CHAPTER 16

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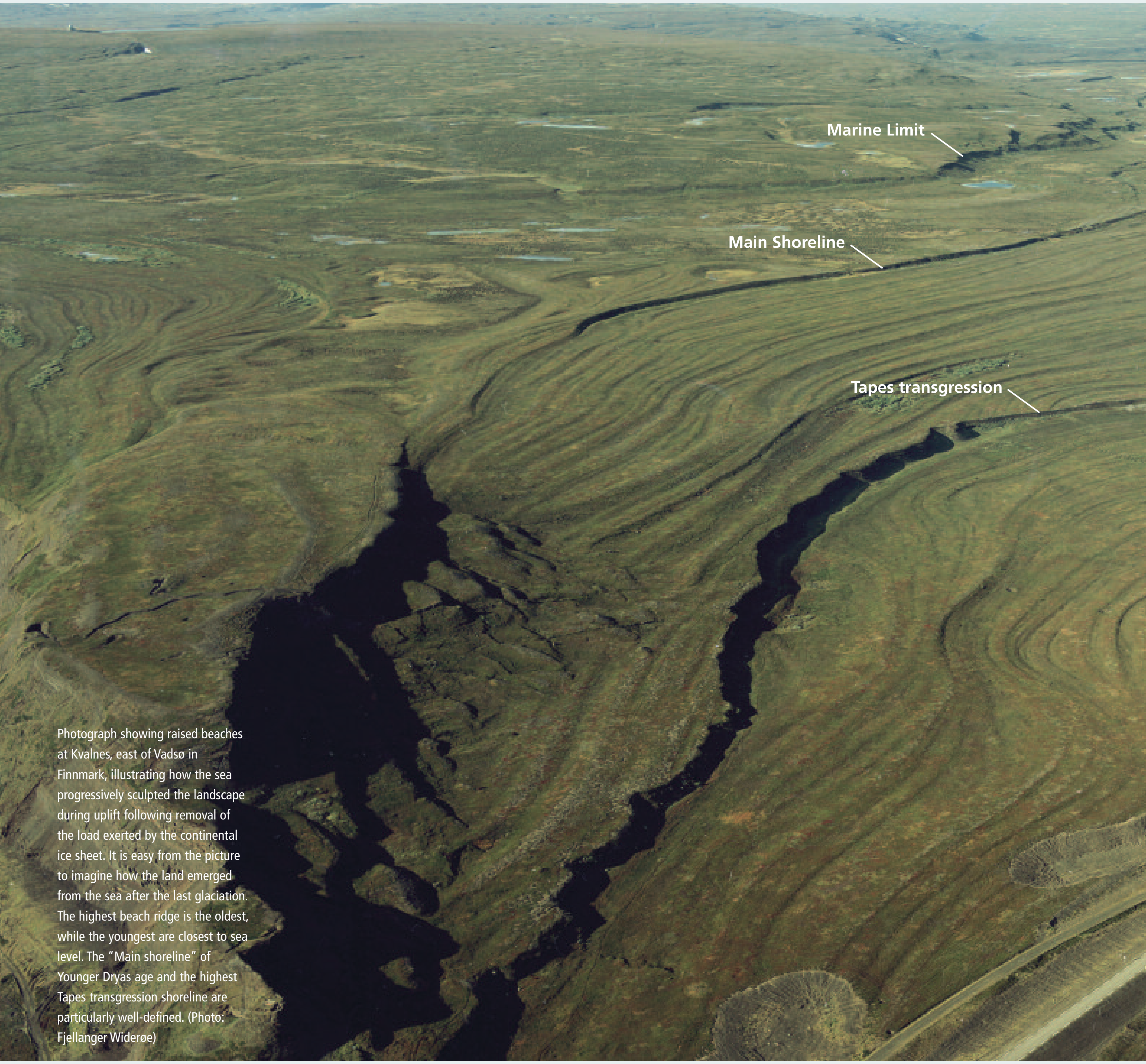
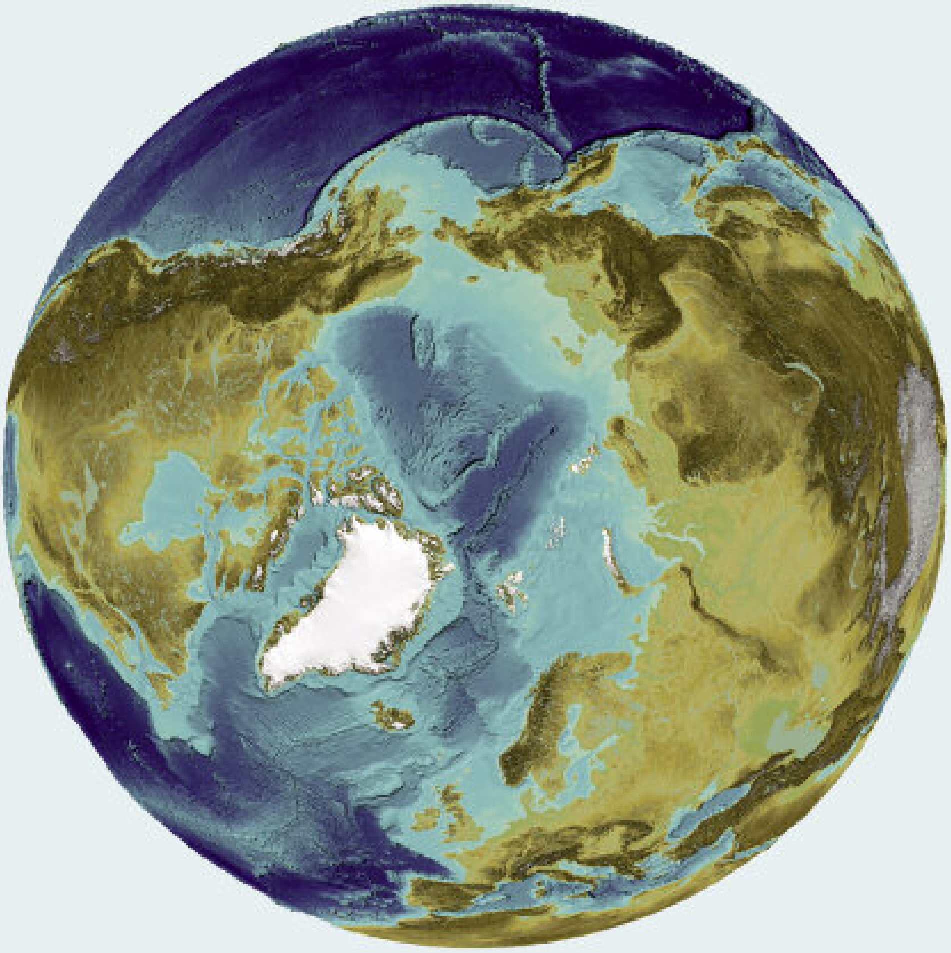


Photograph showing raised beaches at Kvalnes, east of Vadsø in Finnmark, illustrating how the sea progressively sculpted the landscape during uplift following removal of the load exerted by the continental ice sheet. It is easy from the picture to imagine how the land emerged from the sea after the last glaciation. The highest beach ridge is the oldest, while the youngest are closest to sea level. The "Main shoreline" of Younger Dryas age and the highest Tapes transgression shoreline are particularly well-defined. (Photo: Fjellanger Widerøe)

The emergence of modern Norway

The last 11,500 years – the Holocene

Since the "Ice Age", Norway has undergone several changes. The glaciers retreated and almost disappeared before returning once again, and the landmasses have been uplifted. Thousands of landslides occurred in the valley and fjord sides, rivers have eroded valley floors and deposited their sediments in the fjords. Plants, animals and humans have migrated to Norway. Offshore, the Gulf Stream returned and dramatic changes occurred on the sea floor.



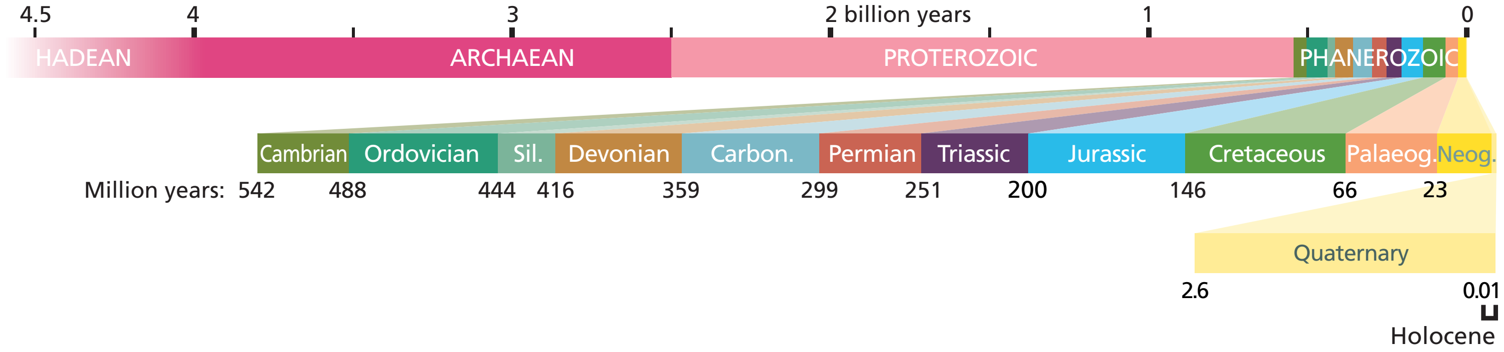
(Illustration: M. Jakobsson)

THE LAST 11,500 YEARS – THE HOLOCENE

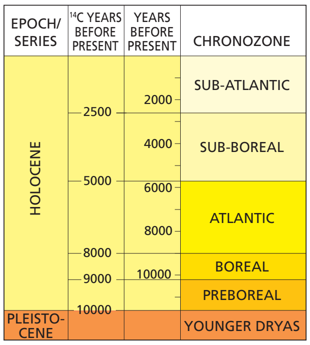
Three principal features characterise Holocene geological development on Earth in general, and Norway in particular. Firstly, the oceans, the crust, and life on Earth had to adapt to events in the wake of the glaciations, not least a global rise in sea level of 125 m in response to the retreat of the continental ice sheets. In Norway, isostatic rebound in response to the removal of the ice load exceeded sea level rise. Europe became green as plants and animals migrated north from their "winter quarters" in the Mediterranean. The same happened in North America. Secondly, humans for the first time began to influence large tracts of the Earth's surface. They cut down forests and cultivated land, in some places resulting in marked increases in erosion. Extensive areas were covered in asphalt and concrete. Today, the great cities can be seen from the Moon. Thirdly, geological processes continue today as they have done in the past. Tectonic plates continue to drift, causing earthquakes and volcanic eruptions. During the Holocene Norway has been subject to great rockfalls and clay landslides, river erosion, delta progradation, and the advance and retreat of its glaciers.

Introduction

The Holocene Epoch represents the last chapter in Norway's geological history.
It is also the shortest, encompassing "only" the last 11,500 years of geological history.



The Holocene is the most recent geological Epoch. Its name is taken from the Greek words *holo,* meaning "complete" or "entire", and *cene* meaning "new" or "contemporary". There are many reasons for paying it special attention. Humans came to exert a dominant influence in Norway, and the climate was subject to some variation also during this period. What can these variations tell us about our future climate? Geological processes, such as floods and landslides, continue to affect us directly.



Subdivision of the Holocene epoch – the last 11,500 years.

We shall begin by describing the processes that took place in the ocean and which influenced climatic improvement and the retreat of the continental ice sheet, which in turn provided habitable living conditions for Norway's first human immigrants. As we saw in the previous chapter, the last remnants of the continental ice sheet disappeared early in the Holocene. In this chapter we shall look at the consequences of glacial retreat, and at isostatic and eustatic movements and the resulting shoreline displacement in particular. These processes both began before the Holocene, but became more conspicuous during this period. We shall see how plant species colonised Norway, and look at what they and the glaciers can tell us about climate history. Geological processes never rest, and the landscape is in constant change, so at the end we shall describe dramatic geological events such as landslides and flood waves.

Holocene stratigraphic terminology is derived from palaeobotanical studies conducted by A. Blytt and R. Sernander at the end of the 19th century. Blytt associated so-called *boreal* and *subboreal* flora with continental climates, and *Atlantic* and *sub-Atlantic* flora with oceanic climates. So although these terms were originally used in a climatostratigraphic context, they have since gained chronostratigraphic status. The table shows a proposal made in 1974, now widely used, in which stratigraphic subdivisions are based on radiocarbon (^{14}C) years. However, the development of precise dating methods and reliable calibrations means that today we can describe Holocene ages directly in terms of "years before present" or "years BC or AD". In this chapter all ages will be referred to in calendar years.

The Gulf Stream and warmer climes

The Gulf Stream, which is largely responsible for making life as we know it sustainable at Norwegian latitudes, returned with full vigour after the last glaciation and gave rise to new life in the oceans and on land.

In the previous chapter we saw that northern Europe's climatic history was closely linked to the development of the Gulf Stream. Previously, it was thought that the Gulf Stream did not enter the Norwegian Sea during the glaciations, but recent research has revealed that even during the glaciations, it periodically extended as far north as Svalbard. However, then the Gulf Stream was cooler than it is today. Its influence was weaker and possibly detectable only some distance from the Norwegian coast. It was only immediately after the last glaciation that it became the massive and stable influence with which we are familiar today.

The full force of the Gulf Stream appeared in Norwegian waters about 11,500 years ago, introducing currents which winnowed the sediments on the continental shelf and upper part of the continental slope. As clay and silt particles were taken up by the currents, sand and gravel remained on the sea floor. At the same time, increased amounts organic remains, including the carbonate skeletons and shells of foraminifera, gastropods and other shellfish, were introduced. Fine-grained particles were deposited in troughs on the shelf, in deeper waters on the continental slope, or in the outer parts of the fjords. For example, Holocene clays reach up to 30 m thick in Andfjord. In general, Holocene sediments are absent on the outer shelf where erosion is active. Along the upper part of the continental slope north of the Storegga slide, it is possible to trace a silt deposit in which small variations in grain size reflect fluctuations in intensity of post-glacial Gulf Stream currents.

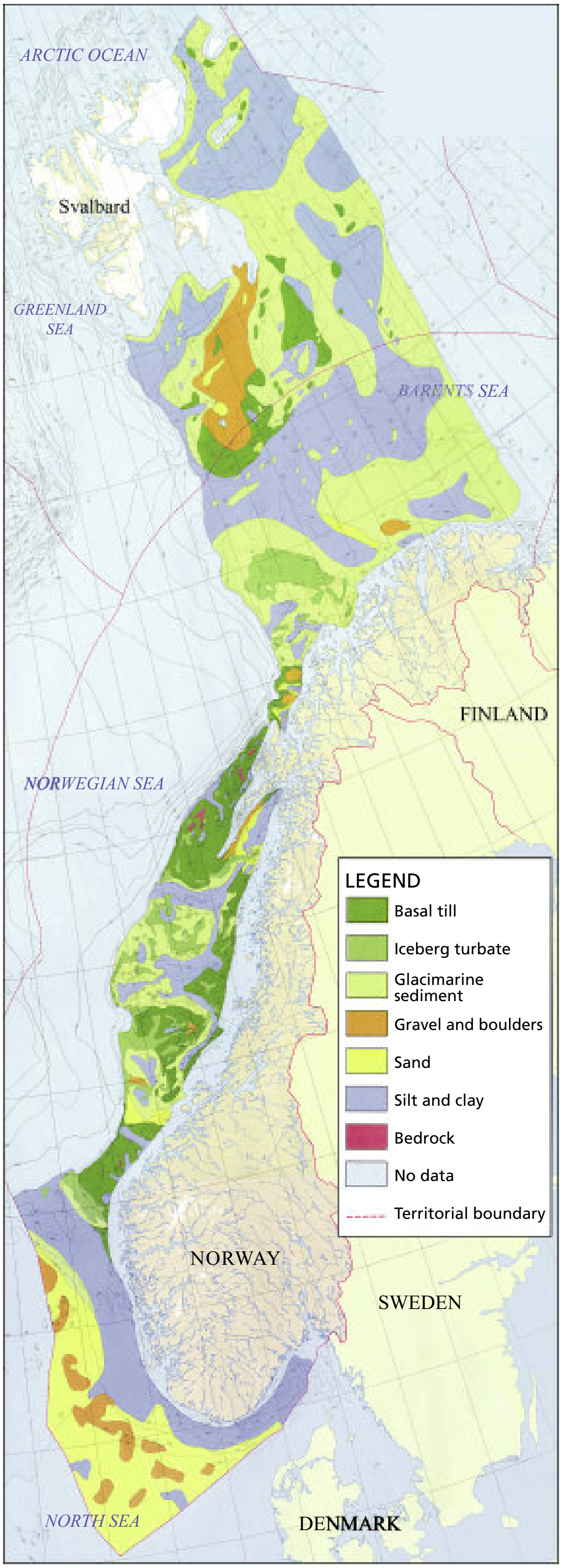
During the Holocene, corals have become important components of continental shelf deposits. Several coral reefs have been discovered during the last two decades, largely as a result of the detailed sea-floor mapping of oil and gas pipeline routes. Coral reefs are traditionally associated with shallow, tropical, waters. However, the Norwegian reefs, which are composed mainly of the cold-water coral *Lophelia pertusa* are found in deeper, and much darker waters. Extensive Lophelia reefs exist west of Fedje in Hordaland, on the Sula Ridge offshore Trøndelag, in the Træna Deep, and in several Norwegian fjords. They thrive best at temperatures between 4 and 8 °C. On the Sula Ridge, the reefs form part of an elongate chain some 13 km in length, up to 750 m across, and up to 35 m high. Recently, a reef ten times larger has been discovered off the island of Røst in Lofoten. In time, these reefs will be transformed into limestones and marbles.

Photographs of coral reefs from about 300 m depth on the Mid-Norwegian continental shelf. LEFT: A red perch swimming among corals. RIGHT: A study of the biodiversity and beautiful colours seen on Norwegian coral reefs. Note also the dead corals (brown) which gradually accumulate to form calcareous sediments. (Photo: M. Hovland)

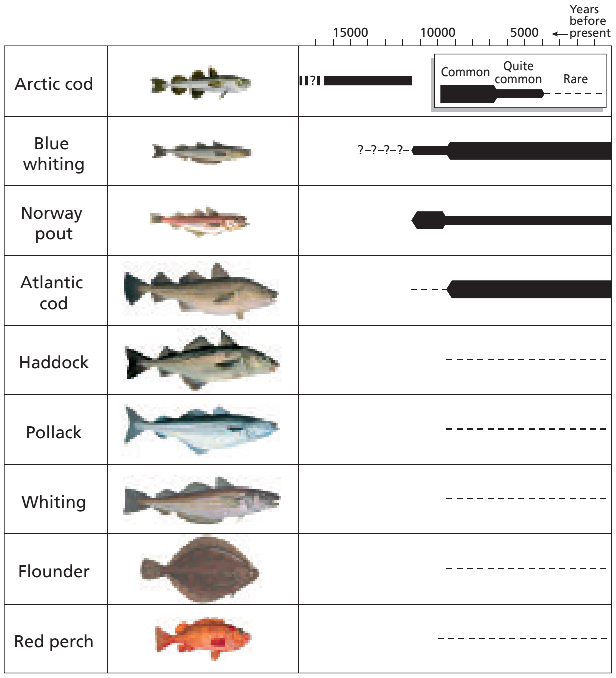
Arrival of the Lofoten cod

The appearance of the Gulf Stream's warm and saline waters promoted a renewal of the marine ecosystems. Many of the shellfish and gastropods which are common along the Norwegian coast today, such as common mussels, horse mussels, and the common periwinkle, can only survive in the warm waters of the Gulf Stream. They were absent during the glaciations, and first appeared along the western Norwegian coast during the mild Allerød interstadial (about 13,500 years ago), but disappeared again with the advent of the cooler Younger Dryas period. It was not until the end of the last glaciation, some 11,500 years ago, that they returned to the Norwegian coast, together with several other species.

What is less well-known is that fish species have also left traces of their movements. Inner-ear bones called *otoliths* are the most resistant parts of the fish skeleton. They are also unique to individual species. The only otoliths found in Andfjorden and the Malangen Trough in sediments deposited from the time of ice sheet retreat and up until 12,000 years ago are those of the polar cod. Today, this species inhabits the waters beneath and close to the sea ice in the northern Barents Sea, having disappeared from the shallow banks offshore Troms when the drift ice retreated northwards. From 12,000 years ago, species such as Norway pout and blue whiting appeared in large numbers, together with smaller populations of Atlantic cod. Atlantic cod did not arrive in large numbers before about 9,400 years ago, from which time it would have been possible to mobilise the great cod fisheries around the Lofoten islands and the fishing banks offshore Troms. It was also at this time that species such as haddock, pollack, whiting and red perch made their appearance.



Map showing the distribution of seabed sediments on the Norwegian continental shelf and in the Barents Sea. (From Vorren and Vassmyr)



LEFT: The figure shows the frequency of otolith fossils in sediment cores demonstrating the post-glacial invasion of fish species onto offshore banks in the Vesterålen and Troms regions.
(Modified from Gaemers and Vorren)

Norway rises from the sea

Many people have wondered how it is possible that sea shells are found several metres above sea level. How did they get there? How old are they? As the sheer weight of the ice sheet was reduced, the land rose and former shorelines and seabed became dry land.

The best-developed ancient shorelines are found in the far north of Norway, and it is here that the most epoch-making discoveries have been made. When the French "Recherche" expedition travelled to northern Norway and Spitsbergen in 1838, it had long been recognised that sea levels had once been much higher, but the causes were the subject of debate. The most common explanation was simply that sea levels had fallen. Then Auguste Bravais discovered that the shorelines in Finnmark were not horizontal, but the individual shorelines were located at increasingly higher levels as one moved inland. From this, it was only a short step to invoke uplift of the Earth's crust as an explanation, and that this phenomenon was greatest where the ice sheet had once been thickest, and least along its margins. Thus, from that time, there was no need to invoke changes in sea levels, although as we now know, paradoxically, global sea levels have in fact risen since the last glaciation.

Close to the principal ice divide above what is now the Gulf of Bothnia, the Scandinavian Ice Sheet was perhaps 3,000 m thick. This exerted an enormous load on the crust, which sank into the molten, plastic aesthenosphere supporting it, resulting in isostatic depression amounting to several hundred metres. At a rough estimate, the specific gravity of ice is one third that of rock, so 3,000 m of ice will produce an isostatic depression of 1,000 m. The lateral displacement of material from beneath Scandinavia caused the land and the seabed beyond the margins of the ice sheet to rise. However, due to the rigidity of the upper crust, both downward and upward movements were accommodated by gentle flexure.

Shoreline displacement – an interaction between land and sea

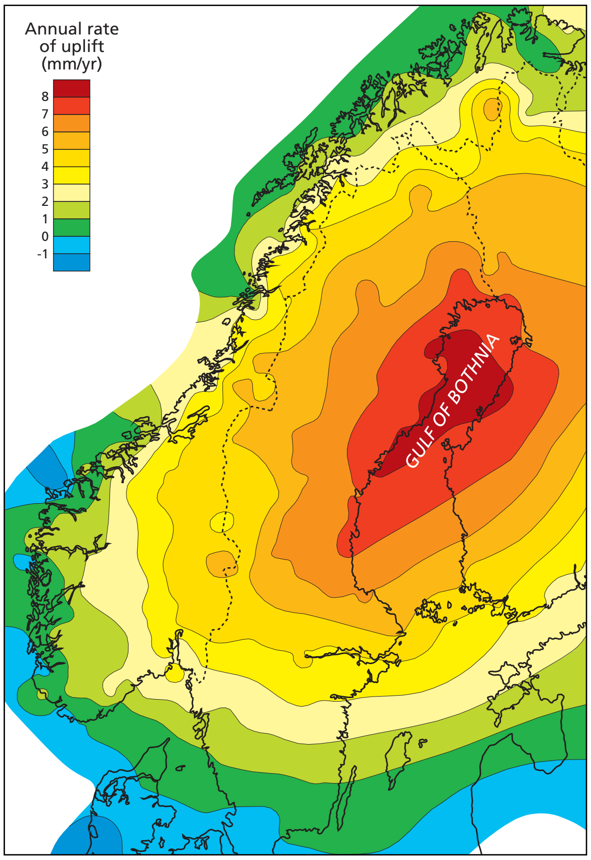
When the ice sheet retreated, the crust began to rise by means of isostatic uplift in order to restore equilibrium. However, molten rock flows very slowly, and uplift did not keep pace with the retreat of the ice. As the ice sheets expanded they extracted water from the oceans and, during the last glacial maximum, lowered global sea levels by about 120 m. As the ice melted contemporaneously with uplift across Scandinavia, water returned to the sea and global sea levels began to rise. However, across much of Norway, and for most of the time, uplift occurred faster than sea level rise, resulting in a *regression*, during which older shorelines were raised and the seabed progressively exposed. Exceptions to this are found in some of the outermost coastal regions. In the period between about 9,500 and 6,500 years ago, sea levels rose faster than uplift during an interval known as the *Tapes transgression*, named after a

Photograph from the coast of Nord-Troms showing the Main shoreline (M) cut into bedrock. The Tapes shoreline (T) is located at a lower level in unconsolidated sediments. (Photo: T. Vorren) shellfish commonly found in beach deposits, and during which the sea transgressed the land. Global sea levels rose during this period due to large volumes of freshwater supplied by melting of the North American and Antarctic continental ice sheets.

Scandinavia continues to rebound at the present day. The rate of uplift is greatest in the Gulf of Bothnia at 9 mm per year, or almost 1 m per century. In the innermost parts of Oslofjord the land has risen by 36 cm during the last century, and by about the same amount in the Trondheim area. In the outer coastal districts of western and northern Norway uplift has most probably ceased. In contrast, the land is sinking in Denmark and the Netherlands in the south. This is due to the fact that, in an attempt to restore isostatic equilibrium beneath Scandinavia, the bulge-like upward flexing of the crust formed beyond the ice sheet during its advance is now gradually sinking back into the aesthenosphere following the retreat of the ice.

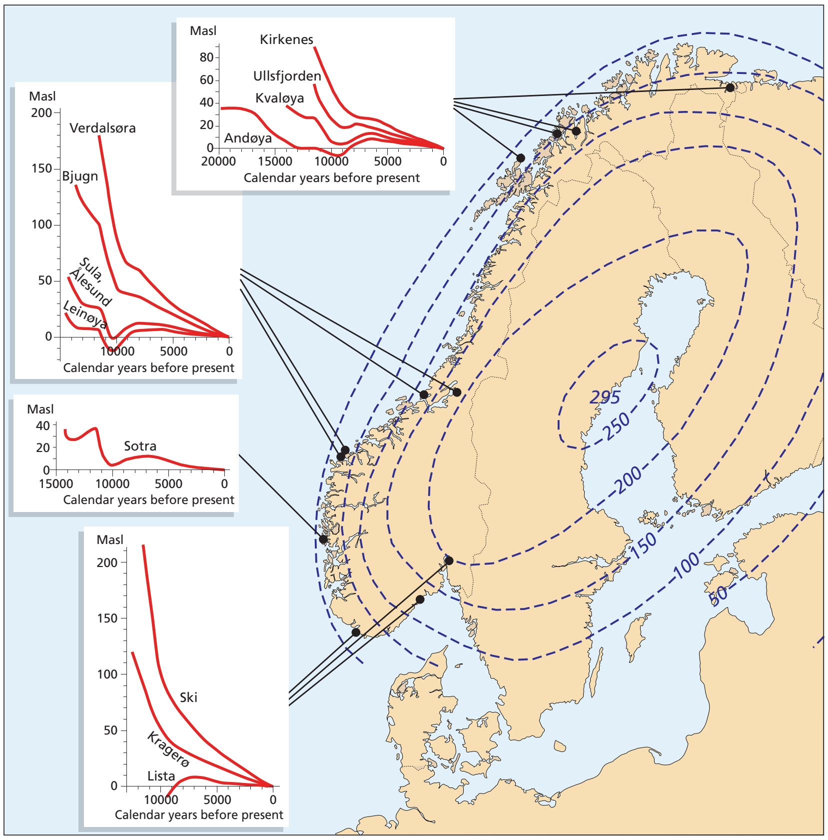
Two distinctive shorelines

The highest recorded post-glacial sea levels are known as the Marine Limit (ML). In general, the ML is lowest in western coastal regions where isostatic depression exerted by the ice was least. For example, in the inner part of Hardangerfjord it is situated at 120 m above sea level (a.s.l.), whereas it is recorded at 60 m a.s.l. in the Bergen area, but at only 30 m a.s.l. on the islands west of Bergen. The highest recorded ML is in Oslo, where it is over 222 m a.s.l.. In the Trondheim area it is at 175 m a.s.l., and at 40 m a.s.l. in Tromsø. At many localities, the ML is clearly defined by an ice-front delta, today often recognised by the presence of a gravel quarry. In general, the ML becomes younger further inland because it was formed along the margin of the retreating ice-front. However, the ML is not a reliable measure of the entire magnitude of continental uplift because uplift itself started as soon as the ice became thinner. Therefore a great deal of uplift occurred while the land was still occupied by glaciers.



Map showing present-day continental uplift. Note that the greatest rate of uplift is occurring in the Gulf of Bothnia – close to 9 mm per year. (Modified from Dehls et al.)

At several localities, there are two shorelines in particular which form characteristic features in the landscape. These are associated with the Younger Dryas and the Tapes transgression, respectively. The Younger Dryas shoreline (the "Main shoreline") was



RIGHT: The dashed lines denote the altitude of the marine limit (ML) across Fennoscandia. The marine limit denotes the highest sea level attained following the last glaciation. It rises progressively towards the Gulf of Bothnia because the ice thickness, and thus also the magnitude of continental uplift, was greatest there. Note that the lines connecting marine limit elevations are not contemporaneous. Coastal areas were the first to become ice-free. As a result, coastal marine limits are the oldest. Relative sea level curves are displayed on the left and illustrate the variation in shoreline elevations at given locations at different times. These demonstrate that while transgressions occurred periodically along the coast, inland areas have been subject to continuous regression.

The distinctive Main shoreline at Kvæøya in Troms (at 40 m a.s.l.), defining the upper limit of cultivated land. Most houses are built at this elevation. (Photo: To-Foto)

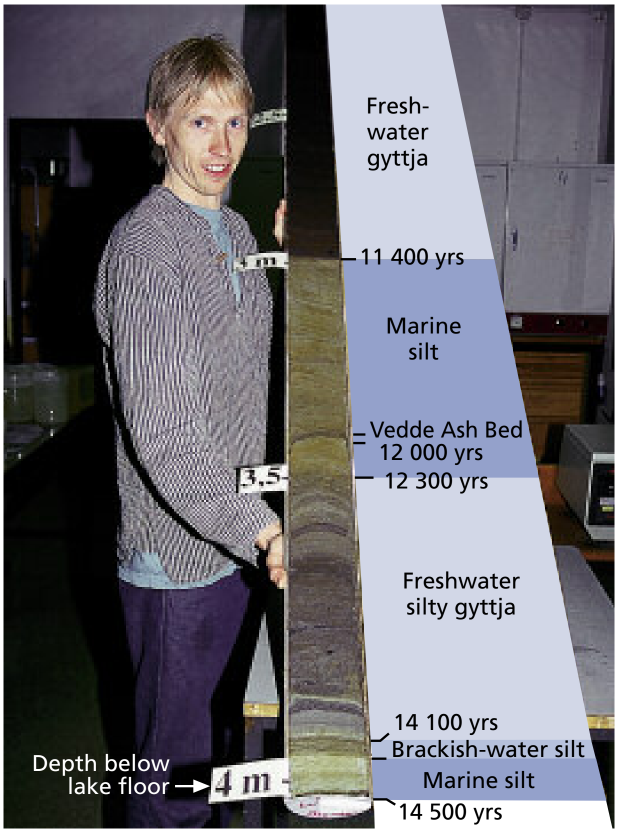
formed during the cold climatic interval between 12,800 and 11,500 years ago and, naturally, these shorelines are found only beyond Younger Dryas terminal moraines. At several localities in northern Norway, the Main shoreline appears as an erosional feature cut into the bedrock, most probably as a result of frost-weathering processes. The Tapes shoreline marks the highest level reached by the Tapes transgression. Where there are unconsolidated sediments, both shorelines form broad terraces or raised banks, and it is quite common to find farms aligned along them.

Driftwood logs from Siberia – at 100 m above sea level in Svalbard

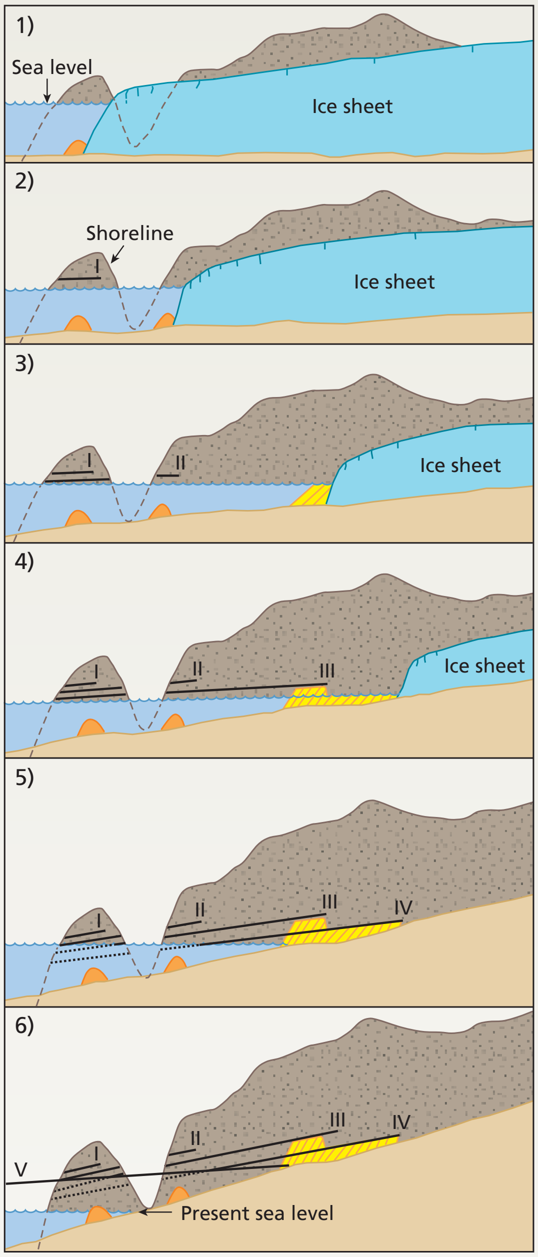
Driftwood logs and whale skeletons are frequently encountered both on present-day beaches and on older raised beach ridges in Svalbard. These are often

BELOW LEFT: A 7,180 year-old driftwood tree trunk excavated at 32 m a.s.l. on a valley side on Edgeøya, Svalbard, indicating the sea level at the time of deposition. (Photo: J. Mangerud)

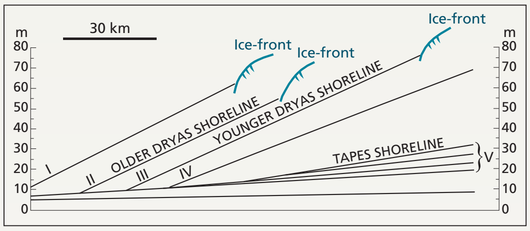
RIGHT: Sediment core from the Langevatnet lake at Drange in Hordaland, illustrating how shoreline displacement is dated. Today the lake is situated at 50 m a.s.l. The marine silt buried at 4 m below the lake bottom was deposited when sea level was some 50 m higher than it is today. This is overlain by sediments containing brackish-water microfossils. From these we know that 14,100 years ago, the shoreline was situated precisely 50 m higher than at present. These are overlain by freshwater sediments that reflect sea levels below the lake threshold until 12,300 years ago. A new marine horizon indicates that sea levels rose sufficiently to transgress the Langevatnet lake once again. This occurred during the Younger Dryas interval, when the ice sheet advanced. At the beginning of the Holocene the ice retreated rapidly and the land was uplifted. Three metres of freshwater muds have been deposited during the last 11,400 years. All relative sea level curves (see figure on previous page) are constructed using cores of this type, retrieved from lakes at different elevations.



ISOBASES AND SHORELINE DIAGRAMS



Geologists describe shoreline displacement using *isobases, shoreline diagrams* and *relative sea level curves (also called shoreline displacement curves)*. Isobases are lines or contours denoting locations of equal uplift since a given point in time. In constructing a shoreline diagram, geologists first draw a profile at right angles to the isobases and project the elevation of successive shorelines onto the profile. By connecting shoreline markers of the same age from different localities, a line is produced showing the elevation of the shoreline above sea level from the present-day coast to the inner fjord areas and fjord valleys. Of course, a shoreline can only be formed after the area is deglaciated. The oldest shorelines are thus found only in the outer coastal areas which were the first to become ice-free after the last glaciation. The figure (left) shows the development of shorelines along a profile extending from the coast and landward along a fjord. As the ice sheet retreats, the land is subjected to uplift, and successive shorelines are developed at lower elevations. During one interval, sea levels rose more rapidly along the coast than the landmass was uplifted. The earlier developed shorelines were transgressed during an event known as the Tapes transgression. The Tapes transgression is most noticeable along the outer coast, and can be traced as far inland as the point where isostatic uplift has always exceeded eustatic sea level rise.



Simplified shoreline diagram from western Finnmark. Roman numerals correspond to the figure (left).

very well preserved due to the cold climate. Tree trunks enter the sea at the mouths of the great Siberian and northern Russian rivers, and are then carried frozen in the drift ice across the Arctic Ocean. After two to three years they reach Svalbard's beaches where they can be exploited by huntsmen and scientists alike. Researchers have dated driftwood and bones from stranded whales at various elevations above sea level and have reconstructed shoreline displacements in Svalbard during the last 13,000 years. The results show that the centre of uplift, and thus also the location of the Barents Sea Ice Sheet's principal ice divide during the last stages of the last glaciation, was located to the east, close to Kong Karls Land or, most probably, in the ocean east of the archipelago.

Reshaping the old seabed – river erosion and clay landslides

Glacio-isostatic rebound has resulted in the emergence of several thousand square kilometres of new land. This has mostly consisted of ice-polished rock, but clay flats, strand plains, till and sand and gravel deposits also emerged. Today, most of Norway's inhabitants live on a relict seabed.

As soon as the seafloor emerged, it became subject to erosion by rivers and streams. The rivers excavated new valley floors at increasingly lower elevations, reworked large volumes of former seabed clays, sands and gravels, and transported them to deltas and out into the fjords. Gradually, steep slopes were carved into these sediment masses, triggering innumerable clay landslides of different sizes.

As long as the rivers eroded into relatively unconsolidated deposits such as clay or sand, erosion itself, and denudation of the valley floors, kept pace with sea level changes. In this way shoreline displacement controlled landscape development far inland along the valley systems. However, at locations where resistant bedrock obstacles led to the formation of waterfalls and lakes, features such as these determined the elevation of river courses higher up the valleys. In such cases, levels of erosion became independent of uplift.

Shoreline displacement was so rapid during the first 2,000 years after the retreat of the ice (6-7 m per 100 years in Trøndelag and eastern Norway) that it promoted intense fluvial erosion. This is reflected in the abundance of coarse-grained sand and gravel ter-

Fjord bottom sediments are the foundation of this undulating agricultural landscape at Kvål in Gauldalen, including ravines and relict landslide features. Landslides and ravines have eroded into the clay flats after they were uplifted. The boundary between cultivated land and the wooded hills denotes the maximum elevation of sea level (marine limit) immediately after the ice sheet had retreated. (Photo: H. Sveian) races. Later, when rates of uplift declined, rivers adopted graded, less-steeply inclined profiles, and transported mostly sand or finer-grained material.

Several valleys have changed so radically in appearance that Stone Age humans would find our modern landscape unfamiliar. Shoreline and river outlets have moved several tens of kilometres down the major valleys. Rivers continued to reshape the valleys, and the remains of earlier valley floor features can now be seen as relict terraces which, under favourable circumstances, can be used to reconstruct previous generations in valley development. Such landscape reconstructions provide an important basis for unravelling our archaeological and cultural heritage.

Eastern Norway and Trøndelag – dominated by clay deposits

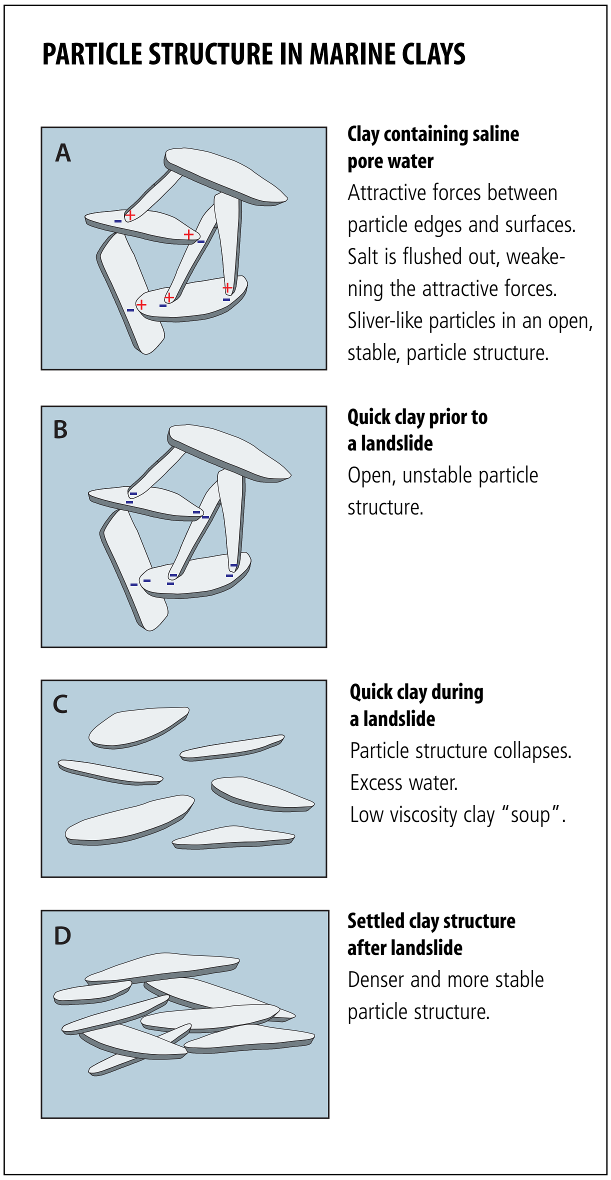
Most marine clays in Norway were deposited during the retreat of the major ice sheets. At some localities in the lower parts of major valleys, close to the end moraines, clay thicknesses can be greater than 150 m. They were deposited very rapidly. For example, in the inner part of Verdal in Nord-Trøndelag, 50 m of clay was deposited during a period of no more than 500 years, equivalent to a rate of at least 10 cm per year. The most extensive marine clay deposits are found in the lowlands of eastern Norway and Trøndelag. It is also here that we find the most elevated marine limits (ML) combined with large areas of relatively flat lowlands. In southern Norway, the ML is too low, and in western Norway the terrain too steep, for extensive clay deposits to have been preserved on land. In these areas, they are found on the seabed within the fjords. In northern Norway, however, valleys such as Målselv in Troms and Korgen in Nordland are occupied by large volumes of marine clay.

Today, clay landscapes are intensely incised by erosion, and are characterised by V-shaped ravines, saucer-shaped slide scars, and relict ridges, although agricultural levelling in several areas has removed many of their original erosional landscape features.

Quick clay!

Under certain circumstances, quick clays can form within marine clay deposits, usually within zones or “pockets” of varying size where ion-deficient fresh water has gradually replaced the original saline pore waters.

A minor slide on a steep slope may be sufficient to trigger a massive quick clay landslide almost instantaneously. When quick clay loses its support, its internal structure collapses, and it starts to flow. The landslide then rapidly propagates backwards. In the presence of excess formation water, the viscosity of clay decreases instantaneously, and it flows as a soup-like liquid, carrying with it rafts of dry and brittle topsoil. Rafts such as these have saved many a human life. After the landslide, when the clay settles, the rafts form low-relief mounds, and relict landslide terrains can often be recognised by their gently undulating surfaces. Slide scars are often pear-shaped with a narrow outflow channel.



Transformations in clay particle structure from original deposition, via landslide behaviour, to redeposition.

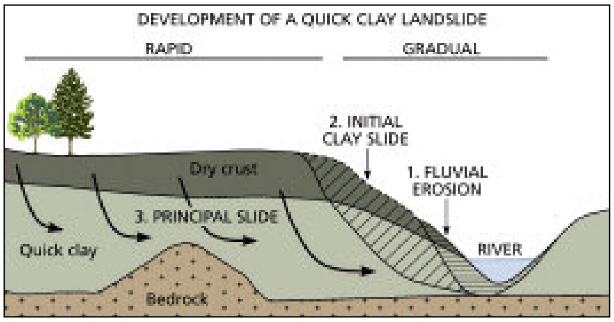
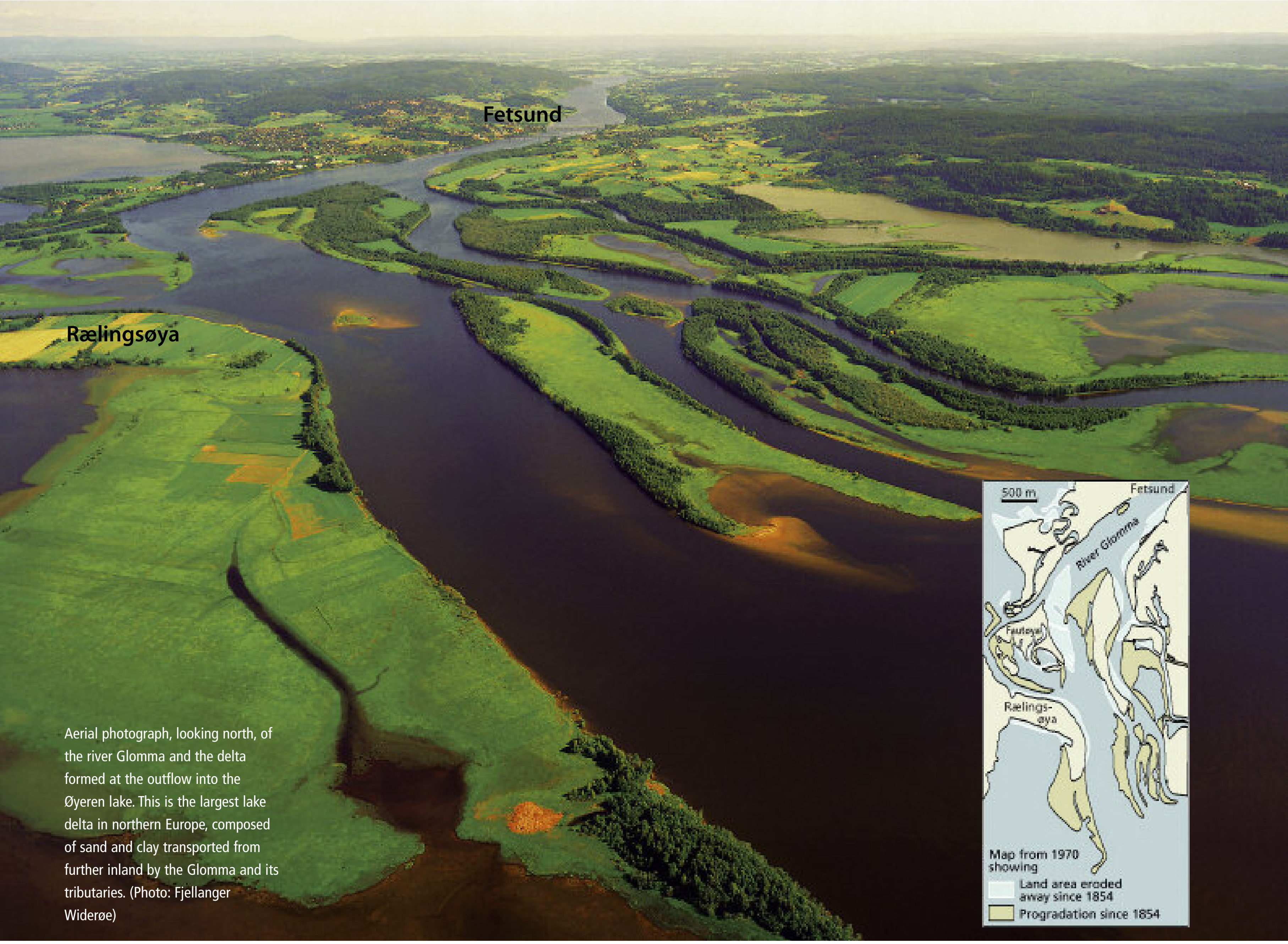


Figure showing the normal progression of a quick clay landslide. The process is triggered by river erosion (1). This results in an initial landslide within the clay mass (2), followed by the main landslide (3). (Modified from N. Janbu et al.)



Aerial photograph, looking north, of the river Glomma and the delta formed at the outflow into the Øyeren lake. This is the largest lake delta in northern Europe, composed of sand and clay transported from further inland by the Glomma and its tributaries. (Photo: Fjellanger Widerøe)

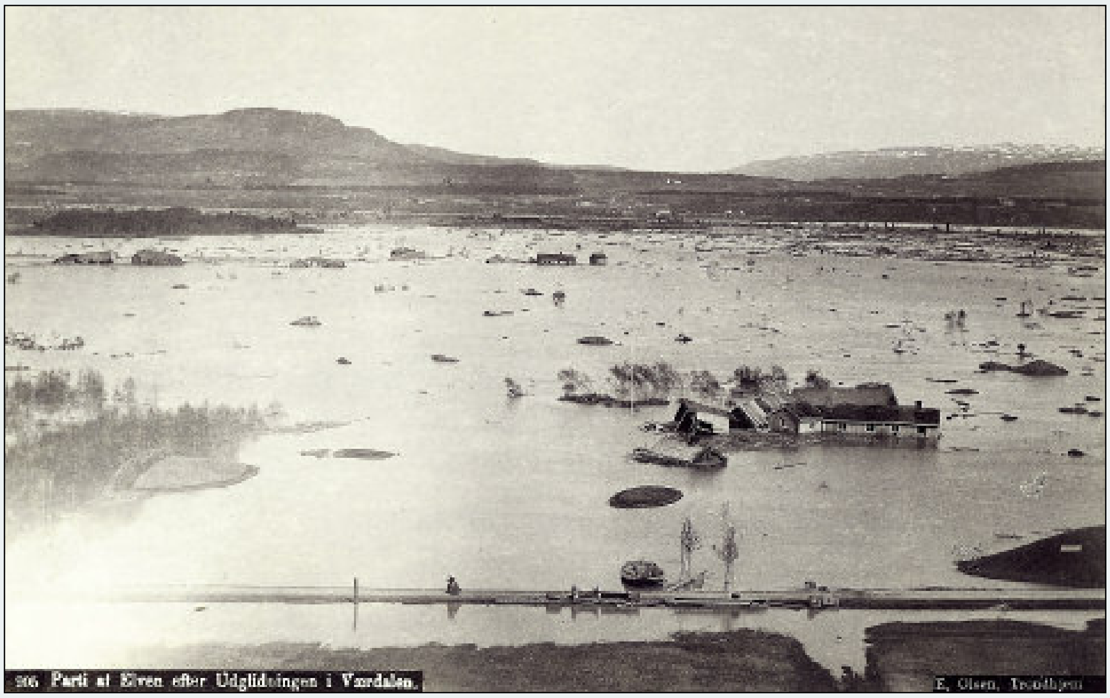
INSET: Map showing approximately the same area as in the oblique-angled photograph, illustrating how the delta has changed since it was surveyed in 1854. Note that the river Glomma has eroded Fautøya island, and has deposited an equivalent area of new sediment on the inner meander bends. The delta appears to have prograded several hundred metres into the Øyeren lake, although this may be exaggerated because the 1854 map counted less wetland area as "dry" land than the 1970 survey.

In Norway, terrible tragedies involving massive quick clay landslides have occurred both in prehistoric times and in recent history, although only a few of those mapped by geologists are identified in written or oral sources. Mapping has revealed that in the more extensive clay areas, slide scars are closely spaced together. In Verdal municipality alone, approximately 100 such scars have been identified, and many of these are very large. There are also several in the Romerike area. This simply confirms that, from a geological perspective, quick clay landslides are normal occurrences even though many years may elapse between major events.

Quick clay landslides are most frequently caused by a river eroding into the foot of a slope, and "puncturing" quick clay zones. Some may have been triggered by earthquakes, and excavation or quarry infill by humans has also generated landslides. Thousands of Norwegians are living in quick clay areas. This should provide no cause for concern provided they do not disturb the terrain inadvertently. Safety measures include the control of erosion by redirecting river courses, into drainage ducts if necessary; the removal of unconsolidated sediment from vulnerable localities in order to reduce undue loading; restraint from excavation at the foot of slopes; the construction of stabilising counterweight berms; the addition of salt into clay deposits, and so on. With safety in mind, it is important to be aware of where quick clay deposits are located.

THE 1893 VERDAL LANDSLIDE

"*Shortly after we got up speed again I saw the other topsoil raft being torn to pieces. In their desperation, father and brother Annæus fell to their knees and prayed to God for help, but they sank at once into the clay, which then closed over their heads. I saw a hand come up but then everything disappeared. We stopped soon afterwards but we didn't know where we were.".* This was how one eye-witness described the dramatic and tragic loss of a father and brother.



The valley floor at the site of the Verdal landslide seen from the southern side of the valley. River water has flooded over the landslide itself.

The massive quick clay landslide in Verdal in 1893 represents one of Norway's greatest natural disasters. The entire slide was generated during a three quarter of an hour period just after midnight on 19 May 1893. A clay "soup" spilled across the plain in the valley floor "faster than a horse can gallop". It has since been estimated that an almost incredible volume of 55 million m^3 of material flowed with a velocity of between 70 and 80 km/h. The slide scar occupied about 3 km^2, and the slide itself flowed out over an area of about 8 km^2 across the valley floor. Both humans and animals were carried away on topsoil rafts or the remains of their destroyed houses and roofs, some as far as 6 km. Of the 250 people who lived in the area affected by the landslide, 116 lost their lives. Altogether, 105 buildings were destroyed. The landslide dammed up the Verdal river producing the so-called "Vuku lake", which occupied an area of about 3 km^2, and which gradually drained away after a few weeks. The river excavated a new course above the clay mass and gradually eroded down through the landslide to its previous level. Later, in September, a smaller landslide occurred towards the rear of the larger slide. This alone was as large as the 1978 Rissa landslide and, once again, the river became dammed up, although on this occasion the "Vuku" lake remained for the entire winter.

Material damage following the Verdal landslide amounted to a staggering sum. The Norwegian parliament immediately granted emergency aid, and the extent of fund-raising activities and offers of relief from both home and abroad reflected the attention that the disaster had aroused. Today, the material costs of such a landslide would run into billions of Norwegian kroner.

SOIL FORMATION IN NORWAY

By Rolf Sørensen

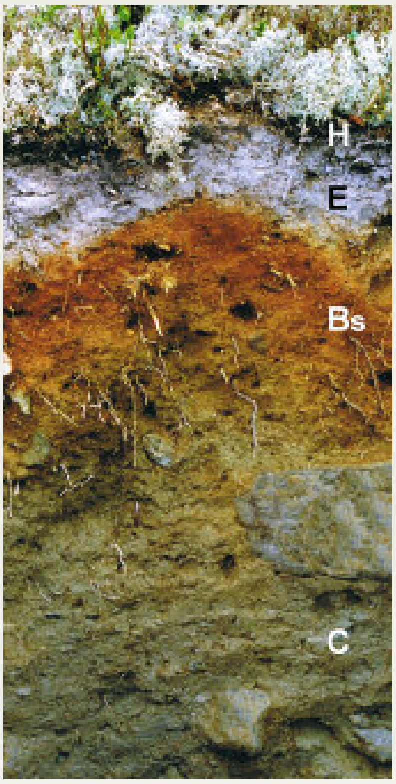
The remnants of weathering-profiles, or paleosols, have been reported on the Sub-Cambrian Peneplain, at several horizons within Mesozoic successions on the continental shelf and in Svalbard, and on "the Palaeic surface" on the Norwegian mainland. Remnants of deep weathering are reported from several locations, although local hydrothermal alteration may have provided an alternative mode of formation in some cases.

Norway's present-day soils began to form during the last deglaciation, and when the glacio-isostatically submerged coastal areas became dry land during the Holocene regression. However, in some localities characterised by interstadial or inter-glacial sediments, such as Hardangervidda and Finnmarksvidda), weak paleosols have been recognised. In the earliest deglaciated land areas, such as Jæren and in northern Troms and Finnmark, soil formation began as early as *Allerød* time, some 12,800 – 14,000 years ago, as vegetation became established under the influence of mild climatic conditions. However, during the subsequent, cold, *Younger Dryas* event some 11,500 – 12,800 years ago, most of the virgin soils were disturbed by solifluction, much as they are in the high mountain areas and in Svalbard at the present day. In Norway, glacial tills, normally transported only a few kilometres by the ice masses, form the dominant 'parent material' for soil formation, and soil composition reflects to a large degree the properties of the underlying bedrock. In regions where permeable parent materials are poor in plant nutrients, soil formation was rapid, and podzolic soils were developed a few centuries after deglaciation. In areas with more fertile parent materials, deciduous forests dominated during the 'Holocene climatic optimum'. Deciduous forests produced less acid humus and a more favourable environment for macro- and micro-organisms. Here, higher levels of production of organic matter, together with active bioturbation, produced a brown earth soil profile. In southern Norway some 6,000 years ago, soils such as this formed the basis of the first instances of cultivated farmland.

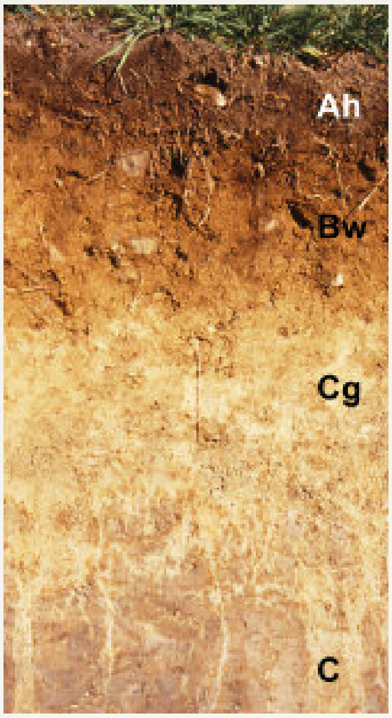
With the immigration of spruce (*Picea excelsa*) in the Late Holocene, a marked change in soil formation occurred, reflecting the cooler and more humid climatic conditions that developed over large parts of Norway at this time. Throughout most of Norway, the dense spruce forests and their associated undergrowth produced a more acid humus, which resulted in a rapid podzolisation of the sandy parent materials.

Marine clays are generally fertile, but exhibit very low permeability and, in their natural state, areas underlain by clays are frequently waterlogged. Here, soil formation has been retarded and a special soil profile has developed, characterised by a thick, often peaty, layer of organic material with a sharp boundary at its base overlying almost unweathered clay.

Large areas of Norway are covered by peat soils, which started to form shortly after deglaciation. Peat bogs are often developed in depressions that evolved from small lakes, but large areas of peat lie directly on flat or sloping land, particularly in the western and northern part of Norway, where the peat itself was exploited for fuel and soil improvement. Peat bogs are geological archives that preserve a record of changing climate and vegetation and illustrate the development of cultural landscapes during the Holocene.



Podzol profile developed under sub-alpine spruce and birch forest, with heather and lichen as ground vegetation. Gausdal in Oppland.
H: Litter and humus layer
E: Bleached (eluviated) layer.
Bs: Accumulation of iron oxides (Fe_2O_3) removed from E.
C: Slightly weathered parent material of a silty basal till developed from sandstones and phyllite.
(Photo: L. T.Strand)



Brown earth profile, developed under grass and herb vegetation and deciduous forest. Frogn in Akershus.
Ah: Mull layer
Bw: Some accumulation of Fe_2O_3
Cg: Weathered marine clay, affected by ground-water.
C: Slightly weathered, moderately well drained marine clay.
Light-coloured spots and lines are former root-channels, and desiccation cracks formed when the clay soil rose above sea-level, several thousands years ago.
(Photo: R. Sørensen)

LANDFORMS

By Johan Petter Nystuen

The landforms of mainland Norway vary in extent, age and origin. Major landforms include strandflats, coastal cliffs, skerry coasts, fjords, lowland areas below Holocene maximum sea levels, valleys, mountain plateaus and high alpine mountains. There are numerous types of small-scale landforms. Some of the major landforms represent palaeic surfaces of Precambrian to late Cenozoic age, whereas most are the products of Pleistocene and Holocene weathering, erosion and deposition.

The *strandflat* represents the lowland coastal margin, formed by a combination of weathering and marine and glacial erosion during the Pleistocene,and may encompass both large and innumerable small islands. The strandflat landform is particularly well developed along the coasts of Møre, Trøndelag and Nordland, and was occupied by early, post-glacial, fishing and hunting settlements. Today, many towns and local communities built on the strandflat continue to prosper from the fisheries, agriculture, and other commercial industries. *Coastal cliffs* develop where high-relief headlands are exposed to marine wave action, and often represent important nesting habitats for many species of seabirds. A fine example is found at North Cape in Finnmark. The *skerry* coast is characteristic of areas in southern and south-eastern Norway that were outside the influence of intense ice-stream erosion. This landform is distinguished by numerous small islands and skerries separated by sounds, inlets and sailing corridors. The skerry coast was settled by humans during the earliest Holocene, and is today a very popular summer holiday destination.

The skerry coast type in the Hvaler islands southeastern Norway. The glaciated skerries consist of Precambrian granite. The hills at the skyline is the west coast of Sweden, here formed as an escarpment running parallel to a fault within the Precambrian granite basement rock. Photo: Tormod Klemsdal.

The Norwegian *fjords* are world-renowned landforms, and both Geirangerfjorden and Nærøyfjorden are listed as UNESCO World Heritage sites. The fjords are the result of the glacial erosion of broad, pre-glacial valleys and plains by major Pleistocene ice-streams in response to the late Neogene uplift of western Scandinavia. The fjord districts are occupied by many agricultural, industrial and trading towns and settlements. *Lowland areas* are characterised by glaciomarine and marine clays, and gravelly sand deposits that form submarine ice-margin ridges. These are found in south-eastern Norway, in Jæren in the south-west and in Trøndelag in central Norway. Lowland areas have become established as major agricultural districts since the Bronze Age. Marine terraces, gullies and scars formed by quick clay landslides are characteristic morphological features in these areas.

The oldest morphological components within the major valleys are the remnants of palaeic surfaces of broad, late Mesozoic-Cenozoic valley systems, whereas the typical U-shaped valley profile is the product of erosion by Pleistocene ice-streams. V-shaped valleys are young features, formed by the downcutting action of rapidly flowing mountain streams at sites of abrupt increases in slope gradient. Cultivated and forested soils in the valley districts are developed on till, glacio-fluvial terraces and alluvial fan deposits, and on sand and silt deposits that form levées and floodplains along present-day river courses.

The valley at Lesja in central southern Norway is a broad and mature main palaeic valley, primarily formed prior to Pleistocene glaciations. The valley is located in an arid region close to the main water divide in South Norway and is drained by the River Gudbrandsdalslågen, flowing to the southeast, left at the photo. Rows of threes in the meadows are planted to trap snow that by melting increases the moisture of the soil. Photo: Tormod Klemsdal.

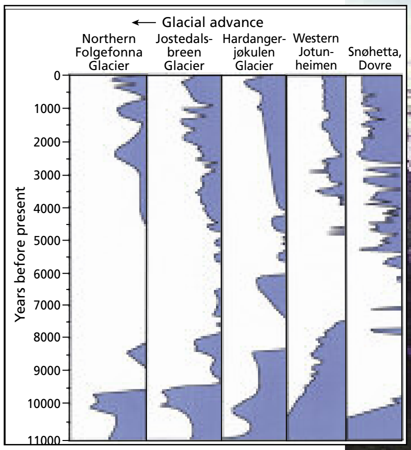
At their heads, the valleys pass into the *mountain plateaus,* most of which are modified palaeic surfaces. In Norway, the oldest of these is the 'sub-Cambrian peneplain', sculptured by later fluvial and glacial erosion. Remnants of palaeic surfaces are also found within the *high alpine mountain* regions that have been shaped by the action of glaciers into peaks, horns, pinnacles, arêtes and cirques. Weathering and soil-forming processes dominate present-day Norwegian landforms.

Norway's dynamic glaciers

Between 8,000 and 4,000 years ago the Norwegian glaciers had either disappeared or were severely reduced in extent. Our modern glaciers are thus virtual newcomers. During the "Little Ice Age", which reached its maximum during the 18th century, most Norwegian glaciers were larger than at any time since the last glaciation.

In many cases, marginal moraines formed by "Little Ice Age" glaciers are very clearly defined. At many localities they are marked by distinct changes in vegetation, characterised by barren rock and gravel proximal to the moraine, and normal high-altitude vegetation including mosses, heather and scrub beyond it. The terminal moraines may be dated by measuring the diameter of encrustations of the yellowish-green lichen, Rhizocarpon sp. On "Little Ice Age" marginal moraines, these are approximately between 10 and 12 cm in diameter, and decrease towards the glacier. Beyond the limit of the "Little Ice Age" moraines, the lichen may cover extensive surface areas. Since modern glaciers reached their maximum extent during the "Little Ice Age" in the middle of the 18th century, it follows that any older moraines were destroyed or erased by these advances. Thus, in order to find out how the expansion of the glaciers has varied with time, sediment cores have been retrieved from lakes located beyond the outermost marginal moraines. Here, fluctuations in glacial advance can be interpreted from studying alternating horizons of glacial and organic-rich sediments.

BELOW: Diagram showing fluctuations in glacier advance in southern Norway during the Holocene. Note that all the glaciers studied have disappeared entirely at least once during the last 10,000 years.



Glacial drift landscape from the "Little Ice Age" in front of the Nigardsbreen glacier in Jostedalen. The outermost moraine ridge was formed in 1748. (Photo: B. Wold)

During the period immediately following the last glaciation, there were two episodes of ice advance in southern Norway, the first about 10,000 years ago, and the second about 8,200 years ago. In the period between about 8,000 and 4,000 years ago, glaciers were either very restricted or had completely disappeared. During the last 4,000 years they have varied in size. During the Medieval period, glaciers retreated as a result of warm summers. In contrast, during the "Little Ice Age", they expanded significantly, and the majority advanced to locations they had not reached since the end of the last glaciation.

The "Little Ice Age"

Due to regional differences in climatic development, the term "Little Ice Age" is applied somewhat inconsistently from country to country, but it generally refers to the period between 1550 and 1850 AD In the Alps most glaciers reached their maximum extent in the mid-19th century, about 100 years later than the Norwegian Jostedalsbreen glacier.

Reconstructions of average annual Northern Hemisphere temperature trends for the last millennium do not show a highly variable climate during the "Little Ice Age" with a gradual cooling trend up until the 20th century. There were also significant

PLANTS COLONISE THE LAND

By Karl-Dag Vorren

"Ice age" vegetation. The start of plant colonisation depends on the extent of the ice sheet. On Andøya unique lacustrine sequences have been discovered which show that the area was deglaciated as early as 26,000 years ago. Until about 15,500 years ago, vegetation was characterised by polar desert species such as grasses, *Draba* species, Arctic cress and Arctic poppy. About 15,000 years ago a marked warming was accompanied by the transition to a more humid Arctic climate and the more widespread occurrence of mountain sorrel and willow. Birch, possibly in its dwarf form, appeared about 14,000 years ago in southern Norway. In the north the first willow and dwarf birch appeared. About 13,000 years ago an abrupt transition to a dryer and cooler climate promoted the development of a sub-Arctic steppe vegetation including wormwood species, grasses and willow, while any birch scrub disappeared from southern Norway. In the north, these communities are replaced about 12,500 years ago by a marked transition to a more humid Arctic climate accompanied by several species associated with snow hollows such as buttercup species and sedges. Between 12,200 and 11,500 years ago, in particular, open communities dominated by heather moorland became dominant, much as we find in the lower mountain belt today.

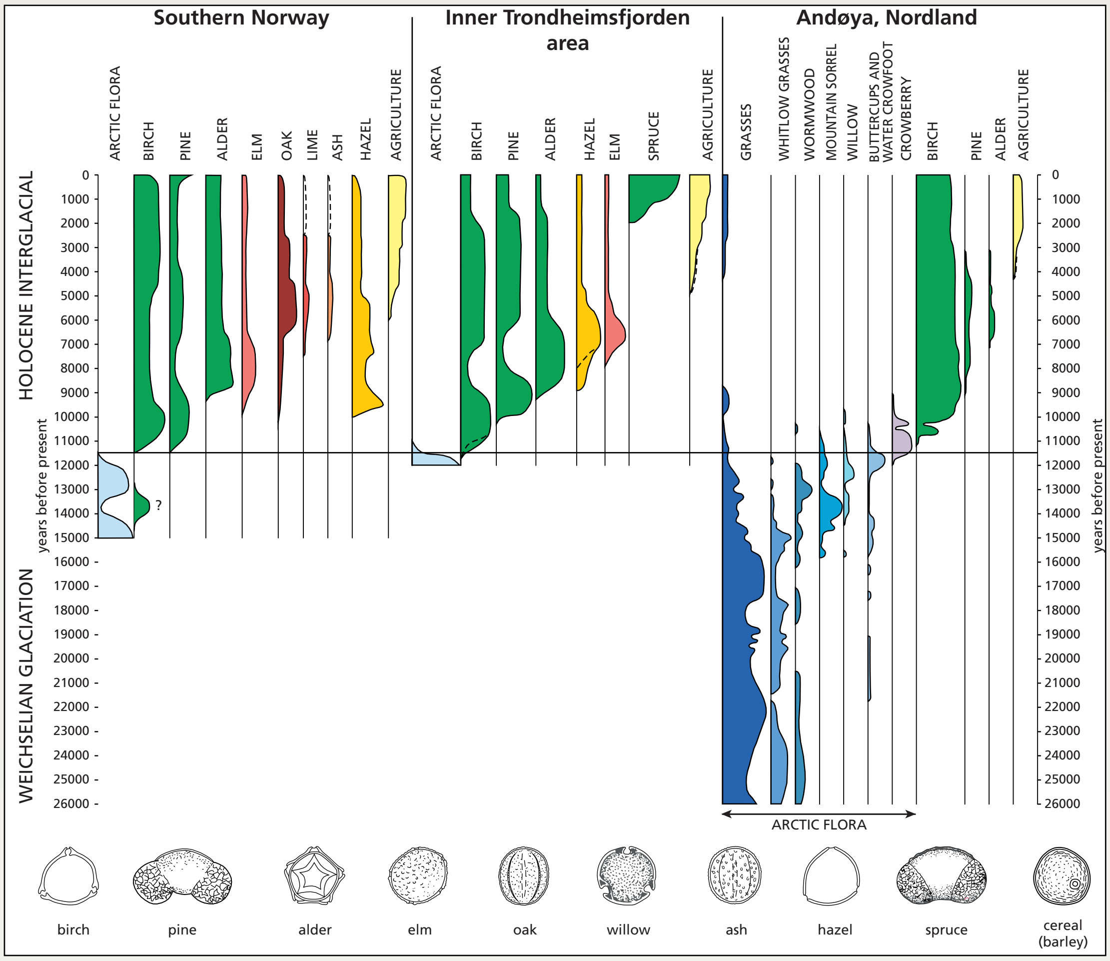


Diagram showing the main features of plant colonisation in southern, central and northern Norway since the last glaciation. To both right and left is a time-scale in calendar years. Curves in shades of blue denote tundra or polar desert species. Green denotes boreal (northern) tree species, while shades of red and orange denote thermophilic trees and shrubs. Yellow denotes the appearance of agrarian plants. Below: Key pollen types. Most pollen grains are between 0.02 and 0.06 mm in size.

Vegetation of the Holocene Climate Optimum. Birch was the first tree species to invade Norway after the last glaciation. At the beginning of the Holocene, birch forest dominated the lowlands throughout southern Norway and climatically favourable fjords further north. Later, pine forests became established in southern Norway, but it was some time before pine made its appearance in Trøndelag, probably in the form of two sub-species, the first arriving in the south via Denmark, and the other from the east. Heather moorlands existed along northern coasts until about 10,000 years ago. To survive the last glaciation, thermophilic tree species and herbaceous plants had retreated to the Mediterranean, and thus had a long return journey to Norway. In southern Norway, thermophilic woodland communities including hazel and elm were established between 10,000 and 9,000 years ago, while pine arrived in Trøndelag. The Holocene Climate Optimum occurred between about 8,500 and 5,500 years ago. In the south it was characterised at first by black alder, elm and hazel, and later by oak forests, with lime and ash in locations with the most favourable soils. In Trøndelag, this period is characterised by elm and hazel, and pine and grey alder in the north. A change in climate occurred between 5,500 and 4,500 years ago involving a drop in summer temperatures of between 2 and 3 ^{0}C. In the interior, high-altitude areas, the tree-line moved some 200 to 300 m downslope as a result. The thermophilic forest communities retreated and hardier species became more dominant. At the same time, humans began a gradual transition from a purely hunting culture to agriculturally-based settlements. This had a significant influence on the more thermophilic forest communities. Agricultural development in southern Norway appears to have begun as early as between 6,000 and 5,000 years ago, in Trøndelag probably between 5,000 and 4,000 years ago, and in northern Norway between 4,000 and 3,000 years ago. The initial establishment of farmsteads has been traced to about 2,900-2,800 years ago, coinciding with a new transition to a cooler and wetter climate. The Norway spruce migrated into both eastern Norway and the Trøndelag and Helgeland regions, and established an entirely new woodland community, culminating in the period between about 200 and 700 years AD. Spruce arrived from Central Europe via Finland and Sweden. In the far northeast a sub-species of spruce occurs which survived the glaciations in south-eastern Russia. The southern sub-species continues to migrate towards the ocean in the west.

regional temperature differences during the "Little Ice Age". Many temperature reconstructions from climate archives such as annual tree rings, corals, varved sediments, ice-cores, glaciers, historical records, and so on, demonstrate that while some regions experienced mild climatic conditions, others were much colder, in terms of both their seasonal and annual variations. However, in general terms, the interval now known as the "Little Ice Age" was one of the Holocene's coldest.

Lower summer temperatures or increased winter precipitation?

It was previously thought that lower summer temperatures were the main cause of glacial advance in Scandinavia during the "Little Ice Age", but is it possible that the major ice advance in western Norway at the beginning of the 18th century was the result of increased winter snowfall?

Historical sources, geological studies, and measurements taken in the glacier foreland, all demonstrate how the Nigardsbreen glacier has varied in size from the early 18th century to the present day. Since mass balance measurements were first conducted at the beginning of the 1960s, the glacier's annual net balance has been strongly influenced by winter snowfalls. Measurements also show that the glacier front takes about 20 years to respond to mass balance changes.

Available records of summer temperature variations based on annual tree rings indicate that summers during the first half of the 18th century were not in themselves cool enough to explain the major advances of the Nigardsbreen glacier. In fact, there was a general trend of *increasing* summer temperatures at the beginning of the 18th century. In addition, records from Central England show a significant and prolonged trend towards higher winter temperatures from the end of the 17th, and throughout the first half of the 18th, century. In Norway, mild winters promote greater levels of precipitation and thus increased snow accumulation on the glaciers. Thus, it appears that the *main reason* for the major advance of the Nigardsbreen glacier at the beginning of the 18th century was an increase in winter snowfall, and not lower summer temperatures.

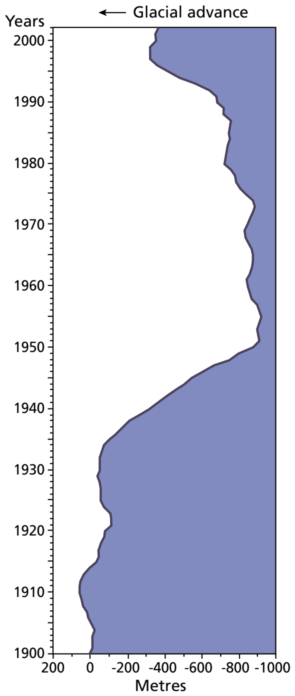
Western Norwegian glaciers; out of phase with the rest of the world

Globally, the majority of glaciers are currently in retreat as a result of higher summer temperatures and/or reduced winter precipitation. However, the opposite was the case in western Norway in the 1990s. Between 1955 and 1997 the ice-front of the Briksdalsbreen outflow glacier, extending west from the major Jostedalsbreen ice cap, advanced almost 600 m. It advanced some 322 m between 1992 and 1997 alone, representing an average of 18 cm per day! The record annual advance was 80 m in 1993-94. However, of all the Jostedalsbreen outlet glaciers, the Kjenndalsbreen in Loen in Sogn og Fjordane advanced the most. Aerial photographs show that from the middle of the 1960s and up until 1997, it advanced as much as 920 m, compared with 560 m at the Briksdalsbreen ice-front. The Melkevollsbreen glacier in Oldedalen advanced 770 m during the same period. However, in net terms, the elongate and gently-inclined eastern outflow glaciers extending from Jostedalsbreen have melted back during the same period; Lodalsbreen 1050 m, Fåbergstølsbreen 750 m, Tunsbergdalsbreen 350 m, and Nigardsbreen 310 m. Aerial photographs of the major Folgefonna glacier show that between 1959 and 1997 the Bondhusbreen and Nedre Buerbreen glaciers advanced by about 180 and 110 m respectively. We must go back to the first half of the 18th century to find advances equal to those that occurred during the 1990s.

Temperature and precipitation data from meteorological stations in Western Norway indicate that glacial expansion during the 1990s was probably the result of increased levels of snowfall in the late 1980s and early 1990s. There is a time lag between changes in winter snowfall and/or summer temperature and the response in terms of movement of the ice-front. In the case of the Briksdalsbreen, the mean frontal time lag is three years. It is the shorter and steeper maritime glaciers with short response times that have advanced most during the 1990s. The more elongate and gently-sloping outflow glaciers have not as yet begun their advance in response to the increased snowfalls of the 1990s because their response times are longer.

Many of Svalbard's glaciers are less than 3,000 years old

The cold, Arctic landscape of the Svalbard archipelago, where glaciers occupy 60 % of the landmass, and several glaciers calve into the fjords, is a major tourist attraction. However, only a few thousand years ago the landscape was quite different. Here, we shall describe the glaciers in Linnédalen, a beautiful tributary valley in the outermost part of Isfjord, which are representative of most glaciers in western Svalbard. Several cores (see figure) from beneath the Linnévatnet lake provide evidence of the evolution of the landscape around it. In the lower part of the cores, and overlain by between 4 and 10 m of lacustrine sediments, we encounter marine clays, indicating that Linnédalen was a fjord arm following the last glaciation. This is confirmed by the presence of raised shorelines some 70 m above sea level along the valley side. At about 8,500 years BC the area became uplifted and Linnévatnet was cut off from the sea and became a lake. However, the lacustrine sediments deposited at that time are in marked contrast to their modern counterparts. At the base we find a homogeneous silt unit which datings indicate was deposited at a rate of less than 0.5 mm per year. Both the slow rates of deposition and the absence of laminae indicate that no meltwater streams emptied into the lake, and thus that neither the Linnébreen nor any other glacier was present in the valley.



Variations in the Briksdalsbreen glacier ice-front between 1900 and 2002. Note the great retreat during the 1930s and 40s, and the marked advance during the 1990s. The retreat of the 1930s and 1940s was the result primarily of high summer temperatures (high rates of melting or ablation), while the advance of the 1990s was caused by high rates of winter precipitation (increased accumulation).

THE HARDANGERJKØKULEN GLACIER – THE LAST 11,000 YEARS

By Atle Nesje and Svein Olaf Dahl

Studies of four localities in the Finse area have made it possible to reconstruct fluctuations in the size of the Hardangerjøkulen glacier since the last glaciation. The ice sheet retreated from the Finse area about 10,000 years ago. At about the same time, glaciers which occupied the high-altitude plateau now occupied by the Hardangerjøkulen advanced and deposited terminal moraines just beyond the "Little Ice Age" moraines. Some 9,500 years ago, the ice retreated before renewing its advance some 8,200 years ago. These studies indicate that the Hardangerjøkulen melted away entirely during two prolonged periods; between 8,150 and 7,000 years ago, and between 6,000 and 5,500 years ago. The Hardangerjøkulen has thus not been ever-present from the end of the last glaciation to the present day. In the period between 5,500 and 4,000 years ago, the ice-front underwent significant fluctuations, although it has been present in some form since 4,000 years ago. The Hardangerjøkulen reached its maximum extent during the "Little Ice Age", most probably during the middle of the 18th century. Age determinations demonstrate that the "Little Ice Age" advance started in about the year 1400 AD.

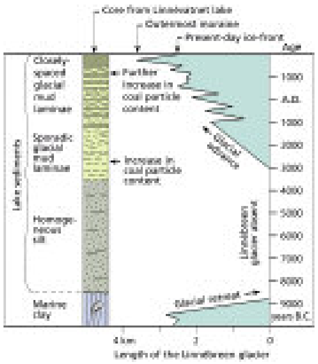
Photo: Fjellanger Widerøe

"LITTLE ICE AGE" NATURAL DISASTERS IN WESTERN NORWAY

Historical written land tax records show us that during the "Little Ice Age", significant damage was inflicted on farms and agricultural land in western Norway by landslides and glacial advance, especially in the period between 1650 and 1750. Most devastation occurred in the final decade between 1740 and 1750, and 1743 stands out as being of particular importance. On 12 December heavy rain caused several flood-induced landslides, resulting in extensive damage to a total of approximately 130 farmsteads from Boknafjord in Rogaland in the south to Sunnmøre in the north. On that day dramatic events are recorded at the Tungøyane farm in Oldedalen in Nordfjord; "On 12 December *1743 major damage was caused at Tungøen by a landslide from the glacier. Houses and their furniture, people, and every kind of animal were carried away. Only a farmhand, a 12-year-old boy and two cows could be saved*". Between 1710 and 1735 the ice-front of the Nigardsbreen, an eastern outlet glacier from the Jostedalsbreen, advanced by about 2.8 km (at an average rate of 110 m per year), and destroyed several farms. Mathias Foss, a priest at Jostedal at that time , wrote about the events after 1742: "*...but from the actual date to a year later in 1743 alone, the glacier advanced more than 600 metres, and widened immeasurably as well, carrying houses away and throwing them aside with great volumes of earth, gravel and great stone blocks, and reducing them to splinters which can still be seen today...*".

Gradually, these sediments were overlain by laminated, millimetre-thick horizons of fine-grained silt and sand characteristic of meltwater streams which, during the warmer summer months were coloured grey by glacial rock flour. At about 3,000 years BC, coal particles appear in the lake sediments, demonstrating that the Linnébreen glacier had begun to erode into the bedrock, which is the only source of coal in Linnédalen. Sediments from more recent centuries are finely laminated as a result of seasonal summer supplies of glacial mud. Rates of deposition are also ten times greater than those during the early Holocene. The glaciers were starting to behave very much as they do today.

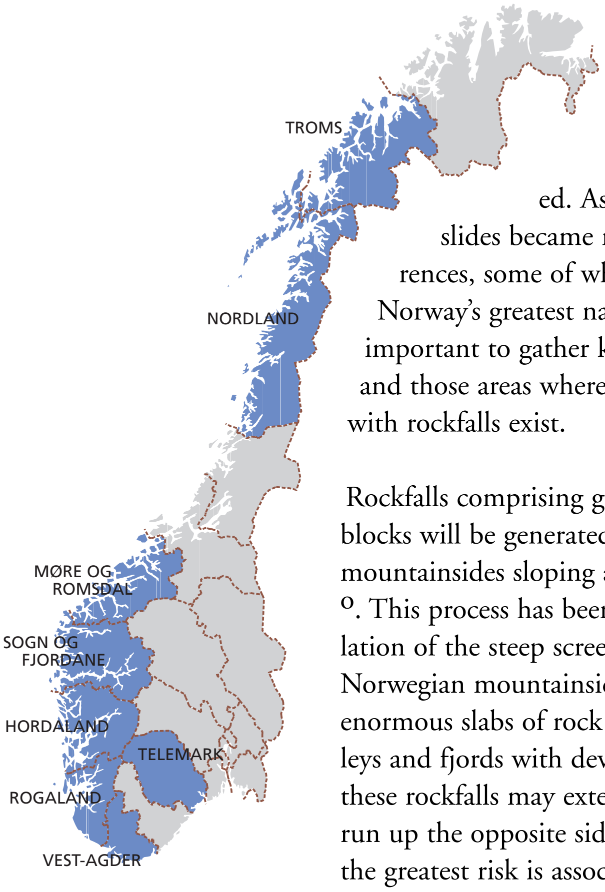
Within the sands making up the raised beaches in Svalbard, the shells of species such as common mussels, horse mussels, Icelandic cyprine mussels, and common periwinkle are very common, especially in the climatically favourable inner parts of Isfjord. However, although these species are common along the Norwegian coast today, it is too cold for them to survive in Svalbard. Their presence indicates that the ocean was once some –3-4 °C warmer than it is today. Several of these shells have been radiocarbon dated and results confirm those obtained from studies of glacial processes; that the warmest period occurred between 8,200 and 6,500 years BC. However, some warm-water shellfish are found in sediments as recent as 2,000 years BC, and a single mussel specimen has been discovered dating from Viking times.



ABOVE: Simplified representation of a 10-metre core from the Linnévatnet lake. The true depth scale has been converted to a time scale. The homogeneous silt horizon was deposited very slowly, and is in reality much thinner in relation to the laminated sediments than is shown in the time-calibrated diagram. The curve (right) shows the advances and retreats of the Linnébreen glacier, based on interpretations of a series of cores. Note that during the period from 9,000 to 3,000 years BC, the glacier was absent, but that it is now some 3 km long.

Rockfalls in the mountains

Over geological time, the Laws of Nature are remorseless. Bedrock is eroded, the landscape weathered and levelled, and sediments transported to the ocean. After the land was exposed by the glaciers, rockfalls and landslides were released – sometimes with devastating effect.



Map showing those Norwegian counties where unstable rock slabs have been identified.

Many steep mountainsides carved by glacial erosion were left unsupported and unstable when the ice retreated. As a result, rockfalls and landslides became natural and frequent occurrences, some of which have resulted in Norway's greatest natural disasters. It is therefore important to gather knowledge about their causes and those areas where potential risks associated with rockfalls exist.

Rockfalls comprising great masses of detached blocks will be generated at intervals on all steep mountainsides sloping at greater than about –40-45 °. This process has been responsible for the accumulation of the steep screes commonly observed on Norwegian mountainsides. However, in some cases, enormous slabs of rock will be released into the valleys and fjords with devastating power. The largest of these rockfalls may extend across a valley floor and run up the opposite side. From a human perspective, the greatest risk is associated with massive rock slabs which collapse into fjords creating flood waves which, in extreme cases, may be hundreds of metres high. The greatest rockfall in Norway in historical times was the Tjelle landslide in Langfjorden in Romsdal in 1756, during which about 15 million m^3 (approximately 40 million tonnes) of rock generated a series of flood waves over 50 m high. Twenty-eight people lost their lives in this disaster.

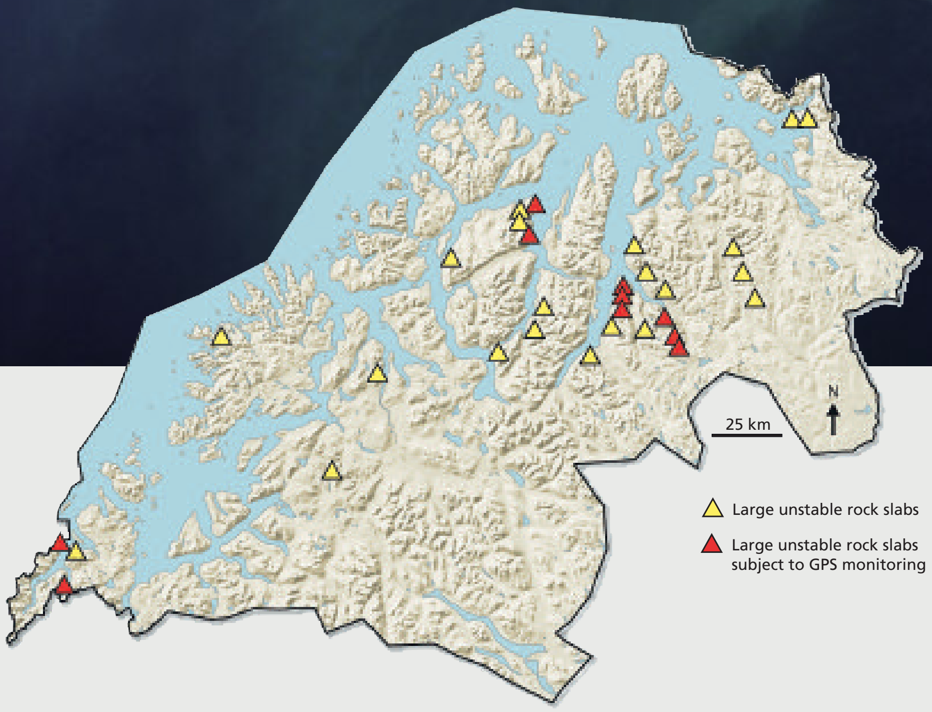
Rockfalls in western and northern Norway

Geological mapping has revealed that massive rockfalls have been triggered in the past throughout Norway, mostly along the steepest mountainsides in the west and north. In the northern regions of western Norway historical records indicate that two or three major disasters resulting from rockfalls and flood waves occur each century. The best documented are those at Loen in Sogn og Fjordane in 1905 and 1936, and the Tafjord disaster of 1934. Flood waves generated during these events accounted for a total of 175 lives.

Rockfalls have been quite frequent in the innermost fjord districts of Møre og Romsdal, within a zone extending from Geirangerfjorden to Tafjord, in Romsdalen, and northeast to Sunndalen. Seismic surveys, boreholes and datings of rockfalls in Tafjord and Romsdalen reveal that several have been generated during the last 5,000 years. However, the situation in northern Norway is somewhat different.

Historical records from northern Norway are poor, and in Troms there is only one historical record of a major disaster resulting from a rockfall and subsequent flood wave. This involved a rockfall from the Pollfjellet mountain in Lyngen in 1810 which generated a massive flood wave that destroyed houses belonging to three farms in Lyngsdalen with the loss of 14 lives. Geological mapping both on land and in the fjords has shown that numerous major rockfalls have occurred in Troms, especially within a zone extending from Balsfjord in the south to Reisadalen in the north, with an especially high concentration in Kåfjord. The largest rockfall so far identified occurred in Grovfjorden, involving about 100 million m^3 of rock and extending over a length of 4 km. Some of the rockfalls in Troms crashed into the fjords, producing giant underwater screes. The cave-like spaces between these giant blocks have become favourable habitats for molluscs and barnacles. As a result of post-glacial uplift, some of these screes are now exposed on land, and the ages of the shells and barnacles they contain reveal that many of

View of Furuflaten and Lyngsdalen, in Lyngen in Troms. The Pollfjellet mountain (right foreground) was the site of a major rockfall in 1810 which generated a tsunami resulting in the loss of 14 lives. (Photo: Fjellanger Widerøe)



Map showing the distribution of unstable rock slabs in Troms. The red triangles denote localities monitored by GPS.

the major rockfalls in Troms occurred between 11,500 and 10,500 years ago, immediately following the last glaciation.

Rockfalls – causes and risks

The main cause of major rockfalls is the combination of steep mountainsides and zones of weakness in the bedrock. However, it is often difficult to determine the precise trigger of individual rockfalls. Build-up of water pressure in bedrock fracture systems following rainfall is one of the major causes. Frost-shattering related to either present-day or relict permafrost may also be a significant factor in some areas. In particular, melting of permafrost immediately following the last glaciation may have been an important cause. In many places around the world, rockfalls are triggered by earthquakes, and this is probably also a factor in Norway. For example, earthquakes generated by movements along a young tectonic fault in Kåfjord in Troms have been identified as the trigger for several rockfalls in this area. Of those rockfalls which have been dated, several may have been triggered during a short period immediately after the retreat of the glaciers. This was a time during which there was significant uplift,with major pressure changes and movement within the crust, and when it would be reasonable to expect major earthquake activity. A young fault has been identified in Innfjord in Romsdalen which may explain the great concentration of rockfalls in the innermost fjord districts of Møre og Romsdal.

Clearly, a high concentration of historical rockfalls in a given area is in itself a warning that the area may be at risk in the future. In northern and western Norway in particular, movement along open fractures or intense deformation has been detected in the vicinity of many large rock slabs. The Børa crag, just south of Trollveggen (the “Troll Wall”), in Romsdalen is a good example. Here, an enormous slab of rock measuring over 2 km in length and over 200 m across has been identified, exhibiting innumerable fractures which penetrate both the bedrock and moraine deposits. Some of the fractures are over 20 m deep and several metres in width. Major fractures have also been identified in the mountains high above Tafjord in Møre og Romsdal, and Storfjord in the Lyngen area in Troms. Geologists are faced with an enormous challenge in terms of mapping, stability analysis, monitoring, and the issue of warnings associated with major rockfalls and flood waves.

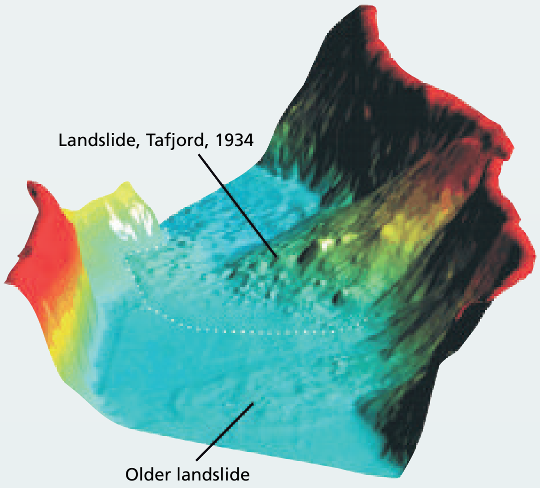
Fractures at the summit of the Børa crag above Romsdalen, showing how the rock slab (right) has moved. (Photo: J. Gellein)

THE 1934 TAFJORD DISASTER

"... At once I saw an enormous, powerful wave rolling past Uksneset. It crashed over the quay and destroyed the light. My sister came running in and we both looked out. It was as if the village beneath us was being smashed by the sea. We realised what was happening. We heard people screaming in spite of the noise. The screams were terrible, and they wouldn't stop! My sister's face was as white as a sheet, and she slammed the door so as not to hear the screams coming from outside". This is an eye-witness account of the events in Tafjord one spring night in 1934, as re-told by Astor Furseth in the book "Doomsday Mountain" (Dommedagsfjellet).

Photographs of the settlement at Tafjord before the flood wave struck (left), and afterwards (right).

The Tafjord disaster of 7 April 1934, during which 40 people lost their lives, is one of the greatest natural disasters in recent Norwegian history. One and a half million cubic metres of rock crashed from a height of 730 m into the narrow fjord below. On its way it took with it the great Heggurda scree. The combined rock mass probably amounted to about 3 million m^3 or between about 8 and 9 million tonnes. The rockfall generated enormous 60-m high flood waves which washed across the fjord. In the small settlements of Tafjord and Fjørå, where many people lost their lives, the waves reached heights of 16 and 13 m, respectively. Three great waves crashed over the settlement at Tafjord.



Model of the base of the fjord showing deposits resulting from the Tafjord landslide of 1934.

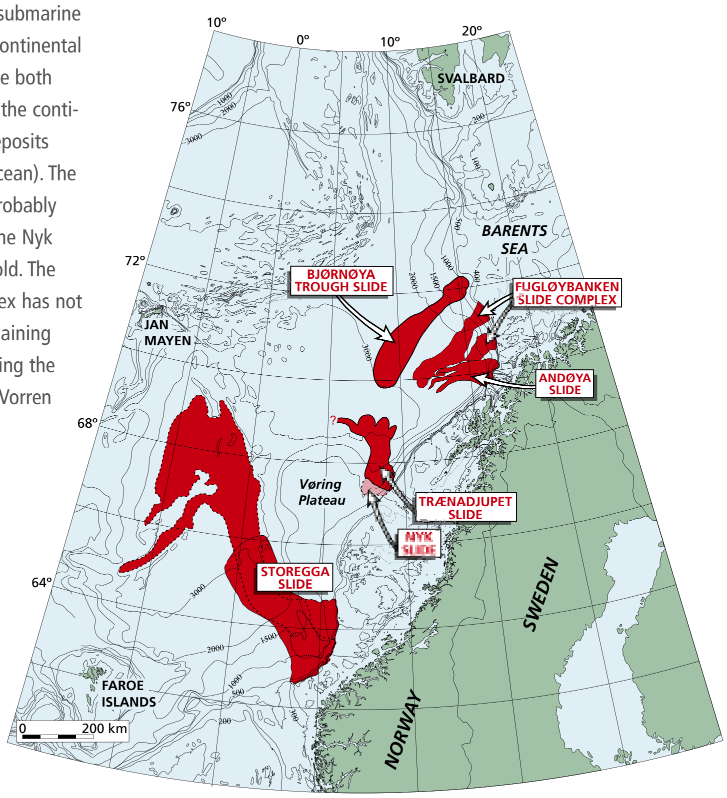
The inhabitants of Tafjord were aware that there was an expanding fracture high on the Langhammaren crag, but it was not considered to be a serious risk. People probably knew of this major fracture, which was situated approximately 150 m from the cliff edge, from as early as the turn of the century. Some locals had confirmed that it had widened by at least 1.5 m within a generation. During the month before disaster struck, several minor landslides had been generated in the screes below the Langhammaren crag. Such warnings were also given prior to the disasters at Loen in 1905 and 1936. These disasters have taught us that it is possible to make measurements that can be linked to landslide warning systems in the future.

Giant submarine slides and tsunamis

Several slide scars on the Norwegian continental slope have aroused attention because of the risk submarine slides represent for seabed oil installations, and the damage that a tsunami may cause along the coast.

The Bjørnøya Trough slide is one of many identified on the continental slope that were triggered prior to the last glaciation. However, many of these slide masses have since been partly infilled by younger deposits. Here, we shall look more closely at the three major post-glacial submarine slides; the Andøya slide, the Trænadjupet slide, and the Storegga slide.

The Andøya slide is situated on the continental slope offshore Troms. It occupies an area of 9,700 km^2, of which the slide scar covers 3,600 km^2. Slide deposits extend some 190 km across the sea floor. Relief across the scar is irregular, and displays elevated areas some several kilometres across and which rise up to 800 m above the seabed. In its lower regions, the slide deposits themselves exhibit gentler relief with highs standing less than 50 m above the surrounding seabed. It is likely that several of these highs represent massive slabs of sediment transported from shallower levels.



Map showing the largest submarine slides on the Norwegian continental slope. The red areas denote both slide scars (uppermost on the continental slope), and slide deposits (downslope in the deep ocean). The Bjørnøya Trough slide is probably more than 200,000, and the Nyk slide about 19,500 years old. The Fugløybanken slide complex has not been dated. The three remaining slides were generated during the Holocene. (Modified from Vorren et al.)

The Trænadjupet slide extends from the shelf break to depths of 3,000 m along the continental slope west of the Lofoten islands. The area affected by the slide covers 14,100 km^2. Slopes of various magnitudes are identified within the slide scar, together with sediment flow deposits and giant slabs of sediment, measuring up to 0.3 × 1 km, and 20 m in thickness, which have been transported some distance downslope before coming to a halt.

The Storegga slide is by far the largest of its kind, located on the continental slope off the coast of the Møre-Trøndelag region. Here, a 290 km-long escarpment marks the headwall of the slide scar. About 5,600 km^3 of material, equivalent to 1,400,000,000,000 dumper truck loads, has slid out from the scar! The scar alone occupies an area of 34,000 km^2, and material within the slide deposits covers 112,500 km^2, equivalent to one third of Norway's total land area! Much of this material has been deposited on the floor of the Norwegian Sea as sediment flows. Several distinct slide events have been identified within the slide scar itself, and it is possible to see how younger slides truncate older events. Probably all these events occurred in rapid succession.

The slides have been dated by taking sediment cores from the slide scars and conducting radiocarbon dating on the oldest sediments deposited after the slides were generated. In addition, the Storegga slide has been dated using sediments deposited by the flood wave that was generated by the slide itself. Results reveal that the Andøya slide, which is the least reliably dated, is estimated to be about 10,000 years old. The Storegga slide is reliably dated at 8,100 years, while the Træna Deep slide was generated some 4,000 years ago. Smaller slides were also generated in the same area between then and 3,000 years ago.

Tsunamis flood the coast

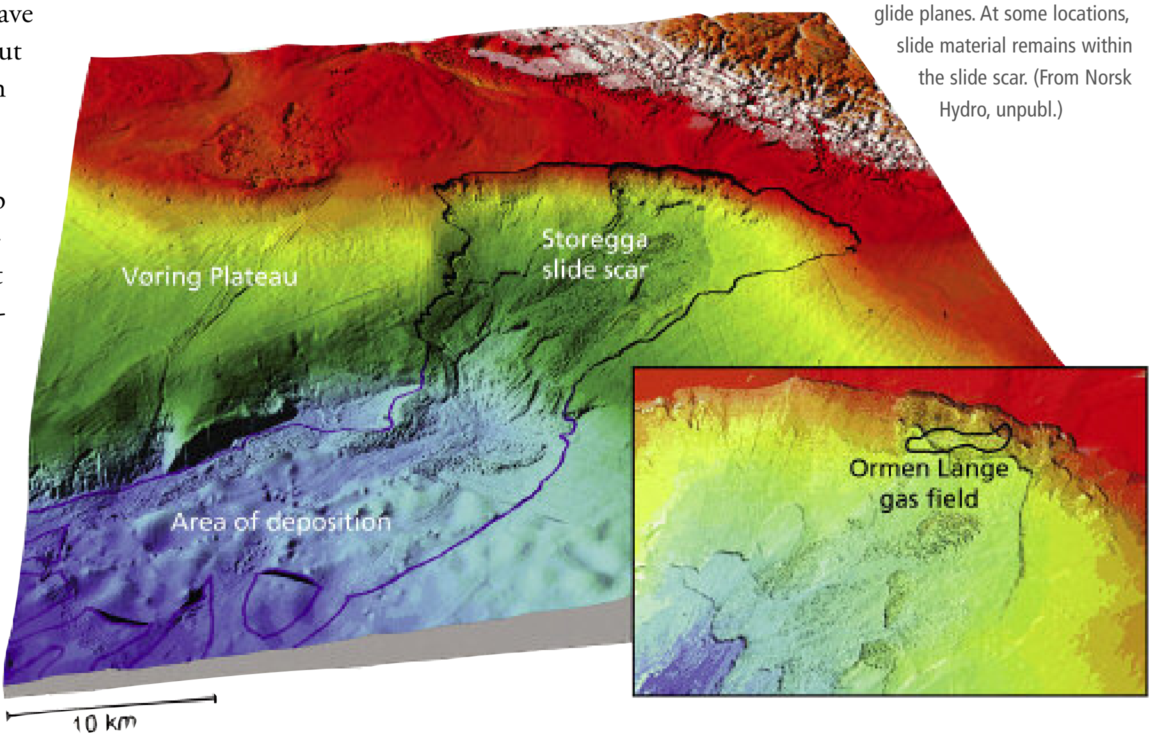
The great submarine slides have completely altered seabed topography, and have also left their mark along the coast. When the Storegga slide was triggered, it drew down with it massive volumes of water and thus created a major flood wave. Flood waves of this type triggered by submarine slides or earthquakes are called *tsunamis* after the Japanese word, and are common occurrences in those parts of the Pacific Ocean which are subject to frequent earthquakes.

The Storegga-tsunami carried with it sand and a variety of shells and fish species onto land, and cores from lakes at different elevations above present-day sea level have been used to estimate its height. It would first have encountered the Norwegian coast as a trough, because water was initially dragged seaward by the slide. In the Møre region, sea levels were lowered by more than 10 m, later to rise by some 20 metres as the crest arrived along the coast. These waves were high, but no more so than those experienced by seafarers out in the North Sea. The major difference was the wavelength. The Storegga slide would have taken about an hour from the time the trough along the coast was at its minimum, until the crest reached its maximum at the same location. On encountering the coast, the tsunami wave did not "break" in the normal sense, but simply transgressed inland, and as such can be compared to an extreme flood tide. It extended for several hundred metres inland along the valleys, and up to a couple of kilometres at some locations. It is not difficult to imagine that this must have been a terrifying experience for the Stone Age peoples who inhabited the coastal areas at that time, and many probably lost their lives.

The height of the wave would have diminished as the tsunami propagated to the north and south of the Møre area, but traces have been mapped from Scotland to Troms. On the Shetland islands, it reached more than double the height experienced in the Møre area, and modelling indicates that the wave achieved enormous heights in some of the fjords. The hazards which tsunamis represent, and the fact that the giant Ormen Lange gas field (see Chapter 14) is located immediately beneath the Storegga slide scar, makes it imperative that we find out how often these giant slides occur, and what causes them.

Why do submarine slides happen?

Geologists are not entirely sure what triggered the great submarine slides, but several causes have been discussed. It is possible that they were triggered by different mechanisms. All the slides are situated in areas that are subject to abundant sediment supply, a factor which in itself promotes sediment instability. Another cause may involve the presence of shallow gas pockets or gas hydrates, which may become transformed into gas. Gas hydrates are found in sediments at several locations on the Norwegian continental slope, and increases in bottom temperatures or lowering of sea levels may trigger the release of gas from the hydrate zones. Today, however, most researchers believe that the slides were triggered by earthquakes. Several earthquakes have been registered in the recent past along the Norwegian continental slope. The headwalls of all the slides discussed in this chapter are located in the outer zone of the Fennoscandian post-glacial uplift area, and it is just at locations such as these that earthquakes would be expected to have occurred during the Holocene.



Seabed topography across the Storegga slide. Note the slide scar (uppermost), part of which abuts against the present-day shelf break. Seaward of this is the area occupied by the slide deposits. Beyond this, mud flows generated by the slide have transported sediments to the deepest parts of the Norwegian Sea. The detailed figure illustrates how material has moved along a series of glide planes. At some locations, slide material remains within the slide scar. (From Norsk Hydro, unpubl.)