shelf (Rokoengen & Frengstad 1999), and the coast of Helgeland could have been ice-free or covered by ice for a very short interval (Olsen 1997a, Olsen et al. 2001b, c).

The Weichselian interstadial no. 5 is thought to date from c. 27 ka to the Late Weichselian maximum ice advance c. 24 ka BP. It is named *Hattfjelldal interstadial II* in inland central Norway (Olsen 1997a, Olsen et al. 2001b) and is thought to correlate with the Hamnsund interstadial in coastal western Norway (Valen et al. 1996).

At 24-21 ka BP the inland ice reached its maximum extension in Weichsel (LGM 1; Olsen 1997a). The ice margin was situated at the shelf edge along the entire western part of the Mid-Norden area (Rokoengen et al. 1995), but whether the highest mountains in Møre were ice-covered or not is still an open question (Nesje et al. 1987, 1988, McCarrol & Nesje 1993). On Andøya, in the northern part of Norway where the coastal mountains are relatively high and the shelf outside is very narrow, there are indications of ice-free parts, but no conclusive proof is yet available (Vorren et al. 1988, Møller et al. 1992).

The Weichselian interstadial no. 6 is thought to date from the interval between the two major ice advances during the broad Late Weichselian maximum. It is named *Trofors interstadial* in inland Norway (Olsen 1997a, b, Olsen et al. 2001b, c) and Andøya interstadial in coastal northern Norway (Vorren et al. 1988). The coast and the valleys were possibly ice-free, but the mountains were probably partly glaciated. The age of this interstadial is c. 17-21 ka BP.

The second ice advance of the Late Weichselian maximum occurred at c. 17-15 ka BP (LGM 2; Olsen 1997a). Generally, the ice extension in the west reached the same size during LGM 1 and LGM 2, and it ended, probably at both maxima, abruptly at the shelf edge as the glacier was calving when the water depth increased (e.g., Andersen 1979, Vorren & Plassen 2002). However, the outer parts of the shelf were possibly not ice-covered everywhere during the youngest ice advance. Vorren et al. (1988) advocated that the shelf west of Andøya was ice-free and consequently the northernmost part of Andøya was also ice-free. The main deglaciation started c. 15-14 ka BP (Chapter 8).

Chapter 7 The Nordland map of Quaternary Deposits (Enclosure 4)

7.1 Compilation of the map

The Quaternary geological map of the county of Nordland (Bargel 2001) is the most detailed map of that kind produced so far from this area. The map data are at a scale of 1:250,000 and better, but as the county is more than 500 km from north to south, the plotted version was reduced to 1:400,000 for practical reasons. Enclosure 4 was printed from the PDF-file on the attached CD-ROM (Enclosure 8).

The county map was produced as generally described in Chapter 2. Several earlier published maps at scales of 1:50,000-1:100,000 form the basis of the work (Bargel & Bergstrøm 1993, Bargel & Olsen 1995, Bergstrøm 1995, Follestad 1981, 1988a, 1990a, 1992a, in prep. a, b, c, d, e, Olsen et al. 1996a, 1996b, 2001e, Sveian 1979a, 1979b, 1980a, 1980b, 1984a, 1984b, Sveian & Vallevik 1983, Sørensen in prep.) (Fig. 7.1). These maps were digitalised and used in the county map without simplification except for the symbols for morphological details, grain sizes, etc. that are not shown.

The remaining part of the county was aerial-photo interpreted, mainly by myself kindly assisted by Bjørn Bergstrøm, Lars Olsen, Arne J. Reite and Knut Riiber, and the most probable interpretation was drawn on topographic maps at a scale of 1:50,000. About 5,000 photographs at scales of c. 1:15,000 and c. 1:40,000 were studied. The interpreted areas were then checked in the field, most thoroughly along the roads, more sparsely, or not at all, in the mountains and the most distant areas. Consequently, the reproduction of details varies, which is readily visible on the map. A simplified classification of the surficial deposits was used on this map, as only the main genetic groups are included (Ch. 2.4).

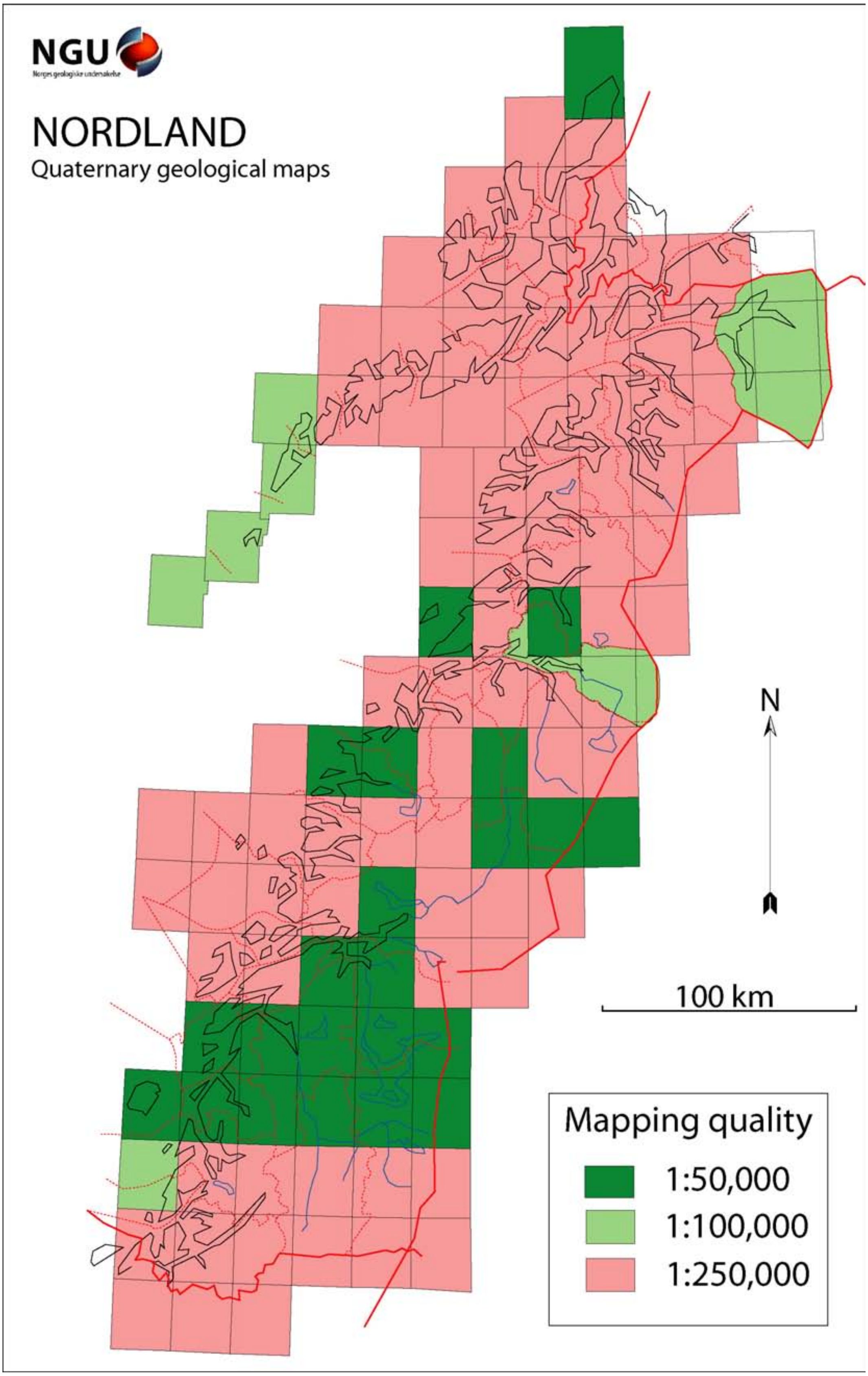


Fig. 7.1
The mapping quality of the surficial deposits in Nordland shown on the 1:50,000 map grid from the State Mapping Authority (Statens kartverk). Compiled from NGU´s map catalogue available on the web site http://www.ngu.no/.

7.2 Regional description

The morphology and the sediments in Nordland will be described using the same criteria as for the Central Fennoscandian Map of Quaternary deposits (Bargel et al. 1999a). Several geographically different areas were defined, and the criteria used were:

a) The changing character of the landscape, and
b) The regional distribution of the different Quaternary deposits

In Nordland the equivalent areas are:

1) The coastal area including the strandflat
2) The fjords, valleys and the island archipelago in the north, and
3) The mountains

Generally, the Quaternary deposits are extremely sparse and exposed bedrock is the most dominant feature (Fig. 7.2, Fig. 7.3, Fig. 7.5, Fig. 10.2, Fig. 11.23).

1) The coastal area includes the strandflat and the outermost part of the fjords. The strandflat (Ch. 4.3.2) is present along the entire coast of Nordland and has its best expression along the Helgeland coast where it extends 50-60 km from the coastline (H. Holtedahl 1998). The greater part of the strandflat is situated below sea level, but the supramarine parts show characteristic and often quite spectacular landforms (Fig. 4.4). The onland termination of the strandflat is commonly marked by a cliff, often several hundred meters high, occasionally with wave-washed caves, as many monadnocks on the islands have too (Sjoberg 1988) (Fig. 7.2, Fig. 10.5). Wide scree deposits can often be seen below these cliffs. Very little sediment occurs on the strandflat; usually only scattered wave-washed sediments and bogs are present. Marine clays are occasionally situated beneath these sediments. Moraines representing the Older Dryas or the Younger Dryas Substages are locally present. They are sometimes heavily wave washed and the characteristic ridge form is partly destroyed, as with the Vega moraine, the Tjøtta moraine (Andersen et al. 1982) and most of the moraines on Andøya (Fjalstad 1997).

2) The fjords and the valleys dissect the mainland heavily; even though the linear distance from north to south is c. 500 km, the mainland's coastline is almost ten times as long. The length of the coastline including the islands is close to 10,000 km. The distance from the sea to the present watershed is less than 10 km in several tributary fjords situated at the inner end of the wide Vestfjorden, namely Tysfjorden, Skjomenfjorden (Fig. 7.3) and Rombaksbotn (Bargel et al. 1995a). Very few other fjords and accompanying valleys penetrate the entire county from the west to the east; more commonly the fjords trend partly perpendicular to the coastline and partly parallel to it, as do the valleys. The same pattern can be seen in the Lofoten-Vesterålen area where huge islands predominate and NS-trending sounds separate them. As a result of the glacial erosion, most of the fjords are overdeepened by several hundred meters. Many of the fjords have acted as confluence basins for the ice flow.

Fig. 7.2
The Træna islands are situated c. 40 km off the coast of Helgeland, Nordland. The mountains are monadnocks on the strandflat, which is close to 60 km wide in this area. Several large coastal caves are situated at the base of the steep mountain at the centre of the picture. The well-known Trænstaven (336 m a.s.l.) to the right is here seen from the east. Photo: Terje H. Bargel.

Moraines representing the Younger Dryas Substage are present in most of the fjord mouths, except for the area west of Svartisen where the Younger Dryas moraines occur near the fjord heads, which is the most frequent location of the Preboreal moraines in Nordland. Below the marine limit, small areas of marine clay are situated, most frequently on low-lying isthmuses and in the valleys. The clays in the valleys are frequently covered by fluvial sediments, which are often coarse-grained because of the rough topography (Fig. 7.4).

Vast areas of marble and dolomite, which exist in greater parts of the county, are normally heavily weathered, and karst terrain, including caves, is abundant. The greatest underground karst lake in Scandinavia is located in the Trofors area (e.g., Horn 1947, Lauritzen 1986). Monzonitic rocks in the county are frequently deeply weathered, especially in the Hamarøya and the Lofoten-Vesterålen areas (Peulvast 1985).

3) The mountains most often emerge at steep angles directly from the coastal strandflat to heights up to 600-800 m a.s.l. (Fig. 7.2, Fig. 10.2, Fig. 10.5). However, the highest mountains are situated close to the main watershed, e.g. Oksskolten at 1916 m a.s.l., Suliskongen at 1907 m a.s.l. and Storsteinsfjellet at 1894 m a.s.l. (Enclosure 7). Most of the mountains have very little Quaternary deposits and are often heavily ice-polished. A few exceptions exist: On the Saltfjellet plateau and in the Børgefjellet and Røsvatnet basins thick till dominates vast areas; even hummocky till is found.

On some higher mountains frost shattering or exfoliation has produced block fields, and talus is relatively common (Fig. 7.5). Several relatively large plateau glaciers and many cirque glaciers exist in the mountains. The mountains on the Lofoten and Vesterålen islands give a quite different impression due to the heavy werathering of monzonitic bedrock (Fig. 7.6, Fig. 10.3).

Fig. 7.3
The Sørskjomen fjord south of Narvik is a good example of a strongly glacially eroded fjord.
Photo: Terje H. Bargel.

Fig. 7.4
Most of the rivers in Nordland normally have high discharges, and combined with rough topography the sediments are most often coarse, as along the river Vefsna on this photograph. The partly forested terrace in the right background is the local postglacial marine limit (123 m a.s.l., see Ch. 11.9.3).
Photo: Terje H. Bargel.

Fig. 7.5
Talus produced by exfoliation of Reinoksfjellet in the Gjerdalen area, Salten district.
Photo: Terje H. Bargel.

Fig. 7.6
Weathering on Vestvågøya, Lofoten. Heavy weathering of monzonite rocks has produced rugged mountain topography and much weathering products.
Photo: Terje H. Bargel.

Chapter 8 Deglaciation of Central Fennoscandia and Nordland

8.1 Introduction

A short version of the deglaciation history of Central Fennoscandia and Nordland including the shelf area (Fig. 1.1) will be given below. The deglaciation of the Finnish area is described first followed by the Swedish area. Next, the deglaciation of the Norwegian shelf and then the onshore areas of Norway conclude this chapter. It will probably be helpful to have the stratigraphical model of Central Fennoscandia in mind when reading the first part of this chapter (Fig. 6.5). The map of offshore and onshore ice-marginal lines in Central Norway (Enclosure 5) and the correlation chart for the Weichselian in Central Norway (Enclosure 6) will also be essential to acquire an impression of the deglaciation pattern of the Norwegian area. The geographical names used are included in Enclosures 7 and 9.

8.2 The Eastern side of Central Fennoscandia

8.2.1 The Salpausselkäs and the Baltic Ice Lake

The ice margin retired from the Russian area in a north-northwesterly direction and reached the coast of the southeastern part of Finland c. 12.5 cal ka ago (Niemelä 1971) (Fig. 8.1). During the Allerød most of the southeastern part of Finland, including eastern Karelia, was deglaciated (the *Heinola-deglaciation*, e.g. Rainio 1985). Due to isostatic depression, the *Baltic Ice Lake* flooded parts of the area at this time (Fig. 8.3 A). The lake existed c. 13.0-10.3 cal ka ago according to Fredén (1994) or 13.5-10.3 cal ka ago (Brunnberg 1995).

In the early Younger Dryas, the ice margin, which now had been divided into several lobes (Ch. 6.2.2), advanced 50-80 km from the most proximal Allerød position and deposited the *Salpausselkä I* ice marginal formation in front of, and between the ice lobes (marginal and interlobal deposits). In North Karelia the marginal deposits are fairly wide marginal formations composed of two parallel arms. The oldest arm is found east of Ilomantsi, and the youngest arm, called the *Tuupovaara end moraine*, is found south-southwest of Ilomantsi (Fig. 8.2). The end moraines show that the ice front retreated in North Karelia during the

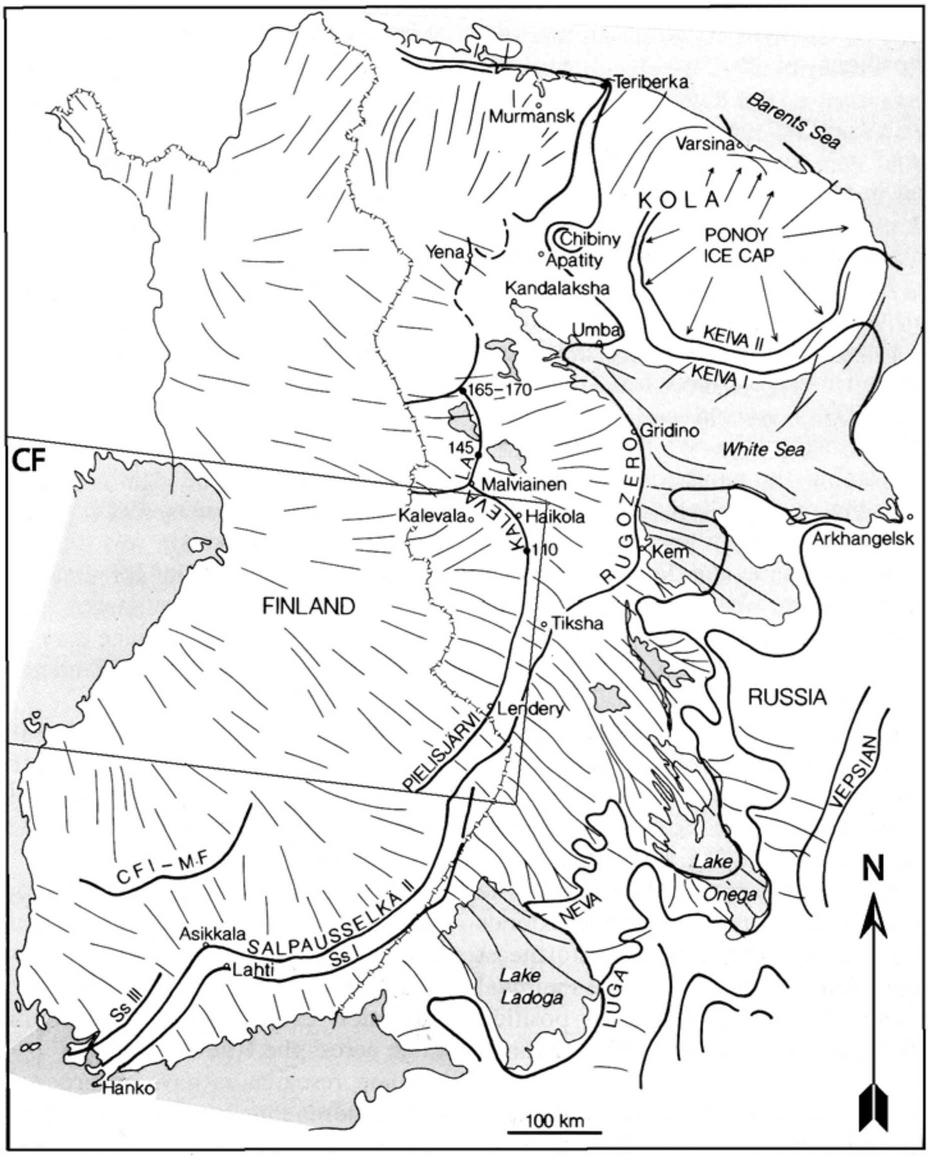


Fig. 8.1
Major end moraines in Finland, Russian Karelia and on the Kola Peninsula. The Rugozero and Karelia end moraines with their correlatives are of Younger Dryas age. The elevations of some marginal deltas are given. The main ice flow directions are indicated. The correlations in Russia are after Ekman & Ilyin (1991). The Central Fennoscandian map sheet area is indicated (CF). Slightly modified from Raino et al. (1995).

Salpausselkä I, but remained stationary farther west, south of the Central Fennoscandian area (Rainio et al. 1986).

Salpausselkä II has a north-south orientation in North Karelia and terminates just east of Joensuu (Fig. 8.2). The Salpausselkä II was deposited in late Younger Dryas. It can most probably be correlated with the *Koitere end moraine formation*, which continues in a north-easterly direction across the Finnish/Russian border (Fig. 8.2). The correlative end moraine in Russia is called the *Rukajärvi* or the *Rugozero end moraine* (Fig. 8.1).

The *Pielisjärvi end moraine* extends north-northeastwards from a position just north of Joensuu. The moraine was formed after the drainage of the Baltic Ice Lake, and is of the same age as *Salpausselkä III* in southwestern Finland (Fig. 8.1, Fig. 8.2). In Russia, the Kalevala end moraine is probably a direct continuation of the Pielisjärvi end moraine, but many Russian scientists are of the opinion that the Kalevala moraine is of Salpausselkä II age (Rainio et al. 1986).

The absolute ages of the different end moraines in Finland were obtained by varve chronology, which gives ages in calendar years BP. Salpausselkä I was deposited 11.3-11.1 cal ka ago, Salpausselkä II 10.8-10.6 cal ka ago and Salpausselkä III 10.5-10.4 cal ka ago.

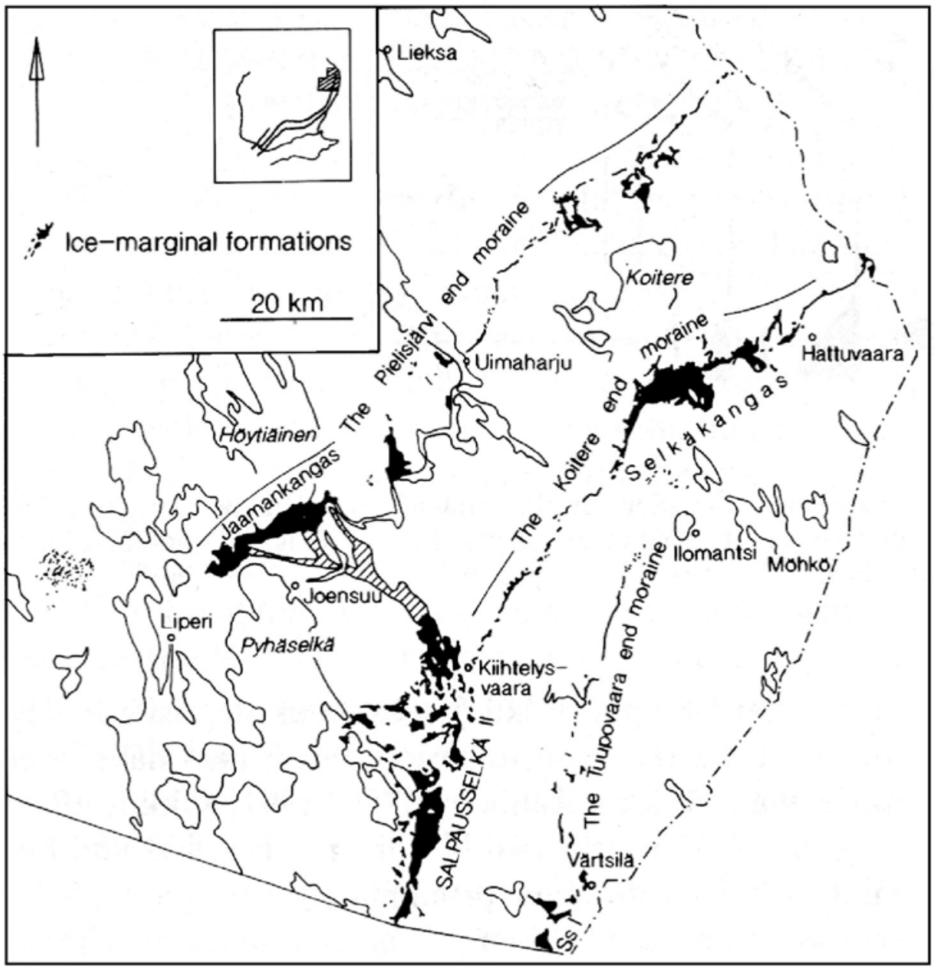


Fig. 8.2
Major end moraines in Finnish North Karelia: The Tuupovaara, Koitere and Pielisjärvi end moraines are correlated with the Salpausselkä I, II and III, or Ss I, Ss II and Ss III, respectively. The interlobate esker system between the Kiihtelysvaara and Jaamankangas marginal delta complexes is shaded (Rainio et al. 1995).

8.2.2 The Yoldia Sea

The ice margin recessed in a northwesterly direction after the Salpausselkä events. The Baltic Ice Lake was drained at about the same time as the ice margin retreated from the Salpausselkä II position (Svensson 1989). The water level rapidly dropped about 25 metres, and the new water level, which communicated with the ocean, is called the Yoldia Sea (Fig. 8.3 B). The ice sheet melted partly by calving in the Yoldia Sea in areas where the ice margin was situated in deep water. However, the water depths were generally low, and ordinary down-wasting was the dominant melting mechanism, to a great extent governed by the topography.

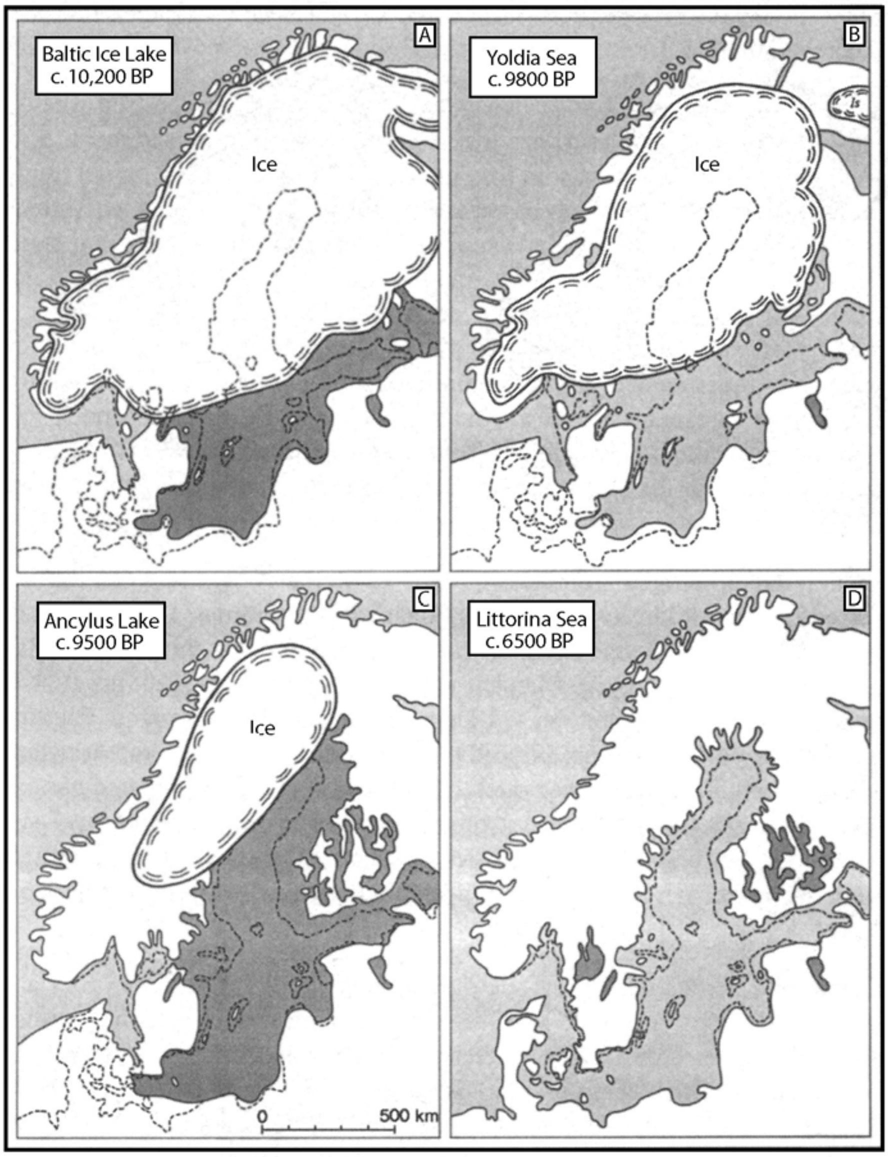


Fig. 8.3
The main Baltic Lakes with ages in ^{14}C years BP. Dark and light shading indicate fresh and salt water, respectively. Slightly modified from Lindström et al. (2000).

Long ice-tongues were located in the valleys. They were eventually isolated from the main ice and became dead in a dynamic sense, as documented by lateral erosion channels in the valley sides.

The Finnish part of Central Fennoscandia was deglaciated c. 9.5 cal ka ago. The Yoldia Sea continuously flooded the low-lying areas as they became exposed, and the highest sea level, 285 m a.s.l., in eastern Sweden, was reached at the end of the life of the Yoldia Sea. The sediments in the Yoldia Sea are mostly clays, and the oldest clay deposits show marked annual rhythmicity or *varves*. In the area around the Gulf of Bothnia the late- and postglacial developments are dated in calendar years by varve chronology (e.g., Björck 1995). An earlier interpretation of the De Geer moraines was that they formed annually. However, varve chronology has shown that the ice margin retreated c. 200-500 meters each year, while the De Geer moraines in the area are separated by less than 100 m. This clearly shows that several De Geer moraines were deposited during a year (Zilliacus 1987, Aartolahti et al. 1995).

8.2.3 The Ancylus Lake

Due to isostatic uplift of the inlet area, the Yoldia Sea was eventually separated from the ocean, and the Ancylus Lake emerged (Fig. 8.3 C). The water level then rose and transgressed vast areas in Finland and Sweden. The lake existed c. 9.5-8.0 cal ka ago. The inland ice disappeared from the Gulf of Bothnia during this period. Characteristic grey homogeneous clays and black sulphide-bearing clays were deposited. The highest sea level along the western coast of Finland, in Österbotten, at 210-190 m a.s.l., existed during this period (Glückert et al. 1993).

8.2.4 The Littorina Sea

Due to interaction of the isostatic uplift of the central part of the Ancylus Lake, and the eustatic elevation of the ocean, a connection between the two water tables was established. The Ancylus Lake was partly drained, and salt water entered the basin, creating the brackish Littorina Sea (Fig. 8.3 D). This event is marked in the sediments by an exceptionally clear lithostratigraphic change. In this sea greenish clay, rich in organic material, methane and salt-water diatoms was deposited. This sediment is today the most fertile soil in the area around the Gulf of Bothnia. All raised shorelines and shore deposits on the Finnish side were created during the Littorina Sea period, less than 7.0 cal ka ago (Winterhalter et al. 1981).

8.2.5 Sweden

At the Weichsel maximum, the ice divide was probably located in the Gulf of Bothnia. During the deglaciation, the ice divide moved westwards towards the mountain chain, and was situated just east of the mountains when it finally broke up and disappeared (e.g., Ljugner 1949, Lundqvist 1994). The ice margin moved northwards through Sweden and northwestwards across the Yoldia Sea. The deeply submerged Ångermanland was the first area in the Swedish part of Central Fennoscandia that was deglaciated. Sweden's highest coastline, at 285 m a.s.l., is located here (Fig. 8.4). This event is not properly dated, but it is tentatively thought to have happened c. 9.3 cal ka ago.

No end moraines from the deglaciation phase are found in the Central Fennoscandian area of Sweden. For this reason, and due to lack of chronostratigraphical control of the late Quaternary deposits, we only know the outlines of the deglaciation from this area (Fig. 8.4). The coastal De Geer moraines, transverse ridges of considerable dimensions, drumlins etc., were probably all deposited below sea level towards the end of the last glaciation. This age is inferred because the ridges look young, and because they fit into a logical deglaciation pattern. These criteria are still valid as used in a model for glacial development in Central Fennoscandia, although the same criteria have failed as age indicators for the last deglaciation in northeastern Sweden (Lagerbäck & Robertsson 1988). The inland position of morphological units from earlier glaciations is not known, and they cannot, therefore, be separated from younger features. Above the highest shoreline the ice sheet melted down vertically without producing end moraines. The most striking deglaciation phenomena from these areas are the erosion of the till by melt water (Fig. 5.6) and the accompanying deposition of long esker-trains in the valleys (Fig. 4.13) and huge deltas in the sea.

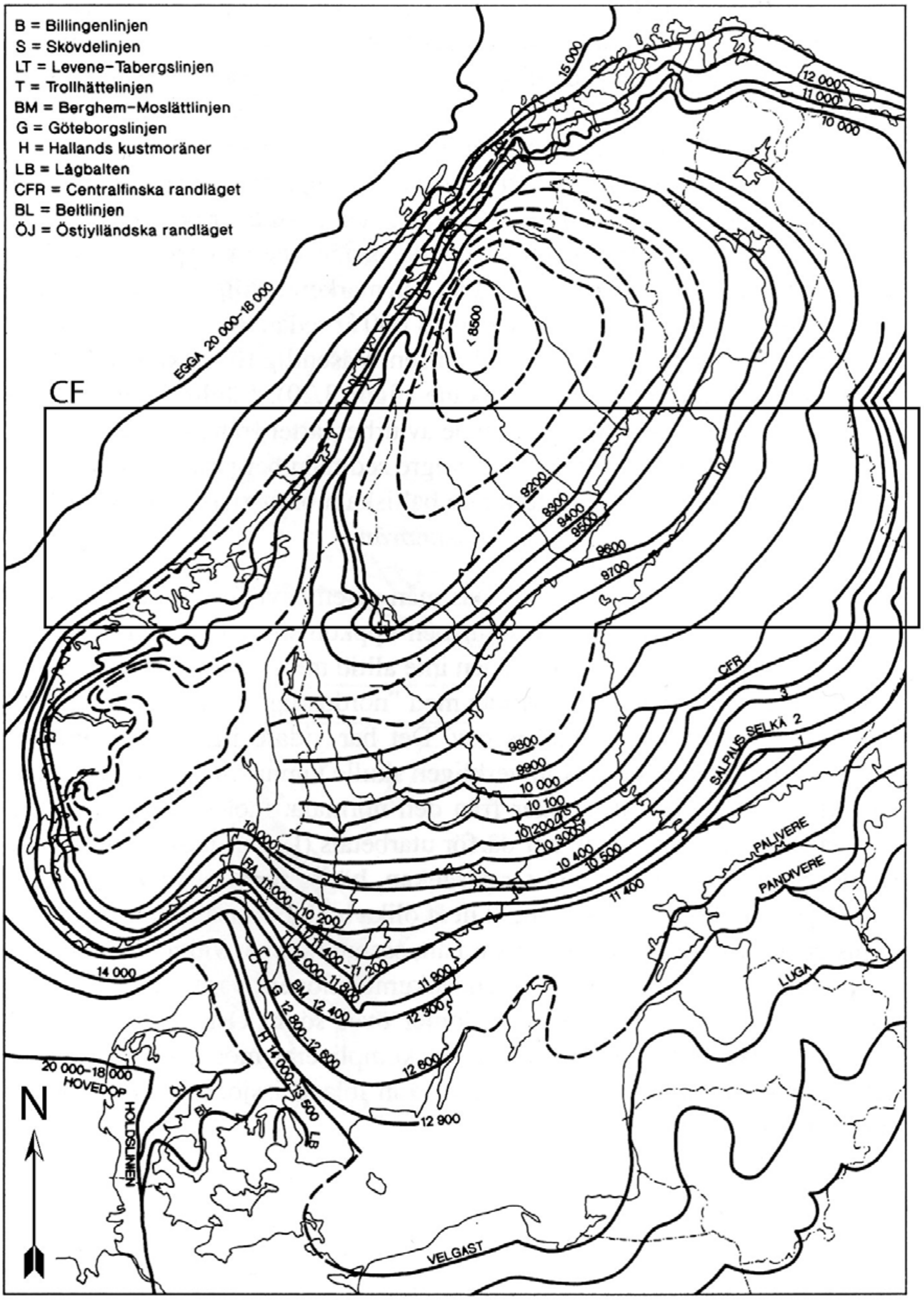


Fig. 8.4
Ice recession lines that show the deglaciation pattern in Fennoscandia. The Central Fennoscandian map sheet area is framed. The ages on the eastern side of Sweden are based on varve chronology; the other ages are based on ^{14}C-ages. As the varve chronology gives absolute ages and the ^{14}C-method gives somewhat lower values, different ages are presented on the same recession line. Lindström et al. (2000).

8.3 The western side of Central Fennoscandia and Nordland

In the thesis the Norwegian part of Central Fennoscandia is occasionally called Central Norway as a geographical abbreviation, and the area under consideration is shown on Enclosure 5, which also includes the latest interpretations of the ice marginal deposits onshore and offshore. A correlation chart for Central Norway is found on Enclosure 6. Most of the geographical names used in the text is shown on Enclosure 7 and 9 and on the *Figures* in this Chapter and on Fig. 10.1. and Fig. 11.1.

8.3.1 The Continental Shelf

It is generally accepted that the continental shelf off Norway was completely covered by glaciers during the Weichselian maximum (e.g., Holtedahl 1993). A glacier expansion of these dimensions into the open ocean could probably only have been possible because of the c. 120 m (or possible more) lowering of the sea level (Fairbanks 1989, Fedje & Josenhans 2000), leaving great shelf areas below shallow waters, and possibly even as dry land. Andersen (1968) and Rise & Rokoengen (1984) have reported possible submerged shorelines off Troms and in the northern North Sea, respectively.

O. Holtedahl (1940, 1960) proposed ice-marginal features and terminal moraines along the shelf edge, e.g. the huge Skjoldryggen off the coast of Helgeland and the Egga moraines off Troms. Andersen (Fig. 8.5) (1965 a, b, 1968, 1975, 1979, 1981) indicated several moraines on the shelf off Troms and Nordland. The youngest of these interpretations were based on the shape and position of the ridges as seen on bathymetrical registrations. Seismic data have later revealed their morainic composition, although some ridges proved to be bedrock features (Bugge et al. 1974, 1976, 1978, Lien 1976, Rokoengen & Bugge 1976, Rokoengen et al. 1977, 1979, Bugge 1980, T.O. Vorren et al. 1983).

Andersen (1968) argues, based on the position of the moraines on the shelf edge, that Egga I probably represents the last glacial maximum (LGM). Andersen (1975, 1979, 1981) assumed that Skjoldryggen is correlative with Egga I, and if so, it has an LGM age. A younger moraine, Egga II (Andersen 1975), or the Vesterålen ridge (Lien 1976), probably represents a slightly younger phase of the LGM, but a younger age could also be possible according to Andersen (1975).

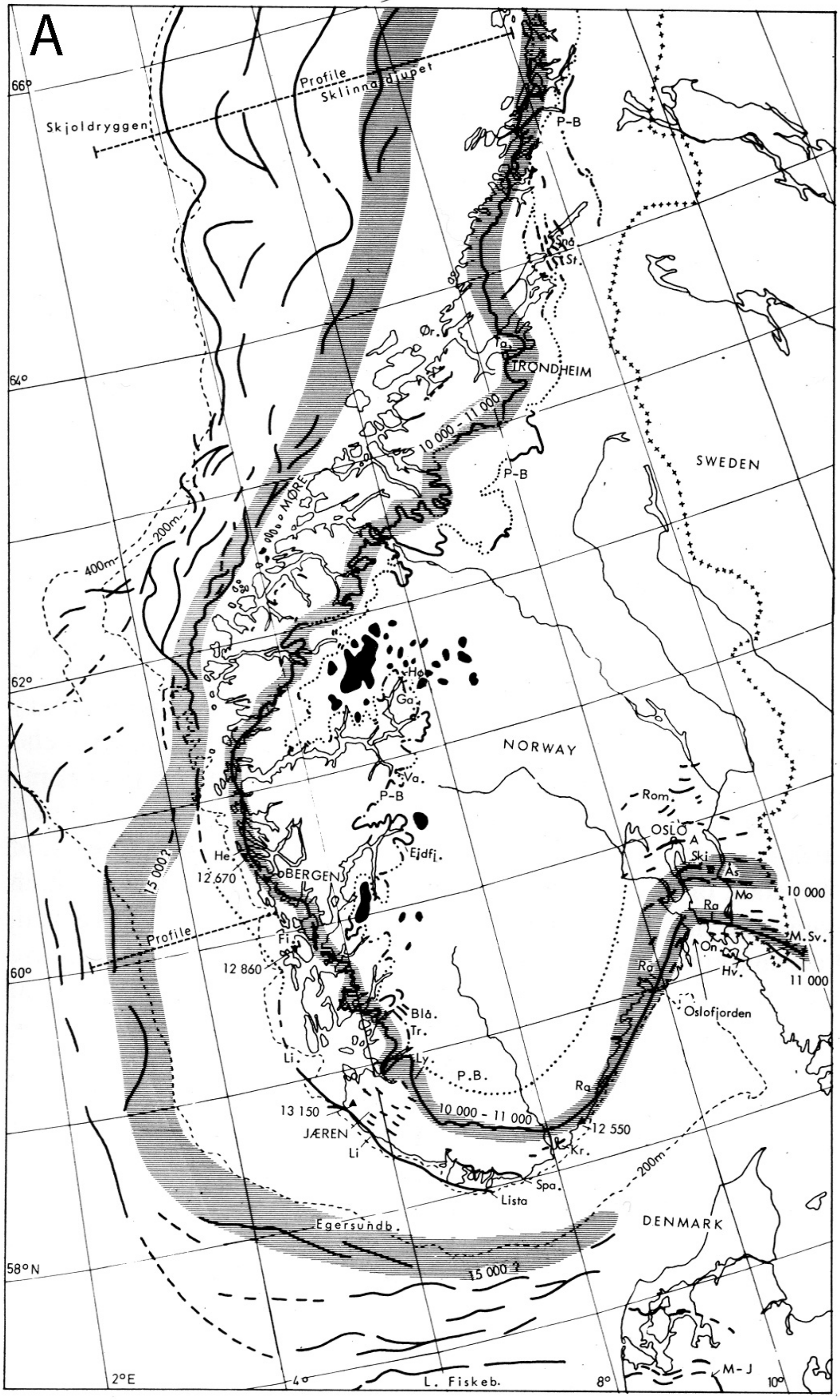


Fig. 8.5 A
Map showing the inferred ice recession lines on the continental shelf off Southern Norway (Compiled by Andersen 1979).

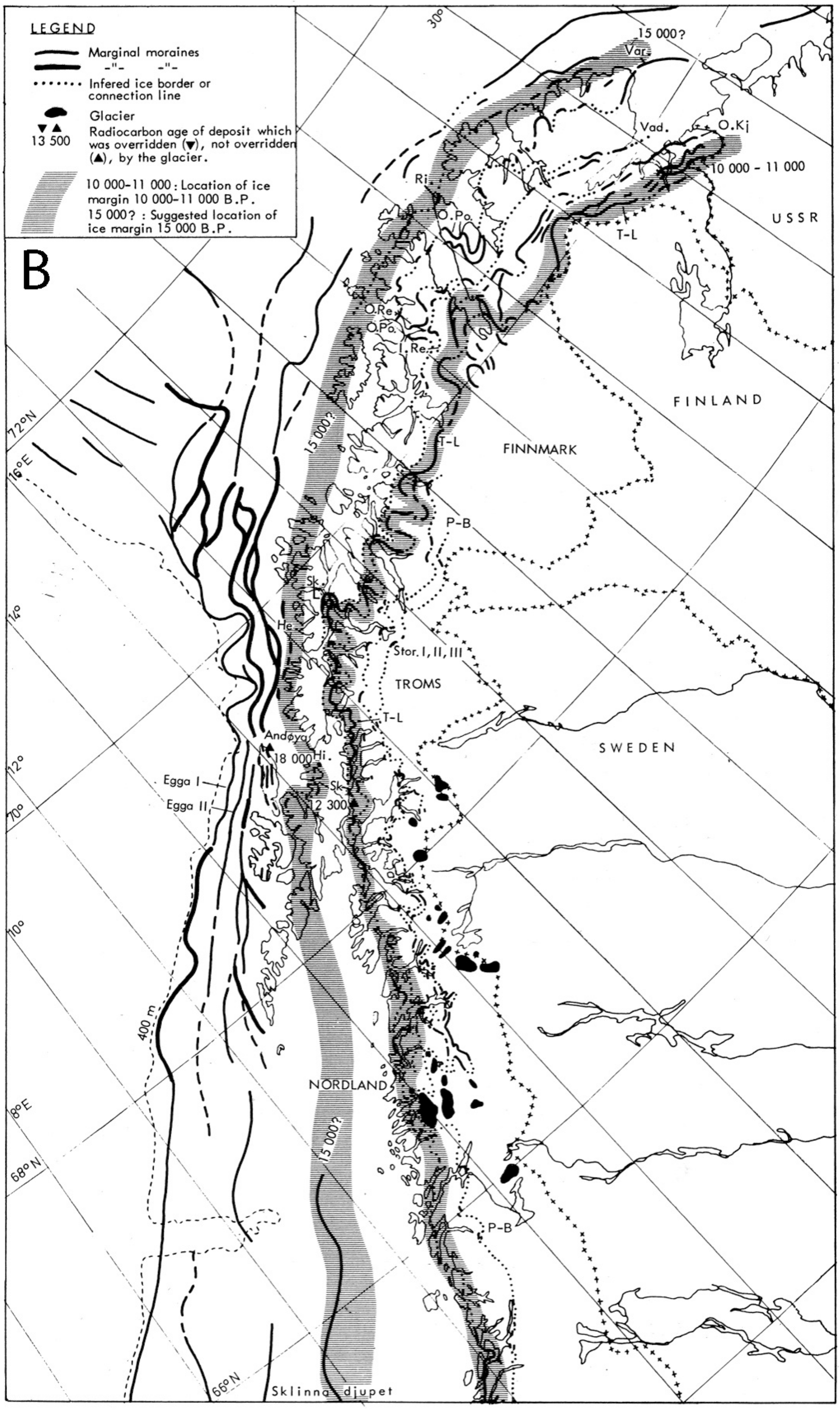


Fig. 8.5 B
Map showing the inferred ice recession lines on the continental shelf off Northern Norway (Compiled by Andersen 1979).

Olsen (1997a) and Olsen et al. (2001a, b, c) are of the opinion that the ice extension to the west was of about the same size during the late glacial maximum called LGM 1 and the slightly younger phase called LGM 2 at 24-21 ka BP and 17-15 ka BP, respectively, and it ended abruptly, in both periods, at the shelf edge (Fig. 6.4 C). This hypothesis predicts that the outer parts of the shelf were not ice-covered everywhere during LGM 2.

Rokoengen et al. (1977) proposed three ice front positions off the Lofoten-Vesterålen islands (Fig. 8.6), only partly in accordance with the reconstruction of Andersen (1979) (Fig. 8.5 B). The age of the outer glacial unit was thought to be c. 13 ka BP, based on dating of shell fragments found in overconsolidated clay. The middle glacial unit was tentatively dated to 12.2-12.0 ka BP. The inner glacial unit was not dated. Several older age determinations on Langøya and the assumed age of the Langøy event at c. 14-13 ka BP, which is located proximal to the inner glacial unit, present a contrast (Rasmussen 1984a, b) (Ch. 8.3.4).

Bugge (1980) mapped three till units on the shelf off the coast of Møre and Trøndelag (Fig. 8.7). The *Storegga moraine* is situated close to the continental edge and is underlain by an older, thick till unit. The middle unit is called the *Haltenbank moraine*, and marks the last ice advance on the shelf. The youngest unit, the *Sula moraine*, is less distinct and is situated close to the outer islands along the coast. Newer investigations have led to proposed changes in the distribution of the moraine units (Rokoengen et al. 1995, Rokoengen & Frengstad 1999). Based on radiocarbon determinations, Bugge (op. cit.) suggested that the inland ice reached the shelf edge some 13 ka BP in this area and retreated to Haltenbanken at 12.4-12.3 ka BP.

This conflicts with the age of the well-dated Outer Coastal moraines of c. 12.5 ka BP at Djupvika (Bergstrøm 1994) and elsewhere on the coast of Nord-Trøndelag at c. 12.4-12.0 ka BP (Sveian & Olsen 1991, Olsen & Sveian 1994, Olsen & Riiber 1997) and 13.4 ka BP on Vega (Andersen et al. 1981). Investigations from Sunnmøre (Mangerud 1991, Larsen & Ward 1992) and Nordmøre (Follestad 1990c) have indicated sediments with a maximum age of c. 12.8-12.6 ka BP.

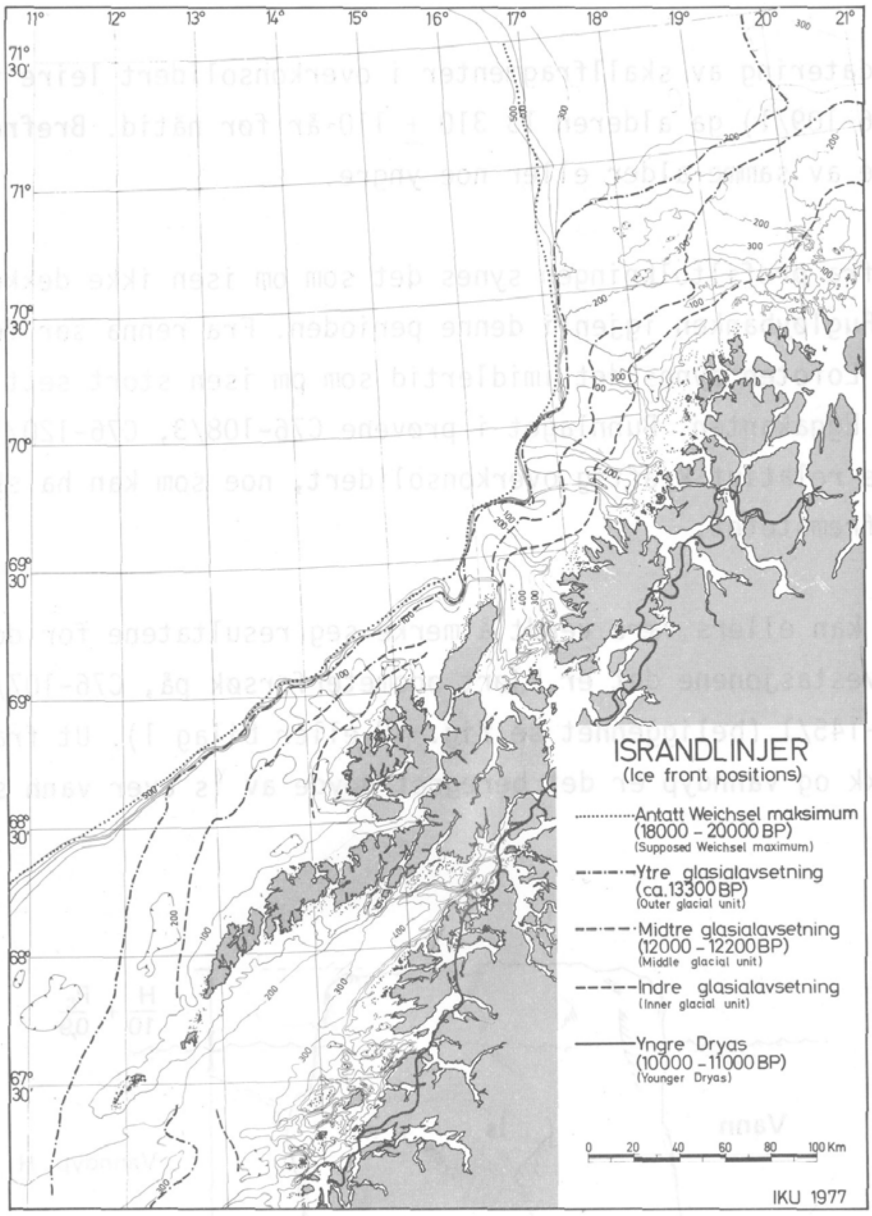


Fig. 8.6
End moraines on the shelf outside Nordland and Troms, as proposed by Rokoengen et al. (1977).

The *till tongue model* was developed by King (1980) and King & Fader (1986), and predicts a way to distinguish between till and intervening glaciomarine sediments. By application of this model it will be possible to map the extent of the till material and, partly, the fluctuations of the grounding line of the ice. King (1993) and King et al. (1987, 1991) have, by implementing the model on seismograms, identified several till tongues on the mid-Norwegian shelf. Samples containing shell fragments have been found in some of the till units. The second youngest till tongue that reaches the shelf edge, is dated to 15.3 ka BP as a maximum age. The youngest till tongue corresponds to the outer part of the Storegga moraine of Bugge (1980) and is dated to 13.5 ka BP (Rokoengen & Frengstad 1999), which is in accordance with Bugge's results.

As concluded by Rokoengen et al. (1995) and Rokoengen & Frengstad (1999), the many diamictic units on the mid Norwegian shelf seem to have been deposited as numerous till tongues. This supports the evidence of rapid shifts in the extent of the ice sheet during the Mid- and Late Weichselian in Norway, as suggested by Olsen (1997a). If the previously mentioned age determinations on the shelf and onshore are correct, the deglaciation of the shelf must have taken place in less than 1,000 years according to Rokoengen & Frengstad (1999).

The shelf moraines indicated on Enclosure 5, are drawn with these new ideas in mind.

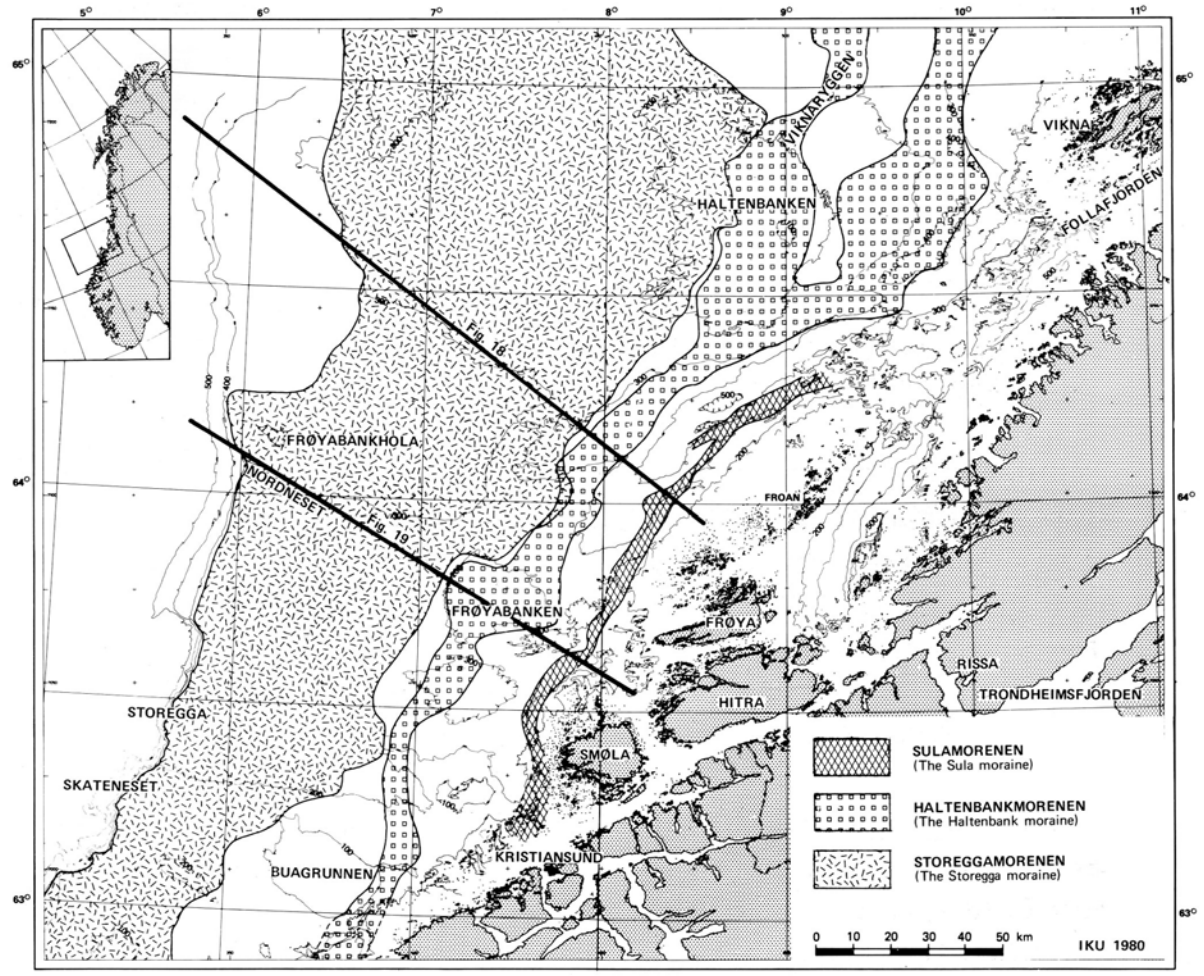


Fig. 8.7
Distribution of moraine units on the Møre-Trøndelag shelf as proposed by Bugge (1980).

8.3.2 The fjords

In the outer part of Trondheimsfjorden and some nearby tributaries, there are seismic registrations indicating ridges that are interpreted as moraines deposited by a fjord glacier moving outwards along Trondheimsfjorden, probably in the time range 12-11.8 ka BP (Ottesen et al. 1995b). These ridges are interpreted to be slightly younger than the Outer Coastal moraines, and if so, they represent an event not identified elsewhere in this area. Ottesen et al. (op cit.) did not consider the possibility that these ridges could have been deposited during the late Bølling or Older Dryas, and then be a part of the Outer Coastal moraines, but this could be an alternative interpretation.

In Vestfjorden, two large transversal moraine ridges strongly indicate two readvances of the Vestfjorden glacier (Rokoengen et al. 1977) (Fig. 8.6). New detailed bathymetrical data have been obtained by multi-beam echo sounding. Two younger transversal moraine ridges that are situated east of the ridges mapped by Rokoengen et al. (1977) have been recorded (Fig. 10.1). Swarms of longitudinal structures along Vestfjorden that are interpreted as flutes support the view of the Vestfjorden glacier (D. Ottesen, NGU, pers. comm. 2002). If all the four ridges just mentioned are moraines, they show an active ice margin in the period after the Weichsel maximum, but they are probably older than the Younger Dryas. They could tentatively be correlated with the Flesen-, the D- or the Skarpnes events in Andfjord at c. 15-14.5 ka BP, c. 13.5 ka BP and c. 12.2 ka BP, respectively (Bargel et al. 1999c, T.O. Vorren & Plassen 2002). This view is supported by a radiocarbon date of 13,675 ± 75 obtained from glaciomarine sediment just west of the Røst moraine that is thought to be the approximate age of the moraine (Raymond Eilertsen, University of Tromsø, pers. comm. 2003).

In Andfjord, T.O. Vorren et al. (1983, 1988) proposed an ice flow that deposited four till units inside the shelf edge. Vorren & Plassen (2002) mapped five moraines, The Egga I, Bjerka, Egga II, Flesen and D-events respectively, which were probably deposited in the range >22-13.2 ka BP. The Egga I and Egga II moraines are situated on the shelf edge just northwest of Andøya, which means that the glacier first retreated and then readvanced at > 14.6 ka BP (see Olsen 1997a). The age of the Flesen stadial is thought to be c. 15.5 ka BP. The youngest stadial, D, is timed at 13.8-13.2 ka BP. These submarine moraines are correlated with moraines on Andøya (Chapter 8.3.4).

8.3.3 Summary and discussion – the shelf and the fjords (Enclosure 5)

The ice extension on the continental shelf was of about the same size during the two phases of the Weichselian maximum at 24-21 ka BP and 17-15 ka BP, respectively. The ice margin ended abruptly in both periods at the shelf edge, but the outer parts of the shelf were probably not completely ice-covered during the youngest ice advance. The main deglaciation of the shelf started c. 15-14 ka BP, but ice-lobes deposited till tongues on the shallower parts of the shelf and moraine ridges in the Vestfjorden at c. 15-14.5 ka BP, c. 13.5 ka BP and at c. 13 ka BP. Then the shelf deglaciated rapidly.

The conflicting dates acquired from the shelf and from onshore localities may well be a result of the ^{14}C-plateau in the atmosphere, and therefore in the oceans, that occurred at c. 12.5 ka BP (e.g., Stuiver et al. 1993, 1997) Alternatively they could be the result of misinterpretation of overconsolidated marine sediments formed by grounding shelf ice or icebergs (e.g., Olsen 2002) as till, or local glaciation on the shelf or the coastal mountains, probably during the Older Dryas. The co-existence of ice lobes that reached the shelf along the bathymetrical depressions and an ice-margin in the coastal areas outside the depressions could also be an alternative. The varying, but generally rising sea level during this part of the deglaciation, as the world's glacier ice vanished, have probably accelerated the calving of the shelf ice and promoted a rapid deglaciation of the shelf.

8.3.4 Ice free areas on Andøya during the Weichselian maximum?

Near the northern end of Andøya, there is a c. 15 km long N-S-trending mountain chain (Fig. 8.8). The area is heavily dissected by cirques, but some narrow, elevated plateaus exist; they are possible remnants of the paleic surface (Reusch 1901b, Gjessing 1967). The highest mountain on Andøya is Sverigetind at 512 m a.s.l. (Fig. 8.9).

At a locality called Bjørndalen by Fjalstad (1997) there is an overconsolidated stoss-side moraine (Fig. 8.8). This moraine is thought to have a Weichselian maximum age (Undås 1967, Møller & Sollid 1972, Bergström 1973, Vorren et al. 1988, Flakstad et al. 1985, Vorren & Laberg 1996, Fjalstad 1997).

Near Oksebåsen, 1-2 km north of Bjørndalen, there is a block-rich deposit, which is interpreted as a local moraine by Undås (1938). Møller & Sollid (1972) thought that a glacier in Andfjorden deposited the formation, contemporaneously with the moraine at Bjørndalen.

These supposed moraines at Bjørndalen and Oksebåsen (the Røyken moraines) are situated distally to the lake Øvre Æråsvatnet in which the bottom sediments were deposited before c. 22 ka BP (Alm 1993).

At Bleik, on the northwestern part of Andøya, there is a moraine complex with several parallel ridges and hummocky moraines (Undås 1938, 1967, Grønlie 1940, Flakstad et al. 1985) (Fig. 8.8). Møller et al. (1992) and Fjalstad (1997) are of the opinion that the outermost of these moraines has a Weichsel maximum age. Age determinations distal to the moraine gave ages of c. 18 ka BP and >40 ka BP. The event is called the *Bleik-Oksebåsen event* (Fjalstad 1997, Fig. 8.9), and it is correlated with the Røyken moraines.

If the dates and the interpretations are correct, two elongated mountainous areas, c. 5 and 12 km long, on the northern part of Andøya, could have been ice-free during the Weichselian maximum (Vorren et al. 1988, Fjalstad 1997) (Fig. 8.9).

There is, however, a conflict between this view and the proposed Weichselian maximum moraines on the shelf edge outside Andøya. As demonstrated by T.O. Vorren et al. (1988) ice-free areas on Andøya and ice on the shelf edge just outside may have existed simultaneously as the northwestern part of Andøya could have been a nunatak.

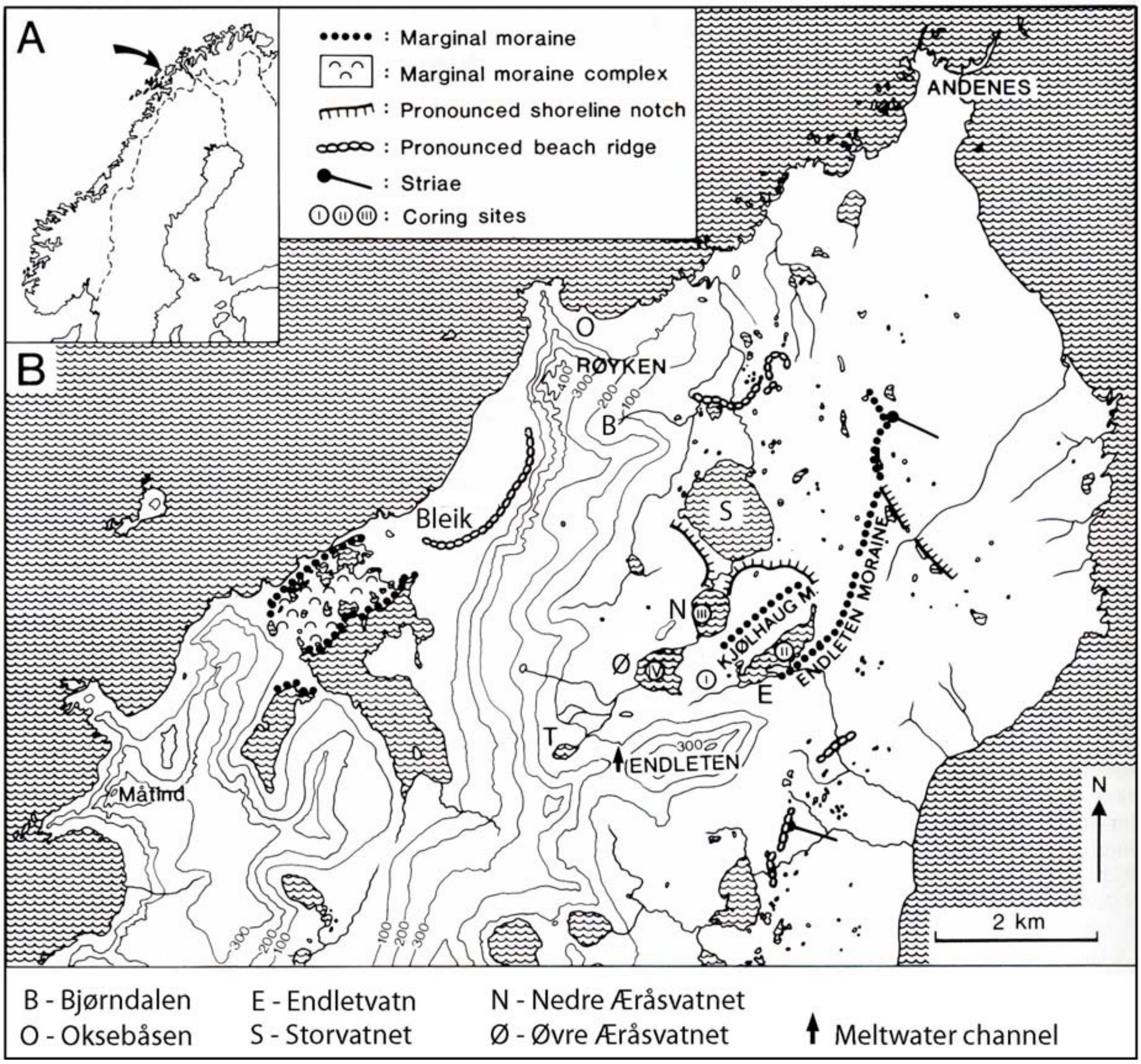


Fig. 8.8
The northern part of Andøya showing localities mentioned in the text. Slightly modified from Alm (1993).

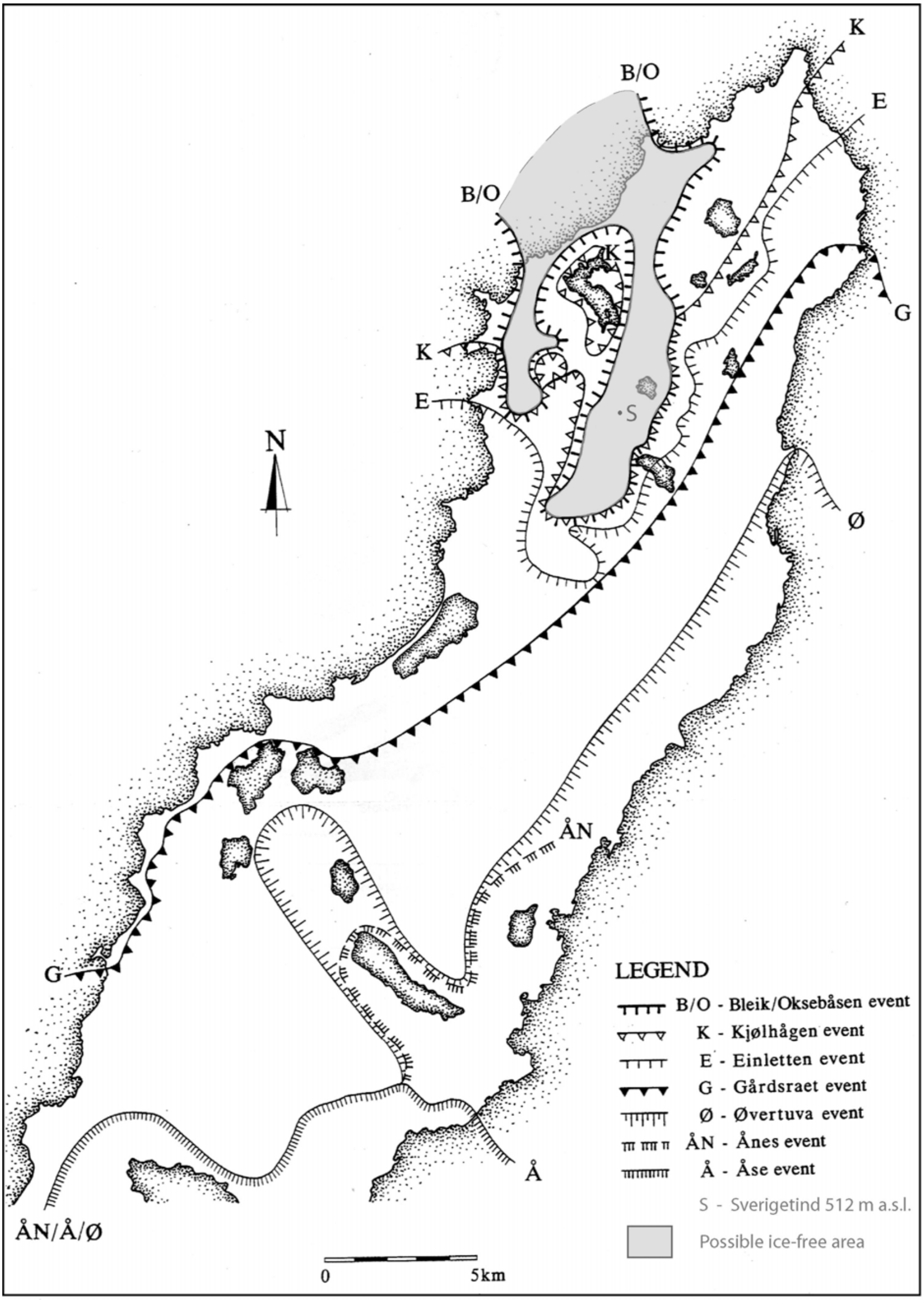


Fig. 8.9
The middle and northern part of Andøya, with ice marginal positions. From Fjalstad (1997).

8.3.5 The deglaciation of Lofoten and Vesterålen (Enclosure 5)

Whether the northern part of Andøya was ice free or not during the Weichsel maximum, the Vesterålen and Lofoten islands were most probably the first parts of Norway that were deglaciated, as advocated by several writers (e.g., Undås 1938, 1967, Grønlie 1940, 1951, Bergstrøm 1973, Vorren 1978, Vorren et al. 1988, Alm 1993, Fjalstad 1997). The distant seaward location is compatible with such a conclusion.

Very little information concerning the Quaternary existed from these islands until a few decades ago. Møller & Sollid (1972) constructed detailed equidistant shoreline diagrams and tried to correlate and date the moraines using their corresponding marine levels. The oldest moraines were called the *Andøya moraines* A1, A2 and A3, respectively (Fig. 8.10). Møller and Sollid (op. cit.) thought that the oldest moraine (A1) represented the Weichselian maximum. Younger moraines were called the *Hinnøya, Astafjord* and *Tromsø-Lyngen moraines,* respectively. Møller (1982) presented a slightly modified deglaciation model from this area, based on computer simulation of the shore-level displacement.

The difficulty with the shoreline method is that it is easy to misinterpret the relative relationships between the moraines and the shorelines as the method assumes that land upheaval is even over long distances. Additionally, neither an eventual forebulge that may amount to as much as 100 m in places (Aber 2002), nor the great relief on these islands (Chapter 10) are accounted for. It is therefore problematic to use this method as the only criterion, as also pointed out by Andersen (1975).

Lofoten

Ordinary deglaciation studies have never been performed on the Lofoten islands, probably due to an almost complete lack of moraines that can be safely regarded as deposited by a regional glacier. According to Møller & Sollid (1972), the LGM glacier margin, represented by the A1 moraines, was located just northwest of the Lofoten islands, the A2 moraines were situated on the islands Vestvågøya and Moskenesøya, and the younger A3 moraines and Hinnøya moraines were located on Austvågøya (Fig. 8.10). The moraines on these islands have been remapped and partly reinterpreted as a part of this thesis (Chapter 10).

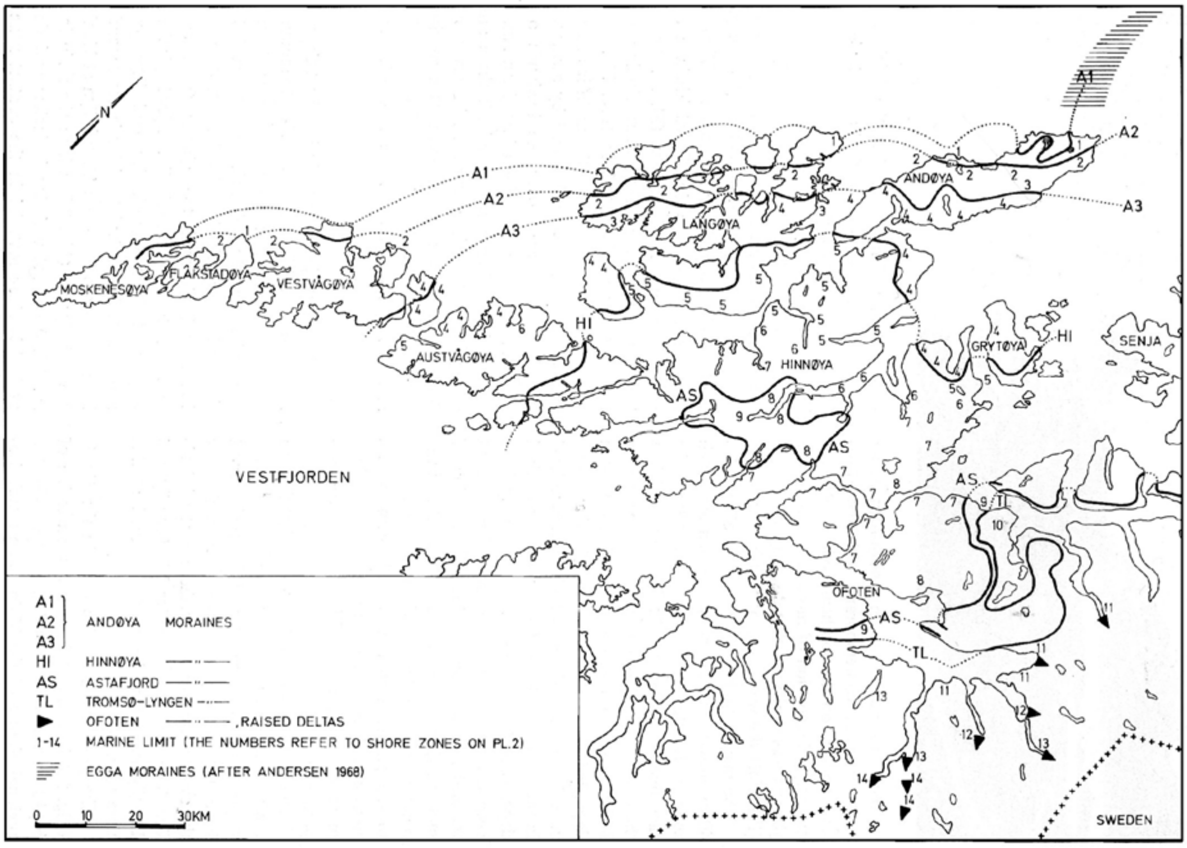


Fig. 8.10
A deglaciation chronology for Lofoten, Vesterålen and Ofoten based on raised beach features (Møller & Sollid 1972).

Vesterålen

According to Møller & Sollid (1972) the A1, A2, A3 and Hinnøya moraines are to be found on Andøya from the northern to the southern tip, respectively (Fig. 8.10). By introducing biostratigraphy and radiocarbon age determinations into Quaternary geological research, it has been possible to make more progress in understanding these features. As on many previous occasions, revitalisation of sciences often happens in the border zone between them. Plant-geographical research methods such as studies of pollen in cores from lakes and bogs have given important input to palaeoclimatological knowledge. Used in a deglaciation context, the step forward has been enormous from mollusc-ecological and shoreline studies which dominated Quaternary geology in the first half of the 20th century. The botanist K.D. Vorrens biostratigraphical studies of bogs on Andøya (K.D. Vorren 1978) may be regarded as a breakthrough, at least in northern Norway. T.O. Vorren et al. (1988) and Alm (1993) followed up this work in their investigation of two neighbouring lakes.

The situation on Andøya during the Late Weichselian maximum is described in Ch. 8.3.3. On the northern tip of Andøya, slightly proximal to the proposed LGM ice position, there are three small lakes (Fig. 8.8). In the lake *Øvre Æråsvatnet,* the lacustrine sedimentation started before 21.8 ka BP, possible after an ice advance older than 22 ka BP (Alm 1993). This ice advance could be the regional advance at LGM I described above and used by Olsen (1997a) in his reinterpretation of the LGM. T.O. Vorren et al. (1988) dated glaciomarine sediments in the lake *Nedre Æråsvatnet* to be older than 19.5 ka BP. A short ice advance postdating the sediments at 19.0-18.5 ka BP was proposed to represent the LGM. This was correlated with an advance in Andfjorden, which reached the shelf edge, the I event (Vorren et al. 1983) or Egga II (Vorren & Plassen 2002). The third lake, *Endletvatn,* which is the most easterly lake, was ice-covered until c. 18.0 ka BP (K.D. Vorren 1978).

The composite sediment log from these lakes presents continuous strata from the LGM until today; this has given excellent possibilities for study of climatic changes and glacier oscillations during this period. Based on pollen analytical work and radiocarbon dates, Alm (1993) and Fjalstad (1997) described the deglaciation of Andøya (Fig. 8.8, Fig. 8.9).

During most of the period 22.0-12.8 ka BP the vegetation on the northern part of Andøya was grass-dominated and generally poor in species. This indicates a dry, glacial situation. At 21-19 ka BP an interstadial situation dominated, the *Andøya interstadial* (Alm 1993). This was followed by a climatic deterioration with an ice advance, which culminated at about 18.8-18.5 ka BP. The lakes Endletvatn and Nedre Æråsvatn were ice-covered, but not Øvre Æråsvatn. The moraine at Kjølhaug was deposited close to Øvre Æråsvatn; this event was called the Kjølhaug moraine by T.O. Vorren et al. (1988) and the *Kjølhågen event* by Fjalstad (1997). The Kjølhaug moraine was tentatively correlated with the Bjerka event in Andfjord (T.O. Vorren & Plassen 2002).

The following climatic amelioration at 18.3-17.9 ka BP accelerated organic production in the lake Øvre Æråsvatn, but the minerogenic content in the sediments is sparse, which indicates a cold, dry climate, probably permafrost and consequently very little fluvial drainage.

Several small, rapid climatic variations followed, and only few moraines were deposited. Warmer periods occurred at c. 17.4-16.8 ka BP and c. 16.0-15.0 ka BP, while colder, almost high arctic conditions occurred at c. 16.8-16.0 ka BP and at c. 15.0-13.0 ka BP. An ice readvance at c. 16.0-15.5 ka BP, called the *Einletten event* (Fjalstad 1997), deposited two moraines, the Endleten moraine (T.O. Vorren et al. 1988) and the Stave moraine (Flakstad et al. 1985). These moraines cannot be directly correlated, but shorelines indicate that they are synchronous. T.O. Vorren & Plassen (2002) tentatively correlated the Endleten moraine and the Egga-II event. Three discontinuous moraines are found on the northeastern side of Andøya; they could have been deposited at c. 15.5-14.5 ka BP by a halt, or a small readvance of the glacier, the *Gårdsraet event* (Fjalstad 1997). If correct, this is the same age as the *Flesen moraine* in Andfjord (T.O. Vorren et al. 1983, 1988). T.O. Vorren et al. (1988) correlated the Flesen moraine with the *Kirkeraet moraine*, which Fjalstad (1997) supposed to be younger. The correlation is speculative as discussed by T.O. Vorren et al. (1983). The correlative moraines are called the *A2 moraines* by Møller & Sollid (1972).

Farther south, on the western side of Andøya, there is a system of ridges interpreted as moraines (Enquist 1918, Undås 1938, Bergström 1973). They are thought to have an age of c. 15.5-14.5 ka BP, and are called the *Øvertua event* (Fjalstad 1997). The predicted age is close to that of the Gårdsraet event. The dating was done indirectly by shorelines and is therefore less precise than radiocarbon determinations. The event was called the *A3 event* by Møller & Sollid (1972).

Several De Geer moraines in the valley Ånesdal on the central part of Andøya show a continuing fast recession of the ice margin. A long ridge in the eastern end of the valley (Undås 1938, Møller & Sollid 1972, Bergström 1973) is proposed to be the most easterly of the De Geer moraines in this valley, probably deposited at c. 13.5-13.0 ka BP, and called the *Ånes event* (Fjalstad 1997).

On the southeastern end of Andøya there is an ice contact slope. It can be traced continuously for several km in a northeasterly direction, partly as a ridge (Holmsen 1924, Undås 1938, Møller & Sollid 1972, Bergström 1973). Sections in this deposit show tectonized glaciofluvial material below till, which indicates an ice advance called the *Åse event* (Fjalstad 1997). The age is thought to be c. 13 ka BP. The Bjørnskinn moraine is correlated with the A3 moraines of Møller & Sollid (1972) (Fig. 8.10).

Langøya

On the island Langøya the oldest moraines observed are situated along the outer margin of the island (Enclosure 5). The moraines are thought to have been deposited at c. 14-13 ka BP, and are called the *Langøy event* (Rasmussen 1984b). The correlation of the moraines is partly tentative, as it is based on just a few radiocarbon determinations, which permit the correlation, even though the moraines themselves havee not been dated directly. Marine limit observations, however, contradict this correlation. Rasmussen (op cit.) claims that the correlation is preliminary. The Langøy event is tentatively correlated with the Åse event on Andøya and with some moraines on Hadseløya. Several moraines of the Langøya event are rather large and were deposited by a glacier which moved towards the west and southwest from an ice dome situated in the middle of the island (or at Hinnøya), and not by a northwest-moving glacier as supposed by Møller & Sollid (1972), who operated with a quite different glaciodynamic model. In their reconstruction they correlated the moraines on Langøya and Hadseløya with the Andøya moraines A2 and A3 and with the Hinnøya moraines.

8.3.6 Moraines older than the Younger Dryas in Møre (Enclosure 5)

Several attempts have been made to reconstruct the ice margin during the deglaciation of the coastal districts of Møre. Based on scattered submarine marginal moraines Larsen et al. (1988) proposed three tentative phases in the area around Ålesund. Follestad (1986) indicated an ice margin named the *Bremsnes moraines,* based on a few terminal moraines in the fjord areas. The ages of these moraines are inferred to be 13.5-12.0 ka BP. The correlation is quite hypothetical as there are no indications of synchronized deposition due to an ice advance. The moraines in question could alternatively have been deposited though not contemporaneously as the floating and calving ice margin reached some obstacles on the coast, which prevented the withdrawal for some time while the equilibrium profile of the glacier was re-established, as described by Kjenstad & Sollid (1982).

The oldest radiocarbon dating so far from the deglaciation in Møre is 12.8 ka BP, obtained from De Geer moraines between the cities of Molde and Kristiansund (Follestad 1990b). De Geer moraines are very common in the Møre area, and they are all located below the postglacial marine limit (Larsen et al. 1991). In this area several radiocarbon dates ranging from c. 12.6 to c. 11.5 ka BP have also been obtained (Larsen et al. 1988).

An ice advance at 11.5-12.0 ka BP deposited several small moraines in the fjord districts, the *Tingvoll moraines* (Follestad 1984b, 1985b).

On the island of Smøla a marginal moraine indicated on the Ice-flow Indicators map (Bargel et al. 1999c), was earlier supposed to be somewhat older than the Tingvoll moraines. Recent investigations show that the deposit is not a marginal moraine, but an erosional remnant of an overconsolidated till sheet. Shell fragments found in the till by the present author have been radiocarbon dated at 38.950 ± 780 ka BP (TUa-3012) (Table 1.1, Ch. 1.2) indicating that the till was probably deposited by an ice advance before the Ålesund interstadial (Mangerud et al. 1981).

8.3.7 Older Dryas events

Outer Coastal moraines in Trøndelag (Enclosure 5)

Radiocarbon dates on molluscs and gyttja indicate that the coastline outside Trondheimsfjorden was deglaciated c. 12.5 ka BP (Reite 1994c, Andersen et al. 1995), which is 1.5 ka earlier than postulated by, e.g. Reite et al. (1982). Submarine and subaerial moraines in the outer parts of many fjords, often associated with extensive till sheets, were earlier correlated and named the *Ørland moraines* (Øyen 1914, Holtedahl 1929, Undås 1942). As demonstrated by Richter (1957), the promontory Ørlandet is not a moraine, but a washed, blocky glaciomarine formation.

Later scientists named these outermost glacial formations the *Outer Coastal moraines* (Andersen et al. 1995) or *Line 1* (Sveian 1997) (Fig. 8.11). These moraines outside Trondheimsfjorden and along the Fosen peninsula probably do not represent an ice advance; they are not even strictly synchronous, but the moraines might partly be due to the stabilization of the ice profile on land as a reaction to the preceding heavy calving on the shelf (Kjenstad & Sollid 1982, Sveian 1997). Farther north however, at Lauvsnes, near the city of Namsos, an ice advance of c. 4 km has been documented (Sveian 1997).

Even though much information indicates climatic fluctuations in Norway during this time period, the late Bølling or Older Dryas (e.g., Marthinussen 1961, 1974, Andersen 1960, 1968, 1975, Anundsen 1977, Mangerud 1977, Andersen et al. 1981, 1982, 1995, Olsen 2002), this may not have been the situation in the outer Trondheimsfjorden area (Reite 1994c, Sveian 1997). In the outer part of Trondheimsfjorden and some nearby tributaries, there are however seismic registrations indicating ridges that are interpreted as moraines deposited by a fjord glacier moving outwards along Trondheimsfjorden, probably in the time range 12-11.8 ka BP (Ottesen et al. 1995). These ridges are interpreted to be slightly younger than the Outer Coastal moraines, and if so, they represent an event not identified elsewhere in this area. Ottesen et al. (op. cit.) did not consider the possibility that the ridges could have been deposited during the Late Bølling or Older Dryas, and then be a part of the Outer Coastal moraines.

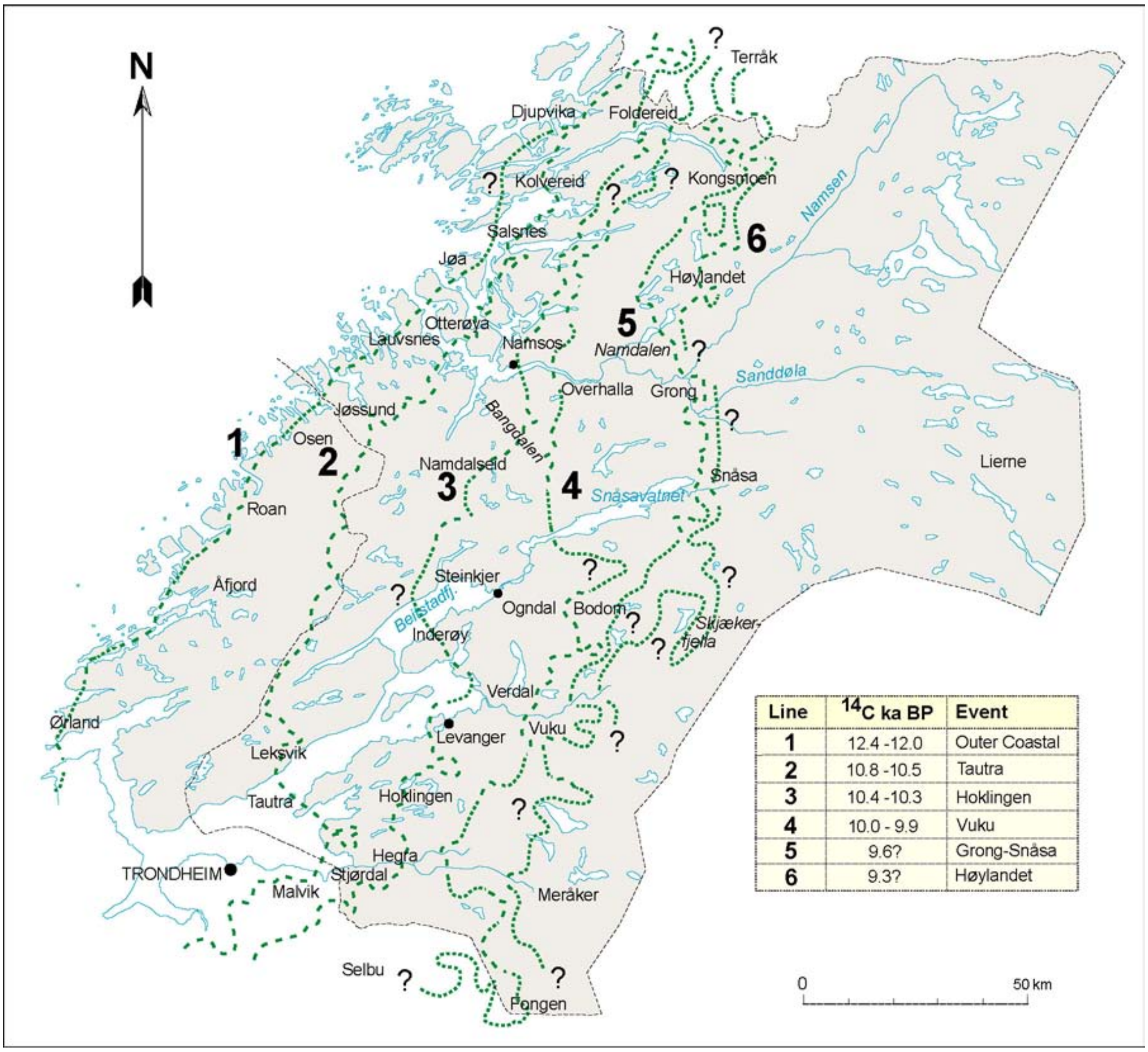


Fig. 8.11
The northern Trøndelag county and Fosen peninsula showing six late- and postglacial end moraine lines. Slightly modified from Sveian (1997).

At Djupvika, just south of the island Leka, the Outer Coastal moraines coincide with the Younger Dryas ice margin. This is beautifully demonstrated in a gravel pit where two glaciation phases, dated to 12.5 ka BP and 10.5 ka BP respectively, are separated by deglaciation sediments (Bergstrøm 1994).

Older Dryas events in Nordland (Enclosure 5)

In the southern *Helgeland* area, marginal moraines older than the Younger Dryas are found at one location. On the island of Vega there is a distinctive, blocky terminal moraine. Shell fragments from the *Vega moraine* have been radiocarbon dated to 13.4 ka BP, which is thought to represent a maximum age for the moraine (Andersen et al. 1981). This moraine is the oldest dated so far from the deglaciation of Helgeland (Fig. 8.12). Detailed Quaternary geological mapping of Vega, performed by E. Sørensen (in prep.), shows that the moraine is wave-washed and occupies a broad zone on the strandflat. The shells were found in till, but the locality has not been properly described. Even though the age achieved at Vega is high, the moraine is correlated with the Outer Coastal moraines in Trøndelag, the Tingvoll moraines on Møre, the Vassdal moraines in Salten and the Skarpnes moraines in Troms with a presumed age of c. 12.3-12.2 ka BP (Andersen et al. 1981, 1995).

Andersen et al. (1979, 1981) and Rasmussen (1981) defined the *Vassdal moraines* in the Glomfjorden area. Datings at c. 11.7 ka BP represents a minimum age for these moraines. In the outer coastal area northwest of the glacier Svartisen, several new dates with a mean age of 12.2 ka BP give good documentation of the age of this proposed Older Dryas ice advance, which is shown to be of at least 10-15 km length in the area (Olsen 2002).

Based on observations of marine limits, Møller & Sollid (1972) concluded that a local ice cap covered the central part of *Hinnøya* during the Skarpnes event and deposited the *Astafjord moraines*. Several moraines located in the valleys on the western side of Hinnøya are probably correlative with the Skarpnes event. The ice-sheet was situated to the east of Hinnøya at that time according to Rasmussen (1984b), but new research indicates that the Skarpnes ice advance reached at least to the middle part of Hinnøya (Bergstrøm et al. 2001b).

Several moraines on *Langøya* have been correlated by raised shorelines to the Skarpnes event. The positions of these moraines show that local cirque- and valley glaciers deposited them (Rasmussen 1984b). The continental ice sheet probably recessed from Langøya during the Allerød. A local ice cap on the island prevailed for some time and deposited numerous local moraines in the valleys (Rasmussen 1984b). Bergström (1973) distinguished five generations of cirque moraines in the area.

8.3.8 The Allerød-Younger Dryas transition

During the subsequent deglaciation in the Allerød, the ice margin probably recessed several tens of km in many fjords, much helped by calving. The magnitude of this recession is only sporadically known. In Trondheimsfjorden the ice margin probably recessed to the inner parts of the fjord.

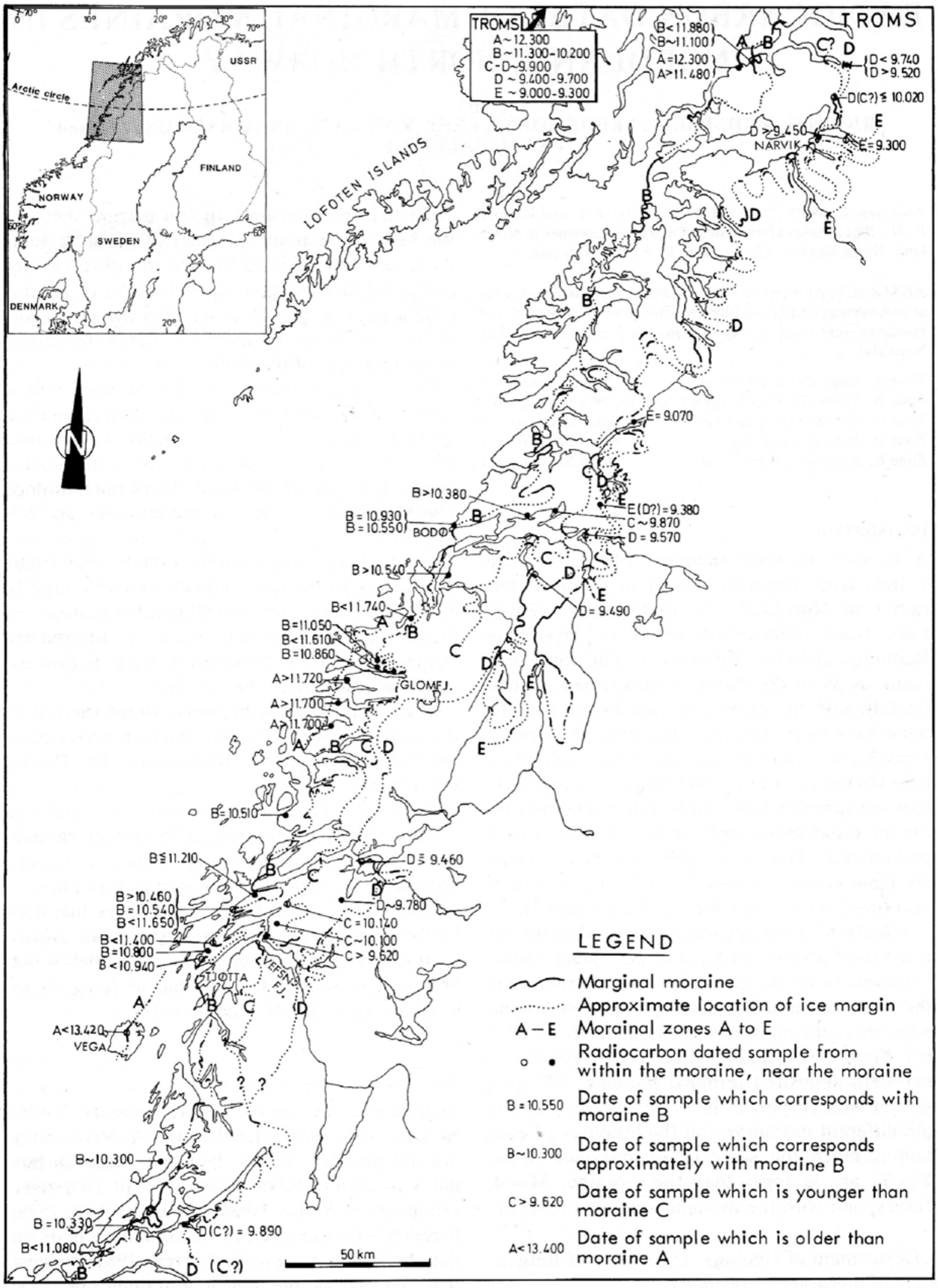


Fig. 8.12
Radiocarbon dates and marginal moraines in Nordland, except Lofoten and Vesterålen, according to Andersen et al. (1981).

Radiocarbon dates on bivalves and gyttja from the outer part of Trondheimsfjorden at c. 11.8-12.1 ka BP (Reite et al. 1982, Selnes 1982, Kjemperud 1986, Reite 1987, 1988, Løfaldli et al. 1981) show that the calving was fast, probably accelerated by the great water depth, which is today more than 500 m.

In the mountainous areas around the outer part of the fjord the ice-feed from the inland areas was cut off, and large, isolated ice caps were left. Small ice-contact deltas along the fjord were highly probably deposited from these ice remnants according to Reite (1994c). The correspondent marine levels show that the deltas were synchronous and were deposited during a relatively short time interval during the Younger Dryas (Lasca 1969, Reite 1983a, b, 1984, 1990, 1994a, 1995).

8.4 Younger Dryas readvances

8.4.1 The Møre area

Reconstructing the Younger Dryas ice marginal line in Møre has been a challenge not met until recent years. This heavily dissected part of Norway has made regional work difficult to perform until modern aerial photographs and infrastructure were available.

Based on one or two very marked deltas in the main valleys and corresponding lateral moraines along the valley sides, a correlation of the marginal deposits has been proposed, even though no dates for the moraines are available so far (Sollid & Sørbel 1979, Sollid & Reite 1983) (Fig. 8.13). A Younger Dryas age is inferred based on a) the position relative to older dated localities, b) raised shorelines related to the moraines, and c) the size and consistency of the moraines throughout the area.

Detailed mapping of the Quaternary deposits performed in recent decades by the Geological Survey of Norway, has given new data which have made it possible to redraw parts of the Younger Dryas ice marginal line in Møre (Follestad 1987, 1994a, b). The ice advances are marked in some areas by a double set of parallel moraine ridges, such as the *Reinsvatn moraines* in the Sunndalen district (Follestad 1987). The most prominent feature of the Younger Dryas ice margin in Møre is the irregular pattern where ice tongues had extended tens of kilometres in the valleys, some of them all the way to the fjords, leaving the high mountains ice-free except for numerous local glaciers. Some of these cirque glaciers even protruded down to the fjords. Reite (1968) and Sollid & Sørbel (1979) assumed that the moraines were of Younger Dryas age, mainly based on their position outside the Younger Dryas ice margin and in relation to a lowered glaciation limit.

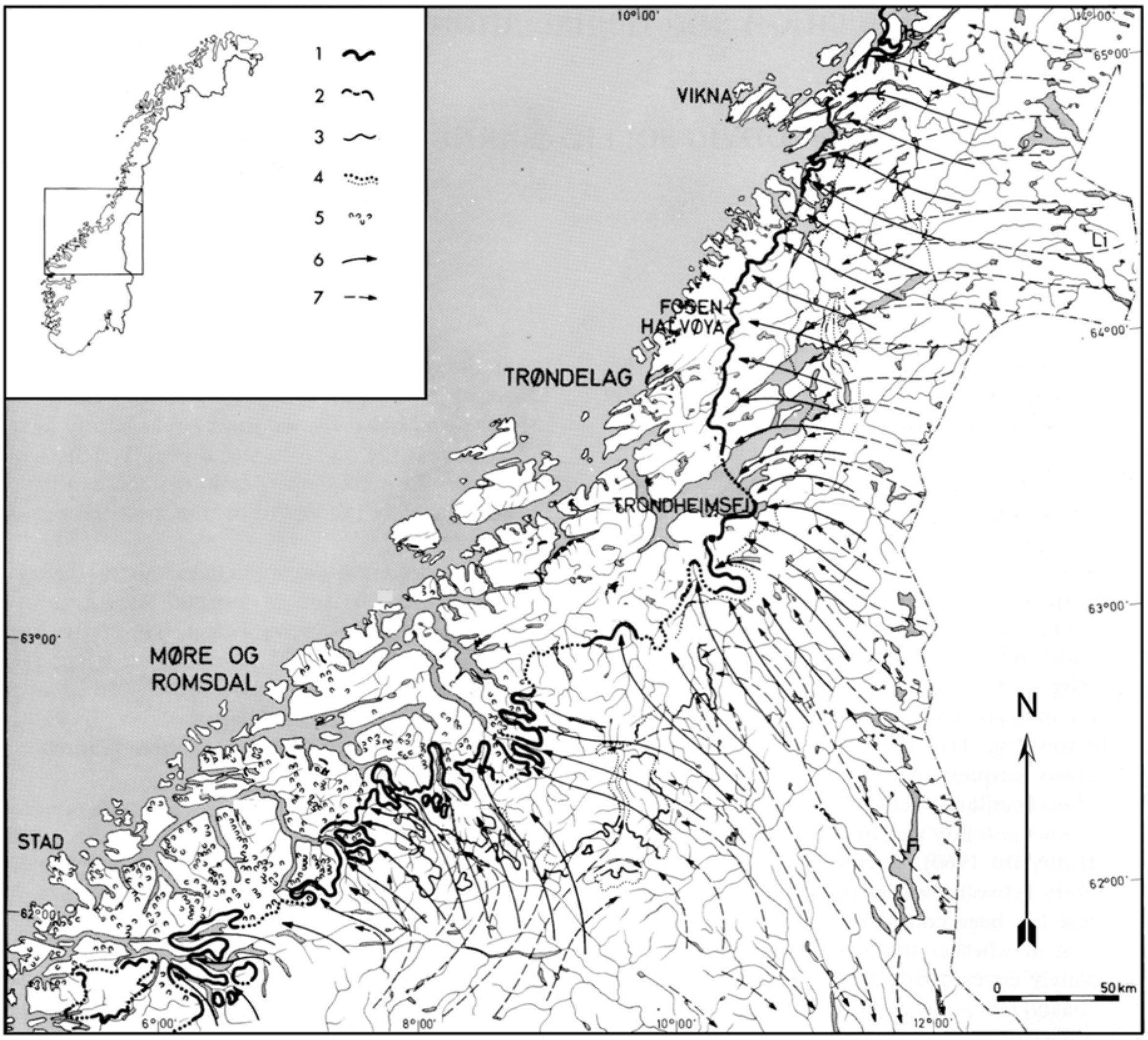


Fig. 8.13
The main glacial geological features of Central Norway after Sollid & Sørbel (1979, 1981). Various moraines (1-4; thick lines - Younger Dryas), cirque moraines (5) and ice flow lines (6 - Younger Dryas ice flow, 7 -Holocene ice flow) are shown. The area includes most of the Norwegian part of the Central Fennoscandian map sheet area.

8.4.2 The Trøndelag area (Enclosure 5)

In the Trondheimsfjorden area there are many huge moraines that were deposited during the Younger Dryas glacier readvance. The moraines are mostly located in the outer parts of the great valleys. The moraines are dated to 10.8-10.5 ka BP, the *Tautra moraines* (Reite et al.

1982). Distinct shorelines in solid bedrock that are found just outside the moraines, but not elsewhere, indicate a cold climate (Reite 1995). This marked phenomenon has been described from several localities along the Norwegian coastline (e.g., Rekstad 1915, 1917b, Andersen et al. 1981, 1982, Rasmussen 1984b). The moraines were not only deposited in the fjords, but also in the mountainous areas between the fjords. The deposits are mainly glaciofluvial in the valleys and push moraines elsewhere, which shows the readvance nature of the Younger Dryas glacier (Reite 1995). The ice margin readvanced possibly as much as 20 km in some fjords. This almost continuous line of moraines has made it possible to reconstruct the ice margin with high precision in most of the area.

Scattered moraines and till fabric could indicate a rapid, short-lived ice readvance along Trondheimsfjorden in early Younger Dryas, c. 10.9 ka BP. Feragen (1997) tested this hypothesis, but no conclusive proof was found. On the other hand, the moraines in question, just northeast of the city of Trondheim, are possibly built up with interfingering till/clay beds with the till on the landward side, indicating that the ice was moving from the land to the sea (A. Reite, pers. comm. 2002). These contradictory data indicate that further work has to be done to solve the problem.

North of the city of Trondheim, the Tautra moraines can be traced almost continuously across Trondheimsfjorden (Fig. 8.11, Fig. 8.13). The small island Tautra is the only visible part of a submarine moraine, which is one of the biggest moraines in Norway. The moraine line crosses the Fosen peninsula in a northerly direction, and can then be followed along the coast inside the Vikna islands where a great glaciofluvial ice-marginal deposit is situated at Kolvereid. Huge marginal moraines cross the fjords outside the city of Namsos and in front of the lake Salsvatnet, which is dammed by the moraine. The Younger Dryas ice-marginal line coincides with the Outer coastal moraine line at Djupvika just south of the island Leka as mentioned earlier. At this point the ice margins from the two different readvances reached the same position. North of this point the Younger Dryas ice margin reached a more distal position than the older readvance, which means that there had probably been a slight change in the position of the inland ice dome, and that the ice in the Follafjorden-Bindal area was relatively more dominant during the Younger Dryas than it had been before. This is more fully treated in Part III of this thesis.

8.4.3 Nordland (Enclosure 5)

Earlier scientists tentatively correlated the largest ice marginal moraines in Nordland to the Ra in southeastern Norway. This happened to be correct in many cases, but in the Ofoten and Salten areas age determinations have shown that the largest moraines were of Preboreal age (Andersen 1975), Ch. 8.5.1.

The Younger Dryas moraines in Nordland were mapped and dated by Andersen (1975) and Andersen et al. (1979, 1981, 1982). Two Younger Dryas Substages are defined, the Tjøtta Substage and the Nordli Substage (Andersen et al., 1982, 1995) (Enclosure 6, Fig. 8.12, Enclosure 5).

The Tjøtta Substage

The moraines representing the Tjøtta Substage are mostly located in the coastal areas, in the outer parts of the fjords, occasionally in the lower parts of tributary valleys. As pointed out by Andersen et al. (1981), the moraines that are of Younger Dryas age (the B-event) are, in general, the largest and most distinctive moraines on the coast except for the Ofoten and the Salten areas. Even though they are mostly located to the fjords, the moraines can tentatively be traced more or less continuously along the coast. Most of the moraines were deposited in the sea, and these are often composed of coarse foreset beds in addition to some diamictic material (Fig. 8.14). The wave wash that frequently happened during the regression, has, in some cases, been very intense and flattened the crest of the moraines, e.g. the Tjøtta moraine and the Bodø moraine. Seismic registrations in some fjords in the southern part of Nordland (Helgeland) have shown marked moraine ridges more than 100 m thick (Andersen et al. 1982).

Many age dates have been acquired from shells found in the moraines, and they show that the age of the moraines is bracketed between c. 11.0-10.4 ka BP which is an early-middle Younger Dryas age. This is the same age as the Ra moraines in southeastern Norway (Sørensen 1979), while the Tautra Substage in Trøndelag has been dated to 10.8-10.5 ka BP. The main moraines are the Heilhorn, Tjøtta, Glomfjord and Straumøy moraines, which have been correlated with the Tromsø-Lyngen moraines (Andersen et al. 1981). The Main (Younger Dryas) shoreline often corresponds with these moraines and has been useful in the correlation work.

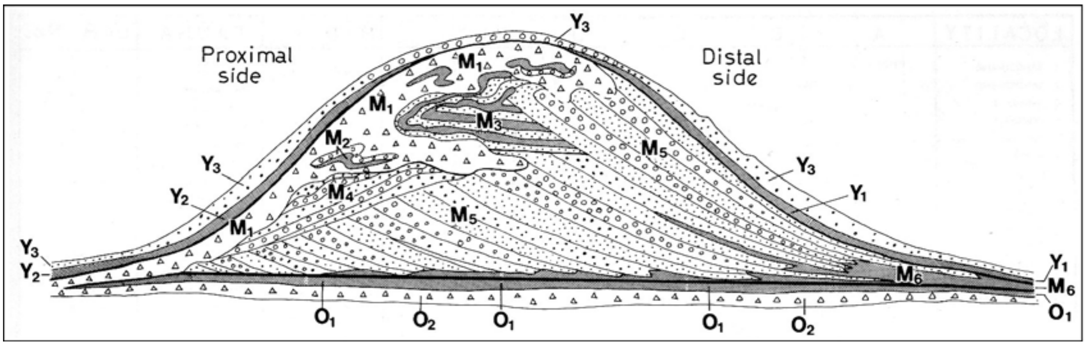


Fig. 8.14
Cross-section of an end moraine deposited in the sea.
M_1: till, M_2: folded marine sediments. M_3: marine sediments. M_4: glaciofluvial sediments. M_5: "foreset" beds, glaciofluvial, glaciomarine and flow till. M_6: glaciomarine sediments
Y_1-Y_2: glaciomarine sediments that are younger than the moraine. Y_3: Postglacial marine sediments, including beach deposits and reworked till.
O_1: glaciomarine and marine sediments that are older than the moraine. O_2: older basal till or bedrock. (Andersen et al. 1981).

Description of selected localities (Fig. 8.12, Enclosure 5 and 7).

The moraines in the Bindal area are described in Chapter 11.

In the *Vistenfjorden-Velfjorden* area observations of the Main shoreline are used to indicate that the ice margin was located inside the coastline. Some scattered moraines in the mountains are tentatively correlated with the Tjøtta Substage. Detailed mapping of this area (Follestad in prep. e) has not recognised all of the moraines indicated by Andersen et al. (1982) in the tentative reconstruction of the ice margin. At the mouth of Vistenfjorden sparker registrations show a 100 m thick and 1.5 km broad till-like material, which is thought to be a moraine that is correlative to the Tjøtta moraine.

At *Tjøtta* there is a low, broad, wave-washed moraine (Rekstad 1925b, Andersen et al. 1982, Follestad 1992) that was deposited by the Vefsnfjorden glacier. This moraine is the type locality for the Tjøtta Substage. Shells from the moraines in this area are radiocarbon dated to c. 11.0-10.5 ka BP, which is an early Younger Dryas age (Andersen et al. 1982). Some km north of Tjøtta, a huge, tectonized glaciofluvial deposit is situated, the Breimo moraine, which is correlated with the Tjøtta moraine.

Between *Sjonafjorden* and the glacier Svartisen a few, small moraines are described that are tentatively correlated with the Tjøtta moraine. On the sea-bottom between the islands outside the *Sjonafjorden-Ranafjorden* area, several huge ridges interpreted as moraines are situated. Seismic registrations show more than 500 m of sediments at the mouth of Ranafjorden. The sub-marine moraines are correlated with some rather long moraines on several of the islands in the Nesna area (Andersen et al. 1982).

Just outside the western margin of the glacier Svartisen and Engabreen tributary there are several huge, spectacular moraines. The end moraine in front of Engabreen was deposited in historical times according to Rekstad (1929) and Theakstone (1964). This conclusion is based on the fact that no end moraines are to be found distally to the Engabreen moraine, and the Main Shoreline is situated just outside the moraine. According to Rasmussen (1981, 1984a) the glacier probably did not reach much farther during the Younger Dryas than it has in historical times. Rasmussen (1979) defined the *Glomfjord event* in this area, which he correlated with the *Straumøy event* south of Bodø. The Glomfjord event has been dated to c. 11.0-10.9 ka BP (Rasmussen 1981) or c. 10.8 ka BP (Olsen 2002).

On the southern side of Saltenfjorden, on the island Straumøy, there are several moraines. Ages of 10.5 and 10.4 ka BP indicate the minimum age for this event called the *Straumøy event* (Andersen et al. 1979). The diffuse, broad ice-marginal zone, which is probably correlative with the Tjøtta event, can be followed through the city of Bodø where thick diamictons dominate. Shells from correlative glaciomarine clays are dated at 10.9 ka BP (Andersen 1975) and 10.5 ka BP (Marthinussen 1962).

Younger Dryas events north of Saltenfjorden and Skjerstadfjorden were mapped and described by Andersen (1975), several years before the Tjøtta Substage was defined. The moraines in northernmost Nordland were therefore correlated with the Tromsø-Lyngen Substage. Later the Tjøtta Substage was correlated with the Tromsø-Lyngen Substage (Andersen et al. 1982)

Between the city of Bodø and Tysfjorden there are few moraines of the Tromsø-Lyngen age. Grønlie (1940) proposed that the ice-marginal zone was situated along the outer fjord districts, but Marthinussen (1962) advocated a marginal zone close to the heads of the fjords. Andersen (1975) found several separate lateral moraines and blocky accumulations in the outer fjord areas, and thought that the ice margin could have been situated within a broad zone along this coastline. According to Andersen et al. (1981) the ice margin could have been situated up to several tens of km from the coastline, but Olsen (2000) found that the coastline alternative is preferable. The position of the ice margin proposed on Enclosure 5 is based on the latest results.

Several writers have discussed the Younger Dryas or the Tromsø-Lyngen marginal zone in the *Vestfjorden-Ofotfjorden area*, and many positions have been presented (Fig. 8.15). Due to the diffuse nature of the marginal deposits in this area, most of the proposals are based on raised shorelines, which is not an accurate method (Andersen 1975). Grønlie (1940) proposed that the ice-margin crossed the outer parts of Ofotfjorden and Tysfjorden. Marthinussen (1961) advocated an ice-margin across Rombakfjorden (Rombaken) to the east of Narvik, probably not located to the Rombak moraine, but to a smaller moraine just south of Narvik. Dahl (1967, 1968) located the ice-margin in a shallow part of Ofotfjorden between the proposals of Grønlie (1940) and Marthinussen (1962). Møller & Sollid (1972) acclaimed this solution. Andersen (1975) based his correlation on several radiocarbon datings and presented a more distant location for the ice-margin, across Vestfjorden from the western part of Tysfjorden to the island Tjeldøya. In these areas there are great accumulations of diamicton and several moraines that possibly represent the Tromsø-Lyngen event. Based on ^{14}C datings of shells from tills, Bergstrøm et al. (2001) have proposed an even more westerly position of the Younger Dryas ice margin, across Vestfjorden at Otterøya on the southern side of Hinnøya.

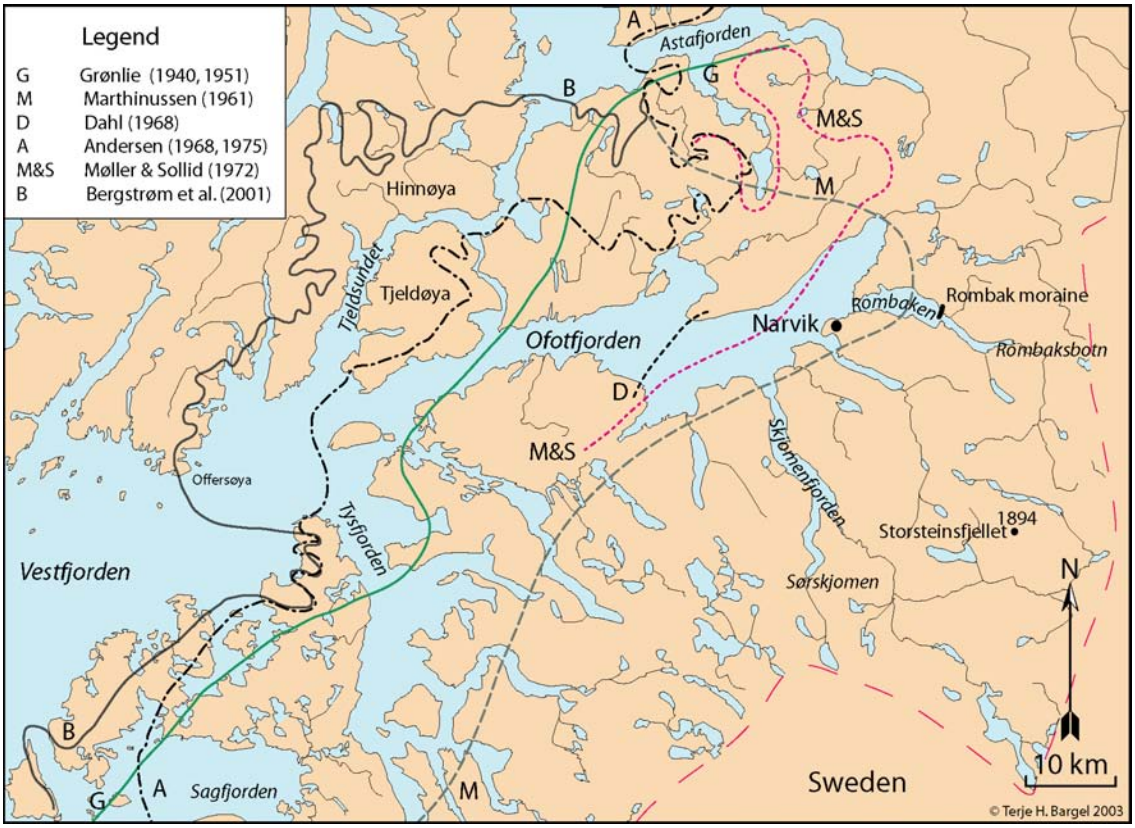


Fig. 8.15
Map of the Ofotfjorden area showing reconstructions of the Tromsø-Lyngen (Younger Dryas) ice margin described in the literature. Modified from Andersen (1975).

On the *Lofoten* and *Vesterålen islands* there are cirque-moraines and rock-glaciers in most of the mountains that were higher than the Tromsø-Lyngen glaciation limit. On Hinnøya there are only small, local cirque-moraines in connection with recent glaciers, even though the mountains are higher than the Tromsø-Lyngen glaciation limit. According to Rasmussen (1984b) this is a strong indication that the central parts of Hinnøya were covered by a large, local ice cap by that time. This seems to be an impossible conclusion as no great accumulation areas are situated above the Younger Dryas glaciation limit, only peaks and steep valley sides. The ice on Hinnøya outside the Younger Dryas ice margin must probably have been in the form of valley glaciers that have originated in smaller accumulation centres (cirques). Several ice-marginal accumulations deposited by these valley glaciers are identified. Dating from a bog on a delta in Sigerfjorden at 10.4 ka BP and the pollen content, show a Tromsø-Lyngen age according to Rasmussen (1984b).

Møller & Sollid (1972) thought that the ice margin was situated in the fjords of southern Troms and Ofoten with no connection to the supposed ice cap on Hinnøya. Andersen (1975) located the ice-margin slightly differently, but does not mention the situation on Hinnøya.

A new model, based on mapping and age determinations, indicates that the inland ice sheet readvanced at least 20-50 km, to the central parts of Hinnøya during this event (Bergstrøm et al. 2001) (Fig. 8.15, Enclosure 5).

8.4.4 Late Younger Dryas readvances (Enclosure 5, Fig. 8.11)

Trøndelag

The ice recession from the Tautra moraines was of the order of 20-50 km to the east (Reite 1995). Then a new, short-lived readvance deposited the *Hoklingen moraines* at c. 10.4-10.3 ka BP (Reite et al. 1982, 1999a, Reite 1994c, 1995, Sveian 1997, Sveian & Solli 1997, Sveian & Rø 2001). These moraines are mostly situated on the undulating lowland at the inner end of Trondheimsfjorden and in the mountains north and south of the fjord. Correlative ice-marginal deposits are partly single ones south and east of Trondheimsfjorden, but northeast of the fjord the moraines are more or less continuous and easy to correlate. At the inner end of the fjord there are several parallel ridges, which show that the ice margin was not quite stable. The Hoklingen moraines can be traced from Berkåk in the south to Terråk in the north, but correlation to moraines in Møre to the southwest is problematic.

The Nordli Substage

The moraines representing the Nordli Substage are mostly located to the middle and inner parts of the fjords in Nordland. Most of the moraines are distinctive ridges, but they are considerably smaller than the moraines representing the Tjøtta Substage. According to Andersen et al. (1981) moraines of the Nordli Substage (C-event) may be represented in the Tosenfjorden area, but correlation to the later Narvik I Substage (the oldest part of the D-event, Andersen et al. 1995, Enclosure 6) is more likely, based on the ages obtained. Only in the Vefsn area can the moraines be followed for a long distance. In the Salten and Ofoten areas some scattered moraines are tentatively correlated with the Nordli Substage,

The age of the Nordli Substage is c. 10.2-10.1 ka BP (Andersen et al. 1981, 1995), which is within the range of the Hoklingen Substage in the Trondheimsfjord area (Reite et al. 1982, Sveian 1997) and the youngest part of the Tromsø-Lyngen Substage in Troms (Andersen 1968).

Locality descriptions

Scattered moraines south of Ranafjorden, the *Nordli moraine* in Vefsn, and some correlative lateral moraines in the Vefsnfjord area are dated to c. 10.2-10.1 ka BP (Andersen et al. 1981, 1995). Based on detailed mapping of end- and lateral moraines (Follestad 1990a, Bergstrøm (1995), Olsen et al. (1996b) proposed some smaller changes of the marginal zone in the Vefsn area.

Several moraines at the mouth of some small tributaries to Skjerstadfjord are tentatively correlated, the *Skjerstad moraines,* and dated to c. 9.9 ka BP. They have been tentatively correlated with the Nordli Substage (Andersen et al. 1979, 1981).

In the Ofoten district the oldest moraines of the Narvik-Bjerkvik event could be correlated with the Nordli Substage (Andersen et al. 1981), but they could also represent an older phase of the Narvik I Substage (Ch. 8.5.1) (Andersen et al. 1995).

8.5 Preboreal readvances (Enclosure 5)

In the *Møre area* very few moraines younger than the Younger Dryas have been identified. In the Sunndalen area scattered moraines dated to 9.7 ka BP have been reported (Follestad 1987), but no ice margin has been reconstructed. Follestad (1994b) advocated a dead-ice situation at a relatively early phase of the Preboreal deglaciation.

Proximal to the Younger Dryas ice marginal deposits at the inner end of the *Trondheimsfjorden area* there are numerous deposits such as moraines, large glaciofluvial deltas, kame terraces, eskers and sandurs (Sveian 1989, Reite 1995, Sveian & Solli 1997). In this hilly lowland the retiring ice-front had several halts due to topographic obstacles or narrow parts in some valleys. Radiocarbon dates and stratigraphical studies have been used to separate ice readvance moraines from ice margin standstill deposits. Two, or possibly three episodes of Preboreal ice readvance deposited end moraines east and north of Trondheimsfjorden.

The *Vuku moraines* have been dated to 10.0-9.9 ka BP (Reite et al. 1982, Sveian 1989, 1997, Sveian & Solli 1997, Sveian & Rø 2001). This readvance deposited huge moraines in the valleys and small, partly continuous moraines in the mountains. The correlation is tentative in areas with scattered moraines, such as north and south of the fjord.

The *Grong-Snåsa moraines* are not directly dated, but are probably from c. 9.7 ka BP, and are mostly correlated tentatively, but also by coinciding raised shorelines in some localities (Bergstrøm 1991, Sveian 1997, Sveian & Solli 1997, Sveian & Rø 2001). In the mountains a set of tentatively correlated discontinuous end moraines with a possible age of c. 9.5 ka BP have been mapped northeast of the Trondheimsfjorden area (Reite et al. 1982, Sveian 1997, Sveian & Solli 1997, Sveian & Rø 2001). Almost no correlative moraines are found east and south of the fjord.

A few moraines in the Namdalen area are tentatively correlated and named the *Høylandet moraines* (Bergstrøm 1992). Their age is thought to be c. 9.5 ka BP or possibly younger.

8.5.1 Nordland (Enclosure 5 and 6)

Andersen et al. (1981) correlated numerous moraines represented in most of Nordland with a mean age of c. 9.5 ka BP to the *D-event*. Andersen et al. (1995) divided the D-event and correlated the moraines with an age of c. 9.9 ka BP with the *Narvik I Substage*, and moraines with an age of c. 9.6 ka BP with the *Narvik II Substage*. The *E-event* (Andersen et al. 1981) or the *Rombak Substage* (Andersen et al. 1995) was dated to c. 9.3 ka BP. As many as six parallel moraines were observed, but normally there are two or three moraines.

Preboreal moraines are found scattered in some valleys in *southern Helgeland*, but correlation is hampered by lack of age determinations and the lack of continuity of the moraines. Andersen et al. (1981) proposed a tentative correlation, but found it difficult to differentiate between the C- and the D-events south of Vefsnfjord (Fig. 8.12). A radiocarbon dating from a moraine situated at Terråk at 9.9 ka BP shows an early Preboreal age, and is then correlative with the Narvik I Substage (Andersen et al. 1995) and the Vuku Substage (Reite et al. 1982).

Bargel & Olsen (1995) proposed minor modifications of the location of the D-event, based on detailed mapping of moraines south of Mosjøen. Bargel et al. (1999c) proposed a separation of the C-event and the B-event at Tosenfjord. None of these proposals seems to be correct. The Terråk area has been remapped and reinterpreted as a part of this thesis (Chapter 11).

The Narvik I and the Narvik II Substages (the D-event)

Rana. Marked marginal moraines situated in the middle Ranafjorden area, e.g. the Finneidfjorden and Hemnesberget moraines, have been dated to be slightly older than c. 9.5 ka BP (Andersen et al. 1981). Detailed mapping of the Quaternary deposits in the area has revealed many small end moraines (Follestad 1988a, 1990a, Bargel & Olsen 1995, Bergstrøm 1995, Olsen et al. 1996b, 2001d). Correlation is complicated due to a lack of age datings and the possible influence of a local glaciation centre in the mountainous area of Okstindan. Bergstrøm (1995) presented a detailed reconstruction of several phases of the late Preboreal ice margin in parts of the area.

Salten. The *Finneid moraine* was one of the most spectacular ice-margin deposits in the Salten area, but most of it has been excavated. A shell dating at c. 9.6 ka BP probably represents a maximum age and the moraine is correlative with the *D-event* (Andersen 1975). A few moraines at the eastern and inner end of Skjerstadfjord, several long, lateral moraines along the western sides of Misværdal and the Misvær moraine are tentatively correlated with the Finneid moraine (Andersen et al. 1979, 1981, 1995). In a southern direction, the ice-marginal zone during the D-event was tentatively located to the west of the glacier Svartisen by Andersen et al. (1981). According to Blake (1998) and Blake & Olsen (1999), the Svartisen glacier was separated from the main ice sheet at c. 9.6-9.0 ka BP. Between Svartisen and Ranafjorden there are almost no end moraines correlative with the D-event.

Ofoten. Just north of Narvik there are 3-4 parallel moraines in the mountains that are tentatively correlated with a raised ice-contact delta. The delta is younger than 10.0 ka BP (Andersen 1975). These deposits can be correlated with moraines in Gratangsbotn in Troms, dated to 9.7-9.5 ka BP (Andersen 1968). Other correlative moraines in Ofoten are situated at the mouths of the tributaries to Ofotfjorden, the *Narvik-Bjerkvik moraines* or the *D-event* (Andersen 1975). Most of these moraines were described by Dahl (1968). South of Ofotfjorden, scattered moraines in the inner fjord districts are tentatively correlated with the Narvik-Bjerkvik moraines, partly due to correlative marine levels, and thought to be of Narvik I or Narvik II age.

The Rombak Substage

Moraines that are correlative to the Rombak Substage are not found in the southern part of Nordland. However, along the western side of Saltdal, a huge marginal moraine can be traced for more than 30 km, the Ølfjell moraine. In places there are two parallel ridges. In Bjøllådalen at the southern side of Saltfjellet correlative moraines show that the Bjøllåvatnet ice lake (Rekstad 1913c) was dammed during this event, called the *Ølfjell event* by Sveian et al. (1979). This event has been correlated with the Rombak Substage (Andersen et al. 1981, 1995).

In the inner fjord areas between Bodø and Narvik there are several undated marginal moraines and raised terraces, which have been tentatively correlated with the Narvik II Substage (Andersen 1975, Andersen et al. 1981) or the Rombak Substage (Andersen et al. 1995).

The most prominent and known ice-marginal deposit in Ofoten is the *Rombak moraine*, which is situated on a rock promontory at the mouth of Rombaksbotn. The moraine is more than 1 km long, and was first mentioned by Sjögren (1909), later by Vogt (1913), and investigated in detail by Dahl (1968). Andersen (1975) dated shell from the Rombak moraine at 9.3 ka BP, which is the typical age of the Rombak Substage. Correlative raised deltas are situated in some valleys south of Narvik (Dahl 1968, Møller & Sollid 1972, Andersen 1975, Bargel & Bergstrøm 1993).

The Rombak Substage was tentatively correlated with the Høylandet event in the Trøndelag area (Bergstrøm 1992, Sveian 1997).

Younger moraines

End moraines younger than the Rombak Substage are found in the Saltdalen area. The moraines were deposited during the *Lønsdal event* (Bøen 1980). These are the youngest moraines found in Nordland except the sub-recent moraines in front of existing glaciers. This fact, combined with the existence of vast glaciofluvial and fluvial sediments in the valleys could mean a fast melting of the last ice remnants after the Rombak Substage.

8.6 Conclusions - the deglaciation of Central Fennoscandia and Nordland

The main glacial, interglacial and interstadial episodes in Central Fennoscandia and Nordland can be summarized as follows (Fig. 6.5, Enclosures 5 and 6):

1. Strata that probably represent most of the Pleistocene have been described from the continental shelf off Norway.
2. Saalian deposits, which correlate with oxygen isotope stage 6, and Holsteinian and Elsterian deposits, which may correlate with one or more of the oxygen isotope stages 7-11, are relatively common in Mid-Finland.
3. Eemian sediments have been described from one locality in Central Norway in the coastal area and in seismic profiles from the continental shelf off Norway. In Finland, Eemian sediments have been described from several localities.
4. The Weichselian interstadial no. 1 is considered to correlate with the Brørup interstadial in Denmark, which may be correlated with the Jämtland interstadial (older part) in central Sweden, the Oulainen interstadial and the Horonkylä interstadial in central Finland and the Peräpohjola interstadial in northern Finland and Sweden.
5. The Weichselian interstadial no. 2 is considered to correlate with the Odderade interstadial in northwestern Germany, the younger part of the Jämtland interstadial in

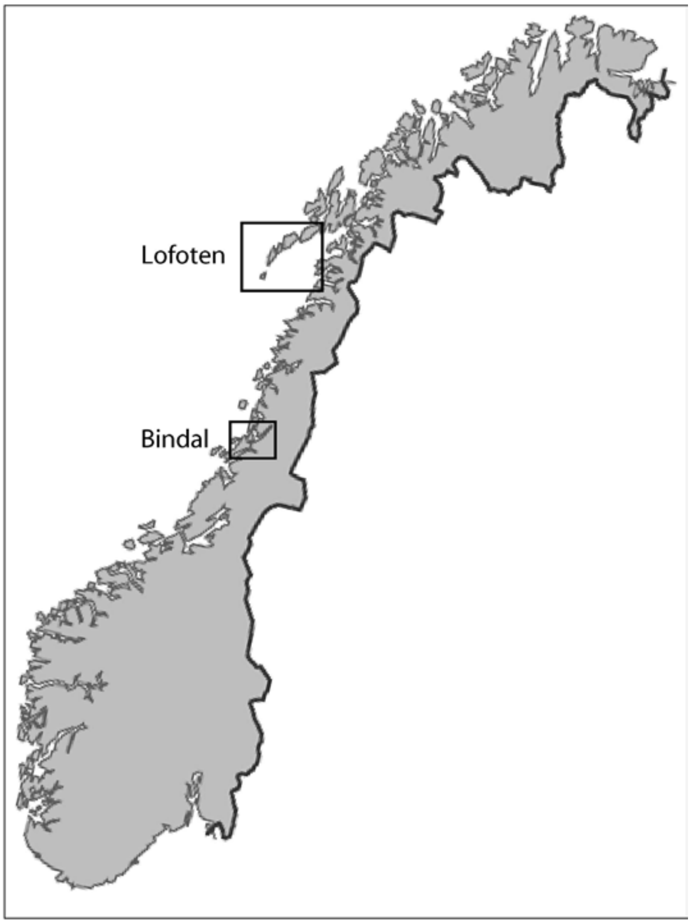
central Sweden, the Mertuanoja interstadial in central Finland, the Tärendö interstadial in northern Sweden and the Peräpohjola interstadial in northern Finland.

6. The Weichselian interstadial no. 3 is considered to be of Middle Weichselian age. It is inferred to correlate with the Bø interstadial in coastal southwestern Norway (50-55 ka BP). Possible correlatives are, e.g. the Tärendö interstadial in northern Sweden and the interstadial represented by the Horonpa sponge deposits in central Finland.
7. The Weichselian interstadial no. 4 is considered to be from the late Middle Weichselian. It is named Hattfjelldal interstadial I in the inland region of central Norway and is inferred to correlate with the Ålesund interstadial, which existed some 28-39 ka BP in southwestern coastal Norway. The continental shelf off Norway probably remained ice-free for a long period until after 30 ka BP.
8. The following ice expansion was limited. Sediments in coastal caves show that the outer coastline of Møre was ice-covered c. 28 ka BP. Rapid shifts in the extent of the ice are recorded on the shelf, and the coast of Helgeland could have been ice-free or glaciated for a very short interval.
9. The Weichselian interstadial no. 5 is thought to date from c. 27 ka to the Late Weichselian maximum ice advance c. 24 ka BP. It is named the Hattfjelldal interstadial II in inland central Norway and is thought to correlate with the Hamnsund interstadial in coastal western Norway.
10. At 24-21 ka BP the inland ice reached its maximum extension in Weichsel (LGM 1). The continental shelf off Norway was completely glaciated, but the existence of nunataks in Møre and on Andøya is hypothesised.
11. The Weichselian interstadial no. 6 is thought to date from the interval between the two major ice advances during the broad Late Weichselian maximum. It is named Trofors interstadial in the inland region of Norway and Andøya interstadial in coastal northern Norway. The coast and the valleys were possibly ice-free, but the higher ground was probably partly glaciated. The duration of this interstadial was 21-17 ka BP.
12. The second ice advance of the Late Weichselian maximum, LGM 2, occurred at c. 17-15 ka BP. The ice extension in the west was of about the same size during LGM 1 and LGM 2, and it ended abruptly at the shelf edge in both periods, but the highest

coastal mountains and the outer parts of the shelf were perhaps not ice-covered everywhere during LGM 2.

13. The main deglaciation started c. 15-14 ka BP, but ice-lobes deposited till tongues on the western shelf at c. 15 ka BP and c. 13.5 ka BP. The shelf deglaciated rapidly thereafter.
14. A small ice advance reached the outer coastal districts and deposited the Tingvoll moraine, the Outer Coastal moraines, the Vega moraine and the Vassdal moraines at c. 12.4-12.0 ka BP, the Older Dryas Substage.
15. The deglaciation in the Allerød interstadial led to intense calving of the fjord glaciers in the west, especially in the Trondheimsfjorden district, and many valleys were ice-free. In the east, the southeastern part of Finland including eastern Karelia was deglaciated during the Heinola-deglaciation.
16. In the early-middle Younger Dryas, the Salpausselkä I and Tuupovaara end moraines (11.3-11.1 cal ka ago), the Salpausselkä II and the Koitere end moraines (10.8-10.6 cal ka ago) and the Pielisjärvi end moraines (10.5-10.4 cal ka ago) were deposited in the east. The latter is correlated with the Salpausselkä III end moraine in southwestern Finland. In the west, a nearly continuous set of end moraines were deposited, the Tautra moraines and the Tjøtta moraines. Two separate glacial phases may be represented, 11.2-10.8 ka BP and 10.6-10.4 ka BP respectively. The largest end formations are situated in the mouths of the valleys. In the northern part of the Trøndelag area the ice advance in the Younger Dryas was more extensive than during the Outer Coastal Substage. In the late Younger Dryas the Hoklingen moraines were deposited in Trøndelag and the correlative Nordli moraines were deposited in Nordland 10.4-10.3 ka BP.
17. In the Preboreal end moraines were deposited in the inner part of the fjords, the Vuku moraines (10.0-9.9 ka BP), the Grong-Snåsa moraines (c. 9.7 ka BP?) and the Høylandet moraines (c. 9.5 ka BP?) in Trøndelag. Correlative moraines in Nordland are the Narvik I moraines (9.9 ka BP), the Narvik II moraines (9.6 ka BP) and the Rombak moraines (9.3 ka BP), respectively. In the east, the end moraines in Liperi are tentatively correlated with the Vuku moraines.

PART III GLACIER DYNAMICS IN CENTRAL NORWAY AND NORDLAND



Chapter 9 East-west balance and deglaciation of Central Fennoscandia and Nordland - a discussion

9.1 The ice movements

Glacial striae and *roche moutonnées* on bedrock surfaces are the most common ice-flow indicators in most of Norway as in Central Fennoscandia (Chapter 6). Localities with *till fabric* and *drumlin* observations are very sparse. The very few observations at hand on till fabric from deeper strata in the Norwegian part of Central Fennoscandia and in Nordland show the same ice-flow directions as the glacial striae (Hirvas et al. 1986, Bargel et al. 1999c). However, although the age relationships of the ice flows are readily determinable from the till fabric, this is not always the case with striae. The heavily ice-sculptured fjord and valley morphology along the coast of Norway lead us to think that the same paths may have been used by ice flow during several glaciations (Fig. 4.5, Fig. 7.3, Fig. 10.7 C). This view is strongly supported by estimates of very low erosion rates during the last glacial period in some areas, despite the fact that these areas are heavily ice-sculptured (e.g., Stroeven et al. 2002). As the regional ice divide was almost parallel to the coastline and located in Sweden (e.g., Lundqvist 1972), the general ice flow was in a westerly direction (Hirvas et al. 1986, Bargel et al. 1999c).

A representative selection of the ice-flow indicators in Central Fennoscandia is presented on Enclosure 3, and a description is given in Chapter 6.

9.2 The east-west balance

The southwestern coastline of the Central Fennoscandian area (i.e., Møre) with direct exposure to the prevailing southwesterly winds in combination with the high, coastal mountains is subject to extensive precipitation when open-sea conditions existed in the North Atlantic (e.g., Aune 1993). The relatively short distance to the shelf edge, c. 60-80 km (Holtedahl 1993), combined with glacial isostatic downwarping of the Earth's crust, which reduced the effect of the lower sea level during the glaciations (e.g., Fairbanks 1989), led to effective drainage of the ice sheet towards the west, mainly through the valleys, fjords and submarine troughs on the shelf (Andersen & Nesje 1992, Fig. 9.1, Ottesen et al. 2001, Fig. 6.3).

This drainage would lead to a general lowering of the ice surface on the western side and thereby an easterly adjustment of the ice divide (e.g., Ljugner 1945), (Fig. 9.2). The drainage towards the east which crossed mainly land areas, must probably have been less effective,

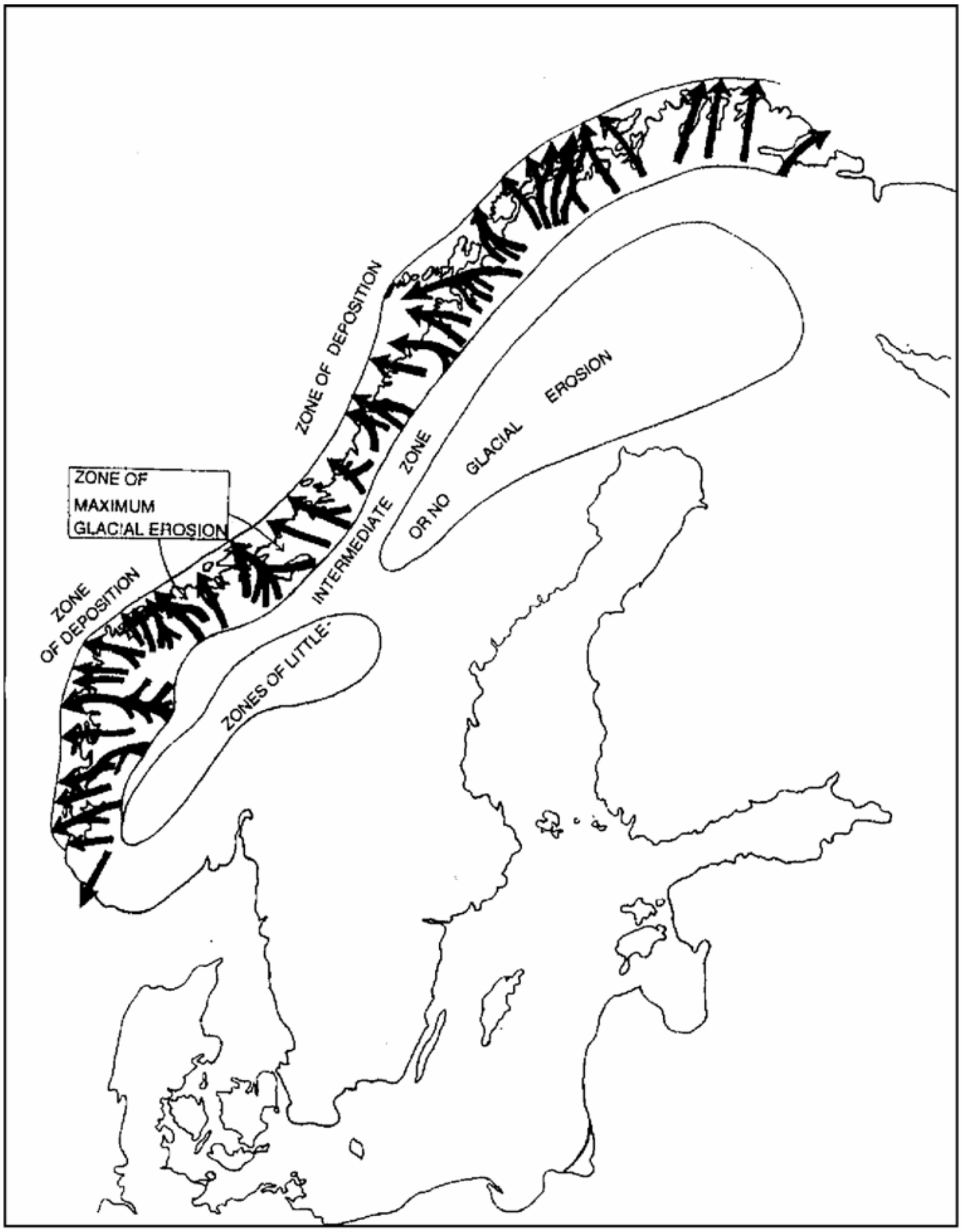


Fig. 9.1
Zones of glacial erosion along the western part of the Fennoscandian ice sheet. The heaviest erosion took place where the deepest fjords and valleys are located, which is roughly outlined on the figure (black arrows). In these areas the drainage of the ice sheet was most effective. From Andersen & Nesje (1992).

even though the narrow and shallow Baltic Sea and Skagerrak acted as drainage channels directed towards the south and southwest for the areas east of the ice-divide zone. Ljugner (1949) proposed a similar easterly migration of the ice divide, but he thought that the reason for this was a change in the precipitation delivery from southwest to southeast. Another consequence of the effective ice drainage towards the west was that the vertical and horizontal extent of the ice sheet along the entire western coast of Norway was highly influenced by even small variations of the ice volumes in the accumulation areas. The effect of this could be, e.g. the rapid shifts in the western glacial extension as proposed by Olsen (1997a).

On the eastern side of the ice divide the changes in the glacial extension were probably slower and much less pronounced, and perhaps hardly recognizable at all, except for possible small variations in the ice thickness. Variation in the extent of the eastern ice-sheet margin is therefore supposed to have happened east of the Central Fennoscandian area (cf. Fig. 8.1). Another implication of the extensive drainage and lowering of the ice surface could be the possibility of ice-free summits on the western side of the mountain chain during most of the Weichselian, as proposed, e.g. by Nesje et al. (1987, 1988).

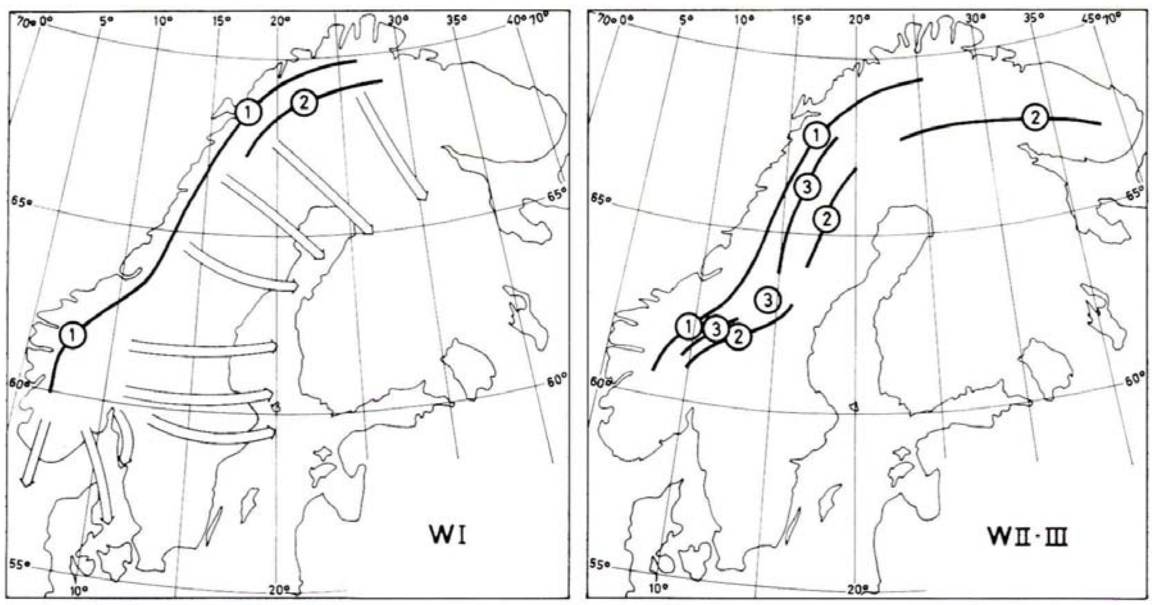


Fig. 9.2
The migration of the ice divide along the Scandinavian mountain range during various stages of the Weichselian glaciations (W I-III), as proposed by Ljugner (1949). The positions are numbered chronologically. This illustration is a modification of Ljugner's ideas presented by Lundqvist (1974). Ljugner's original illustration is shown in Fig. 3.1.

9.3 The deglaciation pattern

As the ice diminished in thickness, the passageways through the mountain chain from the ice-shed in the east to the coast in the west must have been increasingly important to concentrate the ice flow. As seen on topographical maps of Scandinavia, the watershed between Trondheimsfjorden and the southward-directed valleys in southeastern Norway is situated at 660-800 m a.s.l. (Fig. 9.3). The situation is quite different towards the east and northeast where there are only scattered high mountains. The middle elevation is substantially lower in these areas and the watershed is situated at c. 370-400 m a.s.l. at several passes along the mountain chain in the Lierne-Børgefjellet area. Consequently, the ice drainage from the east and northeast was more persistent than that from the southeast, assuming that the ice culmination in the Gulf of Bothnia persisted. This change in the dynamics of the inland ice may explain the large number of late Younger Dryas and Preboreal end moraines north and northeast of Trondheimsfjorden where five or six successive end-moraine events are well defined, while only four are distinguished farther to the south (Reite 1994c, Sveian 1997).

The ice drainage to the west was directed along the main valleys and fjords, e.g. to the Trondheimsfjorden basin. The ice feed was from the east, northeast and southeast, making the fjord a major confluence basin (Reite 1994c). This would have made the ice supply to the Trondheimsfjorden area more sensitive to variations in the ice volume than on the coast outside Møre, as the great variation in the moraines could indicate (Bargel et al. 1999a, b, c).

During the global warming in Allerød time the ice supply from the east diminished, and the recession in Trondheimsfjorden was very fast due to intense calving in the deep fjord (Reite 1994c). In certain periods the fjord must have been filled with floating icebergs and, consequently, many of them must have grounded. Overconsolidated glaciomarine deposits containing shell fragments Allerød and Younger Dryas age are found at several localities in the Trondheimsfjorden area outside the Younger Dryas ice-marginal moraines (Løfaldli et al. 1981, Feragen 1997). These sediments are interpreted as a result of grounding of icebergs from the calving of the floating ice front during the Allerød or, more frequently, of thick sea ice or shelf ice produced in the following cold phase (L. Olsen, pers. comm. 2002).

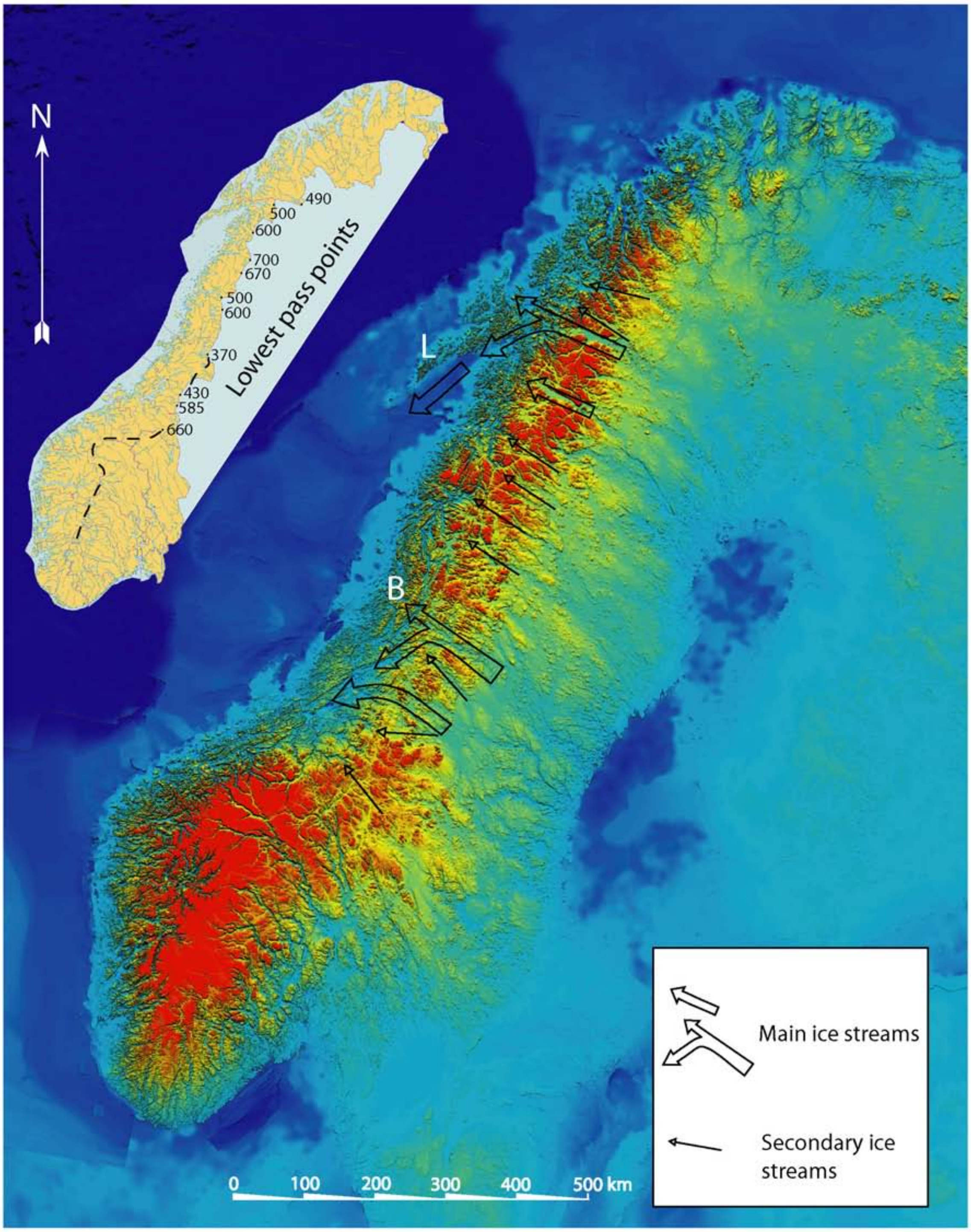


Fig. 9.3
Digital shadow relief map of Fennoscandia showing the dominant passageways of the ice streams during the last phase of the deglaciation. The *Main ice streams* followed the lowest pass points along the mountain chain and they are probably responsible for the youngest (Preboreal) moraines in the corresponding Norwegian valleys. On the inset map, the main watershed in southern Norway is indicated (broken line). In northern Norway, the watershed mostly follows the Norwegian/Swedish border, and here the lowest pass points are shown (figures in m a.s.l.). B-Bindal, L-Lofoten.

Alternatively, an ice readvance to the outer parts of Trondheimsfjorden, as indicated by Ottesen et al. (1995), could have had a consolidating effect on the overrun glaciomarine sediments. Olsen & Sveian (1994) and Olsen (2002) have described comparable sediments at various elevations, but always below the Younger Dryas sea level farther north along the coast of Trøndelag and Nordland. The iceberg drift was most likely also quite extensive outside Trondheimsfjorden. On the island of Frøya, a semicircular ridge, probably produced by a grounding iceberg, is situated in the present littoral zone. Radiocarbon dating of *Mya truncata* from the top of the ridge gave a Younger Dryas age (10,355 ± 65 yr BP; Table 1.1, p. 54). The locality is situated c. 90 km distally to the Younger Dryas end moraines in Trondheimsfjorden.

The generally accepted ice-flow pattern as an ice sheet diminishes is that the flow will follow the main topographic features such as valleys and fjords. There is no reason to argue against this view here, but it has to be pointed out that unexpected ice movements have been observed at several locations. An example of this is the gradual change in flow direction as indicated by striae in the Namdalen-Majavatnet area (Fig. 11.1), initially towards the northwest and swinging gradually through north to northeast (Svensson 1959, Bargel 2001). A similar change is observed in the Dividalen-Altevatnet area in southeastern Troms where the regional west-northwest directed flow changed through north to northeast during the last phases of the deglaciation (Bargel 1996). A probable interpretation of these observed flow patterns is that as the regional ice divide became less important due to, e.g. the presence of topographic obstacles, local glaciation centres may have taken over as dominating ice sources, a situation which is comparable to the Trollheimen example mentioned in Ch. 9.5. High mountains are situated to the southwest of the striae localities in both the above-mentioned examples. This is, of course, not a new observation as numerous writers have described similar flow divergence, but it has often been neglected in many of the earlier models.

9.4 Moraine distribution

North of Trondheimsfjorden, Preboreal moraines are found at the inner ends of most of the longest fjords. Most of the moraines are of medium size, and they are correlated based on scattered radiocarbon datings (Andersen et al. 1981). The correlation across the mountains that separate the fjords is tentative as only small moraines are located in these areas. On the Saltfjellet mountain, however, the Late Preboreal moraines are very large; the Ølfjell moraine, for example, can be followed for c. 40 km. The largest ridge, the Ølfjell ridge, is at most c. 25 m in height, which is somewhat unusual for regional moraines in the mountains (Sveian et al. 1979). In the Saltenfjorden and Ofotfjorden areas, the Late Preboreal moraines are also huge, but most of the few moraines of this age that are located in the mountain area between these fjords are small (Andersen 1975).

This moraine pattern may be partly explained by the bedrock morphology in this area. As is the case farther south, low-lying passageways exist in the mountain chain in the northern part of Nordland. Just east of Saltfjellet, in Sweden, there is a wide area occupied by several elongated lakes at 400-500 m a.s.l. that are oriented along a NW-SE trend. In the fjord districts to the west, several moraines are situated. The Kebnekajse mountain massif occupies the area farther north and would have formed an effective barrier to ice flowing towards the mountainous area between Saltenfjorden and Ofotfjorden as the inland ice became thinner, and only relatively few and small moraines are found in this area. North of the Kebnekajse mountains, Torneträsk, Ofotfjorden and Vestfjorden acted as an ice-drainage channel towards the southwest, but ice flow was also directed northwards to Andfjorden, diverted by the mountainous Lofoten and Vesterålen islands.

The watershed just west of Torneträsk is located at c. 500 m a.s.l. Farther north, the Altevatnet lake area at c. 500 m a.s.l. was another ice-drainage channel from the eastern part of Torneträsk towards Bardudalen. Many large moraines are situated in the fjords and valleys in the Ofoten area and farther to the north. As in the Trøndelag area, this shows that large moraines were systematically connected to passageways through the mountain chain. In other areas, the moraines are small or non-existent.

These examples from Trøndelag and Nordland clearly demonstrate that changes in the flow pattern of the inland ice, as the ice shrank, are a reflection of the sub-ice topography. This would have gradually changed the mass-balance of the ice, such that stagnation of the ice front would not have been synchronized. When the ice had its maximum extension and the ice front was situated at the continental shelf, bathymetric depressions on the shelf may have been particularly important in channellising the ice flow to these depressions that may, in turn, have had an important effect on the glacier dynamics on land (Ottesen et al. 2001). The problem of ice flow, localisation of moraines and other glacial deposits and topography are discussed in more detail in Chapter 10, where the Lofoten islands are used as an example.

9.5 Local glaciation centres

An effect of the deglaciation was that ice masses could be dynamically isolated from the main ice sheet and act as glaciation centres for a limited period of time. Great deviations from the regional ice flow could then be the result. This is documented in the Trollheimen-Hitra area where glacial striae are recorded which show that ice flowed towards the north. According to Reite (1994c), this indicates flow from a local ice dome in the Trollheimen area, which was probably active during an early phase of the deglaciation. Local ice domes could also have existed on the continental shelf off Norway, as proposed by Ottesen et al. (2001), but ice movement from such ice domes have not been reported.

As pointed out already by Rekstad (1910) and confirmed by Blake & Olsen (1999), the glacier Svartisen probably acted as a local glacial centre during parts of the glaciations, and deflected the ice flow from inland areas towards Skjerstadfjorden in the north and Ranafjorden in the south. Several smaller glaciers in the county, e.g. Storsteinsbreen, Frostisen and Gihtsetjåhkkå in the Narvik area, Blåmannsisen in Salten and Okstindbreen in Hemnes, may also have acted as local glaciation centres during parts of the glaciation.

Chapter 10 A new deglaciation model for the Lofoten Islands: Evidence of a Late Glacial ice advance, the Lofoten event?

10.1 Introduction

Steep mountains that are heavily dissected by cirques characterise the Lofoten islands (Fig. 10.1, Fig. 10.2). Some of the mountains reach up to more than 1000 m a.s.l. from where steep cliffs lead directly into the sea, especially on the west and northwest sides of the islands.

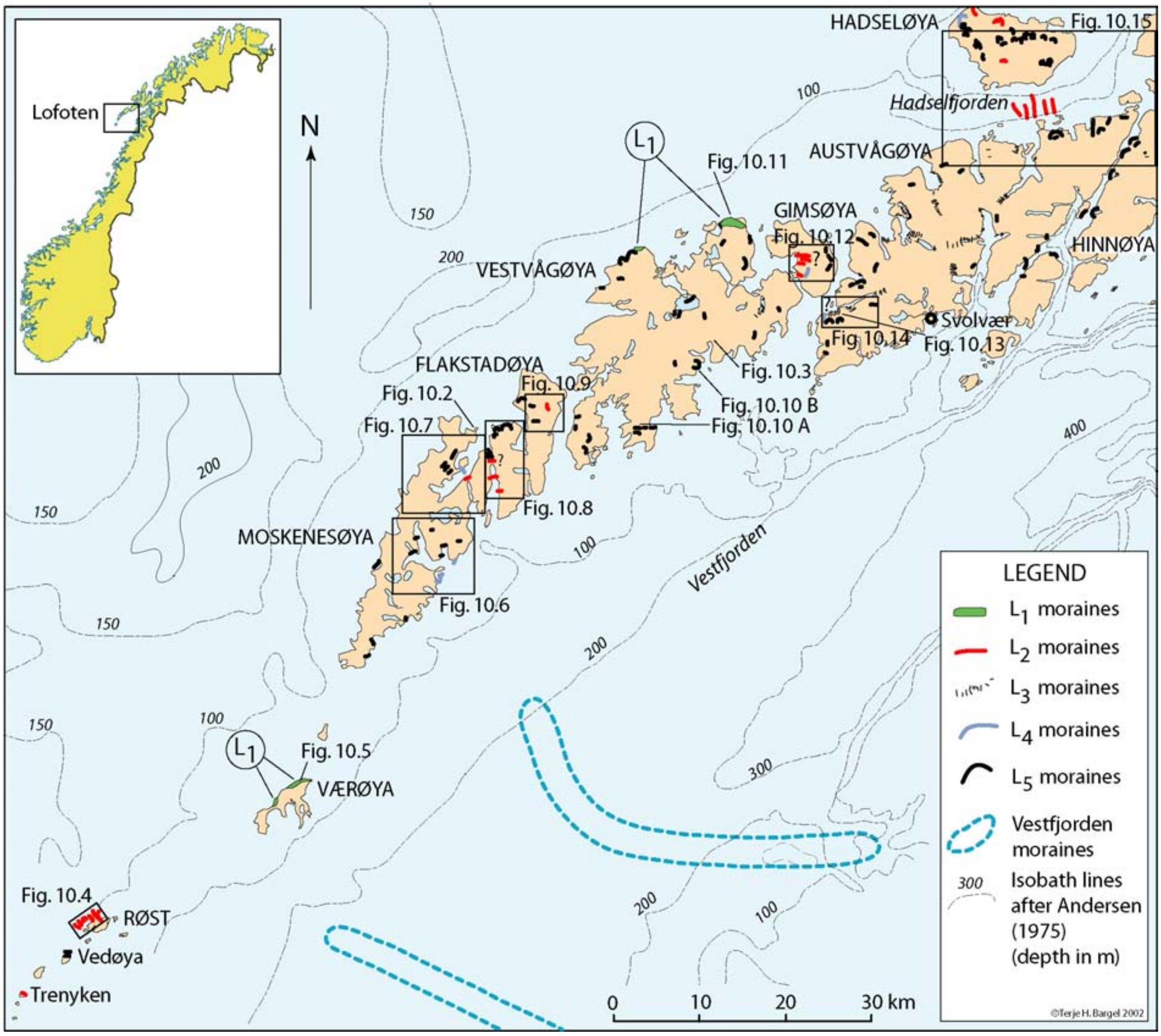


Fig. 10.1
Sketch map of the Lofoten islands that show the location of the mapped moraines and detailed figures shown later in this thesis. The classification into L_1-L_5 moraines is described in Ch. 10.2. The two youngest Vestfjorden moraines are also indicated, cf. Fig. 8.6.

Viewed from the east, the Lofoten appears as a continuous wall of mountains, and the name *Lofotveggen* (the Lofot wall) is a commonly used term in this district. The strandflat is generally submerged but, where not, it is normally narrow and discontinuous (Fig. 10.2).

The sounds between the islands are generally shallow, and most of them are oriented N-S or NE-SW, as are most of the small fjords. The continental shelf outside Lofoten is mostly less than 200 m deep and 80-90 km wide (H. Holtedahl 1993). Vestfjorden, on the eastern side of Lofoten is very broad, up to 90 km east of Værøy. The fjord is also shallow, especially at the outer part where the depth is less than 300 m (Fig. 8.6, Fig. 10.16). However, Vestfjorden is overdeepened, as with most of the Norwegian fjords, and reaches a depth of 627 m at its inner end.

Various igneous rocks of Proterozoic age, mainly granites, syenites, monzonites and gabbros, dominate the bedrock, but some gneisses and schists of Archaean age are also present (Tveten 1978). On the shelf, sedimentary rocks of Mesozoic age are present just outside the littoral zone and form the base of the shallow continental shelf. Quaternary deposits are sparse, as in most parts of Nordland County. Weathering material occupies extensive areas as autochthonous blankets of varying thickness or as talus fans or aprons beneath the numerous steep cliffs (Bargel 2001) (Fig. 7.6, Fig. 10.3). The granites, monzonites and schists are most accessible to weathering.

Thick till is identified at several localities, but probably due to the weathering and periglacial phenomena (soil creep, stone upheaval, etc.) the till is generally almost impossible to differentiate from weathering material on aerial photographs and is therefore most probably underrepresented on the Quaternary geological map (Enclosure 4). However, erratics are observed close to the highest peaks on most of the islands (Grønlie 1940, Bergström 1973).

As already noted by Keilhau (1838) and Helland (1897), most of the moraines are located in the short Lofoten valleys (i.e., cirque valleys). J.H.L. Vogt (1907b) described several moraines that he claimed were a result of local glaciation. He even proposed that the inland ice once covered the continental platform out to the continental break (called Egga or Haveggen). The local glaciation later removed the traces after the main glaciation. Grønlie (1940, 1951) and Marthinussen (1962) reported on late- and postglacial shorelines and constructed shoreline diagrams, data that are relevant when reconstructing the ice distribution and the relative age of the moraines.

Fig. 10.2
View of Fredvang, Moskenesøya, in the foreground and Ramberg, Flakstadøya, in the background showing the typical Lofoten landscape with steep and heavily weathered and eroded mountains, cirques, scree deposits and a narrow strandflat. Photo: Terje H. Bargel.

Fig. 10.3
The weathering processes and accompanying scree deposits are characteristic of many parts of Lofoten. Very little till is present. From Kongsjord, southern Vestvågøya. Photo: Terje H. Bargel.

Bergström (1973) investigated several local moraines in Lofoten. He claimed that at least three generations of moraines could be demonstrated on the island Austvågøya, moraines which he considered to be correlative with the shorelines S_3, P_{12} and P_9 of Marthinussen (1962) with approximate ages of 12.3, 10.3 and 9.9 ka BP (cal.), respectively. Bergström (op cit.) reported a radiocarbon dating from a bog situated proximally to a local moraine at Reknes on Austvågøya, which gave an age of c. 8.5 ka BP (U-105). Consequently, he concluded that the moraine was older, and this dating indicates that the moraine could be of Preboreal or Younger Dryas age.

Møller & Sollid (1972) presented a deglaciation chronology of the Lofoten-Vesterålen-Ofoten area based on correlation of shorelines (Fig. 8.10). The oldest moraines were called the A 1 (Andøya 1) moraines and were thought to be of Weichsel maximum age. The A 2 and A 3 moraines were thought to have an age of 16-15 ka BP and 15-13 ka BP, respectively. According to Andersen (1975), this reconstruction is highly speculative. Andersen's criticism is legitimate, mainly because the reconstructed moraine lines are hardly associated with any true, well developed moraines. In addition, radiocarbon dates were not available and the reconstructed ice margins are difficult to understand glaciodynamically because no account was taken of the dominating ice stream in Vestfjorden and the varying topography (cf. Lofotveggen, mentioned above). This morphological effect was no more emphasised by Tanner (1915) in his glacier flow reconstructions (Fig. 3.4).

However, Møller & Sollid (1973) observed that the inland ice probably had deposited some of the moraines that really did exist. Andersen (1975) mapped the same moraines by aerial photo interpretation only and concluded that they were all deposited from local glaciers. Sollid & Torp (1984) combined these views and categorized the moraines as having been deposited either by local glaciers or by the inland ice, but no proper discussion of the glacial dynamics was presented. Both proposals, i.e., of Møller & Sollid (1972) and of Sollid & Torp (1984), are mostly in conflict with the conclusions of the present study.

During the aerial photo interpretation and the subsequent reconnaissance trips when preparing the Quaternary geological map of Nordland county (Enclosure 4), it became clear to the present writer that several of the deposits that had earlier been mapped as moraines are almost certainly protalus, rock glaciers or other mass-movement forms. What is more important is the fact that the remapping supports the view that several moraines have a position relative to the topography that probably disqualifies the idea of deposition by local glaciers, and in that sense gives some credit to the view of Sollid & Torp (1984).

As the present study is of a preliminary nature the conclusions must therefore be looked upon as a working hypothesis.

10.2 Description of the moraines

Five types of moraines or diamictic material are identified on the Lofoten islands, the L_1-L_5-moraines (Fig. 10.1). The classification is based mainly on geographical and morphological criteria and on the supposed genesis, and a short description is presented here. The moraine types are thoroughly described and discussed in Ch. 10.3.

L_1-moraines are hummocky accumulations of diamictic material situated at low levels (below 100 m a.s.l.) on the northwestern sides of high and steep cliffs facing northwest. The L_1-moraines are probably lee-side accumulations deposited during the last glaciation/deglaciation cycle.

L_2-moraines are single transverse moraines mostly located in the sounds that separate the Lofoten islands. The moraines were probably deposited by a limited expansion of the Vestfjorden glacier during an early part of the deglaciation, which is here called the Lofoten event.

L_3-moraines are moraines of De Geer type that are deposited submarginally during the stepwise recession of the glacier towards a glaciation centre after the Lofoten event.

L_4-moraines are cirque moraines that are located several kilometres from the cirque backwall and indicate a glaciation limit far beyond that expected during the Younger Dryas.

L_5-moraines are cirque moraines that are mostly located in the cirques, the cirque valleys or in areas just outside the cirques. The moraines are the youngest moraines in Lofoten, and were most probably deposited during the Younger Dryas or the Preboreal climatic deteriorations.

10.2.1 Røst

On the Røst group of islands (Fig. 10.1), Møller (1985) described ridges of till that were deposited in front of some coastal caves. On the northern side of Trenyken, which has its highest point at 143 m a.s.l., a 60 m-wide ridge consisting of diamictic sediments is situated in front of, and within the entrance of a coastal cave. The ridge is interpreted as a moraine deposited marginally or submarginally to the ice sheet (L_2-moraine). On the northern side of Vedøya (202 m a.s.l.), two end-moraine ridges located at 35 m a.s.l. were probably deposited by a local glacier (L_5-moraine). A third moraine is situated in the sea, 200-300 m distally to the two above mentioned end moraines (Bargel 2001).

On the western side of Røstlandet (less than 10 m a.s.l.), there are up to nine, elongated, partly submerged ridges that are mostly oriented NW-SE (Fig. 10.4). The ridges are heavily washed, but they were nevertheless interpreted as De Geer moraines by Sollid & Torp (1984). If the moraine interpretation is correct, then they were most probably deposited by a regional ice sheet (L_2-moraines), as there is no cirque large enough in this particular area.

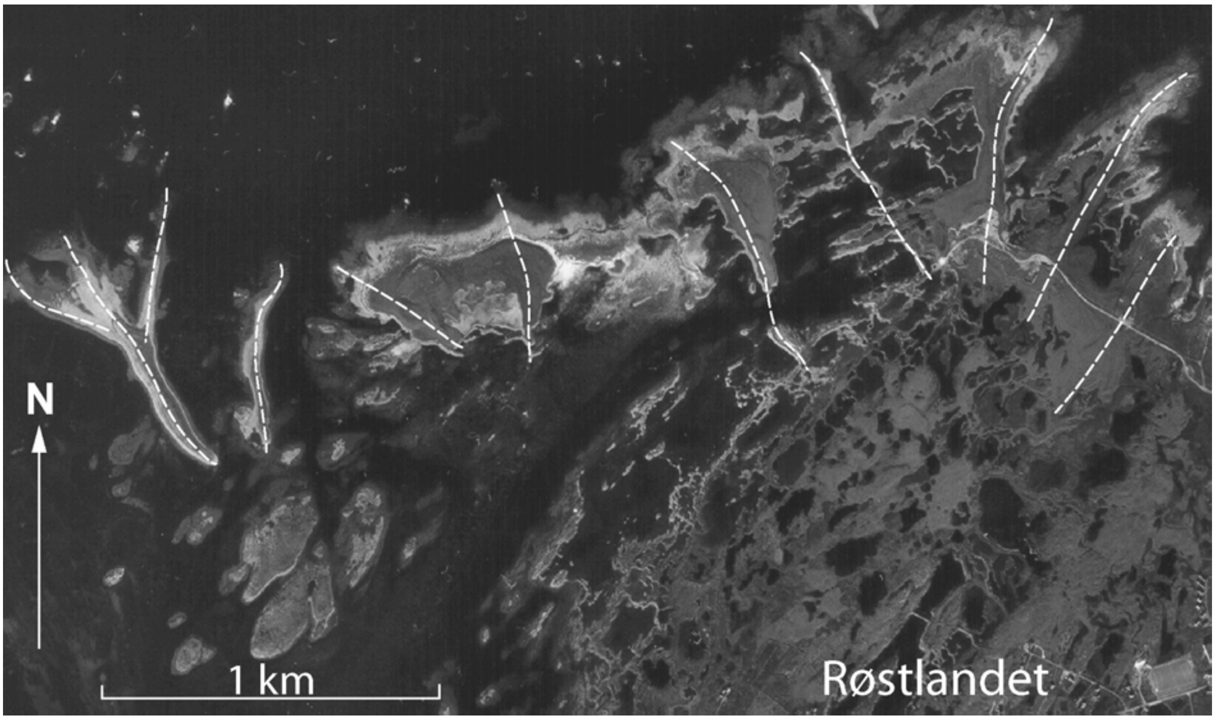


Fig. 10.4
Vertical aerial photograph of the western part of Røstlandet island that shows up to nine, heavily wave-washed moraines of possibly De Geer type. Photo: Fjellanger-Widerøe as.

10.2.2 Værøya

On the northern side of Værøya (Fig. 10.1) there is a NW-facing, almost vertical cliff of 350-400 m height or more. The highest point on the island is 450 m a.s.l. Erratics probably deposited by a regional ice sheet are found at 400 m a.s.l. in the northern part (Bergström 1973). At the foot of the cliff, mounds and ridges and some small lakes are the dominating morphological elements (Fig. 10.5). Bedrock is exposed in the largest mounds, but most of the area consists of diamictic material (L_1-moraines). A protalus ridge is probably present. The area is mostly located at c. 5-10 m a.s.l. and the highest shoreline is at 15 m a.s.l. (Møller 1985), which accounts for the extensive wave wash of most of the area. On some geological maps, e.g. Sollid & Torp (1984), moraines are indicated in this area, but the reconnaissance trip carried out for the present study has shown that this is probably wrong.

Fig. 10.5
The northwestern part of Værøya showing a hummocky terrain of diamictic material located beneath a steep, NW-facing cliff. Photo: Terje H. Bargel.

10.2.3 Moskenesøya

The highest mountain on Moskenesøya (Fig. 10.1) is 1029 m a.s.l. and there are smaller mountains of more than 600 m a.s.l. in other parts of the island. Small end moraines are situated in front of several cirques. Up to three parallel moraines are present. Distances from the moraines to the backwalls of the cirques vary from less than 1 km to c. 3 km (L_5-moraines). In the overdeepened Kjerkfjorden and tributaries, at least two generations of moraines exist. At Reine, a nicely curved end moraine is situated on a sill (Fig. 10.6 B). The shape of the moraine and striae observations show that it was deposited by ice flowing towards the southeast in Kjerkfjorden. This moraine and a smaller boulder accumulation at Hamnøya are tentatively correlated (L_4-moraines).

At Sundstraumen between Moskenesøya and Flakstadøya, a diamictic deposit has caused a narrowing and shallowing of the sound (Fig. 10.7). The deposit is interpreted as a moraine deposited by a regional ice sheet (L_2-moraine), even though it can be argued that coalescing cirque glaciers southwest of Sundstraumen could have deposited the moraine. L_4- and L_5-moraines are also present. Erratics probably deposited by a regional ice sheet are found at 720 m a.s.l. on the southern part of Moskenesøya (Bergström 1973).

10.2.4 Flakstadøya

On Flakstadøya (Fig. 10.1) the highest mountain is 932 m a.s.l. Several moraines are located in cirques that are oriented towards the west and northwest. In the northern part of Flakstadøya the cirque moraines are small and two parallel ridges are mostly present (L_5-moraines). Between the villages Ramberg and Flakstad, three cirque moraines are located in front of relatively small cirques (L_5-moraines, Fig. 10.8 A). In the N-S-oriented Skjelfjorden, a L_2-moraine crosses the fjord c. 2 km from its head and a second one is situated 2 km to the south (Fig. 10.8 A and B). At the isthmus Skjelfjordeidet below 20 m a.s.l., a thick diamicton occupies the valley floor. This could possibly be a L_2-moraine that has been heavily washed by tidal currents during the regression, as the marine limit in the area is at 22 m a.s.l. (Møller 1985).

At Nappskardet, a moraine crosses the valley at the highest point, c. 80 m a.s.l. (Fig. 10.9). The moraine is slightly curved and nearly symmetric, and was most probably deposited from the east by a regional ice sheet. In the same valley, a few km to the west, Møller & Sollid (1972) reported a second moraine that dams the Vareidvatnet at 10 m a.s.l. (named Storvatnet on the map, Fig. 10.9 A). Coarse material is situated in this area, but the existence of a moraine is doubtful as most of the area is occupied by rock avalanche material

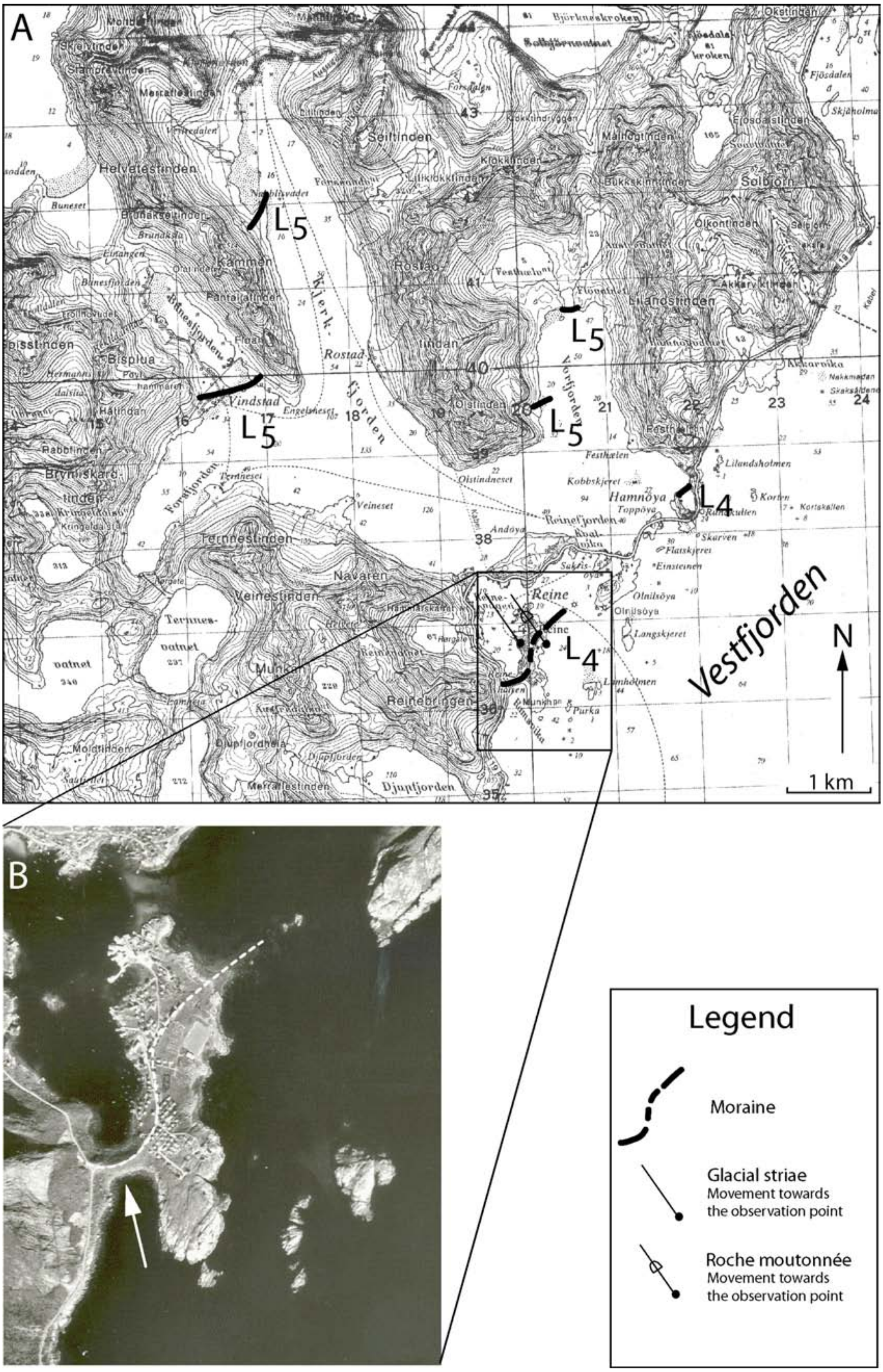


Fig. 10.6
A: Map of the Reine-Kjerkfjorden area showing the cirque topography, the cirque fjords and L_4 and L_5 moraines. **B**: Vertical aerial photograph of Reine that shows the well-marked Reine moraine (arrow). See Fig. 10.1 for location. Photo: Fjellanger-Widerøe AS.

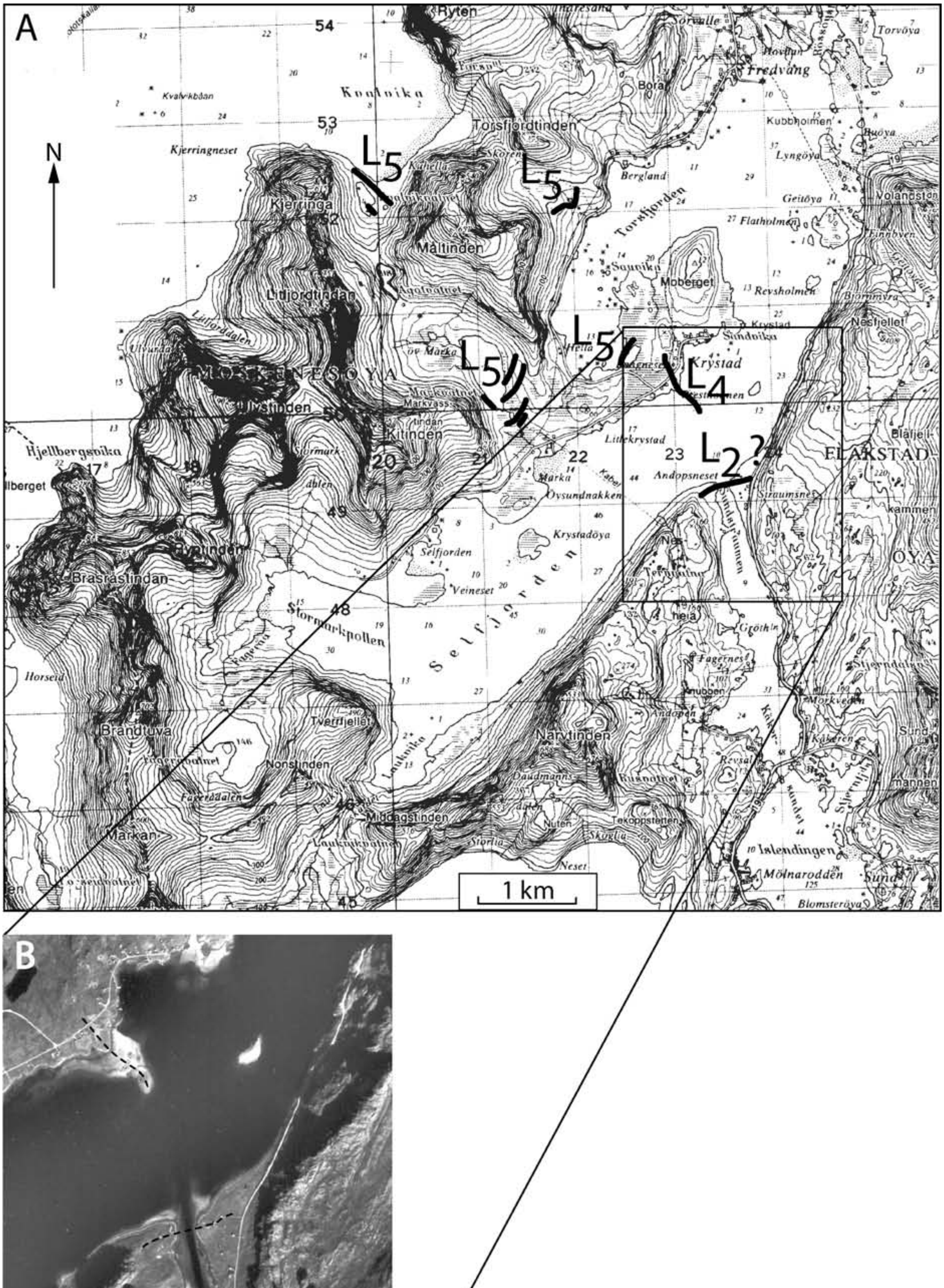


Fig. 10.7 A, B and C
Figure caption is found on the next page.

Fig. 10.7
The Selfjorden area at Moskenesøya (see Fig. 10.1 for location).
A: Map showing the topography with several heavily incised cirques that are oriented along varying trends. End moraines (L_2, L_4 and L_5 moraines) are indicated.
B: Vertical aerial photo showing Sundstraumen; a wave-washed end moraine that could have been deposited from the south by the continental glacier (L_2-moraine), but deposition by the local glacier from the southwest in Selfjorden is also possible. Photo: Fjellanger-Widerøe.
C: The Sundstraumen area viewed from the northeast (from Flakstadøya) showing diamictic accumulations that could represent the washed remains of the L_2-moraine. Photo: Terje H. Bargel.

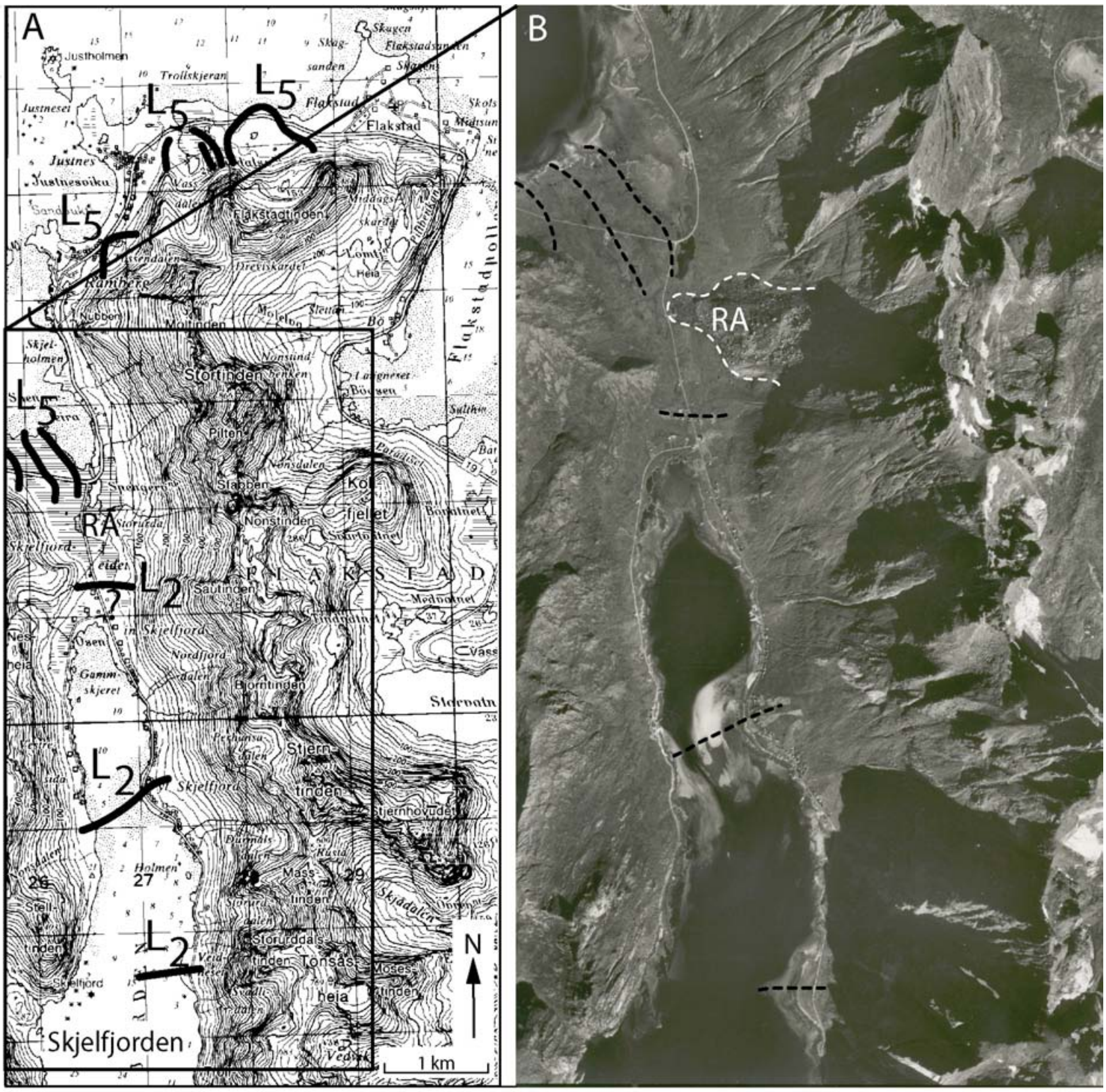


Fig. 10.8
The Skjelfjorden area in central Flakstadøya (see Fig. 10.1 for location).
A: Map showing the moraines (thick lines) that were probably deposited by the continental glacier in Skjelfjorden (L_2 moraines, see Ch. 10.3), and the cirque moraines between Flakstad and Ramberg (L_5 moraines). A giant rock avalanche (RA) is also indicated.
B: Vertical aerial photo of the framed area in figure A showing the Skjelfjorden-Skjelfjordeidet area, the moraines and the cirque and arête topography in the mountains along the eastern side (left) of the fjord. The giant rock avalanche (RA) is readily visible. Photo: Fjellanger-Widerøe.

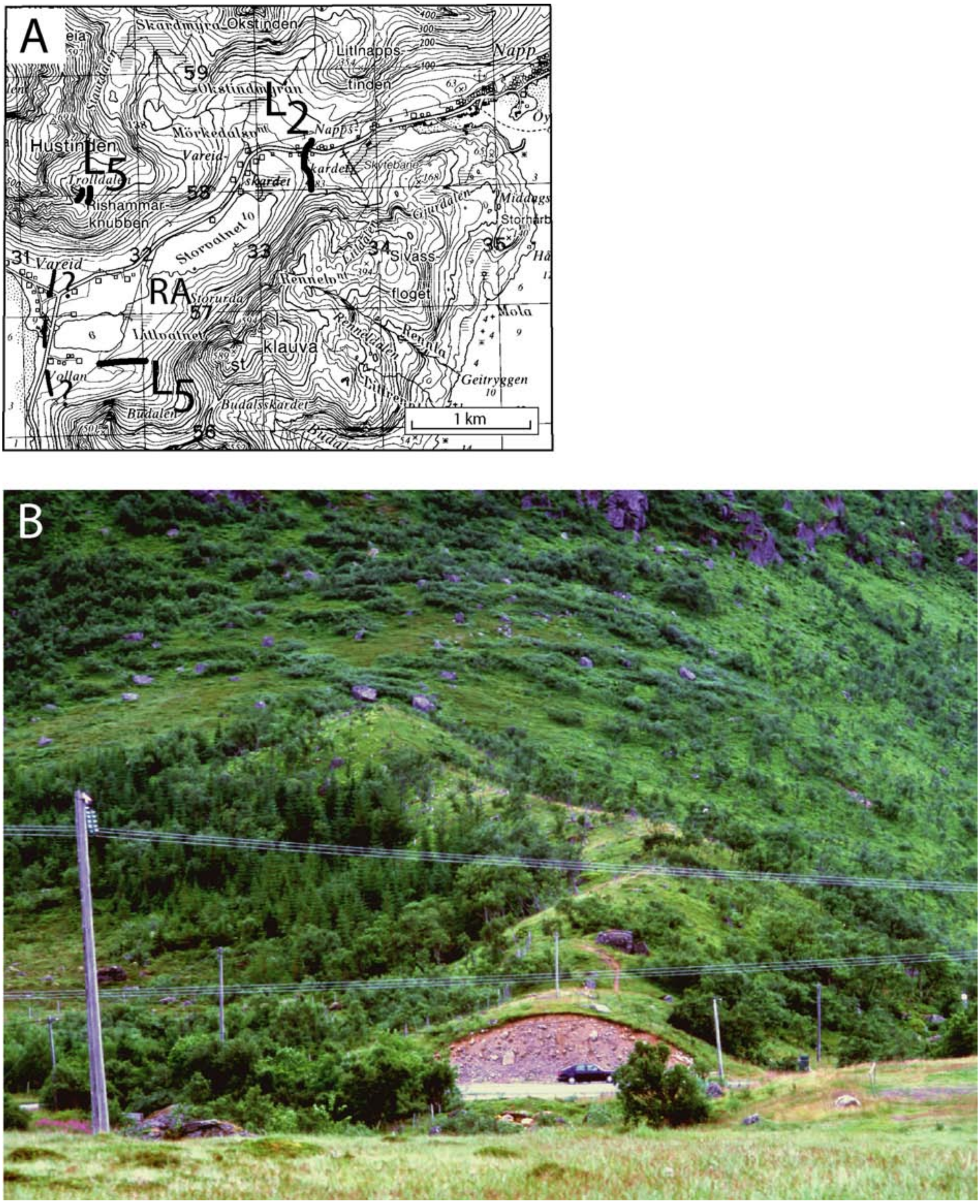


Fig. 10.9
The Napp-Vareid area in northern Flakstadøya (see Fig. 10.1 for location).
A: Map showing the end moraine at Nappskardet that was probably deposited by a lobe from the continental ice sheet (L_2 moraine). A few cirque moraines (L_5 moraines) are also shown. The two lakes to the west of Nappskardet were earlier thought to be dammed by moraines (Møller & Sollid 1972, Andersen 1975). However, Storvatnet is probably dammed by rock avalanche material (RA). Litlvatnet is more questionable as only well sorted, fine-grained material (mostly sand) is observed in the area. Bedrock is exposed along the shoreline to the west. **B**: The slightly sinusoid end L_2-moraine at Nappskardet viewed toward the south. This moraine was probably deposited by an ice lobe from the Nappstraumen area, to the east (left on the photograph). Photo: Terje H. Bargel.

10.2.5 Vestvågøya

The highest mountain on Vestvågøya (Fig. 10.1) is 965 m a.s.l. Peaks of 500-600 m a.s.l or more occur throughout the island. Erratics that were probably deposited by a regional ice sheet are found at 571 m a.s.l. (Bergström 1973). The central part of the island has a broad, valley-like depression with many lakes and ponds at less than 25 m a.s.l. The bedrock is generally heavily weathered (Fig. 10.3). Cirque moraines are present in most of the mountainous areas on the island. Many of the moraines are huge and have well-defined crests; others are heavily wave-washed (Fig. 10.10 A and B). Some of the moraines are C-shaped while others are almost linear. Up to three parallel moraines are present.

Small ridges of De Geer type (L_3-moraines) are located close to a small north-facing valley, which is incised into a mountainous area at more than 500 m a.s.l. These mountains probably acted as one of the many local glaciation centres that existed in Lofoten during periods of lowered glaciation limits. Relatively few local moraines are situated in this area. In several north-facing cirque valleys in the eastern part of Vestvågøya there are thick diamictic accumulations. In most cases, this diamicton is interpreted as a basal till that was deposited as a plain valley-floor fill.

At Kvalnes, however, the diamicton is located on the northwestern side of a high and steep cliff (Fig. 10.11). Two small hanging cirque valleys are present, but they could not possibly have delivered the amount of material that has been accumulated here. Several mounds and ridges that are separated by small depressions are the dominating morphological elements. The tops of the deposits are at c. 100 m a.s.l., and the accumulations are morphologically, and by their position relative to a steep cliff, similar to the diamictic deposits on Værøya (Ch. 10.2.2), and are interpreted to represent a leeside moraine (L_1-moraine), alternatively in combination with scree deposits and/or local glacier deposits.

At Eggum there are two well-marked (but wave-eroded) cirque moraines (L_5-moraines). Redeposited, bouldery, hummocky diamictons are located beneath high and steep cliffs just north of the moraines. According to Møller & Sollid (1972) this material could not have been deposited by local glaciers, but by the main glacier (L_1-moraines). As no cirque or scars are located on the mountainside, this interpretation seems reasonable.

Fig. 10.10
Cirque moraines (L_5-moraines) at Vestvågøya, **A**: Double moraines in Sennesvika, **B**: Wave-washed moraine in Rolfsfjorden. For location, see the map in Fig. 10.1. Photo: Terje H. Bargel.

Fig. 10.11
Hummocky diamictic deposit at Kvalnes, a possible leeside, L_1- moraine. For location, see the map in Fig. 10.1. Photo: Terje H. Bargel.

10.2.6 Gimsøya

The western part of the island Gimsøya (Fig. 10.1) is dominated by the strandflat. Mountains with peaks up to 696 m a.s.l. occur in the southeastern part of the island. At the mouth of a west-northwest-oriented cirque valley, five moraine ridges are present (a-c, Fig. 10.12). The moraine a) is situated on the top of a bedrock sill. According to Møller (1985), the top of the ridge is defined as the marine limit in the area at 27 m a.s.l. The moraine b) dams a small lake and reaches up to more than 30 m a.s.l. There is no contact between the a) and b) moraines, and this was probably also the situation at the time of deposition. A few small De Geer moraines are situated just east of the moraine b), partly submerged in the lake.

A few km distally to these moraines, three ridges c) project slightly above the surrounding bog. Gravel pits show heavily washed sediments that include boulders. These ridges are also interpretated as moraines. A cirque glacier that originated in Jenndalen could have deposited all the five moraines. If so, the b) moraine must be the youngest one (L_4-moraine) because of its most proximal position. In this scenario, the a) and c) moraines could have been deposited by a more advanced ice lobe, and consequently must have been older

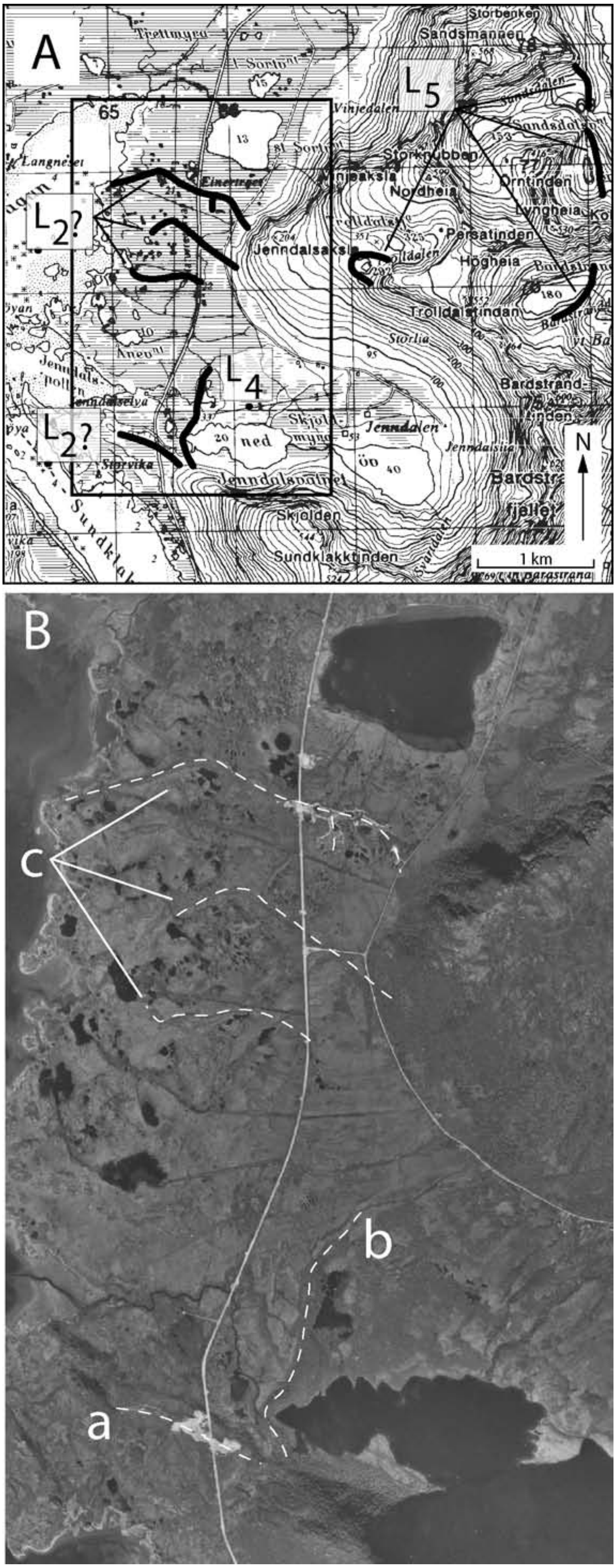


Fig. 10.12

The southwestern part of Gimsøya (see Fig. 10.1 for location). **A**: Map showing the cirque/strandflat morphology and the moraines classified as described in the text. **B**: Vertical aerial photograph of the moraine area (framed on A) with the moraines denoted a-c. Photo: Fjellanger-Widerøe. A glacier that was flowing northwards deposited the a) moraine as L_2-moraine. The c) moraines were deposited from the northeast by a glacier in Hadselfjorden as L_2-moraines (Fig. 10.16). A cirque glacier in Jenndalen most probably deposited the moraine b) as a L_4-moraine. Other interpretations are discussed in the text.

A De Geer-like deposition for these moraines has been proposed by Sollid & Torp (1984). The other De Geer moraines that are mapped on Austvågøya (Ch. 10.2.7) are considerably smaller. Alternatively, the orientation and position of the ridges might indicate that a glacier flowing northwards in the sound Sundklakkstraumen could have deposited them (Møller & Sollid 1973). A third alternative is that one or all of the moraines c) were deposited from the northeast by the Hadselfjorden glacier (Fig. 10.15 A) as L_2-moraines. This last interpretation is used in the reconstruction of the Lofoten event (Fig. 10.16).

10.2.7 Austvågøya

Austvågøya is the largest of the Lofoten islands (Fig. 10.1) and is dissected by several cirque valleys and cirque fjords that almost divide the island into three parts. The highest mountain is 1161 m a.s.l., and this is also the highest peak in Lofoten. Peaks at 700 m a.s.l. or more are found in most parts of the island. Many cirques are present, but very few of them have glaciers today as the present glaciation limit is calculated by the top method at 1000-1060 m a.s.l. (Andersen 1975). Scattered cirque moraines (L_5-moraines) are situated in the western and eastern parts of the island, but almost no such moraines are present in the central parts. However, in most of the fjords and valleys, parallel sets of De Geer moraines are present in great number (Fig. 10.1, Fig. 10.13).

At the mouth of Olderfjorden (Fig. 10.14 A), a marked, 12-15 m-high, curved slope of diamictic material is located on a bedrock platform (Fig. 10.14 C). A less pronounced continuation of the slope parallels Olderfjorden towards the east. At least seven, partly submerged, De Geer moraines are situated north of the slope. To the west of this area bedrock is quite extensively exposed. On the eastern and southern sides of the slope, thick diamictic material arranged in mounds, ridges and lakes occupies an area of up to 2 km^2. A pair of somewhat diffuse ridges that are oriented parallel to the valley side may be traced through this hummocky landscape for almost 2 km (Fig. 10.14 B and C). In a road-cut, boulders, stones and gravel are observed. Just outside three cirques in the valley side to the south, there are several well marked, but fragmented, cirque moraines. The cirques are probably too small to have been the source of the great amount of diamicton present.

A preliminary interpretation is that the deposit is probably a lateral or sublateral accumulation deposited in an area between coalescing cirque glaciers from the south and a valley glacier in Olderfjorden. The glacier could have been stagnant in the hummocky area while the ice front in Olderfjorden was active receding and produced the De Geer moraines. The third element, the fragmented cirque moraines in the south, could have been deposited by advancing cirque glaciers while the dead ice was still situated on the rock platform. The morphological elements could be of the same type as those described as marginal moraine complexes at Bleik on Andøya (Møller et al. 1992), (Fig. 8.8), at Porsanger in Finnmark (Sollid & Sørbel 1988), in southern Norway (Sollid & Sørbel 1994) and on Jæren, southwestern Norway (Knudsen et al. 2003), which indicates the existence of a cold-based, stagnant glacier that produced ridges of Rogen-like type. The area in Olderfjorden is complicated and not easy to interpret geologically, and the deposits should be investigated in more detail.

In Hadselfjorden, just north of Austvågøya, seismic profiles obtained by NGU show several N-S- oriented ridges on the sea floor that are thought to be moraines (Fig. 10.15). This could indicate that the ice margin crossed Hadselfjorden between Hadseløya and Austvågøya, and could also have deposited the c)-moraines at Gimsøya (Fig. 10.12). The present writer tentatively correlates all these moraines with the Langøy event proposed by Rasmussen (1984b), (Fig. 10.16).

Fig. 10.13
Partly submerged De Geer moraines in the Olderfjorden area, Austvågøya, cf. Fig. 10.14. Looking west-southwest from Storhaugen hill (Fig. 10.14 A). Photo: Terje H. Bargel.

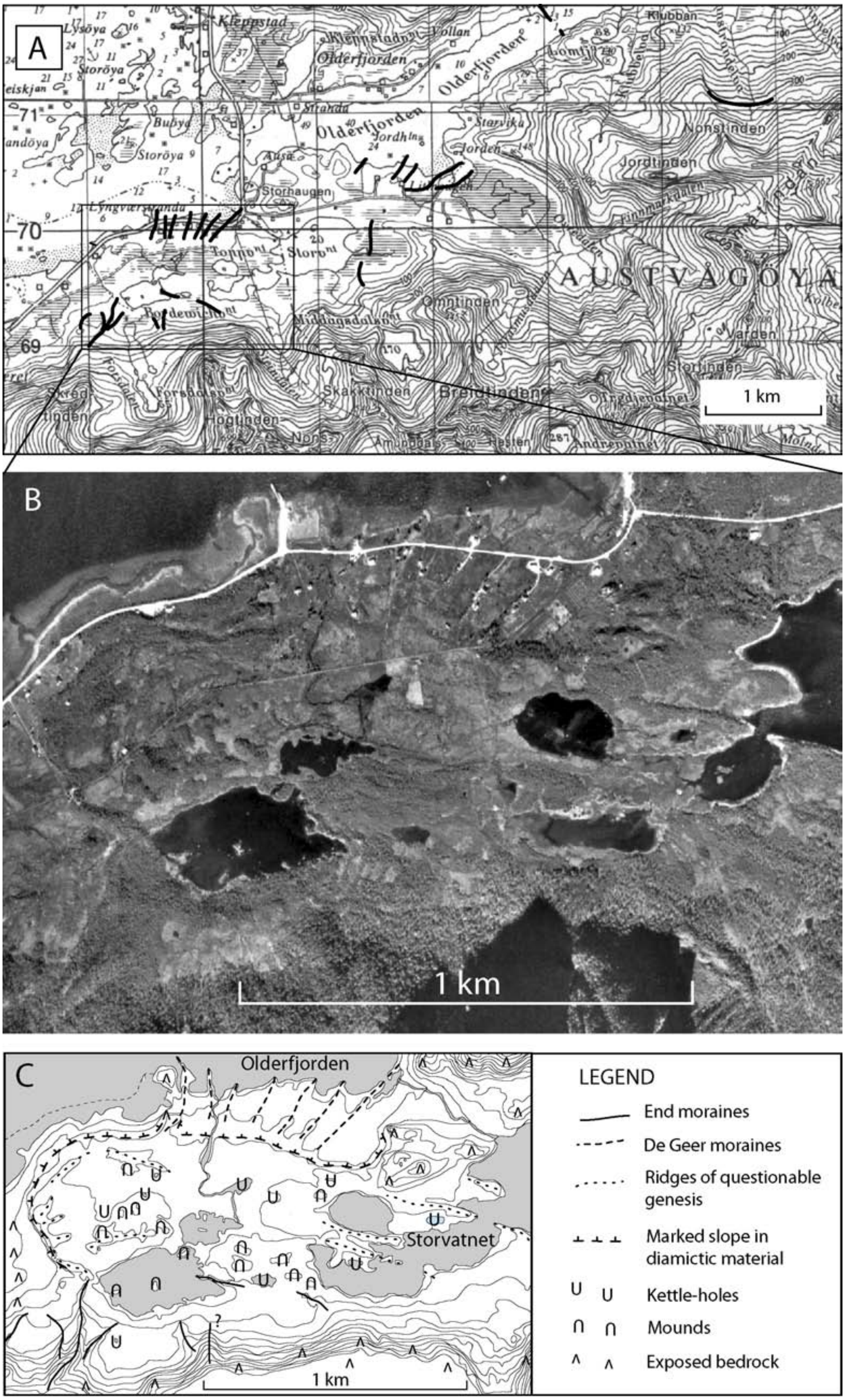


Fig. 10.14
The outer part of Olderfjorden, Austvågøya. **A**: Map showing the main moraines (fat lines) and the bedrock topography. **B**: Aerial photograph of the diamictic area. The objects are not marked in order not to camouflage the details. Photo: Fjellanger-Widerøe. **C**: Detailed topographic map of the same area as in the aerial photograph. Contour interval, 5 m. For location, see the map in Fig. 10.1.

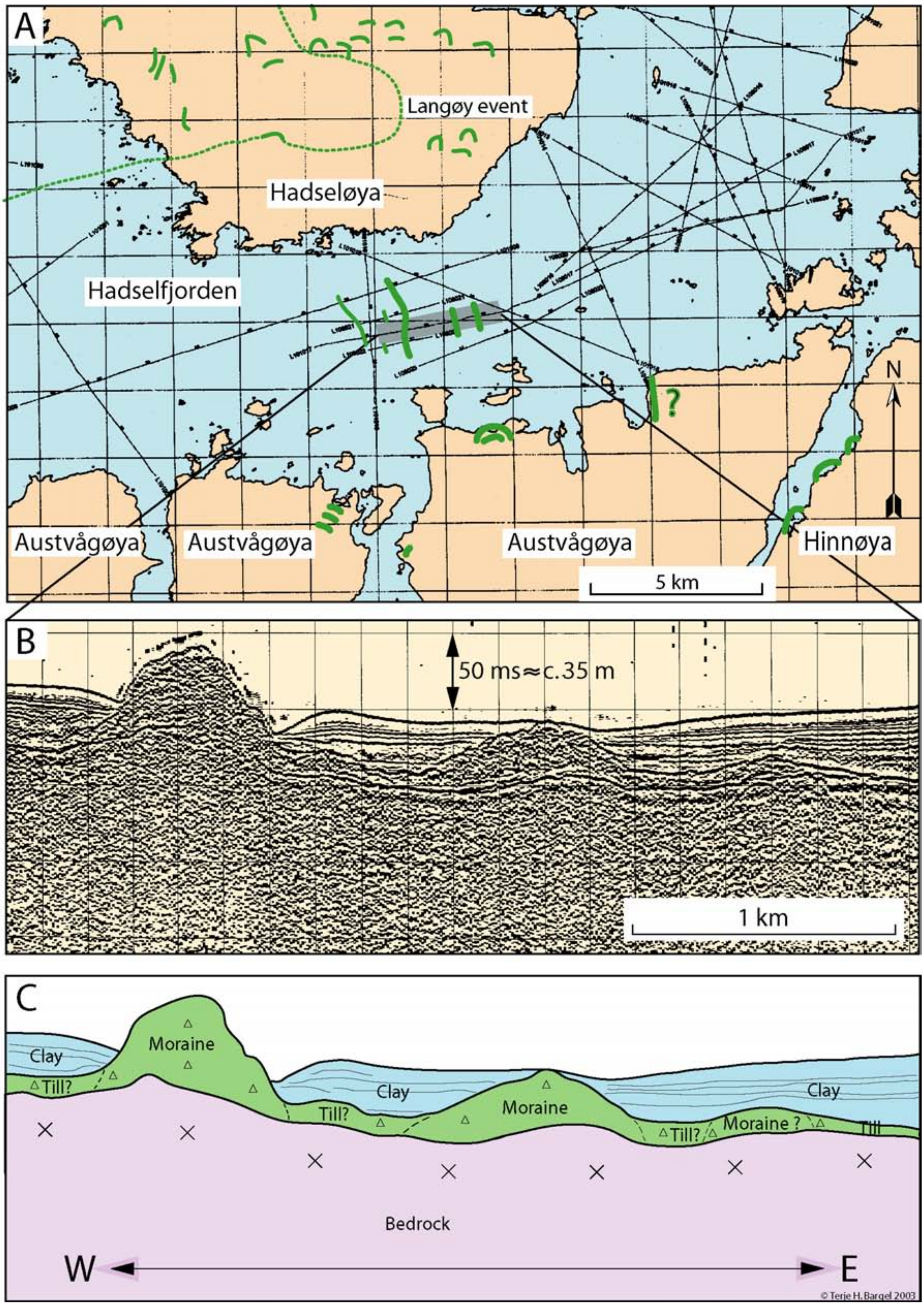


Fig. 10.15
The Hadselfjorden area (cf. Fig. 10.1 for location). **A**: Map of the seismic profile lines measured by NGU in 2001 with the interpreted part indicated by shading. The observed moraines on land and the interpreted moraines on the sea floor are shown in green lines and curves. The Langøy event as interpreted by Rasmussen (1984b) is shown by the dotted, green line. **B**: Seismic registration, and **C**: interpretation of the geology of Hadselfjorden showing three moraine ridges.

10.3 Classification of the moraines and discussion

Five types of moraines or diamictic material are identified on the Lofoten islands, the L_1-L_5-moraines (Fig. 10.1). The classification is based mainly on geographical and morphological criteria and on the supposed genesis of the diamictic material, and should be regarded as a working hyphothesis.

L_1-moraines are hummocky accumulations of diamictic material situated at low levels (less than 100 m a.s.l.) below high, steep cliffs facing northwest. The L_1-moraines were interpreted by Møller & Sollid (1972) as leeside accumulations deposited during the last glaciation/deglaciation cycle. This could be correct on Værøya, as no cirques are present that could have been the source of the huge volumes of diamictic material. At Kvalnes and at Eggum, local material from cirques could have been the source to some of the material. If so, the ice sheet could not have covered the islands completely, even though erratics are observed near the top of the mountains (Grønlie 1940, Bergström 1973). Alternatively, the diamicton could have a local provenance, as talus produced from the cliffs may have been resedimented by the sea or by glaciers. The mounds and ridges present have a resemblance to dead-ice topography, which indicates that they could have been remoulded during melting of the last ice remnants, or by grounding icebergs, shelf ice or sea ice (Olsen 2002) during the deglaciation.

L_2-moraines are single moraines mostly located in the N-S- oriented sounds that separate the Lofoten islands. The transverse positions of the moraines indicate that they were probably deposited in the sea by a regional ice flow from the Vestfjorden area towards the continental shelf outside the Lofoten islands. A tentative correlation of the ice margin during the deposition of the L_2-moraines is proposed (Fig. 10.16). The correlation supposes that an ice advance towards the northwest, which is here named the *Lofoten event*, was the cause of deposition of the L_2-moraines.

The age of the Lofoten event is not known, but if the Egga moraines are of Weichsel maximum age (LGM I and LGM II) of c. 24-21 ka BP and c. 15 ka BP, respectively (Andersen 1968, Olsen 1997a, Olsen et al. 2001a, b, c, Vorren & Plassen 2002), a correlation with the smaller ice readvance recorded at c. 13.5 ka BP (Vorren & Plassen 2002) is proposed. Alternatively, correlation with the Skarpnes-Vega moraines could be possible. If the first proposal is correct, the Lofoten event would correlate with the Flesen event or the D-event in Andfjorden (Vorren & Plassen 2002) and one of the youngest of the large moraine ridges which crosses Vestfjorden between Moskenes and Bodø (Fig. 10.1, Fig, 10.16, Enclosure 5), (Rokoengen et al. 1977). A correlation with the poorly dated Langøy event in Vesterålen (Rasmussen 1984b) is also possible. The fact that moraines of the Lofoten event have been traced only in the southwestern parts of the Lofoten islands could be a result of the local glaciation centred on the higher ground of Austvågøya that reduced the influence of the ice sheet in that particular area.

L_3-moraines or moraines of De Geer type occur quite commonly in low-lying valleys, and may be partly submerged in the fjords. The ridges occur in swarms and they are oriented transverse to the valleys. They are up to 5-6 m in height and up to several hundred metres in length. They are normally interpreted as end moraines or as having been deposited submarginally in cracks in the glacier sole during the deglaciation, which show a stepwise recession of the glacier towards the glaciation centre (e.g., Hoppe 1960, Møller & Sollid 1972, Larsen et al. 1991, Blake 2000); see Ch. 5.2.2. The L_3-moraines are concentrated in the eastern parts of the Austvågøya where the highest mountains in Lofoten are located. It is in these mountains that the glaciation centre in question was probably located. The time of deposition of the L_3-moraines was most likely during the deglaciation after the Lofoten event.

L_4- and L_5 -moraines are cirque moraines that are located in the cirques, the cirque valleys or in areas just outside the cirques. The moraines generally have a C-shape with the concave side facing the cirque, strongly indicating the direction of deposition. The cirques with moraines are most often oriented in the sector from northwest through north to an easterly direction. The L_4-moraines are cirque valley moraines that are located several km from the cirque, as in the case of the Reine moraine. The L_5-moraines are located either inside or just outside the cirque. The L_4- and L_5-moraines are usually located in the same valley/fjord system that clearly demonstrates the age difference. The L_4-moraines are associated with a lower glaciation limit than the L_5-moraines (see below) and represent a relatively large expansion of the local glaciers as they occupied several small fjords. The sparse occurrence of the L_4-moraines could indicate that the glacier fronts terminated in the sea at water depths that were greater than the postglacial rebound, or that the local ice coalesced with the inland ice and no moraines were deposited. If the latter is true, the glacier advance that deposited the L_4-moraines could be correlated with the Lofoten event. However, the shape of the Reine moraine (Fig. 10.6) indicates strongly that there was no fjord glacier occupying this part of Vestfjorden during the deposition.

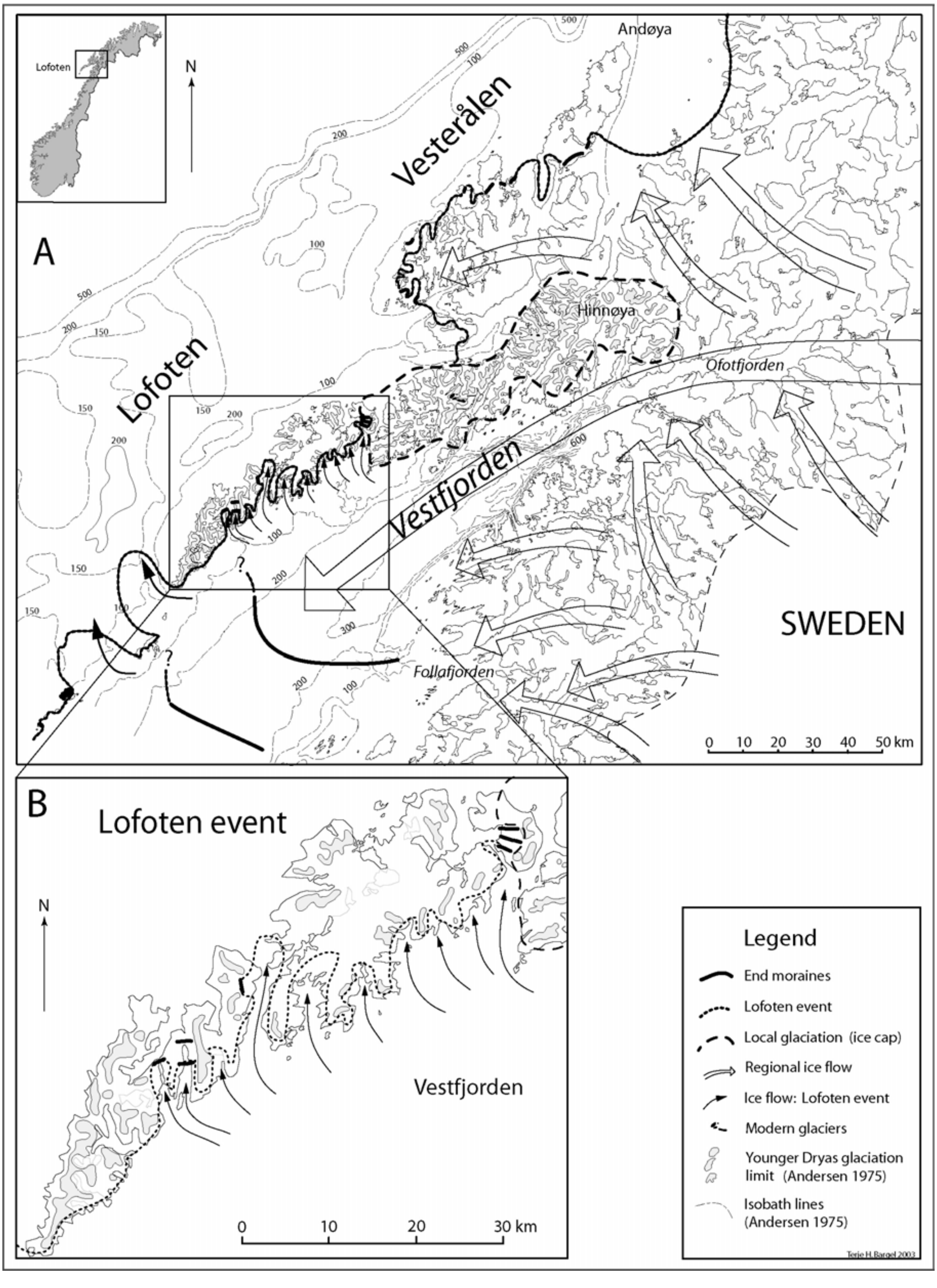


Fig. 10.16
A: Map of northern Nordland showing a reconstruction of the Lofoten event, accompanying regional ice flows, the local glaciation on Austvågøya and Hinnøya, and the coalescing zone of the regional and the local glaciers. The correlative moraines in Lofoten, Vesterålen, Hinnøya and Vestfjorden are also shown. Based on data published by Andersen (1975), Rokoengen et al. (1977), Rasmussen (1984b), Fjalstad (1997) and Vorren & Plassen (2002) and on observations by the present writer.
B: Enlargement of the Lofoten islands showing the Lofoten event in greater detail.

Two or even three, closely spaced moraine ridges commonly represent the L_5-moraines. A well-marked difference exists in the size of the moraines, and in the distance from the backwall of the cirque to the moraine. This variation is closely related to the size and shape of the cirques and whether or not marked sills are present. The L_5-moraines seem to be the youngest moraines, and their deposition may be associated with a modest lowering of the glaciation limit. According to calculations by Andersen (1975) the modern glaciation limit in this area is at c. 1000-1060 m a.s.l. The Preboreal glaciation limit in northern Nordland was c. 270-300 m lower than the present (Andersen 1975). Corresponding figures of the Younger Dryas glaciation limits are 550-570 m (Fig. 10.16). Consequently, most of the highest mountains in the Lofoten islands were situated below even the Preboreal glaciation limit, but the ice expansion was probably concentrated to the nearest valleys as the areas of accumulation must have been small. If this is correct, the most proximal L_5-moraines may have been deposited during the Preboreal, even though it is more likely that they derive from the Younger Dryas or the Older Dryas climatic deteriorations. This conclusion is also in accordance with the shorelines of Marthinussen (1962) and the dating performed by Bergström (1973).

10.4 Conclusions

Based on limited studies of the moraines in the Lofoten islands a new deglaciation chronology is proposed (Fig. 10.16, Enclosure 5):

7. During the Late Glacial Maximum (LGM I), the Vestfjorden glacier expanded northwards through the sounds between the islands, coalesced with the Hadselfjorden glacier from the northeast, and terminated at the shelf break. Local glaciation on the islands was very active and the highest mountains could have been ice covered.
8. During the subsequent deglaciation, the continental glacier withdrew from most of the area, but local glaciers probably still existed.
9. The readvance to the LGM II position at c. 15 ka BP was probably almost as extensive as the LGM I.
10. The main deglaciation started at c. 15-14 ka BP, but ice-lobes deposited till tongues on the western shelf and small moraines in the sounds in the western part of the Lofoten area at c. 13.5 ka BP; the *Lofoten event*. The local glaciation during the Lofoten event was intense, and the local glaciers coalesced with the main ice sheet.

11. Most of the ice probably vanished during the subsequent deglaciation, leaving many sets of De Geer moraines in the fjords.
12. During the climatic deteriorations in the Older Dryas, the Younger Dryas and probably the Preboreal chronozones, the local glaciers expanded causing cirque moraine deposition.

Chapter 11 Deglaciation of the Bindal area, Central Norway: Evidence of a strong topographic influence on a dynamic, active ice margin

11.1 Introduction

Deep fjords that are surrounded by high mountains characterise the Bindal area in southern Nordland (Fig. 11.1). Tosenfjorden is almost 500 m deep and 25 km long and is nearly linear as it follows a NE-SW trending fault. There are no valleys connecting the Tosenfjord with the eastern part of the country due to the presence of long chains of N-S-trending >1000 m-high mountains. The small valley Åbjørdalen is cut off from the main inland valleys by these mountains, with passpoints not lower than 580 m a.s.l. (Fig. 11.3). South of the Bindal area, the narrow Follafjorden is a tributary to the Namdalen valley, which has extensions into the interior region. North of the Bindal area, Vefsnfjorden and the accompanying valleys penetrate into the northern part of Børgefjellet.

The highest mountain on the coast is the Heilhornet at 1058 m a.s.l. Northeast of Tosenfjorden there are peaks up to 1250 m a.s.l. containing cirque glaciers. The highest mountain in this part of Nordland is Kvigtind at 1699 m a.s.l., which also contains glaciers. Rocks deformed during the Caledonian orogeny dominate the area, and two main rock associations, metamorphic and plutonic, are represented (Gustavson 1981). Formations and lenses of carbonate rocks are found in the metamorphic complex (Nordgulen & Bering 1987)

The Bindal area is generally lacking in Quaternary surficial deposits (Svensson 1959, Enclosure 4). In the valleys, there are some glaciofluvial terraces and fluvial deposits, and near the coast scattered deposits of marine clay have been mapped. Accumulations of till with a few metres thickness are also present in some stoss-side positions and in the vicinity of end moraines. The end moraines and raised shorelines have attracted the attention of many earlier writers (Rekstad & Vogt 1900, Helland 1908, Rekstad 1910a, 1917b, J.H.L. Vogt 1913, Grønlie 1940, 1951, Svensson 1957, Marthinussen 1962, Sollid & Sørbel 1979, Andersen et al. 1981, Sollid & Reite 1983). Svensson (1959) mapped some of the moraines in the area (Fig. 11.2).

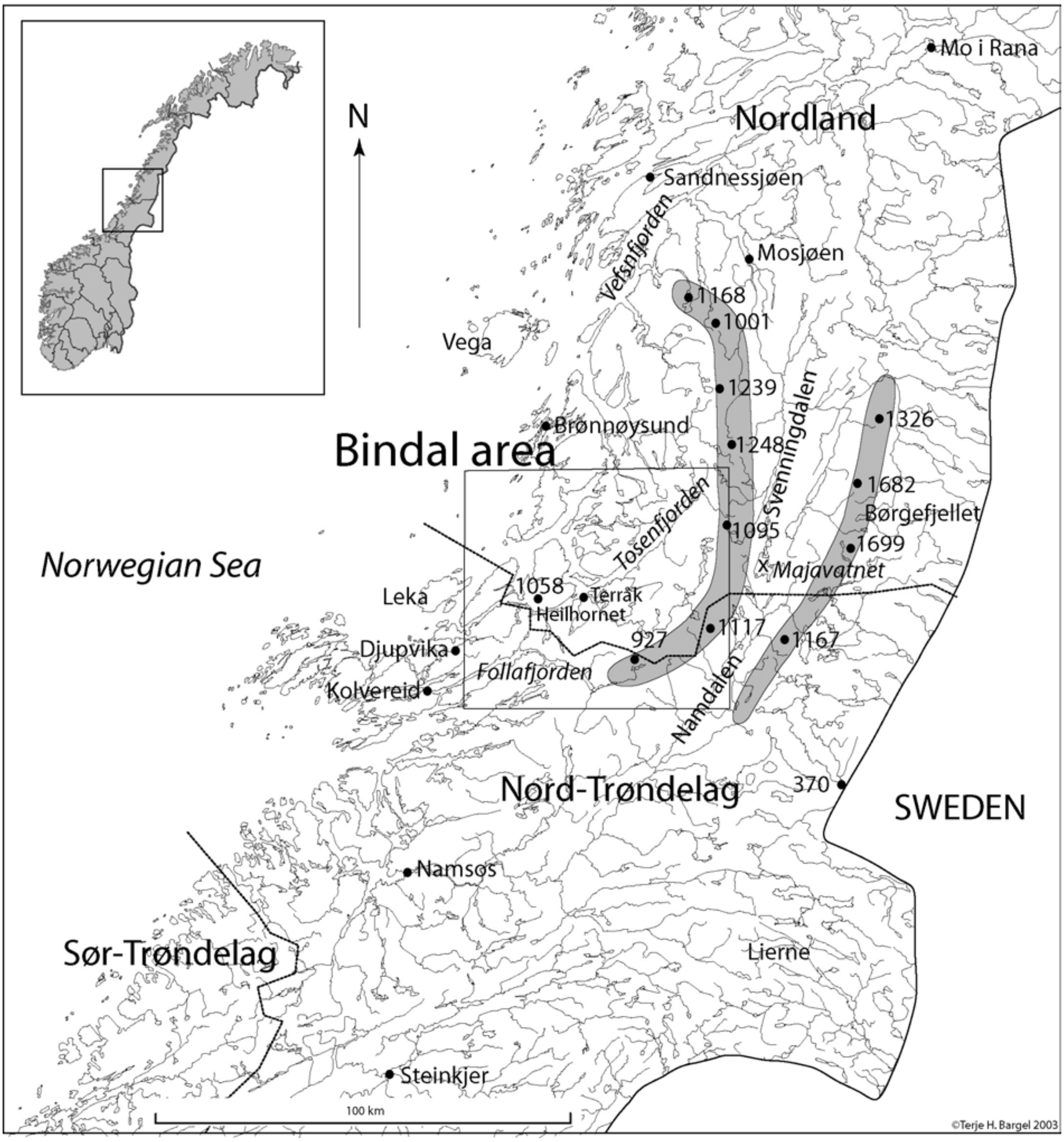


Fig. 11.1
Key map of southern Nordland and Nord-Trøndelag counties showing the two dominating chains of mountains (shaded areas), the highest peaks and the lowest east-west pass point (altitudes in m a.s.l.). The Bindal area (Fig. 11.3) is framed.

The area has recently been remapped and the new data are presented in this chapter. Based on ice-flow indicators, moraines, stratigraphy, radiocarbon datings and the area's morphology, several ice lobes are defined and discussed (Fig. 11.3). Ice lobes have also certainly existed in other parts of the area, but they are not described here.

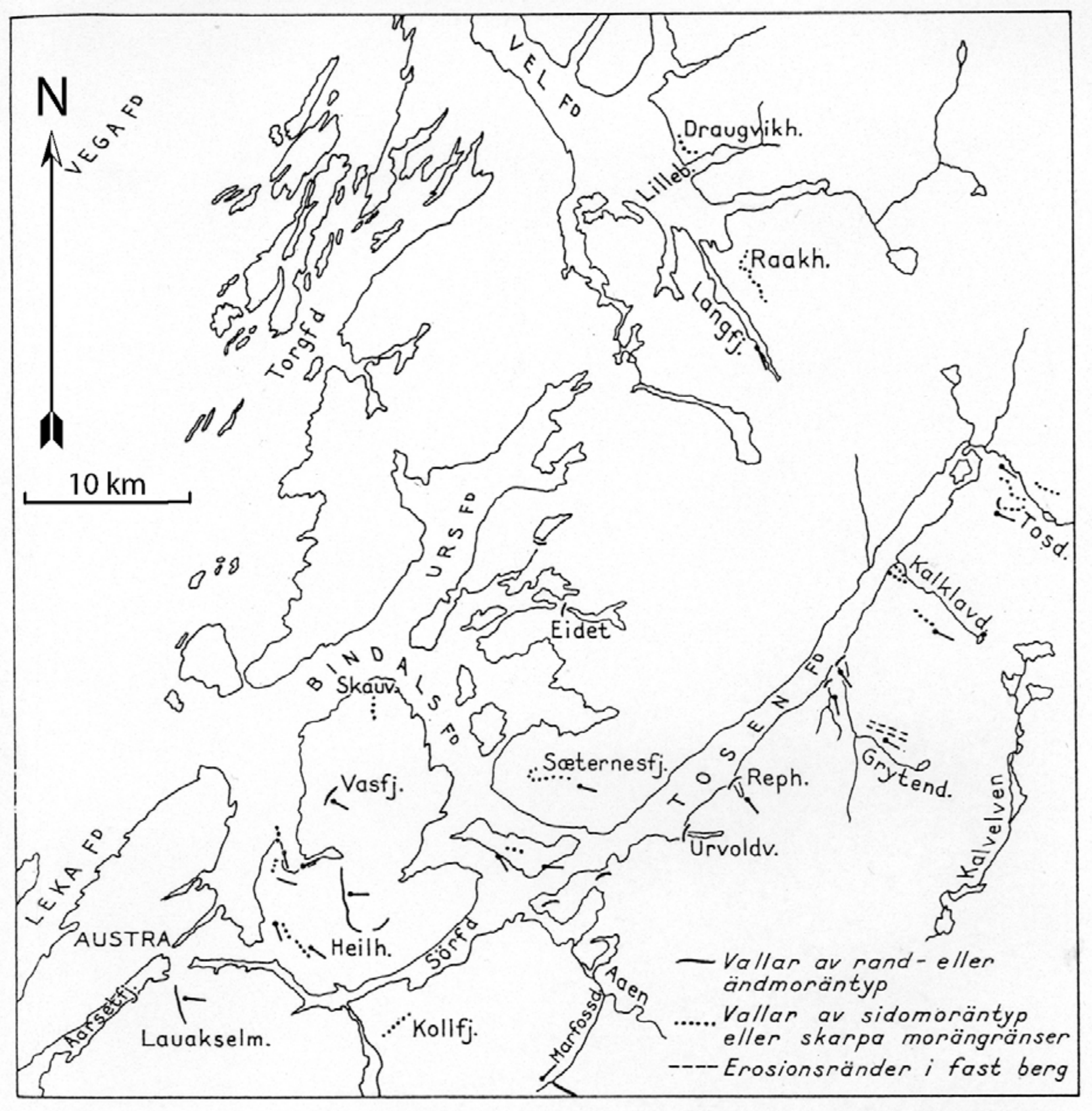


Fig. 11.2
Moraines and glacial striae in the Bindal-Tosenfjord area as mapped by Svensson (1959).

11.2 The Lysfjorden-Horndalen ice lobe

Glacial striae show an ice movement towards the west across the Bindalseidet area. This particular ice lobe deposited several huge moraines within a limited area at altitudes from below sea level up to c. 500 m a.s.l. (Fig. 11.3 and Fig. 11.4).

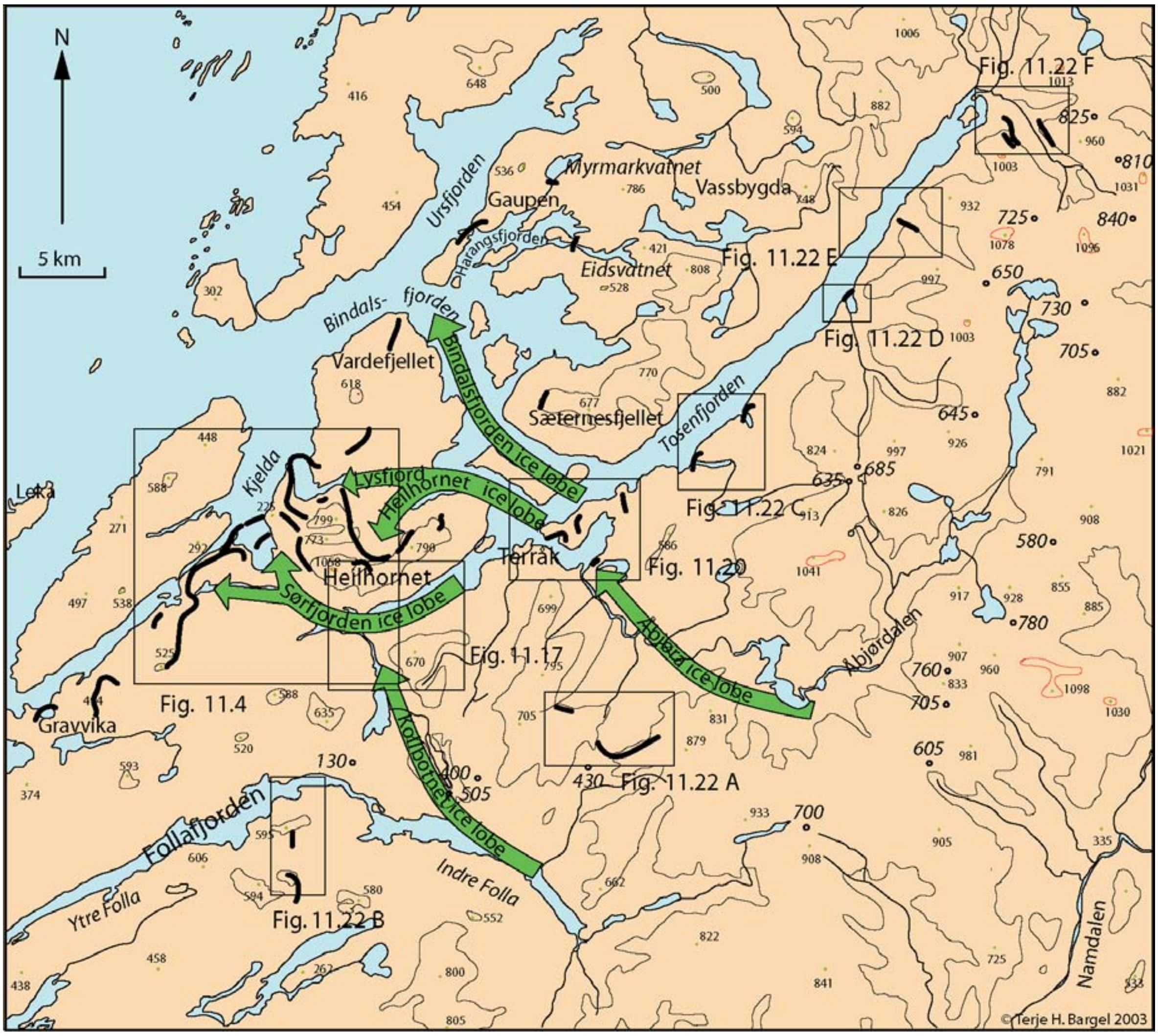


Fig. 11.3
Overview map of the Bindal area and surroundings showing the moraines (black), the inferred ice lobes (green arrows), the passpoints (figures in *italics*) and the location of detailed maps shown in this thesis.

11.2.1 The Lysfjordmana moraine

Description. The huge Lysfjordmana end moraine was probably first introduced in the literature by Rekstad & Vogt (1900), (Fig. 11.4, Fig. 11.5). Lysfjordmana occupies the divide between Lysfjorden and Lysfjordvatnet (Fig. 11.5 and Fig. 11.6). The crest height reaches up to slightly above 130 m a.s.l. near the mountain side at its eastern end. There, the crest profile is smooth but asymmetric as the southern slope is the steepest (Fig. 11.7). West of the road-cut, the crest has an almost horizontal appearance at c. 120 m a.s.l. for more than one kilometre. At the sharp bend in its far western end, the crest height rises and reaches c. 180 m a.s.l. where the moraine ridge disappears near the peak of Heggebærnesfjellet Fig. 11.5). The crest profile on the northern projection of the ridge is sharp and narrow. The first few hundred metres north of the sharp bend show an almost symmetrical profile; there, the ridge is 10-20 m broad at its base and mostly less than 5 m high. The northernmost 500 m is strongly asymmetric due to its position on the steep valley side. The change in crest profile from smooth to sharp occurs at the sharp bend in the southwestern part of the Lysfjordmana where the crest rapidly emerges 4-5 m from a terraced area at c. 134 m a.s.l. This step is interpreted as a wave erosion escarpment, which most probably represents the marine limit. If so, the smooth crest profile to the east of the escarpment is consequently a result of wave erosion.

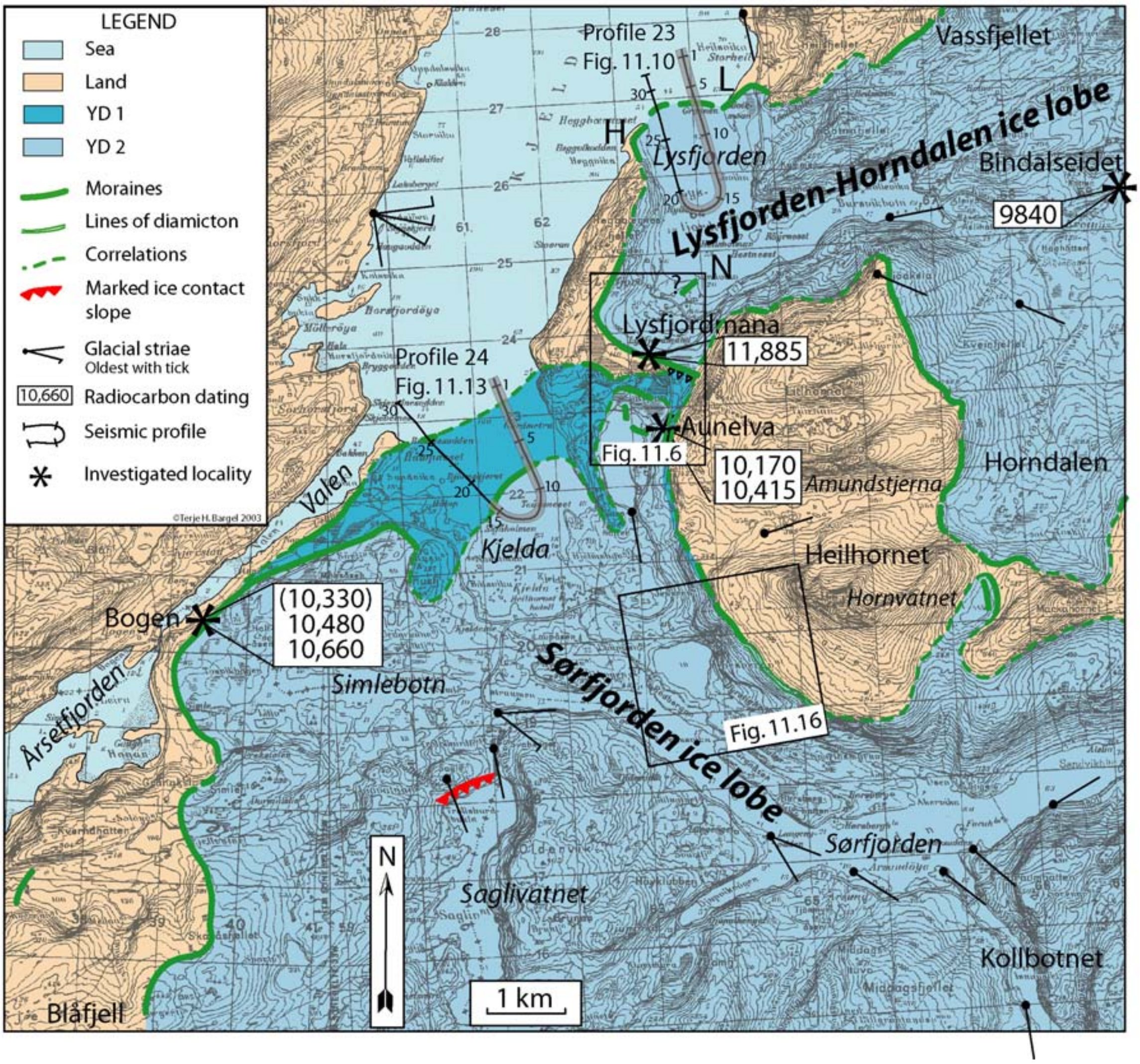


Fig. 11.4
Map of the Heilhornet area showing the topography, moraines, ice-flow indicators, the investigated localities and the seismic profile-lines. The locations of detail figures are framed. The radiocarbon age in brackets, is taken from Andersen et al. (1981). The parts of the seismic registrations shown in Fig. 11.10 and Fig. 11.13 are shaded. H-Heggbærneset, L-Løvikmoan, N-Nausthaugodden.

Fig. 11.5
The curved shape of the Lysfjordmana moraine viewed from the east. The vertical arrow shows the northwestern termination of the moraine. The glacier was located to the right (north). Photo: Terje H. Bargel.

Close to the mountainside in the east, the c. 25 m-high southern slope of the moraine is much steeper than elsewhere for a distance of c. 200 m (framed area in Fig. 11.6). In a small area just above this steepest part, some erratics (angular and rounded) that are resting on a gravelly/stony bed form the highest part of the eastern crest (Fig. 11.7). This steep slope is interpreted as an ice-contact produced by the Sørfjorden ice lobe (Fig. 11.4, Ch. 11.3). The erratics and their elevated bed is probably a small push moraine. The northern slope of Lysfjordmana dips gently in the direction of Lysfjorden.

In the area north of Lysfjordmana, sand washed out from the moraine dominates. At sea level in Lysfjord bay, on a projecting promontory called Nausthaugodden, a pronounced, diamictic crest emerges from the southwest, reaching c. 30 m a.s.l. as the ridge disappears (Fig. 11.6, top right). The ridge could be a moraine, but its orientation makes this assumption questionable. A subglacial (drumlinoid?) genesis is also possible. If the ridge is an end moraine, it must be slightly younger than the Lysfjordmana.

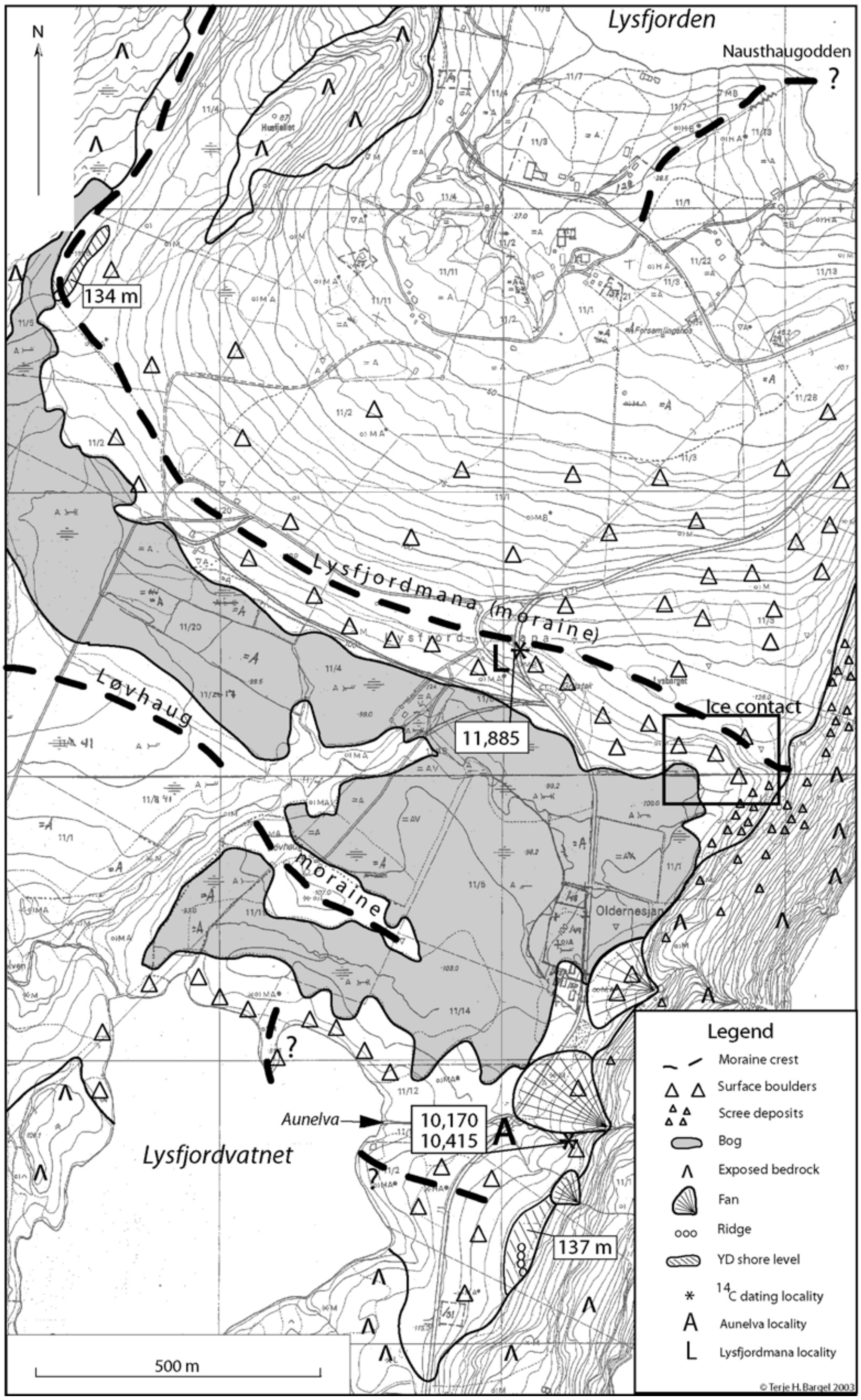


Fig. 11.6
Detailed topographic/Quaternary geological map of the Lysfjordmana end moraine. The moraine was deposited from the northeast. A supposed ice-contact on the distal slope of Lysfjordmana and in the Aunelva-Lysfjordvatn-Løvhaug area is framed.

Fig. 11.7
The inferred ice-contact slope (right-hand side) and the small push moraine at the top of Lysfjordmana (framed area in Fig. 11.6). Photo: Terje H. Bargel.

Many erratics with sizes up to two metres or more are situated at the surface on Lysfjordmana, especially along the steep southern slope, but also in places on the northern slope, especially to the east. The erratics are mostly subrounded, but angular and rounded boulders are also observed. Rounded gravels dominate the surficial sediment.

The internal sediments and structures of the moraine are partly exposed in a c. 10 m-deep and c. 130 m-long road-cut across the moraine ridge (**L** in Fig, 11.6, Fig. 11.8). A relatively symmetrical core of diamicton with stones and boulders occupies the southern part of the section. Some carbonate concretions are located in the central parts of the diamicton. Many shell fragments are found scattered in the central and lower part of the exposure. A fragment of a thick-walled bivalve shell of unknown species found in the centre of the exposure gave a radiocarbon age of 8065 ± 50 yr BP (AMS). In a second attempt, the inner c. 27 % of several fragments were dated, which gave an AMS age of 11,885 ± 75 yr BP (Table 11.1, p. 252).

Fig. 11.8

The road-cut at the top of the Lysfjordmana moraine looking northwest. The till core (left) and the sand formation (right) are indicated. The lag deposit (top blanket) is readily visible. The shell fragments dated to c. 11.9 ka BP was found in the till core.
Photo: Terje H. Bargel.

The northern end of the road-cut is dominated by laminated and cross-bedded sand, which is probably more than 8-10 m thick (Fig. 11.8). The sand is not observed in the other exposures in the ridge so its distribution is not known. The direction of deposition of the sand bed was to the north according to observations of ripples. The sand is situated stratigraphically above the diamicton. A c. 0.5 m-thick, concordant, well-sorted gravel bed caps the section. The sand bed is interpreted as a sub-littoral sediment deposited between the moraine crest and the retreating glacier. Currents and waves deposited the coarse lag on the top during the regression. Several older road-cuts and small gravel pits on the top of the crest and on the southern slope show cross-bedded sand or gravel on top of compact till.

Discussion. Rekstad (1910a, 1917b) concluded, without any arguments, but probably due to the asymmetrical cross profile, that the Lysfjordmana moraine was deposited from the south. Svensson (1959) was of the same opinion based primarily on the direction of glacial striae at the southern end of Lysfjordvatn that shows an ice flow from the south. This observation is correct, but the present author is of the opinion that this striation is associated with the Sørfjorden ice lobe that deposited the Løvhaug moraine (Fig. 11.6, Ch. 11.3.1). At Hylla on the western side of Lysfjorden, Svensson (op cit.) found striae that show an ice movement towards the northwest, which he claimed could have been produced by the same ice flow as the striae at Lysfjordvatn, but they should be somewhat older than the moraine ridge. However, the northwest-directed striae at Hylla could just as well be the result of the diffluenced westerly ice flow across Bindalseidet by the Heggbærneset, and is therefore not proof of deposition from the south. Marthinussen (1962) contradicted Svensson's conclusion because he noticed the U-shape of the ridge opening towards the northeast; hence, the moraine was deposited from that direction. The correlation maps presented by Sollid & Sørbel (1979), Sollid & Reite (1983) and Andersen et al. (1981) are all in favour of Marthinussens interpretation. The present study has also shown that the Lysfjordmana moraine was deposited from northeast.

The youngest AMS-dating of the Lysfjordmana moraine is considered to be too young. This could be a result of contamination of the outer parts of the dated shell fragment as young carbonate could have been available, cf. the concretions mentioned above (S. Gulliksen, ^{14}C Laboratory NTNU, pers. comm. 2002). The oldest age, however, is higher than expected as the Lysfjordmana is thought to be of middle Younger Dryas age, based on tentative correlation with other moraines in the area that have been dated (Table 11.1). The shell fragments are thought to have been included in the moraine as glacially transported material from Lysfjorden, and the high age could simply be the result of shells of that age or it could alternatively be a result of an unexpectedly high reservoir effect. Whatever the case, the dates indicate that the Younger Dryas glacier advance deposited the Lysfjordmana moraine, the *Lysfjordmana event*.

Locality	Lab. no.	Species	Age ka BP	Site	References
Fuglvatnet, Velfjord	T-8617	Mya truncata	9650 ± 110	Littoral	This thesis
Terråk	T-3522	Yoldiella lenticula	9890 ± 230	Glaciomarine	Andersen et al. (1981)
Vassås, Terråk	TUa-3013	Portlandia? fragm.	9820 ± 90	Marine	This thesis
Bindalseidet	T-15323	Mya truncata	9840 ± 65	Littoral	This thesis
Steinsdal, Sømna	T-124	Portlandia arctica	10,300 ± 250	Glaciomarine	Marthinussen (1962)
Lysfjordmana, Lysfjord	TUa-3433	Shell fragment	8065 ± 50	Moraine	This thesis
Lysfjordmana, Lysfjord	TUa-3677	Shell fragments	11,885 ± 75	Moraine	This thesis
Aunelva, Lysfjord	TUa-3014	Macoma baltica	10,415 ± 85	Littoral	This thesis
Aunelva, Lysfjord	T-15636	Mya truncata	10,170 ± 90	Littoral	This thesis
Bogen, Bindal	T-3519	Portlandia arctica	10,330 ± 250	Marine	Andersen et al. (1981)
Bogen, Bindal	T-15324	Hiatella arctica	10,660 ± 180	Marine	This thesis
Bogen, Bindal	TUa-3676	Portlandia arctica	10,480 ± 70	Marine	This thesis
Gravvik, Årsetfjorden	T-3520	Mya truncata	11,080 ± 140	Till in moraine	Andersen et al. (1981)

Table 11.1
Radiocarbon dates from the Bindal-Tosen area.

11.2.2 The Horndalen moraine

Description. Helland (1908) first noticed the long lateral moraine in Horndalen, and it was named the Heilhornet moraine by Svensson (1957, 1959). This name should be avoided, as there are other large moraines in the vicinity of the Heilhornet mountain; therefore, the name Horndalen moraine is introduced here. The Horndalen moraine is located on the western and southern slopes of the Horndalen valley (Fig. 11.4), just north of Heilhornet. In places, the moraine is double crested, and it occupies an apparently sub-horizontal position between c. 390 and 510 m a.s.l. over a distance of c. 5 km (Fig. 11.9). The lowermost position is in the upper end of Horndalen. The height of the ridge is up to c. 25 m, and because of its position on the steep valley side, the profile is not symmetrical.

The northern end of the moraine ends abruptly on the top of the cliffs above the inner end of Lysfjorden, and granitic moraine boulders are the main constituents of the talus fans below the cliff, even though a reddish gneiss forms the bedrock of the steep cliff. On the western side of the ridge the mountainside is rich in granitic boulders, probably produced by frost activity. On the eastern side there is a relatively thin till blanket. The moraine ridge has dammed several small lakes and ponds on the western side, and in places creeks have cut through the ridge. The creek from the lakes Amundstjerna (380 and 364 m a.s.l.) has eroded a 25 m-deep scar in the damming moraine.

The Horndalen moraine crosses the small valley downstream from the lake Hornvatnet (445 m a.s.l.), (Fig. 11.4). However, two other moraines that were deposited by the Sørfjorden ice lobe from the south (see below) dam the lake. According to Svensson (1959) the 225 m-long valley between the Horndalen moraine and the two Hornvatnet moraines is almost completely free of deposits, which contradicts the possibility of deposition of the two moraines from the northeast. The curved shape of the moraines, which are convex towards the north, also indicates this.

Discussion. Svensson (1959) and Marthinussen (1962) correlated the moraine with the Ra and Tromsø-Lyngen moraines, as a Younger Dryas age had been predicted. Sollid & Sørbel (1979) and Sollid & Reite (1983) made a tentative correlation with the Tautra moraines, and Andersen et al. (1981) correlated the Horndalen moraine tentatively with the Tjøtta moraines. Svensson (1957, 1959) assumed that an ice flow towards the west had been responsible for deposition of the Horndalen moraine. This conclusion was based on the location of the moraine in relation to the bedrock morphology and the direction of the glacial striae observed. The difference in height from the northern to the southern end was explained by Svensson (1959) as a sheltering effect of a bedrock promontory, which is located to the east.

Fig. 11.9
View along the Horndalen moraine towards the north. The moraine was deposited from the right. Photo: Terje H. Bargel.

Svensson (1959) proposed the name Middagstind-Heilhorn event as he correlated the Horndalen moraine with the Middagstinden moraines (Ch. 11.7) in the inner Tosenfjord area (Ch. 11.7). As the height difference of these moraines is negligible, and as the latter has a relatively high gradient along the valley side, the Middagstinden moraines are most probably lateral moraines to a valley glacier that is younger than, and not correlative with, the Horndalen moraine. The Horndalen moraine is here tentatively assigned a Younger Dryas age and correlated with the Lysfjordmana moraine.

11.2.3 Additional moraines

On either side of the mouth of Lysfjorden there are small moraine ridges (Fig. 11.4). The moraine at *Heggbærneset* is 400 m long and 30-35 m-high. A corresponding 10-15 m-high ridge is located on the eastern side of the fjord, at *Løvikmoan*. The two ridges are both heavily wave-washed with rounded boulders on the surface. Lysfjorden is overdeepened, and at the sill near its mouth, seismic profiling carried out by NGU in 2001 shows stratified deposits of considerable thickness (Fig. 11.10). These moraines are probably the submarine continuation of the Heggbærneset and Løvikmoan moraines. Marthinussen (1962) indicated that the Heggbærneset promontory could have been partly older than the Lysfjordmana, and Svensson (1959) thought that it was deposited by an ice flow from the south. At *Vassfjellet*, a more than 1 km-long moraine ridge is situated on the eastern and southwestern sides of the summit (Fig. 11.4). On the steep northwestern side of the Litlhornet mountain, facing Lysfjorden, a c. 700 m-long partly terraced moraine is located at c. 220-250 m a.s.l. A gully in the moraine shows a sediment thickness of at least 15 m. Based on glacial-dynamic considerations and the directions of the glacial striae, all these moraines were probably deposited by the Lysfjorden-Horndalen ice lobe.

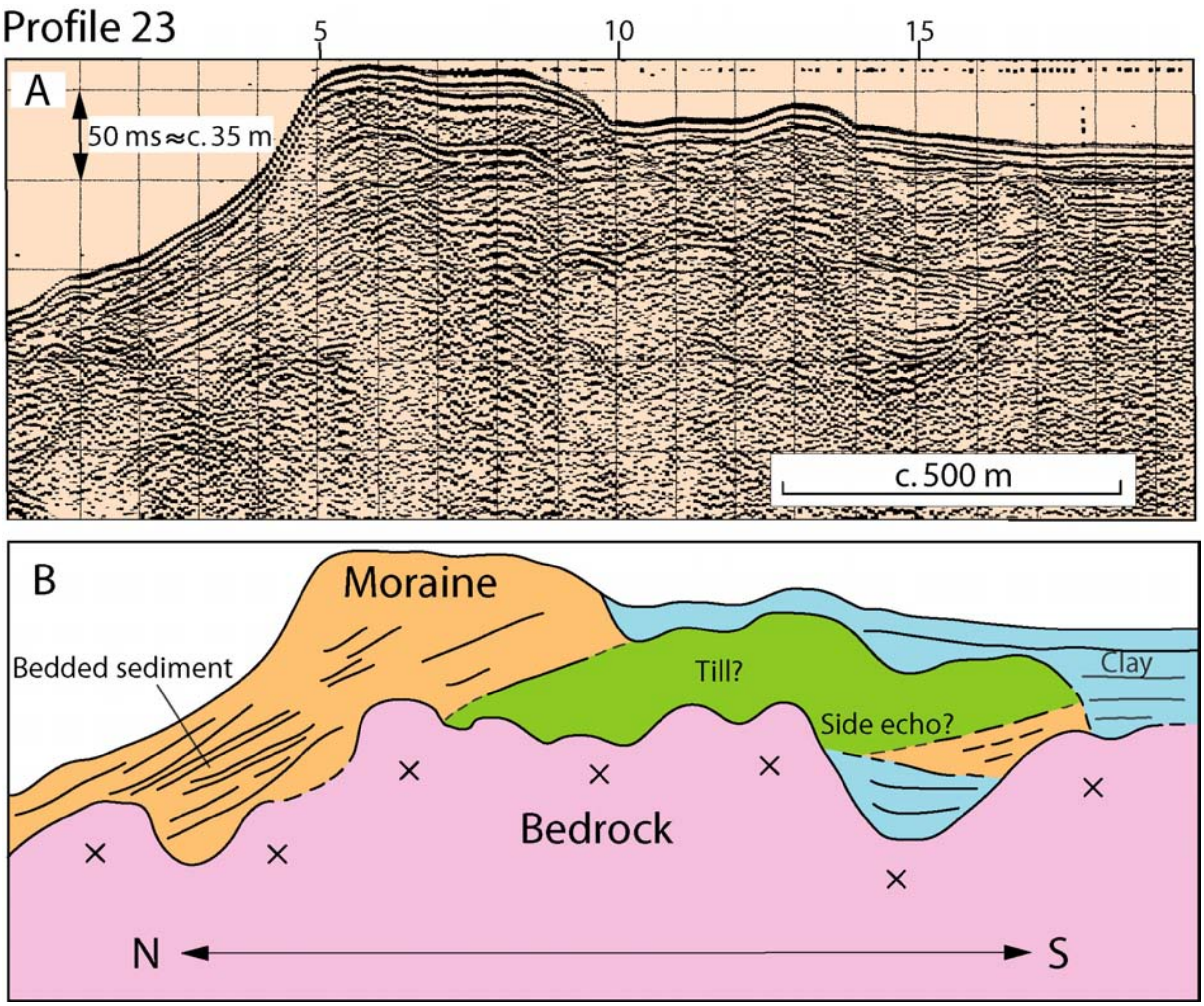


Fig. 11.10
Part of the seismic registrations in Lysfjorden that show **A**: the original profile and **B**: the geological interpretation. The top of the moraine is situated c. 20 m below the sea level. The location of the profile is shown in Fig. 11.4 (shaded part of Profile 23).

11.2.4 Discussion - the Lysfjorden-Horndalen ice lobe

Based on the radiocarbon dating from Lysfjordmana and correlation with the other moraines in the area that are dated, the Lysfjorden-Horndalen ice lobe is probably of Younger Dryas age.

If the correlation of the moraines is correct, the ice lobe had a steep front with a gradient of up to 160 m/km, probably because of the narrowing effect of the valley due to the presence of some steep mountain promontories on either side, and the high cliffs in the area. The relatively small moraines at Heggbærneset and Løvikmoan do not seem to fit glaciodynamically with the huge Lysfjordmana moraine, as an ice lobe in the NW direction could have reached farther out into the fjord. However, the fjord is deep, and the ice front had probably calved. Accumulation of sediment along the grounding line of the ice front, as described by Kjenstad & Sollid (1982), can probably explain the moraine ridges. If so, the ridges are correlative with the Lysfjordmana moraine. The calving could partly be responsible for the relatively steep gradient of the ice front.

Marthinussen (1962), on the other hand, indicated, without any discussion, that the Heggbærneset promontory could have been somewhat older than the Lysfjordmana. On the contrary, the Heggbærneset and the Løvikmoan moraines could well be younger than the Lysfjordmana due to the calving effect, but still have been deposited by the same ice lobe. According to this alternative view, the Heggbærneset, the Løvikmoan and the Nausthaugodden moraines could be correlative and have been deposited by a younger and smaller advance of the Lysfjorden-Horndalen ice lobe. Evidence of a second readvance of the glacier during Younger Dryas is found at other locations in the area, e.g.

the Sørfjorden ice lobe.

11.3 The Sørfjorden ice lobe

Sørfjorden (Fig. 11.3, Fig. 11.4) is c. 110 m deep just outside Terråk and up to c. 80 m deep farther west, where several sills are present. Sørfjorden may be regarded as the natural continuation of the more than 550 m-deep Tosenfjorden, as they are oriented in-line. At the western end of Sørfjorden, a heavily wave-washed moraine at c. 20 m a.s.l., which is a part of the Kjelda-Bogen-Blåfjellet moraine (Ch. 11.3.3), is situated at the western end of Simlebotn; thus Sørfjorden ends at this point. Glacial striae, roche moutonnées and even the fjord profile show a steady ice flow towards the west along the western end of this fjord. The

Sørfjorden ice lobe diffluenced and came to a stop at several rock outcrops where end moraines were deposited. A part of the lobe was directed towards the north, to the Lysfjorden area (Fig. 11.4).

11.3.1 The Lysfjordvatnet area

Description. The lake Lysfjordvatnet (Fig. 11.6) is dammed by blocky till at the northern end. The till surface rises gently from the lake towards the north where an E-W oriented smooth ridge is situated. Marthinussen (1962, p. 56) described it as "faint ridge-formed accumulations of morainic material". The ridge is symmetrical in cross profile, and the top is at 107 m a.s.l., which is c. 7-8 m above the surrounding bog. On the western end the relief is 2-3 m. The ridge is interpreted as an end moraine that has either been subjected to heavy wave-wash during the regression, or the ice has overrun and partly remodelled it. The moraine is here named the *Løvhaug moraine*. Between this ridge and the Lysfjordmana moraine there is an up to 3-4 m deep bog resting on littoral sand. A ravine cuts through the area south of the Løvhaug moraine exposing clay beneath littoral sand. At the southern end of Lysfjordvatnet the bedrock is heavily glacially sculptured and striated, and the indications of a northward-moving ice that deposited the moraine are convincing.

Discussion. Marthinussen (1962) assumed the Løvhaug moraine to represent the outer margin of an ice lobe, which moved towards the northwest and north, and covered the innermost part of Kjeldafjorden. At that time, a small area between the moraines at Lysfjordvatnet and Lysfjordmana moraine was ice-free, and here the sea was in direct contact with the ice margins of the two glaciers, a feature that is especially noticeable on the Lysfjordmana side. Sollid & Sørbel (1979), Andersen et al. (1981) and Sollid & Reite (1983) adapted this explanation in their correlation work. However, the new data show that the Sørfjorden ice lobe was in contact with the Lysfjordmana moraine, as described in Ch. 11.2.1. This could have happened during the same ice advance that deposited the Løvhaug moraine, and this accounts for the two glacier advances in the Lysfjordvatn area.

11.3.2 The Aunelva section

Description. Close to the steep western cliff of Hornfjellet, less than one km south of the eastern end of Lysfjordmana, there is a sandy silt deposit (**A** in Fig. 11.6). The upper level of the deposit is at 127 m a.s.l., and the surface is sloping at 15-20^{o} westwards. A small terrace a few hundred metres to the south at 137 m a.s.l. probably represents the marine limit in the area. The Aunelva river, which has its outlet in Lysfjordvatnet, has cut through the deposit, and a 8-9 m-high section of the sediments is partly exposed (Fig. 11.11). The deposit is interpreted as a glaciomarine, sublittoral sediment that is overconsolidated and has been disturbed by an overrunning glacier.

Discussion. Based on the relatively high marine level (137 m a.s.l.) associated with the deposit, the glaciomarine character of the material and the late Younger Dryas age of the shells, the Aunelva section was probably deposited close to the Younger Dryas ice margin after withdrawal from the maximum position - the steep ice-contact slope in the Lysfjordmana moraine. The disturbed parts of the deposit are probably a result of glaciotectonic activity, caused by glacial overrun of the deposit during the second Younger Dryas glacier readvance, as indicated by the till. If this interpretation is correct, an ice-free period bracketed between c. 10.4 and 10.2 ka BP separates the two Younger Dryas glacier readvances of the Sørfjorden ice lobe. The latest advance probably ended more than 500 m south of the Lysfjordmana moraine and deposited the Løvhaug moraine.

11.3.3 The Kjelda-Bogen-Blåfjell moraine

Description. A moraine ridge can be followed more or less continuously over a distance of 8 km in this area (Fig. 11.4). The ridge is best developed in the Kjelda and Bogen areas, and in the area above the marine limit on the mountain Blåfjell where distinct ridges are situated. The latter was called the *Lauaksel moraine* by Svensson (1959), but as the name Lauaksel is not on modern maps, the moraine is here renamed the *Blåfjell moraine*. The moraine ridge is c. 20-25 m in height and can be traced almost continuously from near sea level at Simlebotn for 5-6 km across Blåfjellet. Below the marine limit the ridge is heavily wave-washed, and in the Simle area the ridge form is hardly recognizable at all, probably due to strong tidal currents across the isthmus at Simle during the regression.

In the Bogen area, the ridge is well defined with the crest reaching 86 m a.s.l., probably helped by bedrock obstacles that are exposed near Årsetfjorden. Towards the northwest the ridge is less pronounced, and a few bedrock exposures are situated along the road just north of Bogen. At c. 1 km north of Bogen the ridge divides into two separate ridges.

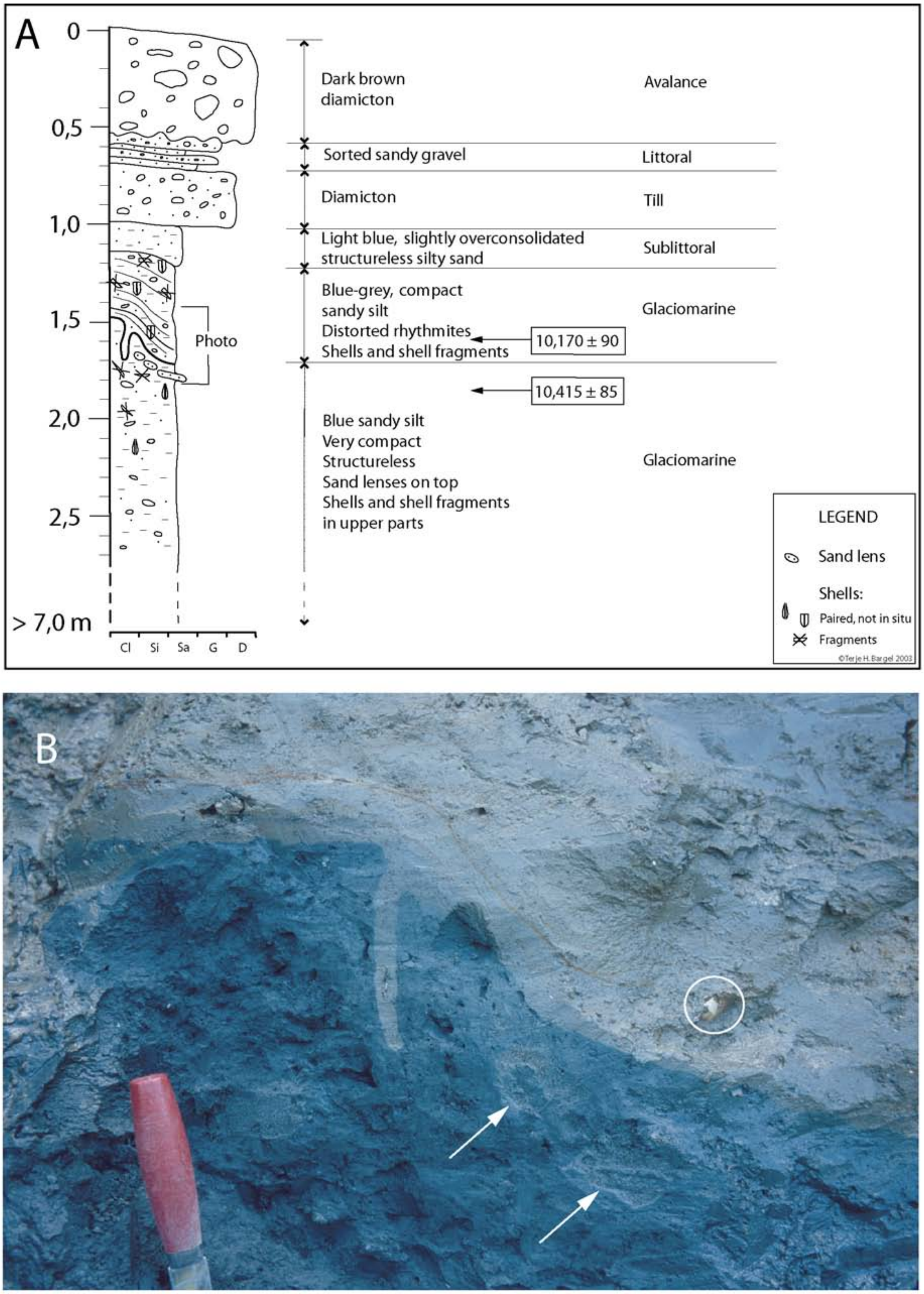


Fig. 11.11
The Aunelva section. **A**: The stratigraphy and **B**: Photo of the shell-bearing part. A partly crushed, paired species of *Mya truncata* is encircled. Arrows show the sand lenses that are also shown on the log. The colour contrast is thought to be a result of oxidation. A plant root causes the hanging tap. Photo: Terje H. Bargel.

The northwestern branch parallels the bay of Valen (Fig. 11.12); and the easterly branch terminates at a small mountain, where the >10 m-high ridge is easily recognizable.

A seismic profile across the bay of Kjelda (Profile 24, Fig. 11.4, Fig. 11.13) indicates a concentration of stratified sediments at two locations across the bay. Marthinussen (1962) reported "some scarce glacial deposits" in this area, which is hardly an exaggeration. Accumulations of cross-bedded sand and gravel are located on the flanks of the ridge where several small, disused gravel pits are situated. These deposits are probably a result of wave washing during the regression.

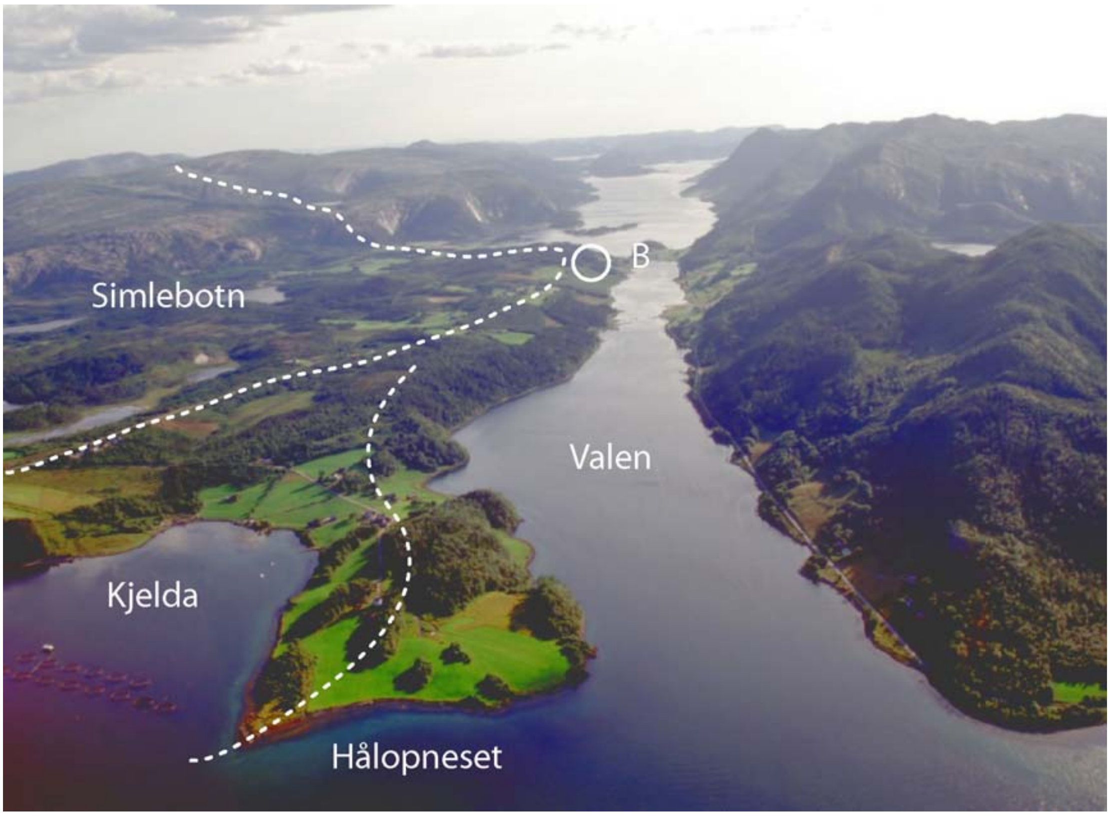


Fig. 11.12
Aerial photograph looking southwest along Valen and Aarsetfjorden (in the background). The moraines indicated by broken lines were deposited by the Sørfjorden ice lobe (Younger Dryas) from the east (left). B - Bogen. The island Austra is to the right. Cf. the map on Fig. 11.4. Photo: Harald Sveian.

The Bogen gravel pit. In the steep distal part of the moraine near Bogen, the sediments are partly exposed in a c. 70 m horizontal and c. 40 m vertical excavation in a disused gravel pit. A compact, matrix-supported diamicton that is rich in rounded stones and boulders is exposed in the backwall of the gravel pit (Fig. 11.14 A).

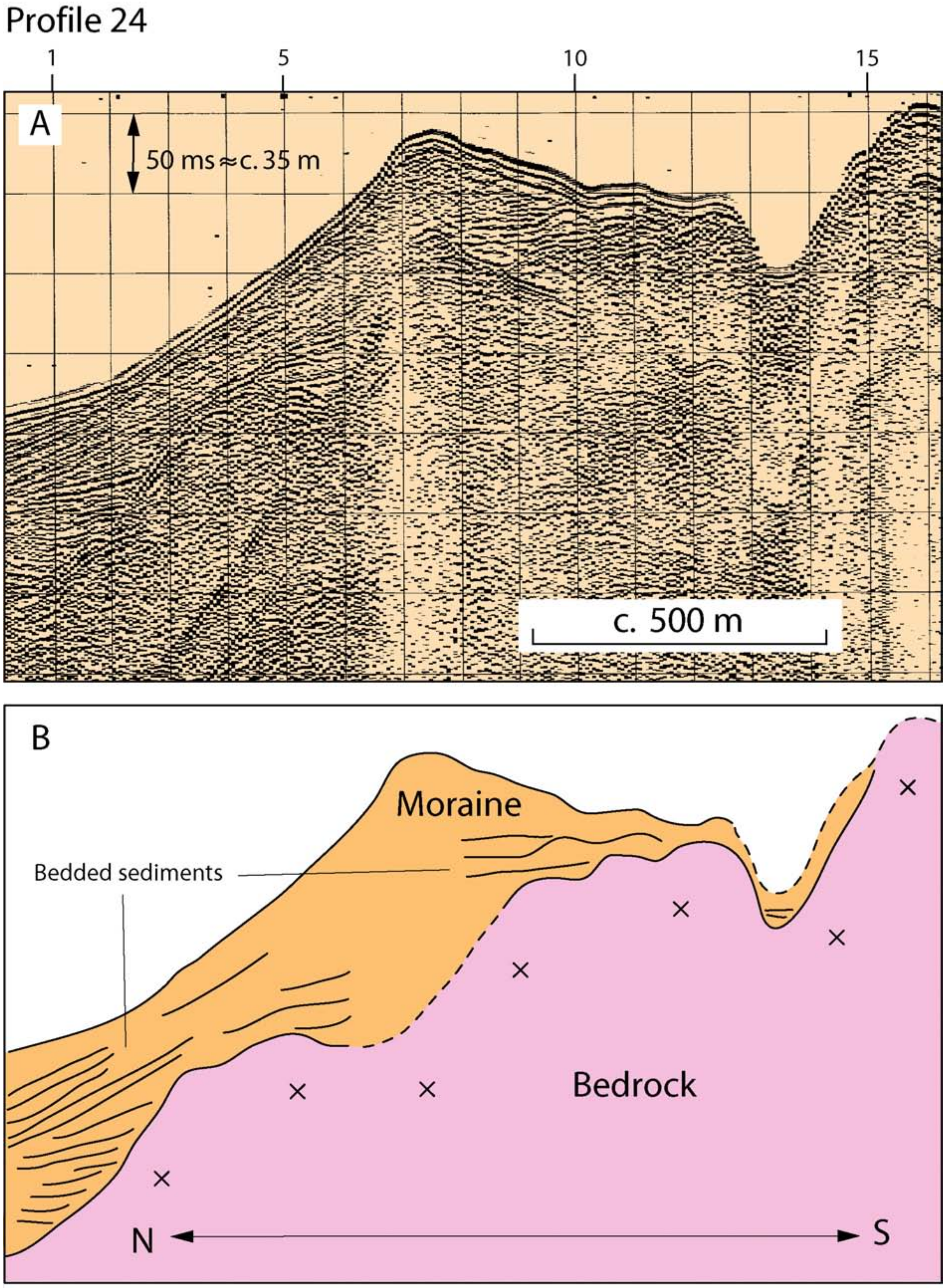


Fig. 11.13
Seismic registrations in Kjelda that show **A**: part of the original profile and **B**: the interpreted geology. The top of the moraine is situated c. 35 m below the sea level. The profile line is shown in Fig. 11.4 (shaded part of Profile 24).

The boulder content and size diminishes upwards. Most of the bedrock material is of a granitic origin. Near the upper part of the exposure, a few sand and silt beds are interbedded in the diamicton (Fig. 11.14 A, Fig. 11.15). Foreset beds of sand and gravel that are dipping 30^o-35^o W (Fig. 11.14 B, C) are situated stratigraphically above the diamicton, but most of the sand and gravel has been excavated. Above the foresets, there are sub-horizontal beds with a great variation in grain size (Fig. 11.14 C). These sediments are interpreted as tidal current deposits partly fed by till flow from higher parts of the distal slope. In a silt bed, numerous redeposited, but mostly unbroken paired shells of *Hiatella arctica* are located. They are dated to 10.6 ka BP. A single paired specimen of *Portlandia arctica* from the same bed has been AMS-dated to 10.5 ka BP. Andersen et al. (1981) dated *Portlandia arctica* from the same exposure, and probably from the same bed, to 10.3 ka BP (Table 11.1). The stratigraphical position shows that the shells are younger than the moraine; consequently, the dates provide minimum ages for the deposition of the moraine.

A shoreline at c. 70 m a.s.l. is located just above the gravel pit, where the sediments are exposed (Fig. 11.14 A, Fig. 11.15). Concordant, laminated fine sand and silt dominate the formation. Ripples show that water currents were flowing southwards. In some places, lenses of gravels are located between the laminae. The formation is interpreted as having been deposited by tidal currents in the narrow sound. The gravels are probably wave-washed deposits derived from higher situated parts of the moraine ridge.

Discussion. The end-moraine complex in the Kjelda-Bogen-Blåfjell area was almost certainly deposited by a westward-flowing glacier in Sørfjorden (Marthinussen 1962, Sollid & Sørbel 1979, Andersen et al. 1981, Sollid & Reite 1983). The glacier must have had an unstable front, as indicated by the diffuse ridges in the middle part, by the double ridges in the north, and by the stratigraphy in the disused gravel pit at Bogen.

Marthinussen (1962), who observed only the northern part of this end-moraine complex, correlated it tentatively with the Main substage or the Tromsø-Lyngen substage, supported by the dating at Steinsdal, Sømna, at 10.3 ka BP (Table 11.1). He also used observations of the Main line rock terraces, shoreline diagram, finds of *Portlandia arctica* just west of the moraine, and the general impression that the Tromsø-Lyngen moraines generally should be the most prominent moraines along the coast. Andersen et al. (1981) dated the moraine, and a middle Younger Dryas minimum age is confirmed by the new datings.

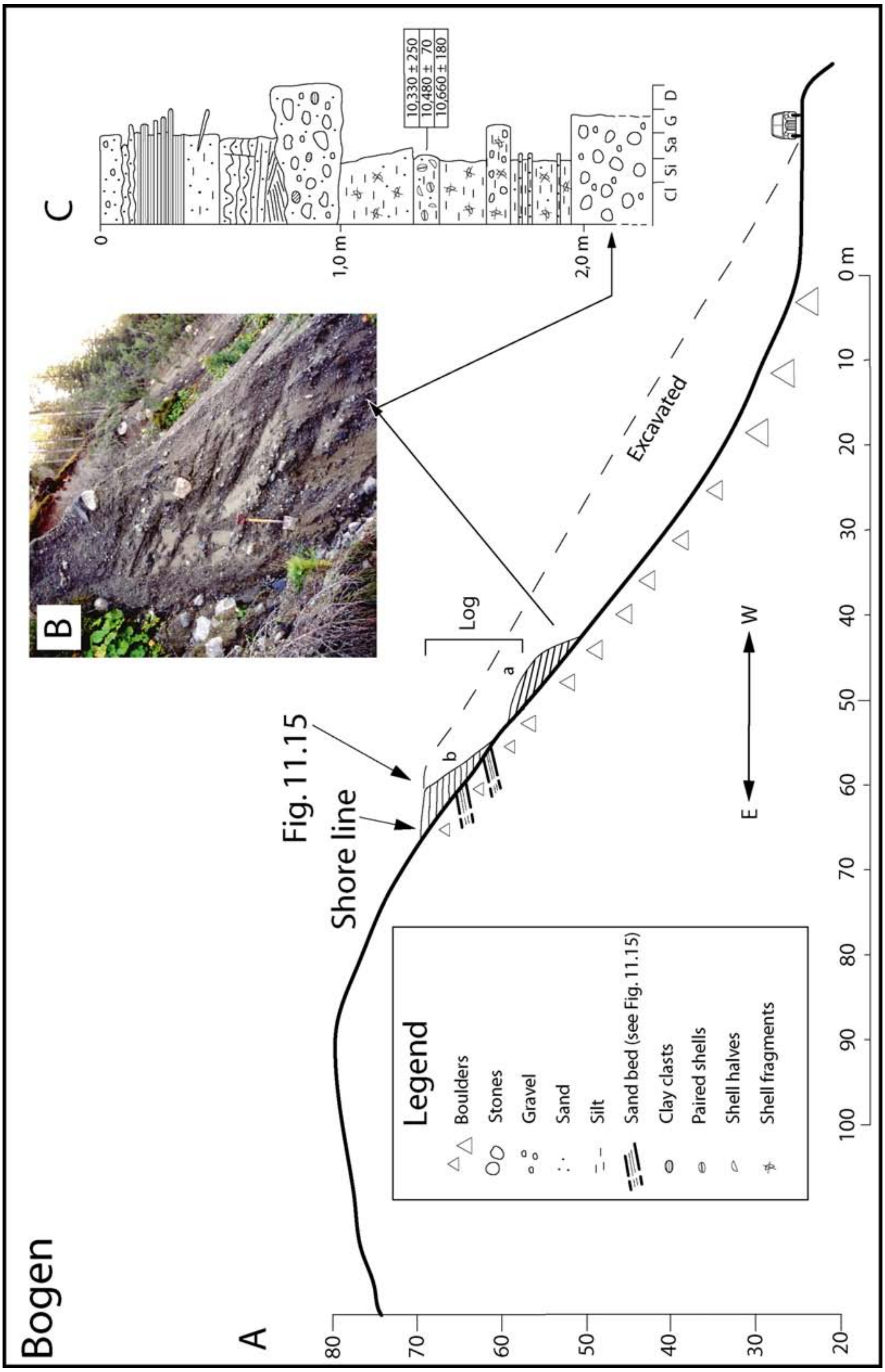


Fig. 11.14
A: A simplified profile of the disused gravel pit at Bogen that show the inferred stratigraphical positions of the beds described in the text. Triangles show observed bouldery diamicton. The boulder content diminishes upwards. **B**: The foreset beds are gravelly with some stones. Photo: Terje H. Bargel. **C**: Sediment log of the shell-bearing sublittoral strata.

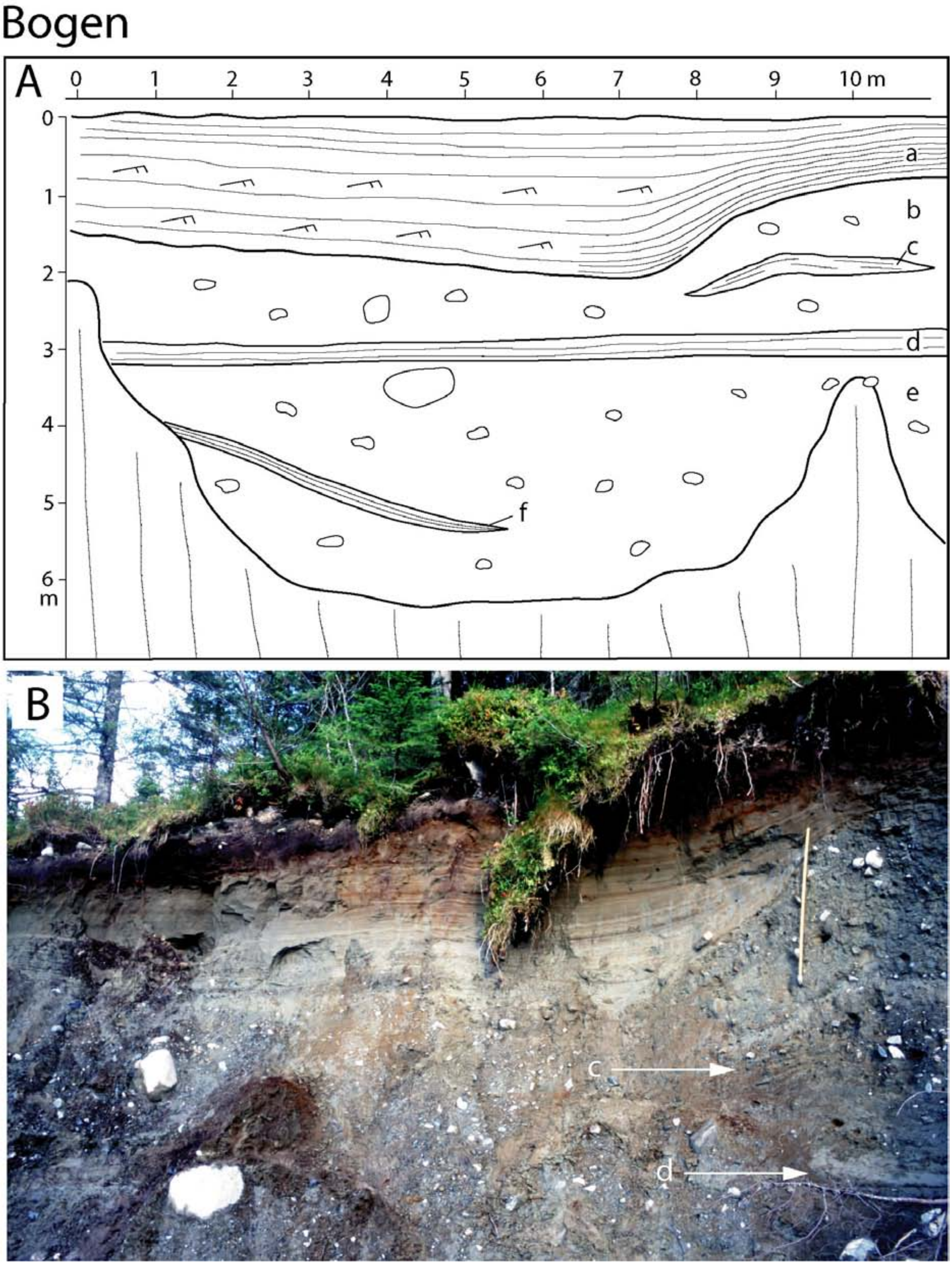


Fig. 11.15
A: Sketch of the upper part of the disused gravel pit at Bogen that show littoral tidal sediments (a) on top of the undulating sand-matrix diamicton of the Bogen moraine: b) and e). The tidal sediments show mostly planar bedding with some rippled interbedded parts. c): a gravelly sand lens, d): a band of sand and silt laminae and some layers of gravelly sand. f): gravelly sand layer.
B: Photo of part of the sketched exposure. Units c) and d) (unfortunately hardly visible) are indicated with arrows. Photo: Terje H. Bargel.

11.3.4 Smaller moraines

On the western side of Heilhornet three, in-line, correlative, lateral moraine ridges are situated at c. 220-400 m a.s.l. (Fig. 11.4, Fig. 11.16), which gives a glacier gradient of c. 140 m/km in this area. On the southern side of Heilhornet, two parallel, sub-horizontal lines of till with scattered blocks are located. Due to the otherwise completely exposed bedrock, these lines are easily recognizable (Fig. 11.16). The lines are separated vertically by c. 25-30 m and are situated at c. 425 m a.s.l. in the east, falling to c. 365 m in the west where they coincide with the eastern end of the three in-line moraines mentioned above. According to Svensson (1959), the moraine lines are probably lateral moraines to what is here called the Sørfjord ice lobe, and if so, this indicates that the ice lobe had two readvances in this area during the Younger Dryas.

Scattered boulders are located on the valley side farther to the east. These can be followed along the southern side of Heilhornet from c. 400 m a.s.l. up to c. 500 m a.s.l. south of Hornvatnet. At the northeastern end of Hornvatnet (445 m a.s.l.), two parallel moraines that were deposited from the south are situated c. 200 m south of the Heilhornet moraine (Ch. 11.2.2). This observation also indicates a fluctuating ice front.

11.3.5 Discussion - the Sørfjorden ice lobe

Several radiocarbon dates strongly indicate an early to middle Younger Dryas age for the Sørfjorden ice lobe. A second readvance is indicated by double moraine ridges and ice-contact slopes in the Lysfjordvatn area and near Kjelda, and by the stratigraphy recorded in the disused Bogen gravel pit. The two parallel moraines at Hornvatnet and the double moraines on the southern side of Lysfjordmana also indicate a twofold ice readvance. The glacier had a mean gradient of c. 45 m/km along Heilhornet, and c. 140 m/km near the front. Assuming that the moraines which are separated vertically by 25-30 m represent two ice advances, and that the mean ice-surface gradient was unchanged, then the second glacier advance would have ended c. 500 m proximally of the first advance. If these assumptions are valid, then the two moraines really could be correlative with the two readvances recorded in the Lysfjordvatn area.

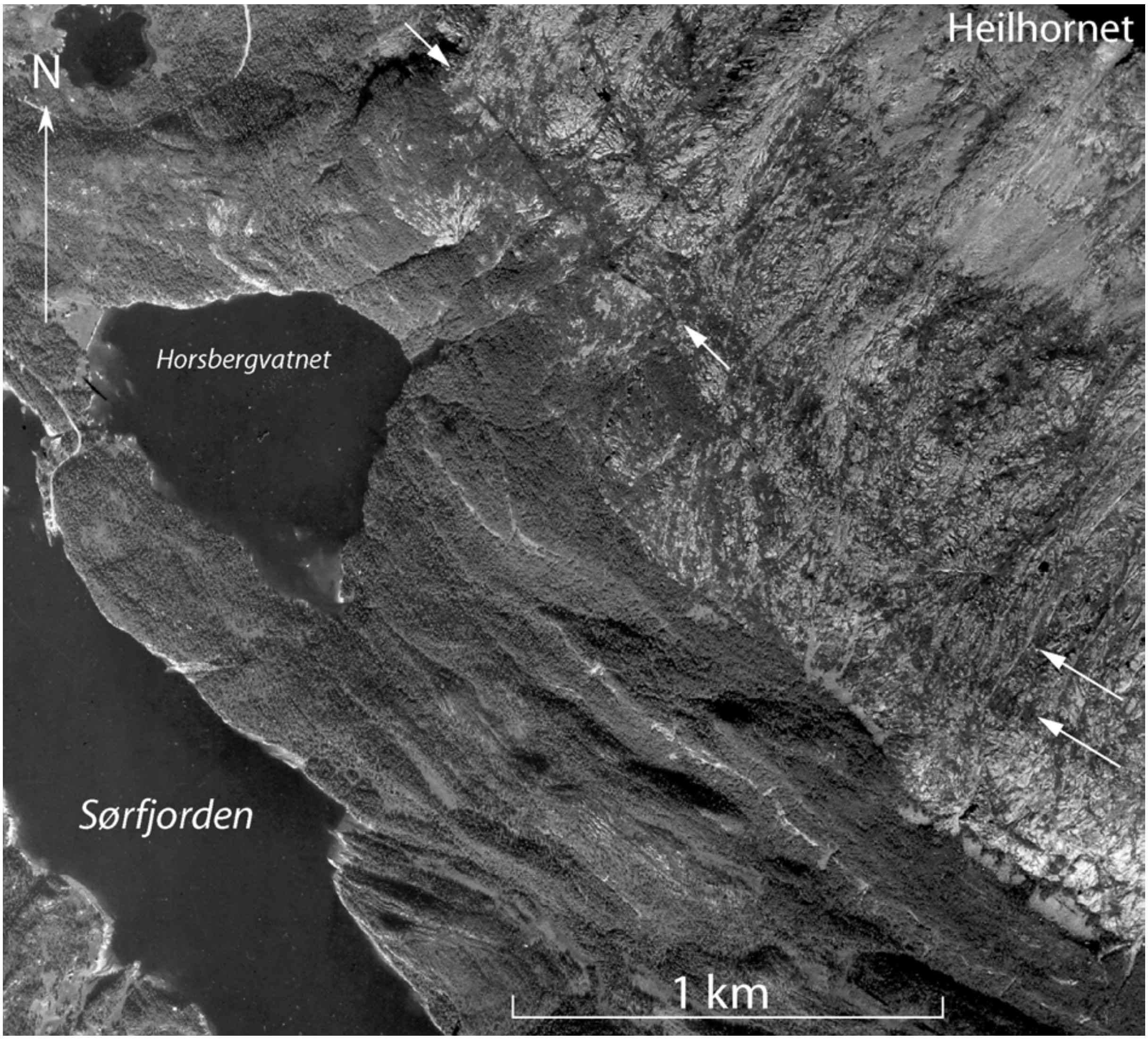


Fig. 11.16
Vertical aerial photograph of the southwestern side of Heilhornet showing double till lines (long arrows) and one thin moraine ridge (short arrows). The upper moraine line is tentatively correlated with the Lysfjordmana moraine and the lower moraine line is tentatively correlated with the Løvhaug moraine. Photo: Fjellanger-Widerøe AS.

11.4 The Bindalsfjorden ice lobe

Glacial striae and roche moutonnées show an ice movement in a northerly direction along the Bindalsfjorden (Fig. 11.3). The great overdeepening of the fjord also indicates this, as the depth is more than 700 m a few km inside the relatively deep sill at c. 400 m, located at the mouth of the fjord in the north.

11.4.1 The Øksninga deposit

On the island *Øksninga* in Bindalsfjorden, several moraine accumulations are situated up to c. 100 m a.s.l. (Fig. 11.20). Helland (1908), Rekstad (1910a, 1917a) and Svensson (1959) noticed the locality, but no one has offered any definite conclusions on the process of deposition. Based on aerial photo investigation, the material is here thought to be basal till deposited as stoss-side accumulations by either the Bindalsfjorden or the Lysfjorden-Heilhornet ice lobe.

11.4.2 The Vardefjellet moraine

Vardefjellet is situated at the northern end of the Heilhornet peninsula, at the mouth of Bindalsfjorden (Fig. 11.3). There are no conspicuous ridges on Vardefjellet, but an elongated accumulation of diamictic material can be followed at elevations of c. 290-320 m a.s.l. almost continuously for more than 1.2 km near the top of the mountain. Svensson (1959), who named the mountain Skauvikfjellet, interpreted the deposit as a lateral moraine to the glacier in Bindalsfjorden and correlated it with Lysfjordmana. Marthinussen (1962) noticed rock terraces just west of the Skauvik promontory (see Ch. 11.9.1) and was of the same opinion as Svensson about the lateral moraine. Later geoscientists have agreed with this interpretation (Sollid & Sørbel 1979, Andersen et al. 1981, Sollid & Reite 1983).

11.4.3 The Sæternesfjellet moraine

At the top of the mountain *Sæternesfjellet,* a subhorizontal zone of probable morainic material, forming short and low ridges, is situated at c. 500-550 m a.s.l. on the southern and eastern sides of the mountain (Fig. 11.3). The accumulation was interpreted by Svensson (1959) as a lateral moraine but, as seen on aerial photographs, the diamictic material is situated on the western side of the mountain top in a leeside position, which indicates that this area of Sæternesfjellet was probably a nunatak at the time of deposition.

11.4.4 The Harangsfjord moraines

In the Harangsfjord area north of Bindalsfjorden, two or three ridges are situated at Gaupen (Fig. 11.3) (Rekstad 1910a, Svensson 1959). These ridges are associated with the Main shoreline and a radiocarbon dating of *Portlandia arctica* at Steindal, Sømna, with an age of

10.3 ka BP (Marthinussen 1962). Small end moraines are situated in front of Eidsvatnet and Myrmarkvatn. These ridges are probably younger than the Gaupen ridges and deposited by an ice flow from the Tosenfjorden-Vassbygda (Fig. 11.25).

11.4.5 Discussion - the Bindalsfjorden ice lobe

The small end moraines and the diffuse lateral moraines that surround Bindalsfjorden are tentatively correlated, primarily based on the assumption of a gradient as, e.g. reported by Andersen (1975) of an ice lobe that was situated in the fjord. Regionally, the Bindalsfjorden ice lobe is tentatively correlated with the Lysfjorden-Horndalen ice lobe of Younger Dryas age based on one radiocarbon dating and the position of the Main shoreline.

11.5 The Kollbotnet ice lobe

The existence of an ice lobe deriving from Follafjorden and flowing in a northerly direction through Kollbotnet towards Sørfjorden (Fig. 11.3, Fig. 11.17) is documented by glacial striae and by roche moutonnées along Kollbotnet.

11.5.1 The Breidvika event

The bay Breidvika is situated in Sørfjorden and is connected to Kollbotnet in the southwest through the Breidvikskardet where the watershed is located at c. 245 m a.s.l. (Fig. 11.17). Sediments have been studied in several gravel pits at Breidvika. At the top of the deposit there are two diamictons separated by a thin sand layer (Fig. 11.18). The diamictons show sequences with a somewhat varied sorting, indicating deposition in the sea. These beds are located stratigraphically above a thick sequence of sorted sediments with northeast-oriented ripples that are interbedded with diamictic sediments (Fig. 11.19). At a lower level in the same gravel pit, there are thick foreset beds (sorted and diamictic) that were deposited towards the northeast. These beds are resting on sand and silt beds, and below this there is a blue-grey till. The silt beds have been checked for foraminifera, but none were found. Higher up in Breidvikdalen, at c. 130-135 m a.s.l., the sediment surface is subhorizontal. In a ravine at the distal end of this deposit, a more than 4 m-thick bed of sand is exposed covered by several metres of gravel. This part of the deposit is probably a shallowing-up sequence.

Discussion. The Breidvika deposit is interpreted as a combined sub-glacial and sub-marginal deposit. The lowermost till could have been deposited from the northeast by the Tosen glacier or by the Kollbotnet ice lobe, as glacial striae on either side of Breidvika show a northeasterly ice flow in this area. After withdrawal of this glacier, marine and later glaciomarine sediments were deposited as the Kollbotnet ice lobe approached. The foreset beds and the ripples show that most of the material in Breidvikdalen was deposited by this ice lobe. The varying diamictic and sorted beds show that the ice front fluctuated to a high degree during most of the depositional period, and was in contact with the top of the Breidvika deposit at least twice.

The shallowing-up sediments were probably deposited in the sea as the ice receded at Breidvikskardet. If so, the marine level during the deposition was at c. 130-135 m a.s.l. A talus fan that is skewed in the northeastern direction is located on the steep mountainside just above Breidvika. This could be the result of glacier distortion. If so, the Kollbotnet ice lobe had a thickness of more than 300-350 m a.s.l. in this area.

11.5.2 The Saglivatnet area

At the northern end of Saglivatnet (Fig. 11.4), a heavily glacially polished rock sill, roche moutonnées and striae demonstrate an ice flow along Saglivatnet towards the north. The same ice-flow direction is observed on the top of Saglifjellet mountain at 212 m a.s.l. A stoss-side till is situated on the southern side of Saglifjellet, and boulders and blocks are observed along the northern shore of the lake and along Saglielva. In a road-cut along Saglielva, a basal till of 2-4 m thickness is exposed on top of the striated rock surface. A few hundred metres to the north, close to the present sea level, only the regional westward striae and rock sculpturing are found, even on southerly exposed rock surfaces. The northerly ice flow along Saglivatnet is supposed either to have terminated here in the narrow valley (as indicated by ice-contact symbol in Fig. 11.4), or the ice had been floating such that no northerly striation was produced at lower levels farther to the north. This ice-flow direction is believed to be the youngest one in the area, the ice deriving from Follafjorden. A tentative correlation with the Breidvika event is proposed.

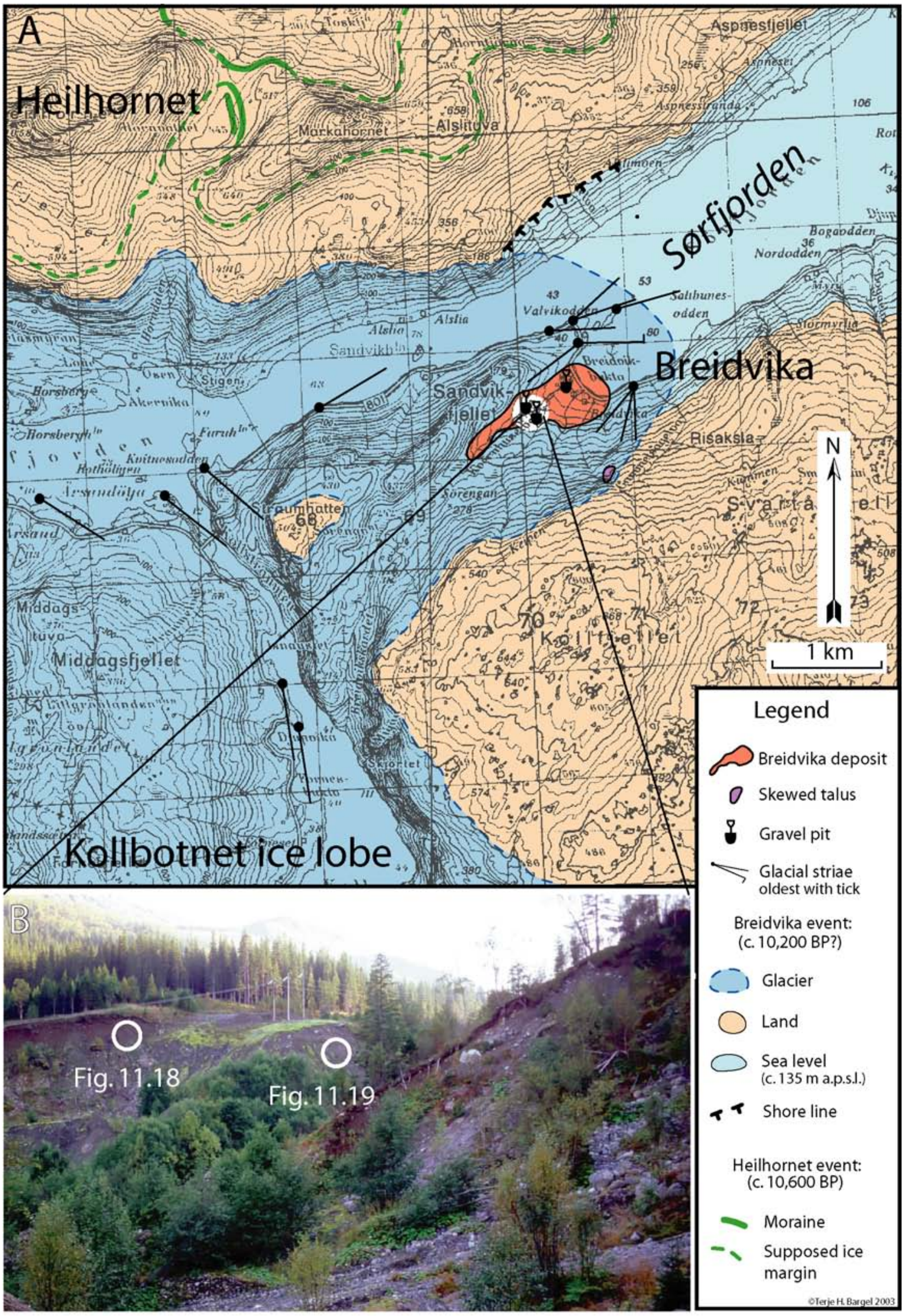


Fig. 11.17
A: Map of the Breivika-Kollbotnet area showing a reconstruction of the Kollbotnet ice lobe during the Breidvika event. The west- and southwest- oriented striae are considered to be the oldest ones in this map area.
B: The upper gravel pits, looking southeast, showing the location of the logs presented in Fig. 11.18 and Fig. 11.19. Photo: Terje H. Bargel.

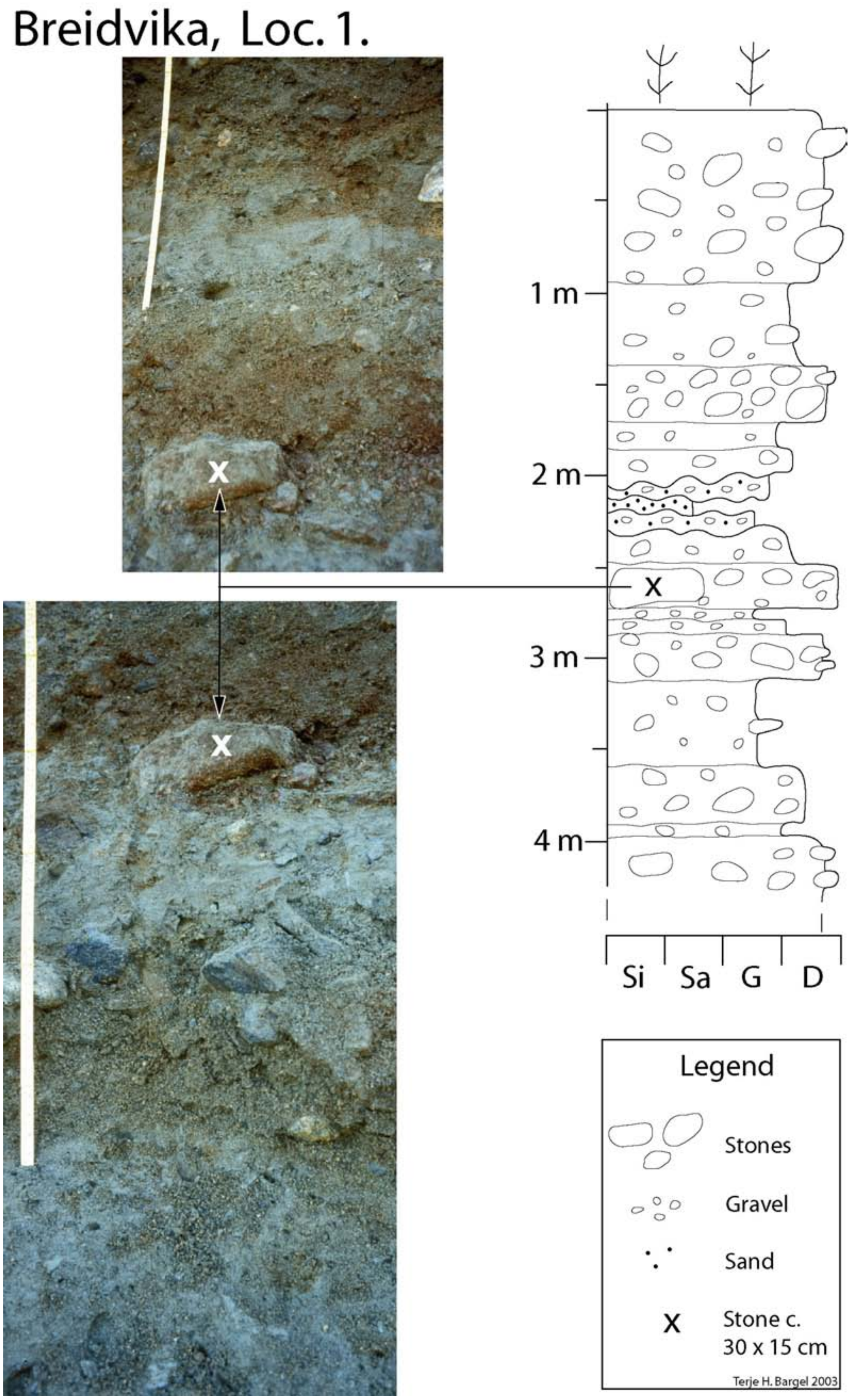


Fig. 11.18
Sediment log and photographs from the upper part of the Breidvika deposit that show two diamictons separated by a thin sand bed. Photo: Terje H. Bargel.

Breidvika, Loc. 2.

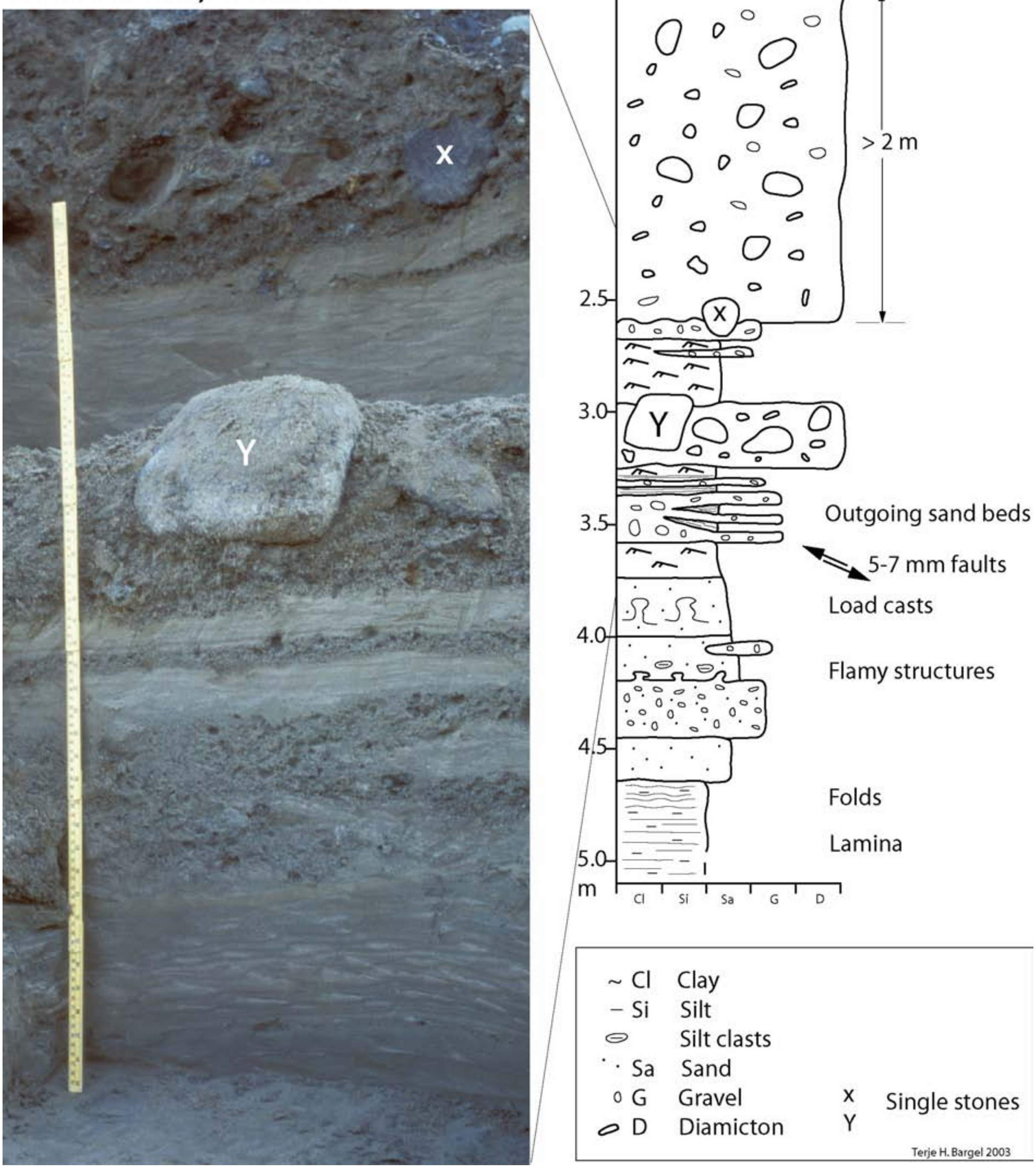


Fig. 11.19
Sediment log and photograph of the middle Breidvika deposit that show stratified beds below a thick diamicton. Photo: Terje H. Bargel.

11.5.3 Discussion - The Kollbotnet ice lobe

The Breidvika deposit shows the existence of the Kollbotnet ice lobe, which is a new element in the deglaciation model of this area. No dates exist, but tentatively a correlation is proposed with moraines in Follafjorden that are thought to have a late Younger Dryas age, the Hoklingen moraines (Sveian 1997) or the Nordli moraines in the Vefsn area (Fig. 11.26, Enclosure 5). The extension of this ice advance in the Sørfjorden area is unknown as no correlative moraines are found, but the ice front could have been located in the Saglivatnet area.

11.6 The Åbjøra ice lobe

The Åbjøra ice lobe is the name given to an ice flow in the Åbjøra valley that terminated in Tosenfjord/Bindalsfjord (Fig. 11.3).

11.6.1 The Vassås event

Description. The Vassås moraine complex is situated between some small rock obstacles at the mouth of the Åbjøra valley (Fig. 11.20). The most pronounced ridge is located between the northern sides of Baulifjellet, where the highest point of the moraine is located at c. 80 m a.s.l., and the fjord. A less pronounced ridge is located a few hundred metres to the southwest. This ridge can be followed towards southwest where it enters the sea close to the northern end of the bridge across the inlet to the bay Osan. The eastern and northern sides of Baulibukta, comprising a gently sloping terrain of diamictic material, are interpreted as an ice-contact slope. In a gravel pit northeast of the church, gravelly foreset beds dipping towards the west are located stratigraphically above partly disturbed sand- and silt layers with rhythmites that contain a few shell fragments in the lowermost part (Fig. 11.21). AMS dating of an unidentified shell fragment gave an age of 9.8 ka BP. Below the silt, there is gravelly, partly sorted diamictic material. The stratigraphic succession contains a variety of sediments and indicates a slightly undulating ice front situated to the east. Andersen et al. (1981) have obtained an age of c. 9.9 ka BP on *Yoldiella lenticula* from glaciomarine sediments at Terråk (Table 11.1).

Discussion. The foreset beds from the Vassås gravel pit show that the moraine was deposited towards the west by an ice lobe in the Åbjøra valley. The structures show a fluctuating ice front at a late phase of the depositional process. The deposition of the Vassås moraine is here termed the *Vassås event* and has been dated to c. 9.8 ka BP.

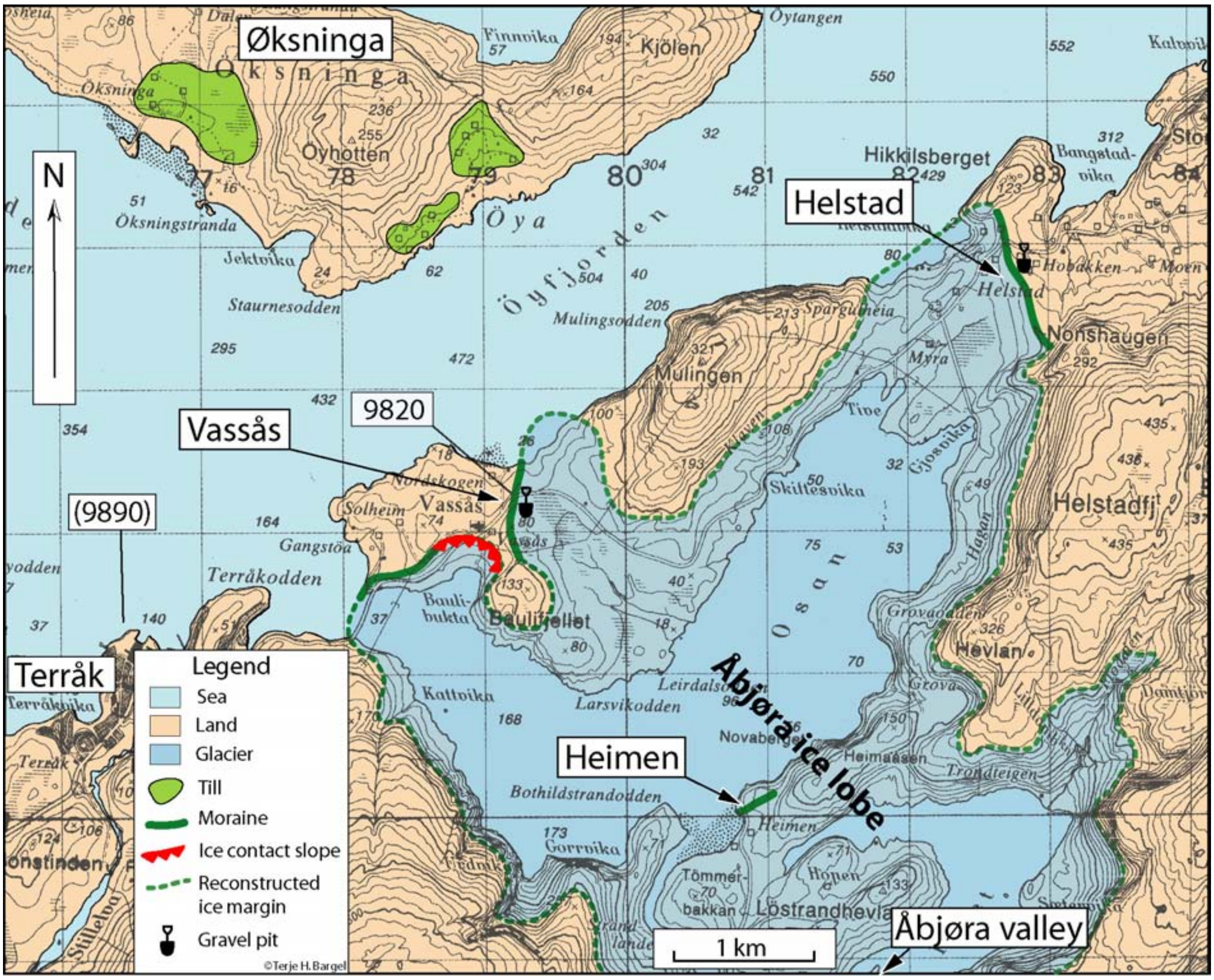


Fig. 11.20
Map of the Terråk area that shows the terminal moraines at Vassås, Helstad and Heimen. The supposed stoss-side till (shaded areas) on the island Øksninga, gravel pits (spades), radiocarbon datings and the reconstruction of the Vassås event are also shown.

11.6.2 Helstad

A huge moraine at Helstad occupies the area between the Nonshaugen and Hikkilsberget mountains (Fig. 11.20). The moraine crest is well defined as it rises towards Nonshaugen, and the highest point exceeds 100 m a.s.l. close to the steep mountain side. In a disused gravel pit close to the Hobakken farmhouses, foreset beds dipping towards the northeast show that an ice lobe in the Åbjøra valley probably deposited the moraine, and it is therefore tentatively correlated with the Vassås event.

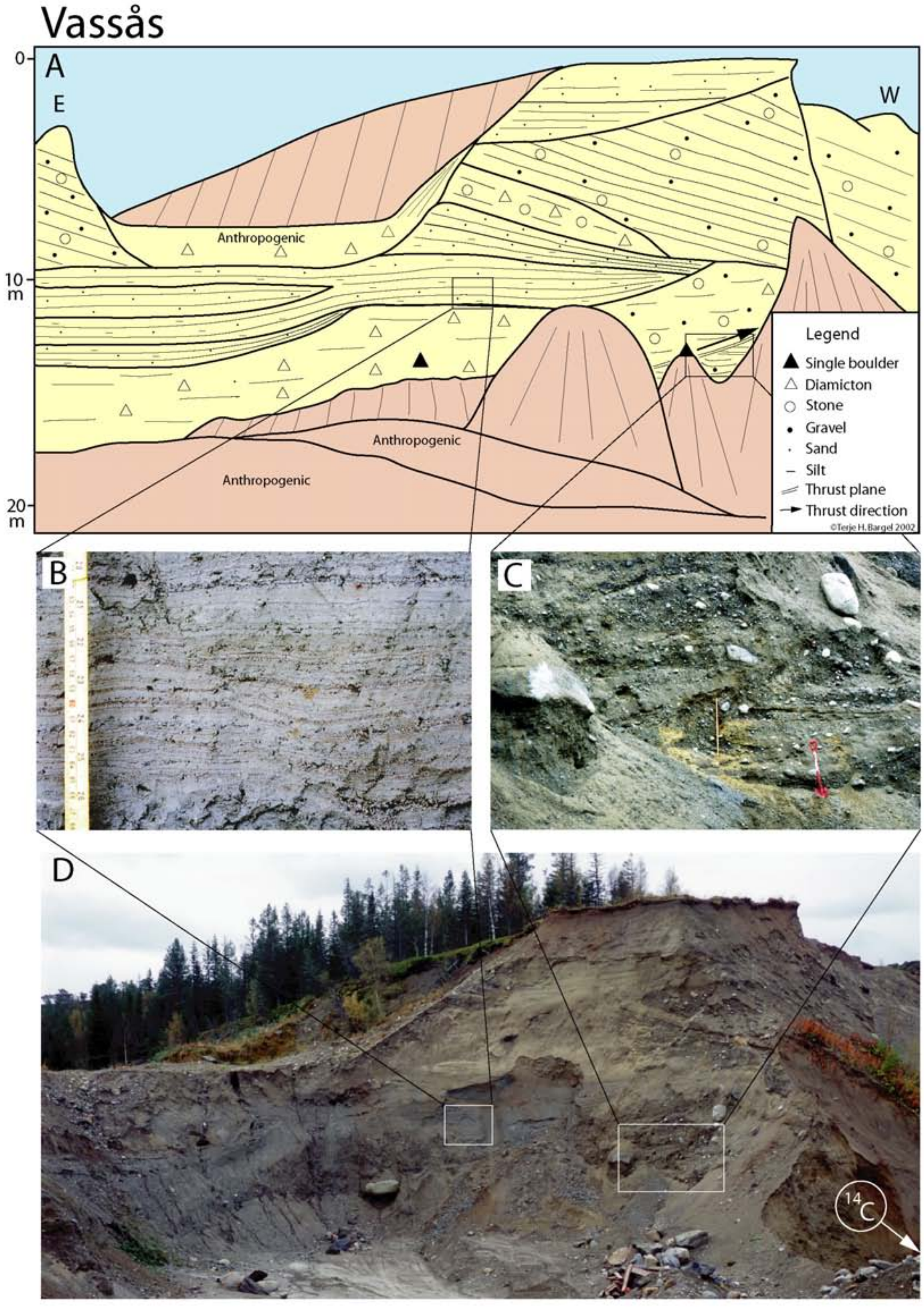


Fig. 11.21
A: Sketch of the Vassås gravel pit. The locations of the close-up photographs B and C are framed. **B**: Close-up of the rhythmites that are composed of sand and silt layers and laminae. Note the disturbed laminae in the centre of the photograph. **C**: Detail from the lower part of the diamicton showing a thrust plane between sorted sediments and the diamicton. **D**: Overview of the Vassås gravel pit. The shell fragments were found in rhythmites located to the right of the section shown. No connection between the shell-bearing rhythmites and those shown here has been observed. Photos: Terje H. Bargel.

11.6.3 The Åbjøra-Follafjorden watershed

In Marfossdalen, there is a 12-15 m-high and 750 m-long moraine with its concave side facing north: this is the *Marfossdalen moraine* (Fig. 11.22 A). The moraine reaches an altitude of up to 525 m a.s.l. According to Svensson (1959), an ice lobe flowing from the northeast, which is a branch of the Åbjøra ice lobe, deposited the moraine.

Two kilometres to the southeast of the Marfossdalen moraine, in the Finnmarkdalen area, several small moraines are located close to the watershed to the Follafjorden. In the southeast, a moraine, partly double crested, can be followed almost continuously for c. 3 km towards the east and northeast. This moraine complex is called the *Finnmarkdalen moraines* (Fig. 11.22 A, Fig. 11.23). The moraine ranges in altitude between c. 450 m a.s.l. in the west and to c. 600 m a.s.l. in the east. In view of the C-shape, with the concave end facing north and the near-horizontal position across the valley, it is reasonable to assume that this moraine, too, was deposited by an ice lobe flowing from the northeast, which is a part of the Åbjøra ice lobe.

In the Follafjorden area two correlative end moraines are located to the southern valley side (Fig. 11.3, Fig. 11.22 B). These moraines are most probably deposited by the Follafjorden glacier.

11.6.4 Small and questionable moraines

In the Åbjøra valley, Rekstad (1910) reported four moraines, at Heimen, Sylta, Hårstad and Åbjørvatnet. Just north of Heimen, at the mouth of the Åelva river there is a conspicuous ridge (Fig. 11.20) located between rock obstacles in the narrowest part of the valley close to the more than 170 m-deep bay of Osan. The ridge has no marked crest, and the material consists of sand and gravel with a few stones that are subrounded to rounded in shape. The Åbjøra valley is extremely rugged due to the bedrock foliation and thrust planes that cut across the valley (Nordgulen et al. 1989). The receding and floating ice front probably had several temporary halts in its retreat when it grounded at the bedrock obstacles, and coarse material was consequently allowed to accumulate at these points while the equilibrium profile of the glacier was re-established, as described by Kjenstad & Sollid (1982) from the Trondheimsfjord area.

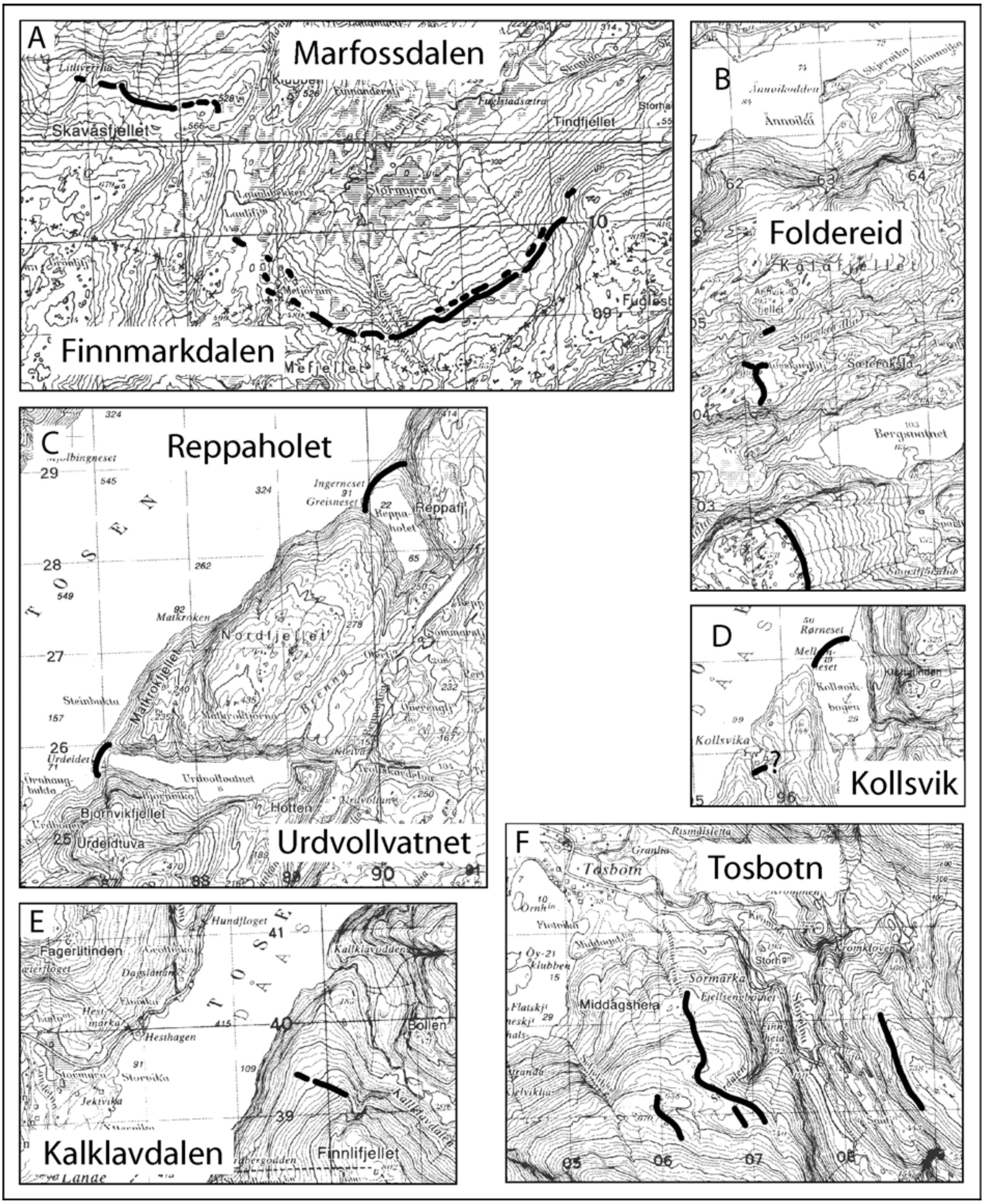


Fig. 11.22
Detail maps that show the moraines in the Tosenfjorden, Åbjørdalen and Follafjorden areas. The location of the areas is shown in Fig. 11.3.

Fig. 11.23
Aerial photograph of the Finnmarkdalen moraine viewed from the northwest. The moraine was deposited from the left. Cf. Fig. 4.8. Photo: Harald Sveian.

11.7 The Tosenfjord area

Along the eastern side of Tosenfjorden, Svensson (1959) described three moraines that are crossing the mouths of small side-valleys. At Urdeidet, a c. 30 m-high moraine ridge dams Urdvollvatnet (8 m a.s.l.); the *Urdvollvatnet moraine* (Fig. 11.22 C). Reppaholet is a bay almost isolated from Tosenfjorden by a huge moraine, the *Reppaholet moraine,* that is more than 60 m high (Fig. 11.22 C). In the bay Kollsvikbogen, a possible moraine forms a threshold between the bay and the fjord; the *Kollsvikbogen moraine* (Fig. 11.22 D). At extreme low water a blocky deposit is exposed. All these three moraines along Tosenfjorden are curved with the steep convex side facing northwest. This strongly indicates deposition by ice moving towards the fjord. The moraines were all deposited below sea level; they were washed during the regression, and are located in the threshold area close to the deep fjord.

In *Kollsvika*, Svensson (1959) described a ridge that is questionable because of the lack of boulders but is rich in fines (?) and rounded blocks; however, no stratigraphical information was given. The present writer is of the opinion that the ridge may be an ice-contact glaciofluvial-glaciomarine deposit (Norwegian: randås). Whatever the final solution to this problem may be, it will not, as far as we know at present, introduce conflicts in our general understanding of the deglaciation. If the ridge is a moraine, it will be considered as a parallel to the three moraines just described, and if the material is of glaciofluvial origin, a glaciomarine deposition could be the answer. In either case, a formation during a late phase of the deglaciation will be the conclusion.

On the southern side of the mouth of *Kalklavdalen* valley, Svensson (1959) described a complex of hummocky moraines and ridges (Fig. 11.22 E). The two most prominent ridges are oriented in line perpendicularl to the Tosenfjord at altitudes from c. 350 to c. 520 m a.s.l.; the *Kalklavdalen moraines*. The longest one is c. 4 m in height; it is asymmetrical and rich in boulders. In the valley side in the middle part of Kalklavdalen, c. 5 km SE of the Kalklavdalen moraines, there is a moraine blanket with a sharp upward termination that is oriented parallel to the valley, and can be found up to c. 690 m a.s.l. This, altogether, indicates that the moraine was deposited laterally to a glacier in the Kalklavdalen valley.

At the mouth of Tosdalen, there are several lateral moraines, as described by Svensson (1959). Along the northern side of Middagstinden, south of Tosdalen, two subparallel moraines have been identified; the *Middagstinden moraines* (Fig. 11.22 F). The higher of the two moraines is located on a flat part of the mountainside, at c. 640 m a.s.l. This moraine is 275 m long; it is slightly S-shaped with a maximum height of 8 m. The lower moraine is c. 1.7 km long and has its lowest end at 305 m a.s.l. from where it climbs straight up in a southerly direction, turns towards southwest at c. 500 m a.s.l., and disappears at c. 540 m a.s.l. A feature comparable to these two moraines is a moraine accumulation on the eastern side of Tosdalen, which is located on the less steep parts of the valley side at c. 600-690 m a.s.l.

11.7.1 Discussion - the Åbjøra ice lobe and other ice lobes in the Tosenfjord area

During the Vassås event, the regional ice flow from the southeast in the Åbjøra valley had to cross local watersheds at 600-700 m a.s.l. between the Åbjøra valley and Namdalen (Fig. 11.3). A mean ice-surface gradient of 50-60 m/km is calculated using the Vassås moraine and the lateral moraines along the watershed to the southeast, assuming that these moraines are correlative. With a steep gradient like this, the height of the ice surface in the feeding area in the Namdalen valley would be situated at c. 900 m a.s.l.; consequently, a less steep gradient and, therefore, a lower ice surface in Namdalen may be a more realistic model. Ice lobes could have branched off from the upper part of the Åbjøra valley glacier and crossed sills towards Tosenfjorden. A sill at c. 650 m a.s.l. had to be crossed if ice lobes were able to reach Tosenfjorden and deposit the Urdvollvatnet moraine and the Reppaholet moraine. An ice lobe that crossed a sill at c. 650 m a.s.l. has deposited the Kollsvikbogen moraine. In addition, ice lobes that crossed sills at c. 650 m a.s.l and c. 725 m a.s.l. probably has deposited the Kalklavdalen moraines and the Middagstinden moraines, respectively (Fig. 11.3. The problem of correlation of the moraines based on these facts is discussed in Ch. 11.10.1.

11.8 Moraines outside the Bindal-Tosen area

In order to provide a complete discussion of the deglaciation of the Bindal-Tosen area, it is necessary to comment briefly on the moraines in the neighbouring areas to the south, north and east.

11.8.1 The Foldafjord area

A huge end moraine of Younger Dryas age that is composed mainly of glaciofluvial material is situated at the mouth of Foldafjorden at *Kolvereid* (Fig. 11.1). In the inner part of this fjord four younger moraine events have been mapped (Sveian 1997). They are tentatively correlated with the Hoklingen, Vuku, Snåsa-Grong and Høylandet Substages (Fig. 8.11, Enclosure 6). At *Djupvika* (Fig. 11.1), the Younger Dryas ice margin coincides with the Outer coastal moraines. This is beautifully demonstrated in a gravel pit where two glaciation phases, dated to 12.5 ka BP and 10.5 ka BP, respectively, are separated by deglaciation sediments (Bergstrøm 1994). Several smaller moraines of Younger Dryas age are situated north of Djupvika, e.g. at *Gravvika* (Fig. 11.3) where a shell dating at 11.1 ka BP is achieved by Andersen et al. (1981).

11.8.2 The Majavatn-Børgefjellet area

In the area east of the Bindal-Tosen district (Fig. 11.1) no moraines have been observed. Glaciofluvial outwash and dead-ice phenomena dominate the Quaternary deposits in this area besides tills that are more extensive than elsewhere in Nordland. A few, small moraines are situated in the valley south of the town of Mosjøen (Follestad 1990a, Bargel & Olsen 1995). In the Vefsnfjord area the moraines are more common as this is the feeding fjord to, e.g. the Tjøtta moraines (Andersen et al. 1982, Follestad 1988a, 1990a, 1992a, Olsen et al. 2001e).

11.9 Marine levels

11.9.1 Rock terraces

Rock terraces are common in the northern part of Norway where they are found almost exclusively outside (distally to) the Tromsø-Lyngen end moraines, and for that reason were probably formed during this cold phase by a combination of frost action and wave abrasion, as noticed by Rekstad (1929) in the Svartisen area, by Marthinussen (1960, 1961, 1962) in Finnmark, Troms and Nordland, and by Andersen (1975) and Rasmussen (1981, 1984a, b) in central and northern Nordland. These observations have been used to indicate the position of the Younger Dryas ice margin in areas where no end moraines are found. Rock terraces at c. 123-129 m a.s.l. are found in Bindal area (Marthinussen 1962). Based on these and several other rock-terrace data from Helgeland, the inclination of the Main shore level is found to be c. 1.0-1.1 m/km in the west-northwest direction (Marthinussen op cit.) (Fig. 11.24). On the northern side of Sørfjorden, a rock terrace is located at c. 135 m a.s.l. (Fig. 11.17), which shows that terraces like this may also be situated proximally to the younger Dryas ice margin.

11.9.2 The Bindalen-Tosen area (Fig. 11.24)

At *Aunelva,* marine silty sediments with shells are located as high as 127 m a.s.l. A terrace situated at <u>137</u> m a.s.l. is believed to be the highest marine level in this area, which should correspond fairly well with the dates of 10.2 and 10.4 ka BP recorded at Aunelva (Table 11.1).

At the southwestern end of the *Lysfjordmana moraine* the marine limit is interpreted to be at c. <u>134</u> m a.s.l. at an escarpment with a marked change in the crest profile (Ch. 11.2.1). This is associated with wave wash just after the retreat of the glacier. The excavation of a rock terrace at Heggebærneset (128.5-129.0 m a.s.l., Ch. 11.8.1) is thought to have occurred during deposition of the moraine or at the second glacier readvance. At the eastern end of the moraine, a terrace-like surface is located at c. 128 m a.s.l. This surface is interpreted as a

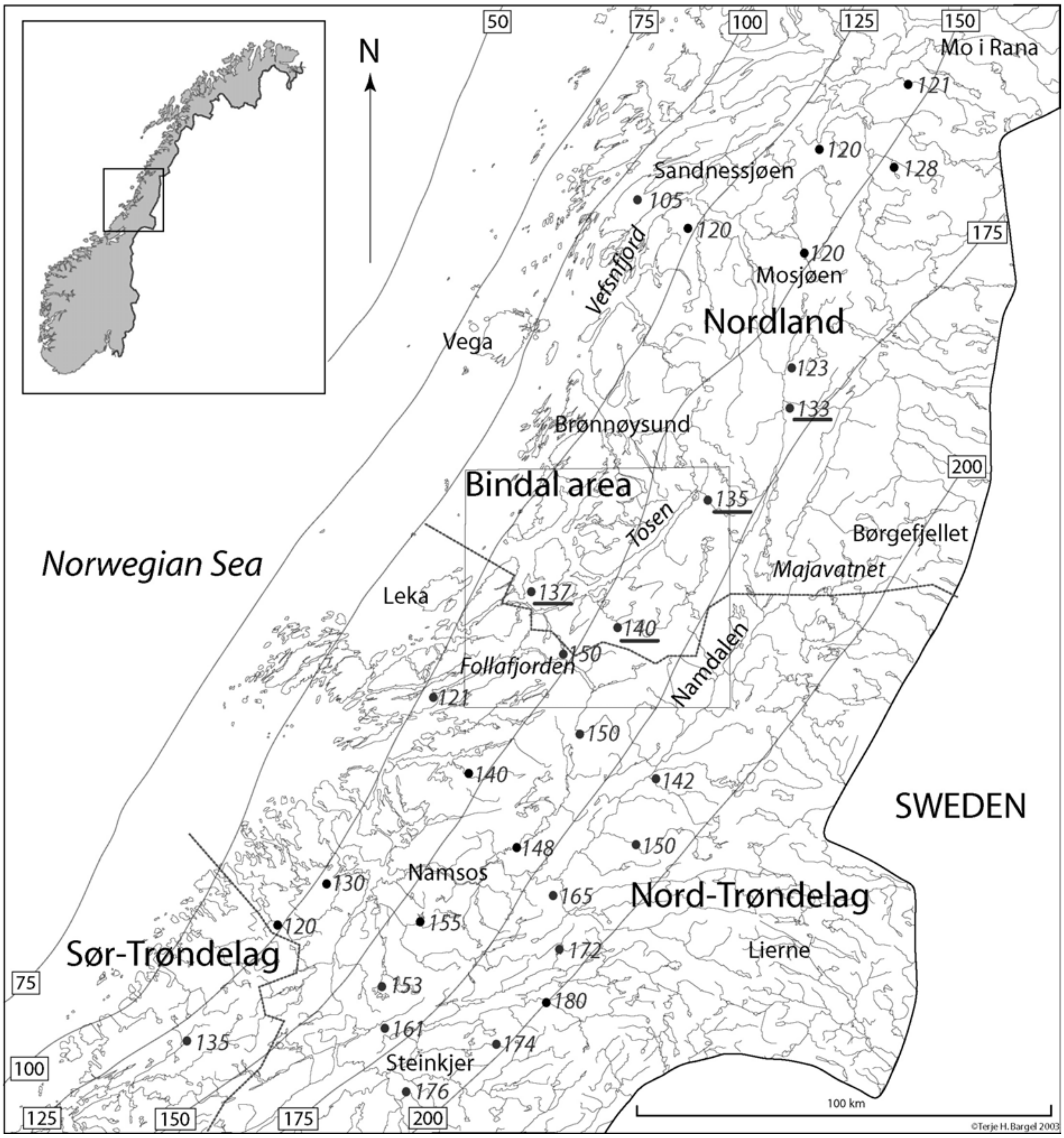


Fig. 11.24
The highest marine levels observed in southern Nordland and northern Trøndelag, based on Follestad (1988a, 1990a, 1992a), Bergstrøm (1995), Bargel & Olsen (1996), Olsen et al. (1996a), Dahl et al. (1997) and this thesis (underlined figures). The numerous observations presented by Rekstad (1922) and Grønlie (1940, 1951) are not included, but the isolines of the highest raised shorelines as proposed by Rekstad (1922, cf. Fig. 3.4) are shown (thin lines with elevation figures inside rectangles). The fit is better on the coast than in the inland areas.

wave-washed area that is lower than the highest marine level. From this same area Rekstad (1910a) reported a marine level at 130 m a.s.l., which is close to the upper level of the moraine at this end. This is most probably too low, as this end of the moraine is heavily wave-washed at the top and was certainly deposited below sea level.

At the *Bindalseidet* local water divide, a disused gravel pit is located at c. 90 m a.s.l.. The gravels are resting on a clay that contains large quantities of molluscs, several of them in situ positions, e.g. *Mya truncata*, *Chlamys*, *Cyprina* and *Littorina*. The gravels are most probably of littoral origin, and the remains of a terrace at 105 m a.s.l. are likely to represent the correlative shore level. *Mya truncata* from the top of the clay bed is radiocarbon dated at 9.8 ka BP (Table 11.1), which is thought to be the approximate age of the 105 m marine level. If this dating is correct, this sea level may be correlated with the Vassås event (Ch. 11.6.1), and the age of the corresponding sea levels at other localities are indicated by use of, e.g. the 1.0-1.1 m/km inclination of the main line as reported by Marthinussen (1962).

In *Breidvika* several shorelines are observed. The highest one is located at c. 124 m a.s.l. However, the deposit is terraced at c. 135-140 m a.s.l., which is thought to represent the marine level.

In *Åbygda,* a huge delta is present that is thought to have been deposited by the melt-water drainage from the Åbjørvatnet lake. According to a detailed map in the scale 1:5,000, the upper level of the terrace is located at c. 140 m a.s.l. A ridge-shaped unit on the top of the terrace could be an end moraine. If this is correct, this was probably the result of a small readvance at a late stage of the deglaciation in the Åbjøra valley.

Kollsvikdalen is situated at the eastern side of Tosenfjorden. According to aerial photographs, the narrow valley is dominated by a fluvial outwash plain. A lower glaciofluvial terrace located at c. 122-125 m a.s.l., and a higher terrace at c. 130-135 m a.s.l., are located in the upper half of the valley. The figures are interpolated on the 1:50,000 map and are therefore not exact. The highest terrace is thought to represent the highest marine level.

In *Tosbotn,* there are several terraces at different levels. The material is mostly cobbles and gravel. Sand is represented in the lowermost terraces. On the top of the highest terrace that is situated at c. 133-135 m a.s.l., there are several kettle holes which show that there was an ice-tongue nearby during the deposition.

11.9.3 Localities outside the area (Fig. 11.24)

A glaciofluvial outwash delta at the confluence of Grønlidalen and Teplingdalen in *Indre Follafjorden* south of Bindal has been levelled at c. 150 m a.s.l. At the entrance to *Folldalen* an ice marginal delta is also situated at c. 150 m a.s.l. In the Namdalen valley, the highest marine level is at 150 m a.s.l. at *Harran* and at 142 m a.s.l. at *Trones* (Dahl et al. 1997). In the Grane area the altitude is c. 123 m a.s.l. on an outwash terrace at the entrance to *Haustreisdalen* (Fig. 7.4) and c. 133 m a.s.l. at *Trofors* (Bargel & Olsen 1995c).

11.10 Discussion and conclusions

A relatively detailed reconstruction of the ice margins during the Younger Dryas and the Preboreal stadials recorded in the Bindal area is presented in Fig. 11.25, Fig. 11.26 and Fig. 11.27. Selected areas are presented in even greater detail in Fig. 11.4, Fig. 11.17 and Fig. 11.20. The reconstruction is based on:

1. The inferred continuity of end moraines
2. Radiocarbon dates of shells
3. The relationship of the deposits to the marine levels
4. Assumed glacier surface gradients
5. The bedrock topography

The radiocarbon dates (Table 11.1, p. 252) are relatively consistent within the Younger Dryas Chron. Even though a possible grouping into, e.g. early and late Younger Dryas seems possible, this will not be stressed here as the number of dates is too few to make a statistically valid conclusion. In addition, the variation in the atmospheric ^{14}C-content during Younger Dryas, as reported by Stuiver et al. (1998), may make such a differentiation problematic. The correlation work is therefore also based on corresponding marine levels, with reference to Grønlie (1940, 1951), Marthinussen (1962) and Dahl et al. (1997). Marthinussen (1962) used the Main shoreline as the main reference level in his correlation work. The general deglaciation principle that the outermost moraine mostly is the oldest one is not always valid, as exemplified by the stratigraphic succession at Djupvika in Nord-Trøndelag county (Bergstrøm 1994), where both the Older Dryas and the Younger Dryas readvances terminated at the same place. However, the assumed age – ice extension relationship is considered to be valid in most cases in this area. Tentative correlation has been made in areas where there are no moraines. The method is based on two logical assumptions: the oldest moraines are situated more distally to the ice centre than the younger ones; and glacial-dynamic considerations claiming that the gradient of the ice surface near the front must be of a reasonable value, which implies that it has to be in accordance with the variations documented by, for example, the lateral moraines in other fjord areas (e.g., Andersen 1954, 1960, 1968, 1975).

A complicating factor when using glacier gradients in reconstruction work is the highly varying influence of the topography on the ice-surface profile. Striking examples are, e.g. the steep profile presented by Andersen (1954) from the narrow Lysefjorden, southwestern Norway, whereas the profiles of the glaciers in the broad fjords Balsfjorden and Ullsfjorden in Troms are less so (Andersen 1968). Vorren & Plassen (2002) are also presenting steep glacier gradients in the narrow fjords of southern Troms in their reconstruction of the Younger Dryas ice margin. Based on these few examples, steep gradients should also be expected in the Bindal area. Whether the ice was partly floating in the overdeepened fjords or not would also be of importance in calculating the gradient.

As a consequence of expected glacier gradients, the endurance of the iceflow across passpoints from one valley to another has been of vital importance in determining how far the ice flow will have reached into the valleys distally to the passpoints. The reconstructions presented here are quite conservative as the valley ice lobes are thought to have been rather steep. This assumption is based on the situation in the Tosbotn area where the lateral moraines have an inclination of up to c. 100 m/km.

11.10.1 The ice flow in southern Helgeland

Just south of the Nordland border, the correlated moraine lines found in Trøndelag converge, and only two glacial events are recognised in the Bindal area as the youngest ones are missing (Andersen et al. 1981, Sveian 1997). The convergence of the moraine lines is probably due to the continuous ice-feed from the east or southeast via the low-lying lake area south of the Børgefjellet massif, combined with the absence of deep and broad fjords that promote rapid calving and ice recession, as, e.g. in the Trondheimsfjorden area. In addition, like the situation southeast of Trondheimsfjorden, the Bindal area was partly sheltered from iceflow from the east by a N-S-trending mountain chain that reaches up to 800-1000 m a.s.l. in the area from the Namdalen to Vefsnfjorden. A second, parallel mountain chain that has a mean elevation of c. 1200-1400 m a.s.l. is situated in the western part of the Børgefjellet area (Fig. 11.1). In the

Børgefjellet area, numerous dead-ice phenomena are observed (Rekstad 1924, Strand 1956, Grønhaug & Gustavson 1960, Gustavson 1973, Sivertsen 1973) that are clearly visible on aerial photographs (hummocky moraines, eskers and lateral terraces, Bargel 2001). These features indicate that a dynamically dead ice was located in the Børgefjellet area while an active part of the ice sheet was probably still flowing in the valleys to the north and south of these mountains, as shown by glacial striae (Svensson 1959, Bargel et al. 1999c).

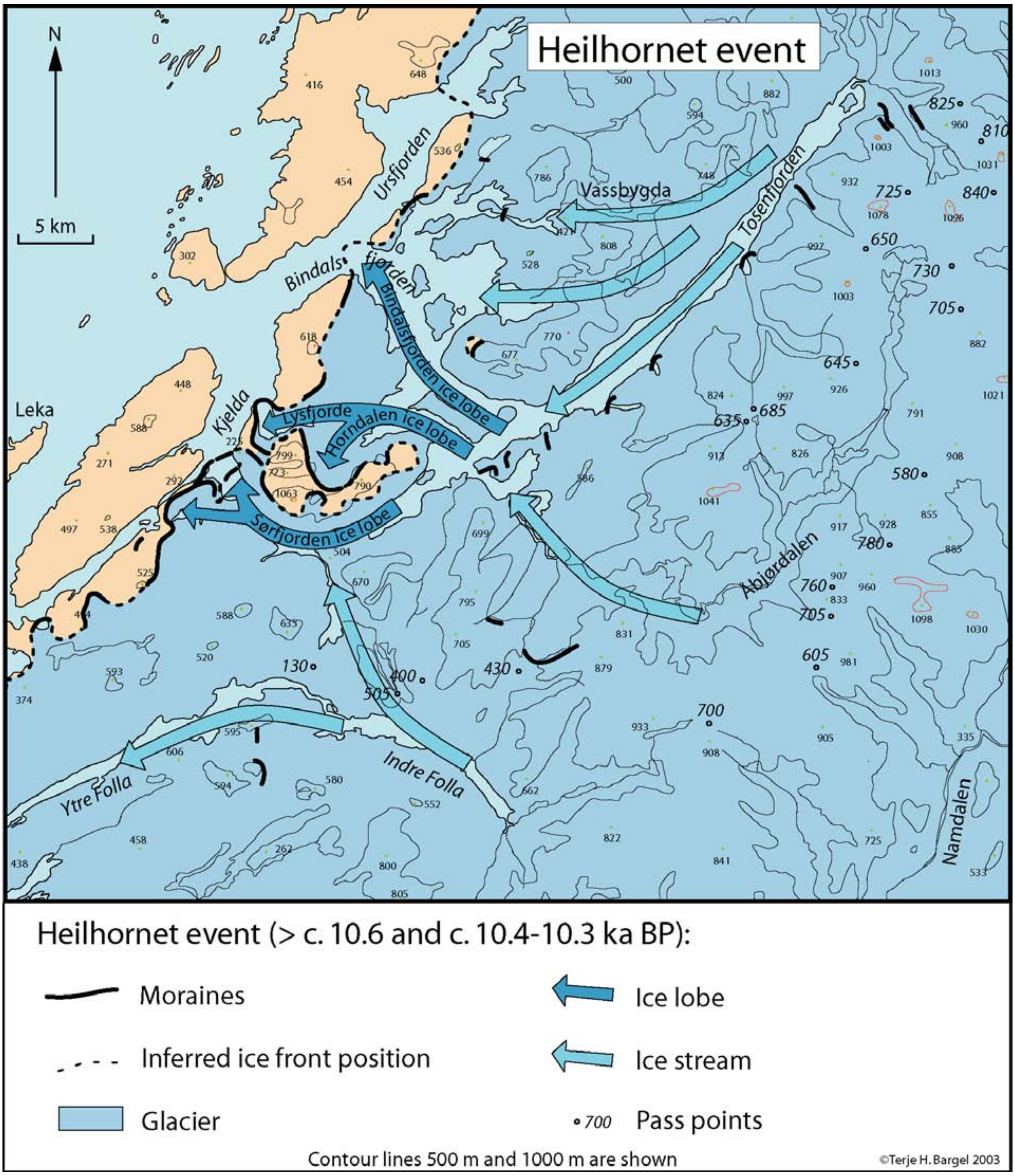


Fig. 11.25
Reconstruction of the Heilhornet event.

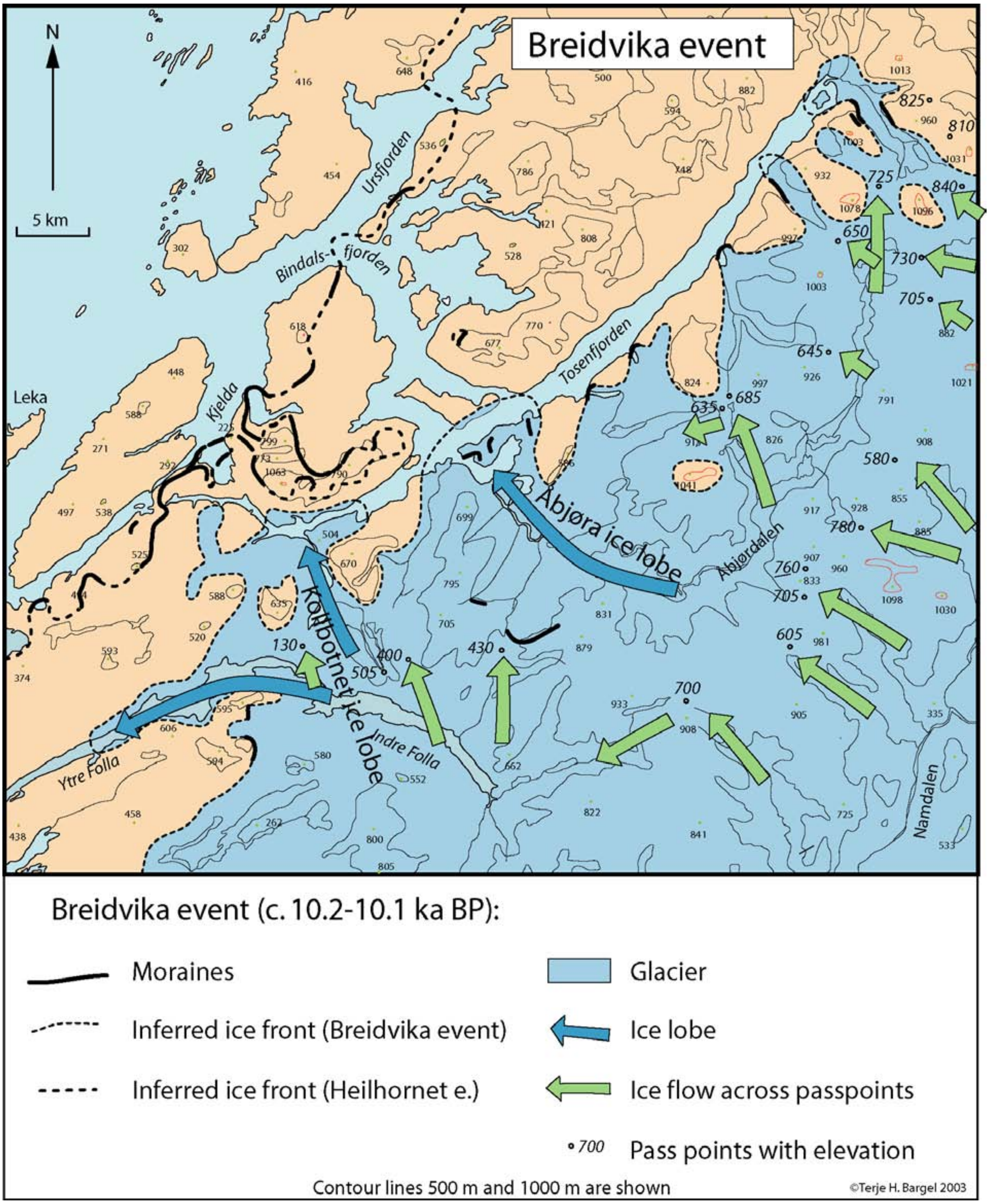


Fig. 11.26
Reconstruction of the Breidvika event.

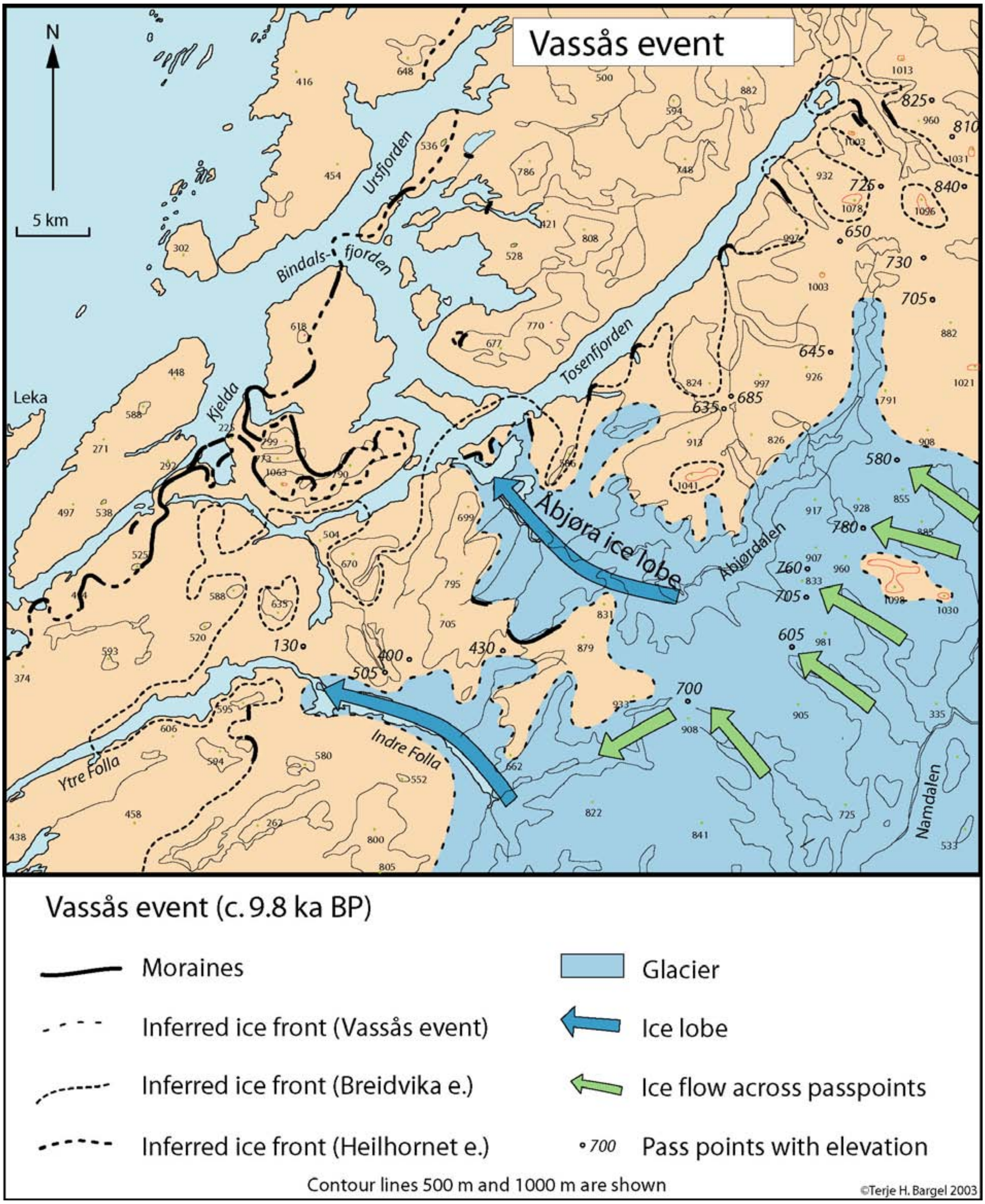


Fig. 11.27
Reconstruction of the Vassås event.

11.10.2 Younger Dryas regional ice advances (c. 11-10 ka BP)

The main ice-advance event in the Bindal area during this interval is named the Heilhornet event (Fig. 11.25). This event is correlated with the Tjøtta Substage, which occurred in two phases at c. 10.9-10.8 and 10.6-10.5 ka BP (Andersen et al. 1982, 1995), and the Tautra Substage, which also occurred in two phases, the Tautra moraines between c. 10.8 and 10.5 ka (Reite et al. 1982, Reite 1994c, Andersen et al. 1995, Sveian 1997).

Two readvances are also recorded in the Bindal area. They are dated to older than c. 10.6 ka BP and c. 10.4-10.3 ka BP, respectively. The new data makes it necessary to slightly modify the earlier reconstructed position of the ice margin in the Heilhornet area (Marthinussen 1962, Sollid & Sørbel 1979, Sollid & Reite 1983, Andersen et al. 1981), and for the first time a detailed reconstruction is presented.

The second main ice advance documented in the Bindal area during Younger Dryas is called the Breidvika event and is thought to have an age of c. 10.2-10.1 ka BP. Based on the age-glacier extensions and ice-surface gradient criteria mentioned before, the event is tentatively correlated with the Nordli Substage at 10.2-10.1 ka BP (Andersen et al. 1995) and the Hoklingen Substage at 10.4-10.3 ka BP (Reite et al. 1982, Reite 1994c, Andersen et al. 1995, Sveian 1997). The apparent deviation of the radiocarbon dates may be an effect of the ^{14}C-plateaus described earlier. This correlation confirms that of the ice flow from the southeast as the last active ice in the area and that the influence of the Tosenfjorden glacier had been reduced substantially.

Massive glacial polishing and striation on the steep valley sides document a SW-directed iceflow along the >700 m-deep Tosenfjorden. Due to the N-S-oriented mountain chains to the east, the ice flow along this fjord, or from the east towards this fjord, must therefore have ended at a relatively early stage of the deglaciation. Glacial striae that are younger than the southwestern flow show an ice flow across the fjord. Consequently, the regional correlation of the small moraines on the eastern side of the Tosenfjord (Fig. 11.3) with the Vassås event (C or D event, Fig. 8.12), as proposed by Andersen et al. (1981), is difficult to understand glaciodynamically because of the high sills that must have been overrun. More specifically, as the ice-push was from the east-southeast, it seems more likely that the ice lobe in Åbjørdalen had a wider influence than the ice lobes in the smaller valleys farther north where several sills had to be overcome. This is also indicated by the late ice flow in a north to northeasterly direction from Follafjorden into Breidvika in the Bindal area. Based on these considerations, the moraines along the eastern part of Tosenfjorden, except the Vassås and the Helstad moraines, are tentatively correlated with the Breidvika event (Fig. 11.26). The Vassås event is consequently younger according to this interpretation.

11.10.3 Preboreal ice advance (c. 10-9 ka BP)

An early Preboreal ice advance is documented in the Terråk-Vassås area and named the Vassås event (Fig. 11.27). This event is correlated with the Narvik I Substage at c. 10.1-9.7 ka BP (Andersen et al. 1995) and the Vuku Substage at c. 10-9.8 ka BP (Reite et al. 1982, Reite 1994c, Andersen et al. 1995, Sveian 1997). Based on glacial dynamic considerations, the new interpretation requires substantial adjustment in the reconstructed position of the ice margin during the Vassås event as compared to that proposed by Andersen et al. (1981).

11.10.4 Conclusions

4. In the Bindal-Tosen area, three main ice-lobe readvances are recorded, namely the *Heilhornet event* in two episodes, older than 10.6 ka BP and c. 10.4-10.3 ka BP, respectively, the *Breidvika event* at c. 10.2-10.1 ka BP and the *Vassås event* at c. 9.8 ka BP. The events are correlated with the Tjøtta/Tautra substages, the Nordli/Hoklingen substages and the Narvik I/Vuku substages, respectively.
5. Strong topographic deviations of the ice flow and a dynamically active ice margin in the Bindal area are recorded. The ice supply to the area changed marked from the northeast and east to the southeast as the ice flow across the high-lying easterly pass points ceased.
6. The latest ice flow was channelled through the lowermost part of the mountain chain, between the Lierne and Børgefjellet mountains, where the elevations are less than 400 m a.s.l.

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ENCLOSURES

1. Maps of Quaternary geology in Central Fennoscandia, sheet 1: Quaternary Deposits, scale 1:1,000,000 (small-scale reproduction).

2. Maps of Quaternary geology in Central Fennoscandia, sheet 2: Glacial Geomorphology and Palaeohydrography, scale 1:1,000,000 (small-scale reproduction).

3. Maps of Quaternary geology in Central Fennoscandia, sheet 3: Ice-flow Indicators, scale 1:1,000,000, and Quaternary stratigraphy, scale 1: 2,000,000 (small-scale reproduction).

4. Quaternary geology in the County of Nordland, scale 1:400,000 (small-scale reproduction).

5. End moraines etc. in the Norwegian part of the Central Fennoscandia and Nordland.

6. Correlation chart for the Weichselian in Central Norway.

7. Map of geographical names (the Norwegian part of the Central Fennoscandia and Nordland).

8. CD-ROM with printable PDF-files of maps 1-4.

9. Map of geographical names (Central Fennoscandia).

COMMENTS ON THE ENCLOSURES

Enclosure 1-4 are reproductions of the Quaternary geological maps, here shown in reduced scales of approximately 1:3.7 million (Central Fennoscandian Quaternary deposits, Geomorphology and palaeohydrography and Ice flow indicators maps), 1:7.5 million (Central Fennoscandian Stratigraphy map) and c. 1:1.35 million (Nordland map).

Enclosure 5 is compiled based on material published by:
Andersen 1968 (Troms)
Andersen 1975 (N. Nordland)
Rokoengen 1979 (The shelf)
Sollid & Sørbel 1979, 1981 (Møre and Trøndelag)
Rokoengen et al. 1980 (The shelf)
Andersen et al. 1981 (Nordland)
Follestad 1984, 1986 (Møre)
Rasmussen 1984 (Vesterålen)
King et al. 1987 (The shelf)
Bergstrøm 1995 (C. Nordland)
Rokoengen et al. 1995 (The shelf)
Bargel & Olsen 1996 (C. Nordland)
Fjalstad 1997 (Andøya)
Sveian 1997 (N. Trøndelag)
Reite et al. 1999 (S. Trøndelag)
Rokoengen & Frengstad 1999 (The shelf)
Bergstrøm et al. 2001 (N. Nordland)
Bergstrøm et al. 2002 (S. Troms)
Rø et al. 2001 (S. Trøndelag)
Olsen 2002 (N. Nordland)
Olsen et. al. 2000a, b
Vorren & Plassen 2002 (Andøya and Andfjorden)
Bargel 2003 (Lofoten and S. Nordland) (this thesis)

Enclosure 8 (CD-ROM) contains the following files:

MNjordkarta.pdf	25,591 kB	Central Fennoscandia: Quaternary Deposits
MNgeomorfkarta.pdf	29,194 kB	Central Fennoscandia: Glacial Geomorphology and Palaeohydrography
MNisraffkarta.pdf	6,519 kB	Central Fennoscandia: Ice-flow Indicators and Quaternary stratigraphy
Nordland.pdf	96,725 kB	Quaternary geology in the County of Nordland
Nordland.tif	50,315 kB	Quaternary geology in the County of Nordland
Nordland.jpg	2,908 kB	Quaternary geology in the County of Nordland