CHAPTER 15

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During the last 2.6 million years, glaciers have at certain times covered large parts, and sometimes all, of mainland Norway, Svalbard and the Barents Sea. Prior to this, uplift of the mainland had occurred, and this continued during the glaciations. Uplift was greatest in the west. A landscape shaped by rivers during the Palaeogene and Neogene (Tertiary) was gradually modified by glacial erosion to form cirques, jagged peaks, valleys and fjords. The resulting sediments were deposited at the continental margin.

View looking northwest across the alpine landscape of Moskenesøya, Lofoten islands. In the foreground the settlement of Reine, situated at the mouth of Kjerkfjord. This landscape has evolved after repeated cycles of erosion by cirque glaciers and small valley glaciers. (Photo: To-Foto)

Glaciations come and go

Quaternary to Holocene (Pleistocene); 2.6 million – 11,500 years ago

The distribution of the northern hemisphere ice sheets during the last ice age, about 20,000 years ago. The adjacent seas were often occupied by much larger volumes of drift-ice than is illustrated here. (After M. Jakobson)

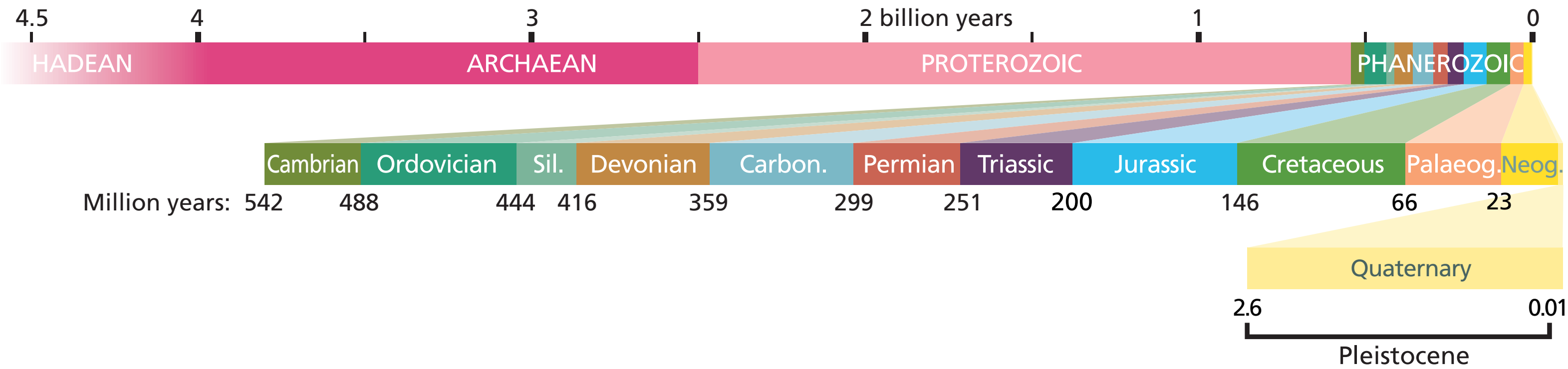
Pleistocene

2.6 million –11,500 years ago

The last 2.6 million years have been characterised by dramatic climatic fluctuations and formation of the continental ice sheets on Scandinavia. For most of the time the dominant frequency of these fluctuations was about 41,000 years, and resulted in relatively small ice sheets until about 900,000 years ago. During the major glaciations of the latter period, the Scandinavian Ice Sheet ice extended south into the European continent. Sea levels fluctuated between 100 and 150 m in step with the advance and retreat of the glaciers.

Introduction

As our story approaches the present-day, we will look at that period of geological history that has done most to shape the spectacular landscape of Norway; the fjords, valleys, cirques and lakes are all the work of glaciers.



Almost all the soil cultivated in Norway today was formed during the last glaciation, the Weichselian, which we shall describe in this chapter. The first glaciers were formed long before this, but about 2.6 million years ago they expanded dramatically both in Northern Europe and throughout the world.

Human evolution also advanced during this period, and modern man (*Homo sapiens*) first appeared about 130,000 years ago. Modern humans arrived in Europe about 40,000 years ago, and a few thousand years later, during the middle of the last glaciation, the Neanderthal hominids became extinct. Several of the largest mammals, including the mammoth, woolly rhinoceros and Irish elk, became extinct either at the end of the last glaciation or at the beginning of the Holocene.

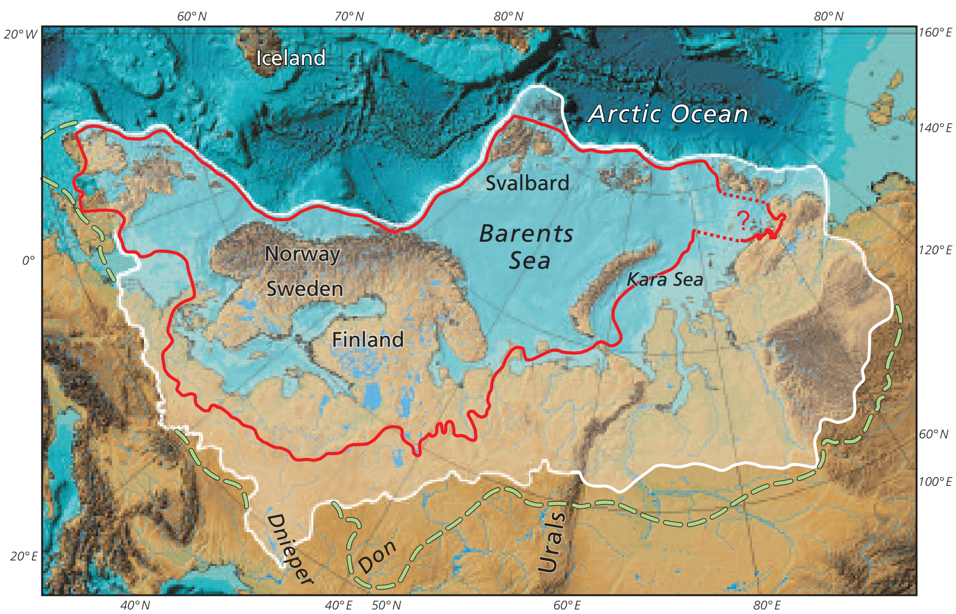
This chapter first describes the number and extent of the different glacial periods and then examines how the glaciers shaped the Norwegian landscape. The glaciers extended across the continental shelves, and most of the products of glacial erosion were transported out onto the continental slope. We shall see what consequences this has had for shaping the Norwegian continental margin. We will then describe discoveries on the mainland that help us interpret the interglacial periods, before describing the last glaciation in Norway. The last ice age, the Weichselian, was by no means a continuous and prolonged winter. Periods of ice advance were interspersed with intervals when the land was almost entirely ice-free. The morphology and distribution of the continental ice sheet during the Last Glacial Maximum, between 25,000 and 18,000 years ago will be discussed. Finally we will follow the melting and retreat of the ice sheet, and in doing so move chronologically into the Holocene, which is discussed in Chapter 16. However, for continuity's sake, we shall describe the entire history of the ice sheet's retreat in this chapter. Relative sea level changes, including glacio-isostatic uplift, will be described in Chapter 16, even though this process had begun during the retreat of the glaciers.

How many glaciations, and how big were the glaciers?

Until the 1960's it was generally assumed that Norway had been subject to four glaciations. Deep ocean sediments have since revealed that there have been more than ten times this many.

Climatic evolution during the last 2.6 million years has two major characteristics. Firstly, global climates have become progressively cooler. Secondly, climate has been characterised by a series of cyclic fluctuations. In the period between 2.6 million and 900,000 years ago, almost 50 such fluctuations or minor glaciations have been recorded. The exact number depends on how finely we subdivide the isotope curves that reveal these fluctuations. The duration of these cycles is either 41,000 or 23,000 (to 19,000) years and their periodicity was controlled by variations in the inclination of the Earth's axis and its precession cycle.

About 900,000 years ago a fundamental change occurred. The ice sheets became much larger, following the 100,000-year cycles of changes in the eccentricity of the Earth's orbit. However, the shorter 41,000 and 23,000-year climatic cycles also continued. Climatic evolution is controlled by interaction between the inclination of the Earth's axis, its precession, and the shape of the Earth's orbit.



The white line denotes the extent of the Scandinavian and the Barents-Kara Sea Ice Sheets during the penultimate (Saalian) glaciation, which ended 130,000 years ago. The red line denotes maximum ice sheet extent during the Last Glacial Maximum some 20,000 years ago. Glaciers that existed on Iceland, in the Alps and other high-altitude areas are not shown. The green line denotes the outer limit of the ice sheet during glaciations prior to the Saalian. (Modified from J.I. Svendsen et al.)

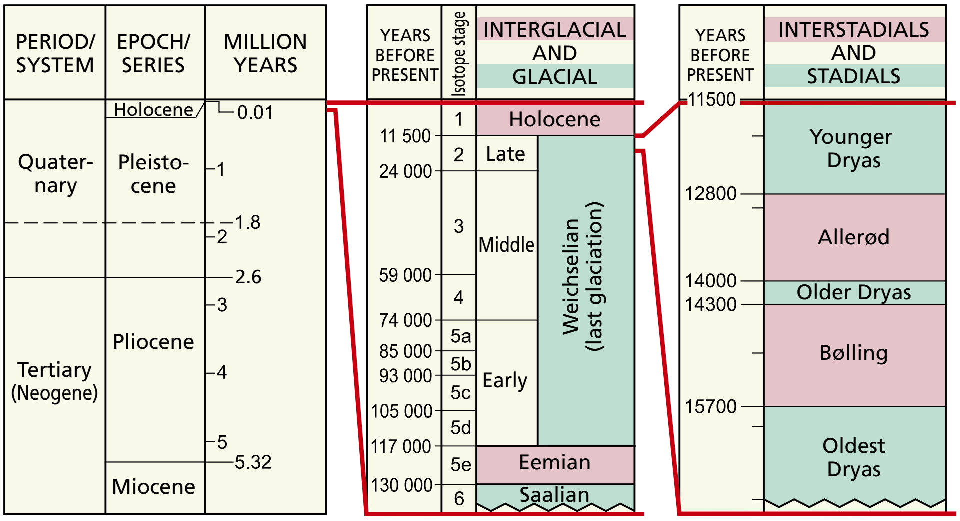
What do we call them?

Naturally enough, our stratigraphic subdivision of the last 2.6 million years reflects these climatic variations. Originally, geological history was subdivided into four periods simply called the Primary, Secondary, Tertiary and Quaternary periods. The first two of these terms have now fallen into disuse and in part also Tertiary (see Chapter 14), whereas Quaternary most is commonly used for the period of large glaciations on the Northern Hemisphere in the last 2.6 million years. The Quaternary is subdivided into the Pleistocene, the theme of this chapter, and the Holocene (Chapter 16).

For the last ten years, the most commonly accepted boundary between late Tertiary (Neogene) and the Quaternary has been some 1.8 million years ago, but this will probably soon be set at the start of the large northern hemisphere glaciations, 2.6 million years ago.

There are several reasons why it is difficult to define subdivision of this geological interval. One is that rivers and glaciers erode much more material than they deposit on land; another is that most glacial and other continental deposits cover only a very short time interval. For this reason the oxygen isotope curve derived from deep-sea sediments provides the best foundation of our modern global Quaternary time scale.

In Northern Europe, glacial periods are named after rivers encountered at the furthest point of advance of the ice sheet in question. The last is thus termed



LEFT: Stratigraphic subdivision of the last 6 million years. The full line shows the proposed lower boundary for the Quaternary at 2.6 Ma and the stippled line the proposed boundary at 1.8 Ma. CENTRE: Stratigraphy of the last 140,000 years showing glacials and interglacials. RIGHT: Column showing the interstadials and stadials during the final period of the last glaciation. The centre column also displays a subdivision based on the marine oxygen isotope record. Here, ideally, interglacials were originally denoted by odd numbers, and glacials by even numbers. However, geologists initially made a misjudgement when assigning the numbers. We now know that isotope stage 3 was only a mild interval during the last, Weichselian, glacial period, while 2 and 4 were cooler intervals, also within the Weichselian. In fact, only the oldest part of stage 5 belongs to the last European (Eemian) interglacial. The remainder of level 5 belongs to the Weichselian.

the Weichselian (Weichsel), after the German name for the Polish river Wisla. Two previous, more extensive, glaciations are termed the Saalian (Saale) and Elsterian (Elster), respectively, both after rivers in Germany. Intervals between the glacial periods, during which temperatures were at least as high as those we experience today, are termed *interglacials*. A challenge facing scientists is that new research has revealed two probable glaciations (and corresponding interglacials) between the Elsterian and Saalian events. The last major interglacial (prior to the Weichselian) is termed the Eemian (Eem), after a river in the Netherlands where deposits from this interval were first discovered. The Eemian interglacial lasted only for about 15,000 years and ended about 115,000 years ago. Shorter periods of milder climate during glaciations are referred to as *interstadials*, while the coolest periods involving glacial advance are called *stadials*.

In Norway, only the final stage of the last glaciation can be described in any detail. Most deposits from earlier glaciations were eroded and removed by later ice sheets. For the last deglaciation we use terms that have their origin in Denmark. At the end of the 19th century leaves of the mountain avens (*Dryas octopetala)* were discovered in clay deposits. This beautiful white flower is currently common in the Norwegian mountains, thus its discovery clearly indicated that the climate in Denmark had been much cooler in the past. This period was named the Dryas. Later, in 1901, a peat horizon was described from a clay quarry at Allerød north of Copenhagen. It revealed a milder climatic interval which was named the Allerød interstadial. However, leaves of *Dryas* were found in clays both above and below the peat, and thus the names “Older” and “Younger” Dryas stadials were introduced. Later, an additional milder climatic interval, the Bølling interstadial, was identified within the Dryas, requiring a further subdivision.

The Scandinavian Ice Sheet invades Northern Europe

Ice sheet and glacier extensions are best obtained from mapping terminal moraines and other deposits that mark locations where the ice-front terminated. Deposits from earlier and minor glaciations have largely been eroded and removed by later and more extensive ice sheets. However, by studying oxygen isotopes in foraminiferal skeletons (see text box), geologists are able to calculate how much water was bound up in the ice sheets at different times. However, we must remember that these methods apply globally. For Norway and Scandinavia, it is thus only possible to make an approximation of the extent of the earlier glacial advances. At their maxima, it is likely that the ice sheets before 900,000 years ago extended to the Norwegian coast, and it is possible that the shallow sills encountered at the mouths of the fjords in western and northern Norway define the furthest limits of advance for many of these ice sheets.

During the major Middle and Late Pleistocene glaciations, the ice sheet advanced south into Continental Europe. Terminal moraines from the penultimate, Saalian glaciation, which ended about 130,000 years ago, are found in Germany and the Netherlands. The ice reached equally far south during the Elsterian glaciation. The age of this advance is disputed, but recent research indicates that it occurred about 400,000 years ago. During the Saalian glaciation, a long glacial tongue extended south into the Dnieper valley in Ukraine. It reached as far south as 49 °N and only stopped some 250 km north of the Black Sea coast, thus achieving a record for the southern extremity of the Scandinavian Ice Sheet. Further east, and during an earlier glacial period about 600,000 years ago, the ice sheet reached as far south as 50 °N in the Don valley in Russia.

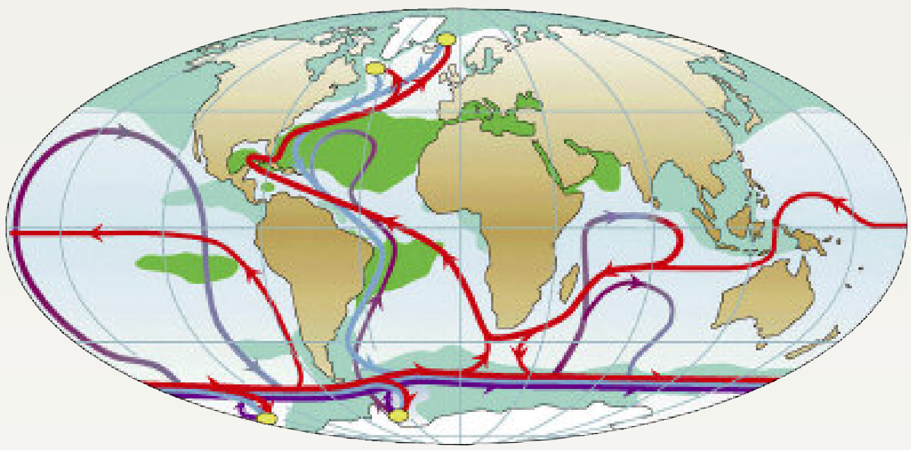
It is relatively straightforward to define the furthest limits of glacial advance at the Atlantic margin. The continental shelf was overrun by advancing ice sheets during several glacial cycles, but it always halted at the shelf break. For an ice sheet to rest on the sea floor, at least one tenth of its total thickness must be above sea level. “Ice walls” that rise above the sea surface are not sufficiently robust mechanically to achieve heights of more than 50-60 m, and they fre-

THE CHANGING INFLUENCE OF THE GULF STREAM

Norway and Svalbard have not always been grateful beneficiaries of the warm and salty water masses of the Gulf Stream. At certain periods its influence in the Norwegian Sea has been reduced. Variations in its influence are revealed by sediments and deep and shallow-water marine fossils. A detailed history of the Gulf Stream and its influence on climate has been reconstructed based on deep-sea sediments.

The Gulf Stream has its origins at the equator and, as its name suggests, it passes through the Gulf of Mexico before continuing north along the east coast of the USA. It then crosses the North Atlantic and enters the Norwegian Sea by passing between the Faroe Islands and Scotland. In the Norwegian Sea its correct name is the Norwegian Current, but the term Gulf Stream is most commonly used. The Gulf Stream impinges on the Norwegian coast, where it mixes with coastal waters and provides Norway with ice-free harbours. Between the Faroe Islands and the UK, the Gulf Stream exhibits temperatures of 7-9 °C. The volume of water in the Gulf Stream varies greatly, with most estimates indicating flows from between 3 to 12 million m^3/sec. In the northern Norwegian Sea-Greenland Sea, Arctic and Atlantic water masses mix and water becomes denser and sinks to deeper levels. It then returns to the Atlantic as a bottom current at a temperature of about 0 °C.

Thus the Gulf Stream also transports enormous amounts of heat on its journey north. This is demonstrated by the fact that the Greenland Ice Sheet is located on the western side of the Norwegian-Greenland Sea whereas Norway on the eastern side enjoys the warmest climate on the planet in relation to its latitude. It is not difficult to imagine how climate would change if the Gulf Stream's influence should become reduced, or if it turned away and no longer flowed into the Norwegian Sea.



Map showing global ocean current circulation patterns, of which the Gulf Stream is a part. Red lines denote surface currents, while yellow circles indicate areas where water is cooled and sinks to form deep-sea currents (blue and violet lines). Green denotes areas of relatively high salt concentration (>36 parts per thousand), while dark blue indicates areas of lower salt concentrations (<34 ppt). Because all the currents are linked, an alteration in one part of the system will have consequences at all other locations.

quently break up before reaching these heights. Thus, if water depths exceed 500-600 m, glacier tongues start to float, and the process of iceberg "calving" begins.

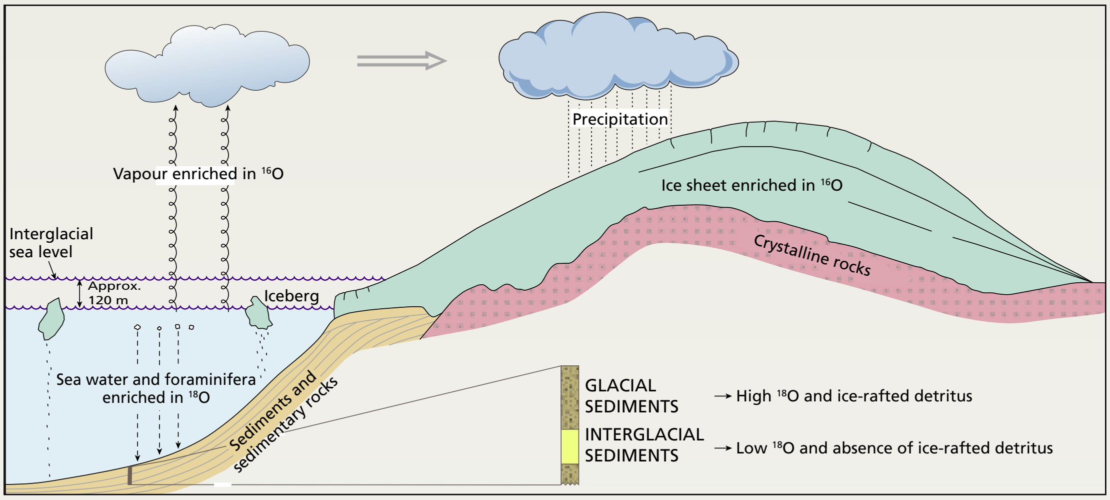
Ice sheets on Svalbard and in the Barents Sea

Today, 60 % of Svalbard is covered by glaciers and northern Novaya Zemlya is almost entirely covered by ice. It is possible that the extensive ice sheet that covered the Barents and Kara Seas, termed the Barents-Kara Sea Ice Sheet, had its origins in these and other archipelagos. At its maximum, it was of equivalent magnitude to a continental ice sheet and, somewhat surprisingly, its central and most elevated domes were located above the present-day Barents and Kara sea basins. It was from these areas that the ice sheet advanced onto mainland northern Russia and across Svalbard. During the Saalian glaciation, extensive areas of western Siberia and Russia were covered by the ice sheet. The Barents-Kara Sea Ice Sheet merged with the Scandinavian Ice Sheet off the coast of Finnmark but for the most part both ice masses behaved independently with regard to their mass balance and ice flow.

The largest ice sheets – exceptions to the rule

Based on isotope measurements conducted on fossil organisms in sea-floor sediments, geologists have produced a simplified classification of the magnitudes of both global and Scandinavian Ice Sheet

CLIMATE HISTORY FROM OXYGEN IN CARBONATE SHELLS AND GLACIER ICE



The element oxygen exists mainly as one of two isotopes, ^{18}O and ^{16}O. Minute marine creatures called foraminifera extract these isotopes directly from sea water and incorporate them into their calcium carbonate ($CaCO_3$) skeletons. When foraminifera die their skeletons become incorporated into sediments that accumulate on the seabed. By extracting cores of these sediments and analysing the foraminifera, geologists are able to measure changes in the relative proportions of the two oxygen isotopes in sea water during geological time.

These are valuable data because these relative isotope proportions in sea water, and thus in the foraminifera, change with time. This is due primarily to two factors, and both are linked to climate. The first of these is temperature; in warm water ^{16}O is enriched relative to ^{18}O in foraminifera shells. The second factor is related to the volume of water in the sea, which is determined by the volume of water bound up in glaciers. The ^{16}O isotope evaporates more easily than the heavier ^{18}O isotope. Thus, during a glacial period, water in the glaciers becomes enriched in the ^{16}O isotope, while the remaining sea water becomes correspondingly rich in ^{18}O.

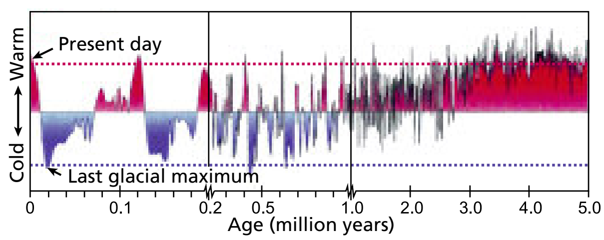
In this way both glacier ice and deep ocean sediments can reveal continuous records of climate history through geological time. The isotope composition (oxygen and other isotopes) within the ice is thus dependent on the temperature where the snow falls, providing us with a genuine "palaeothermometer" which records temperature at a given location through geological time. In addition, air bubbles trapped in the ice contain samples of the atmosphere from which we can measure, for example, greenhouse gas contents. Ice at the base of the Greenland ice sheet is some 100,000 years old and has provided us with a detailed record of climate variations during the last glacial period, while cores from the Antarctic provide data from several hundred thousand years back in time.

Deep-sea sediments allow us to analyse events from millions of years in the past. Rock fragments and sand dropped from melting icebergs which have calved from glaciers also provide an important record of past climates. During recent decades, several cores have been taken from the world's oceans, including the Norwegian Sea. Climate histories that these have revealed demonstrate that several rapid and dramatic changes have occurred in the recent geological past.

activity during the last 2.6 million years. There are three scenarios which together illustrate the massive fluctuations in ice sheet distribution during the 100,000-year period covered by the great "ice age":

1) Interglacial periods with local glaciers restricted to the mountains, during which climatic conditions were similar to the present-day or perhaps a little cooler or warmer. Scenarios such as these have arisen repeatedly throughout the entire epoch under discussion. **2**) Periods during which the Scandinavian Ice Sheet extended to the Norwegian coast. This occurred relatively often throughout the entire period and was dominant between 2.6 and 0.7 million years ago. **3**) Periods during which the ice advanced across Sweden and Finland, and reached as far as southern Germany. This scenario is restricted to relatively short intervals within individual glacial periods, and first occurred 0.9 million years ago.

It is estimated that scenario 1 lasted for about 1.2 million years in total, scenario 2 for about 1.3 million, and scenario 3 less than 200,000 years.



Curve showing variations in oxygen isotope concentrations in deep-sea sediments during the last 2.75 million years. The curve reflects mainly the volume of the Earth's ice sheets. About 2.75 million years ago the ice sheets began to advance and retreat in cycles of 41,000 and 23,000 years. This pattern continued until 0.9 million years ago when cycles of 100,000 years became dominant, during which time the ice sheets expanded. However, both the 41,000 and 23,000 (to 19,000) cycles remained important during this period. Note that the time scale is adjusted at 0.2 and 1.0 million years. (Modified after J. Thiede)

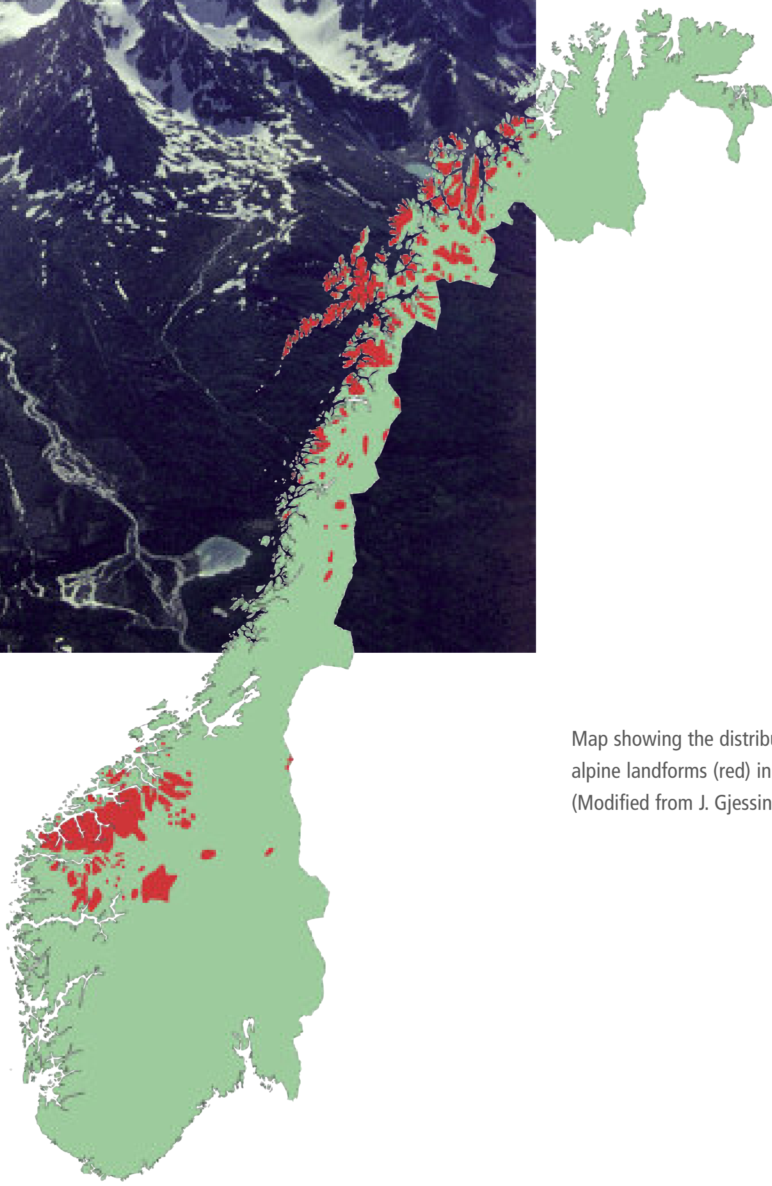
The legendary mountains are not as old as they seem

In the early Palaeogene (early Tertiary) the Norwegian landscape was gently undulating, interspersed with isolated low mountain areas. Since then Norway has been uplifted and, during the glaciations, has evolved its well-known mountainous landscape characterised by deep valleys and fjords.

In 1901, the geologist Hans Reusch wrote that southern Norway was made up of two main landscape types. In the mountains he described the vast, gently undulating high-altitude plateaus, such as Hardangervidda or the mountains around Østerdalen. Reusch named these the "palaeic", or "ancient" surface, and suggested that they were formed originally as lowlands which were later subject to massive uplift. His argument was that today's valleys and fjords made such striking incisions into the palaeic surface that they must be much younger, and formed by other processes. Reusch himself, and more recent studies, suggested that the palaeic surface comprises several "levels" which may be interpreted as representing different phases of the uplift process. This is yet to be fully explained, but there appear to have been at least two significant phases involving continental uplift adjacent to the Norwegian and Greenland Seas, including Norway and Svalbard, in recent geological history. The first of these, which occurred during the early Cenozoic some 65-55 million years ago, resulted from uplift generated by mantle material upwelling beneath Iceland. The second phase occurred during the Late Cenozoic. Uplift was greatest during this phase, probably as much as 1,000 m at some locations in southern and northern Norway. In the Trøndelag region the magnitude of uplift was somewhat less,

Aerial view looking east across the Jotunheimen mountains with the summits of Fannaråki (Fa) and Hurrungane (H). Initially, during the Tertiary these high-altitude, mountain massifs emerged above a lowland landscape close to sea level. The remains of the lowland plains have today been transformed into mountain plateaus, here represented by Sognefjell (S). Following uplift, valleys were eroded into the earlier lowlands, here represented by the Helgedalen/Bergsdalen valleys (B), and which are hanging valleys in relation to the Fortunsdalen valley (Fo) in the foreground. (Photo: Fjellanger Widerøe)

Characteristically rugged summits of the Lyngen Alps in Troms are typical of so-called "alpine" morphology. The photograph shows examples of cirques, horns, and arêtes. (Photo: G. Corner)



Map showing the distribution of alpine landforms (red) in Norway. (Modified from J. Gjessing)

and this is reflected in Norway's present-day topography. Geologists do not have an unambiguous explanation for the uplift phenomenon, although part of it lies in a response to the intense erosion of the continental landmasses during the glaciations. Isostatic uplift has compensated for the removal of eroded material. However, this alone cannot account for the total magnitude of the uplift phenomenon.

Minor glaciers create cirques and jagged peaks

During the Quaternary Norway experienced for long periods only minor glacial activity. This situation is characteristic not only of the very beginning and end of a glaciation, but also of interglacials and the milder interstadials during the glaciations themselves. The very first glaciers were formed in high-altitude regions such as Jotunheimen, Rondane and the Lyngen Alps. As the climate cooled at the beginning of each new glacial period, local cirque glaciers advanced and merged to form extensive plateau glaciers and elongate valley glaciers. Eventually, the amalgamated ice mass became so large that it could be termed a continental ice sheet. Cirque glaciers located closest to the coast were the last to merge with the ice sheet. For this reason the Sunnmøre Alps in Mid-Norway and, in particular, the Lofoten islands, were subject to only localised glaciation for much longer periods than the mountains further inland.

The first glaciers were formed after snow drifts, accumulating on the higher mountain slopes, were gradually transformed into ice. The embryonic glacier thus developed against an ever-steepening back wall, forming a concave depression, or cirque. Almost all of the existing smaller glaciers in Norway are cirque glaciers. As cirque glaciers erode backwards from opposite sides of a mountain a narrow ridge, or arête, develops, separating the cirques. The backward erosion of several cirque glaciers towards the same summit eventually

View across Aurlandsfjorden. The fjord is deeply incised into the gently undulating palaeic surface. (Photo: fjord.com)

THE NORWEGIAN STRANDFLAT – COASTAL PLAINS AT THE FOOT OF THE MOUNTAINS *By Inge Aarseth*

The "Strandflat" is the geological term for the low-lying foreshore and beach features that occur along the entire Norwegian coast from Ryfylke in the south to Nordkapp in the north. The inner margin of many strandflats is marked by steep cliffs, and some islands thus resemble great fedora hats floating on the sea, with the strandflat representing the brim. Strandflats are best developed in the Nordhordland and Outer Trøndelag areas, and along the Helgeland coast. Here, they may reach 20-40 km across and extend inland to the foot of the coastal mountains. The islands of Smøla and Frøya are good examples of the strandflat's characteristic flat relief. Around these islands and on the Helgeland coast, the strandflat extends offshore down to 30-40 m below sea level. These submarine features were probably formed in the same way as their subaerial counterparts. That strandflats are found from about 60-70 m above sea level inland, to 30-40 m below sea level at their outer limits, is due to the fact that the inland areas were subject to greater uplift after their formation. In general, strandflats extend for only short distances along fjords, where they occur as low, flat, rocky ledges. This is because the fjords were occupied by glaciers during periods when the coast was subject to weathering and, in addition, that glacial erosion of the fjords may have removed some of these ledges.

The formation of the strandflat has been the subject of much debate. Today, many researchers believe that the coast was free of ice for long intervals during the glaciations, similar to conditions along the margins of Svalbard and Greenland today. Seawater and spray found its way into fractures along the rocky coasts and promoted frost weathering. The products of weathering were then removed from the foreshore, first by wave action and later by glaciers. Gradually the glaciers excavated valleys below sea level and when the ice retreated, the sea invaded to form the familiar fjords and sounds. This provided further weathering processes with several means of attack, and many coastal islands developed a low-lying and regular bedrock topography, with a well-defined inner margin bounded by steep mountainsides. Since weathering was most intense close to sea level, this steep margin was maintained during colder periods. However, the mountainsides were also subject to weathering, and landslides produced great taluses at the foot of the slopes which were removed during the glaciations. These processes served to reduce the extent of mountainous areas on the islands, and correspondingly increased the area covered by the strandflat. It is likely that conditions have been favourable for the formation of the strandflat for at least half the duration of the glaciations.

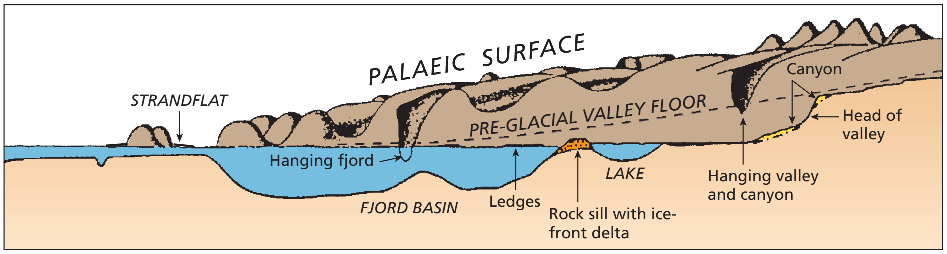
The Norwegian strandflat landscape has been of great benefit to coastal communities and has sustained dispersed human settlement in the form of small towns which have benefited from the protection provided by the strandflat from the open ocean. The shallow offshore flats are spawning grounds for many fish species, and are also exploited for aquaculture.

Photograph of the island of Skuløya, north of Ålesund, looking northwest and illustrating a well-developed strandflat. Several relict shorelines from the last glacial and post-glacial periods are developed on the strandflat. Farm buildings are strung like beads on a necklace along the raised beach ridge from the Tapes transgression. Further inland there is an older foreshore deposit of Younger Dryas age (YD). The marine limit (ML) is also very well-defined.

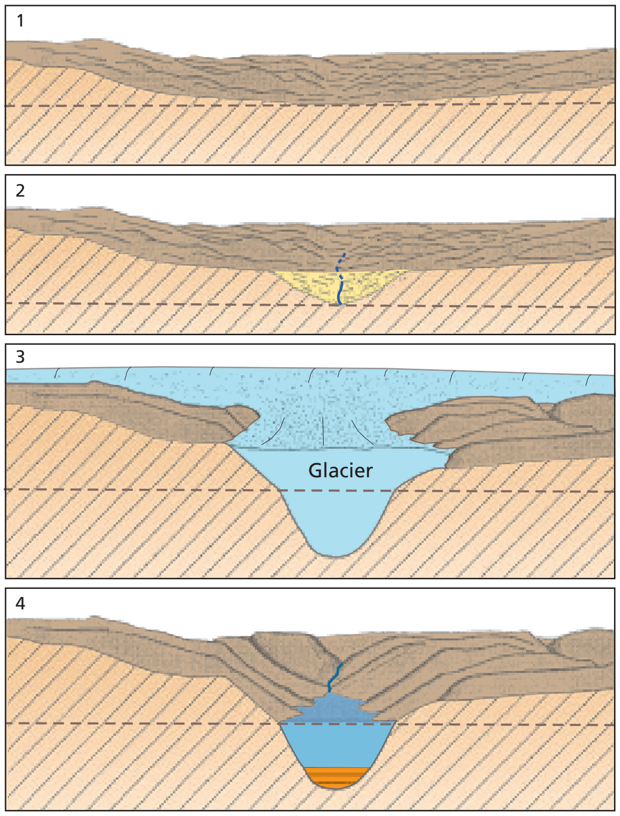
results in a sharp, angular peak, horn or "tind". The cirques themselves are often the sites of lakes when the ice melts or retreats. The end result of this process is what we now refer to as an "alpine" landscape, such as we encounter in the Jotunheimen, the Møre region, and along the coasts of northern Nordland and Troms. Today's tourist honey-pot of Lofoten is a special case in that the cirques here have been eroded down to the present sea level and even below it, with the result that the spectacular peaks rise straight out of the sea. However, if the Lofoten landscape had been sculpted by minor glaciers alone, we would have expected enormous volumes of sediment to have accumulated adjacent to the cirques, causing erosion itself to run out of steam. In fact, the arrival of the continental ice sheet assisted the process by repeatedly removing the erosional products.

Valleys and fjords

Fjords are among the most striking landscape features on Earth, and are found only in glaciated areas such as Norway, Iceland, Greenland, Alaska, Chile, the Antarctic and New Zealand. Fjords are beyond doubt the result of glacial erosion, and this is confirmed by the fact that they are typically over-deepened, rising at their mouths to a shallow sill.



ABOVE: Schematic longitudinal profile showing different landforms along a typical fjord and valley system. Glacial erosion has affected at least the part of the fjord bottom located below the level of the sill at its mouth. The dashed line denotes a theoretical valley floor profile prior to glacial erosion. (Modified from J. Gjessing)



LEFT: Formation of the Norwegian fjords. The dashed line denotes sea level during the different stages. 1: The palaeic surface close to sea level. 2: Probable multi-phase uplift of landmasses during the Tertiary, and initial valley formation by fluvial erosion. 3. Formation of a fjord by glacial erosion during the Quaternary glaciations. 4. Today's interglacial situation in which the fjord sides are modified by mass wasting, while sediments accumulate on the seabed. (Modified from A. Nesje and I.M. Whillans)

The fjords and major valleys essentially follow river valleys established prior to the glaciations. At many localities today we can see the remains of the older river valley floor in the form of ledges on fjord and valley sides. In simple terms, the origin of fjords is as follows. During continental uplift in the Cenozoic, rivers began to erode and cut valleys into the palaeic surface, partly along established zones of weakness in the bedrock. At the beginning of the glacial periods, local glaciers advanced from high altitudes and merged to form outlet glaciers which followed the river valleys and reshaped them. The valley sides became steeper, and sills and basins were sculpted into the valley floors. After successive glaciations some of the valley floors became over-deepened below sea level and fjords were formed. During the interglacials, mass movements along the valley sides produced sediments that were later removed by new glaciers on their return. Erosion of the valleys and fjords continued throughout the major glaciations, and they developed into important drainage conduits for faster-flowing "ice streams" within the continental ice sheets.

At 205 km long and 1,308 m deep at its deepest point, Sognefjorden is Norway's largest fjord. It is estimated that in sculpting this fjord, glacial erosion has removed 7,610 km³ of rock. Along the fjord itself, this involved erosion to depths of 2,000 m, and an average reduction in the elevation of the surrounding catchment area by 600 m. The major valley systems in eastern Norway, which are also glacial in origin, have undergone a somewhat less dramatic erosional history, involving deepening estimated at about 250 m below the palaeic surface.

Tracing the flow of the continental ice sheet

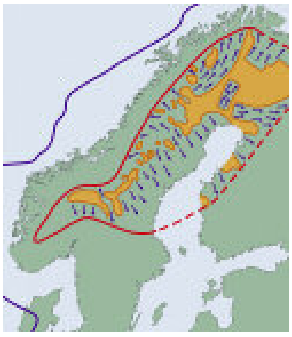
From the dome-like culmination of a continental ice sheet, or ice divide, ice flows downwards and outwards towards its margin. Ice movement occurs at right angles to the contours at the surface of the ice sheet, even if its base is grounded on an upslope. We can thus construct a model of an ice sheet by recording the flow directions indicated by striations scoured into the bedrock by rock fragments embedded in the sole of the glacier. Other features can provide clues as to the direction of ice flow. Drumlins are elongated, streamlined, ridges of unconsolidated sediments, but which have characteristic blunt terminations oriented in the direction of ice movement. Swarms of drumlins are well-developed on the mountain plateaus of southern Norway, and on Finnmarksvidda. Crag-and-tail is a similar feature consisting of a rock "crag" facing the direction of ice movement, against which the ice has left a tail-like moraine in its wake. "Erratic" blocks can be traced to their origins, as in the case of the distinctive rhomb porphyry lavas from the Oslo area. Several of these have been encountered in Denmark and northern Germany, thus providing evidence that ice must have flowed south from Scandinavia to the Continent. Based on observations of flow-direction indicators and erratics, geologists can reconstruct the distribution and morphology of the continental ice sheets. It is from the last (Weichselian) glaciation that such clues are best preserved and, as we shall see later in this chapter, it is these that have been studied in the greatest detail.

Glaciers also protect the landscape

Glaciers do not always slide along the glacier sole. In some situations they become frozen to the substrate which thus becomes protected from further erosion.

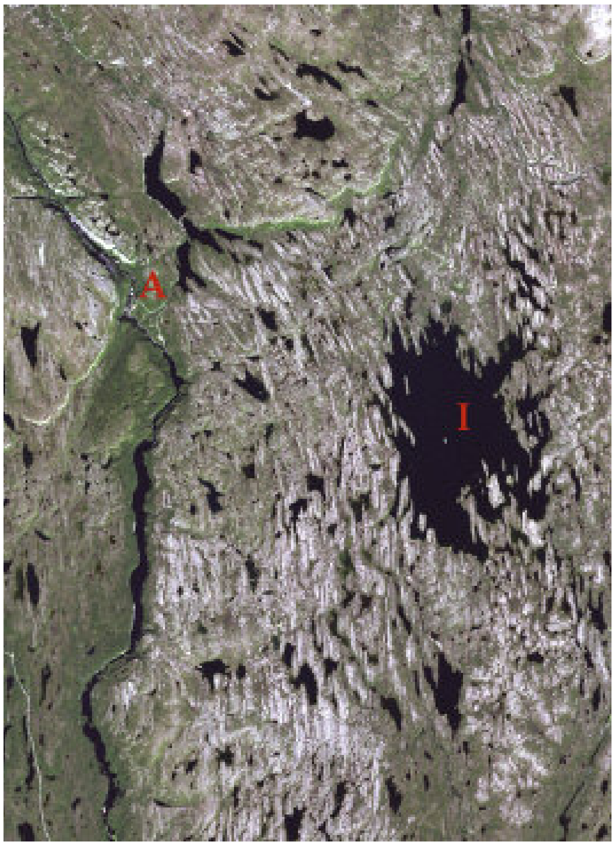
Man sitting beside a large block of rhomb porphyry found near Hamburg in Germany. The block was transported by the Scandinavian Ice Sheet from the Oslo area during the penultimate (Saalian) glaciation. (Photo: J. Ehlers)

A view looking east from Eriksbueggi, showing the flat relief across the Hardangervidda mountain plateau. The relief represents part of the palaeic surface, formed initially as a lowland plain close to sea level. During glaciations the continental ice sheet was periodically frozen solid to the substrate. As a result, these high-altitude plateaus have been subject to only limited glacial erosion, even though the depressions now occupied by lakes were excavated by glaciers. Note the boulder-rich till in the foreground.



Map showing minimum extent of the area where the ice sheet was frozen to bedrock during the last glacial maximum (red line), and during its retreat (orange). The blue line denotes maximum distribution of the ice sheet during the last glaciation, and the arrows indicate the direction of glacier movement. (Modified after J. Kleman et al.)

Glaciers of this type are called "cold-based glaciers" and the ice-flow consists only of internal deformation of the ice. In central Scandinavia, we find deposits that give no indication that glacial erosion took place for example during the Last Glacial Maximum. Here, as the ice sheet grew, the deepest parts of the glacier became frozen to the ground, with the result that landscape features formed prior to the glaciation in question were preserved. Locally the ice sheet was probably cold-based at high altitudes adjacent to fjords, while at the same time the glacier sole was at the pressure melting point within adjacent valleys and the fjords themselves. This resulted in extensive erosion along the base of the fjords, while ancient landscape features, including block fields, were preserved at higher altitudes.



Landsat satellite image showing drumlins and flutings on the Finnmarksvidda mountain plateau. The great lake (I) is Iesjavri, with the Altadalen valley and the Alta hydroelectric dam (A) on the left. Note how the ice sheet has moved northwards and then veered towards the west in the direction of Altafjord (upper left). These landforms were formed at the end of the last glaciation. (From B. Johansen)

GLACIERS AND ICE SHEETS

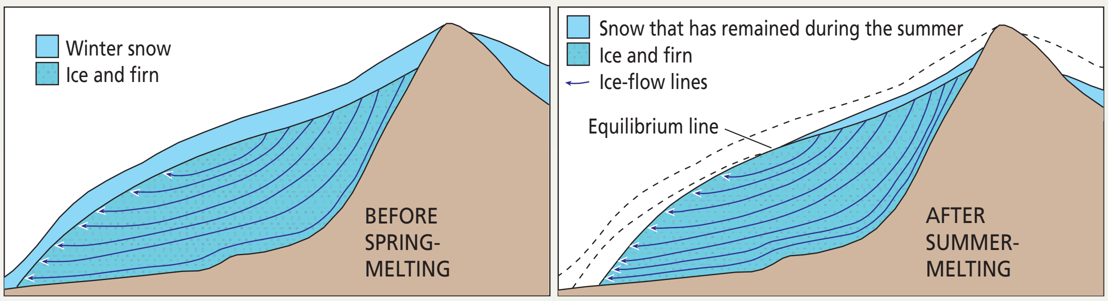
Landscape development during the Quaternary is greatly influenced by glacial activity. Glaciers are most commonly classified according to their size and morphology. The most common types are 1) *continental ice sheets*, such as the Greenland Ice Sheet, 2) *marine ice sheets*, which are of similar magnitude to continental ice sheets, but which extend across continental shelves – the Barents Sea Ice Sheet is a good example, 3) *plateau glaciers or ice caps,* such as the modern Jostedalsbreen glacier, and 4) *valley and cirque glaciers,* such as we find today in the Jotunheimen mountains, the Sunnmøre region and the Lyngen Alps. An *ice-shelf* (5) is a floating glacier – the present-day Ross Ice Shelf in the Antarctic is a good example.

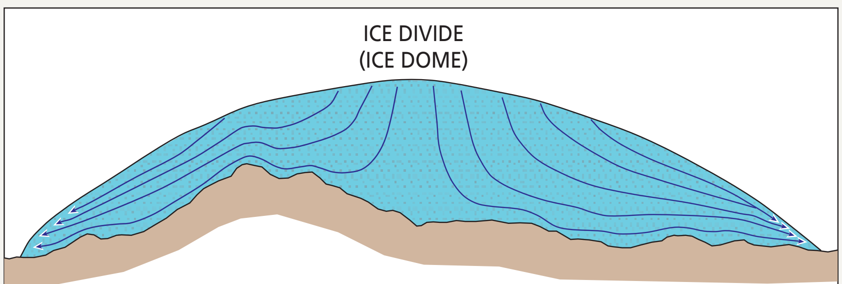
Glaciers may also be classified according to the temperature conditions within the ice mass itself. In *polar glaciers* the temperature is below the pressure melting point throughout. These ice masses are thus frozen to underlying bedrock, and are often termed *cold-based glaciers.* In a *temperate glacier*, the ice mass is at the pressure melting point, and these are termed *warm-based glaciers*. This difference is important because cold-based glaciers erode to a much lesser degree. A s*ub-polar glacier* contains zones both above and below the pressure melting point.

The behaviour of a glacier is critically controlled by its *mass balance* as determined by the relationship between the supply (*accumulation*), and loss *(ablation*), of snow and ice. In Norwegian latitudes, accumulation occurs during the winter, but in the Antarctic it may snow throughout the year. Ablation occurs by melting during the summer and by calving at localities where the glacier terminates in water. When accumulation and ablation are approximately equal, the glacier is said to be in equilibrium. If accumulation exceeds ablation the glacier will expand and advance, but it will retreat if ablation exceeds accumulation. In the case of small glaciers, the response at the ice-front to a change in the mass balance will be noticed abruptly, perhaps within 3-5 years. However, for larger glaciers it may take several decades before the glacier snout responds to increased accumulation.

The ice flow is generally at right angles to the contours on the surface of the ice. It is thus possible for ice at the base of a glacier to move uphill. Snow falling on the surface of a glacier is buried and gradually transformed into ice which then moves downwards and outwards to the glacier margin. In valley and cirque glaciers the ice flow is different above and below the equilibrium line; above, ice along the margin flows towards the main trunk of the glacier, whereas below the equilibrium line ice moves outwards towards the glacier margin. Thus lateral moraines are formed only below the equilibrium line.

In recent years it has been demonstrated that continental ice sheets contain "rivers" of ice, or *ice streams*, which flow much faster than the surrounding ice masses.

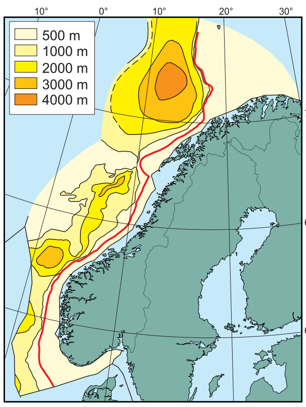




Section through a continental ice sheet showing ice flow-lines

The continental margin expands and takes shape

Most of the products of glacial erosion on the Norwegian mainland were eventually deposited on the continental slope, where today we encounter glaciogenic sediments up to between 3 and 4 km thick.



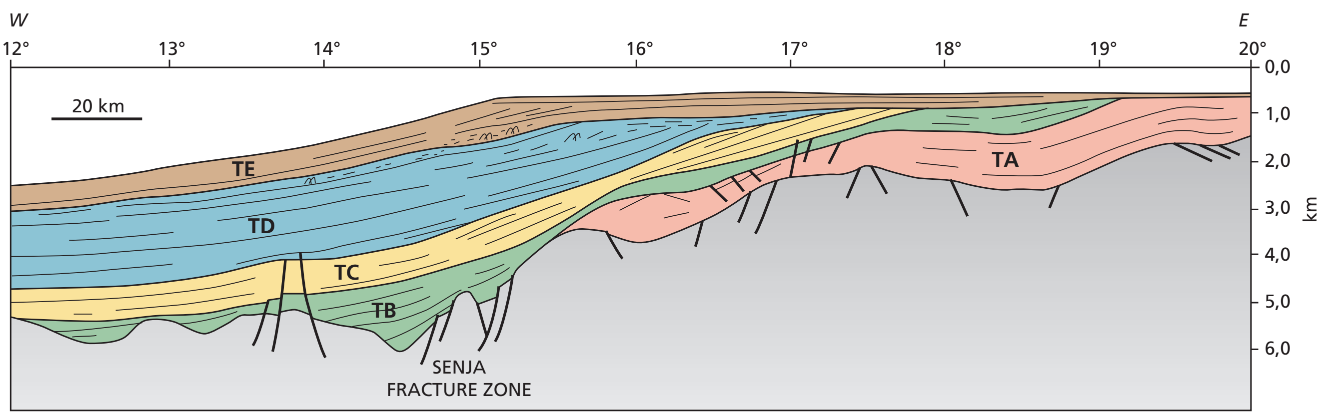
Map showing thickness of the late Pliocene and Pleistocene sediments along the Norwegian continental margin. East of the red line there has been significant erosion, and there the Pleistocene sediments rarely exceed 300 m in thickness (Modified from F. Riis)

The entire outer continental margin from the North Sea to Spitsbergen has been built out by glaciogenic sediments, much of which were transported across the shelves by meltwater rivers and deposited along the continental slope during minor glaciations between 2.6 and 0.9 million years ago. However, there is evidence to suggest that even during these early periods, the glaciers themselves periodically advanced out onto the shelves. The discovery of 1.1 million year-old tills in the North Sea is evidence of ice advance in this area, and rock fragments from Scandinavia found in even older sequences in the Netherlands were almost certainly transported much of the way by glaciers.

The wedge of sediments encountered on the shelf seaward of Nordland County exhibits features suggesting that the ice sheet had advanced onto the continental shelf during its deposition. It is also possible that glaciers reached the Barents Sea shelf break during the early Pleistocene, and perhaps even earlier offshore Spitsbergen. Recent research indicates that the first major ice-caps developed in the north. However, it was only during the major glaciations that we find clear evidence for marked glacial erosion and the universal deposition of till on the continental shelf.

In general terms, the glaciations taken together represented a period of continual erosion of the Norwegian mainland and inner continental shelves, including the Barents Sea and Svalbard. Geologists estimate that the combined late Pliocene and Pleistocene erosion amounted to almost 1,000 m in the southern Barents Sea, and up to 3,000 m in Svalbard. Prior to the glaciers entirely occupying the Barents Sea basin, rivers and glacial meltwater streams were the most important agents of erosion. The remains of this landscape can be seen on the sea floor today, and were first discovered during bathymetric surveys by the Norwegian polar explorer, Fridtjof Nansen.

Erosion redistributed the load exerted on the crust, resulting in uplift of the Norwegian mainland and inner shelves while at the same time the distal parts of the continental margins subsided under the new load of sediments. This has had important implications for oil exploration in the Barents Sea, in that while many wells have encountered residual oil, most of the liquid hydrocarbons have leaked away. This is explained by the fact that erosion caused the release of pressure in the original oil reservoirs, with the result that gas expanded and forced the oil out.



Geoseismic profile through the Bjørnøya Trough Mouth Fan along latitude 72° 30′ N . Sequences marked TC, TD and TE were deposited during Quaternary glaciations. Sequences TA and TB were deposited during the Palaeogene. The maximum total thickness is over 3,000 m.

Shelf troughs and fishing banks – sculpted by the ice

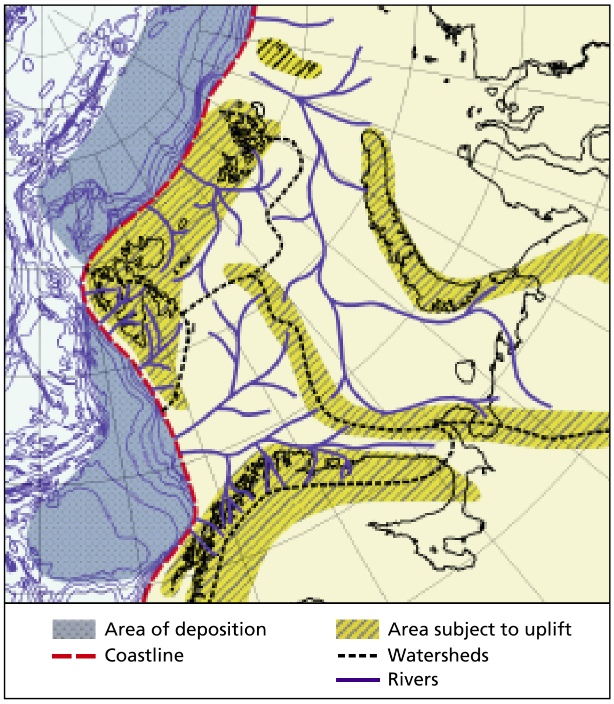
The clearest evidence of the glacial action on the continental shelf is provided by the great longitudinal and transverse troughs and channels that resemble glacial valleys. Longitudinal channels run parallel to the coast and are often located at the boundary between hard crystalline basement rocks on the landward side and less resistant sedimentary rocks on the seaward flank. The most spectacular is the Norwegian Channel, which can be traced from Oslofjorden, around the entire southern Norwegian coast, and northwards offshore western Norway. It is more than 700 m deep at its deepest point in the south, shallows to only 220 m in its middle section, before once again becoming deeper at its mouth.

Transverse channels and troughs are normally deepest (about 400-500 m) close to the coast, and commonly form the seaward extensions of fjords. They were formed by fast-flowing ice streams that extended from the coastal fjord glaciers and out onto the shelf. Where the continental shelf is narrow, these troughs are rarely more than 20 km across, although they are somewhat wider on broader shelf areas. The Bjørnøya Trough is 170 km wide and 600 km long. These troughs and channels became conduits into which ice streams from within the continental ice sheets drained towards the shelf break. The largest ice streams were located in the Bjørnøya Trough, the Trænadjupet Trough seaward of Vestfjorden, and the Norwegian Channel.

Glaciogenic deposits on the continental shelf

The uppermost sedimentary units on the continental shelf comprise a sequence of unsorted sediments, a so-called *diamicton*. In the inner shelf areas this sequence varies in thickness between 0 and 300 m, while adjacent to the shelf break it may exhibit spectacular thickness increases. In the past, the origin of the diamicton has been disputed, but it is now clear that it comprises a diversity of till deposits and glaciomarine sediments. Detailed bathymetric mapping of the continental shelf has revealed drumlins and other ridge-like features that were formed parallel to the direction of ice movement.

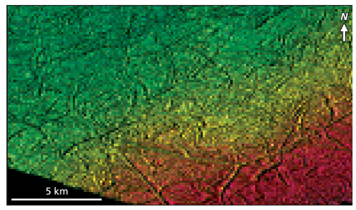
The ice sheet deposited terminal moraines at many locations as it advanced across the shelf. The largest is the Skjoldryggen Ridge, located close to the shelf break offshore Nordland County. It is between 100 and 150 m high. On the Tromsøflaket and Fugløybanken fishing banks we find moraine ridges up to 40 m high and several kilometres across.



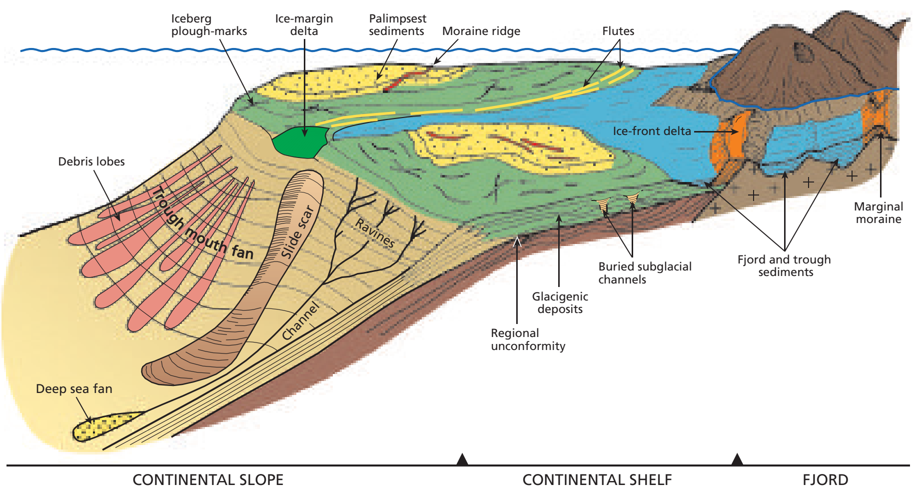
Reconstruction of a possible fluvial drainage system in the Barents Sea based on the surface relief revealed below the glacial deposits. This system was formed by rivers (including glaciofluvial rivers) prior to the major glaciations. (Modified from Vorren et al)

Moraine ridges encountered offshore Sogn, Møre and Trøndelag are up to 60 m high and 10-15 km across. When the ice retreated from the shelf by calving, the troughs and channels in particular became the recipients of sediments transported seaward by meltwater rivers and icebergs. However, the icebergs also contributed by disturbing older shelf deposits, and plough-marks formed by icebergs are common, especially in water depths of between 120 and 400 m. They are formed by the iceberg's keel as it drags along the sea floor, driven by currents and the wind. Some of these icebergs were giants. The deepest plough-marks are 25 m deep, 2,100 m across, and several kilometres long. Deposits generated by such massive disturbance are termed "iceberg turbate". The irregular sea-floor relief produced by the action of icebergs at the end of the last glaciation has provided interesting challenges for today's engineers in the planning and laying of pipelines.

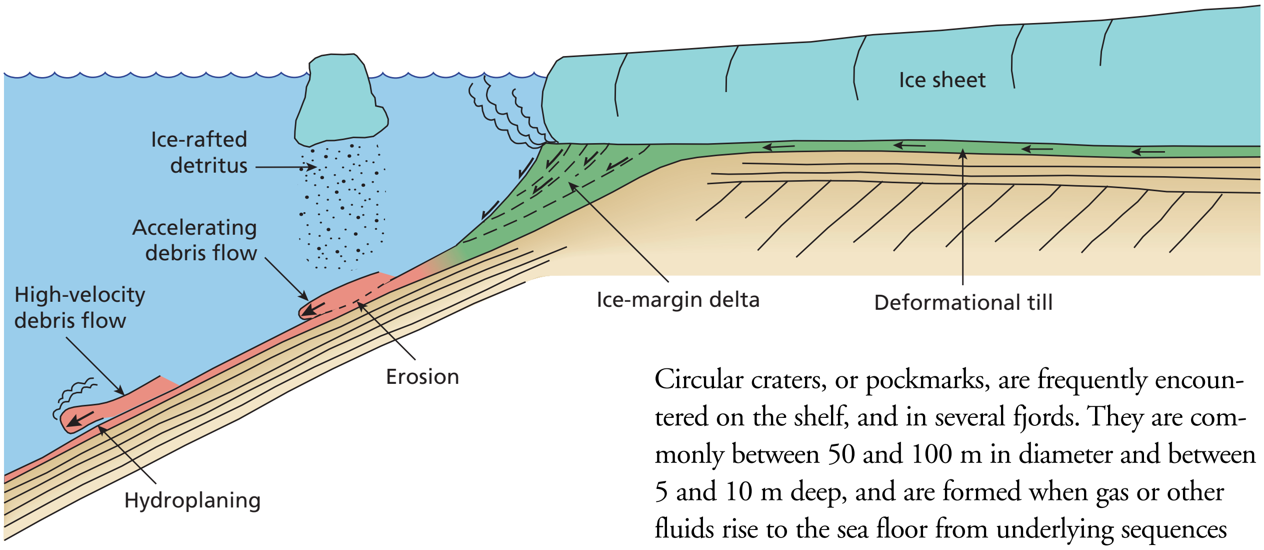
BELOW: A 3D-seismic image of closely-spaced iceberg plough-marks in the Barents Sea at about 72° 30′ N and 23° 27′ E. Plough-marks are between 30-500 m across, 1-20 km in length and 2.5-25 m deep. (After B. Rafaelsen et al.)



Block diagram illustrating the most important morphological and sedimentary features on the Norwegian continental shelf. Present-day sea level is denoted by the wavy blue line drawn around the mountains, and above the continental shelf. Palimpsest sediments are composed of a mixture of glacial deposits and Holocene calcareous deposits containing shells and foraminifera. (Modified from Vorren)

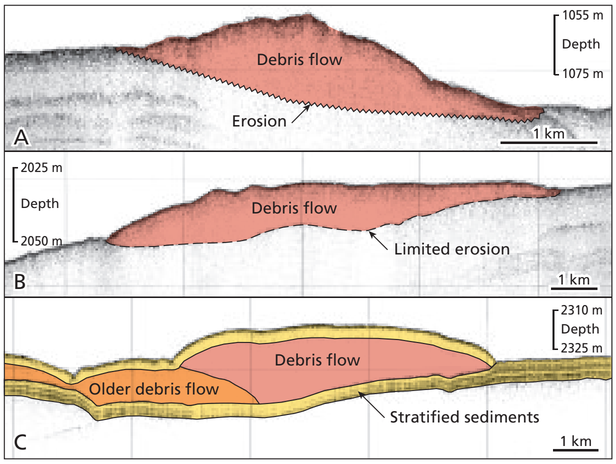


Schematic illustration of depositional progradation and other processes at the continental shelf break. The ice sheet transports material at its base to the shelf break as deformational till. Here it is deposited as a moraine delta. Sediments are thence transported downslope as debris flows. Material is also dropped from icebergs calved from the ice sheet as it melts.



Circular craters, or pockmarks, are frequently encountered on the shelf, and in several fjords. They are commonly between 50 and 100 m in diameter and between 5 and 10 m deep, and are formed when gas or other fluids rise to the sea floor from underlying sequences and erode surrounding sediments as they are released.

Seismic cross-sections of debris flows on the Bjørnøya Fan. A. On the upper part of the fan the debris flow has eroded its base. B. Further downslope there is less erosion. C. In the lowermost figure taken from more than 2,300 m water depth, the finely-bedded sediments beneath the debris flows have not been affected. The debris flow has simply flowed over these sediments on a film of water. (Modified from J.S. Laberg and T. Vorren)



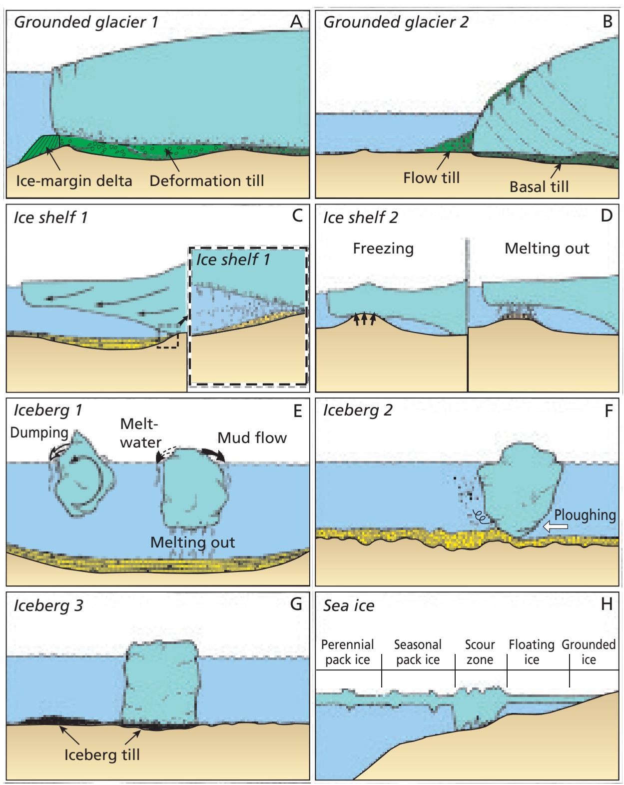
Gigantic trough mouth fans

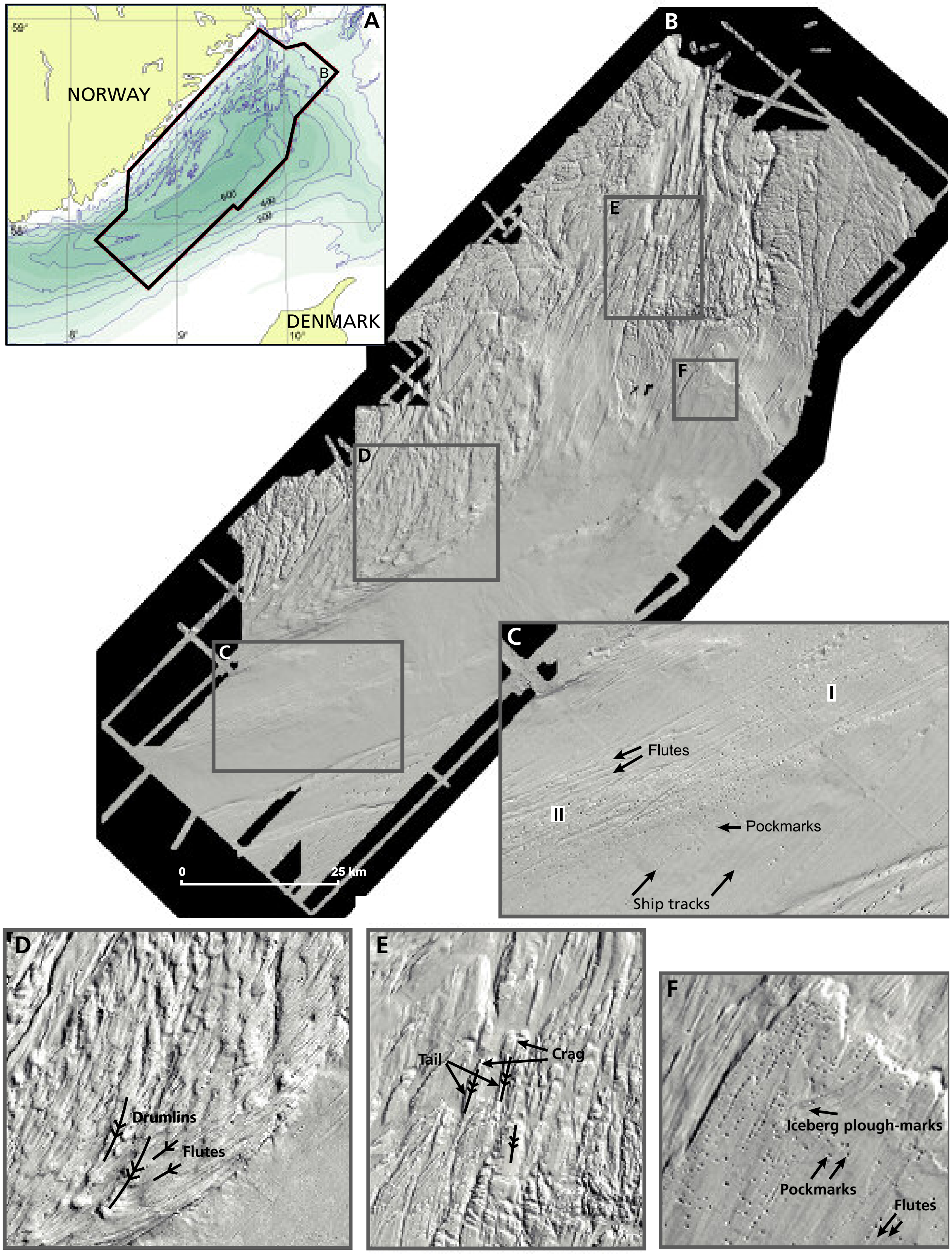
By far the largest glacial sedimentary deposits in Norwegian territory are the gigantic sediment fans encountered at the mouths of major troughs and channels on the continental shelf. These are called *trough mouth fans*, and represent enormous accumulations of sediment eroded from mainland Norway. From south to north, the largest are: the North Sea Fan, the Bjørnøya Fan and the Storfjorden Fan. The Bjørnøya Fan is largest and extends over 215,000 km², equivalent to two-thirds of the area of mainland Norway. The largest fans exhibit the gentlest slopes, and both the Bjørnøya and North Sea Fans are inclined by less than 1 degree, whereas much smaller fans offshore Svalbard exhibit gradients from 2 to over 3 degrees.

Most of the sediments in these fans accumulated during the Late Pliocene and Quaternary. When the ice sheet advanced to the shelf break, glaciogenic material was transported beneath the ice streams as "deformation till". The ice streams acted as conveyor belts transporting material as far as the point (the grounding line) where the ice sheet no longer rested on the sea floor, but floated in the sea. Some material was transported directly down the continental slope, but often it was first deposited as an ice margin delta at the shelf break, extending along the upper part of the continental slope. Accumulations of this type were unstable and subject to periodic mass movements.

The younger parts of the trough mouth fans are formed mainly of debris flows derived from these mass movements, and are composed of unsorted till material mixed with glaciomarine sediments accumulated on the way. Debris flows could travel distances up to 200 km downslope into the deep ocean basins.

Schematic diagrams illustrating the various modes of formation of the unsorted, so-called diamicton, on continental shelves. (Modified from Vorren et al).



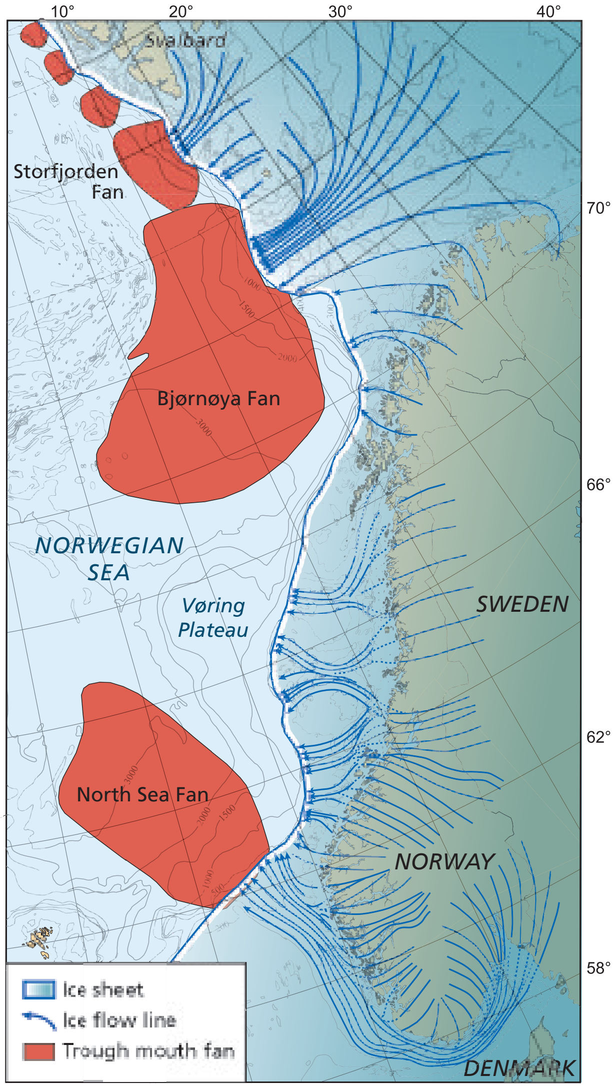


Multi-beam echo sounder data from the Norwegian Trench showing several types of parallel ridges that reflect the direction of glacier movement. We can also see plough-marks formed by a grounded iceberg moving along the seabed (F), and a number of circular pockmarks (C and F) formed by fluids seeping from the subsurface. (Modified from O. Longva and T. Thorsnes)

Each debris flow deposit is between 500 m and 40 km across, and between 5 and 60 m thick. The largest fans possess the most extensive debris flows.

It is difficult to comprehend how a debris flow can travel as far as 200 km along such a gently inclined slope. By utilising high-resolution seismic data we note that on the upper parts of the continental slope the debris flows have eroded into the surface of the fans. However, on the lower slopes they have apparently flowed without eroding the surface. This is explained by the fact that they are lifted above the seabed and glide on a film of water in a process similar to the hydroplaning of a car. Friction is dramati-

Map showing the maximum western extent of the Scandinavian and Barents ice sheets during the last glaciation. The ice-flow pattern (arrows) has been reconstructed by analysing directional indicators on the seabed which were formed during the last glaciation. It is likely that this pattern was similar during older, major glaciations. Seaward of the ice streams, trough mouth fans have accumulated during several glaciations. (Modified from Vorren)



cally reduced, allowing the debris flows to travel enormous distances along gently inclined slopes.

Trough mouth fans as glacial archives

Debris flows provide evidence that the continental ice sheets advanced to the shelf break. During the interglacials, as today, sediment supply to the shelf break is restricted, and only a thin apron of coarse sediments accumulates along the upper continental slope, while silts and clays are deposited further downslope. On seismic profiles we see a clear division between debris flows originating from successive glaciations. Geologists have identified five such sequences on the North Sea Fan, indicating that the glacier reached the shelf break at this location a total of five times. Eight such sequences have been identified on the Bjørnøya Fan, and seven on the Storfjorden Fan. This may indicate that a greater number of large glaciations are represented in the north than the south, but it may simply indicate that there were more climatic fluctuations during the same number of glacial periods in the north. It is also possible that existing seismic data does not have sufficient resolution to provide the answer to this question.

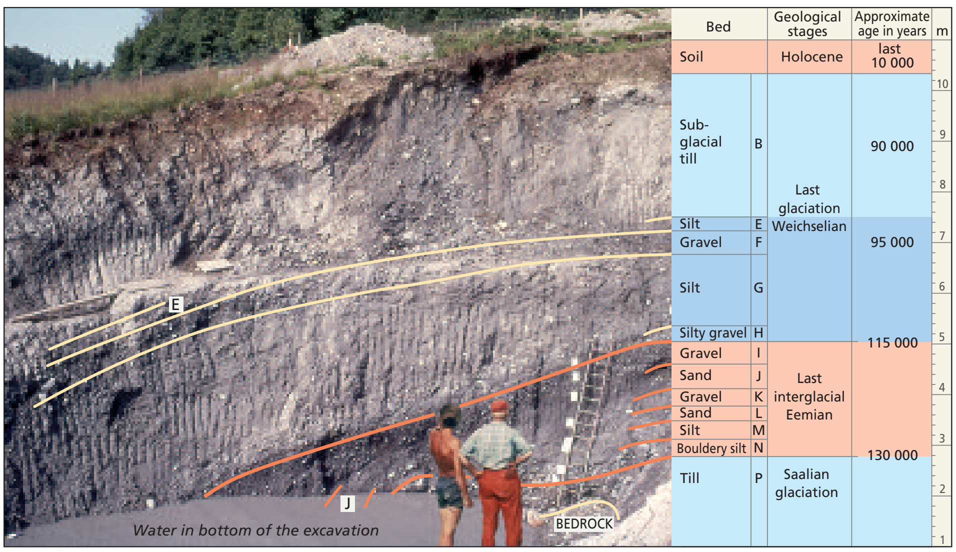

Example of a glacier and glacifluvial delta from one of Spitsbergen's fjords. (Photo: A. Nøttvedt)

Interglacials revealed on land

Until 1970, no undisturbed interglacial deposits had been identified on the Norwegian mainland, and it was thought that the ice sheets had either removed them or disturbed them to such an extent as to make them unrecognisable.

There was thus quite a sensation among geologists when, in 1968, deposits from the last interglacial were discovered at Fjøsanger, near Bergen. Glacial erosion in Norway has been most intense in the western fjords, and this discovery was made along the foreshore of a deep fjord called Nordåsvatnet. We can only suppose that it is by pure coincidence that these sediments are preserved, since there is nothing at Fjøsanger that is not typical of numerous other similar locations in western Norway.

As so often is the case in the history of science, the Fjøsanger discovery was made while geologists were looking for something completely different. At the end of the 1960s the shell-bearing tills of Hordaland County were surveyed. Radiocarbon dating indicated that the shell fragments were between 11,500 and 14,500 calendar years old, and thus from the close of the last glaciation. At Fjøsanger, a small clump of organic mud was discovered in an otherwise typical shell-bearing till. The mud contained pollen of oak, hazel, holly and spruce trees, indicating the existence of a forest that thrived in a much warmer climate than at the present day, thus providing evidence of a warm interglacial. Radiocarbon dating of the shells in the till at Fjøsanger revealed an age greater than 50,000 years. A borehole later confirmed that sediments from the Eemian interglacial were probably present beneath the till, so a massive excavation was conducted in 1975-76.



View of the excavations at Fjøsanger, looking south. The quarry is filled with water, but bedrock can be seen in the lower right-hand corner of the photograph. In contrast to the overlying greyish, glacial deposits, interglacial sediments are browner in colour due to their organic content. The boundaries between the beds are indicated on the right of the picture and for some beds through the entire photo. However, sequences are not displayed to their best advantage because the excavation wall is curved. The vertical striations in the wall have been made by the excavator. The scale on the right shows the elevation in metres above sea level. (Modified from Mangerud et al)

Digging in sediments and time

The excavation was 10 m deep and penetrated to the bedrock. The bedrock is overlain by till which was deposited during the earlier Saalian glaciation, since this is in turn overlain by Eemian deposits. Fossils in the lowermost Eemian interglacial sequence are similar to those from the end of the last glacial period, and the sediments are deep-water silts, reflecting glacio-isostatic depression from the Saalian glaciation. Within the silt we find Icelandic scallops (*Chlamys islandica*), thick piddock shells (*Hiatella arctica*) and other species that today are encountered only between Lofoten and Svalbard, demonstrating that the seawater was much cooler than it is today. However, Icelandic cyprine mussels (*Arctica islandica*), common periwinkles (*Littorina littorea*) and horse mussels (*Modiola modiolus*) soon invaded the region, indicating that the water was becoming warmer due to the appearance of the Gulf Stream along the western Norwegian coast. Pollen blown from the mainland is dominated by meadow grasses and plants that tolerate cool climates and which require abundant light, indicating that this interval preceded the arrival of the trees. In fact, birch was the first to appear, closely followed by pine. Thereafter, most of the herbaceous plants were outcompeted by dense forest vegetation.

Temperatures similar to southern Denmark today

Oak was the first thermophilic (warm-loving) tree species to make its appearance in Fjøsanger, as it did

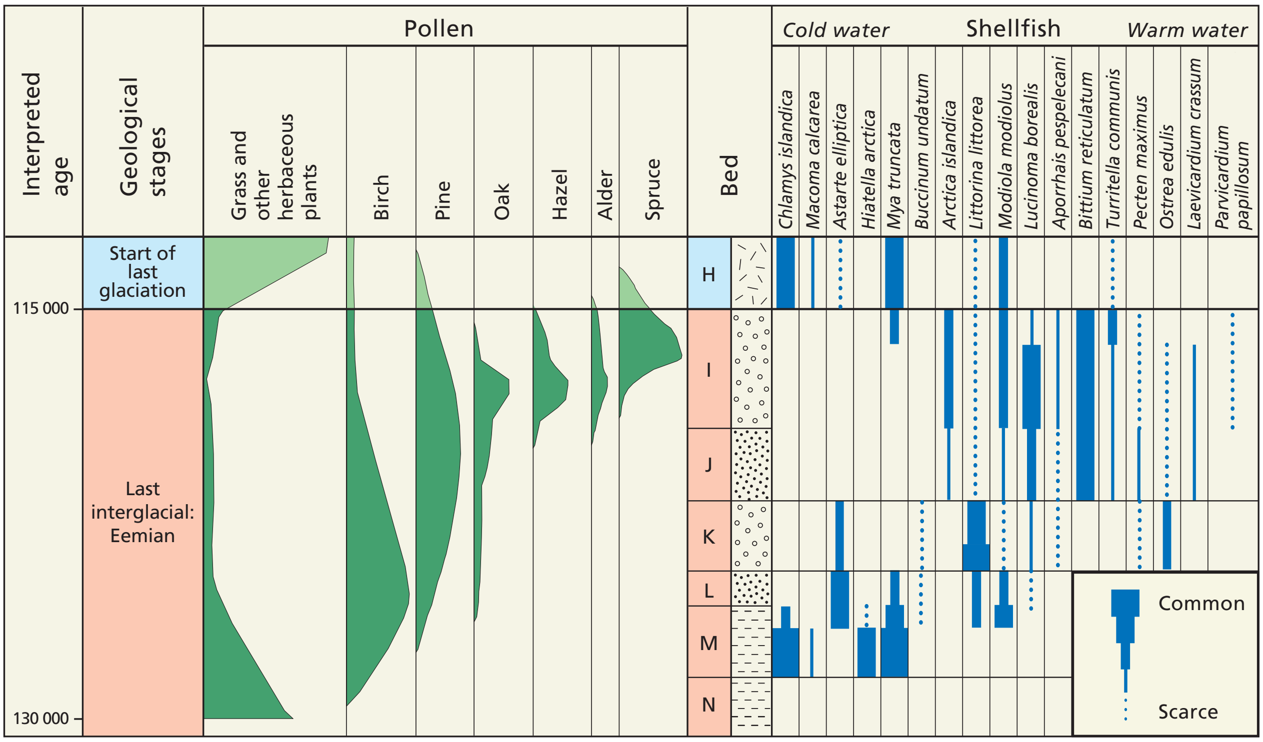


Diagram showing selected fossils from the interglacial sequences at Fjøsanger. In the central column the beds are assigned identical upper case characters as in the photograph on the previous page. Note, however, that only the Eemian and the earliest Weichselian units are included here. In the simplified pollen diagram, tree species are arranged in the order in which they made their appearance. Species curves reflect the relative amounts of pollen present. Shellfish and other gastropod species that today inhabit the coolest waters, e.g. Svalbard, are displayed on the left, while those that live in warmer waters, e.g. Denmark, are shown on the right. Note that initially, cooler conditions prevailed both on land and in the sea (beds N and M). The warmest conditions occurred during deposition of the lowermost part of bed I, but gradually became cooler again during the deposition of the rest of bed I and very cold during the deposition of bed H. (Modified from Mangerud et al.)

across Europe from its "over-wintering" habitats in the Mediterranean. This is in contrast to the Holocene when both hazel and black alder arrived in Norway ahead of oak. During the warmest part of the Eemian there was a rich, mixed oak forest around Fjøsanger-Bergen, dominated by oak, hazel and black alder, and a high proportion of holly. At that time, the forests resembled those of southern Denmark today. The sea was correspondingly warm, and was inhabited by warm-water scallops and oysters, and even a species of shellfish (*Parvicardium papilosum*) which today is not found north of the English Channel.

Spruce appears in the upper Eemian sequences. Spruce has not reached this part of western Norway following the last glaciation. However, it did so during the Eemian to the extent that it became the dominant forest species. Compared with more thermophilic species, spruce was favoured because the climate towards the end of the interglacial became cooler, although other factors may have played a role. However, both the shellfish and, in particular, the foraminifera, indicate that also the sea temperatures fell during the final stages of the Eemian.

Are the Fjøsanger deposits really from the last interglacial?
Until recently no physical dating method existed for deposits of this age and type. However, the similarity between the pollen diagram from Fjøsanger and those from the Eemian in Denmark and Germany provides important evidence; the early appearance of oak, the abrupt rise of the pollen curve for each tree species, and the late peak of spruce. The appearance of tower shells (*Bittium reticulatum)* also indicates an Eemian age because these are not found in sediments from older European interglacials. In addition, recently-developed thermoluminescence dating methods have confirmed that these deposits are of Eemian age.

A further interesting aspect of the Fjøsanger deposits is that they demonstrate that the locality has been uplifted by at least 15 m since the Eemian interglacial because the marine deposits from the close of the interglacial occur up to these elevations. At this time glacio-isostatic uplift following the Saalian glaciation probably had been completed, in much the same way as uplift following the Weichselian glaciation has been completed in this area today. The aforementioned 15 m must thus be a component of a tectonic uplift and/or an isostatic response compensating for the erosion of bedrock during the last glaciation.

Further Eemian discoveries

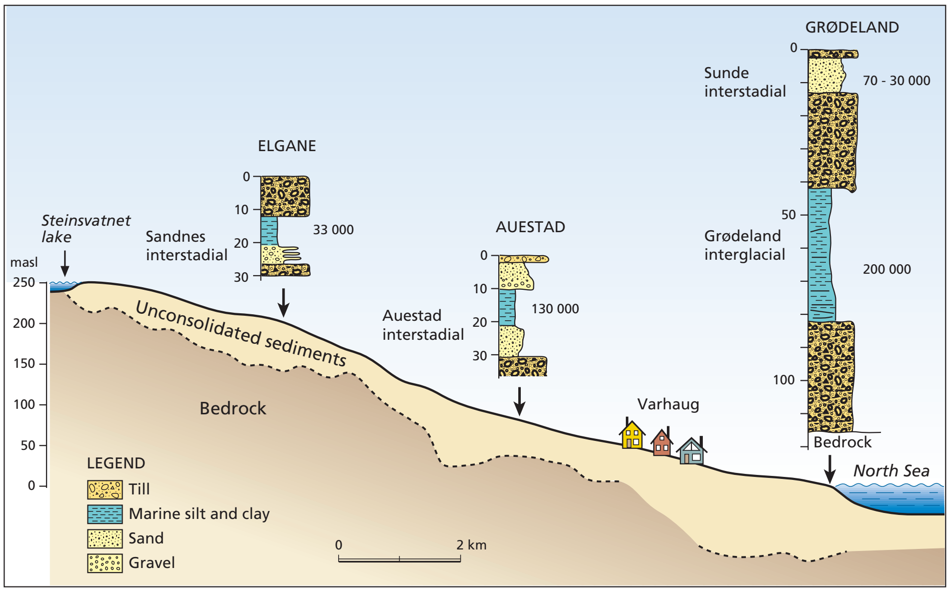
Eemian deposits are also found at the base of an old clay quarry at Bø on the island of Karmøy in Rogaland. Pollen, shellfish and foraminifera closely resemble those at Fjøsanger. At Skarsvågen on the island of Frøya in Nord-Trøndelag, a shell-bearing mound was discovered, dating from the beginning of the last interglacial. It is overlain by an organic-rich, pollen-bearing horizon indicating that thermophilic trees such as oak and holly were common at higher latitudes than they are today. Spruce also appeared on Frøya. A 2 cm-thick, hard and compact peat horizon was found at a location at Vossestrand in Hordaland. The peat was originally perhaps 30 cm thick, and contains pollen indicating the existence of dense, spruce-dominated forests. It appears that the end of the last interglacial evolved over all of southern Norway as the "age of the spruce". This is unlike the situation today where natural spruce forests are found only in eastern Norway and Trøndelag. Other Eemian finds, or discoveries of re-deposited pollen of Eemian age, have been made at Kroken in Sogn, Førresbotn on the Haugesund peninsula in Rogaland, and at Hovden on Hardangervidda.

Older interglacials on Jæren and Finnmarksvidda

The Jæren region of south-western Norway, with its sandy beaches, wind-blown dunes and thick Quaternary deposits, can be described as a small piece of Denmark that somehow got attached to Norway. A borehole at Grødeland penetrated fully 126 m of till, clay and sand before it encountered bedrock. The most interesting discovery here is that between 42 and 82 m depth, alternating units of foraminifera-rich sand and silt of marine origin were encountered. Amino-acid dating indicates that this sequence is about 200,000 years old and thus much older than the Eemian interglacial. The lowermost metres contain foraminifera which today live in the Arctic, while the sediments themselves indicate that they were deposited close to an ice-front at the end of a glaciation. Higher in the sequence warmer water species appear, and the fauna resembles that which we find off the coast of western Norway today. This is evidence of an interglacial with temperatures similar to the present day, which has been named the Grødeland interglacial. It probably represents the penultimate Norwegian interglacial. Even higher in the sequences the distribution of foraminifera provides evidence of the return of colder waters, and the advent of renewed glaciation.

The northern Norwegian mountain plateau, Finnmarksvidda, is characterised by thick till deposits. Recent research has demonstrated the presence at several locations of sediments older than those from the last glaciation. Here, interglacials are represented by lacustrine sediments or, more commonly, by zones of brown soils sandwiched between till deposits. Soils dated with various luminescence methods, and belonging to the Eemian interglacial, are preserved at Vuolgamasjohka, Vuoddasjavri and Sargejohka. At Sargejohka we also find evidence of an older interglacial which has been dated to about 260,000 years, from which pollen analyses indicate the existence of birch forests mixed with pine, not unlike conditions encountered in the area today.

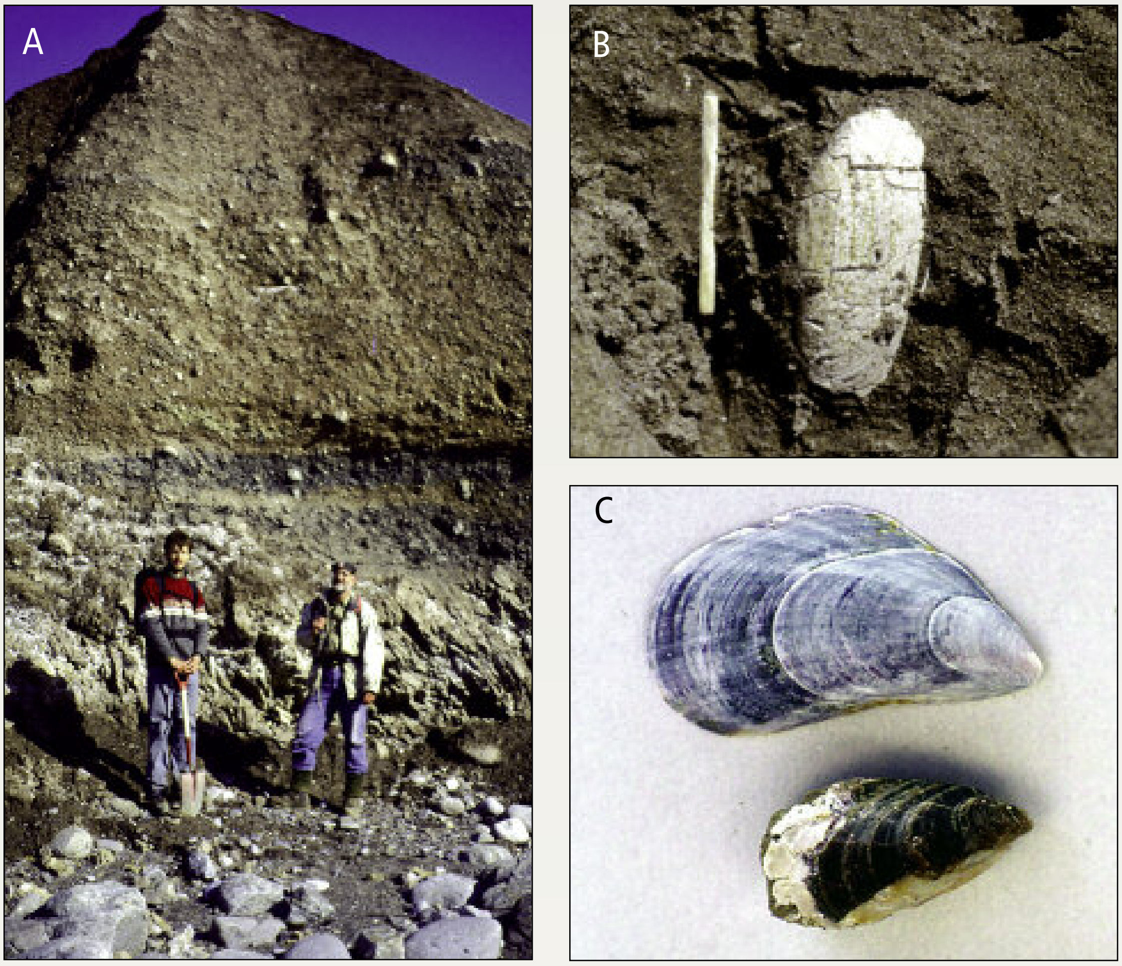
Schematic cross-section through Jæren at Varhaug in south-western Norway, with the North Sea on the right, and the Høgjæren hills on the left. The dashed line represents the boundary between unconsolidated sediments and bedrock as revealed by seismic data. Sequences encountered in drill holes at closely neighbouring localities are projected onto the profile. Marine sediments of various ages are encountered between the moraine sequences, and the names and interpreted ages of these are displayed. (Modified from H.P. Sejrup et al.)



Excavation at Sargejohka on the Finnmarksvidda mountain plateau. The brown-coloured sequences at about 10 m depth contain organic-rich lacustrine sediments from the so-called Bavtajohka interglacial, which is dated to about 260,000 years using luminescence methods. (Photo: L. Olsen)

OLD INTERGLACIAL DEPOSITS IN SVALBARD

The landscape of Svalbard is, as on mainland Norway, strongly influenced by glacial erosion. By calculating the volume of sediments deposited on the continental slope, it is found that bedrock equivalent to a layer up to 3,000 m thick has been eroded during the glaciations. The fjords of Svalbard are the most striking result of glacial erosion. It was therefore surprising when amino-acid datings of shells indicated that marine sands overlain by a till along the southern shore of Kongsfjorden are as old as one million years. This discovery demonstrated that no major glacial erosion or uplift had occurred at this locality during the last million years, and also that the bedrock strandflat here is old, since it was overlain by sediments of this age.



A) Exposure at Kongsfjordhallet. Above the figures there is a blue-grey till. The brown-coloured unit above it (approx. 1 m above their heads) is the so-called Cyrtodaria*-horizon, which is about 1 million years old. B) A* Cyrtodaria angusta *fossil from this horizon with a match for scale. (Photos A and B: S. Funder) C) Two fossil mussels (*Mytilus edulis*) from Kapp Ekholm; the upper specimen is 10,000 years old and the lower 125,000 years old.*

These datings have since been confirmed by further discoveries at Kongsfjordhallet, along the fjord's northern shoreline. Here, 30-40 m-high sections have revealed several horizons of marine sand and silt interbedded with till. An extinct shellfish (*Cyrtodaria angusta*) was found in the oldest marine sand units. The youngest known specimen of this species is from Tjörnes on Iceland where it is about 1 million years old, providing evidence that the Kongsfjordhallet units are also of this age. The 1 million-year age has also been confirmed by a palaeomagnetic sample indicating that the Earth's magnetic field was reversed at the time of deposition. The most recent palaeomagnetic reversal occurred about 780,000 years ago, so the Kongsfjordhallet sequences must be at least this old.

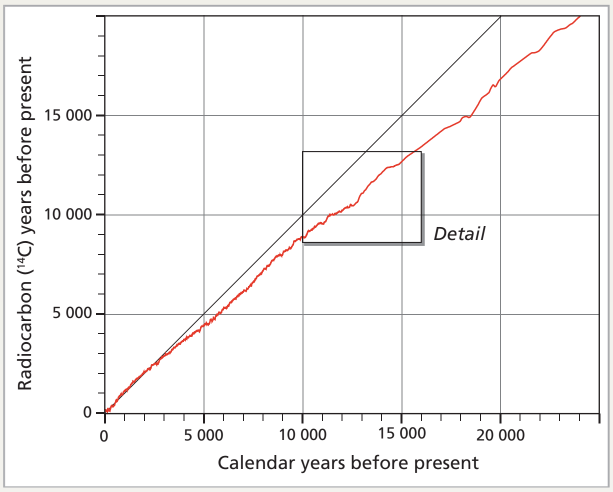
There are also several localities in Svalbard with sequences believed by geologists to have been derived from the last interglacial. Fossil blue mussels (*Mytilus edulis*) have been found at Kapp Ekholm in Billefjord. Today, the seas around Svalbard are not warm enough for mussels to survive, but they were common between about 10,700 and 4,500 years ago during a milder period in the Holocene, and during the Eemian interglacial.

RADIOCARBON YEARS ARE NOT THE SAME AS CALENDAR YEARS

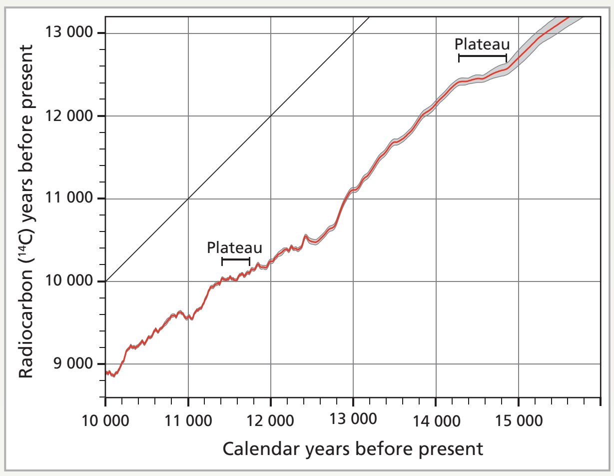
The radiocarbon (^{14}C) method has become the most widely-used method for dating material younger than 50,000 years old. It was previously taken for granted that a radiocarbon (^{14}C) year was of the same duration as a calendar year, but recent research has shown that this is not the case. Carbon is made up almost entirely of the isotope ^{12}C, together with a small proportion of the heavier ^{13}C. In addition, cosmic radiation produces a minute amount of the radioactive ^{14}C isotope in the upper atmosphere. This then forms carbon dioxide ($^{14}CO_2$), which is taken up by plants during photosynthesis in the same way as standard $^{12}CO_2$. The food chain ensures that all living organisms possess a constant ratio of the ^{14}C and ^{12}C isotopes. However, when plants and animals die they no longer take up new carbon and, since ^{14}C is radioactive, it decays at a rate reducing it to half the amount after 5,570 years (the half-life). If we measure the ^{14}C content in a wood fragment buried in a peat bog, and find that the ^{14}C content is one half of that in living plants, it must be 5,570 years old. If the content is halved again, the age must be 11,140 years.

A prerequisite for the use of radiocarbon dating is that ^{14}C concentrations in the atmosphere have been constant in the past, so that we can assume that we know how much ^{14}C there was in a sample when radioactive decay began. However, studies involving the dating of annual tree rings have shown that this is not the case. The wood does not take up new C after the annual tree ring is formed. By counting annual rings back in time and dating them with the ^{14}C method, we can determine the age for each ring, both in calendar years and ^{14}C years. In this way it is possible to compare and calibrate the two time scales. Such studies have revealed significant variation in the "duration" of ^{14}C years. There are two reasons for these variations. (1) Because the level of cosmic radiation that reaches the Earth's atmosphere varies, the production of ^{14}C varies. (2) The flux of ^{14}C from the atmosphere to the ocean is not constant. Today, scientists have discovered numerous tree stumps along the River Danube which are dendrochronologically linked together 12,000 years back in time. Their annual rings have also been radiocarbon dated. By comparing the results, so-called calibration curves have been constructed from which it is possible to determine directly the true calendar-year age from any obtained ^{14}C age (see figures). A precise calibration of any ^{14}C age can be obtained using the program found on: http://radiocarbon.pa.qub.ac.uk/calib/.

As long as it is possible to count annual rings in trees, we can regard such calibration curves as reliable, at least with errors no greater than 20 years. For age determinations older than 12,000 years (equivalent to about 10,300 ^{14}C years), i.e., older than the end of the last glacial period, the level of uncertainty is much greater. Here, calibration curves are based on counting annual sediment layers in lacustrine (varves) or marine sediments, Uranium-series dating of corals, etc. In this book all ages are given in calendar years, unless otherwise specified.



The straight line represents how the ratio between ^{14}C years and calendar years would appear if they were directly equivalent. The red line illustrates the true relationship. The differences are quite small for the last 2,000 years, even though they can diverge by as much as a couple of hundred years. In contrast, a ^{14}C age of 8,000 years is equivalent to 9,000 calendar years. Further back in time the divergence is even greater.



An enlarged segment of the curve shows that a sample with a ^{14}C age of 10,000 years lies on a plateau entailing that the sample could vary from 11,400 to 11,800 calendar years old. Similarly we can see that a ^{14}C age of 12,500 years means that the sample could be anything from 14,200 to nearly 15,000 years old. The uncertainty (± standard deviation) is illustrated by the grey shading around the curve.

KARST LANDSCAPES, LIMESTONE CAVES AND CLIMATE *By Stein-Erik Lauritzen*

Limestone and dolomite are dissolved slowly by running water and, over long periods of time, the landscape in limestone areas becomes grooved and furrowed with deep fissures, shafts, and conical depressions (dolines). Surface water finds its way into these fissures and will eventually widen them sufficiently to form caves. Streams that reach limestone areas will thus often disappear into swallow holes and emerge as springs elsewhere. The entire landscape system of surface topography, groundwater and caves is termed *karst*.

Karst is quite common throughout Norway and in Svalbard where limestones occur, and the best examples are developed in areas characterised by marbles (metamorphic limestones). This is also the case in the Oslo region, where most karst caves occur in contact metamorphic limestone. In Svalbard, karst is found in both carbonates and in gypsum sequences. The most important karst areas in Norway are found in the counties of Nordland and Troms. In Caledonian provinces, limestones have been folded and stretched to form elongated, narrow strips which can be several kilometres in length, but only a few tens of metres thick. In such areas the characteristically Norwegian *marble stripe karst* is formed. Over a distance of 500 m, marble stripe karst terrains in the Svartisen area in Nordland may contain two kilometres of cave systems down to a depth of 50 m. The most spectacular karst features in Norway are the grottos. About 1,500 limestone grottos have been identified in Norway, of which the most extensive has more than 15 km of passages. The deepest descends to 580 m with individual shafts of up to almost 130 m deep.

The limestone grottos in Norway may be up to two million years old, and the sediments within them very well preserved. Cave deposits thus provide interesting natural historical archives. When rainwater seeps through soil, it takes up acids which are capable of dissolving fractured limestone. When this water later seeps through to the cave roofs, some of the dissolved carbon dioxide is released from the water droplets and limestone is precipitated in the form of dripstones. Under cold climatic conditions, permafrost inhibits the formation of dripstones, and during glacial periods the grottos become filled with water. In both cases, dripstone growth is halted. Dripstone can thus only form under warmer climatic conditions, for example, during interglacials and interstadials.

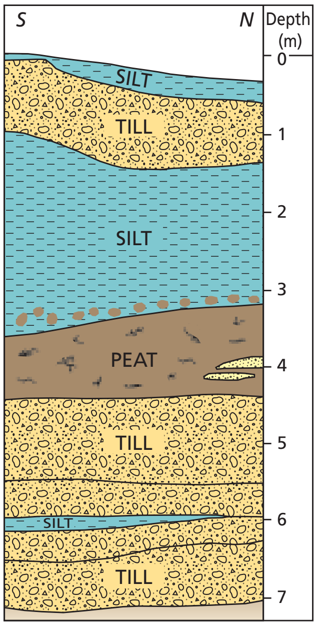
By using thorium-uranium dating methods, which are valid for ages of almost 700,000 years in the past, geologists are able to date periods of dripstone growth as determined by climate. A 420,000 year-old stalagmite from Rana in Nordland contained pollen of both birch and aspen, together with soot from a forest fire. Dripstones also contain an oxygen isotope signal transmitted via rain and snowfall, expressed in terms of the temperature-dependent ratio between the ^{18}O and ^{16}O isotopes. Furthermore, intervals during which brown-coloured bog waters entered the caves during spring floods produce annual layers in dripstones. Variations in these dripstone signals make them very accurate tools for dating climatic changes, and have been used to construct detailed climate curves for the Holocene, Eemian and older interglacials.

Marble stripe karst from Pikhaugene in Nordland.

Typical dripstone gallery from a cave in Nordland.

Mild intervals during the last glaciation

The last glacial period was not, as previously thought, simply a prolonged winter. There were several advances and retreats of the continental ice sheet.



Depositional sequence at Dalseng in Brumunddalen. The peat unit is interpreted to be of Brørup age; i.e. about 100,000 years old. This occurrence of peat of this age and thickness is unique for Norway. (Adapted from M. Helle et al.)

Several discoveries have been made that show that the ice sheet advanced and retreated many times during the last glaciation, the Weichselian. A main problem with nearly all of these finds, whether they involve thick sedimentary sequences or fossils, is the scarcity of reliable age determinations. We shall describe in more detail some of the best-dated sites.

Another visit to Fjøsanger allows us to examine the advent of the last glaciation. The pollen diagram shows that grasses and heather increase to 20 % at the boundary between beds I and H. Such high values are found only in a forest-free landscape. Apparently a deterioration of the climate occurred at the I-H boundary which effectively killed the forests. The landscape was then transformed into tundra, dominated by grasses and heather, with some juniper and occasional birch trees in sheltered locations. The fossil shell content demonstrates that this climate change is also reflected in the marine environment. All the thermophilic species died out, and cold water species returned. The fact that terrestrial flora and marine fauna altered simultaneously and so dramatically is evidence of a weakening of the Gulf Stream's influence. Geologists are not certain how rapidly this climate change occurred, but it is likely to have been within a few centuries, perhaps only decades.

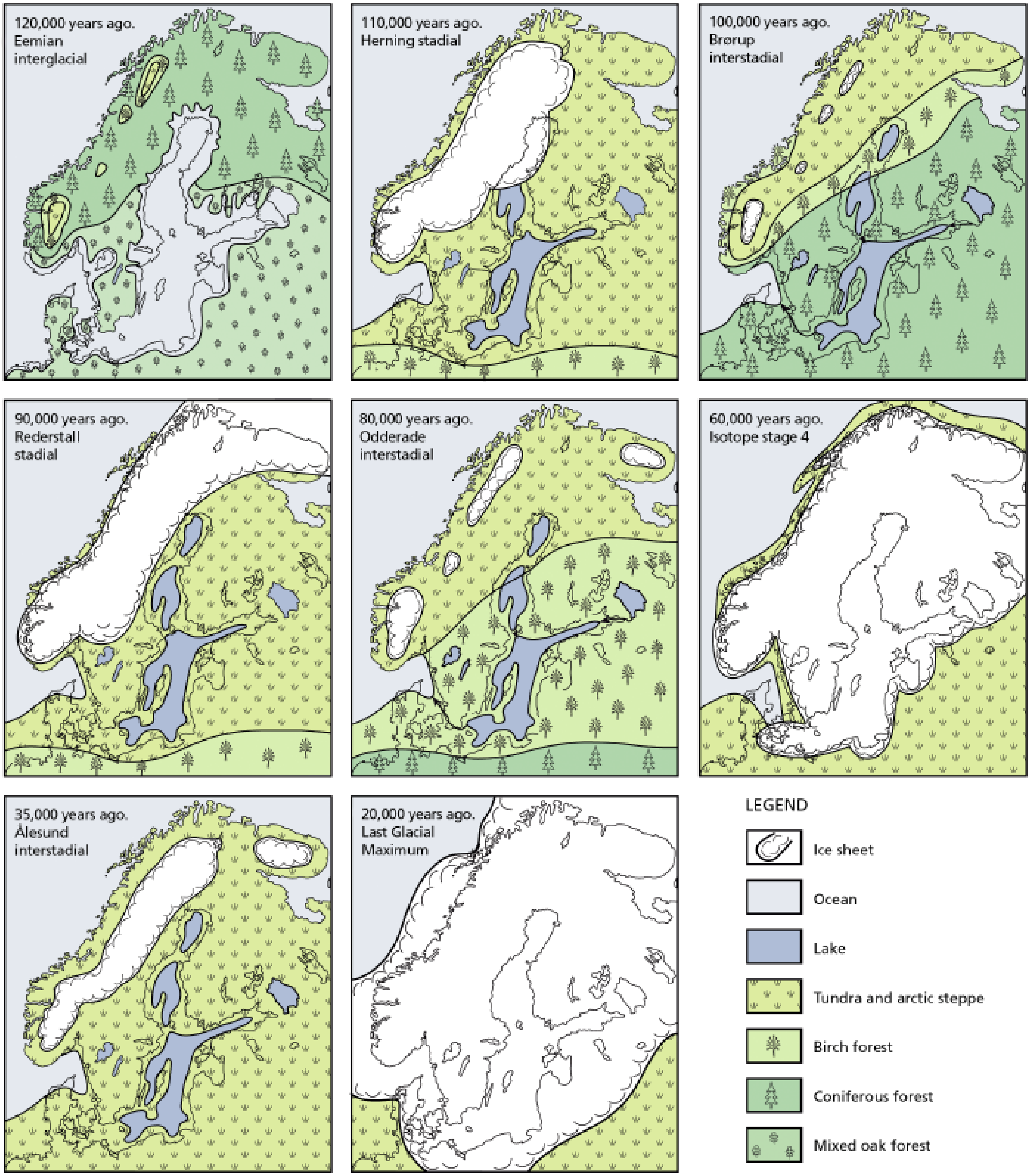
The silt unit at Fjøsanger (unit G in photograph) is a typical glaciomarine deposit, containing a low diversity, cold-tolerant fauna, with rock fragments dropped from icebergs. The fragments comprise gabbros and anorthosites, which are common in the mountains east of Nordåsvatnet, and were transported by a glacier which calved in the fjord. This is considered evidence for the first growth of the ice sheet following the Eemian interglacial.

However, in the succeeding gravel unit (F) only rocks derived from the slopes above Fjøsanger were encountered, and no far-travelled pebbles. The gravel contains numerous shells, and the glaciomarine silt component is absent, indicating that the glacier had receded when this unit was deposited. This period is named the Fana interstadial, and is correlated with the European Brørup interstadial.

How far inland did the ice retreat?

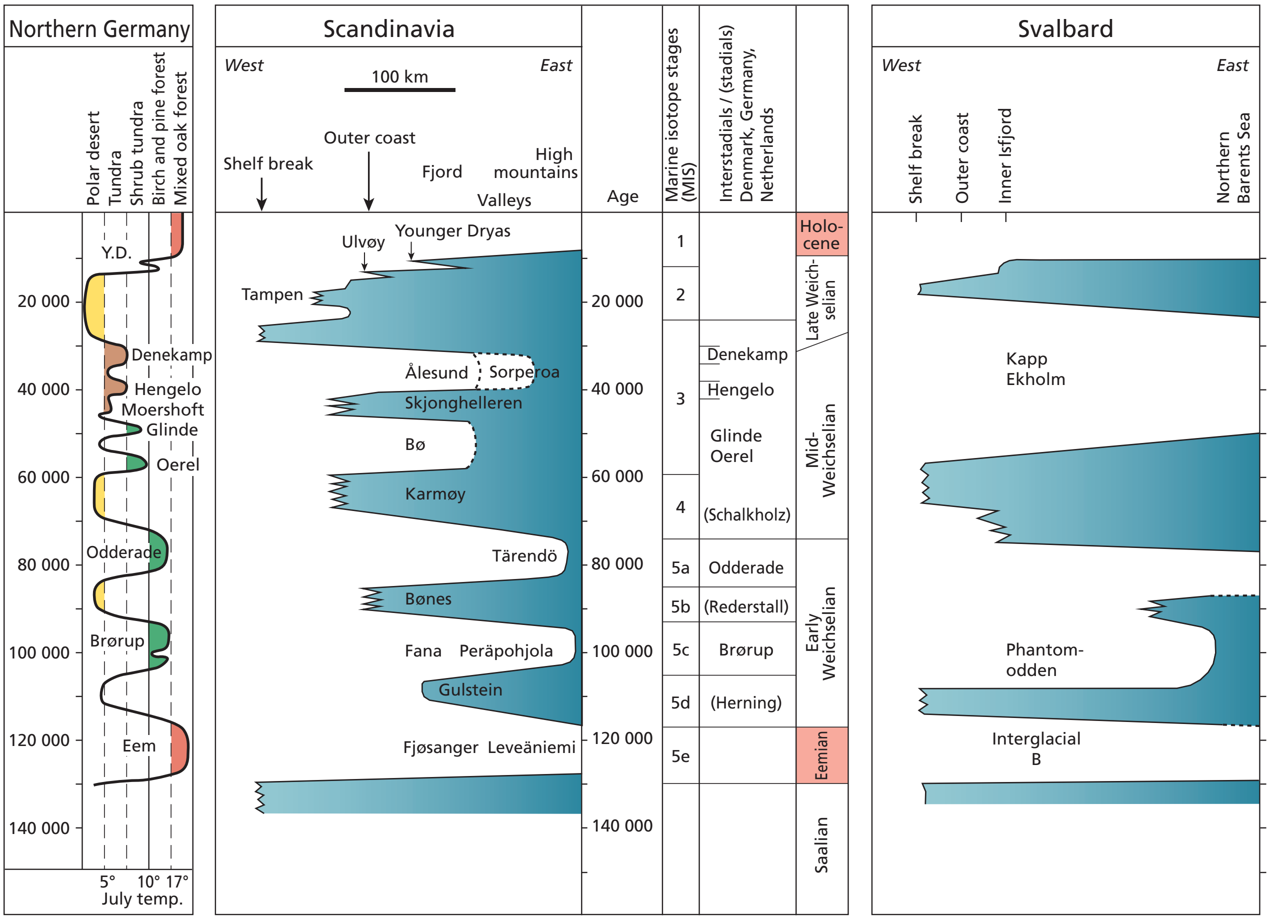
The discovery of interstadial deposits along the coast demonstrates that the ice-front retreated as the climate became warmer. However, to find out how far back the ice-front retreated, we must find inland localities. The last record of pine and birch forests in Denmark and Germany during the Weichselian glaciation was during the Brørup and Odderade interstadials, about 100,000 and 80,000 years ago, respectively. In northern Sweden, sediments from two Weichselian interstadials have been identified, both of which contain birch pollen. These correlate with the Brørup and Odderade interstadials, and indicate that the Scandinavian Ice Sheet was restricted to high altitudes during these intervals.

An interesting Norwegian inland locality is at Dalseng in Brumunddalen (Hedmark). Here, a 1 m-thick and highly-compacted peat bed is recorded between two till beds. Pollen from the peat suggests a development from tundra to open birch and juniper woodland before returning to tundra again. During the warmest period, pine and spruce also made an appearance and, critically, larch trees invaded the birch copses, indicating that this interval can be correlated with the Brørup interstadial in Denmark and Germany. The interpretation is then that the ice sheet advanced across the Dalseng locality during the Herning stadial about 110,000 years ago, but retreated again during the Brørup interstadial. Subsequently the latter became warm enough for the growth of trees and formation of peat. During the next stadial, the Rederstall, about 90,000 years ago, the glacier advanced again and a lake formed in Brumunddalen along the ice edge. Silt

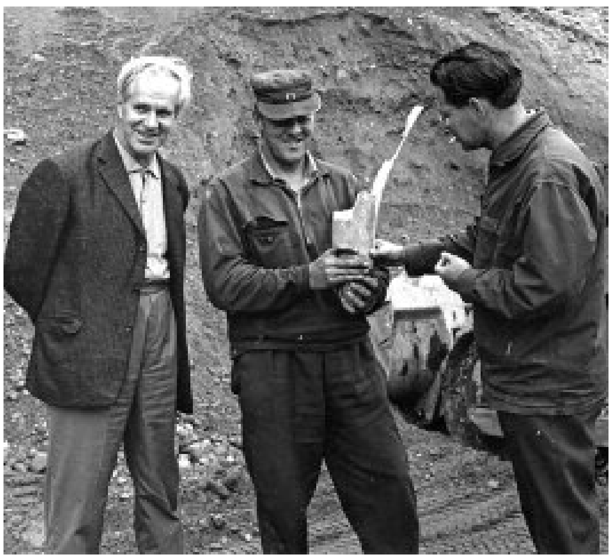


Reconstruction of palaeogeography and vegetation zones in Scandinavia during the last (Eemian) interglacial, and the last (Weichselian) glaciation. (Developed from earlier versions by J. Lundquist and J. Mangerud)

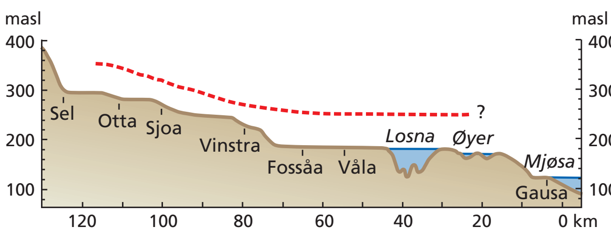
Curves, termed *time-distance diagrams* by geologists, illustrating how the distribution of the Scandinavian and Barents Sea-Svalbard Ice Sheets varied during the last glaciation. The curves are designed to show the relative position of the ice margin. For example, there was no Scandinavian ice sheet during the Eemian interglacial. Thereafter, glaciers began to develop in the mountains, valley glaciers formed, and at some locations extended into the fjords during the Gulstein/Herning stadial some 110,000 years ago. This interval was succeeded by the milder Brørup Interstadial, during which the ice margin receded. An equivalent curve for Svalbard is also shown, but in this case the centre of the ice sheet is thought to have been located on Kong Karls Land or further east. The column on the extreme left shows vegetation types and July temperatures in northern Germany. (Modified from Mangerud et al)



which now overlies the Dalseng peat was deposited in the lake. Finally, the ice advanced once more across the locality on its way to the coast.



Tractor-driver Oddvar Lunde presents the mammoth tooth he discovered to palaeontologists Anatol Heintz (left) and Gunnar Henningsmoen (right). This was the 13th example of a mammoth finding in Norway. The discovery was made in 1967 in a gravel quarry at Kvam in Gudbrandsdalen. (Photo: K. Henningsmoen)



Longitudinal profile along the Gudbrandsdalen valley. The red line denotes the elevation of the valley floor when it was filled with glacial outwash sediments during the Gudbrandsdalen Interstadial. (Modified after O.F. Bergersen and K. Garnes)

Numerous interstadial deposits in Gudbrandsdalen

Gudbrandsdalen and its tributary valleys represent the area in Norway's interior where we find the most localities with interstadial deposits below till, and where 18 of the 20 Norwegian mammoth finds have been made. Both the deposits and the mammoth remains were earlier assigned to the Gudbrandsdalen interstadial, an interval previously correlated with the Brørup interstadial. However, today we believe that these finds stem from several different ice-free periods.

At Kvam on the Gudbrandsdalen valley floor, there are thick deposits of almost horizontally bedded sand and gravel, with some gently-inclined internal cross-beds, interpreted as glacial meltwater outwash, or sandur. The gravel consists of rocks such as gabbro, indicating that much of the material was derived from the Jotunheimen mountains. Several mammoth remains have been found in these deposits. The sandur was formed during a period when Gudbrandsdalen was ice-free, but when the Jotunheimen glaciers were more extensive than they are today and therefore had outlet glaciers down valleys such as Ottadalen and Sjodalen. The remnants of the sandur deposits reach as high as 50-60 m above the present river level, and at the time of formation the entire valley was probably filled with sand and gravel up to this level, forming a broad, flat valley floor. The height of the deposits suggests that this valley fill extended continuously from Otta and down-valley to Fåvang.

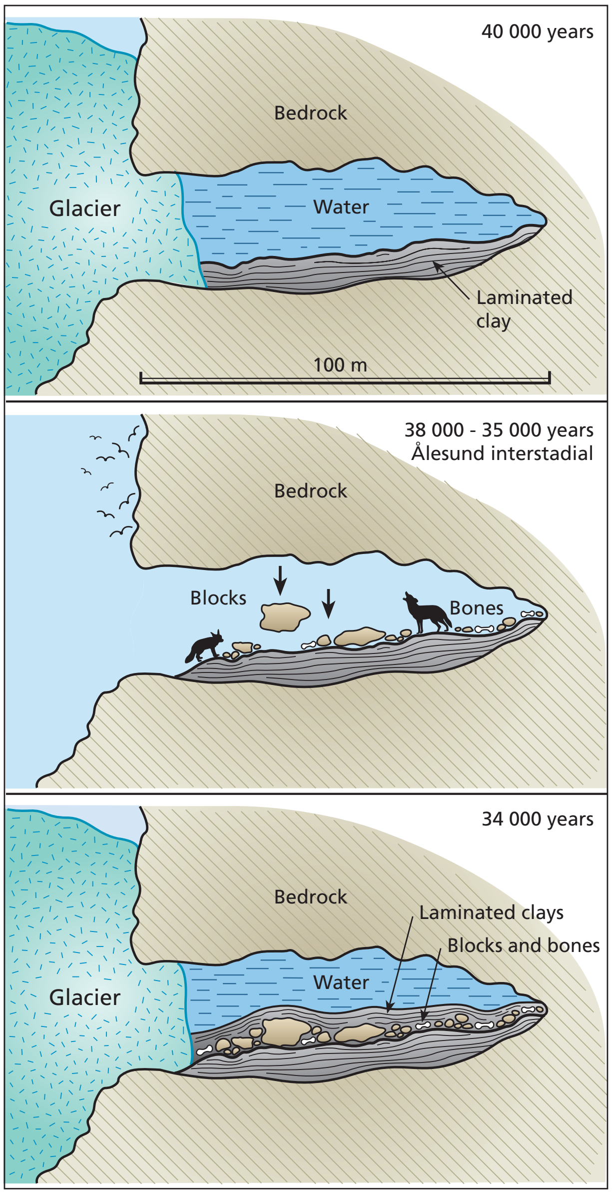
The Sunnmøre caves reveal their secrets

The most reliably-dated Norwegian interstadial from before the Last Glacial Maximum is called the Ålesund interstadial because deposits were first discovered while excavating the foundations of a house in the city of Ålesund. Here, however, we shall concentrate on sequences from the Ålesund interstadial found in three caves in the Sunnmøre region; Skjonghelleren, Hamnsundhelleren and Olahola. These are typical coastal caves, formed by wave action when sea levels were somewhat higher than they are today. The caves are now situated some 40-60 m above sea level, which is higher than sea levels have been since the last glaciation.

The cave floors are strewn with blocks which fell from the roofs and walls, together with a few bones carried in by animals. During his excavations in the Skjonghelleren cave in 1877, geologist H. Reusch discovered a laminated clay deposit beneath the uppermost block-bearing unit, which he interpreted to represent a lake deposit. The only way that a lake could have formed was for a glacier to block the cave opening. Subsequent drilling and seismic surveys were conducted at Skjonghelleren in the 1980s, and revealed deposits 15-20 m thick. There are three stratigraphic units containing blocks that have fallen from the roof during earlier ice-free intervals. Between the block-bearing units are beds of laminated clays deposited in glacial lakes during ice sheet advances. In the following we shall only describe the youngest units.

Just below the floor of all three caves there is a laminated clay sequence about 1 m in thickness, deposited in an ice-dammed lake during the Last Glacial Maximum. Between this and the next clay sequence, the Ålesund interstadial is found as a block-bearing bed containing bones. About 30,000 bones have been found in this bed in Skjonghelleren and some 15,000 in Hamnsundhelleren, the majority of which are small bird bones which cannot be identified. Numerous radiocarbon datings have been performed on the bones and have revealed ages of between 34,000 to 29,000 ^{14}C years. For samples this old reliable calibration curves converting ^{14}C years to calendar years have not yet been developed. However, a method has been employed which pro-

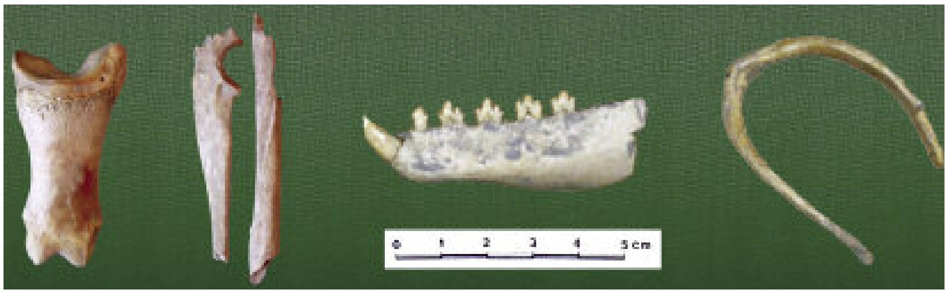
The "Mammoth pit" at Haugalia, near Kvam in Gudbrandsdalen. Thick sequences of glacial outwash sands and gravels deposited during the Gudbrandsdalen Interstadial in the early stages of the last glaciation, overlain by till. (Photo: K. Garnes)



Simplified profile through the Skjonghelleren cave on Valderøya island in Sunnmøre; some older units are omitted. When the ice sheet had advanced enough to block the cave entrance (some 40,000 years ago), it dammed up a lake in the cave in which clays were deposited. During the Ålesund Interstadial, between 38,000 and 35,000 years ago, the cave was open and blocks fell from the roof. In the same bed thousands of bones have been found indicating that there was a seabird nesting cliff outside the cave. The bones probably represent the remains of winter provisions brought in by arctic foxes. Later, the glacier advanced once again and blocked the entrance. The "bones-and-block" bed was then sealed by a new layer of clay. (Modified from E. Larsen and J. Mangerud) vides us with the bonus of a palaeoclimatic interpretation from these cave deposits.

The compass needle doesn't always point north

Certain clay particles are magnetic and, when deposited in water, will orient themselves like compass needles along a north-south axis. Today, we can measure the orientation of these mineral compass needles in the caves' clay deposits, and it appears that the North arrow does not always point towards the North Pole but even towards locations near the equator. This is the result of what geologists call a palaeomagnetic "excursion". During deposition of the clays above the Ålesund interstadial, the magnetic pole was initially located in the Indian Ocean, and then later migrated to its present position. These excursions are known from other locations in the world, where they have been dated. The oldest is known as the Laschamp and the youngest, Mono Lake. However, we can make an even more precise correlation.



Some of the 38,000-35,000 year-old skeletal remains found in the Skjonghelleren cave. From left to right: the toe-joint of a polar bear, a bone from the foreleg of an arctic fox, the lower jaw of a ringed or harp seal, and the "wishbone" (clavicle) of a Brunnich's guillemot. (Photo: A.K. Hufthammer)

Laminated clays in the Skjonghelleren cave. The clay was deposited in a lake dammed up by a glacier located at the cave entrance. Above the figure note the large block which fell from the roof, and on which someone has written his name. (Photo: R. Peersen)

In many of the drill cores taken from the 3,000 m-thick Greenland ice sheet, each individual annual layer of snow and ice has been recorded. Thus these cores provide an exceptionally detailed chronology measured in calendar years. During magnetic excursions, the Earth's magnetic field is weakened, and this increases the intensity of cosmic radiation reaching the planet's atmosphere. Cosmic radiation produces isotopes such as ^{10}Be and ^{36}Cl in the atmosphere, which are precipitated with snow. These isotopes have been measured in the drill cores, and peaks equivalent to the Laschamp and Mono Lake palaeomagnetic excursions have been identified. In this way, the clay beds both above and beneath the Ålesund interstadial deposits can be correlated with the Greenland ice cores. The results indicate that the Ålesund interstadial lasted from about 38,500 to 34,500 "ice-core" years which, if they have been counted correctly, are also the equivalent calendar-year age.

Seabird colonies in Sunnmøre

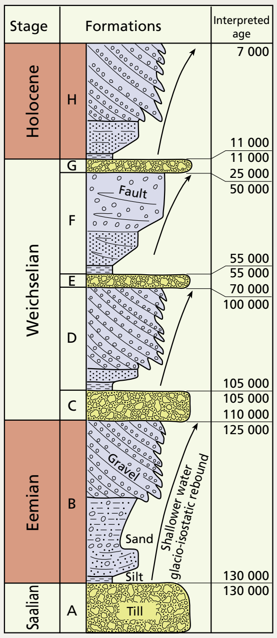
Most of the bones identified in these caves are derived from the little auk, or other auk species and the Brunnich's guillemot. These are seabirds which nest in their thousands in colonies in Svalbard, as is the case for puffins and kittiwakes, whose bones have also been found. In Svalbard the arctic fox is a frequent visitor to the colonies during the nesting season, when it will take both eggs and chicks. It is likely that the cliffs outside the Sunnmøre caves were similar rich seabird colonies. The foxes would have brought food for the winter into the caves. Bones also reveal that the foxes had been on the beach and had raided the carcasses of seals and polar bears, and of grouse and reindeer further inland.

The presence of reindeer in Sunnmøre indicates that an ice-free belt existed, extending south along the coast. This provided the animals with sufficient food, and allowed them to migrate from the central European tundra. This is supported by discoveries of this age in Jæren. There are also finds at locations such as Lillehammer in Oppland, Gudbrandsdalen, Selbu in Sør-Trøndelag and Hattfjelldal in Nordland, all of which indicate that much of Norway was free of ice during the Ålesund interstadial.

Clearly the Ålesund interstadial enjoyed a climate supporting a fauna similar to that encountered today along the west coast of Svalbard. However, finds of the bones of common and velvet scoters, together with coalfish and, at another locality, the Icelandic cyprine mussel, indicate that for a limited period climatic con-

GLACIAL FLUCTUATIONS IN SVALBARD AND THE BARENTS SEA DURING THE LAST GLACIATION

There are several localities in Svalbard which demonstrate that the archipelago was ice-free during periods of the Weichselian glaciation. Along the foreshore at Ekholm in Billefjord there is a 1km-long and 30 m-high section which preserves four quite similar sedimentary sequences. The youngest (see photograph) has a till at its base, providing evidence that a glacier moved across the area. The till is overlain by marine silts containing cold-water shells, deposited during a glacial retreat when the foreshore was at least 70 m higher than it is today. The shells are 11,500 years old. There is a coarsening upwards to sands and gravel that reflect a shallowing of the water as a result of glacio-isostatic uplift. Within the coarser units we find *Arctica islandica*, *Zirphea crispate* and several other species that require waters some 2-4 °C warmer than are found in the fjord today.



LEFT: A summary log of the sequences at Kapp Ekholm. There are four cyclic sequences, each of which has a basal till at its base. These are overlain by sediments deposited in progressively shallower water.
RIGHT: The photograph shows a 20 m-high section of the youngest sequence. Immediately above the foreshore we can see a till (about 2 m thick) from the last glaciation. On the right of the picture this is overlain by pale-coloured horizontal units containing deep-water silts. The overlying sands and gravels that dip to the left were deposited by up-fjord, long-shore drift. These units are of Holocene age, and provide evidence of the last uplift event.

Sedimentologically, the three oldest sequences resemble Holocene units. Thus, we have deposits representing four cycles of ice build-up, followed by subsequent retreat and glacio-isostatic rebound. Kapp Ekholm is located only 14 km beyond the ice-front of the great Nordenskiöldbreen glacier that calves in the inner part of the fjord at the present day. It thus seems likely that when Kapp Ekholm was free of ice, the Svalbard glaciers were almost as small as they are today. The lowermost and oldest sequence represents the deglaciation of the Saalian glaciation and Eemian interglacial. The upper three cycles demonstrate that a glacier subsequently advanced and retreated again across the Barentshavet-Svalbard area at least three times during the last glaciation. The first advance is estimated to have occurred some 110,000 years ago, while the second, which is also recorded at other locations in Svalbard, is dated to about 60,000 years old. The youngest of the three cycles records a Late Weichselian advance and subsequent melting at the beginning of the Holocene.

Kapp Ekholm also provides indirect evidence of extensive ice sheets that occupied much of the Barents Sea basin. Glaciations restricted to Svalbard could never have produced the glacio-isostatic lowering and subsequent rebound that have been recorded in the depositional cycles at Kapp Ekholm. These demand the existence of extensive ice sheets that repeatedly occupied the greater part of the Barents Sea.

ditions were more like those on the present-day coast of Finnmark. This suggests that the Gulf Stream reached the Norwegian coast, although not with the same vigour and warmth that it exhibits today.

Numerous rapid advances and retreats

The cave deposits show us that the Sunnmøre coast experienced two cycles of ice sheet advance and retreat within the space of less than 10,000 years during the period between 40,000 and 30,000 years ago. The Greenland ice cores have revealed that temperatures frequently rose by 10-15 °C during periods of just a few decades, while cooling processes were more prolonged. It is thus natural to ask whether these climatic fluctuations occurred on both sides of the Norwegian Sea. Correlations indicate that most of the variations recorded in Greenland and western Norway are common to both areas. In Greenland however, the glacial advance prior to the Ålesund interstadial appears to have started during a mild interstadial. Glacial modelling allows researchers to utilise climate changes recorded in Greenland to model developments in Scandinavia. It indicates that the apparent extensive and rapid fluctuations of the ice-front observed in western Norway are indeed possible. For example, modelling indicates that during the Ålesund interstadial the ice sheet was restricted to the mountains, but that it expanded over most of the land area during the intervals shortly before and afterwards, supporting the evidence provided by field observations.

The ice sheet expands to its maximum

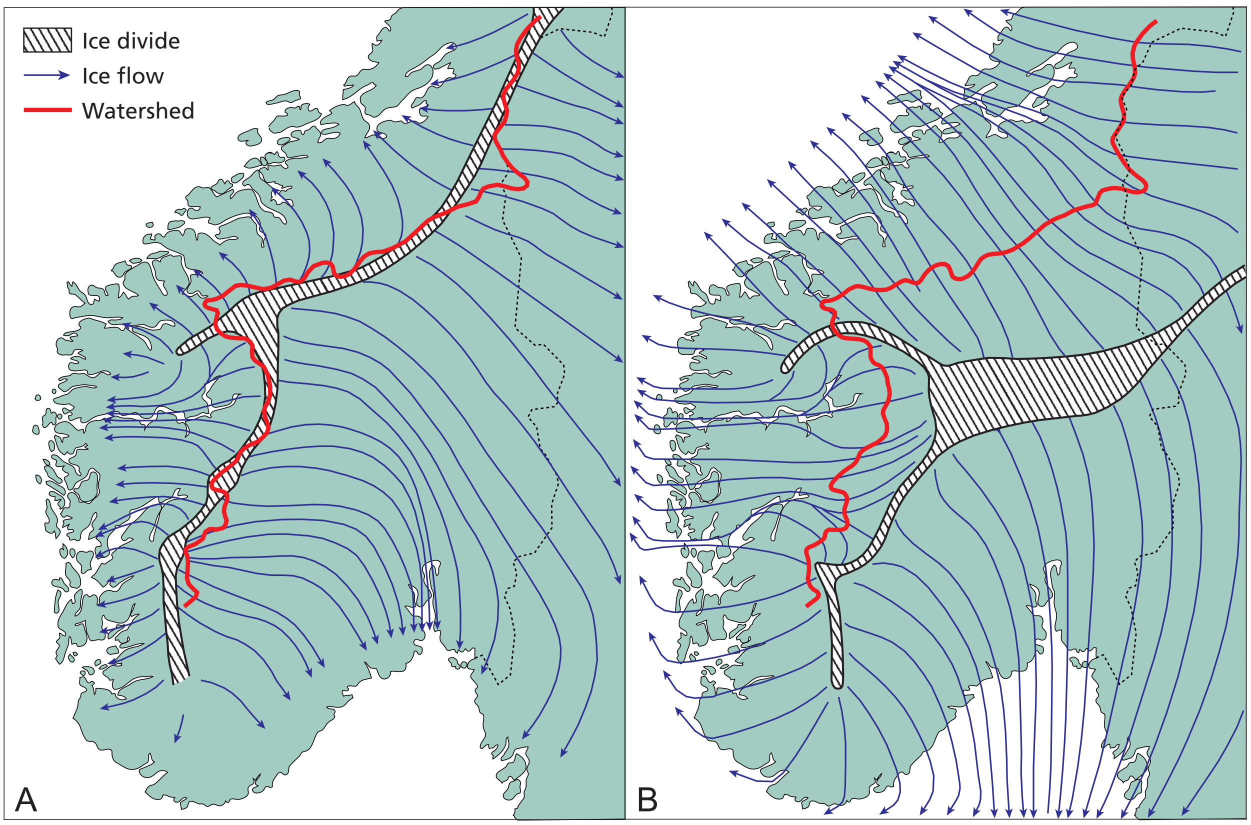
The great continental ice sheets of northern Europe and North America expanded even further towards the end of the last glaciation, and reached their maximum between 18,000 and 25,000 years ago. But what happened to the Barents Sea glaciers?

Norwegians are familiar with glaciers in the high mountains where the climate is cold, whereas it seems paradoxical that an ice sheet should have its highest elevations in the middle of an ocean. However, this is precisely what occurred in the case of the Barents-Kara Sea Ice Sheet. At its maximum, the ice flow in this ice sheet was radiating from the Barents Sea, across Svalbard and, on the opposite side, into the interior of northern Russia. Probably the embryonic ice sheets first accumulated and advanced from groups of islands and shallow water shoals.

There has been a prolonged and lively debate among geologists regarding the extent of the Barents Sea-centred ice sheet during the Last Glacial Maximum. Raised beaches on Svalbard's eastern islands provide evidence of the largest glacio-isostatic rebound and indicate the former presence of an ice sheet culmination in the northern Barents Sea. The discovery of recessional moraines on the Fugløybanken fishing bank offshore western Finnmark demonstrates that the Scandinavian and Barents Sea ice sheets had merged, and also confirmed that the entire Barents Sea had been covered with ice. This is also supported by other observations, e.g. glacial lineation on the seabed that can be followed all the way to the shelf break.

Several age determinations of between 21,000 and 30,000 ^{14}C years have been obtained from the upper sediments on the Barents Sea floor. In

LEFT: Map showing the ice divide and interpreted directions of ice flow during an early phase of development of the ice-sheet. RIGHT: Map showing the situation during the Last Glacial Maximum, when the ice divide was located some distance to the east and south of the main watershed.



Svalbard too there is evidence that this was a cold, but ice-free, interval. The ice sheet must thus have developed and reached its maximum extension after this time; i.e. within a period of a few thousand years. Foraminifera from cores indicate that the north-western Norwegian Sea was open at that time, allowing water to evaporate and provide snow to promote accumulation of the Barents Sea Ice Sheet.

In the south-west, the Barents Sea Ice Sheet was dominated by the ice stream draining along the Bjørnøya Trough. It is estimated that it travelled at a speed of 2.5 km/year at the ice-front, and that it calved 200 km^3 of ice annually. This is comparable with rates of discharge currently measured in the river Danube. For long periods the ice-front's western limit was located at the shelf break, where it deposited ice-margin deltas and generated debris flows.

However, the eastern flank of the Svalbard-Barents-Kara Ice Sheet reached its maximum extent much earlier in the Weichselian, some 80,000-90,000 years ago, at which time it had its centre in the Kara Sea. From here it expanded far into the Russian mainland to the south. In contrast, during the western maximum some 20,000 years ago, the eastern flank did not even reach the south-eastern Barents Sea coast, and barely extended across Novaya Zemlya and into the western Kara Sea.

The ice divide of the Scandinavian Ice Sheet did not follow the water divide

The oldest glacial striations and flow-direction indicators in tills reveal that the ice divide was initially located along the principal fluvial water divide, as we would expect during periods of deteriorating climate. Later, the principal ice divide migrated far to the east into Sweden and towards the south in the Østerdalen-Gudbrandsdalen region. This shift was mainly the result of faster ice flow to lowland areas through the deep valleys and fjords towards the west. Here the calving of icebergs was also most active.

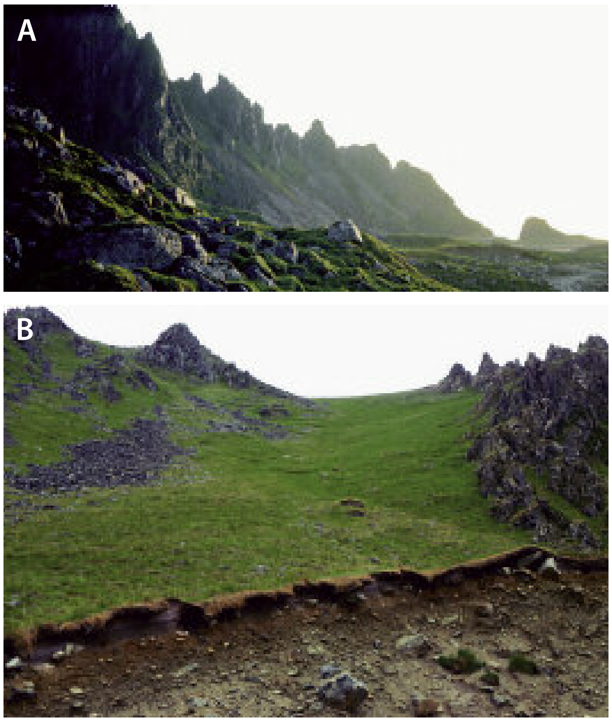
However, the observations do not show a gradual migration of the ice divide, but an apparent sudden shift. The likely explanation is that the ice sheet became cold-based, meaning that the sole became frozen to the substrate and left no signs of ice flow. The ice divide could thus have migrated gradually without leaving any trace. It would not have been until the deglaciation that the temperature at the sole of the glacier again reached the pressure melting point, thus allowing glacial striae to be formed.

Photograph showing two sets of glacial striations in a relatively soft phyllite from the Indre Sogn area. The older striations (E) are located leeward of the younger set (Y). The direction indicated by the oldest set can be determined from small tails formed on the lee side of quartz lenses in the rock.

It is likely that changes in patterns of precipitation also influenced the migration of the ice divide. Today, most precipitation falls along the western coasts of Scandinavia. However, during the coldest periods of the glaciations most, if not all of the Gulf Stream turned towards Portugal and thus did not reach Scandinavia. Today's cyclone path was then more often directed farther to the south, resulting in increased precipitation on the eastern flank of the Scandinavian Ice Sheet.

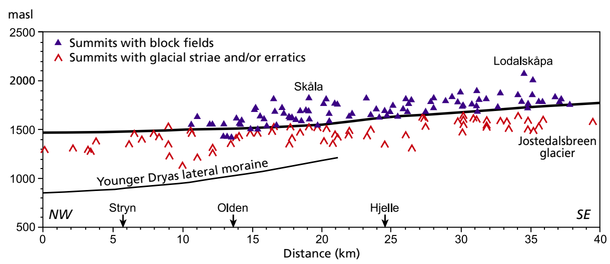
Within the ice sheet, the ice flow was radially outwards from the highest domes, or laterally from the elongate principal ice divide from Gudbrandsdalen to the Gulf of Bothnia, in the same way as is observed in the Greenland and Antarctic ice sheets today. In the latter ice sheets, glaciologists have identified fast flowing, virtual "rivers" of ice, called *ice streams*, where the ice moves much faster than the ice along its borders. On Greenland, such ice streams reach velocities of up to 1 m/h, and excess snow from large areas of the ice sheet is drained by these ice streams.

As described earlier, ice streams occurred within the Scandinavian Ice Sheet. They were active more or less permanently along the fjords of western and northern Norway, and periodically also along the major valleys in eastern Norway and in Sweden. More surprising is that ice streams also existed across the flat lowlands of Finland and the Norwegian continental shelf. Ice streams occurred along most of the troughs that we now observe on the shelf. A particularly large example was that which occupied the Norwegian Channel. It extended into Jæren in south-western Norway and carried with it rhomb porphyry fragments from the Oslo Region, and



A: These rugged, angular peaks at Røyken at the northern tip of Andøya were probably not covered by ice during the last glaciation. B: On the mountainsides at Bleik, a little further to the south on Andøya, weathered material has accumulated between the peaks.

Block field in gneisses at Vardafjellet (1,163 m above sea level) south of Haugsvik near Voss in Hordaland. The weathered, pale-coloured vein is evidence that the rocks making up the block field have undergone only minimal horizontal movement. (Photo: A. Nesje)



Longitudinal profile through Nordfjord in Sogn og Fjordane, showing the altitude of summits with block fields and those with glacial striations. (Figure modified after E.J. Brook et al.)

chalk, flints and coal fragments from Denmark and the Skagerrak. It may be mentioned in passing that the discovery of coal fragments promoted drilling for coal in Jæren during the 1870s.

Maximum extent and age of the Last Glacial Maximum

In the west, offshore Norway, the Scandinavian ice sheet reached its outer limit at the continental shelf break. In southern Denmark and throughout northern Germany, Poland, Belarus, and Russia, its maximum extent is clearly defined by terminal moraines and extensive outwash plains. In fact, it is possible to trace the boundary from an atlas simply by following the outer limit of the distribution of lakes.

Direct and indirect datings indicate that the glacial maximum occurred between 18,000 and 25,000 years ago. However, there are very few really accurate dates. It is also unlikely for such an extensive ice sheet that the maximum extent was reached simultaneously around the entire margin, partly because the dynamic response of different segments of the ice sheet varied, depending on the amount of snow accumulation. We can see examples of this today in Greenland and the Antarctic. In addition, the ice sheet ranged across different climatic zones. In the south-western sector of the ice sheet (for example in SW Norway) snow fall was high and the summers relatively warm, giving high turn-over of snow and ice. In contrast, at the north-eastern flank in the area of Franz Josef Land, conditions were extremely cold and dry throughout the year. Here, the ice margins will have responded very differently to changes in climate.

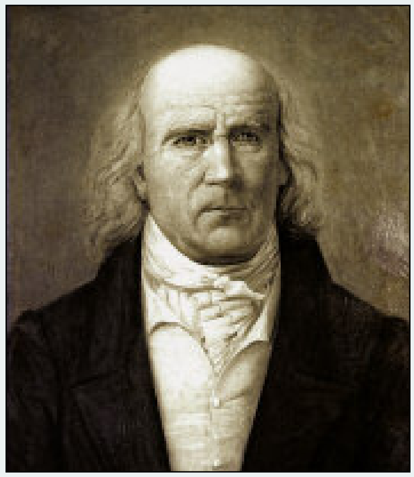
Did nunataks appear above the continental ice sheet?

For over a century, Norwegian scientists have debated whether isolated mountain summits, or nunataks, were emergent above the surface of the continental ice sheet. The debate began when botanists discovered that the distribution of some plant species could best be explained by the fact that they survived the glaciations on nunataks.

Sharp and intensely fractured alpine peaks are typical of high mountains in the Møre and Troms regions. It is difficult to imagine that the ice sheet flowed over these features without either smoothing them or removing them completely. Adjacent, less rugged, mountains form areas where the entire surface is covered in angular blocks that have been weathered loose from the *in situ* bedrock. There can be no doubt that these block fields were formed prior to the Last Glacial Maximum. These observations are interpreted by some as evidence that the ice sheet did not cover these surfaces. In Nordfjord in Sogn og Fjordane, geologists have identified a well-defined boundary between the relatively low-altitude mountain summits that have been smoothed by the ice, and higher summits covered in block fields. This boundary occurs at about 1,500 m above sea level at Stryn in Sogn og Fjordane, and rises to 1,700 m at the Jostedalsbreen glacier, and is interpreted to represent the ice surface as it appeared some 20,000 years ago.

J. ESMARK, A PIONEER IN GLACIAL RESEARCH *By Bjørn G. Andersen*

During the Younger Dryas, Lysefjord in Ryfylke was occupied by a 25 km-long and 1,000 m-thick fjord glacier. The glacier deposited conspicuous, boulder-rich, lateral moraines which today form narrow terraces along both sides of the fjord. An outflow glacier from the main ice mass flowed into Haukalidalen and deposited the well-known "Esmark moraine" – a 30 m-high, angular, terminal moraine ridge, which forms a crescent-shaped feature across the valley floor, and dams the Haukalivatnet lake. Locally, the ridge is called Vassryggen, meaning the ridge at the lake. In his paper "Contributions to Earth History" in 1824, Professor Jens Esmark described Vassryggen and the sandur plain in front of the ridge, and compared them with ridges and meltwater river plains that he had seen close to the front of modern glaciers at different locations in the Jotunheimen mountains. Based on these observations he concluded emphatically that the entire Haukalidalen valley was once occupied by a glacier, and that the greater part of Norway was once covered with glacial ice, extending to sea level.



Jens Esmark.

During the initial decades of the 1800s, several scientists had shown that the Alpine glaciers were once much more extensive than was observed at that time. However, in Scandinavia, researchers continued to interpret both erratic blocks and bedrock striations as having been caused by boulders of rock transported by enormous floods that had cascaded over even the highest mountain summits (the "boulder flood" theory). Lyell's "drift theory", involving the deposition of morainic material directly from icebergs, was also in vogue. In his paper, Esmark provided evidence that the flood theory could not explain the transport of the erratics. He described large erratics from several Norwegian localities found enclosed in masses of fine sand and gravels (that we today call till), and maintained that it was impossible simultaneously for the same water masses to have transported and deposited blocks of such a size within so fine-grained a matrix. He also made detailed studies of erratics found on the high-altitude ridges and summits and concluded that these could only have been transported to such altitudes by ice sheets. *He went on to make further observations providing evidence that Norway had once been subject to extensive glaciations.*

It was not until the middle of the nineteenth century, and some decades after Esmark's initial observations and conclusions, that the glacial theory in general began to become widely recognised and accepted. This was principally the result of the efforts of the Swiss Louis Agassiz, while in Scandinavia, Professor Theodor Kjerulf was one of the first at that time to explain natural phenomena using glacial theory.

The "Esmark moraine" (Vassryggen), situated between the lake and the green fields in the foreground.

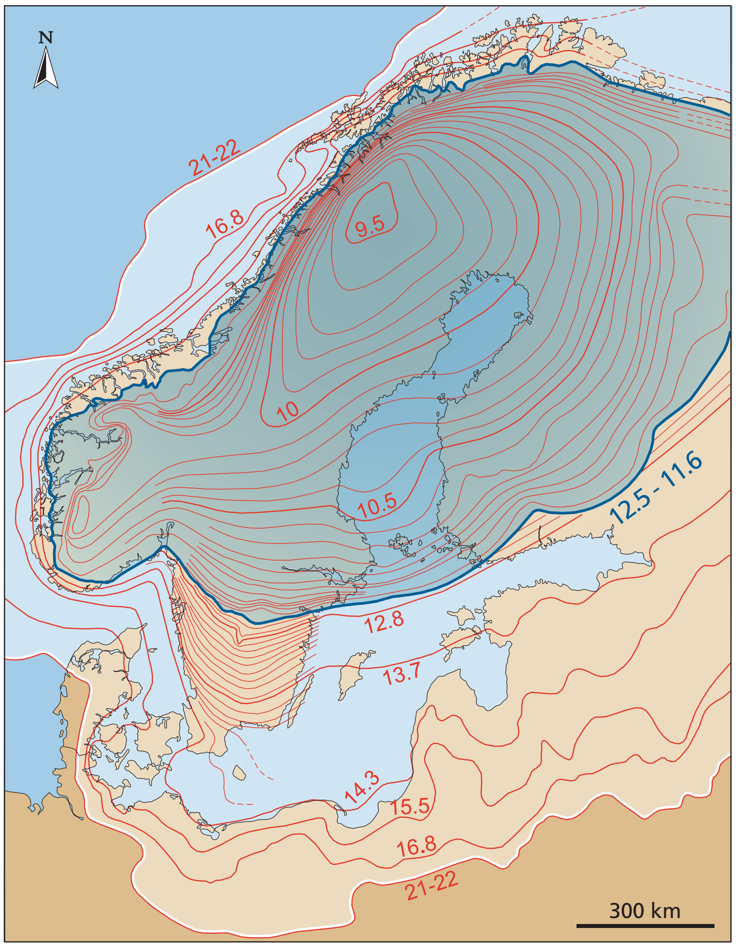
The question remains whether the block fields and jagged summits could have survived *beneath* the ice sheet? Earlier we mentioned that some parts of the ice sheet were cold-based and frozen to the underlying bedrock. This is more likely to occur at high altitudes where the ice is thinner than in the valleys, and where extremely low prevailing air temperatures are more likely to have penetrated to the base of the ice. In the Norwegian mountains, and even more so in Sweden, it has been demonstrated that older sediments and block fields have survived beneath the ice sheet. In Svalbard, erratics are found on top of the block fields, so there can be no doubt that ice passed over these without disturbing them. Age determinations indicate that the ice last passed over these areas in Svalbard some 60,000 years ago.

For the moment we must accept that the debate surrounding the Norwegian nunataks has yet to be resolved. Block fields in the Gudbrandsdalen-Østerdalen area extend so far down the mountainsides that it is unreasonable to suppose that the ice was so thin in this areas. It is much more likely that they survived beneath the ice sheet. On the other hand, it is more reasonable to assume that coastal mountains were emergent as nunataks, because the ice drained out into the fjords and because water depth limited the extent of the ice sheet.

The entire continental ice sheet melts away – in only a few thousand years

At some time, the mass balance of the ice sheet shifted from positive to negative, meaning that the yearly mass of ice which melted or calved away was larger than the mass of accumulated snow. This shift came when solar radiation during the summer months attained a northern hemisphere maximum.

Map showing the stages of retreat of the Scandinavian Ice Sheet. Ages for the various positions of the ice margin are shown in thousands of calendar years. The line marked "12.5-11.6" (blue) denotes the outer limit of the ice sheet during the Younger Dryas stadial. (Modified after J. Kleman and A. Strømberg, unpublished)



Offshore Norway, and in the Barents Sea area, the ice-front terminated in the sea. Here, the calving of icebergs was the most important mechanism for ice attrition. The major difference between calving and melting is that the former is largely controlled by non-climate related factors. Recession by calving is also an almost irreversible mechanism. This is easiest to illustrate in deep fjords with a shallow sill at their mouths. Having reached the sill, the glacier will rest on the bottom. However, when the ice-front first recedes from the sill by melting, it will soon begin to float and then rapidly retreat into the fjord by calving, regardless of any change in climate.

The ice retreats in fits and starts

The deglaciation history can be subdivided into three stages. During the first stage, from the Oldest to the Younger Dryas (about 18,000 to 12,800 years ago), the ice-front melted and calved in fits and starts as it retreated from the continental shelf and the outer coastal regions. As the ice-front receded, the ice sheet became thinner at its centre, so that mountain summits inland emerged above the ice surface. Even as the ice-front retreated the climate remained relatively cool for much of this time.

During the second stage, the Younger Dryas between 12,800 and 11,500 years ago, climate deterioration resulted in an ice sheet re-advance. The Younger Dryas has thus become a landmark for reconstructions of the deglaciation, because this is the only period for which the ice margin can be physically mapped as end moraines around the entire periphery of the Scandinavian Ice Sheet.

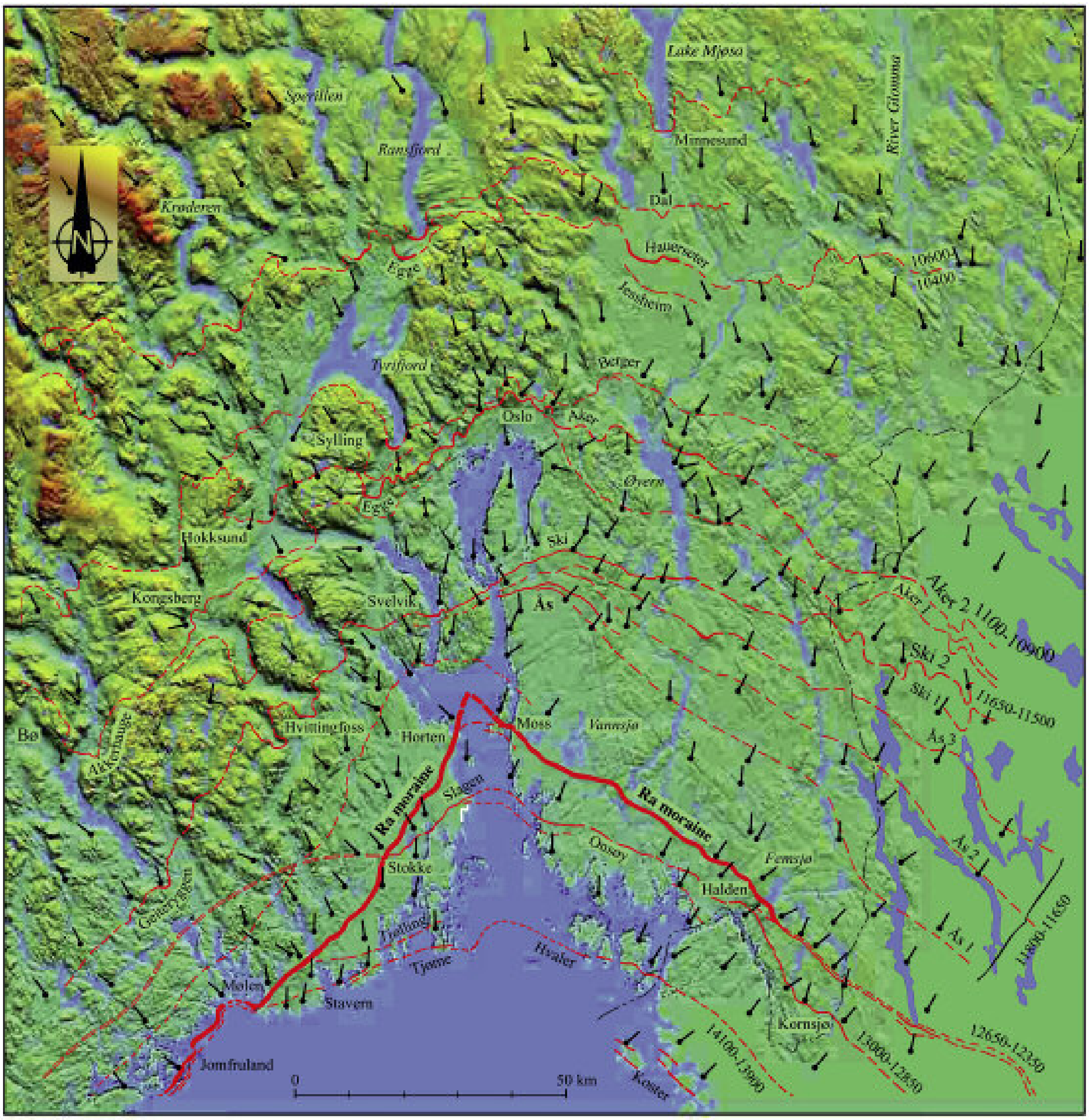
At the onset of the Holocene, here considered as the third stage of deglaciation, it became so warm that the ice sheet calved back and melted away during a hectic period of slightly more than 1,000 years. However, melting and recession during this period were also locally interrupted by stagnation or minor glacial advances. Each summer, approximately 10-15 m of ice was lost from the lower parts of the glacier surface by melting. This is equivalent to 10,000-15,000 mm of rain falling during a single summer, and resulted in immense meltwater rivers. The majority of sand and gravel deposits exploited commercially on mainland Norway today were formed by these rivers.

Oslofjorden – an ice highway and a calving bay

When the ice sheet was at its maximum, Oslofjorden became the site of a powerful ice stream, transporting ice in much the same way as a conveyor belt, and effectively carrying the excess ice generated in eastern Norway and parts of Sweden. It continued around the coast of southern Norway via the Norwegian Channel and out to continental slope. However, when the retreat began, the opposite occurred. The ice-front calved more rapidly back in the over-deepened channel and fjord than it receded on the adjacent land. Today, around Oslofjorden we find a series of end moraines that mark halts or re-advances, all of which form coves within the fjord characteristic of calving bays. The development is recorded in glacial striae on both sides of the fjord. The oldest sets show ice flow parallel with the fjord, while the younger sets show flow towards the calving bay in the fjord.

Enormous volumes of till, sand and gravel, in the form of moraine ridges and deltas, were deposited at the ice-front as it receded in this area. Even larger volumes of clay were deposited in the sea beyond the ice-front. During the retreat the foreshore in the Oslo area was situated some 220 m higher in than it is today. This is the highest marine limit in Norway. Sediments deposited during the retreat have laid the foundation for some of Norway's most productive agricultural settlements in the Østfold, Vestfold, Ringerike and Romerike districts.

In the outer parts of the fjord there are three recessional moraines, the Koster and the Tjøme-Hvaler,

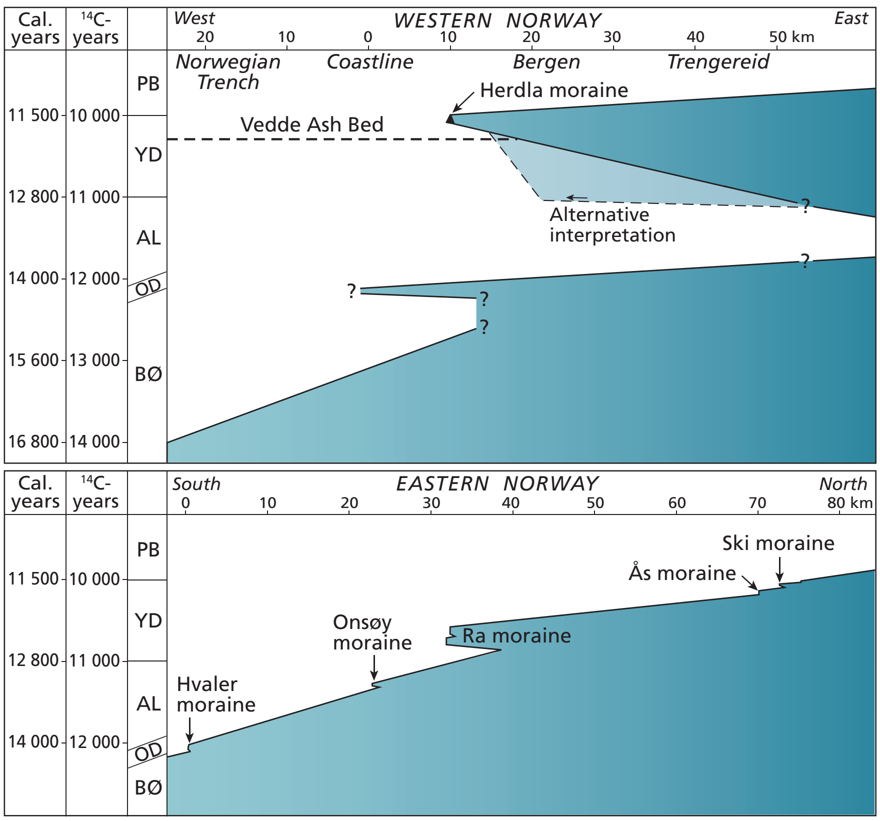


Map showing the location of marginal moraines in the Oslofjorden area. (Map constructed by R. Sørensen) which are about 14,000 calendar years old, and the Slagen-Onsøy, which is about 1,000 years younger. The moraines mark the sites of short-duration stops, or possibly minor re-advances, of the ice-front. These moraines are relatively small, and much of their sediment was reworked by wave action during emergence. However, all three can be traced into Sweden where they merge with better-defined moraine ridges.

The Ra moraine and younger end moraines

The Ra moraine, which was formed during the Younger Dryas stadial, is the most pronounced ice-marginal deposit in the Oslofjorden area. It is also the largest of its kind in mainland Norway. The moraine ridge varies from some hundreds of metres to several kilometres across, and merges with the marine clays deposited on its seaward flank. At some locations, two or more ridges can be distinguished. The ice-front terminated in the sea and rested on the sea floor along most of its margin along a line between Halden in Østfold and Grimstad in Aust-Agder.

Only a few major sections of the Ra moraine are described. These occur where gravel quarries have been cut into glaciofluvial deposits where the Ra crosses valleys. The greater part of the Ra ridge probably consists of till alternating with mass movement deposits. The latter derived in part from sediments that slumped from the ice-front, and in part from unstable till which slumped or was reworked by wave and current action along the submarine ice-front.



Time-distance diagrams showing fluctuations of the ice-front at the end of the last glaciation. Left-hand columns show time scales in both calendar and ^{14}C-years. The lower curve starts with the Hvaler moraine in outermost Oslofjorden in eastern Norway. Thereafter, the ice-front for the most part retreated the entire time, but underwent minor advances to the Onsøy and Ra moraines. The upper curve is from the Bergen region in western Norway. There are two significant differences between the curves. The Younger Dryas (Ra) moraine in the Oslofjorden area was formed during the middle of the Younger Dryas, whereas the Younger Dryas (Herdla) moraine near Bergen was formed at the very end of the Younger Dryas. The other difference is that from 14,500 to 11,500 years the ice margin had retreated some 80 km in Oslofjorden, whereas by 11,500 years ago the ice sheet in the Bergen region had re-advanced to approximately the same location it had assumed 14,500 years ago. (Modified from Mangerud)

Glaciomarine clays containing shells, and dated to the middle of the Allerød interstadial, have been discovered beneath tills about 10 km inland of the Ra moraine at Kragerø on the western shore of Oslofjorden. This is clear evidence of a glacial re-advance. In map view we can see that the Ra advance was greatest on the fjord's western side. Here the Ra moraine cuts across all older end moraines, showing that south of Langesund in Telemark, the ice margin re-advanced over the entire area deglaciated after formation of the Tjøme-Hvaler moraine. In contrast, on the eastern side of the fjord, the recessional moraines are neatly aligned one behind the other as one progresses inland, indicating that the ice-front retreat was largely uninterrupted. The advance on the western side is linked to an increase in snowfall in south-western Norway during the Younger Dryas, as described below.

The Ås-Ski moraine demonstrates that the ice-front made some short stops at the end of the Younger Dryas. The ice-front had retreated at an average rate of between 30-40 m a year from the Hvaler to the Ski moraine. However, the subsequent rate of retreat increased to over 100 m per year. In the Oslo area, the Aker moraine provides evidence of a short stop early during the Preboreal. Today, the inhabitants of the Norwegian capital are more than happy that the moraine dammed up lakes such as Sognsvann, Bogstadvannet and the drinking water reservoir at Maridalsvannet.

In the Romerike district there are numerous ice-marginal deposits, including those at Berger, Jessheim, Hauerseter, Dal and Minnesund. These are distinct from the older moraines in that they lack till deposits, and do not form distinctive ridges. They consist entirely of meltwater deposits in the form of ice-front deltas, while at Hauerseter and Minnesund the delta is overlain by sandurs. The shift from till to meltwater deposition indicates that the climate had become warmer. For several decades Oslo has been supplied with gravel and sand from the Romerike ice-front deltas. Seaward of these, thick glaciomarine clay sequences were deposited.

Dry river courses in the mountains

At many localities in the Norwegian mountains there are dry meltwater channels, often in highly unusual situations in relation to present-day drainage patterns. Good examples are found in the

Aerial photograph of Sarpsborg in Østfold, with the Sarpsfossen falls and Borregård chemical works on the right. The entire town is built on the Ra Moraine. The moraine ridge is massive enough to have dammed up several lakes in the Østfold region. The white line denotes the approximate location of the ice-front when the Ra Moraine was deposited. Forests dominate the vegetation on the thin soils landward of the Ra. In contrast, the moraine itself is composed of thick unconsolidated sediments which sustain large farms in both the Østfold and Vestfold regions, although many of these have since been consumed by urban expansion, as is the case in Sarpsborg. The soils seaward of the Ra moraine (foreground) are clay-rich. The clays were deposited on the seabed some distance beyond the limits of the moraine itself. (Photo: Fjellanger Widerøe)

area from the Dovrefjell massif to south of Rondane, and further east towards Sweden.

Most of these dry channels run along hillside slopes, and have undoubtedly been formed by meltwater running along the ice sheet margin. Since the ice itself formed one bank of the channel, many of these channels have only one bank. Channels often occur in series, formed one below the other as the ice gradually melted downwards into the valley. At some locations, it is likely that a channel was formed each summer, so that the sequence indicates the annual down-melting of ice.

The dry channels indicate that large volumes of ice and snow melted at high elevations on the ice sheet. In Rondane, channels are encountered at altitudes of up to 1,600 m above sea level, and it is apparent that from the ice-front and all the way up to the ice summit, more ice melted during the summer than was precipitated as snow during the winter. Thus the ice sheet was climatically dead. Meltwaters followed the slope of the ice surface and formed supraglacial streams. When these streams encountered the hillside, they would curve and continue along the edge of the ice. The channels in the Rondane-Femunden area demonstrate that the principal drainage direction was towards the north-west and thence across the current drainage divide to the Nordmøre and Trøndelag regions. Today, rivers from Rondane-Femunden drain in the opposite direction, towards the Glomma river basin to the south. This means that the highest ice dome, which represented the watershed for the supraglacial rivers, was located far to the southeast of the present day fluvial watershed.

As long as glacial ice occupied the valleys, the drainage direction was controlled by the slope of the surface of the ice sheet, which in the Rondane-Femunden area was directed towards Møre and Trøndelag. However, as the ice melted and the passes gradually became exposed, first minor, and later larger, lakes were successively dammed up between the passes and the ice edge in the south. The first and highest of the overflows from eastern Norway to the Møre and Trøndelag regions extended from Folldalen's highest tributary valleys, located furthest west within the River Glomma's catchment area, and across to Drivdalen. Subsequently, high-altitude passes between Folldal and Røros acted as overflow channels to the Orkla and Gaula rivers. Finally the large Nedre Glåmsjø Glacial Lake developed in Østerdalen, the valley of the Glomma River (see text box). This lake had its outlet through the lowest pass, Rugldalen, from Eastern Norway to Trøndelag.

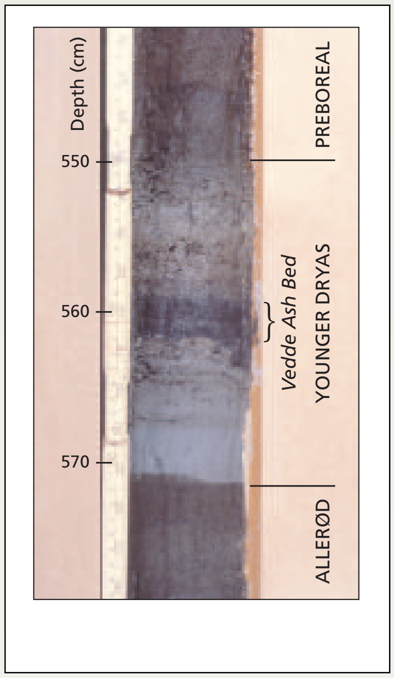
Since no organic material has been found in the sediments, the melting of the ice sheet in the high mountains is not dated with the radiocarbon method in the same way as the retreat in the coastal regions. However, geologists are able to make some reconstructions of this period. The southern margin of the ice sheet which dammed the Nedre Glåmsjø Glacial Lake some 10,300 years ago was located

A USEFUL ASH BED FROM ICELAND

There are no active volcanoes on mainland Norway. It was thus something of a surprise when a core from a lake in the Sunnmøre region revealed a volcanic ash bed that was up to 25 cm thick. It is true that at most localities the thickness of the horizon is only between 1 and 5 cm, but even this is very thick for an accumulation of particles that have drifted some 1,300 km in the atmosphere before coming to earth. Indeed, chemical analysis confirmed that the ash had been transported from Iceland, and most probably from the Katla volcano. Volcanic ash consists of minute rock particles, most of which are thin glassy platelets resulting from bursting lava bubbles. The largest of these is no more than 0.3 mm across, while most are less than 0.1 mm in diameter.

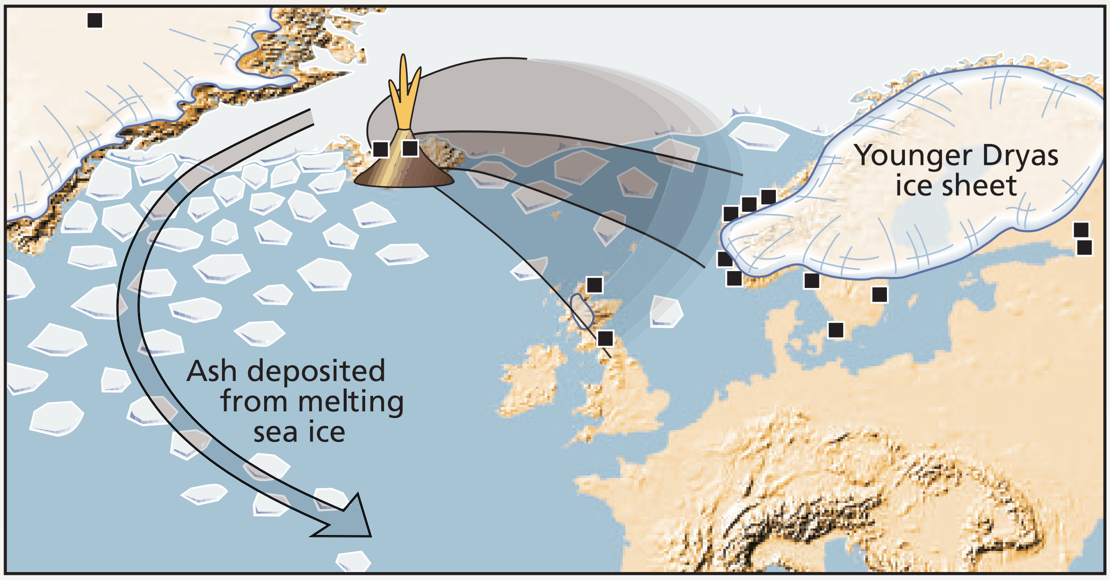
The ash horizon is called the "Vedde", after a locality on the island of Sula near Ålesund where it was first discovered. The Vedde Ash Bed in the lake sequences has been dated to the middle of the Younger Dryas, with a ^{14}C age of 10,300 years, equivalent to 12,000 calendar years. It was most probably derived from the largest volcanic eruption in Iceland for more than 100,000 years.

The Vedde Ash is easy to identify and has thus proved to be a very useful correlation tool between lacustrine, marine and glacial deposits along the coast of western Norway. The Vedde Ash has also been found in Scotland, Sweden, and as far east as Russia and in ice cores from the Greenland ice sheet. It is also found in marine cores throughout the Norwegian Sea between Norway and Iceland, and also further south in the Atlantic. To the latter area it was clearly transported by sea ice; it was deposited on drift ice in the Norwegian Sea that floated southwards and melted in the North Atlantic, where the ash sank to the sea bed.



The Vedde Ash in a core from Lerstadvatn lake in Sunnmøre.

Map showing the dispersal of the Vedde Ash from the eruption in Iceland 12,000 years ago. The black squares denote locations where the Vedde ash has been found, either on land or in ice cores. As indicated, it is also found in seabed cores over an extensive area.

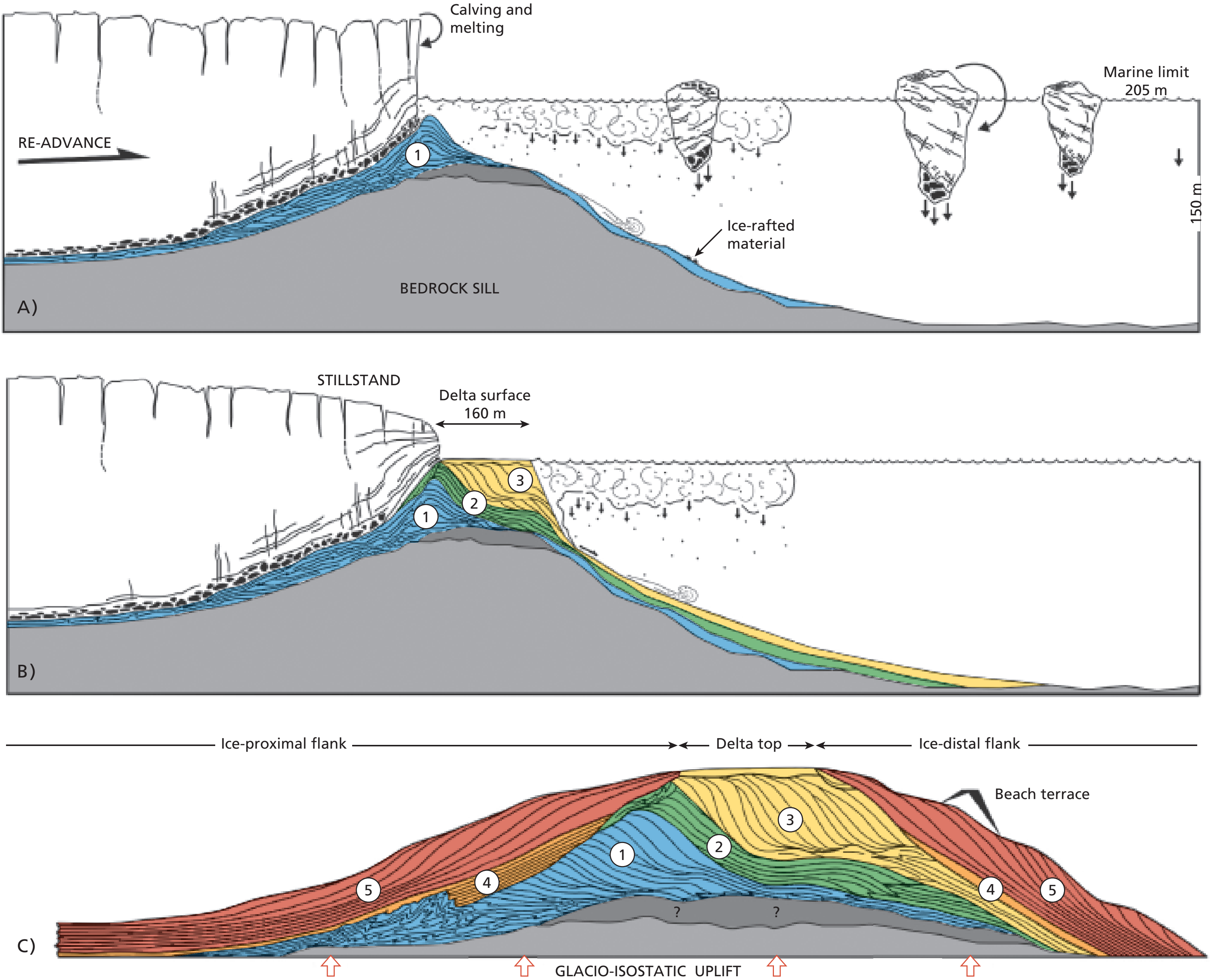


close to Elverum in Hedmark (see text box). We also assume that the high-altitude meltwater channels described above could not have been formed during or prior to the Younger Dryas because the climate then was too cold to be able to melt sufficient volumes of ice so high up on the ice sheet. If this is correct, their formation can thus be dated to between 11,500 and 10,300 years ago. If measured from 1,600 m above sea level to the valley floor, this gives a round figure of about 1,000 m during a period of 1,200 years, or a little less than 1 m of ice per year.

The Hordaland ice-front – back and forth like a pendulum

In Hordaland, western Norway, it appears that the ice sheet had difficulty making up its mind. On two separate occasions the ice-front retreated only to re-advance again prior to the final deglaciation.

The first indications we find of ice-free land areas in Hordaland are the 15,000 to 14,300 year-old fossils discovered in 1941 during the layout of a new cemetery at Blomvåg, west of Bergen. The discovery of huge bones of the bowhead whale caused researchers



FORMATION OF THE MONA RIDGE AT MYSEN. IN PRINCIPLE, THIS IS REPRESENTATIVE FOR MANY OTHER GLACIER-FRONT DELTAS IN NORWAY.

A. The glacier has deposited till and gravels (1) which are then overrun by the advancing glacier and deposited as a moraine ridge. Clay and silt particles are transported in suspension beyond the ice-front prior to sinking to the bottom to form extensive clay deposits. Icebergs release and drop sand and rock fragments onto the seabed.

B. Glacial advance has halted. Glaciofluvial sands and gravels (2 and subsequently 3) accumulate fast so that the ice-marginal ridge is build up to sea level and forms a delta with characteristic foreset and topset beds (3). The glacier margin is now blocked by its own sediments, and is no longer able to calve.

C. Profile through the Mona Ridge today. After the deposition of unit 3, the ice-front retreated and clays (unit 4) were deposited along the ridge flanks. During glacio-isostatic uplift large volumes of sand and gravel were reworked by wave action and draped over the older ice-marginal deposits (5). (Modified after I. Lønne et al. 2001)

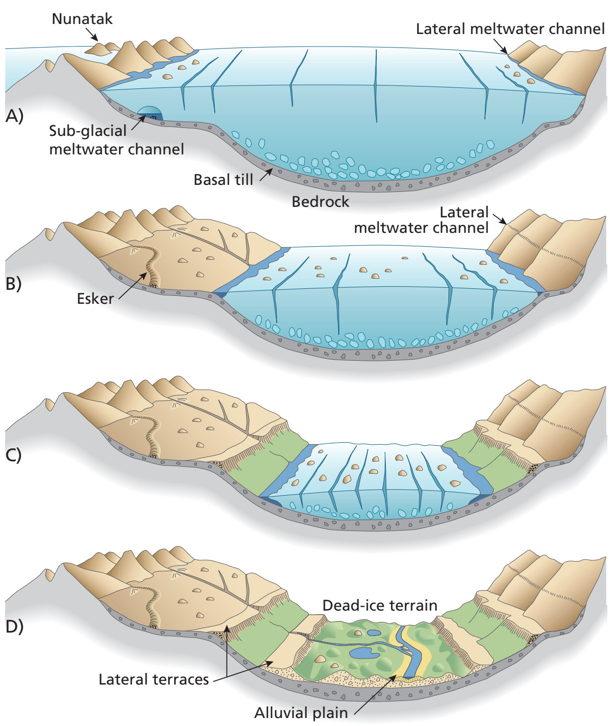
to be notified. A number of other bones and mollusc shells were also found, indicating that the sequence had been deposited in shallow water under similar climatic conditions to those on the coast of Finnmark today. The discovery of reindeer antlers and bones showed that even as early as 15,000 years ago, there was sufficient pasturage to enable these animals to migrate north from Denmark and Germany.

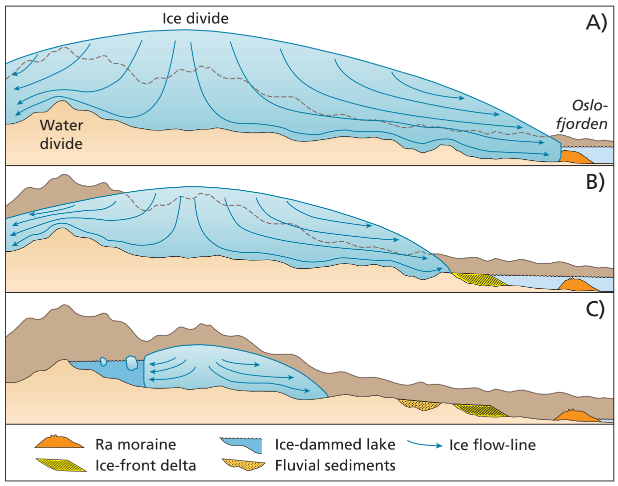
However, the fossil-bearing sequence was overlain by a till, indicating a short-term re-advance during the Older Dryas. Blomvåg is situated on an island close to the open ocean, so the ice-front again terminated offshore.

There are many localities in Hordaland from which shells have been dated to the Allerød interstadial.

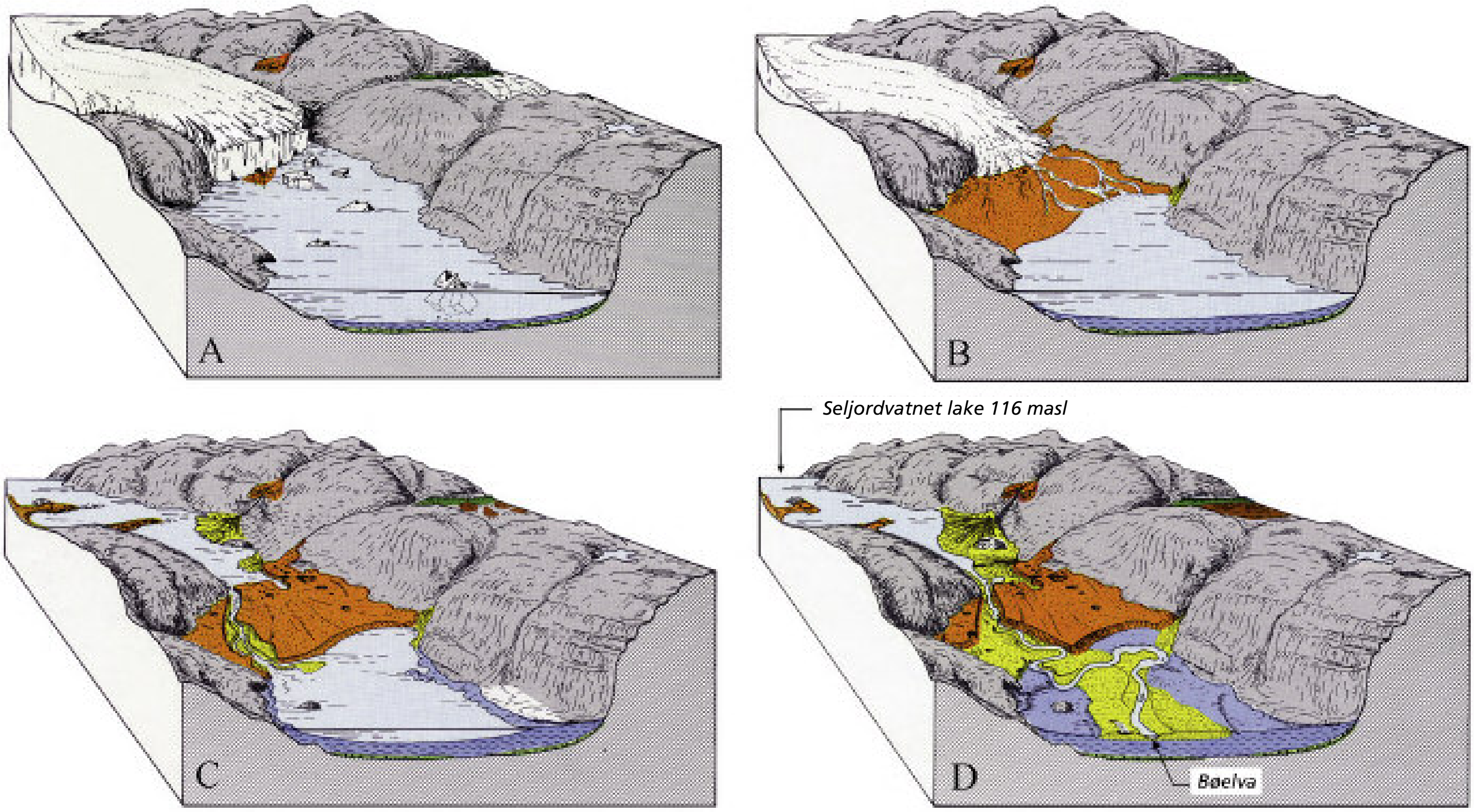
These gently inclined linear features were once the banks of meltwater channels situated between the valley side and the glacier. The most elevated channels are the oldest. The streams followed the ice edge as it receded down the valley sides. It is possible that these relict lateral channels represent annual events. The channels terminate in a crevice incised into the valley side. Water flowing in the channels most probably disappeared into this crevice beneath the ice. View looking towards the Slådal mountain road south of Lesja in Oppland. (Photo: I. Aarseth)

In valleys in Central Norway, glaciers melted vertically downwards. Mountain summits emerged first, and meltwater flowed along the ice margins and formed lateral drainage channels. Streams also flowed in tunnels beneath the ice where sand and gravel were deposited as eskers (A and B). Lateral terraces were formed (C) as material was deposited between the ice and the valley side. The last remnants of the glacier were covered by large volumes of material which was deposited as mounded ablation till, in what is known as dead-ice terrain (D).





Schematic diagrams of the continental ice sheet, from Oslofjorden in the south and across the divide to Sør-Trøndelag in the north. The uppermost stippled brown line denotes the highest mountain summits, while the lower profile denotes the valley floor. Figure A illustrates the situation during the Younger Dryas and the formation of the Ra Moraine. Figure B illustrates a period during the Preboreal when the Aker and Hauerseter moraines were deposited. Figure C illustrates the situation immediately prior to the breaching of the ice-dammed Glåmsjø lake. (Modified from J.L. Sollid and K. Kristiansen)



BLOCK DIAGRAMS SHOWING THE FORMATION OF LATE QUATERNARY SEDIMENTS SOUTH OF THE SELJORDSVATNET LAKE IN TELEMARK. THIS FIGURE IS A GOOD ANALOGUE FOR MANY OTHER VALLEYS.

A. The glacier has melted and calved back from Oslofjorden. Today it is about 60 km from the lake to the fjord, but at that time relative sea level was 134 m higher in the Seljord area, so the sea followed the ice-front inland as it retreated. Calving ceased when the valley became shallower and narrower. Well above the glacier in A is a gravel deposit (orange) which was formed along the margin when the glacier was thicker.

B. Melt-water rivers, most of which emerge from beneath the ice, form a delta composed of sand and gravel within which blocks of glacier ice are buried. Silts and clays (dark blue) are transported and deposited in the fjord. The glacier pauses for long enough for the delta (Herremoen) to be accumulated to above sea level. The ice-front deposit is probably about 11,000 years old.

C. The glacier margin has retreated leaving another two minor ice-marginal deposits (orange), which now form headlands extending into the lake. Because relative sea level is now much lower, the river Bøelva has begun to erode into the ice-front delta. Low-lying terraces are formed along the river and sand is transported and deposited above the clays in the valley floor. At Herremoen several of these glacial river courses are currently preserved, and the buried ice has melted and produced "kettle holes".

D. The landscape today. Herremoen consists of a well drained soil dominated by pine trees, which is typical of many gravel deposits in eastern Norway. The river Bøelva has deposited sand above the clay along the centre of the valley. Tributary streams have also deposited fans both in the lake and along the valley. (Modified after I. Jansen)

RIGHT: View looking north showing an esker northwest of the Haugtjørn pass at Vårstigen in the Dovre region. The mountain Vesle Elgsjøtangen (1,450 m above sea level) is in the background on the right. (Photo: J. Tolgensbakk)

LEFT: A horseshoe-shaped moraine at Kråkenes, just south of Stad in Sogn og Fjordane, deposited by a small cirque glacier (located under the mountain wall in shadow) during the Younger Dryas. A glacial river ran close to where the houses now stand and thence out into the lake seen in the foreground, which contains glaciolacustrine sediments from this period. (Photo J. Mangerud)

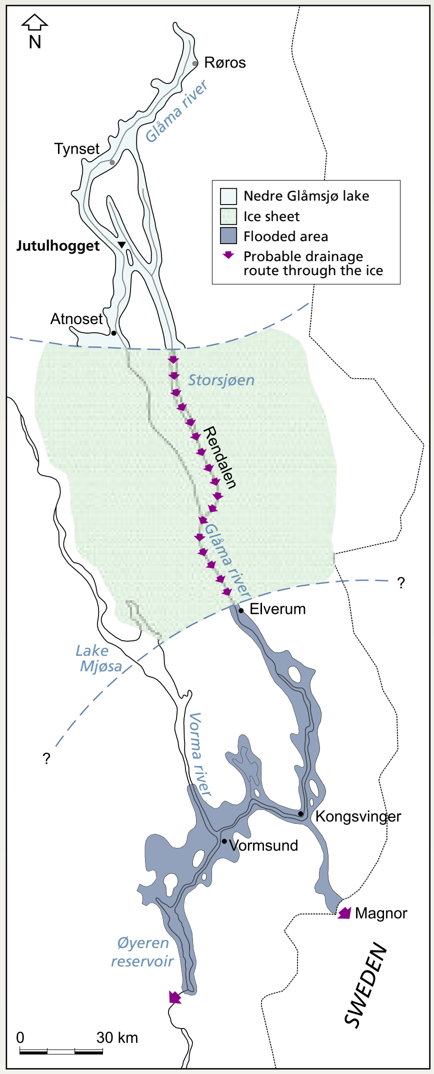
THE GLACIAL LAKE NEDRE GLÅMSJØ AND ITS JØKULHLAUP *By Oddvar Longva*

The term "jøkulhlaup" has been adopted to describe the massive floods that result after the sudden breach of ice-dammed lakes. Such events have been common in Iceland in the recent past. The largest recorded jøkulhlaup in Norway involved the breach of the Nedre Glåmsjø glacial lake towards the end of the last glaciation. The lake was formed between the ice divide in Østerdalen and the watershed to Trøndelag in the north. The outlet was northwards through the small valley Rugldalen, close to Røros. As the ice-front gradually retreated southwards, the lake expanded, extending from Rugldalen all the way to Atnaoset (see the map). During the summers, melting caused large volumes of mud to be transported into the lake. Whereas sand and silt sank rapidly to the lake bed, clay, which sinks much more slowly through the water column, was deposited primarily during the winter when the rivers were frozen. These bedded seasonal glacial lake sediments are locally known as "kvabb". They are composed of pale, sandy, summer horizons, and darker, clay-rich, winter horizons.

When the lake margin reached a point a little south of Atnaoset, the ice dam in the south burst, and the lake was drained. At this point in time, Nedre Glåmsjø was larger than Lake Mjøsa, currently the largest lake in Norway, and contained about 100 km³ of water.

Initially, the water forced its way beneath the ice sheet by melting through a vast tunnel, and the drama of the jøkulhlaupet had begun. Since most of the lake occupied Østerdalen, the breach caused the water to flood over the Barkaldskjølen pass, at first probably either beneath or along the ice sheet, and then later as an open waterfall. Eventually about 90 km³ of water cascaded over the pass, carving out the great Jutulhogget canyon, and depositing an enormous fan of rock debris into the Tyldalen valley.

Flood waters from the Glåmsjø lake then surged down the Rendalen valley and out into the Østerdalen valley again at Rena, where they reached the ice margin and the sea near Elverum. At this time "Oslofjorden" extended all the way north to the ice margin through a narrow channel at the southern end of what is today the Lake Øyeren reservoir. Another arm of the sea extended from Sweden and through a channel that extended between Magnor and Kongsvinger. These narrow channels could not accommodate the rapid surge of flood waters into the fjord. As a result, sea levels rose by about 40 m at Elverum, 35 m at Vormsund and about 30 m at the southern end of the Øyeren reservoir, to the extent that the flood also extended inland reaching lakes Mjøsa and Hurdalssjøen. It has been calculated that the maximum discharge through the Kongsvinger area was about 350,000 m³/sec, or three times that through the Amazon system today. The jøkulhlaup probably lasted for about 14 days.



Distribution of the remains of the ice sheet and the areas flooded after the breach of the Nedre Glåmsjø lake.

Traces of the flood are clearly visible on the clay-rich lowlands of the Vormsund district in Akershus. Extensive areas of agricultural soil are underlain by a thick sequence of flood-deposited silt, locally known as *Romeriksmjelen*, comprising flood channels and sandbanks. In addition, we find great plough-marks left by icebergs that succeeded the flood, together with many 10-100 m-wide circular swamps which occupy kettle holes formed by stranded icebergs.

Jutulhogget in Hedmark, seen from Tylldalen (Rendalen) and looking west towards the river Glåma. During the sudden breach of the ice-dammed lakes at the end of the last glaciation, meltwater eroded deep into the ridge and flowed in a direction towards the camera. (Photo: O.T. Ljøstad)

Dark-coloured plough-marks made by icebergs in the clay-rich lowlands at Vormsund.

The presence of mussels (*Mytilus edulis*), horse mussels (*Modiola modiolus*) and common periwinkles (*Littorina littorea*) demonstrates that the Gulf Stream had returned and gave warm ocean water in much the same way as during deposition of the Blomvåg sequences, although it was not as warm as it is today. Conditions similar to those on the present-day Finnmark coast provide a more correct picture. The easternmost occurrences of shells indicate that in Hordaland, the ice-front was located some distance inland during the Allerød interstadial.

However, what is most remarkable about the shells, or shell fragments to be more precise, is that they occur in basal tills. This means that the glacier had subsequently advanced over the sea floor and partially crushed the shells, but had not managed to grind them down entirely. This indicates that they were only transported for a short distance beneath the glacier. Most importantly, this glacial advance must post-date the shells in the till. Datings indicate that the re-advance started late in the Allerød and continued through the entire Younger Dryas. At the very end of the Younger Dryas, after deposition of the Vedde Ash, the Herdla Moraine was formed.

In Hordaland, the ice-front advanced at least 50 km during the Younger Dryas, and probably much further than this. Glacier ice occupied the deep fjords, reaching thicknesses of up to 1,500 m at locations that had been entirely ice-free during the Allerød interstadial. It has also been demonstrated that a relative sea level rise started in the Allerød and continued throughout the Younger Dryas, but it was restricted to the area from Jæren in the south to Stad in the north. This indicates that both the major glacial re-advance and the relative sea level rise were caused by increased snow accumulation centred on the Hardangervidda mountain plateau and the western Norwegian mountains.

Following the Younger Dryas, the ice-front calved and melted back very rapidly. All western Norwegian valleys contain ice-front deltas which mark locations where the ice-front paused. In each case, the top surface of the delta provides the altitude of the relative sea level when the ice margin halted at the site. Deltas of this type are typically found at the mouths of the tributary valleys of Hardangerfjorden, Sognefjorden and other deep fjords. The reason for this is that ice calved back rapidly in these deeper fjords, leaving the tributary valley glaciers stranded. Near the head of Hardangerfjorden and Sognefjorden distinctive end moraines that can be traced over long distances indicate a halt or probably a re-advance of the ice-front. Since similar re-advances can also be traced at other locations in Norway, the moraines probably resulted from a short-lived climatic deterioration rather than any form of dynamic adjustment on the part of the ice sheet; possibly unlike many of the other Preboreal moraines.

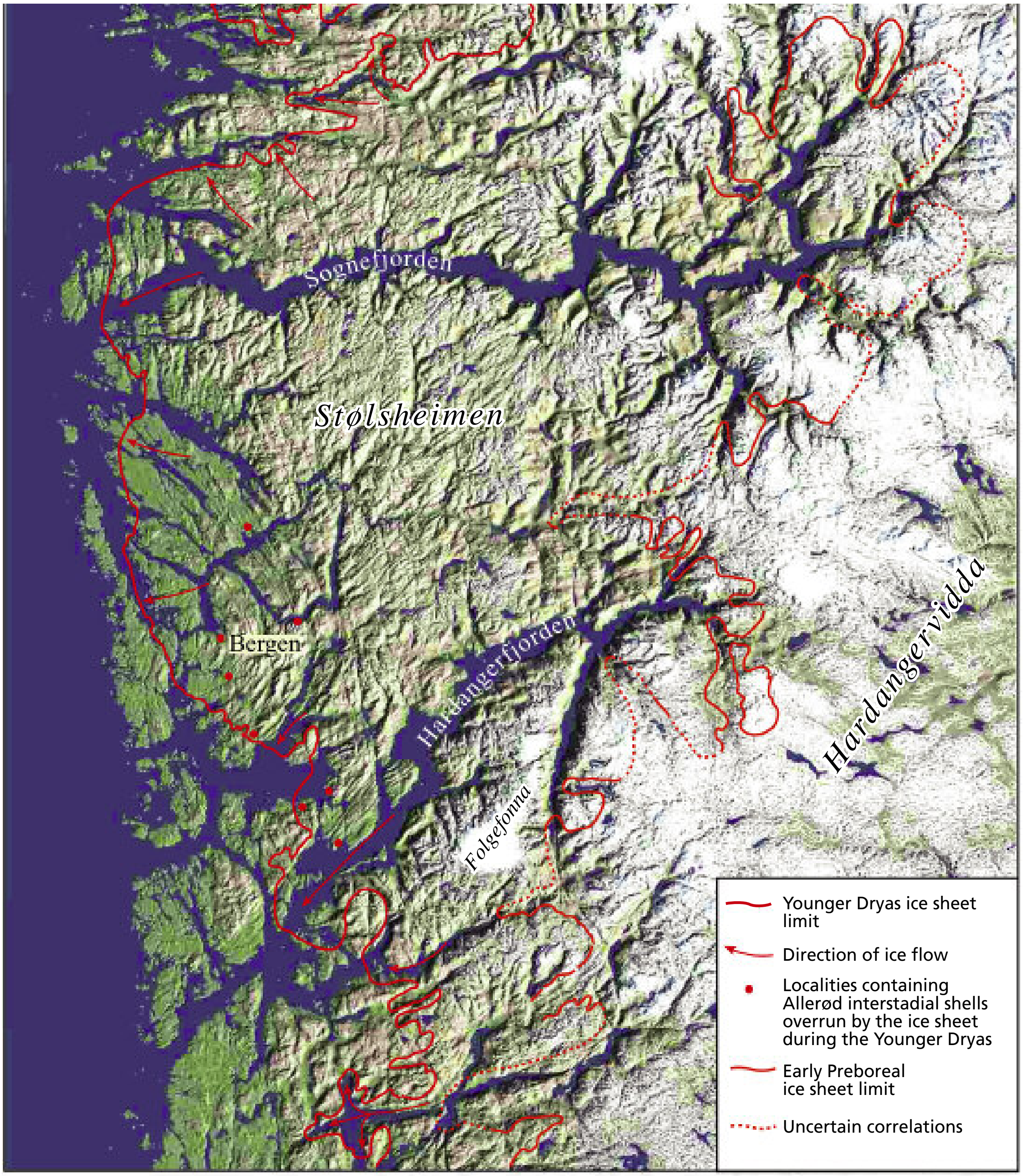
This gravel quarry at Sjøholt in the Sunnmøre region is typical of hundreds found at various locations along the Norwegian coast. It exhibits a meltwater delta with foreset beds dipping towards the sea and overlying almost horizontal topset beds deposited as the meltwater river flowed on top of its own foresets and prograded seaward. The boundary between the foreset and topset beds reflects the sea level at the time of formation; in this example about 60 m higher than today. (Photo J. Mangerud)

Typical basal till exposed near Danmarksplass in the centre of Bergen. The till was deposited beneath a glacier, and is completely unsorted, consisting of all grain sizes from boulders to clay. In the lower part it contains shell fragments because the ice sheet which deposited it during the Younger Dryas had advanced over marine clays of Allerød age. (Photo J. Mangerud)

Glacial retreat in Trøndelag

The Trøndelag region boasts six pronounced recessional moraines which can be traced more or less continuously across the area. The Kysttrinnet moraine of Older Dryas age is located far out on the coast. In the marine clays deposited seaward of Kysttrinnet, bones of the bowhead whale have been found at Utvorda, Roan and Stokkøya. These remains are between 12,500 and 12,200 ^{14}C years old. We are unable precisely to calibrate and convert ^{14}C ages of this magnitude to calendar years, but geologists estimate that the true age is between

Map showing the ice sheet margin in parts of western Norway at the very end of the Younger Dryas, 11,500 years ago. Glacier limits on mountains located just proximal to the ice-front and emergent above the ice as nunataks are not shown. In the upper left, note the southern margin of the contemporaneous, but entirely independent, Ålfoten ice cap. The map also shows early Preboreal marginal moraines in the inland fjord areas (about 10,500 years old). The correlation of the Preboreal moraines is uncertain and the different segments are possibly not strictly synchronous. Local glaciers probably existed on mountain plateaus (e.g. Folgefonna peninsula and Stølsheimen) beyond the limit of the ice sheet during the Preboreal. (Terrain model by H. Fossen, geology compiled by J. Mangerud)



Lateral moraines at Fruo and Hadlet in the Veigdalen valley on the Hardangervidda mountain plateau. These moraines were formed during the Preboreal glacial re-advance illustrated in the map above. (Photo: T. Vorren)

The broad ridge that dams up Eidsvatnet lake (centre of photo) at the mouth of the Fortunsdalen valley, a tributary to the inner Sognefjorden (in the foreground), is an end moraine deposited during the Preboreal (see map on previous page). The low moraine was deposited below sea level, since the relative sea level was then some 100 m higher than it is today. (Photo: Fjellanger Widerøe)

14,000 and 15,000 years. At Utvorda, shells were discovered together with whale bones, both indicating that the climate was very similar to that in the Bjørnøya-western Svalbard region today.

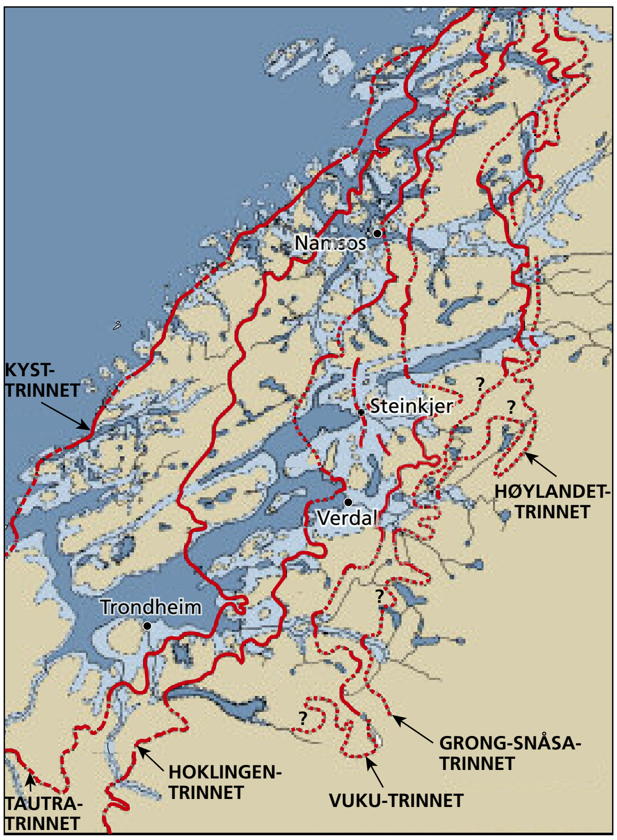
Deterioration of the climate during the Younger Dryas produced two well-defined marginal moraines. The Tautratrinnet moraine was formed by a glacial advance that ended in the middle of the Younger Dryas. The ice margin then receded some distance prior to the formation of the Hoklingentrinnet moraine at the end of the Younger Dryas. This means that the development during the Younger Dryas was similar in the two lowland areas of Trøndelag and Oslofjorden, but different from that in Hordaland where the ice sheet achieved its maximum extent late in the Younger Dryas. This contrast is probably the result of several factors, including the fact that in Hordaland extensive high-altitude mountain plateaus are situated close to the coast, and that western Norway received more precipitation. In the Trøndelag and Oslo areas, greater expanses of the ice sheet remained below the equilibrium line because of the low elevation and less precipitation.

A further interesting similarity between developments in Trøndelag and the west side of Oslofjorden can be seen in map view. If we trace the Tautratrinnet moraine northwards we see that it transects the Kysttrinnet moraine at its northern extremity. Here, at Djupvika in Sør-Trøndelag, there is a gravel quarry containing deposits from both of these events, separated by a clay horizon deposited during the interval when the ice-front was further inland.

In Trøndelag there are three moraines of Preboreal age; the Vuku, Grong-Snåsa and Høylandtrinnet moraines. The distance between the six Younger Dryas-Preboreal moraines is greatest in Trondheimsfjorden which, like Oslofjorden, acted as an enormous calving bay. As the ice retreated, the foreshores in Trondheimsfjorden were situated almost 200 m higher than they are today, promoting extensive calving activity and a more rapid retreat.

Gradually the ice-front retreated east of the principal watershed. Then several ice-dammed lakes which drained towards the west were formed between the glacier and the watershed. Terraces and raised beach-

The island and peninsula in the picture form parts of the Hoklingentrinnet moraine at Straumen in Inderøy, looking towards the southwest. They almost block the small fjord Børgin (in the foreground) from the major Trondheimsfjorden (in the background). (Photo: H. Sveian)

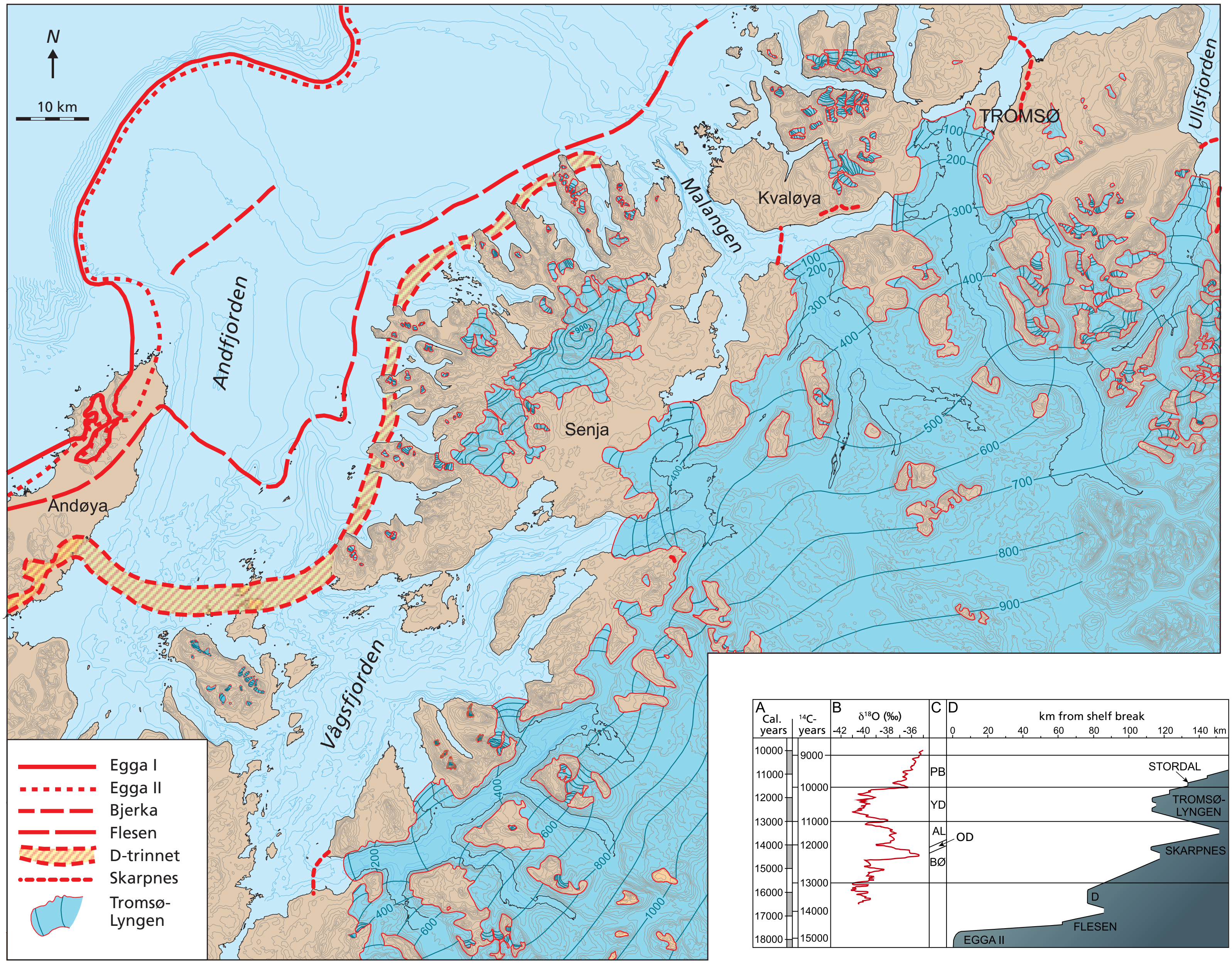


Map of the Trøndelag region showing the main ice-marginal formations. Present day land areas which were below sea level during the deglaciation are shown in light blue. The ages of the various events are about: 14,200 years (Kysttrinnet), 12,500 years (Tautratrinnet), 12,000 years (Hoklingentrinnet), 11,500 years (Vukutrinnet), 11,100 years (Grong-Snåsatrinnet), and 10,800 years (Høylandstrinnet). (Modified from B.G. Andersen)

es can for example be seen today at Klumplifjellet in Lierne in Nord-Trøndelag.

A complete deglaciation history revealed in Vesterålen and Troms

In Vesterålen the ice retreat has been mapped and dated further back in time than at any other location in Norway. This is because a continuous depositional sequence from the Weichselian maximum to the present-day is preserved both on Andøya and offshore in Andfjorden. Early in the 1900s geologists postulated that Vesterålen in Nordland, together with Andøya, must have been released from the ice sheet's grip at an early stage. Researchers at the University of Tromsø confirmed this in the late 1970s and 1980s when they discovered uninterrupted sequences extending back fully 25,000 years in lakes at the northern tip of Andøya. Lake deposits ranging over such a long time span are found only in Germany and further south. With the aid of pollen and other fossils from these sediments it has been possible to construct a climate curve. The curve exhibits several fluctuations, but in general terms



Map showing marginal moraine events between Andøya and the Lyngen Alps. The Egga-I moraine is the oldest. The Bjerkatrinnet moraine was overrun by the younger Egga-II event. The extent of the ice sheet northwest of Andfjorden during events older than the Skarpnestrinnet moraine is uncertain. The ice sheet during the Younger Dryas is marked in blue-green, with ice sheet surface contours annotated in relation to present-day sea level. Several local glaciers were formed beyond the margin of the Younger Dryas ice sheet margin, as was also the case during the Skarpnestrinnet event.

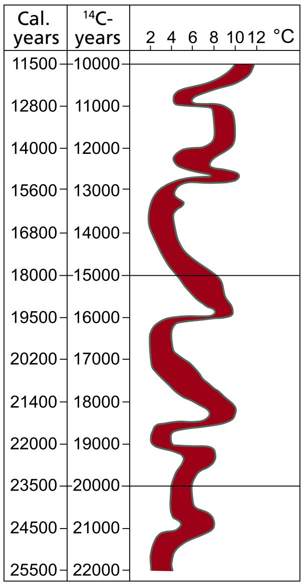
Time-distance diagram from Vesterålen and Sør-Troms. Column B shows an oxygen isotope curve from the Greenland ice sheet illustrating climatic conditions during the same period. There is a good correlation between warmer and cooler periods demonstrated in the Greenland ice core, and ice sheet retreats and advances in Vesterålen and Sør-Troms. (Modified from T. O. Vorren and L. Plassen)

demonstrates an increasingly warmer climate throughout the interval from 25,000 to 11,000 years ago.

Mapping of the moraines and stratigraphic studies both on land and offshore has revealed a total of eight glacial advances, or stillstands of the margin of the continental ice sheet between 25,000 years ago and the end of the "ice age" some 15,000 years later. These have been named Egga-I-trinnet, Bjerkatrinnet, Egga-II-trinnet, Flesentrinnet, "D-trinnet", Skarpnestrinnet, Tromsø-Lyngstrinnet, and Stordaltrinnet moraines. Even though parts of northern Andøya have been deglaciated since the Egga-I-trinnet moraine was formed 25,000 years ago, the ice stream in Andfjorden did not begin its final retreat until about 17,500 years ago. Warmer summers were responsible for initiating the final retreat, aided by rising sea level as a result of melting of the North American Ice Sheet. It was at this time that the ice margin probably started its retreat from the outer continental shelf, in all areas from the North Sea to Svalbard. When the ice-stream in Andfjorden became thin enough to float, it calved back at a rate of more than 300 m per year. However, this retreat was interrupted by two minor

Section through an ice-front delta of Younger Dryas age in Ullsfjord in Troms. The ice-front was located to the left, and the meltwater river flowed to the right, depositing delta sediments in Ullsfjord, where the relative sea level at that time was located about 65 m above today's sea level, equivalent to the level of the top of the delta. (Photo: G. Corner)

advances represented by the Flesentrinnet and "D-trinnet" moraines. There is also fossil evidence suggesting that Atlantic water was present in these areas during the early stages of the retreat.



Curve showing average summer temperatures on Andøya from the last glacial maximum to the Holocene. The curve is based on the analysis of fossil plant remains and pollen found in lacustrine sediments on northern Andøya. It reveals a general warming of the climate up until the Holocene, although this trend was interrupted by several cooler periods. The calibration of ^{14}C-years to calendar years becomes increasingly uncertain further back in the past. In the oldest segments of the curve, errors may be as much as 1,000 years. (Modified from T. Alm)

During the Older Dryas stadial there was a significant glacial advance which in Troms is represented by the Skarpnestrinnet moraine. At some locations, the Skarpnestrinnet is located only a few km outside the Tromsø-Lyngtrinnet moraine of Younger Dryas age, and at others even within it, where it has thus been destroyed by the younger advance. During the mild Allerød interstadial, glaciers calved and melted all the way to the heads of the fjords, and enormous volumes of sediments were deposited. However, during the Younger Dryas the ice sheet re-advanced; in the Vågsfjorden-Andfjorden area by more than 40 km where it severely eroded and reworked the recently deposited fjord sediments. The Younger Dryas glacier response in Troms was thus more like the situation in western Norway than that in Trøndelag and Oslofjorden.

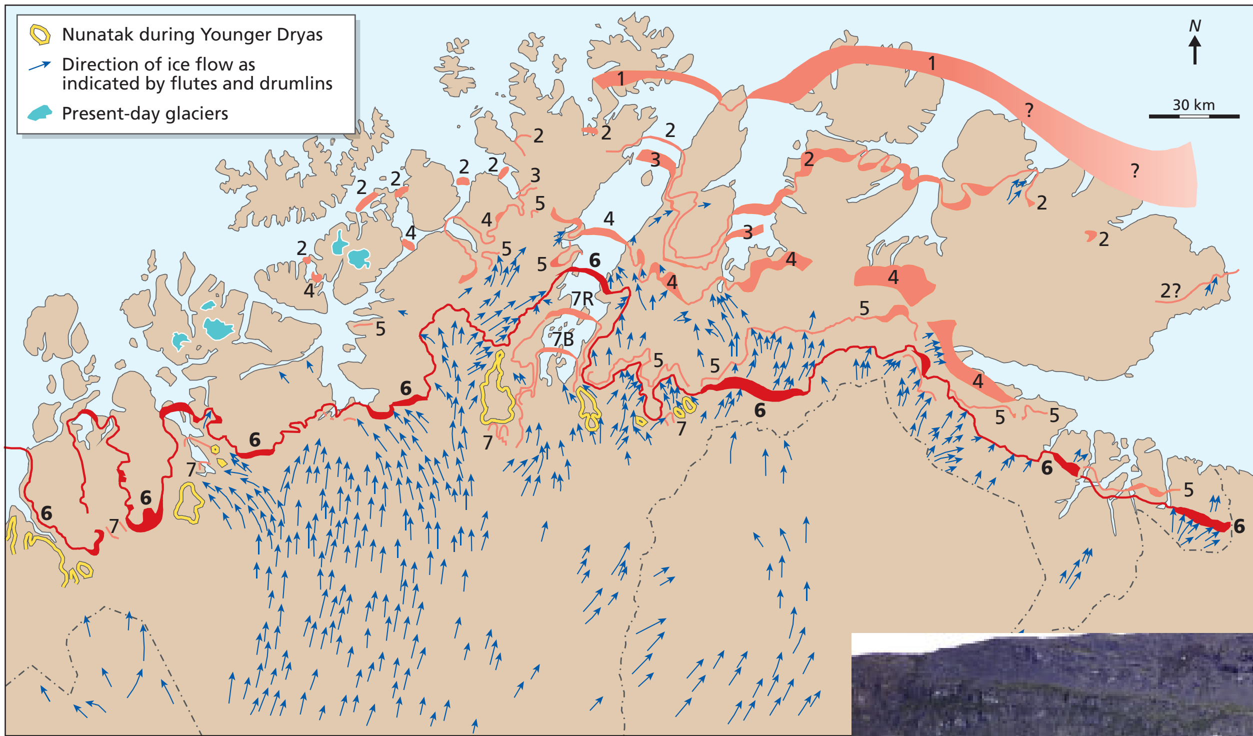
Following the Younger Dryas, the warmer climate resulted in a major retreat, although this was interrupted by minor periods of stillstand of the ice margin during the interval between 11,500 and 10,500 years ago. In Troms, the Preboreal moraines are called Stordalstrinnet, after a locality in Ullsfjord. Three phases of the Stordalstrinnet have been identified and, as elsewhere in Norway, it appears that while one of these represents an interval of deteriorating climate, some of the Preboreal ice-front deltas are the result of a stabilisation of the ice-front at fjord and valley sills.

Marginal moraines across Finnmark

In Finnmark, marginal moraines from the Younger Dryas provide the most conspicuous morphological feature from the deglaciation period. They are collectively known as Hovedtrinnet (the Main stage), and can be traced almost continuously throughout the county. In the west, the Elvebakken moraine in Alta is one of the larger examples, and in the east, Kirkenes airport is constructed on a Younger Dryas ice-front delta. The volume of sediments in the Finnmark moraines is greater than that found in moraines in the other coastal regions in Norway, probably because of more unconsolidated material on Finnmarksvidda in the hinterland.

Several older moraines are identified distal to the Hovedtrinnet moraine, especially in the Porsangerfjorden area. From the oldest to the youngest these are known as Risviktrinnet, Ytre Porsangertrinnet, Korsnestrinnet, Repparfjordtrinnet and Gaissatrinnet. Marine shells, or any other material suitable for radiocarbon dating of the end moraines, have hardly been found in Finnmark. However, it is generally assumed that Gaissatrinnet is of early Younger Dryas age and that the outermost Risviktrinnet may be as old as 18,000-20,000 years. It is a striking feature that the distance between the Finnmark marginal moraines becomes greater towards the east. This may be linked to the fact that the Scandinavian and Barents Sea Ice Sheets continued to be merged in the eastern areas when the oldest moraines were formed.

It is interesting to note that three Preboreal moraines, Rotnestrinnet, Bjørnestrinnet and



Map showing marginal moraines in Finnmark. The most continuous and well-defined marginal moraine system is the Hovedtrinnet (6) of Younger Dryas age. The others are, from oldest to youngest: The Risviktrinnet (1), Ytre Porsangertrinnet (2), Korsnestrinnet (3), Repparfjordtrinnet from the older Dryas (4), and the Gaissatrinnet (5). Some small Preboreal moraines are also shown: Rotnestrinnet (7R), Bjørnnestrinnet (7B) and Korselvtrinnet (7K). (Modified from J.L. Sollid et al.)

End moraine of Younger Dryas age crossing Kåfjord near Alta. The outflow glacier was located to the right.

Korselvtrinnet, have been identified on the high-altitude Finnmarksvidda plateau. These are situated above the marine limit in an area of very gentle topographic relief, so it is unlikely that they represent mechanical adjustments of the ice margin. In the context of Preboreal moraines elsewhere in Norway, we have concluded that *at least* one, most probably the oldest of the Preboreal moraines was the result of a climatic deterioration. A Preboreal climatic deterioration event has been recorded in the Norwegian Sea, and has been interpreted as the result of an influx of glacial meltwater. However, possibly all three Preboreal moraines in Finnmark represent climatic deteriorations.

Disappearance of the Barents Sea-Svalbard Ice Sheet

The oldest Barents Sea fossils post-dating the retreat of the ice sheet are found in the west and north, and are about 16,000 years old. However, these are probably organisms that migrated into the area some time after the beginning of the retreat itself. Ice-rafted detritus and oxygen isotopes in sediment cores from the Norwegian Sea suggest that there was an abundant supply of icebergs and meltwater about 17,500 years ago. There is reason to believe that these were derived partly from calving and melting of the Barents Sea Ice Sheet. It is likely that the Bjørnøya Trough became ice-free during this period and, with an average ice sheet thickness of 1 km, drainage volumes must have been of the order of about 510 km³ annually, equivalent to the discharge through the Mississippi today.

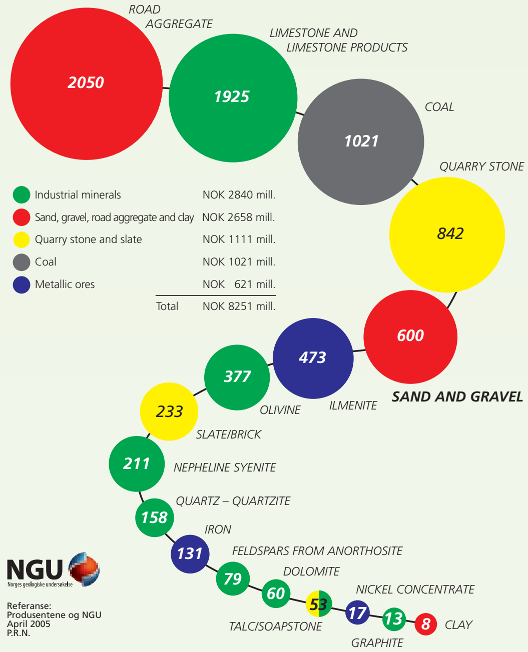
During the Younger Dryas the Barents Sea Ice Sheet was already subdivided into local ice caps centred over eastern Svalbard, Franz Josef Land and Novaya Zemlya. West of Novaya Zemlya, the extent of the Younger Dryas ice-cap is probably marked by the great Admiralty Bank moraines. On the other hand, local glaciers on the west coast of Svalbard were, somewhat surprisingly, smaller than their present-day counterparts. This is different from Younger Dryas development throughout western Europe, and must be the result of limited precipitation, since the summers were cooler than they are today.

Ice recession deposits in Svalbard are radically different from those on the mainland. Ice-front deltas and meltwater outwash gravels, which dominate the mainland fjords and valleys, are almost entirely absent in Svalbard. The main reason for this is that most of the ice in Svalbard was lost by calving of icebergs which then floated out into the sea, leaving no scope for outwash sediments in Svalbard.

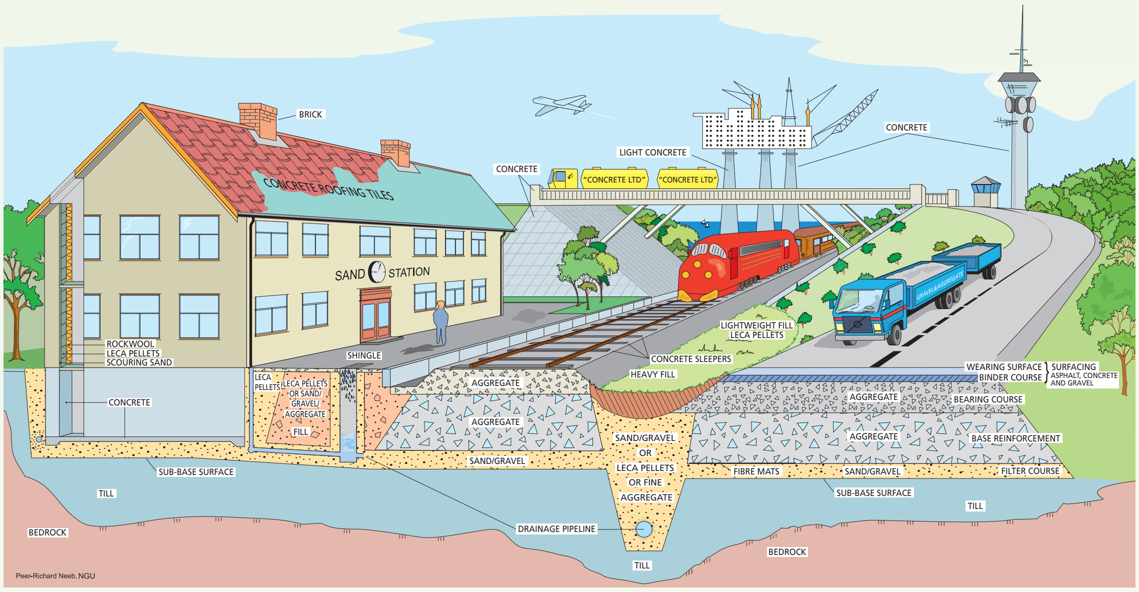
BUILDING RAW MATERIALS *By Peer-Richard Neeb*

Raw materials such as sand and gravel serve a wide diversity of purposes in the building and construction industry. The everyday terms "sand and gravel" describe the unconsolidated sediments which in geological terms are sorted according to strictly-defined grades; *sand* being from 0.06-2 mm, *gravel*, 2-64 mm, and *cobbles,* 64-256 mm. The material is often crushed and sorted into the required commercial grade. In Norway, most material is extracted on land in gravel quarries situated above the water table, but some is taken from rivers and fjord deltas.

Given the magnitude of the resource, building raw materials represent significant commercial value in the long-term, amounting to a total of several hundred million Norwegian kroner. The Norwegian Geological Survey's database ("*Grusdatabasen*" at: www.ngu.no) has registered a total of about 12 billion m³ of sand and gravel above the water table. About 15 million tonnes of sand and gravel are extracted annually, resulting in a turnover of about NOK 600 million for the producers. Annual per capita consumption in Norway is 3.2 tonnes of sand and gravel, and 5.5 tonnes of road aggregate.



Sand and gravel constitute some of the most important mineral raw materials produced on mainland Norway. The value as supplied by the producers (2004, NOK mill.).



The uses of sand, gravel and road aggregate as a building raw material.

In nature, sand and gravel are most often concentrated in deposits where running water has played an important role in the depositional process. Of particular importance are glaciofluvial deposits formed during the retreat of the continental ice sheets. These include recessional moraines, or other delta and outwash deposits formed at locations where meltwater rivers emerge into fjords, lakes or ice-dammed lakes. At some locations, younger, post-glacial, alluvial and beach deposits, and reworked till may be exploited. The industrial quality of sand and gravel deposits is dependent on the mineralogy of the rocks they contain, and on their mechanical properties. The various applications of the raw materials, such as concrete constructions, roads, airports, domestic housing, and so on, all place different demands in terms of quality.

Sand and gravel deposits may also provide valuable drinking water reservoirs. Norway's largest groundwater aquifer is located in deposits of this type at Gardermoen in Akershus, the so-called *Gardermoavsetningen*. Since the land on which sand and gravel deposits are found can have several other uses, such as agriculture, building developments, underground repositories, the cleaning of waste water, and so on, it is not infrequent that land management conflicts arise. Geological information will thus become an increasingly important factor influencing decisions linked to land-use policy.

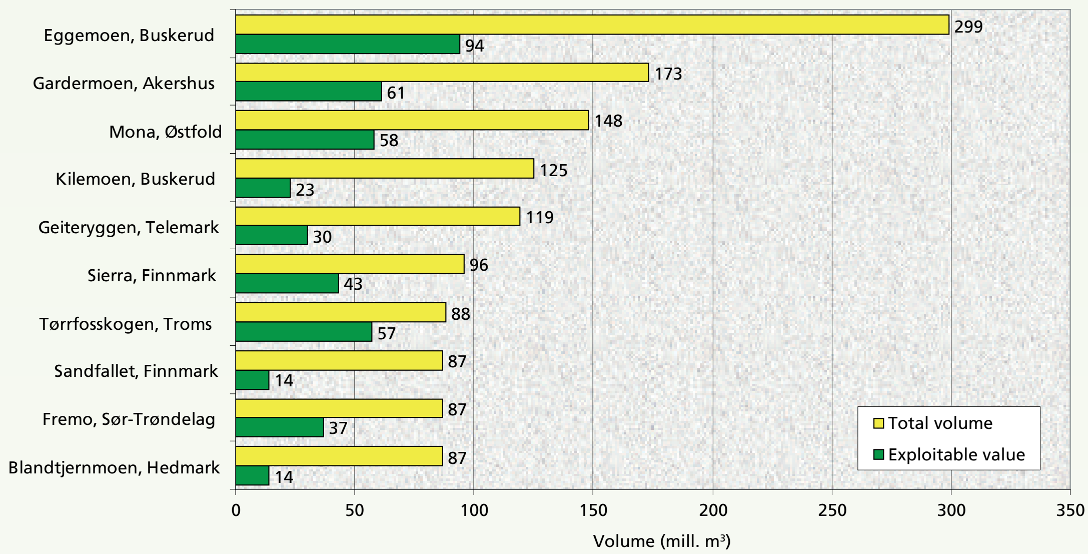
As a building raw material, clay is extracted at Rælingen in Akershus for the production of LECA pellets. In Telemark, clay is extracted for brick manufacture at Bratsberg in Bø, and at Sandnes in Rogaland. In 2004, a total of 230,000 tonnes of clay was extracted, with a production value prior to firing and refining of NOK 8 million.

SAND AND GRAVEL IN THE OSLO REGION *By Peer-Richard Neeb*

The five largest sand and gravel deposits in Norway (ranked according to volume) are located in the southern districts of eastern Norway. In terms of the size of the depositional feature, the Eggemoen deposit at Hønefoss in Buskerud and the Gardermoen deposit near Jessheim in Akershus are the largest in the country. The Monaryggen deposit at Mysen, the Kilemoen at Hønefoss and the Geiteryggen at Skien are all glaciofluvial deposits which contain important volumes of building raw materials which ought to form the foundation for long-term supply policies for the regions concerned. However, the exploitable volumes are somewhat less than the total volumes due to a combination of variable quality, the level of the water table, and land use restrictions.

Gravel extraction from glacial outwash deposits located east of the E6 motorway by the company Grefsrud AS in Jessheim. View looking north.

RIGHT: Map showing the development of pro-glacial unconsolidated sediments at Hauerseter in the Romerike region about 9,500 ^{14}C years ago. Gardermoen international airport is denoted by (G). A glacial outwash delta was formed by the action of meltwater rivers that dumped enormous volumes of rock, gravel and sand from two subglacial tunnels, one at Li (L) – Lisanduren, and the other at Trandum (T) – Trandumsanduren. The material was initially deposited as an ordinary delta in the sea just beyond the snout of the glacier. However, over time it emerged above sea level to form an alluvial plain cut by numerous channels which are illustrated by the black lines in the figure. The highest sea level achieved was some 205 m higher than it is today. Today, the deposit is an important source of building raw materials for the region. (Figure modified after Andersen)



Calculated total and exploitable volumes for each of the ten largest Norwegian sand and gravel deposits.