CHAPTER 17

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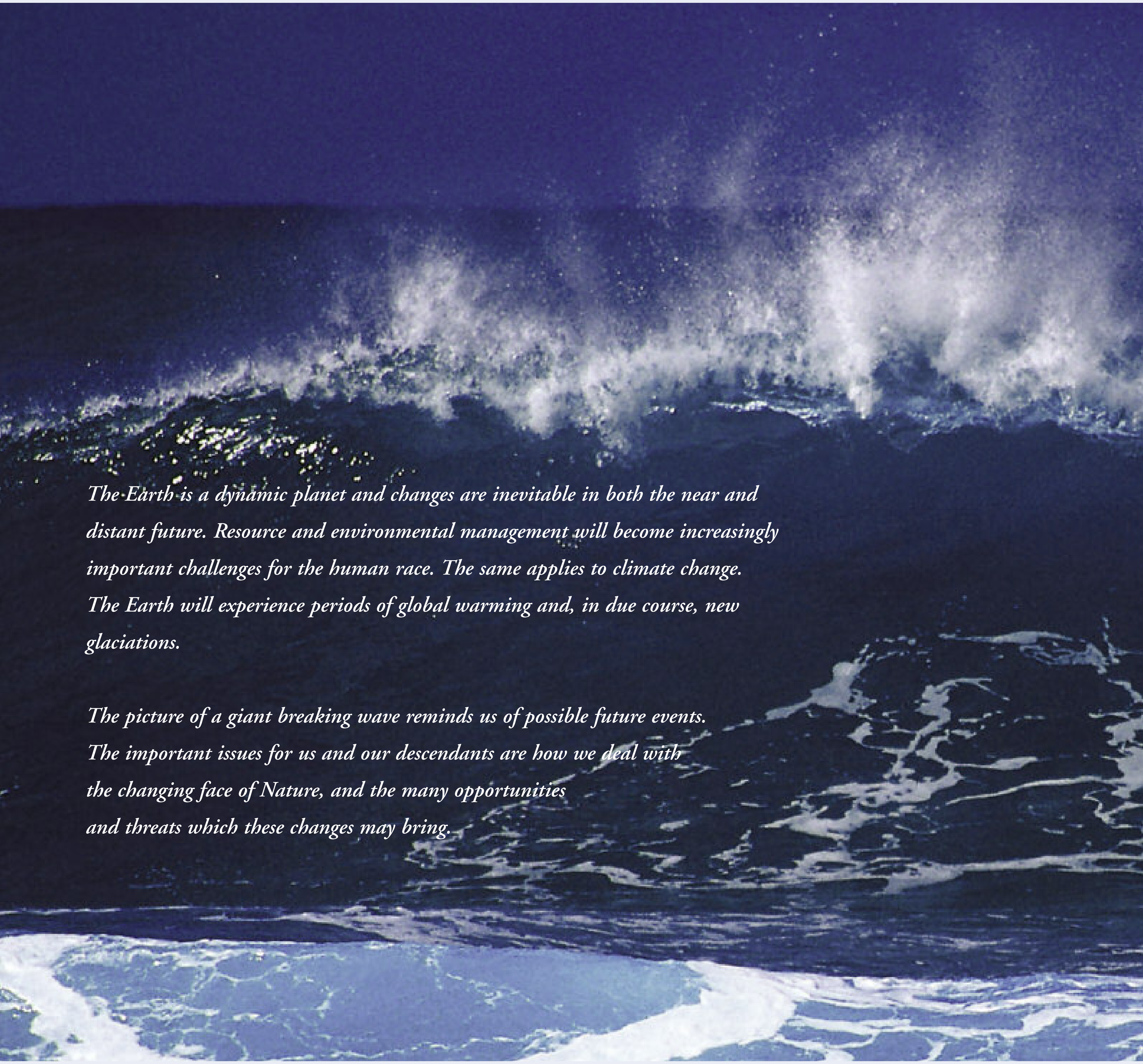


The Earth is a dynamic planet and changes are inevitable in both the near and distant future. Resource and environmental management will become increasingly important challenges for the human race. The same applies to climate change. The Earth will experience periods of global warming and, in due course, new glaciations.

The picture of a giant breaking wave reminds us of possible future events. The important issues for us and our descendants are how we deal with the changing face of Nature, and the many opportunities and threats which these changes may bring.

What does the future hold?

Geohazards, climate change and continental drift

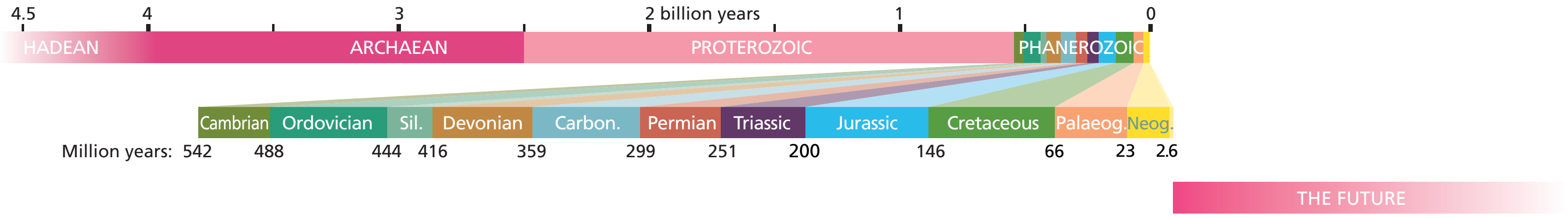
Locations of the continents in 50 million years. Black lines denote spreading axes, and red lines subduction zones. Red circles denote mantle plumes or «hot spots». (Illustration: T.H. Torsvik)

THE NEXT 50 MILLION YEARS

From the Cambrian to the present day, Norway has drifted from the southern hemisphere, across the equator, and north to its present location. If we project ourselves 50 million years into the future, the Earth's surface will have changed its appearance. Norway will have drifted a further 600 km to the north and the North Atlantic will be almost twice as wide as it is today. To the south, the Atlantic is in the process of closing, and this process will gradually progress northwards. The Mediterranean Sea will have disappeared after a collision between the African and the Eurasian plates. Our planet's geological change processes will produce great changes in the distribution of flora and fauna, and of possible human settlement.

Introduction

In 1814, the founders of the Norwegian constitution promised each other "Concord and Loyalty until the Dovre mountains crumble". From a human perspective, the permanence of the mountains is assured. However, in geological terms this is not the case, because we are dealing with much more extended time scales.



The forces of nature driving the geological processes which have shaped Norway are as active as ever. The Earth is a dynamic, "living" planet. Geological change processes will continue and, in time, even the Dovre mountains will "crumble". External agents such as chemical weathering and the action of glaciers, landslides, the wind, and running water will continue to denude and reshape the landscape. In addition, internal forces, combined with plate tectonic processes, will form new landmasses, shift these to new latitudes, and continually modify the planet's geography and topography, its ocean currents and climate.

We are all familiar with the sudden and violent expressions of natural change processes such as volcanic eruptions, earthquakes, floods and landslides. Events such as these can have devastating impact on human communities over very short periods. Normally, however, natural processes advance so slowly that it is difficult within our limited time perspective to register the changes they cause.

However, in the *short term*, it is the sudden events, and issues such as the management and allocation of natural resources, global warming, and climatic variations, which represent the key challenges for the human race. Are we able to meet these challenges and adapt to them or, indeed, mitigate their effects, on regional and global scales? Do we have sufficient information to make the right choices? And what about longer-term changes? For example, for how long will Norway be habitable if and when a new ice age approaches? Perhaps we need not concern ourselves so much with events in the distant future. But there is no doubt that in the *long term* Norway will be transformed. Its mountain peaks will be worn away or uplifted to new heights, its rivers will find new courses, and the landscape will be dramatically altered. If we gaze into the *far distant future*, plate tectonic forces will continue to push and pull at Norway and its surrounding landmasses and oceans, causing them gradually to change their form and relative positions on the Earth's surface. It is likely that continental drift will promote global changes in climate and biological evolution at least as all-encompassing and dramatic as in the geological past.

In this chapter we can only describe some of the possible future scenarios. As human beings, issues such as *geohazards, resources, the environment* and *climate* concern us the most, since these will directly affect our immediate descendants. Other topics of this chapter include the influence of *uplift processes* and *plate tectonics*. For instance, *uplift processes* will continue to affect Norway for tens of thousands of years still, while *plate tectonics* will drag the country northward for millions of years to come. - All assumptions one can make about the future are bound to be laden with uncertainty. Whereas some scenarios are based on observable trends, others are founded on accumulated geological data, theoretical knowledge and various modelling studies. However, scenarios such as these will enable us to prepare for the future, stimulate us to seek out new information, and perhaps also fire our imagination.

Geohazards – monitoring and warning systems

Geohazards include natural disasters associated with earthquakes, volcanic eruptions, flood waves, tsunamis, river floodings, rockfalls and landslides. Each year, our newspapers, radio and television report the numerous natural disasters that beset the planet, many of which have enormous consequences for human life and property. Norway is not immune. Can we become better at providing warnings and reducing the effects of these geohazards in the future?

In Norway, with its steep mountains and fjords, history has taught us that rockfalls and landslides represent perhaps the greatest threat to human habitation. During the last 150 years alone about 2,000 people have lost their lives in such accidents, and no doubt Norway will continue to be threatened by landslides and rockfalls in the future. We have seen some examples of such events in Chapter 16. Statistics based on historical data indicate that during the present century alone, we can expect between 2 and 3 major rockfalls, the same number of mudslides, and between 3 and 4 major snow avalanches, in addition to numerous minor slide and rockfall events. Increased precipitation induced by climate change may increase these frequencies.

Landslides, rockfalls, and floods are all natural geological processes resulting from the continuous dynamic interaction between the Earth's external and internal forces. They can be triggered by earthquakes, heavy rainfall, high pore pressure in bedrock fracture systems, natural rock pressure, frost-shattering and human activity. In due course, these events will combine to level out and change the landscape, and in so doing transport rock, sand and gravel via the rivers and fjords out onto the progressively aggrading continental shelf.

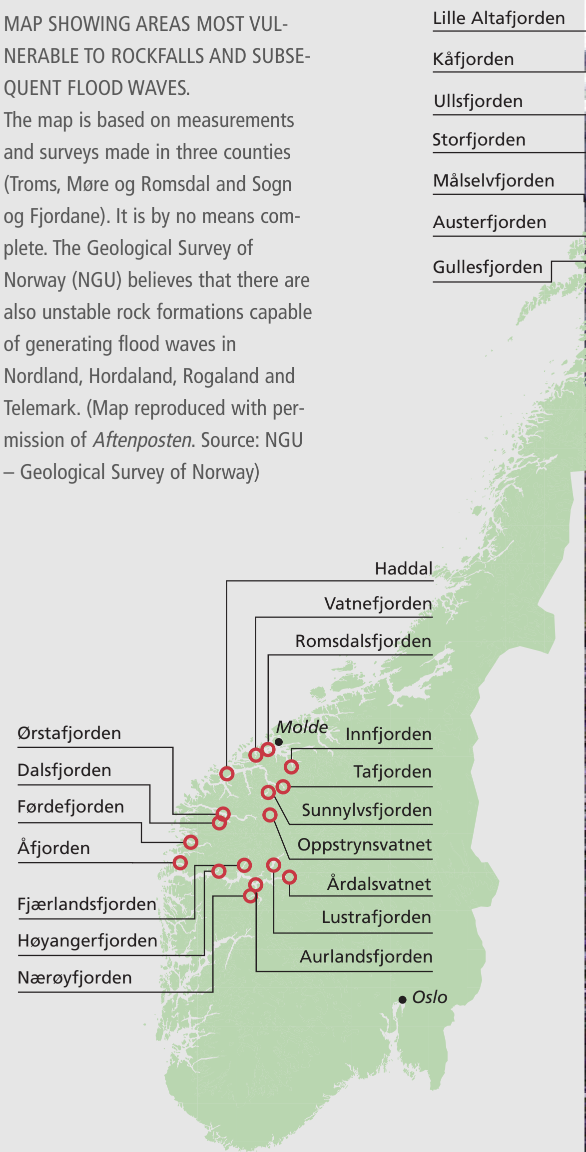
Earthquakes can also trigger rockfalls and landslides in Norway, although major earthquakes are relatively rare here compared with other regions in the world. At the back of the book there is a map showing historical earthquake activity in Norway. It also shows the areas which are most vulnerable in the future. NORSAR (The Norwegian Seismic Array) has calculated that mainland Norway and the continental shelf can expect on average earthquakes up to magnitude 6 on the Richter scale at intervals of one per century. A 6.2 magnitude earthquake took place SE of Spitsbergen as late as in 22 February 2008. - Earthquakes of magnitude 7 will occur much less frequently.

Historically, earthquake activity in Norway has remained relatively constant over time, but society has become increasingly more vulnerable to their consequences during the last 150 years. Norway has been transformed from an agricultural- and fisheries-based nation to a complex industrial society with large towns and cities, power stations, railway networks and roads, numerous tunnels, oil installations, pipelines, factories and other large buildings. Building regulations now recognise that the threat of major earthquakes is greatest in Western Norway, along the coast of Nordland, and in the Oslofjorden area. The material damage caused by future earthquakes may be considerable.

As a result, major efforts are being made in the mapping, modelling, and monitoring of geohazards, the installation of warning systems and, where necessary, projects to mitigate risk, especially in the case of mudslides, major rockfalls and potential flood waves. In the future, major focus will be directed in working to enhance and further develop the precision of predictive tools and warning systems. Where river

MAP SHOWING AREAS MOST VULNERABLE TO ROCKFALLS AND SUBSEQUENT FLOOD WAVES.

The map is based on measurements and surveys made in three counties (Troms, Møre og Romsdal and Sogn og Fjordane). It is by no means complete. The Geological Survey of Norway (NGU) believes that there are also unstable rock formations capable of generating flood waves in Nordland, Hordaland, Rogaland and Telemark. (Map reproduced with permission of *Aftenposten*. Source: NGU – Geological Survey of Norway)



Major fractures across the Børa crag in Romsdalen. Systematic measurements and monitoring of potential rockfalls may reduce the extent of damage and the risk of fatalities. (Photo: NGU)

LEFT: Clay landslide at Baastad near Øyeren in Akershus in 1974. Parts of eastern Norway are subject to quick clay landslides. Quick clay was deposited during a marine transgression following the last glaciation. The mapping of historical landslides, and a better understanding of the mechanisms which trigger slides, are important in reducing risk and providing warnings of future events. (Photo: Fjellanger Widerøe)

GEOHAZARDS – MONITORING AND WARNING SYSTEMS *By Lars Harald Blikra*

The collapse of large masses of rock into fjords or lakes may result in catastrophic flood waves. Risk management associated with flood waves is conducted primarily by monitoring, warning systems and, in emergency situations, evacuation. Today, we have a range of different monitoring systems, and technological advances are continually providing us with improvements. In Norway there are numerous unstable rock formations, but monitoring systems are in place for only very few. Crackmeters have been placed across fractures to monitor large unstable rock masses at Åkerneset above Sunnylvsfjorden in Stranda municipality in the Sunnmøre region since 1985. Measurements are continuously transmitted telephonically, and warning can be given if any dramatic increases in movement of the formation are detected. Today, some of these unstable rock masses are moving at rates of between 3 and 4 cm per year (*). Increases in rates of movement have been recorded prior to several of the great historical rockfalls. Continuous monitoring of unstable rock mass movements allows us to develop warning systems and contingency plans.

However, tension rods provide only one form of monitoring. Distance measurements have traditionally been the principal method of monitoring rock movements. Today, GPS methods are commonly used, both for mapping changes in movement over given intervals of time (for example, annually), and for continuous measurements. Today, measurement sensitivity and accuracy is very high, and movements of only a few millimetres can be detected. In some cases, seismic monitoring is used to provide information about movement and deformation in unstable areas. This method is soon to be used at Åkerneset.

In recent years, new methods based on radar and laser monitoring technologies have been employed. Technologies have been developed which permit radar satellites to detect vertical movements of less than 1 mm per year. As access to satellite data increases, monitoring by satellite will become more widespread. Ground-based radar systems have also been developed which can detect movements along entire mountainsides. In Tafjord in Møre og Romsdal, efforts are now being made to monitor risk using radar emitters located in settlements away from the slope itself, while reflectors are placed in the unstable zones. This has the advantage of having the instrumentation and its energy supply located close to settlements, leaving only the reflectors on the mountainside. These measurements are extremely accurate, and radar emitters can be placed at up to 4 km from the rock formations under surveillance. Similar methods based on laser technology are also being developed, although here the distance between instrument and detectors presents greater challenges.

In many situations, it is necessary to monitor both rock movement and changes in hydraulic pressure in boreholes, and various types of monitoring system are employed in such cases. Pore pressure is often a controlling factor in the stability of rock masses, and it is therefore important to monitor variations in this parameter. This type of monitoring is often combined with measurements of climatic factors such as precipitation and snow melt, which can also influence rock stability. Both borehole and climate monitoring systems are currently being installed at Åkerneset.

In global terms, expertise in monitoring and the provision of warning systems linked to major rockfalls and landslides has advanced dramatically in countries such as Italy, Switzerland and Japan. In Norway, efforts are being made to accumulate expertise, not least by establishing links with the International Centre for Geohazards (ICG), where Norwegian institutions such as the Norwegian Geotechnical Institute (NGI), Geological Survey of Norway (NGU), NORSAR (Norwegian Seismic Array at the Norwegian Seismological Research Centre at Kjeller), University of Oslo and the Norwegian University of Science and Technology (NTNU) are involved as partners.

Crackmeters placed across fractures at Åkerneset provide continuous measurement of any expansion. (Photo: L.H. Blikra)

A climate monitoring station at Åkerneset records wind speed and direction, temperature, precipitation, solar radiation and snow depth. (Photo: L.H. Blikra)

(*) A collapse and subsequent rock slide at Åkerneset will involve between 20 and 25 million m^3 of rock. If the slide reaches the fjord, it will generate a flood wave which will overwhelm Hellesylt and continue into Geirangerfjord towards Geiranger.

flooding is concerned, the Norwegian National Water Authority supervises a continuous monitoring programme which keeps track of all river discharges, in the interests both of the electricity producers and the need to be able to warn of flood hazards so that measures can be taken to mitigate potential damage. Similar programmes have been developed for other geohazards. With increased population and urbanization, the need to develop a system for managing geohazards («Earth Systems Management») is increasing all the time.

Is it possible to warn of flood waves (tsunamis)?

History records that Norway has been subject to several major flood waves, most recently during the last century (see Chapter 16). In Norway, flood waves are most commonly generated by rockfalls or landslides descending into fjord arms along steep mountainsides or, more rarely, by major offshore earthquakes caused by fault displacements on the seabed. Such earthquakes can also trigger submarine slides. A good example is the Storegga slide that occurred 8,100 years ago, and which was one of many such events triggered after the last glaciation.

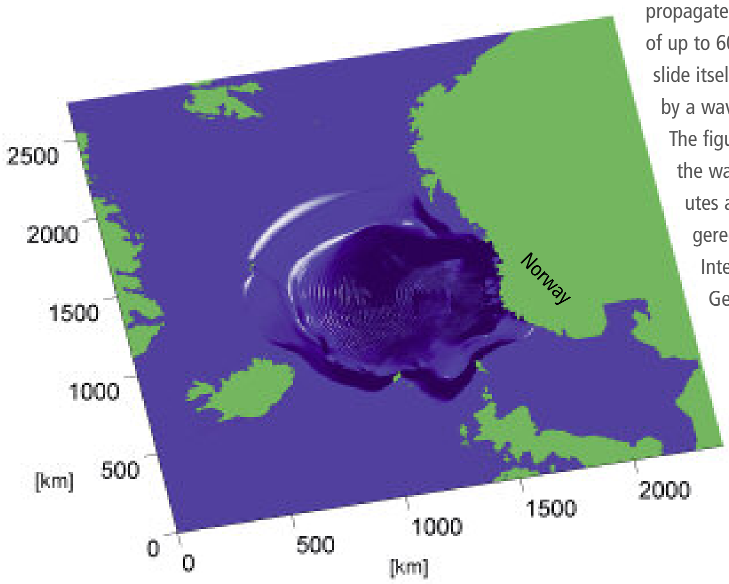
In Norway, landslides and rockfalls along steep mountainsides represent the greatest risk in terms of the generation of flood waves. High mountains, deep fjords, and unstable rock formations form a potentially lethal combination which, in the event of an extreme accident, is capable of generating flood waves up to 75 m high. Such phenomena generally produce localised waves, which have little effect outside the immediate area of the fjord itself. Key measures include detailed geological mapping of areas at risk, and a systematic monitoring of fracture development in potentially hazardous mountain areas. Simulation models are used to identify locations along the sides of fjords which are most vulnerable to flood waves in the event of a major rockfall. The results of such models ought to be a standard component of municipal contingency plans in areas vulnerable to landslides and rockfalls.

The second major cause of large flood waves (tsunamis) is earthquake-related submarine slides or fault movements on the seabed. Tsunamis are capable of impacting on extensive areas of coastline, far beyond the local fjords. Historically, and in contrast to Pacific coasts, the Atlantic has not been subject to major events of this kind, with the notable exception of the great earthquake and tsunami of 1755, which destroyed much of the city of Lisbon in Portugal.

Researchers drilling in a bog on Askøy near Bergen for evidence of the 8,100 year-old Storegga slide tsunami. Studies such as this are important for predicting the potential consequences of future flood waves. (Photo: H. Hansen)

This is due to the fact that in the Pacific region, lithospheric plates are colliding and being forced beneath each other at subduction zones, while in the Atlantic the plates are moving away from each other along the mid-oceanic ridge segments. Earthquakes at spreading plate boundaries such as the mid-Atlantic normally involve less intense fracturing, and are generally of lesser magnitude, than is the case at compressive subduction zones. The risk of tsunamis is thus somewhat lower in the vicinity of Norway than in more tectonically active parts of the world.

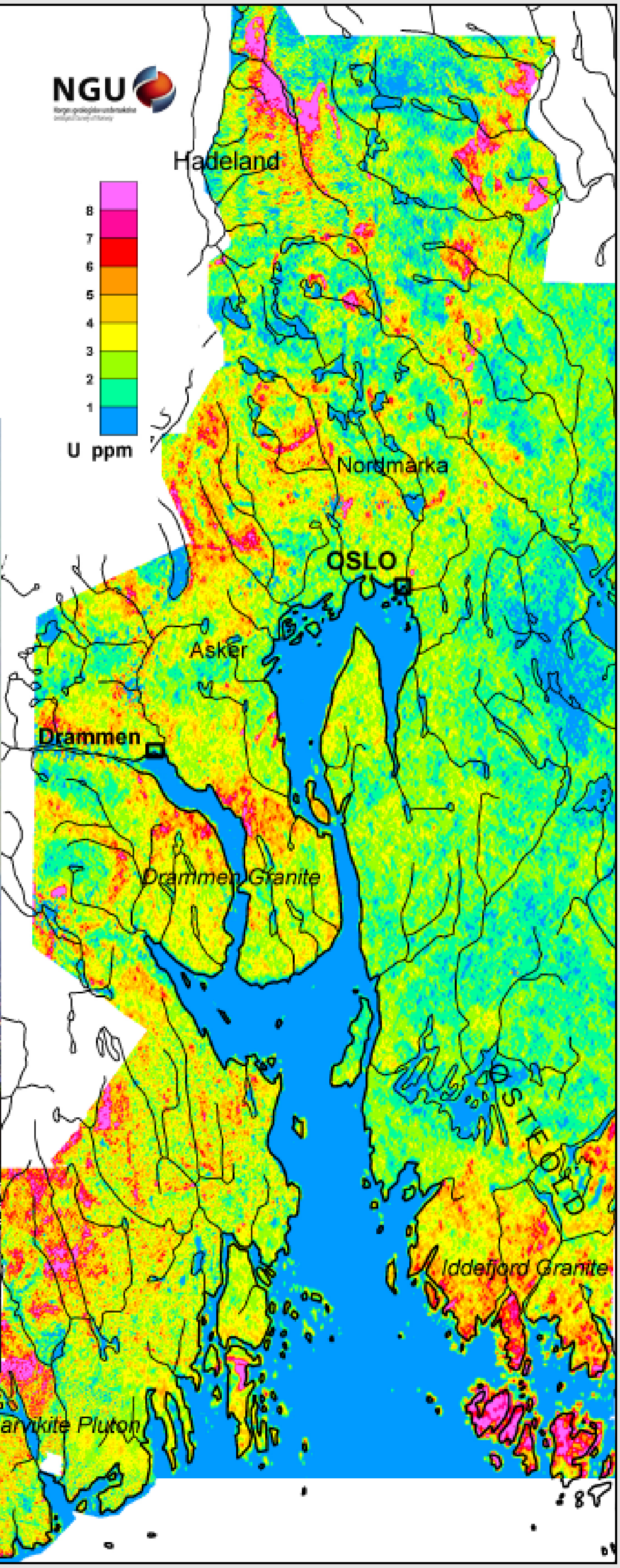
Tsunami waves 90 minutes subsequent to slide



Numerical simulation of the tsunami generated in the Norwegian Sea following the Storegga slide. The wave propagated outwards with a velocity of up to 600 km/hour. Close to the slide itself, land areas were flooded by a wave more than 12 m high. The figure illustrates the form of the wave approximately 90 minutes after the slide was triggered. (Figure: IGC - International Centre for Geohazards)

Map showing uranium concentrations in parts per million (ppm) in surface rocks, calculated from radiation measurements taken by plane and helicopter. The highest concentrations are associated with the Alum Shale and uranium-bearing granites.

The Iddefjord granite in Østfold, parts of the Drammen granite, and the Alum Shale outcropping between Asker and Hadeland all contain high concentrations of uranium. This map provides an important starting point for the construction of radon risk maps, and for assessment of geothermal heat potential in the Oslo area. (Figure modified after O. Kihle and M. Smethurst)



Aerial survey of natural radioactivity and Earth's magnetic field, Oppegård in Akershus. (Photo: H. Wisløff)

Global awareness of the phenomenon increased dramatically after the catastrophic tsunami which followed the extremely powerful earthquake offshore Sumatra in the Indian Ocean on 26 December 2004. The event could not have been prevented, but an adequate warning system would have helped save many lives. Warning systems have been in existence around the Pacific Rim since 1949, but are lacking in the rest of the world. It is technically entirely feasible to establish an Atlantic warning system, and Norwegian scientists have participated in research projects to develop such systems. Any future warning system will comprise several components including instrumentation, simulation models, data communication and mass education programmes.

Natural threats – both local and global

Nature provides us with numerous challenges and threats of disaster. Some are local, and others global, in their extent, threatening in extreme cases possible mass extinctions similar to those at the Permian/Triassic and Cretaceous/Tertiary boundaries.

Local geohazards include phenomena about which society must become increasingly aware in the future. Threats of landslides, rockfalls and flood waves are especially important in this respect. Local geohazards also include phenomena such as radon, a naturally-occurring radioactive gas. In Norway, radon is common in some of the plutonic granitic basement rocks outcropping in the Oslo area, where it is also present in the Alum Shale. All rocks and soils may contain small amounts of naturally-occurring radioactive elements such as uranium and thorium. Radiation from these substances is normally very weak and generally represents no health risk. However, radon produced by the radioactive decay of uranium can cause lung cancer if it is allowed to build up over prolonged periods in poorly-ventilated buildings. In Norway, poor ventilation during long, cold winters means that mortality rates due to radon are higher than in most other countries. The Norwegian Radiation Protection Authority has calculated that between 5 and 15 % of all cases of lung cancer in Norway are caused by radon, and that between 100 and 300 people die each year of radon-induced lung cancer. A reduction in the incidence of cancer due to residential radon can be achieved by identifying rocks or unconsolidated sediments which contain uranium, and conducting residential radon surveys. Radon can also enter buildings in the water supply so it is equally important to monitor groundwater sourced from uranium-bearing rocks.

The correlation between radon and lung cancer is a result of research efforts within the scientific discipline of *geomedicine*, which addresses the need to protect society from harmful chemical substances and radiation in the environment. Research is conducted into both naturally-occurring phenomena and sources of manufactured pollution, such as the storage of heavy metals and radioactive waste.

In other countries, volcanic eruptions represent serious threats to local populations, but this is currently not the case in Norway, where the only active volcano is Beerenberg on the island of Jan Mayen, where the last eruption occurred in 1985. Further eruptions can be expected in the future, but their effects are likely to be local.

Geohazards of global extent

Such events are much rarer, but have received increased attention in the scientific literature and media in recent years. They include phenomena such as meteorite impacts, supervolcanoes, reversals of the Earth's magnetic field, major changes in sea level, etc. Events such as these are capable of exerting an enormous influence on global climates and the biosphere. They are well documented in the geological record, and will most probably occur in the future, albeit at extended intervals. In statistical terms, the probability of such events occurring in "our" time is very low, but their potential significance demands systematic monitoring. - An additional threat, global climate change, is dealt with in a separate section.

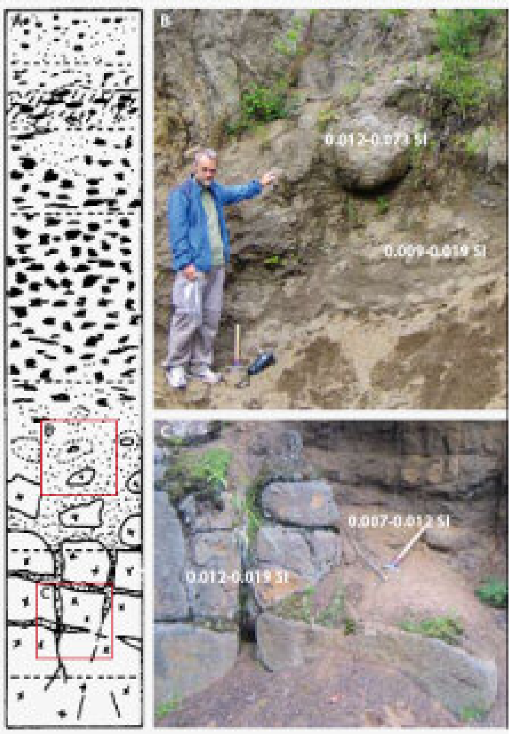
The last documented major meteorite impact was the Tunguska event in western Siberia in 1908. If the meteorite had exploded in the atmosphere just a few hours later, it could have devastated any one of the larger western European cities, instead of laying waste a barren and deserted region of Siberia. Today, huge telescopes are employed to monitor outer space and gather important information about bodies that might be on a collision course with Earth. With our modern space technology, we may be able to alter the course of or disintegrate threatening meteorites or comets in the future.

Supervolcanoes are gigantic volcanoes, many times larger than those active today. During the Permian, several of the major active volcanoes in the Oslo Region could justly be classified as supervolcanoes (see Chapter 9). Much later, in geological terms, at the Cretaceous - Palaeogene boundary, possible supervolcanoes were active on the Vøring Plateau on the Mid-Norwegian shelf. These have since been identified by geophysical mapping of the shelf conducted by oil companies and the Geological Survey of Norway (NGU). Today, it is generally accepted that the Yellowstone National Park province in Wyoming in the USA can be classified as a latent supervolcano. The eruption frequency of supervolcanoes is probably of the order of once every 100,000 years. Further research and observation are bound to arouse increased awareness of such phenomena in the future.

Ancient deep weathering causes problems for tunnel projects

Zones of weakness, combined with the presence in the bedrock of swelling clays, have been recurring problems for Norwegian tunnelling contractors. Practical experience has shown that underground construction projects in eastern Norway frequently encounter difficulties. In the early part of the twentieth century, construction of the underground Holmenkollbanen rail track encountered so many problems that the contractors went bankrupt. Similar problems were encountered and associated with rockfalls in the Oslofjorden, Hasle and Hanekleiv tunnels between 2003 and 2006. Perhaps our modern tunnels could be described as man-made geohazards?

The Lieråsen railway tunnel located between Asker and Drammen was another major project beset by problems. Construction began in 1962, but after five years only half the tunnel's length had been excavated. The cause of the delays included zones of "poor quality" rock that were the sites of frequent rockfalls and water leakage. In this case, the tunnel could only be completed by changing the original plan and altering its course. During the last decade, problems associated with the Romeriksporten tunnel project have been well publicised, and have entailed cost overruns amounting to approximately one billion Norwegian kroner. The several tens of planned tunnel projects in the Oslofjorden area alone represent the largest Norwegian investment projects outside the oil industry.



(A) Characteristic tropical deep-weathering profile subdivided into six different zones (defined by R.I. Acworth). The uppermost and lowermost zones are characterised by coarse-grained gravel and sand, whereas the two middle zones are more clay-dominated. Deep weathering normally extends to depths of 100 metres, but in fractured bedrock it may extend significantly deeper, i.e., to between 200 and 300 metres. Photographs B and C show examples of deep weathering in the two lowermost zones.
(B) The remnants of deep weathering in regional zones of weakness at Djupdal near Larvik. The relatively coarse-grained products of the deep weathering of larvikite form gravels that are used as aggregate for local forest tracks. Residual fragments of unweathered larvikite remain as so-called "corestones". This is a characteristic feature of the deep weathering profile in the present-day tropics. The white numbers denote the reduced levels of magnetic susceptibility in the deep weathering zones, compared with the "fresh" larvikite. These features are also observed at several other deep weathering localities in Vestfold and Buskerud.
(C) Incipient deep weathering along fracture zones in larvikite at Thorsås in Siljan. The figures denote that the magnetic susceptibilities are lower within the deep weathering zones than in the unweathered larvikite.
(Both photos: O. Olesen)

Hot, aqueous fluids associated with volcanic activity and the formation of granite batholiths in the Oslo Region and other locations in Norway have resulted locally in clay-mineral alteration of the bedrock. However, in order to understand the regional distribution of swelling clays in eastern and southern Norway and in Trøndelag, we must examine other geological processes. Studies of geomorphology and the gneissic basement below Jurassic and Cretaceous rocks in Skåne in Sweden have demonstrated that zones of weakness are to a large extent the result of chemical weathering under sub-tropical climatic conditions. The products of deep weathering, in the form of swelling clays and kaolin, are also found in the gneissic basement below Jurassic and Cretaceous rocks on the island of Andøya, and offshore on the continental shelf.

Humic acid derived from decaying vegetation made the groundwater acidic. This "aggressive" water flowed through fractures in the underlying bedrock, attacking the original minerals, which were then gradually broken down into clay minerals. This weathering process took place across the entire landscape surface over a period of several millions of years. Along open fracture zones, the weathering extended deep into the bedrock (deep weathering). Later, during the Late Cretaceous transgression, when the sea encroached onto the mainland and sea levels rose by 300-400 metres, the weathered rocks were overlain by claystone and chalk sediments similar to those that we encounter in the North Sea today. Initial uplift of eastern Norway began at the end of the Tertiary era, between 10 and 20 million years ago. During the glaciations, the ice masses and melt water removed the unconsolidated sediments that had protected the older weathering products. At the same time they also removed the uppermost zone of weathering, but did not extend down into the deepest fracture zones where the weathering products are now encountered, preserved at depths of more than 200 metres in the most pronounced zones. The successive stages of this process are illustrated schematically in Chapter 12.

GEOHAZARDS – MONITORING AND WARNING SYSTEMS *By Odleiv Olesen*

The Earth's magnetic field induces a secondary magnetisation in basement rocks that in turn contributes to the measured magnetic field. When rock-forming silicate minerals are broken down as a result of tropical conditions or hydrothermal alteration to form clay minerals such as smectite and kaolin, highly magnetic minerals such as magnetite will be altered to form less magnetic iron oxides and hydroxides (rust). It is this process that produces the red colouration characteristic of tropical soils. Deep weathering will thus give rise to a negative anomaly in the measured magnetic field. A method of filtering has been developed to accentuate the magnetic signal from deep weathering zones.

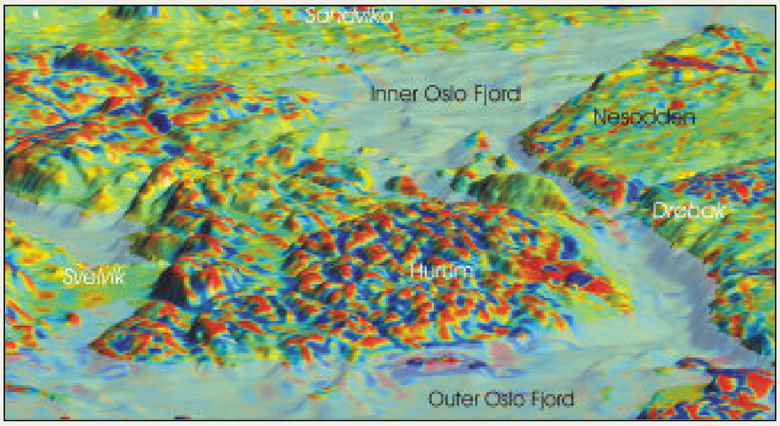
Coincident troughs (overlapping negative anomalies) observed both in the filtered magnetic field and filtered geomorphological data can be exploited as indications of the presence of deep weathering. Depending on the signal-to-noise ratio, the presence of deep weathering can be interpreted as "probable" or "possible". This method also has the advantage of working in submarine conditions if water depths do not exceed 50-100 metres.

This so-called "AMAGER" method (Aeromagnetic and Geomorphological Relations) appears to be valid for the majority of plutonic rocks and their altered products in central eastern Norway, although its usefulness in areas dominated by poorly-magnetised sedimentary rocks appears to be somewhat limited.

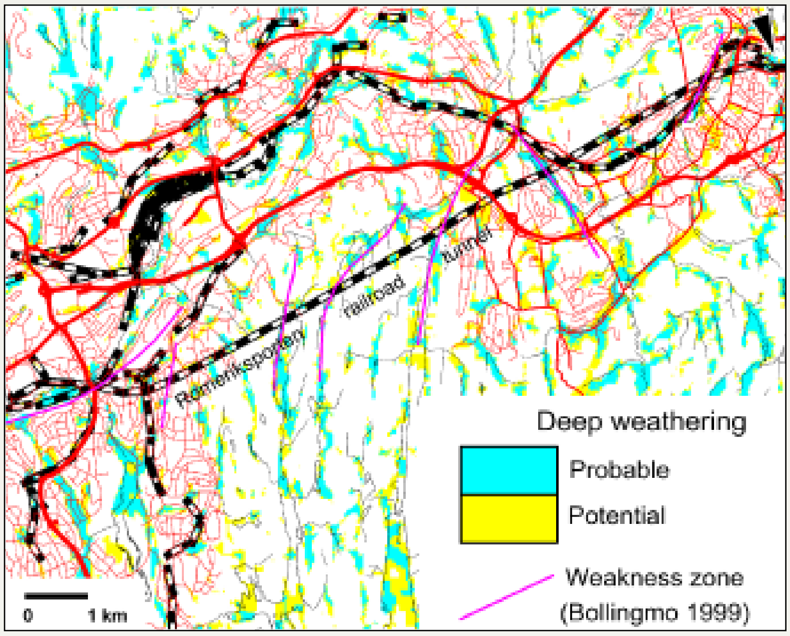
The excellent results achieved with this method are due to the combination of high resolution aeromagnetic measurements and detailed, digital topographic data. This innovative approach has resulted in a robust method of mapping the distribution of deep and eroded zones of weathering in central eastern Norway, along the southern Norwegian coast and in Trøndelag. It will also be possible to use the method in western Norwegian strandflat terrains and in northern Norway.

Since the effects of deep weathering diminish with depth, the problems of tunnel stability become less as the overburden above the tunnels increases in thickness. This fact is an important consideration during the planning of new tunnels. The presence of swelling clays and kaolin in deep weathering zones normally occludes the flow of groundwater in the shallowest bedrock strata (the uppermost 50-200 m). The risks of water leakage may thus increase with depth, as experience has demonstrated in various tunnel projects in eastern Norway. Experience from these projects has also shown that the major water leakages normally originate from fractured bedrock adjacent to, or between, major fracture zones. This knowledge can also be applied when drilling for groundwater.

The figures illustrate reliable correlations between observed zones of poor bedrock quality in tunnels and proven indications of deep weathering using the new method. The method has been tested in the Romeriksporten, Lieråsen and Hvaler tunnels, where more than 90 % of the known fracture zones in these three tunnels have been mapped.



Three-dimensional perspective across Oslofjorden and Hurumlandet. The filtered magnetic field is superimposed on a digital terrain model. The red and blue shading denotes high and low magnetic values, respectively. Depressions in the terrain often coincide with low magnetic values.



Interpretation of the distribution of deep weathering in the Østmarka-Groruddalen area to the east of Oslo. The map shows the location of the Romeriksporten railway tunnel together with fracture zones exhibiting poor quality bedrock, interpreted by Per Bollingmo. Zones of weakness in the tunnel, characterised by poor quality bedrock, correlate well with the interpreted zones of deep weathering.

Future environmental and resource management

Human beings are massive consumers of the Earth's renewable and non-renewable natural resources, and global consumption is on the increase. Consumption often places a great strain on the natural environment, and a balanced management of the environment and its resources will become a key future challenge for society in general, and for the scientific community in particular.

Modern humans are massive consumers of all types of mineral resources. For example, on average, each Norwegian uses about 10 tonnes of minerals and stone every year. Globally, the populations of Western Europe and North America consume many times more of most mineral resources than those of Africa and Asia. However, this gap is likely to close in the future as economic growth accelerates in developing countries. Global population growth, combined with higher standards of living, continues to exert enormous pressure on the Earth's natural resources, many of which are termed "non-renewable". Norway does not exist in isolation, and issues linked to our management of the environment and its natural resources must be addressed in the context of global conditions and developmental trends.

Non-renewable resources

Non-renewables include oil, gas and coal, a variety of metals (ores), industrial minerals, building raw materials (sand, gravel and aggregate, in addition to a variety of types of stone) and soils, which are exploited for agriculture. Many of these raw materials are abundant in nature, but are not always located where humans most need them, or where it is most convenient to exploit them commercially. Other resources are in danger of becoming scarce. However, research, improved exploitation technologies, recycling and other measures all contribute to our ability to improve exploitation efficiency, and thus postpone situations of shortage. At the same time, there is increasing opposition among local communities to the location of mines, quarries and major industrial complexes close to housing or recreational areas. Even in the event of the discovery of a new resource, exploitation plans may thus become the source of major and protracted conflicts.

In Norway, traditional mining activities have gradually been abandoned. In their place, a major and vigorous industry involving the exploitation of industrial minerals and dimension stone has emerged (see map at the back of the book). This trend is likely to continue. Norway remains a country rich in metal ores, dimension stone and industrial minerals, all of which may provide opportunities in the future.

Norway is also a major producer and exporter of oil and gas. Naturally, focus will continue to be directed at issues related to the continued commercial viability of these resources. However, here too investment in research and technology is capable of promoting major improvements in exploitation efficiency, and thus extending the "oil boom". Consequently, the term "resource", does not represent a single, fixed figure, but a variable entity whose magnitude is dependent on levels of commercial activity and the technological environment. In any event, although Norwegian oil production has undoubtedly reached its peak, gas production will continue to increase for some years to come.

Prolonging Norway's ability to produce hydrocarbons is dependent on realising the potential of its Arctic territories. Today, we can see the first stages in the race to exploit the hydrocarbon potential of the Arctic Ocean, which may become ice-free within the next hundred years. It has been estimated that perhaps up to 25 % of the world's undiscovered oil and gas resources are located in the Arctic, including the vast Siberian and Canadian sedimentary basins. Svalbard is situated on the Norwegian continental shelf and Norway, as a coastal nation bordering the Arctic Ocean, is actively promoting its territorial claims. These include the oceans north of Svalbard, covering an area equivalent to half of Norway's land area. The four remaining circumpolar states are also staking their claims, and taken together these will encompass great expanses of the Arctic Ocean. In contrast, the environmental groups are actively demanding conservation of the Arctic Ocean and the prohibition of petroleum-related activities.

Renewable resources

Fresh water is a *renewable* resource, and the most important of them all. In many countries, consumption is greater than the resource available. Securing and managing necessary supplies of clean water for drinking and irrigation for future generations will become major tasks. This is a major global challenge, although it may not seem so critical in a rainy country such as Norway. In fact, clean drinking water may become an important Norwegian export commodity, and the foundation of a major future industry.

History teaches us that any resource shortage, whether it is oil, gas or water, harbours the potential for international conflict, perhaps even war. Threats of this kind will present additional major challenges for both politicians and the geoscientific community in the years ahead.

The downside of global resource consumption is that improved living standards inevitably produce increasing volumes of waste and associated environmental problems. A balanced local and global management of resources and the environment is thus a prerequisite for the future survival of our societies. It is vital to ensure the effective storage and disposal of the chemical and radioactive waste which our modern civilisation produces. In Norway, Himdalen in Akershus and Langøya in Oslofjorden are examples of storage and disposal facilities for low-grade radioactive waste and industrial waste, respectively. Both were selected based on geological criteria and with social implications in mind. If future generations are to avoid being overwhelmed by industrial and household waste, society must continue to give high priority to the development of secure storage facilities and safe methods of disposal.

In addressing the aforementioned tasks, geological information is a very important tool, not only in respect of geohazards and climate change, but also in the fields of resource and environmental management and town and regional planning. With this in mind, the Geological Survey of Norway has adopted the motto "*Geology for Society*". In its various activities, the Survey aims to make a major contribution by providing basic geological data to those in the municipal and national institutions with management and planning responsibilities.

Norway's oil and gas resources - how long will they last?

Energy production has become a mainstay of the development of modern industrial societies. In Norway, oil and gas has been a driving economic force since the early 1970s. In recent years (since 1995), oil and gas has on average accounted for 20 to 25 % of Norway's gross national product (GNP), about 45 % of its combined export value, and about 25 % of the nation's total revenues. More than 200,000 people are employed in the petroleum sector. However, oil and gas are non-renewable resources and many people are asking when the "party" will come to an end. In 2004, oil production peaked at about 3.2 million barrels per day, whereas in 2007 it ran at an average of 2.4 barrels per day. Continued reduction is forecasted for subsequent

LANGØYA IN OSLOFJORDEN. As early as the 1700s, the island was exploited as a limestone quarry, supplying the Slemmestad cement works for 87 years until 1989. Today, Langøya has been transformed into a modern treatment and storage facility for industrial waste. The waste is converted into a stable form of gypsum which in due course will refill the quarry. It is estimated that the plant will be filled with industrial waste for a further 20 years, before it is covered in soil and replanted. There will be a continued need for waste storage facilities in the future. Langøya has also for many years been a Mecca for fossil-hunters. (Photo: published with the permission of NOAH).

METAL RESOURCES – ABUNDANCE OR SHORTAGE

By Arne Bjørlykke

During periods of economic growth concerns are always raised about future access to resources. In the 1960s and 70s it was popular among economists to compile resource accounts. In 1972, the book «The Limits to Growth» was published, based on a future scenario study conducted at the Massachusetts Institute of Technology (MIT). The project was commissioned by the Club of Rome which, when it was established in 1968, comprised a group of 30 members from 10 countries under the leadership of the economist and industry magnate Aurelio Peccei. The MIT group concluded that the beginning of the 21st century would herald global shortages of non-renewable resources such as metals, minerals, oil and gas, and that this would lead to runaway price increases, and a growth of onshore mining activities resulting in severe pollution.

These predictions encouraged American corporations such as Lockheed to begin exploration in the 1960s for manganese nodules on the deep ocean floors. It was widely held that the metal resources of the future would be found in these nodules. Many developing countries viewed attempts by the great industrial conglomerates to secure this potential wealth with some concern, and in 1973, preparatory work for the United Nations Conventions on the Law of the Sea (UNCLOS) was begun. Agreement was reached and the ratification process began in 1994. The treaty is interesting because it encompasses half of the Earth's surface. Management of the deep oceans and the manganese nodules was delegated to a UN organization called The International Seabed Authority.

Today, more than thirty years after publication of «The Limits to Growth», there is no longer a perception of shortage regarding metals and minerals, and mining of seabed manganese nodules is not considered to be commercially viable. Why did the group at MIT get it so wrong? They made the error of assuming that all reserves of natural resources were known, and underestimated the extent of new discoveries. They took no account of the development of new exploration and production technologies, which have in fact resulted in lower costs and better environmental protection, both during and after production.

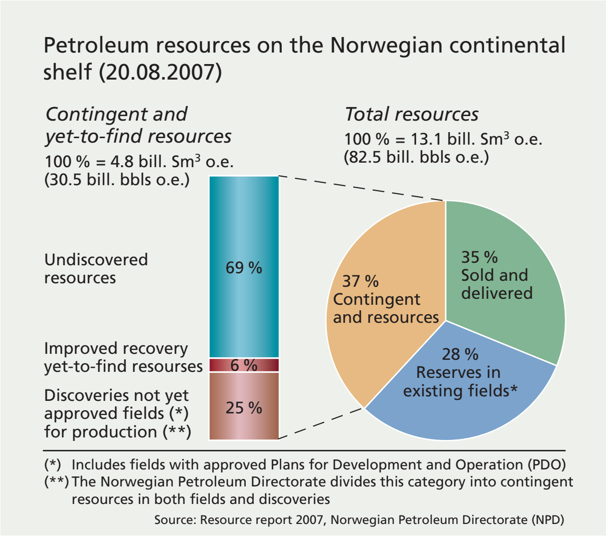
If they had been discovered today, the iron ore mines of the Oslo region, the Caledonide copper and zinc ores, and the Kongsberg silver mines, which have all played major roles in Norway's economic development, would never have been regarded as commercially viable. The prices of metals have fallen in relation to wage levels and other commodities. Abundant metal resources continue to be mined from the interiors of the continents, and production of metals from manganese nodules has not yet begun.

The Iron Age did not come to an end because of a shortage of iron!

Manganese nodules from the deep ocean floor. INSET: Manganese nodules as they appear in nature on the sea floor. They are most abundant in the Pacific Ocean. (Photo: ISA – International Seabed Authority) years. Depending on a number of factors like oil price, politics, research efforts, availability of acreage, exploration success, and environmental considerations it is possible to envisage various scenarios for the future development in oil production: all leading to a slow down in production over the next 2-4 decades. But at significantly different speeds. In contrast, gas production is expected to increase from the present level of about 90 billion m^3 per year to nearly 120 billion m^3 in 2011. Today, the Norwegian continental shelf is described as a mature oil province with major additional gas potential.

The figure shows that the estimated total hydrocarbon resources on the Norwegian continental shelf (including oil, gas, condensate and LNG), are approximately 13.1 billion m^3 oil equivalents (o.e.). About 35 % of these resources have been produced, while the remaining two thirds remain in the reservoirs. Estimates of remaining resources are laden with uncertainty, and the real figure could easily be somewhat higher or lower. The estimate is most probably conservative in that it does not take into account the potential of the so-called "disputed area" in the Barents Sea, situated at the territorial boundary with the Russian Federation, or the northernmost Arctic areas surrounding Svalbard and Jan Mayen. Resource estimates also exhibit a tendency to increase as geological knowledge grows, and in step with new technological advances. The various production scenarios for the Norwegian continental shelf indicate a potential for further 20 to 40 years of oil production, and an extended period for gas production.

It is widely held that hydrocarbon volumes associated with the term "resources" represent an absolute figure. In practice, the industry defines resources as a dynamic entity dependent on technology, investment, the commercial environment in general, and price. It is no simple matter to recover hydrocarbons from reservoirs located several kilometres below the seabed, and the process demands the continuous development of new expertise. Investment in oil-related disciplines such as geology, reservoir-related sciences and well technology will enable us to make new discoveries and enhance recovery factors from existing fields, and thus increase the volume of feasibly recoverable resources. Future increases in resource estimates and a long-term development strategy for the Norwegian petroleum industry will depend on policy decisions made by the authorities and investments in research and technology made by the oil and service companies.



(*) Includes fields with approved Plans for Development and Operation (PDO)
(**) The Norwegian Petroleum Directorate divides this category into contingent resources in both fields and discoveries

Source: Resource report 2007, Norwegian Petroleum Directorate (NPD)

Estimated oil and gas resources on the Norwegian continental shelf 2007. (Source: NPD Petroleum Resource Report 2007)

Peak Oil

Norway's status as a major oil and gas producer must also be viewed in a global context. In due course conventional oil resources will become increasingly scarce, presenting the global community with major challenges. Today, high and ever-increasing levels of global oil production are maintained largely as a result of major discoveries made many decades ago. Debates centred on the concept of "Peak Oil" (the point in time at which production rates reach their maximum), and the consequences for the world's economic and social welfare systems when global oil production begins to fall, have been continuing for several years. Perceptions of shortage are inevitably followed by higher oil prices and increased focus on alternative fossil energy sources such as coal, heavy oil, oil sands, oil shales and gas hydrates. Taken together, these constitute a massive potential resource. Gradual increases in the rates of extraction of these deposits in an environmentally responsible manner will be a major and challenging task in the years to come, both in terms of technology and political will. This can only happen as part of a balanced interaction between the development and exploitation of alternative energy sources such as wind, waves, solar power, bio-fuels, geothermal heat sources and nuclear power. In future decades we will see the exploitation of a wider diversity of energy sources for heat and power generation.

In spite of the many opportunities which enhanced recovery techniques and alternative energy provide, the transition to the "post-oil" era may prove uncomfortable. The process begins not when the last drop of oil has been recovered, but when global oil production is no longer able to satisfy demand.

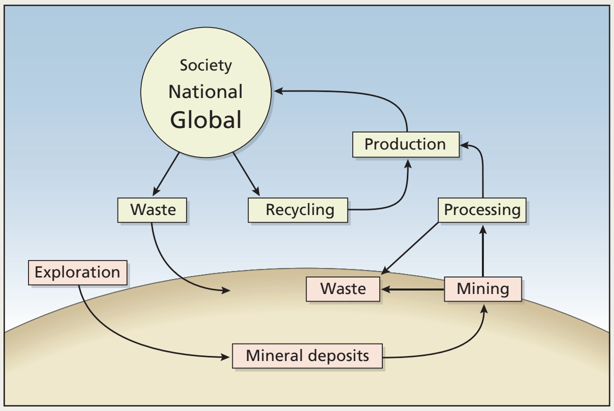
TOMORROW'S INDUSTRIAL MINERALS AND METALS

By Are Korneliussen

The development of the human race is reflected in our ability to exploit minerals and metals. Terms such as the "Stone Age", "Bronze Age" and "Iron Age" are characterized as periods in human history when implements of stone, bronze (an alloy of copper and tin) and iron, respectively, were manufactured and in common use. The industrial revolution of the 1700s was driven in part by our ability efficiently to utilise coal to power steam engines. This laid the foundation for the expansive industrial development which drives our modern civilisation today.

In step with the development of our industrial society, we have seen a dramatic increase in the consumption of metals, industrial minerals, building raw materials and various types of plastic-based products manufactured from oil and gas. A prerequisite for this consumption has been ready access to energy resources such as coal and naturally-occurring oil and gas.

In historical times, humans were capable of utilizing only limited types of ore deposit containing high natural concentrations of certain metals. In the future, advances in high technology will provide us with almost unlimited opportunities to exploit any mineral contained within the crust. In such a situation certain mineral resources will be seen as almost inexhaustible, and limitations on exploitation will only be defined by ease of access of sufficient energy, combined with the potential negative and unacceptable impacts on the natural environment. However, high levels of material recycling, combined with the education of societies towards an ecologically-based and holistic outlook towards mineral exploitation, may make it possible to minimize our perception of potential disadvantages.



The cycle of mineral raw materials illustrating their discovery, recovery, processing, manufacturing processes, and use by consumers - ending with their return to the natural environment as waste products.

New attitudes such as these are implicit in terms such as "sustainable management of mineral resources", by which society strives to achieve optimal methods of exploitation which benefit current generations, while at the same time taking into account the interests of our descendants. Emphasis will be focused on the concept of a given mineral's "life cycle" (see figure). Given this perspective, we anticipate that future societies will give priority to the exploitation of minerals and metals which can be recovered and utilised with minimum damage to the natural environment. This scenario presupposes that society will develop a preference for lighter and stronger materials (composites) derived from oil and gas, light metals, and minerals which require modest levels of energy consumption for their production and use, and which are recyclable. As technological development advances, new mineral- and metal-based products will be developed for an increasingly more complex society.

Nanotechnology, which operates at the atomic and molecular level, is a new branch of science which will undoubtedly make its mark on future societies. Nanominerals are minute crystals with reactive surfaces which make it possible to produce materials with entirely revolutionary properties. They have enormous application potential in fields such as ICT, applied mineralogy, medicine, and the nutritional and environmental sciences.

The most important metals utilised in our modern industrial society are iron, gold, aluminium, lead, copper, nickel and zinc. Important industrial minerals produced in Norway are limestone, quartz, the titanium-bearing mineral ilmenite, olivine, talc, feldspar and nepheline syenite.

Titanium (Ti) is regarded by many as the metal of the future, and Norway has plentiful titanium ore resources. It is much stronger than steel in relation to its mass, and is tolerant of both high and low temperature extremes. It is also highly resistant to corrosion. Not least among its titanium's characteristics, is that there are currently no known harmful impacts of its use either on the external environment or human health. The metal is used mainly as a titanium dioxide pigment in paints, plastics and paper. Use of the metal in its pure form is currently somewhat restricted due to its high price. It will be essential for future societies to develop new and cheaper means of producing titanium in its metallic state.

Silicon (Si) is another metal of the future. It is the most widely distributed element in the Earth's crust after oxygen (O). These two elements combine to form the industrial mineral quartz (SiO_2), which is one of the raw materials used in the production of various types of glass, artificial minerals, ceramics and porcelain, silicon metal, and ferrosilicon. Silicon metal is used in the manufacture of solar cells and in microchips used in various types of electronic equipment.

Today we can make assumptions about how future societies will utilise minerals and metals – or we at least believe we can. In fact, future societies are unknown quantities and may develop in directions which are impossible to predict. However, industrial minerals and metal ore deposits will play an important role as long as human societies maintain highly developed civilisations and have access to abundant sources of energy.

GEOLOGY FOR TOMORROW'S SOCIETY

By Arne Bjørlykke

For over 3,000 years, maps have been an effective aid in presenting large volumes of geological information. They provide a visual presentation of accumulated data and facts which are otherwise difficult to convey in words. However, they also rely on the reader having some degree of geological knowledge. The digital revolution has barely begun but even today, new technologies allow us to communicate with millions of users at no great expense. However, digital media also place new demands on the way we present geological facts and data. If we are to fully exploit these technologies, facts must be presented in ways which our audience can comprehend. The "virtual landscape" has evolved into an important and universally accessible communication platform, and is rapidly overtaking the traditional map as a presentation medium. New technologies allow geology to be visualised directly as pictures, and we can now convey the rock type using a picture of granite instead of the traditional map symbol. In addition, animation techniques allow us more easily to display the critical fourth dimension - geological time.

There is an increasing universal demand for geological information. As humanity continues to alienate itself from its natural environment, natural disasters are perceived as an increasingly greater threat. In most cases, major natural catastrophes cannot be entirely prevented, but it is possible to monitor geological processes and to provide warnings. The rate of continental drift can be measured with very high levels of precision, and the results applied in earthquake research. In the future, radar satellites will be used to track small movements (less that 1 mm) of the Earth's surface on a daily basis. Monitoring of the earth's magnetic and gravity fields will become increasingly important tools in research and public administration. Technological developments in the field of unmanned spy-planes will enhance geophysical data acquisition, both in terms of quality and cost-effectiveness.

The digital landscape allows us to display geology in four dimensions (4D), and we can construct animated histories of how the Norwegian landscape appeared when the dinosaurs roamed the Earth, or during the last glacial maximum. We will soon have a wealth of technological opportunity, constrained only by our lack of information. We still have much to learn about how Norway's bedrock and unconsolidated sediments appear in three dimensions.

Today, we observe a trend in which our attitude to science is reverting to generalism, and we see ourselves increasingly as scientists rather than specialist geologists, chemists or biologists. New disciplines such as biogeology, encompassing in particular the study of organisms living in extreme habitats, are developing rapidly. Increased accessibility to scientific information as provided by new technologies will lead to an expansion of multidisciplinary fields. This will result in better products for the end-users, whose demands are usually not pigeon-holed into distinct scientific disciplines.

In spite of continuous and rapid development in data acquisition and manipulation, the greatest changes will occur in the ways by which data and information are disseminated. Vector data, which can be made directly downloadable to public administration plans and consultants' reports, will facilitate dramatic increases in the way we use geological data. 3D- and 4D-visualisation techniques will make information accessible to a much greater proportion of the population.

By combining mobile telephony and GPS, it is possible to determine precisely where in the world you may be standing to an accuracy of a few decimetres, and to provide comprehensive information about the locality, such as the rock type you may be standing on and how was it formed; whether there are any gold deposits on the site; how much groundwater you can expect to find if you were to drill; the levels of pollution in the soil; any high concentrations of naturally-occurring arsenic or uranium; the presence of deep weathering; information about the potential efficiency of a geothermal well; the vulnerability of the site to quick clay landslides, rockfalls or tsunamis.

Links between mobile telephony and personal computers will make these data and much more besides readily accessible, and society's demand for geological information will continue to expand.

Today, the acquisition of geological field data can be performed efficiently with the help of the latest ICT (Information and Communication Technology). Hand-held PCs with in-built GPS and mobile telephone are available at reasonable cost. Devices such as these are also used to receive data regarding specific localities from internet-based Geographical Information Systems. (Photo: NGU - Geological Survey of Norway)

Future climates – a geological perspective

Climatic conditions on Earth have been in continuous flux throughout the planet's evolution. The enormous variety of sedimentary rocks and unconsolidated sediments, combined with data locked in the great polar ice shields, provide ample evidence of this. Today, it seems increasingly likely that the activities of the human race also contribute to climate change on Earth, and that this human influence is becoming superimposed on natural climatic variation. Human consumption of fossil fuels (coal, oil and gas) increases the concentrations of atmospheric greenhouse gases, reinforcing the greenhouse effect and promoting significantly warmer climates in the future.

What is it that distinguishes human influence on climate change from the effects of natural phenomena? How will future climate change differ from that experienced in the past? To answer these questions we must first examine the factors that influence climate change.

Some aspects of climate change are caused by external factors, while others are the result of internal processes on Earth. Fluctuations in the intensity of solar radiation are an important external factor. Another is the periodic variations in the Earth's orbit around the Sun (the eccentricity of the orbit, the tilt of the Earth's axis with respect to the plane of the orbit and the variations in the time of the year when Earth is closest to the Sun). These orbital factors determine variations in the distribution of solar radiation between winter and summer, and between the northern and southern hemispheres. Examples of internal processes which influence climate change include the instability in circulation patterns in the oceans and the atmosphere, and natural variations in atmospheric concentrations of greenhouse gases, including water vapour.

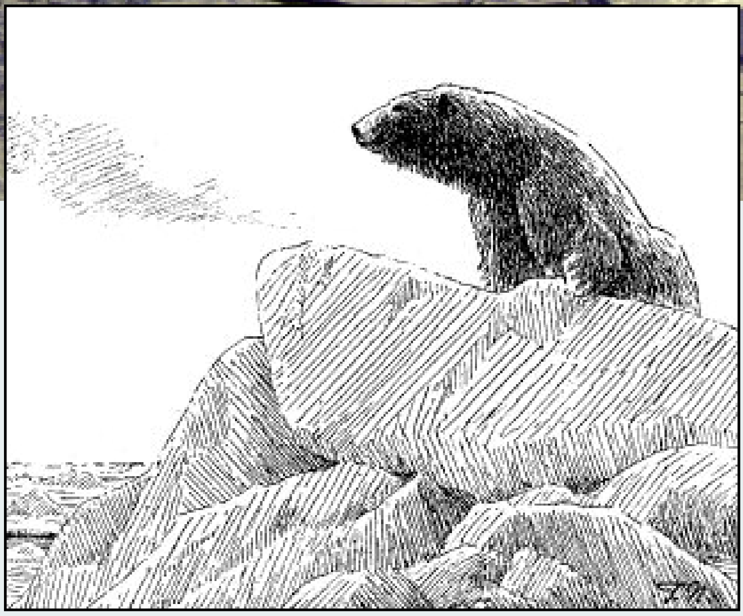
Climate change is also influenced on both local and global scales by the gradual action of plate tectonics and the formation of mountain belts. The relative location of the continents and oceans, the size of the oceans, and the elevation of the continental landmasses above sea level are all key factors in determining the Earth's climate. However, these factors vary extremely slowly over intervals of millions of years. Climate change which occurs over intervals of 100,000 years or less must be due to factors other than these.

Natural influences on climate change

The most important factor in nature which influences climate change is the systematic variation in the Earth's orbit around the Sun, which is influenced by changes in the relative positions of the planets in our solar system. This is the most important driving force controlling glaciation and deglaciation on Earth, and our knowledge of the planet's orbital behaviour allows us to predict future glaciations. This is explained in more detail in the text box.

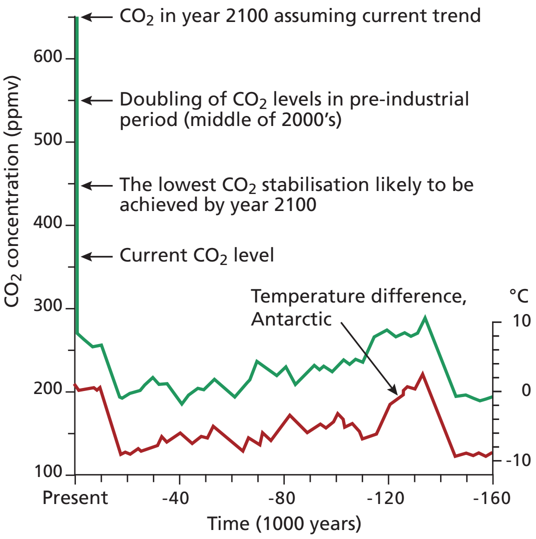
We also know that climate change lasting some tens and hundreds of years may be caused by volcanic eruptions and changes in solar activity. Powerful volcanic eruptions resulting in the discharge of dust and sulphur compounds into the atmosphere will obscure solar radiation, and lead to a succession of cold summers. Climate change due to such processes, and other random events, have contributed to historical fluctuations between warmer and cooler intervals including, among others, periods of crop failure, such as during the "Little Ice Age" between about 1350 and 1800.

Climate change in action in the Arctic Ocean. Depleted summer sea ice permits easier access and places enormous pressure on resources and the environment. The photograph shows three ice-breakers cruising close to the North Pole as part of the 2004 ACEX expedition. The ships are; "Vidar Viking" (foreground), "Oden" (centre), and "Sovjetskiy Sojus" (background). (Photo: M. Jacobsson))

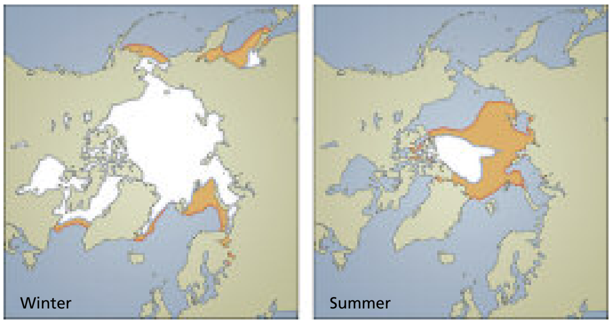


A new ice age on the horizon?

Polar bear on lookout. Drawing by Fridtjof Nansen from his 1924 book "Among the seals and bears".



Past and future atmospheric CO_2 concentrations. Historical natural variation is recorded in air bubbles from ice cores taken from the Antarctic Ice Sheet. The green curve shows variations in CO_2 based on measurements taken from ice cores ranging over 160,000 years, combined with atmospheric data acquired during the last 55 years. The red curve shows the difference in temperature in the Antarctic compared with today's values. Data from the Antarctic demonstrate that during the last 70,000 years, concentrations have never been higher than 280 ppmv. An average of data derived from climate models indicates that a doubling of CO_2 concentrations will result in a global temperature increase of between 2 and 3.5 °C. Warming will be much more intense in the Arctic than elsewhere on the planet.



The distribution of Arctic sea ice using the Bergen Climate Model, and based on a doubling of current atmospheric CO_2 concentrations, a situation that will occur in the second half of this century if current emission rates continue unabated. LEFT: Winter ice distribution. RIGHT: Summer ice distribution. The white areas indicate sea ice distribution after a doubling of CO_2 concentrations. Orange (plus white) areas denote modelled ice distribution assuming that present-day CO_2 concentrations remain constant. The greatest impact of increased CO_2 concentrations is on summer ice distribution. It is likely that by the end of the present century, the Arctic Ocean will be ice-free during the summer months.

Variations in solar radiation resulting from changes in orbital behaviour are small over the Earth as a whole, and require a reinforcing process if they are to exert a major influence on climate. A major factor providing such reinforcement is the accumulation of ice and snow. This promotes cooling because white snow- and ice-covered regions reflect a much greater proportion of solar radiation back into space than areas covered with heat-absorbent vegetation or open ocean. This in turn promotes the further accumulation of ice and snow, and the process becomes self-reinforcing.

The glaciers which shaped Norway's present landscapes started to exert their influence about 3 million years ago when average climatic conditions became cold enough for orbital variations to be reinforced by increased snow and ice accumulation in northern Eurasia and America. The cause of this cooling has been the subject of much debate. Most researchers believe that it resulted from a combination of gradual falls in greenhouse gas concentrations in the atmosphere, changes in the relative positions of the continents (including the emergence of the isthmus of Panama), which in turn altered oceanic circulation patterns, and orogenic activity which modified atmospheric circulation patterns and caused the cyclone paths to shift. Subsequently, repeated cycles of glaciation have been interrupted by shorter interglacials forming part of a rhythmic cycle determined ultimately by the Earth's orbital behaviour.

It is possible to predict the Earth's orbital behaviour with high levels of accuracy, and we can therefore make very reliable prognoses about future climatic change patterns, provided that Nature remains the dominant influential factor and human influence insignificant. This is described in more detail in the text box.

Human influence on climate change

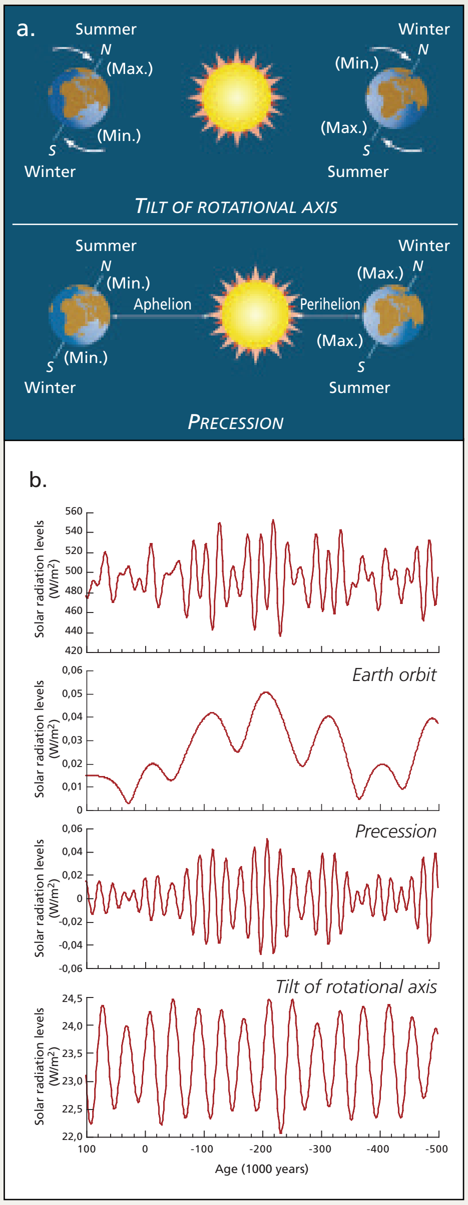
During the next thousand years, greenhouse gas emissions to the atmosphere, combined with short-term variations in solar and volcanic activity, will be decisive in determining future climatic developments. This is because the combustion of coal, oil and gas by humans has effectively succeeded in "short circuiting" one of the large-scale geological cycles. The resulting emissions are being discharged at a much higher rate than would occur naturally. This has resulted in an accelerated increase in atmospheric concentrations of carbon dioxide (CO_2). In combination with other greenhouse gases, such as water vapour, methane and nitrous oxide, carbon dioxide contributes to reinforcing the greenhouse effect. Greenhouse gas concentrations can also result from natural processes, and fluctuations are known to have occurred during the glaciations. However the increases observed today are greater than any previously recorded. Natural variations in atmospheric greenhouse gas concentrations during the last nearly one million years have been measured in gas bubbles extracted from ice cores taken from the Antarctic ice sheets. For example, CO_2 concentrations can vary by 30 % during intervals of several thousand years between glacial periods and interglacials. During a period of only 200 years in the wake of industrialisation, humans have succeeded in increasing concentrations by a further 30 %. During the present century we will most probably achieve atmospheric concentrations of carbon dioxide which are at least twice as high as any recorded during the last 800,000 years. This continued increase will most probably result in a significant period of warming, although it remains uncertain as to by how many degrees tem-

THE EARTH'S ORBITAL BEHAVIOUR

The Earth's orbit around the Sun varies from being nearly circular during certain periods, to elliptical at others. The seasons of the year during which the Earth is closest to the Sun also vary. When the orbit is elliptical, this will impact on the relative warmth of the summers, depending on the distance between the Earth and the Sun during the summer months. The Earth's rotational axis is tilted at an angle of about 23° in relation to its orbital plane. This axial tilt is the reason for the differences we experience between summer and winter, and also explains why Norway enjoys the midnight Sun, and experiences correspondingly long dark winters. In addition, the axial tilt is not constant, but varies between 22° and 24°. This variation alternately increases and decreases the contrast we experience between summer and winter. Thus these three factors; the form of the Earth's orbit, the season during which the Earth is closest to the Sun, and the tilt of the Earth's axis, all combine to control variations in solar radiation from season to season and from region to region. These phenomena can be calculated by astronomers with high degrees of accuracy, both for the past and into the future, and each varies at known frequencies. As early as the 1800s, many glaciologists were suggesting that these relationships combined to produce the glaciations. Between the two World Wars, the Serbian climate researcher, Milutin Milankovic, calculated the effects of variations in the Earth's orbit on the intensity of solar radiation, and an astronomical theory of glaciation was subsequently named after him. More recent research has confirmed the Milankovic theory. We have discovered climate indicators in deep ocean sediments, in boreholes in continental ice sheets, and in continental sedimentary sequences, all of which exhibit precisely the same periodicities as the Earth's orbital parameters (23,000, 41,000, and approximately 100,000 years). This demonstrates that the timing of the start and end of glaciations, and the most marked variations within each individual glaciation, are determined by factors related to the Earth's orbit.

The Earth is currently experiencing somewhat unusual orbital behaviour, and we must go back some 400,000 years, to a prolonged and relatively warm interglacial, to find a comparable situation. At present, the Earth's orbit is approximately circular, and will continue to remain so for several tens of thousands of years. Data acquired from deep Antarctic ice sheet boreholes demonstrate that the interglacial back then lasted for about 30,000 years. Interglacials normally last only about 10,000 years. It is now 11,000 years since the last glaciation ended and, under normal circumstances, we should expect to be on the threshold of a new "ice age". However, the Earth's unusual orbital parameters are effectively extending the current interglacial and we do not anticipate the approach of the new glaciation before about 20,000 years in the future. Results from various climate models confirm this model.

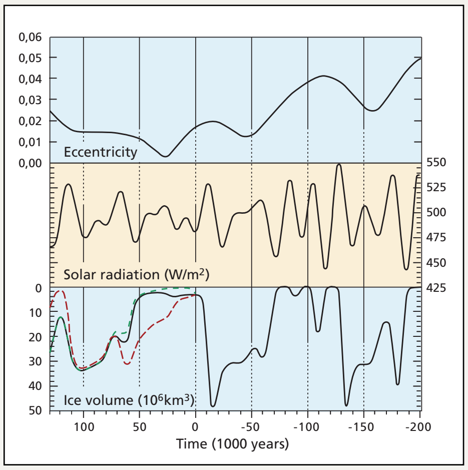
The figure shows that the Earth's orbit is approximately circular at present. As a result, and for some time to come, only weak variations in solar radiation are anticipated during the summer months. Not before 50,000 years will summer radiation levels reach a minimum. The resulting ice volumes on the planet have been calculated using a simplified climate model capable of simulating the accumulation of large-scale ice sheets, and to melt them again as conditions change. Simulations made for the last 200,000 years agree very well with geological observations, including measured changes in atmospheric CO_2 taken from air bubbles sampled from the Antarctic Ice Sheet. Three different CO_2-scenarios have been chosen; **1.** A standard progression as observed for previous glaciations (solid line). **2.** A progression based on a man-made doubling of present-day CO_2 concentrations, which then gradually falls (dashed green curve). **3.** A scenario in which CO_2 concentrations are maintained at the lower values experienced during the glaciations (dashed red line).



EARTH ORBIT VARIATIONS CAUSE CLIMATE CHANGE:

a) The tilt of the Earth's axis (above) determines the contrast we experience between summers and winters. As the tilt decreases, summers become cooler, and vice versa. Precession influences the distribution of solar radiation impinging on the Earth's surface and determines the season of the year when the Earth is closest to the Sun (perihelion). If this occurs during the summer, Norwegians experience intensified solar radiation and warmer summers. When a high tilt angle coincides with the perihelion, summers will be warm. Glaciations always come to an end under such conditions, while the opposite is the case at their inception.

b) Variations in the Earth's orbital parameters for the last 500,000 years, and the next 100,000 years. The uppermost curve shows variations in solar radiation at Norwegian latitudes as a result of changes in the Earth's orbital parameters illustrated in the curves below. The Earth's orbit, its precession, and axial tilt vary in cycles with periodicities of 100,000, 23,000 and 41,000 years, respectively.



Earth's orbital parameters for the next 150,000 years. The figure shows simulated values for the form of the Earth's orbit around the Sun (eccentricity; uppermost), estimated summer solar radiation at 65° N (centre), and a simulation of variations in ice volume on Earth as a result of changes in the Earth's orbit and atmospheric CO_2 concentrations (lowermost). All data is extrapolated from 200,000 years in the past (negative age) and extended 150,000 years into the future (positive age).

peratures will rise, and how fast the process will occur. It is also difficult to predict accurately how this warming will distribute itself across the different regions of the globe.

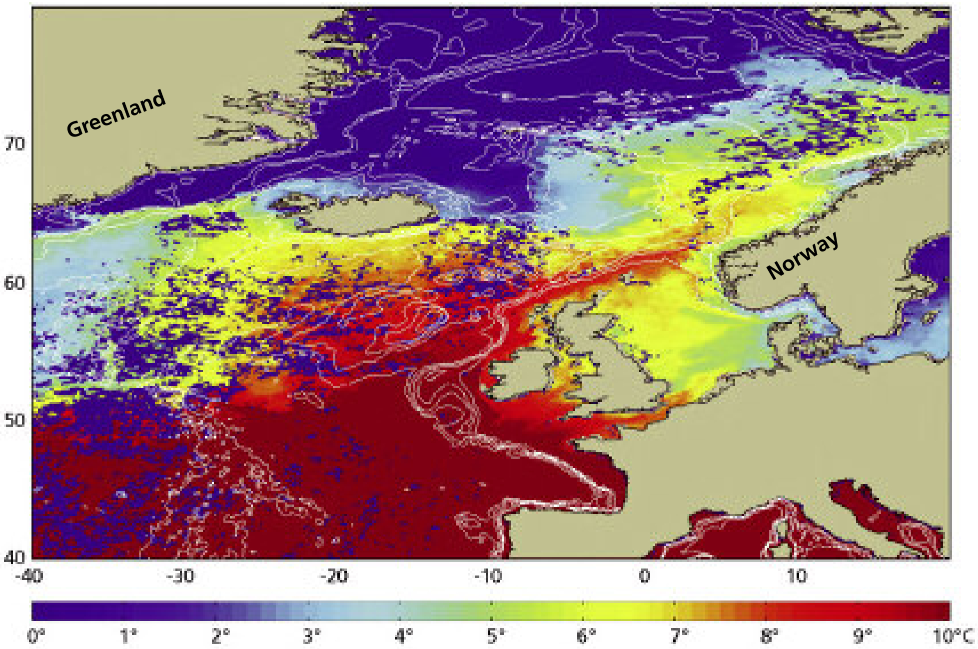
The intensity of future global warming is thus very dependent on the magnitude of man-made emissions. This in turn will depend on economic, technological, and political factors. In addition, fluctuations in solar and volcanic activity will continue to exert their influence. Natural geological cycles will also play a part. Approximately half of the carbon dioxide discharged into the atmosphere is absorbed in Nature, leaving only the remaining 50 % to contribute to climate change. This natural uptake of carbon dioxide is achieved by algae and other vegetation and in forests, the soil, seawater and ocean sediments. When carbon dioxide is absorbed by seawater it is neutralised by reacting with dissolved calcium and then chemically precipitated as carbonate. In addition, CO_2 may be incorporated into carbonates by the action of plants and animals.

In the longer term, the weathering of rocks is also an important process. Carbon dioxide forms an acid when dissolved in water which is neutralised when it reacts with minerals in the bedrock. In due course, geological processes will thus resolve the climatic problems that humans have created for themselves, and concentrations of atmospheric greenhouse gases will return to their present levels. However, natural uptake occurs more slowly than the discharge of man-made emissions. It will therefore take several thousand years to neutralise the excess carbon dioxide, and it is in fact unlikely to return entirely to its original level. We now know that present-day human activities will continue to influence climate far into the future. We are thus on the threshold of a situation which is unique in a geological perspective. We have currently already achieved higher atmospheric greenhouse gas concentrations than the Earth has experienced for probably several million years. We also know that earlier periods of Earth history characterised by high concentrations of greenhouse gases, such as the Carboniferous and the Cretaceous, were also warm.

The issue before us is whether man-made greenhouse gas emissions will result in climate change of such a magnitude that will make it impossible in the long term to return to the climatic conditions that prevail today. For example, it is conceivable that the Earth's climate systems may adjust in such a way as to make new glaciations an impossibility. This is just one of many alternative models under discussion among climate researchers, but there is a great deal of uncertainty surrounding this issue. Another important matter for future debate concerns how the human species will *adapt*, if at all, to climate change, combined with the issue surrounding how we can *slow down* climate change which is now taking place.

If levels of greenhouse gases continue to increase at the rates which we are experiencing today, it is likely that the Norwegian glaciers will disappear entirely during the next century. This will occur even if there are increased winter snowfalls. The tree line will migrate to higher altitudes, and larger areas of the mountains will become forested. This process has already started. The extent of sea ice in the Arctic Ocean will be severely reduced, especially during the summer. There is also a real possibility that the Greenland Ice Sheet will become unstable, and that large areas will disappear. This will result in an increase of global sea levels of between 3 and 6 m, which will have a severe impact on coastlines, not least in countries characterised by densely populated coastal lowlands. However, changes such as these will take several centuries, so the human race will be granted time to adapt. Sea level changes will also be influenced by changes in Antarctic ice volumes. If the Antarctic ever becomes ice-free, global sea levels will rise to between 50 and 70 m higher than they are today.

During the last interglacial, about 125,000 years ago, during which Norwegian latitudes enjoyed



Satellite image showing how warm North Atlantic water masses stream into the Norwegian Sea. This makes a major contribution to Norway's mild climate. Warm air currents also contribute to warming.

The Hardangervidda high-altitude plateau and the Hårteigen mountain are a familiar scene for many Norwegians - but not normally with the conifer forest! The forests have been superimposed to illustrate the upward migration of the tree line during warmer climatic periods in the coming century. It is possible that this is how Hardangervidda will appear to our descendants, very much as it did during the post-glacial climate optimum (Photo/manipulation: P. Bjørstad/E. Bjørseth)

higher levels of summer solar radiation as a result of favourable Earth orbit parameters, geologists estimate that the Greenland Ice Sheet covered a much smaller area than it does today. This would have resulted in sea levels some 2 to 3 m higher than today. Evidence for this is found in several localities around the world. We also know that the tree line was found at higher altitudes during the Stone and Bronze Ages. The Hardangervidda mountain plateau was forested, and glaciers had melted back from the majority of the mountainous areas. All this occurred during a period of warmer summers, which in Norway were caused by more intense solar radiation because the Earth was closer to the Sun in the summer months than it is today. Today, the Earth is at its furthest point from the Sun during the summer in the northern hemisphere, so this phenomenon is not occurring at present, and changes we observe today must have other causes than those which favoured warmer climates for our Stone Age ancestors.

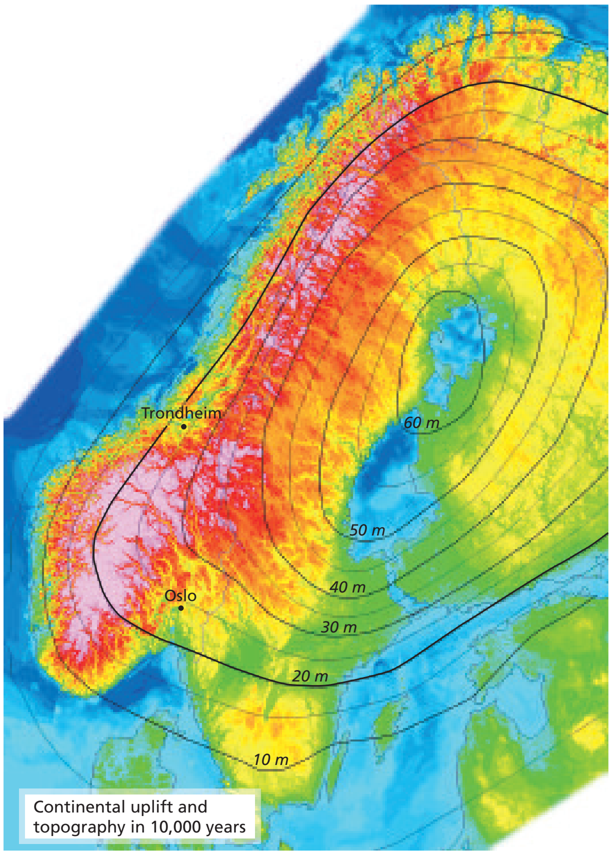
However, there is uncertainty associated with this perspective. For example, what will happen if the transfer of heat towards the Arctic by ocean currents should fail? Climatic patterns, not least in Norway, are critically dependent on the distribution of warm ocean currents along the coast. Satellite images from the North Atlantic demonstrate how warm water masses advance into the Norwegian Sea and combine with warm air currents following the cyclone paths, to make a major contribution to Norway's relatively mild climate. It is possible that global warming will result in a weakening of this warmer current stream, especially if the Greenland Ice Sheet begins to melt. If this happens, it is possible that Norway will experience an intense cooling in several hundred years time. Southern Norway will then experience a climate similar to that in Finnmark today. Currently, climate researchers do not believe that this is the most likely scenario but, given our current knowledge, it cannot be disregarded. We know that changes in oceanic heat transfer were common during the glaciations. However, during the interglacials, such as we are currently experiencing, oceanic patterns appear to have been much more stable.

In the remainder of this chapter we shall examine the ever-changing face of the landscape in the millions of years to come and how these changes will lay entirely new foundations for climate variation.

Continental uplift – Norway ever on the up and up

In their national anthem, Norwegians sing of their love for the mountainous country rising from the surrounding seas. In geological terms, it seems likely that this happy circumstance will continue for the foreseeable future. Since the final retreat of the 3 km-thick ice sheet which covered the landscape during the last glaciation, Norway has experienced continental uplift. Today the land is still rising.

During the last two million years, the Scandinavian landmasses have been subjected to cycles of large-scale subsidence and uplift as a result of successive advances and retreats of the great ice sheets. Since the last ice sheet began its retreat some 16,000 years ago, the interior of eastern Norway has been uplifted nearly 600 m. The rate of uplift is gradually decreasing, but will continue to modify Scandinavian coastlines for tens of thousands of years, particularly in the Gulf of Bothnia and the Baltic Sea. While some uncertainty surrounds sea level rise associated with the melting of the Greenland Ice Sheet, continental uplift is a predictable process which will continue in the future.



SCENARIO 1. Estmated uplift and topography across Scandinavia in 10,000 years. Parts of Oslofjorden and Trondheimsfjorden have become dry land. Oslo and Trondheim have been elevated by more than 20 m above present-day sea level. Fjord arms along the coasts of western and northern Norway have also been uplifted, but relatively little compared with eastern Norway and Trøndelag.

But how much uplift will occur before equilibrium is restored, and what will happen when new glaciations occur? Does uplift have consequences for climate change? By using geophysical models, we can estimate the magnitude of recent uplift and predict future developments. We will now present three future scenarios illustrating how Norway will appear in 10,000 years, 100,000 years, and 1 million years hence, respectively.

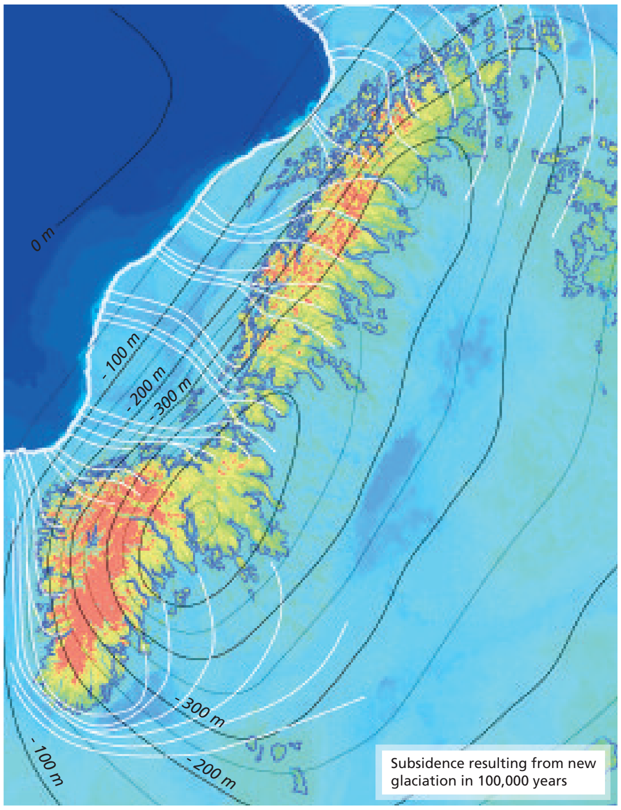
In the first 10,000 year scenario, much of Norway will have been elevated to new heights. The effect will be least along the coast and greatest in the east along the Swedish border, most notably in the Trysil area, where about 30 m of uplift is anticipated. Further east, the floor of the Bothnian Sea and Gulf of Bothnia will be 50 - 60 m shallower than at present, and it will be possible for humans to walk from Stockholm to Helsinki. Uplift will probably continue for about 15,000 years. Ultimately, the Gulf of Bothnia will become a lake, cut off from the rest of the Baltic Sea. Many Norwegian towns will find themselves between 10 and 30 m higher than at present and, along the coast, new settlements will no doubt have occupied the newly emergent sea floor.

In contrast, large areas outside Scandinavia, such as northern Germany, the Netherlands, and the western and southern parts of the North Sea, will continue to subside. These areas have already been subjected to continuous and prolonged subsidence. The discovery of Stone Age implements on the Dogger

Bank provides evidence that some areas of the North Sea were once dry land.

In 20,000 to 30,000 years time, it is likely that the continental ice sheets in the southern and northern Norwegian mountains will begin to advance as a result of natural climatic variation. As the ice sheets progressively thicken and expand, uplift will cease and isostatic depression will begin.

In the second scenario, about 100,000 years into the future, climate researchers predict that Norway will experience the most extensive of a series of ice sheet advances which will begin in about 50,000 years. Previous glaciations will have been interrupted by shorter, ice-free interstadials. The ice sheet will probably extend south to Germany and Poland, and will be thickest (perhaps more than 3 km) in the Gulf of Bothnia. In western and northern Norway, isolated high-altitude summits, or nunataks, will be left emergent above the ice. During periods of maximum ice expansion, all present-day human settlements in Scandinavia will have been destroyed and made uninhabitable. During the millennia of ice advance, ecosystems will have had sufficient time to react and adapt to the newly evolving climate zones, no doubt involving wholesale southward migrations. Any human civilisations which survive the ice advances intact will experience the influx and integration of massive numbers of “climate refugees”. They will have had sufficient time and better opportunities to migrate and adapt than those made refugees following isolated natural catastrophic events such as massive meteorite impacts or supervolcano eruptions, during which climate deterioration will be dramatic and will occur over much shorter time scales.



SCENARIO 2: Subsidence during a major glaciation in 100,000 years. The Østerdalen and Trysil areas will have subsided by almost 600 m under the load exerted by a 2–3 km thick continental ice sheet. The ice sheet will deepen and extend the Norwegian valleys and fjords. In contrast, the lowlands of southern Norway, Trøndelag and Finnmark will not be greatly influenced by the ice.

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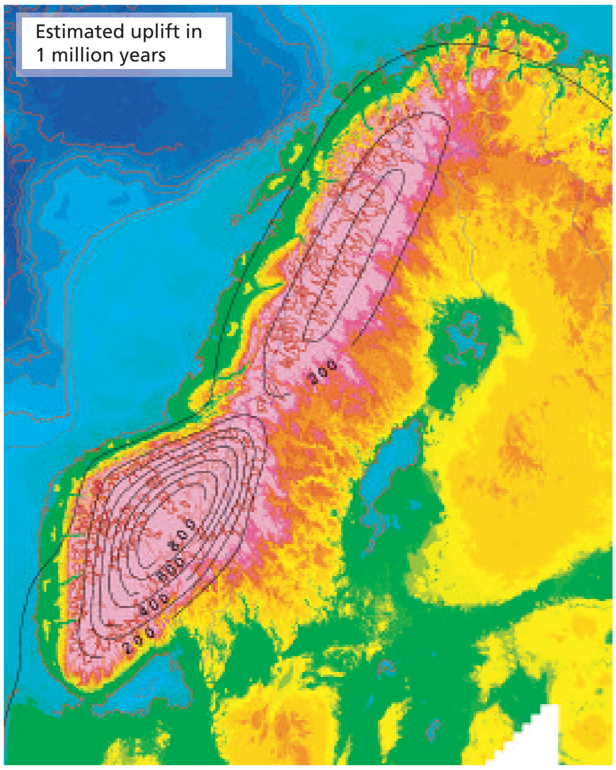


SCENARIO 3: Repeated glacial cycles during a 1 million-year period have dramatically changed Norway’s appearance. Contours denote the extent of the modelled uplift. Norway has been reduced in area compared with the present day and, together with Scandinavia as a whole, has been severely denuded. However, it will take many millions of years and several more glaciations before the area becomes a lowland plain similar to present-day Siberia or Arctic Canada.

If the 100,000 year glacial scenario is followed by abrupt ice retreat, the sea will transgress far inland before the Scandinavian landmass will have had time to respond and begin the process of isostatic rebound. Faults that were effectively locked under the heavy load of the ice sheets may be released and allowed to move, resulting in earthquakes. Massive earthquakes can result from single bedrock displacements of between 20 and 40 m, such as occurred about 10,000 years ago following the last glaciation. Earthquakes of magnitudes up to 8 on the Richter scale will trigger rockfalls and landslides. The Norwegian fjords will be extended eastwards, and Hardangerfjorden will extend further into the Hardangervidda mountain plateau. Any human newcomers to the country will inhabit a familiar land of spectacular landscapes, with mountain ridges separated by deep fjords.

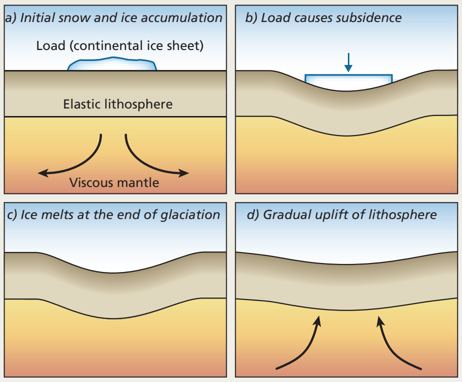
In the third scenario, after about 1 million years, Norway will have experienced a long series of glaciations, and the coastal strandflats will have become much broader than they are today. Today’s high and craggy Lofoten mountain summits will have been worn down almost to sea level, as will also be the case

CONTINENTAL UPLIFT – OBSERVATIONS AND MODELS

In geological terms, we are now living in the aftermath of an extensive glaciation covering the entire Scandinavian landmass. The load exerted by ice sheets resulted in isostatic depression of the landmass in a similar way to that currently occurring in the Antarctic and on Greenland. Accurate measurements demonstrate that at locations in the centre of the ice sheet where the ice was thickest, Scandinavia is currently experiencing uplift at rates of up to approximately 10 mm/year.

PRESENT-DAY UPLIFT IS MEASURED USING THE FOLLOWING METHODS:

- *Coastal water level measurements (often close to harbour towns)*
- *Levelling surveys along inland roads*
- *Fixed GPS instruments*
- *Monitoring of acorn barnacle and bladder wrack markers*



The lithosphere subsides and is then uplifted in response to expansion and retreat of the continental ice sheet.

Acorn barnacle and bladder wrack markers were originally established in the 1890s by the **Geological Survey of Norway** when uplift phenomena in the Gulf of Bothnia were first discovered. There was some concern that equivalent uplift in Norway would result in a shallowing of Norwegian harbours, similar to that occurring in parts of Sweden and Finland. Markers were cut into rocks on the shoreline and the distances down to the upper limits of acorn barnacle and bladder wrack growth were measured. By repeating these measurements over time it was possible to calculate uplift. Cumulative uplift is found by measuring the present height above sea level of shorelines formed at the end of the last glaciation.

When a progressively greater load is exerted on the lithosphere, for example as the result of the accumulation of a continental ice sheet, the asthenosphere flows from beneath the lithosphere which in turn subsides. Since the asthenosphere is highly viscous, much like modelling wax, this process can take many thousands of years. Mantle rocks within the lithosphere and asthenosphere have almost identical chemical compositions, but the higher temperature of the asthenosphere enables it to behave plastically. When the load is removed as the ice melts and retreats, the lithosphere gradually returns to its original position by means of so-called "isostatic uplift". Gravitational acceleration in the Gulf of Bothnia and the Baltic Sea region is approximately 0.0001 m/s^2 lower than in surrounding areas, reflecting a mass deficiency which is the result of the asthenosphere continuing to flow back towards central Scandinavia from what was the periphery of the former ice sheet.

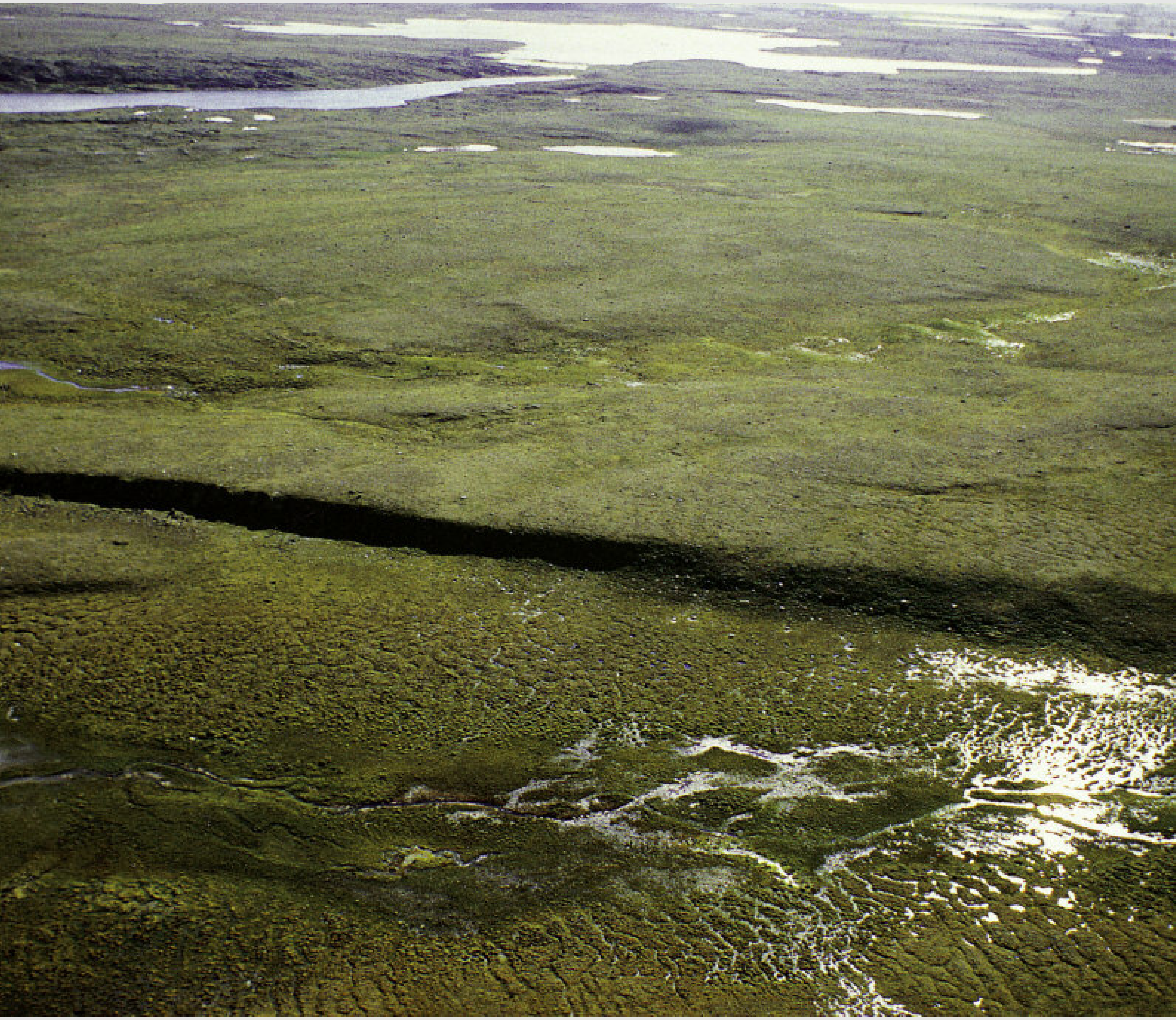
Isostasy is a branch of geophysics which concerns itself with the behaviour of the Earth's rigid upper layer, or lithosphere, as it floats on the plastic and viscous mantle rocks beneath it (the asthenosphere). As described previously, the lithosphere is made up of the Earth's crust and the uppermost part of the mantle.

for the mountains along the coasts of western Norway, Nordland and Troms. New strandflats will be formed along the Finnmark and Skagerrak coasts. Up until the late Pleistocene, basement in these areas had been protected by low-grade metasediments, and there was insufficient time to develop strandflats.

The glaciers will have transported enormous volumes of unconsolidated sediments out to the continental slope, resulting in expansion of the continental shelf. Previously immature hydrocarbon source rocks will become more deeply buried within the sedimentary basins and may achieve temperatures sufficient to generate new oil and gas to occupy the old reservoirs.

In order to maintain regional isostatic equilibrium, the northern Swedish mountains will be elevated by 200-300 m. The southern Norwegian mountains will probably be uplifted by a significantly larger amount (500–1000 m) as a result of extensive coastal erosion, combined with the presence of underlying relatively low density mantle rocks resulting from heating or alterations in their mineral composition. Even though Norway will have drifted only about 10 km to the northeast during the previous 1 million years, the landscape will have altered beyond recognition as a result of 20–30 successive cycles of ice accumulation and retreat (see Chapter 15).

"Ice ages" come and go, and as they do so the land is subjected to a yo-yo effect produced by successive cycles of isostatic depression and uplift. Only when the northern continental landmasses drift south again, and their mountains are reduced to lowland plains, will the cycles of glaciation and deglaciation be broken, and the Earth will once again enter a prolonged era free of "ice ages". This ultimate scenario lies in the far distant future. In a shorter geological perspective, cycles of glaciation will be renewed as soon as atmospheric greenhouse gas concentrations are reduced, and because isostatic uplift continues to elevate the landmasses.



The 80 km-long and up to 8 m-high escarpment along the Stuoragurra Fault on the Finnmarksvidda plateau, formed at the end of the last glaciation. Faults such as this and others in northern Sweden and Finland (up to 150 km long and more than 20 m high), were formed by post-glacial crustal displacements generating earthquakes with magnitudes of between 7 and 8 on the Richter scale. The release of pressure caused by the retreat of the ice after future glaciations will probably trigger similar earthquakes. (Photo: O. Olesen)

The bigger picture – the future of continental drift

If we gaze many millions of years into the future we find that lithospheric plate movements continue to promote continental drift, causing the expansion of some oceans and the disappearance of others. Plate tectonic theory not only explains the great crustal movements of the past, but also allows us to predict future developments.

Plate tectonics is a fascinating theory which explains how continents collide and drift away from each other (see Chapter 2). Periodically, the continents have merged to form gigantic supercontinents which have had a major influence on the evolution of climate and ecosystems. Pangaea is the youngest supercontinent, formed about 330 million years ago during the Late Palaeozoic. The present-day distribution of landmasses and oceans is a direct result of the fragmentation of Pangaea, which began during the Jurassic. It was not until the Tertiary that the North Atlantic Ocean began to open. Greenland separated from the Eurasian plate, of which Norway forms a part. At that time, Greenland formed a distinct lithospheric plate because sea-floor spreading was also active further west in the Labrador Sea.

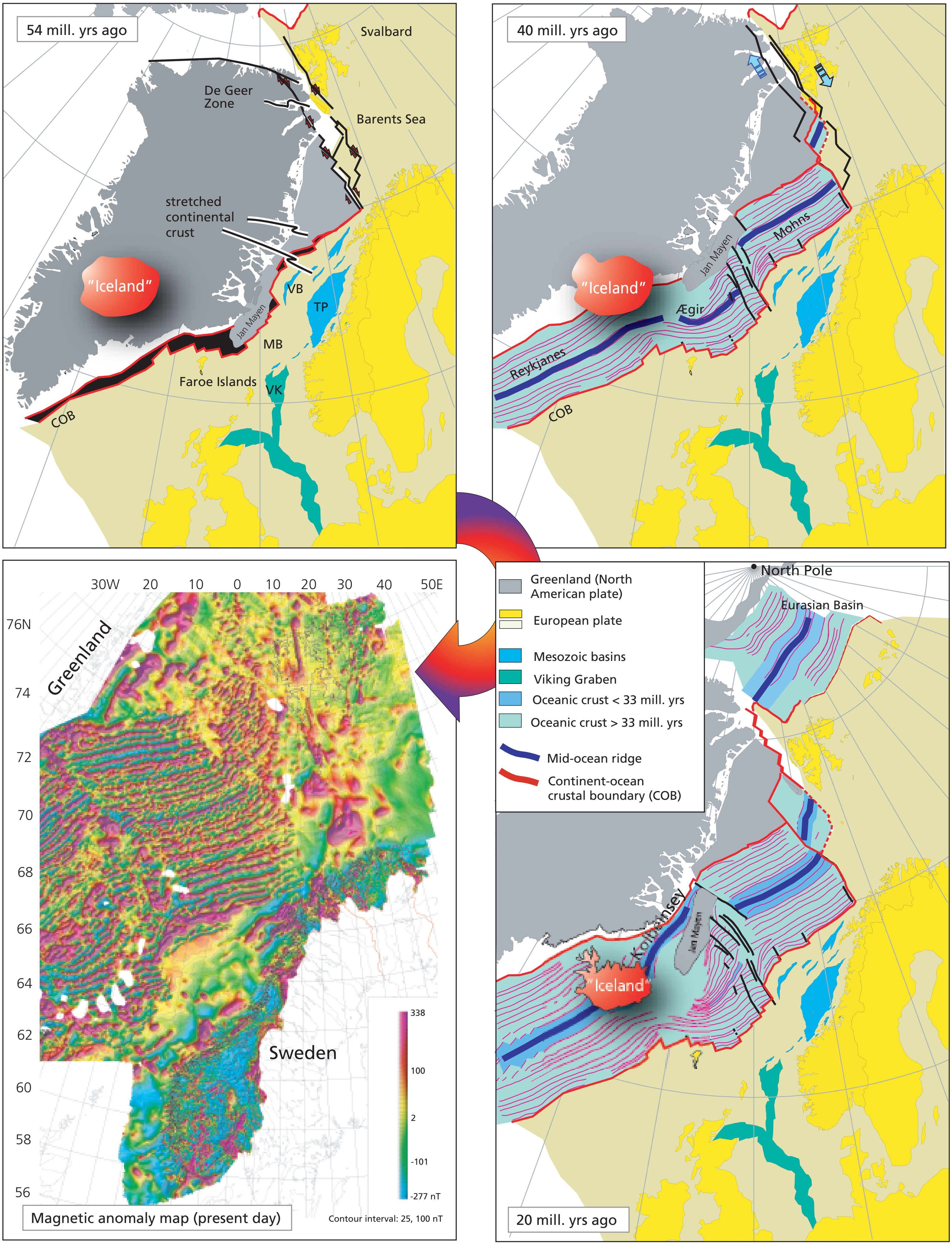
The opening of the north-eastern Atlantic began about 54 million years ago. In the southern and central areas, initial break-up occurred along a line located close to Greenland, while further north towards Lofoten initial fracturing took place much closer to Norway. The opening of the new ocean was accompanied by intense volcanic activity, not least along the margin of the Vøring Plateau. Volcanism was linked to a so-called mantle plume (hot spot) beneath Iceland - a precursor to the modern "Island of the Sagas".

By about 40 million years ago, the north-eastern Atlantic had become 350 - 400 km wide. Svalbard had been displaced laterally in relation to Greenland, thus opening a passage between the north-eastern Atlantic and the Arctic Oceans. Jan Mayen, which today forms a distinct microcontinent, was still attached to Greenland. The north-eastern Atlantic spreading axis comprised three subordinate axial segments (the Mohns, Aegir and Reykjanes Ridges). At this time, the Iceland mantle plume was located near the coast of Greenland and close to the spreading axis. 20 million years ago, the Aegir Ridge axis became inactive, and spreading shifted to the Kolbeinsey Ridge. Jan Mayen became entirely separated from Greenland and occupied its present position, fused to the Eurasian plate.

Future plate tectonics

Using plate tectonic principles and our knowledge of current plate movements, we can speculate as to how the Earth will evolve during the next 50 million years and beyond. Norway's journey north will continue and the North Atlantic will increase in width.

RIGHT: Reconstructions of the North-Eastern Atlantic some 54, 40, and 20 million years ago, respectively, based on magnetic anomalies (map, lower left), and sea floor fractures. These are relative reconstructions, in which Norway (as a part of the Eurasian plate) remains fixed, while both Greenland (as a part of the North American plate) and the sea floor are reconstructed or moved, as appropriate. Various techniques are employed to reconstruct the positions of the continents. In addition, orbiting satellites are used to measure continental movements directly.
(VB = Vøring Basin ; TP = Trøndelag Platform;
MB = Møre Basin; VK = Viking Graben).


54 mill. yrs ago
Svalbard
De Geer Zone
Barents Sea
stretched continental crust
"Iceland"
VB
TP
Jan Mayen
MB
Faroe Islands
VK
COB
40 mill. yrs ago
Jan Mayen
Mohns
"Iceland"
Ægir
Reykjanes
COB
Magnetic anomaly map (present day)
30W
20
10
0
10
20
30
40
50E
76N
74
72
70
68
66
64
62
60
58
56
Greenland
Sweden
338
100
2
-101
-277 nT
Contour interval: 25, 100 nT
Greenland (North American plate)
European plate
Mesozoic basins
Viking Graben
Oceanic crust < 33 mill. yrs
Oceanic crust > 33 mill. yrs
Mid-ocean ridge
Continent-ocean crustal boundary (COB)
North Pole
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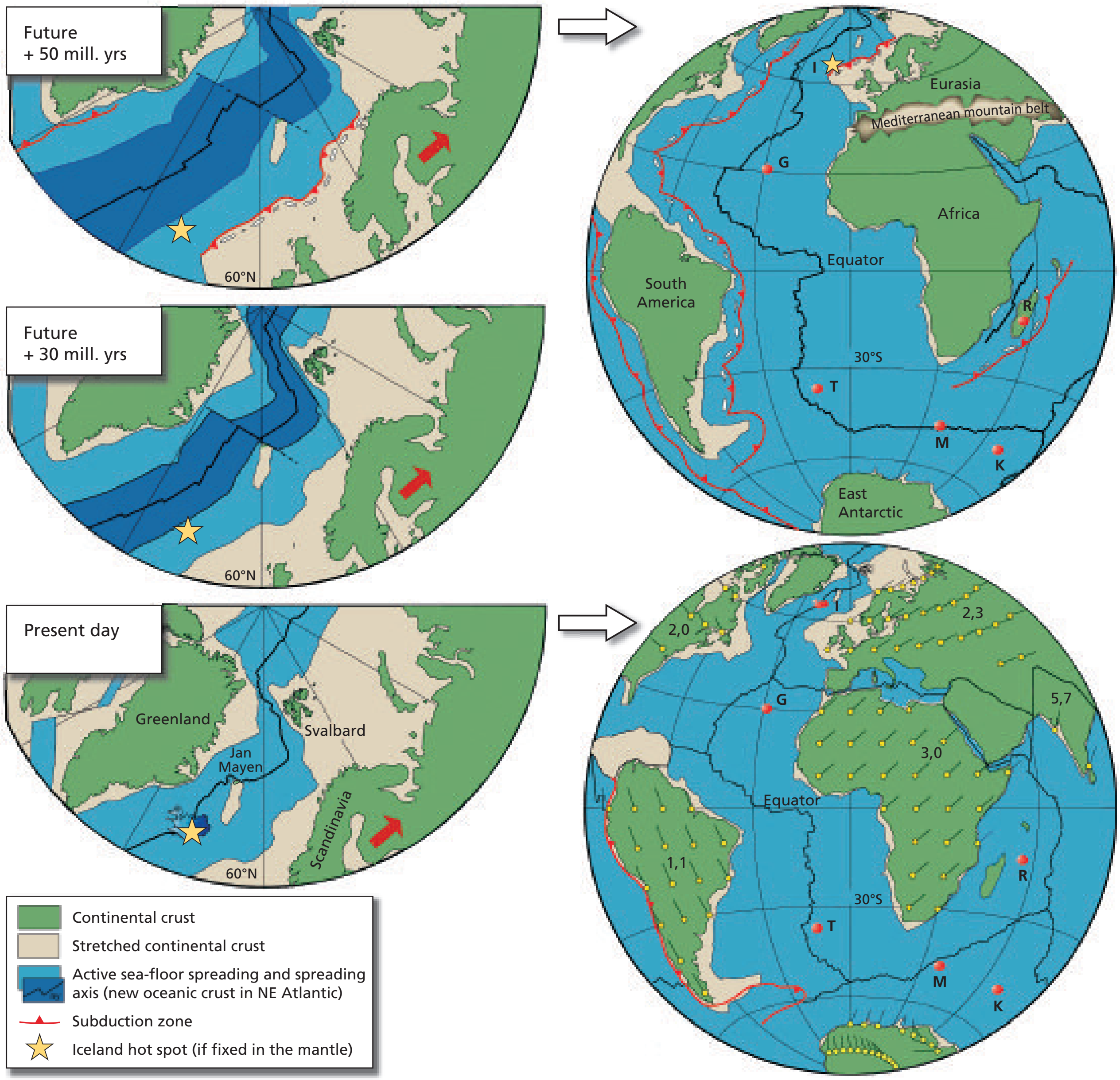

Anticipated evolution of the North-Eastern Atlantic from the present day to 50 million years into the future, combined with global reconstructions (each showing 50 % of the planet at present-day, and in 30 and 50 million years, respectively). Models are based on current plate vectors and average velocities (denoted in figure, below right). Red circles denote mantle plumes (hot spots). (I = Iceland; G = Great Meteor; T = Tristan da Cunha; M = Marion; K = Kerguelen; R = Reunion), which are assumed to remain relatively stationary beneath the mobile lithospheric plates. Red lines denote subduction zones, where plates are in collision. Black lines denote spreading axes.

Sea floor spreading between North America and Greenland ceased about 30 million years ago, and today these continents combine to form the North American plate which continues to drift in a north-westerly direction at a rate of 2 cm/year. The Eurasian plate, of which Norway is a part, is drifting north-eastwards at a rate of 2.3 cm/year. Today, satellites enable us to monitor plate movements with great accuracy, and provide an important verification of plate tectonic theory.

During the next 50 million years, and given constant spreading rates, the Oslo area will have drifted some 1,100 km to the north-east and will be located at 65° N, at the same latitude as Mid-Norway today. Svalbard will be situated between 81° and 84° N, only a few hundred kilometres from the North Pole. Thus in 50 million years mainland Norway will extend between 64° and 75° N. Seen in isolation, and purely from a plate tectonic perspective, the Norwegian climate will become significantly cooler, and this will clearly have an influence on the distribution of flora and fauna. Some species will become extinct, others will adapt, and new forms will appear. Whether the species *Homo sapiens,* which even today has only existed for 200,000 years or so, will have adapted sufficiently to be able to experience these changes, must be regarded as highly unlikely.

The north-eastern part of the Atlantic is the youngest region within the ocean. Normally, dense and ageing oceanic crust becomes increasingly unstable and subduction can occur spontaneously when oceanic crust approaches 150 million years old. This situation presupposes that sea floor spreading is permitted to continue without external interference. Otherwise, subduction may occur at an earlier stage. In 50 million years time, the north-east Atlantic will still be only 100 million years old. At constant spreading rates, the Atlantic will widen and the distance between East Greenland and Western Norway will approximately double – from 1,600 to about 3,000 km. This is bound to have consequences for ocean circulation patterns and currents, and thus also for climate change, which is critically influenced by the spatial distribution of the continents and oceans.

Any future inhabitants of Iceland will witness some very dramatic events. Modern Iceland is linked to a mantle plume located close to the active Reykjanes Ridge. Local upwelling of hot mantle material along the spreading axis ensures that Iceland is emergent above present-day sea level. In due course both the spreading ridge and Iceland itself will move away from the mantle plume, and Iceland will gradually sink below sea level and form a submarine volcanic plateau. Similar processes will occur elsewhere on the planet. For example, the present-day Reunion mantle plume, which was responsible for volcanism in the Deccan in India and on the island of Mauritius, will be located beneath Madagascar in 50 million years time, resulting in intense volcanic activity, while Mauritius and the Deccan will have subsided.

In 50 million years the oceanic crust of the Central and South Atlantic will be 225 and 180 million years old respectively, and an elongate subduction zone will most probably have developed beneath both the South and North American continents, perhaps extending as far north as southern Greenland. The north-eastern Atlantic crust will then be approximately 100 million years old. If the basic constraints on plate movement are altered - for example if North America or Eurasia collides with another continent - it is also possible that subduction may begin in the north-eastern Atlantic. If this occurs, the Atlantic will begin to close again and, after a further 75-100 million years, western Norway and East Greenland may collide yet again, much as they did some 400–500 million years ago. This will result in a new mountain belt along the trend of the ancient Caledonian orogeny.

The movements of other plates are also known, and can be used to make further predictions. The Eurasian and African plates are currently moving towards each other at a rate of approximately 0.7 cm/year. If nothing intervenes to interrupt this movement, and if it continues at the same velocity and in the same relative direction as today, the Mediterranean Sea will close and be transformed into a mountain belt which will form a western extension of the Himalayas. The combined mountain range will extend for 8,000 km and will be of a similar size to the Variscan mountain belt which resulted from the collision between Gondwana and Laurasia during formation of the Pangaean supercontinent in the Carboniferous. This will promote a monsoon climate in Central and Southern Europe and may contribute to the extensive desertification.

The details of future scenarios are of course laden with uncertainty, and many alternative futures are possible. What we can say with certainty is that we humans inhabit a dynamic planet. Lithospheric plate movements will continue to change “the map”, by moving the continents, creating new mountain ranges, altering the outline and depth of the oceans, and generating local and regional climate change. Glaciations will continue to come and go for several millions of years, resulting in cycles of warmer, alternating with cooler, climatic conditions. As in the past, future life forms must adapt to both short- and long-term natural change processes if they are to endure in the battle for survival.

The present-day spreading axis between Greenland and Norway emerges above sea level on Iceland and other volcanic islands in the Atlantic Ocean. The photograph shows the Beerenberg volcano on the Norwegian island of Jan Mayen during the eruption of 18 September 1970. Lava erupted from a field of five craters aligned along a 6 km-long fracture on the volcano’s northern flank. Initially, steam and ash columns rose to a height of several kilometres, followed by lava which flowed down to the shore. Approximately 5 km^2 of new land was created. The pale-coloured material on the mountain is not snow, but volcanic ash. (Photo: J. Naterstad).