Nordic Geoscience and the 33rd International Geological Congress: Introduction

Geology has been of profound importance for the Nordic countries since the Middle Ages. Strong economies were built on an understanding of the occurrence in bedrock of minerals containing metals, e.g., silver, copper, zinc and iron, and eventually led to the establishment of the first Geological Surveys in Norway and Sweden in the middle of the nineteenth century. The geology of Norden ranges from the oldest to youngest rocks on the planet. Based on the papers in this special issue, this introduction provides a brief summary of the geological evolution of Norden, from the Archean of Greenland and northern Fennoscandia to the on-going volcanicity in Iceland on the Mid-Atlantic Ridge. It also refers to aspects of Geoscience that are particularly important for society in Norden, including geo-resources (petroleum, geothermal energy, nuclear energy, metals, industrial minerals and groundwater) and environmental geology (including natural and anthropogenic processes, medical geology, geo-hazards and climate). Information on the early history of geology in Norden and the geological surveys is also included and, finally, an outline of the 33rd International Geological Congress with its main theme "Earth System Science: Foundation for Sustainable Development".

Introduction

This special issue of *Episodes* provides a summary of Geoscience in the Nordic countries: Denmark (including Greenland and the Faroe Islands), Finland, Iceland, Norway and Sweden. It has been designed as a background for and an introduction to the 33rd International Geological Congress (IGC) to be held in the Norwegian capital of Oslo in August 2008. The Congress itself is presented by the Secretary General and the President (Solheim and Bjørlykke, this volume). Nordic Geoscience is treated in two parts: the first focuses on the geology (stratigraphy, structure and tectonic evolution) of Norden, from the Archean to the Present, and the second concerns aspects of our science that are of particular importance for society. This paper presents a brief introduction to the other twenty-five papers in the volume, summarizing the geological history of Norden, the main topics of societal importance and the structure, main themes and other activities of the Congress.

The geology of Norden

The Nordic countries reach across the North Atlantic Ocean from the Scandinavian continental margin of western Eurasia, via Iceland (perched on the mid-ocean ridge) to the Greenland segment of Laurentia. The rocks range in age from the earliest Archean to the Present, and the plate tectonic environments from the accretional and collisional orogens of the Precambrian and mid Paleozoic to the Mesozoic extensional regimes of the continental shelves and the Cenozoic sea-floor spreading in the Atlantic. Climate cooled in the latter part of the Cenozoic and the Quaternary history includes repeated cycles of glaciation and deglaciation prior to Holocene warming and migration of Homo sapiens into the Arctic.

Norden's oldest rocks occur in the Archean/Paleoproterozoic basement of Greenland, and the Fennoscandian (Baltic) Shield. Early Paleozoic successions overlie these cratons, largely undisturbed, except in the Caledonides. This orogen flanks northeastern Greenland and western Scandinavia, continuing northwards via Svalbard to the edge of the Arctic Ocean. Latest Paleozoic, Mesozoic and Tertiary strata are mainly preserved off-shore on the continental shelves, outcropping on land in southern Scandinavia, northeast Greenland and Svalbard.

The oldest known rocks deposited on the surface of the Earth are found in the dominantly ***Mesoarchean*** craton of southwest Greenland (Hölttä, Balagansky, Garde, Mertanen, Peltonen, Slabunov, Sorjonen-Ward, and Whitehouse, this volume). The c. 3.86–3.6 Ga assemblages comprise of pillow lavas, banded-iron formations and metasedimentary rocks with graphite, possibly of biogenic origin. The Mesoarchean crustal terranes in Greenland amalgamated at c. 2.7 Ga. Mesoarchean rocks are also found in the northern part of the Karelian Province of the Fennoscandian shield, but 2.9–2.7 Ga TTG orthogneisses and greenstone belts dominate. Eclogites and Iringora supra-subduction ophiolite occur in eastern Fennoscandia, indicating that subduction-related processes were active in the Neoarchean.

During the ***Paleoproterozoic***, Fennoscandia experienced a long period (2.5–2.1 Ga) of multiphase intraplate rifting. This was followed (2.1–2.04 Ga), both in Fennoscandia and Greenland, by drifting and separation of Archean cratons and formation of new oceans (Lahtinen, Garde, and Melezhik, this volume). The Lapland-Kola orogen (1.94–1.86 Ga) in Fennoscandia, and the Inglefield mobile belt (1.95–1.92 Ga) and the Rinkian fold belt/Nagssugtoqidian orogen (1.88–1.83 Ga) in Greenland are continent-continent collision zones with limited formation of new crust, whereas the Ketilidian orogen (c. 1.8 Ga) in South Greenland displays a convergent setting without sub-

***Figure 1** Norden from the Blue Marble map (Stöckli et al., 2001). Abbreviations refer to: Bjørnøya (B), Faroe Islands (FI), Gotland (G), Jan Majen (JM), Kvitøya (Kv).*

sequent collision. The composite Svecofennian orogen (1.92–1.79 Ga) is a collage of 2.1–2.0 Ga microcontinents and 2.02–1.82 Ga island arcs attached to the Archean Karelian craton and responsible for the main Paleoproterozoic crustal growth of Fennoscandia.

Mesoproterozoic tectonic activity in Greenland and central Fennoscandia is seen in the episodic occurrence of rapakivi granites and continental rift-related magmatic and sedimentary rocks (Bingen, Andersson, Söderlund, and Möller, this volume). The southwestern active margin of Fennoscandia experienced the Gothian (1.64–1.52 Ga) and Telemarkian (1.52–1.48 Ga) accretionary events, and the Hallandian-Danopolian (1.47–1.42 Ga) event affected southern Fennoscandia. The interval between 1.34–1.14 Ga was characterized by bimodal magmatism and sedimentation and followed by the Sveconorwegian orogeny (1.14–0.97 Ga), involving polyphase terrane accretion during collision between Baltica and another major plate. Alternative models for restoring the Sveconorwegian and Grenville (Laurentia) belts at 1.0 Ga are discussed, and the "classical interpretation", involving correlation of the E-vergent thrust system in the former with the W-vergent in the latter, is favored.

Much of the ***Neoproterozoic*** history of the Nordic countries is preserved within the Caledonide Orogen in the mountains of western Scandinavia, eastern Greenland and the Svalbard archipelago (Nystuen, Andresen, Kumpulainen, and Siedlecka, this volume). The various Caledonian allochthons provide evidence of three hundred million years (from c. 900 to 600 Ma) of rifting and extension, following the collapse of the Grenvillian-Sveconorwegian Orogen and accompanying the break-up of Rodinia. The Neoproterozoic sedimentary successions of the Laurentian margin, and partly also the Baltoscandian margin, are characterized by thick siliciclastic formations, overlain by limestones, dolomites and Vendian tillites. Palinspastic reconstruction of the Caledonian thrust-sheets suggests that they were deposited at least in part on continental crust of Mesoproterozoic age, now submerged beneath the Greenland and Norwegian seas and the Barents shelf.

By the beginning of the ***Phanerozoic***, the Precambrian cratons of Laurentia and Baltica were separated by an expanding tract of oceanic crust (Gee, Fossen, Henriksen, and Higgins, this volume). Sedimentation on the Laurentian platform was dominated by Cambro-Ordovician carbonates, characteristic of the low latitude environments that reached from the northern Appalachians to Svalbard. Baltica lay at higher latitudes and was dominated by siliclastic deposition, particularly of kerogen-rich (alum) shales in the Cambrian and carbonates and shales in the Ordovician and Silurian. The Iapetus Ocean, separating Baltica from Laurentia, started closing early in the Ordovician and the continents collided in the early-mid Silurian, with the onset of ***Caledonian (Scandian) Orogeny***. The resulting orogen is now exposed on both sides of the North Atlantic, with W-vergent thrust systems in eastern Greenland and E-vergent in western Scandinavia. Underthrusting of Laurentia by Baltica culminated in the early Devonian with rapid exhumation of the hinterland and collapse of the mountain belt, with extensional faulting and deep erosion.

Further south in Europe, orogeny continued into the late Paleozoic in the Variscides, during the final assembly of the Pangea megacontinent, and was followed by ***Permian*** rifting. The latter extended northwards into southern Scandinavia, where rifting, starting in the latest Carboniferous, was particularly prominent in the Caledonian front of the Oslo area (Larsen, Olaussen, Sundvoll, and Heeremans, this volume). Extensional faulting and igneous activity in this major graben lasted through the Permian into the early Triassic, with widespread volcanism, well-preserved calderas and major batholiths, now excellently exposed in the surroundings of Norway's capital.

During the ***Mesozoic***, Pangea began to fragment and the parts that are now found in Norden drifted northwards from equatorial to temperate climate zones (Nøttvedt, Johannessen, and Surlyk, this volume). Northern (Boreal) and southern (Tethys) oceans were separated by a land-bridge between Scandinavia and Greenland in the Triassic and the successions are characterised by numerous marine transgressions and regressions. Sea-level rise in the latest Triassic resulted in widespread deposition of siliclastics in shallow marine shelf and deltaic environments in the Early and Middle Jurassic. A major phase of extension and rifting occurred in the Late Jurassic and Early Cretaceous and sea-level rise drowned the land barrier between Scandinavia and Greenland; marine shales with highly kerogen-rich intervals were deposited over vast areas of what are now the Nordic continental shelves. Sea level continued to rise during the Cretaceous with deposition of several kilometres of deep water shales, marls and sands in the deepest basins. Shallow marine and coastal plane deposits dominated on the flanking platforms, extending far onto the ancient land areas of southern Scandinavia towards the end of the period.

Latest Cretaceous and earliest ***Tertiary*** rifting in the North Atlantic led to continental break-up between Scandinavia and Greenland in the Late Palaeocene/Early Eocene. This event was associated with regional uplift of the whole of the Norwegian and Greenland seas and adjacent areas, creating an emergent platform along the axial rift zone. The general uplift drastically reduced the size of the basins and expanded the hinterland areas, effectively ending carbonate deposition; the whole region became dominated by marine siliclastics (Rasmussen, Heilmann-Clausen, Waagstein, and Eidvin, this volume). The final rupture of the continental crust in the latest Paleocene/earliest Eocene, was accompanied by the eruption of vast volumes of tholeiitic flood basalts within the axial area, which spread across the whole of the eroded platform. Thereafter, the newly established spreading axis and surrounding lava platforms started to subside and eventually submerged below sea-level.

At the same time as the extension, rifting, volcanism and eventual separation of Greenland from Scandinavia was going on, the western margin of the Barents Shelf was forming along a major transcurrent shear-zone, the De Geer fracture zone. Svalbard moved dextrally from a position north of Greenland in the Mesozoic towards its present position, with the opening of the Greenland Sea, eventually establishing a connection to the Arctic Basin via the Fram Straits. During translation along the De Geer fracture zone, past the northeastern end of Greenland, western Svalbard was influenced by Paleocene transtension, Eocene transpression (with the formation of the West Spitsbergen fold and thrust belt) and subsequent Oligocene oblique separation and rifting.

The opening of the ocean between Scandinavia and Greenland was initially accomplished along a spreading axis (the Aegir Ridge) now located to the east of Iceland. At the end of the Oligocene, the spreading ridge jumped westwards to the presently active Kolbeinsey Ridge, north of Iceland, separating a sliver of continental crust off East Greenland. This subsequently became the Jan Majen microcontinent, at the southern end of which Iceland started to grow.

The composition and structure of the North Atlantic sea floor, dominated by oceanic crust formed at the Mid-Atlantic Ridge, differs greatly from the adjacent continental margins. ***Iceland*** is the only large sub-aerial exposure of the ridge. With its surface rocks younger than 15 Ma, it offers unique possibilities to observe the processes that form oceanic crust (Sigmundsson and Sæmundsson, this volume). Iceland hosts over 30 active volcanic systems of different character, with long fissure eruptions and diking events contributing to the tectonic and magmatic processes of plate spreading. The geological record in Iceland also holds important information on the paleo-climate of the North Atlantic and the interplay of volcanicity and glaciation during the Quaternary.

The profound differences in character of the Nordic ***continental margins***, from the extended, rifted, passive margins between Scandinavia and Greenland in the south to the De Geer fracture zone in the north, are clearly defined in the deeper crustal structure (Faleide, Tsikalas, Breivik, Mjelde, Ritzmann, Engen, Wilson, and Eldholm, this volume). The continental basement of western Scandinavia thins irregularly westwards far out beneath the shelf to the continent-ocean boundary. In the lowermost crust of the outer shelf and ocean boundary zone, a several kilometre thick unit of high P-wave velocity (7.3–7.6 km/sec) is located beneath the area of break-up volcanicity, apparently related to this magmatic event. Further north and in striking contrast, the relatively thick Barents Shelf basement is truncated abruptly along the narrow De Geer fracture zone and the lower crustal high-velocity body is only present locally near Bjørnøya.

During the Oligocene and Miocene, sedimentation on the continental margin was typical of a marine, subsiding passive margin, overprinted by intermittent regional phases of tectonic movement and uplift. In general, the Miocene and Pliocene provide a record of deteriorating climate with oscillating glaciations, which strongly influenced the sediment supply to the shelf, particularly towards the end of the Pliocene and in the Pleistocene. The onset of major glaciations at c. 2.7 Ma, led to deep erosion of the Scandinavian mainland and the deposition of huge sediment volumes on the adjacent shelves. Uplift of the mainland and the Barents Sea areas, due to both tectonic processes and an isostatic response to erosion, continued into the latest Pliocene and was accompanied by the progradation of major sediment aprons onto the continental margins. The largest sediment volumes are found in fans, several kilometres thick, adjacent to major submarine channel systems, e.g., northeast of Kvitøya (easternmost Svalbard), west of Bjørnøya, and in the Møre Basin area at the mouth of the Norwegian Channel.

Much of the younger ***Quaternary*** history has been obscured by the advance and retreat of the last glaciation (Weichselian), which lasted for about a hundred thousand years (Wohlfarth, Björck, Funder, Houmark-Nielsen, Ingólfsson, Lunkka, Mangerud, Saarnisto, and Vorren, this volume). The previous short interglacial (Eemian) apparently experienced temperatures as much as 5 ºC higher than today, with ice-caps like those on Greenland reduced to about half their size and sea-level correspondingly higher. At its maximum, the Weichselian ice sheets occupied much of Norden and those on Greenland extended far westwards through northern North America. Weichselian deglaciation started about seventeen thousand years ago and about ten thousand years later the icecaps and glaciers had retreated to about where they are today. The sudden increase in temperature driving the deglaciation reached a few degrees higher than today and, despite interruptions, persisted to a thermal optimum in the early-mid Holocene, prior to the last five thousand years of irregular slow cooling. Retreat of the Weichselian ice sheets led to isostatic uplift, which continues today in central parts of Norden.

Throughout Earth's history, the planet has been influenced by extraterrestrial phenomena and processes, such as the variations in solar irradiation due to changing orbital paths around the sun, and the impact of meteorites and larger bolides. The importance of ***impact structures*** for the geological evolution and for life on the planet has been recognized increasingly during the last twenty years, particularly with the identification of the major Chicxulub impact at the Cretaceous–Tertiary boundary and its influence on the biosphere (Dypvik, Plado, Heinberg, Håkansson, Pesonen, Schmitz and Raiskila, this volume). In Norden, Europe's largest and most deeply investigated impact crater (drillholes to 6–7 km) is found in the Siljan lake area of central Sweden. Many other impact craters have been identified in the Nordic countries, some of probable Precambrian age; most, however have been found in sedimentary bedrock, ranging in age from the Neoproterozoic to the Late Mesozoic. Even the far distant effects of the Chicxulub impact are well displayed in Norden, in Denmark´s famous Stevns Klint locality.

The long history of crustal growth, outlined above, and the eventual fragmentation of Pangea, with opening of the North Atlantic Ocean, are reflected in the character of the ***deep crust and upper mantle*** (Artemieva and Thybo, this volume). The continental lithosphere of Fennoscandia and Greenland is about 200km thick and the crust in the former is some of the thickest on the planet (c. 60 km) for old Precambrian cratons. Both the crust and lithospheric mantel thin towards the continent-ocean boundary and the North Atlantic Ocean. Interpretation of the deep structure beneath Iceland, located on the Mid Atlantic Ridge, is proving highly controversial, with some authors favouring an abnormally thick (c. 30 km) oceanic crust and others inferring thin (10–15 km) crust beneath the rift axis and thickening to 30 km on the adjacent Iceland-Faroe and Iceland-Greenland ridges. A plume beneath Iceland has been inferred by many authors, based on surface wave tomography, but even this interpretation is not uncontroversial.

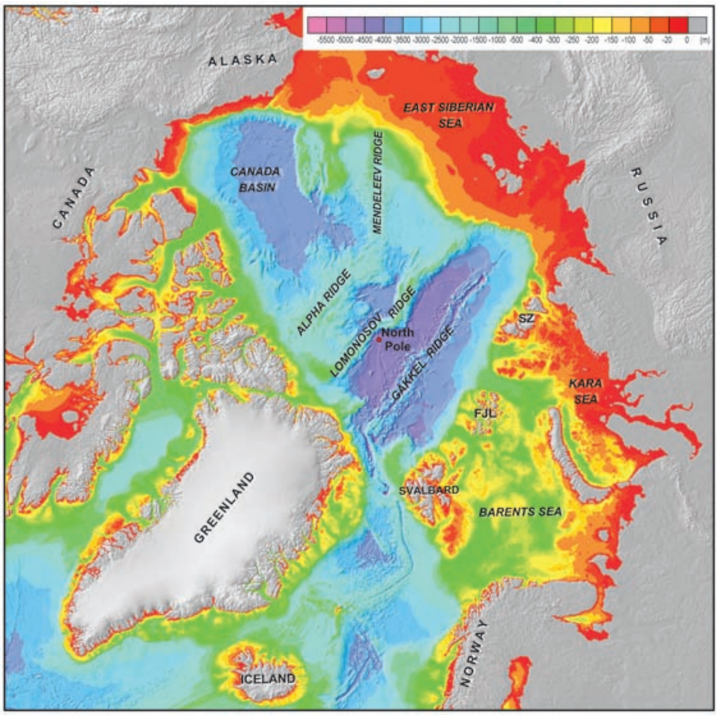

Figure 2 Simplified edition of the International Bathymetric Chart of the Arctic Ocean (Jakobsson et al., 2000). Abbreviations refer to: Franz Josef Land (FJL) and Severnaya Zemlya (SZ).

Geoscience for society

The importance of Geoscience for society in the Nordic countries is illustrated in this volume by a set of papers that range from the georesources in the different countries to the importance of environmental studies (particularly in the context of toxic substances), the impact of natural hazards and the significance of climate change. The history of Geoscience in Norden is also treated, along with some examples of the activities of the different geological surveys.

The importance of ***petroleum*** for the economies of Norway and Denmark became apparent in the 1960's. The discovery of the Groningen Gas Field in the Netherlands in 1959 triggered interest in also exploring the offshore areas of the North Sea (Spencer, Briskeby, Christensen, Foyn, Kjølleberg, Kvadsheim, Knight, Rye-Larsen, and Williams, this volume). Through the 1960`s, the continental shelf boundaries in the North Sea were established, and the first licensing rounds in Norway, Denmark and U.K. were announced. Oil was discovered by the Møller Group already in 1966 in Danish waters and by Esso in the Norwegian waters in 1967, but at the time, they were not regarded as commercial. The first commercial oil discovery, the Ekofisk Field with a Danian chalk reservoir, was discovered in 1969 and put in production in two years later. 1971 also saw the discovery of the extremely important Brent Oil Field, with a Middle Jurassic sandstone reservoir, made by Shell in U.K. waters. The Brent discovery led to the subsequent discoveries of the "Jurassic elephants" of the Norwegian North Sea, e.g., Statfjord, Gullfaks, Oseberg, and Troll. In 1980, exploration also moved north of 62º N into the Norwegian Sea and the Barents Sea. Since the start in the 1960's, these four regions—the Danish and Norwegian North Sea sectors, the Norwegian Sea and the Barents Sea—have seen the great majority of all the exploration in Norden: about 850 wildcat wells, resulting in about 300 oil and gas finds. Offshore West Greenland and onshore Svalbard have also seen some exploration drilling, but without any discoveries. Exploration drilling has also taken place in southern Sweden and in the adjacent Baltic Sea, leading to very small discoveries on the Island of Gotland only. In the Faroe Islands, where exploration started in 2001, one oil discovery has been made so far.

Interest in ***geothermal energy***, as with other renewable energy sources, is increasing rapidly in the Nordic countries. Heat pumps are widely used for space heating in Sweden. However, Iceland, thanks to its young volcanic bedrock and associated high-thermal gradients, is the only Nordic country where geothermal energy can be used to produce electricity (Lund, Bjelm, Bloomquist and Mortensen, this volume). Numerous high-temperature geothermal areas are found at the main volcanic centres on Iceland, where intrusions provide a heat source. Extensive fracturing of the bedrock facilitates the flow of water through the upper crust, resulting in widespread, relatively low-temperature geothermal sources over much of the country. Ninety percent of the houses on Iceland are heated with geothermal energy.

One of the most important sources of energy in Sweden and Finland is nuclear. Hydro and ***nuclear power*** provide most of Sweden's electricity and Finland is expanding its nuclear base with two new reactors. The highly toxic waste from these reactors is in interim storage, awaiting the construction of repositories at c 500 m depth in the crystalline bedrock (Milnes, Stephens, Wahlgren and Wikström, this volume). Both in Sweden and Finland, a similar design has been promoted and Finland is at present building a repository. Secure storage of the radioactive waste in a stable environment is essential, independent of whether or not future generations decide to exploit it further for energy production. Our understanding of the Fennoscandian Shield down to depths of a kilometre has been greatly improved by the wide range of studies of the crystalline bedrock, the Quaternary history and the hydrogeology required for the siting of these repositories.

Mining of ***metals*** in the Nordic countries has a long tradition. Documented mining dates back to the 8th century AD and, historically, mining has contributed substantially to the growth and welfare of the Nordic countries. Today this region is one of the most important metallic mining districts of the European Union. Metals are produced from active mines in all countries except Iceland and related industries are thriving (Weihed, Eilu, Larsen, Stendal, and Tontti, this volume). The historical production of metals was dominated by iron, copper and silver. Currently important ore deposit types include: volcanogenic massive sulphide deposits (Cu, Zn, Pb, Au, Ag), orogenic gold deposits (Au), layered intrusions (Ni, PGE, Ti±V), intrusion-hosted Cu-Au, apatite-Fe deposits, and anorthosite-hosted Ti deposits. Besides these well-documented deposits, new kinds of deposits are being explored, e.g., iron oxide-copper-gold (IOCG) and shale-hosted Ni-Zn-Cu and different types of uranium deposits.

A number of different types of ***dimension stones*** are quarried in all the Nordic countries, some of which are world famous, such as the Nowegian Larvikite and the Finnish Rapakivi granites (Johansson, Larsen, Lehtinen, Persson, Räisänen, Schack Pedersen, Weihed, and Wik, this volume). Rock aggregates are increasingly important, replacing sand and gravel aggregate as construction materials in some countries due to the need to protect ground water supplies. The industrial minerals sector is expanding in most Nordic countries and extensive development has taken place during the last few years. The main commodities mined are carbonate rocks, quartz, feldspar, apatite, olivine and talc.

Access to drinking quality ***ground water*** is normally not a problem in the Nordic countries, which are characterized by many types of aquifers and great differences in groundwater recharge (Knutsson, this volume). Fracture zones in crystalline bedrock provide the most common type of aquifer. Porous aquifers are found in various types of rocks and soils. The most productive are the lava-fields and the pyroclastic rocks in the active volcanic zone of Iceland, but glaciofluvial deposits such as eskers and deltas in Finland, Norway and Sweden, outwash plains in southwestern Denmark and sandurs in Iceland are also very porous. Fractured porous aquifers in consolidated limestones and sandstones are common in Denmark and Scania in southernmost Sweden. Karst aquifers exist in the Caledonian mountain range in Norway and Sweden. Geothermal water with many springs and geysers are common in Iceland and of great economic importance.

Environmental geology, with particular concern for the mining environment, medical geology and urban geochemistry, is a scientific discipline that has developed strongly during recent years in the Nordic countries (Salminen, Kousa, Ottesen, Selinus, Steinnes, Tarvainen, and Öhlander, this volume). In mining environmental studies, methods that are suitable in Arctic conditions have been developed; in medical geology, the input from the Nordic countries has made it an appreciated scientific discipline throughout the world, and in the case of the urban environment, methods developed by geochemists have notably improved the health conditions.

Climate in Norden is much influenced by the Gulf Stream, with warm Atlantic waters from low latitudes being driven northwards along the west coast of Scandinavia into the high Arctic; a complementary current transfers colder waters from the Arctic Basin southwards along Greenland's east coast. Climate variability and change is particularly pronounced in the Arctic, with profound impact on the Nordic countries (Thiede and Johanesson, this volume). A thousand years ago, the Vikings were able to migrate to Iceland and then Greenland, only to be forced out of Greenland by the Little Ice Age, a few hundred years later. Studies of ice-cores from the Greenland ice-cap have shown that the last hundreds of thousands of years were dominated by long glacial periods interrupted by short interglacials (apparently driven by orbital forcing); the glacials also experienced repeated short-lived warming events with rapid changes in temperature. The climate record remains enigmatic and the anthropogenic influence difficult to quantify.

The relatively stable, old bedrock beneath most of the Nordic countries (Iceland excepted) provides an environment that is less susceptible to some of the major ***geohazards*** (e.g., earthquakes) that are experienced in so many other countries (Nadim, Asbjørn, Pedersen, Schmidt-Thomé, Sigmundsson, and Engdahl, this volume). Nevertheless, all the Nordic countries are prone to floods and landslides and, with the exception of Denmark, snow avalanches; the economic consequences can be severe. Building on quick sands, quick clays and mountain sides has proved particularly hazardous in Sweden and Norway. Slide-triggered tsunamis (e.g., in fjords) are also of concern, and research on large submarine slides on the continental shelf has been of importance for the petroleum industry. In Iceland, volcanic eruptions are frequent and the country´s short history is scarred by many eruptions that have claimed lives; earthquakes of magnitude M7 can be expected every century. With regard to the other Nordic countries, Norway ranks highest in terms of earthquake hazards, with one M7-earthquake expected every 1,100 years. Relatively low population density in the geologically hazardous parts of the Nordic countries has implied that human losses have been fewer due to geohazards than in many other parts of the world.

Studies in the Earth Sciences have a long tradition in Norden, and in the eighteenth century Nordic scholars were in the forefront in chemistry, mineralogy and paleontology (Sundquist, Haapala, Hansen, Hestmark and Steinthorsson, this volume). This was also the century when "geology" started to be taught at the universities. In the ninteenth and twentieth centuries, state geological surveys, geological societies, journals and university chairs were established. Nordic geoscientists have contributed greatly to geology, e.g., in petrology, mineralogy, geochemistry, glacial geology, paleontology, stratigraphy, structural geology and geophysics. In more recent years, geology related to the energy issue has been much in focus in the Nordic countries.

The ***Nordic geological surveys*** have brought together information on the geology and natural resources of their respective countries for 150 years. The collective mission of the surveys in our time is to focus on "geology for society" by doing research and providing services, and by making the data easily accessible to the public. The paper by Smelror, Ahlstrøm, Ekelund, Hansen, Nenonen and Mortensen (this volume) gives a brief overview of some research areas and projects currently undertaken by the Nordic geological surveys. These serve as practical examples of how the surveys address important societal problems and challenges that require geological input for their solution.

The Congress programme

As with previous International Geological Congresses, the programme for the 33rd IGC has been designed to cover as wide a range of the geosciences as possible. To emphasize the interdependence of the many disciplines in Geology, *sensu lato*, including geophysics, geochemistry, biogeology and classical geology, the Oslo Congress has been given the informal title "Geoscience World Congress 2008". And to highlight the increasing awareness worldwide of the importance of integrated Earth Science for society, the main theme of the 33rd IGC has been defined as: "*Earth System Science: Foundation for Sustainable Development*".

At the Oslo IGC, global issues of particular societal importance will be explored in plenary sessions as so-called "***Themes of the Day***". They will range from the origin and evolution of life on Earth and in a planetary context, to the supply of essential geo-resources, such as water, minerals and fossil fuels, and environmental and health-related issues, including climate change and geohazards. By combining the latest science with related economic and political presentations and encouraging interdisciplinary interaction and debate, IGC will provide an up-to-date assessment of the present status on these issues. The importance of interdisciplinary interaction in Earth System Science will be emphasized. Our science needs a fully integrated approach on all societal issues.

Major international projects such as the International Year of Planet Earth and the International Polar Year are highlighted in the "Themes of the Day" and the Arctic-Antarctic sessions, respectively. The Nordic countries reach far to the north into the high Arctic. Increased temperatures in recent decades and accompanying reduction in the regional distribution and thickness of the sea ice, particularly during summer months, has focussed interest both on the sensitive Arctic environment and also on the possible exploitation of the Arctic's natural resources. The northern sea-route from the Pacific (via the Bering Straits) to the North Atlantic (via the Kara Straits), pioneered by Nordenskiöld in the late nineteenth century, is beginning to look more like an opportunity than just a daunting challenge. Discoveries of hydrocarbons beneath the Barents and Kara seas are stimulating new surveys over the less hospitable shelves further east. They are also promoting a greater interest in the Arctic Basin itself, with its ridges and deep troughs (Figure 2). Jurisdiction over the continental shelves, out to the continent-ocean transition zone, is governed by the United Nations Convention on the Law of the Sea (***UNCLOS, 1982***). The 33rd IGC will provide a forum for review of the wide range of geoscientific research that has been going in this context since the 1980's.

Excursions are also in important part of the Congress programme. About thirty pre- and post-Congress excursions are in the programme for the 33rd IGC. Not all are fully booked and a few additional participants are welcome. The excursions will be run in all five Nordic countries, including Greenland and the Faroe Islands; also in Russia and Ukraine. Excursions 2, 9, 44 and 56 deal with onshore analogues to the Late Palaeozoic, Mesozoic and Tertiary geology of the continental shelves. Excursions 4 and 5 are dedicated to the past and present tectonic development and the general geology of Iceland. Excursions 6 and 7 deal with the volcanic stratigraphy and the glacial history, respectively, of the Faroe Islands. Excursions 12, 15, 47 and 48 cover the classical Precambrian ore deposits of Scandinavia and the Kola Peninsula, while Excursion 54 deals with the genesis of mineral deposits in the Urals. Excursions 16, 18, 42 and 51 are dedicated to the Precambrian geology of Scandinavia including the Sederholm migmatites in Finland and the Neoproterozoic glaciation facies exposed in Finnmark. A related excursion to the Ukrainian Shield is offered as No. 52. Paleozoic foreland geology and Late Paleozoic rift geology of southern Norway and Sweden are dealt with by Excursions 23, 24, 25 and 50. A related excursion, No. 10, deals with Paleozoic impact craters. Three excursions, Nos. 28, 29 and 34, offer transects of the Scandinavian Caledonides. Excursions 21 and 26 present recently established Norwegian geoparks, of which the first one already has the status of a UNESCO European Geopark. Aspects of Quaternary geology are presented in excursions 11A, 11B, 39 and 40. A special excursion on issues related to disposal of nuclear waste is offered as No. 14. In addition to these pre- and post-Congress excursions there will be several one-day excursions offered, covering topics like classical fossil localities, paleo-impact craters, Neoproterozoic basin development, Paleozoic geology of the Oslo area, urban geology, and geothermal energy.

Proposals for twenty-two ***Workshops*** and ten ***Short Courses*** were accepted for inclusion into the science programme (a few of these have been later withdrawn or diverted into symposia). The workshops are arranged by individuals as well as organizations and represent a variety of themes, dealing with issues ranging from geoscience information and education, the future role for geoscientists in society and on the labour market to various problems of scientific character, like stratigraphic classification, paleontological data analysis and geochemical and risk mapping. The short courses are given by individuals, dealing with, e.g., airborne exploration geophysics, medical geology and mineralogy, paleoseismology, source rock modelling and numerical modelling in Earth sciences.

The International Geological Congress after 2008 in Norden, will be held in Australia. Towards the end of the 33rd IGC, a special symposium on ***Oceania*** will provide the backcloth for an invitation to join the 34th IGC in Brisbane in 2012.

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The 33rd International Geological Congress, Oslo 2008

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The 33rd International Geological Congress is being organised jointly by the Nordic countries and to be held in Oslo, Norway, August 6–14th, 2008. This "Geoscience World Congress 2008" will run up to 40 parallel science sessions, poster sessions, an extensive exhibition, short-courses, workshops, and business meetings; about 50 exciting pre- and post-Congress excursions are planned. The excursions include all the Nordic countries, as well as Greenland, Svalbard, the Faeroes, Russia and Ukraine. All major geoscientific themes are being covered by the Congress which has been divided into two parts, Sunday 10th August being without Symposia and dedicated to workshops, short courses, business meetings and excursions. Through a series of "Themes of the Day", seven themes with major societal impact will be covered in plenary sessions with invited lecturers, including a key-note "StatoilHydro lecture" given each day during the lunch interval. The venue is set up to offer a compact Congress with easy access to all sessions and other events. An extensive social and cultural programme is also being arranged.

Introduction

The International Geological Congress (IGC) was founded in 1876 and the first meeting was held in Paris in 1878. Thereafter, for more than 100 years, the IGCs have been the main global multidisciplinary platform for exchange of ideas and experience among geologists and other geoscientists. IGCs, taking place every four years, are the "Olympic Games" for geologists. The 33rd IGC will give the participants specialised symposia of high quality, presenting overview papers and thematic sessions for the geoscience community as well as society at large. Excursions have always been an important part of IGC and this tradition will be continued in Oslo 2008, with about 50 exciting excursions to choose from.

Over the years, the number of participants has gradually increased, from the initial 312 in Paris 1878, to the 7281 of the 32nd IGC in Florence, Italy in 2004 (Abbate et al., 2005). The Nordic countries have hosted the Congress twice before, in Stockholm 1910 (Sunquist and Nordlund, 2004), and in Copenhagen 1960 (Sørensen, 2007). The five Nordic countries, Sweden, Denmark, Iceland, Finland, and Norway decided to join forces and announced their candidature at the congress in Rio de Janeiro in 2000. The formal bid was submitted in 2002 and the 33rd IGC was awarded to the Nordic Countries, during the 32nd Congress in 2004.

Arranging an International Geological Congress is a major challenge, and much work has been focussed on obtaining support of various kinds. The organisers of the 33rd IGC are honoured to have his Majesty the King of Norway as patron of the Congress. UNESCO has also offered its patronage, clearly demonstrating the importance of the Congress for society at large.

Two major international events are closely related to the Congress. The International Polar Year (IPY) runs from 2007 to 2009, and with the Congress' strong emphasis on the Arctic, a close connection to IPY is natural. The International Year of Planet Earth (IYPE) was ratified by the UN General Assembly in 2005, and is also running in the period 2007–2009. The IYPE has chosen to focus on ten main themes, all with great societal importance. Several of these themes are also main themes of the Congress, and will be treated in full-day plenary sessions. Through these "Thematic Days", the 33rd IGC offers participants an overview of the state-of-the-art in research, as well as an unique possibility to discuss their relevance and the impact on society. Together, they contribute to the main message of the Congress—Earth System Science: Foundation for Sustainable Development.

Organisation

A Nordic congress organisation structure (Figure 1) was set up to handle the preparations. The legal entity behind the Congress is a "Nordic Foundation for IGC". The foundation is registered in Norway and is led by a board with one member from each of the Nordic countries, appointed by the Academy of Sciences in each country. The 33rd IGC Organising Committee consists of 12 members: President, Secretary General, Vice-Presidents (VPs) for Science, Finance, Operations, Communication and International affairs, VPs for Iceland, Sweden, Finland, and Denmark, and a representative for the Congress' PCO, Congress-Conference AS in Oslo. Subcommittees have been organised under the various VP's areas of responsibility (Figure 1). Contact with the 32nd IGC Organising Committee in Italy was established early and the experience from the Florence Congress, as published in the 32nd IGC General Proceedings, has been of great value in the preparatory work.

The Organising Committee has spent much effort in obtaining sponsorship from external sources to keep the registration fees at a moderate level. Norway's biggest oil company, Statoil (now StatoilHydro), agreed at an early stage to be the Congess' main sponsor. Other companies form the petroleum sector, as well as companies from other fields, such as the Nordic mining industry, have provided financial support to the Congress. The Norwegian Government and the Research Council of Norway are also key sources of funding. Additional important support has come from the Nordic Council of Ministers and from other Nordic governments and research councils.

The venue

The venue chosen for the Congress is the Norway Convention Centre (Figure 2) at Lillestrøm, located 20 km east of Oslo City Centre. The venue consists of 4 main halls, as well as an attached hotel, which also holds lecture rooms. In addition to the existing, permanent and semi-permanent lecture halls, a set of temporary auditoriums will be built inside Hall D (Figure 2). Up to 40 oral sessions will run in parallel in lecture halls ranging in size between 80 and 500 seats. Hall B will be used for daily plenary sessions ("Themes of the Day"), whereas Hall C is allocated for the poster sessions and the exhibition, "GeoExpo 2008". The Convention Centre will also be

33rd IGC Organising Committee

President	Arne Biørlykke	Geological Survey of Norway (NGU)
Secretary General	Anders Solheim	Norwegian Geotechnical Institute (NGI)
VP International Relations	Richard Sinding-Larsen	Norwegian University of Science and Technology (NTNU)
VP Finances	Finn Roar Aamodt	Statoil ASA
VP Science Programme	David Gee	Uppsata University, Sweden
PCO Company Representative	Øivind R. Lie	Congress-Conference AS
VP Operations	Ellen Ramberg	Ramberg Consulting AS
VP Communications	Berit Forbord Moen	Geological Survey of Norway (NGU)
VP for Denmark	Johnny Fredericia	Geological Survey of Denmark and Greenland (GEUS)
VP for Sweden	Olle Selinus	Geological Survey of Sweden (SGU)
VP for Finland	Elias Ekdahl	Geological Survey of Finland (GTK)
VP for Iceland	Kristinn J. Albertsson	University of Iceland
Science Programme Coordinator	Björn Sundquist	Uppsala University, Sweden

Figure 1 The 33rd IGC logistic structure.

Figure 2 The venue for the 33rd IGC, the Norway Convention Centre, which is located midway between Oslo City Centre and the Gardermoen International Airport, roughly 15 min. train ride from either side. The lower right inset shows the centre outline. Hall B will be used for the "Themes of the Day" and plenary lectures. GeoExpo 2008 and the poster presentations will be located in Hall C, whereas additional lecture halls will be built inside Hall D.

Table 1 Programme for the "Themes of the day" at the 33rd IGC.

Date		Theme
Thursday	7 August	Early life and survival of the fittest—Did Darwin get it right?
Friday	8 August	Climate change: past, present, future—What is anthropogenic?
Saturday	9 August	Geohazards—Can society cope?
Monday	11 August	Water, human health and the environment—Is groundwater a hazardous resource?
Tuesday	12 August	Mineral resources in a fast growing global economy—Are there any natural limits?
Wednesday	13 August	The energy race—What will be the future energy mix?
Thursday	14 August	Earth and beyond—From a cosmic perspective.

the venue for the opening and closing ceremonies. Lunches (complimentary) are also served in the centre during the Congress.

Hotel accommodation with a wide range of price levels, is offered both in the city centre and the surroundings, as well as near the Oslo International airport, north of the Congress venue.

Transport between the city centre and the venue will be arranged by train and/or buses.

Science programme

Symposia

The scientific programme of the Congress was initiated mainly through a "bottom-up process", in which the global geoscience community was invited to propose symposia. This resulted in more than 600 suggestions. The Science Committee (SciCom) reviewed the proposals, merged overlapping proposals and identified and filled "holes" in the programme. This process resulted in a total of about 450 symposia which were presented in the science programme when registration opened on September 1st, 2007. Good suggestions for symposia subsequently have been accepted, with the aim of having as comprehensive a multidisciplinary programme as possible, in accord with the informal title 'Geoscience World Congress 2008'.

Three categories of Symposia are being arranged, referred to as General, Special and Topical, as in previous IGCs. They will run in parallel throughout the Conference. The time allocated to each symposium will be dependent on the number of related contributions (abstracts) received by 29th February 2008. Division of these symposia contributions between oral and poster presentations will depend on the recommendations of the conveners and the capacity of the many parallel sessions.

General Symposia will cover all the main Geoscience disciplines. They are organised in related groups to allow easy navigation within the overall programme. A group of coordinators was selected to coordinate the submission of symposia within broad geoscientific topics. These coordinators also act as convenors for some of the symposia within their topic. *Special Symposia* at the 33IGC are dedicated to Regional Geology and include all the continents—Africa, Asia, Europe, North America, South America and Oceania (including Australia and New Zealand). Arctic and Antarctic symposia are included within these Special symposia, as are global geological projects. *Topical Symposia* are of interdisciplinary character and cover a very wide range of subjects that are of particular interest for Earth Science today. They range from basic geoscience to societal issues and managerial-organizational problems. All aspects of the International Year of Planet Earth (IYPE) will have a place amongst these symposia as will the geoscience of the International Polar Year (IPY).

Themes of the day

Seven themes of importance for society have been chosen for particular priority in the programme. These themes each have a dedicated day of the Congress (Table 1), which is divided into morning and afternoon sessions, separated by a lunch-time plenary lecture. The morning sessions are dedicated to presentations of the geoscientific aspects of the theme. After the "StatoilHydro Lecture", the afternoon sessions will focus on societal, political and economic aspects and the day will end in a panel debate and press conference. All presentations will be given by invited lecturers. Ministers from the Nordic governments are being invited to contribute to the afternoon sessions and participate in the panel debates.

Excursions

About 50 pre- and post-Congress excursions are being prepared (Figure 3). These cover all the Nordic Countries, including Iceland and the Faeroe Islands. In addition, there are excursions to Svalbard, Greenland, NW Russia and Ukraine. The length of the excursions varies from 2–3 days up to nearly 2 weeks, and the price varies, of course, according to length and location. One-day excursions in the Oslo area will be arranged during the Congress. The prices of excursions have been kept as low as possible, and some of the more expensive ones (e.g., to the High Arctic) are being sponsored to reduce the price for the participants. The excursions cover a wide range of Nordic and Arctic geology, and will also give the participants insight into the natural and cultural heritage of the region.

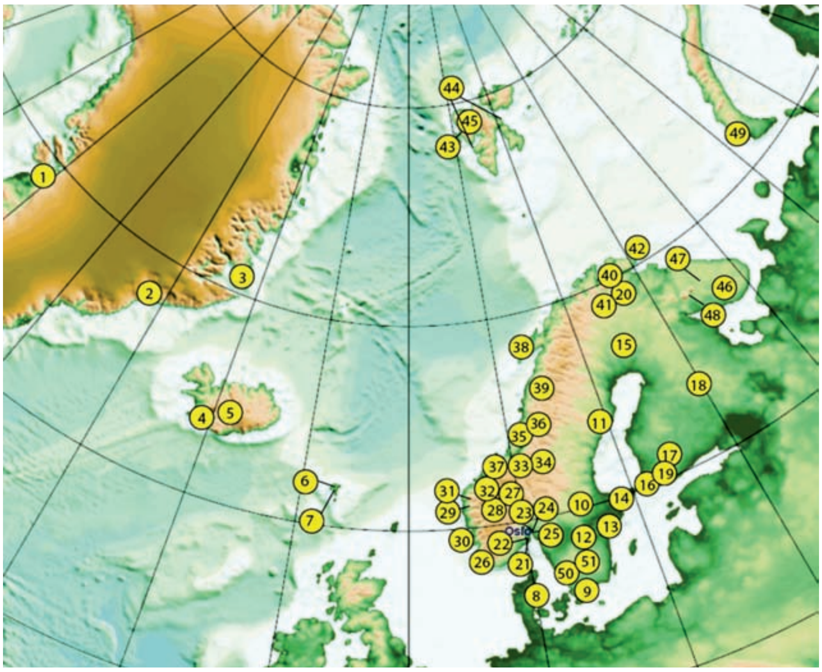

Figure 3 Planned excursions at the 33rd IGC. Some excursions may be cancelled or merged, and updated information is given on the Website (www.33igc.org). The programme also includes excursions to Ukraine and the Urals, not shown in this map.

Workshops, short-courses, and business meetings

The 33rd IGC is a meeting place where many activities other than the symposia will take place. A wide range of short (single-day) courses have been proposed. These will be run by experienced lecturers and are designed for all who wish to widen their knowledge of particular subjects. Workshops form another arena, which provide an opportunity for specialists to discuss particular subjects that are less suitable for symposia. These may, for example, include international projects or new technologies that are attracting particular interest. Workshops, short-courses and business meetings are announced on the website, and participants need to register their attendance.

Many of the commissions, projects, and affiliated associations of the International Union of Geological Sciences (IUGS) hold business meetings at IGC. In addition, other associations, companies, etc. have been encouraged to hold their meetings during the Congress. Rooms are provided free of charge. The workshops, short-courses, and business meetings will primarily be concentrated to Sunday 10 August, but may also be arranged at other times, dependent on the availability of rooms.

The Exhibition "GeoExpo 2008"

More than 2,500 m^2 of the venue are dedicated to the exhibition. Our aim is that the GeoExpo exhibition at the 33rd International Geological Congress should be one of the largest and most valuable exhibitions for all geo-related industry as well as for all governmental and private organisations operating in geosciences. Being located in Norway, we expect many Congress participants to come from the petroleum and mining industry. New frontiers in exploration are being opened in the Arctic areas, with its many environmental and technological challenges. We hope that these issues will be addressed at the GeoExpo, and that the Congress will be the main meeting place to discuss these important topics.

The exhibition will be located in the same hall as the poster presentations (Hall C, Figure 2), and will be a natural meeting point for all participants. Exhibitors will be clustered in "villages" where visitors can scan through geological surveys of the world, universities, science publishers, computer companies, consultancies, oil companies, etc. With the present-day tough competition to attract good young geoscientists, we also expect many companies to use the GeoExpo 2008 as a venue for recruitment.

The social and cultural programme

We aim at providing an entertaining social and cultural programme for the thousands of participants from all over the world coming to the 33rd IGC. The events, all announced on the website, include opening and closing ceremonies, icebreaker party, an evening in the new Oslo Opera House, a rock/jazz club, and an outdoor barbeque party in the Oslo Botanical Gardens. The cultural programme will introduce the participants to the cultural life in all the five Nordic countries. In addition to the official programme, Oslo is a lively city with numerous bars, restaurants, and music clubs; guides to what is going on in Oslo during the period of the Congress will also be provided. There will be plenty of opportunities to have a good time in Oslo in August 2008, outside of the Congress hours.

Final words

The IGCs are arranged only every four years. The 33rd IGC, with its wide-ranging and exciting excursion programme, many workshops, short-courses, business meetings, and a varied cultural and social programme is the main Geoscience venue for 2008. The last IGCs have seen a steady increase in the number of participants, and we aim at continuing this trend. Our major goal is not only to provide a forum for the world's geoscientists to present and discuss the latest developments in their own disciplines, but also to focus the World's attention on the importance of Earth Science for Society. Our hope is that the success of the 33rd IGC will encourage participation in the 34th IGC to be held in Brisbane, Australia in 2012.

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Archean of Greenland and Fennoscandia

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The North Atlantic craton in southern West Greenland mainly consists of a tectonic collage of Mesoarchean continental crustal terranes, which were amalgamated at c. 2.7 Ga and are currently exposed at mid-crustal amphibolite to granulite facies levels. Tonalitic orthogneisses predominate, intercalated with slightly older tholeiitic to andesitic metavolcanic rocks and associated gabbro-anorthosite intrusive complexes. The North Atlantic craton also contains enclaves of Eoarchean, c. 3.86–3.6 Ga orthogneisses and supracrustal rocks including the Isua greenstone (or supracrustal) belt. This is the oldest known assemblage of rocks deposited at the surface of the Earth, comprising mafic pillow lavas, banded iron formations and metasedimentary schists with local disseminated graphite of possible biogenic origin. Eoarchean rocks have not been found in Kola and Karelia in Fennoscandia where most rocks are 2.9–2.7 Ga tonalitic-trondhjemitic-granodioritic orthogneisses with intercalated coeval greenstone belts and amphibolites. Mesoarchean 3.0–3.2 Ga rocks are found in the eastern and western parts of the Karelian province. Subduction-related rocks like the Iringora supra-subduction type ophiolite and basalt-andesite-dacite-rhyolite series volcanic rocks in many greenstone belts, as well as eclogites are found in the Archean of Fennoscandia. A clear distinction between Greenland and Fennoscandia is the abundance of 2.75–2.65 Ga igneous rocks in Fennoscandia which indicates that these two cratons had a separate evolution during the Neoarchean.

Introduction

Archean crust underlies much of Greenland and the eastern part of the Fennoscandian Shield. Williams et al. (1991) proposed that at the end of the Archean there was a supercontinent, Kenorland, whose breakup led to the formation of several minicontinents which were then reassembled together with intervening juvenile terranes in the Paleoproterozoic. Bleeker (2003) argued that instead of one supercontinent there were several distinct, transient, Neoarchean supercratons. He grouped the present Archean cratons into clans based on their degree of similarity, where each clan could represent the progeny of a different supercraton. One of these, 'Superia', probably included both the Karelian craton (including Kola) in the present Fennoscandian Shield and the Hearne and Superior cratons in North America (Bleeker and Ernst, 2006). According to paleomagnetic reconstructions (Mertanen et al., 2006) where Greenland forms part of the Laurentia supercraton together with the Superior craton, the Baltica supercraton could have been assembled with or has been close to Greenland in the late Neoarchean (Figure 1). The reconstruction is based on paleomagnetic results from coeval 2.45 Ga dykes from the Superior and Karelian cratons. The dykes are thought to originate from the same magma source and represent concurrent early Paleoproterozoic rifting of the Archean basement. By using the other paleomagnetic polarity option, Baltica would locate at the other side of the equator on the opposite paleolatitude of about 30º.

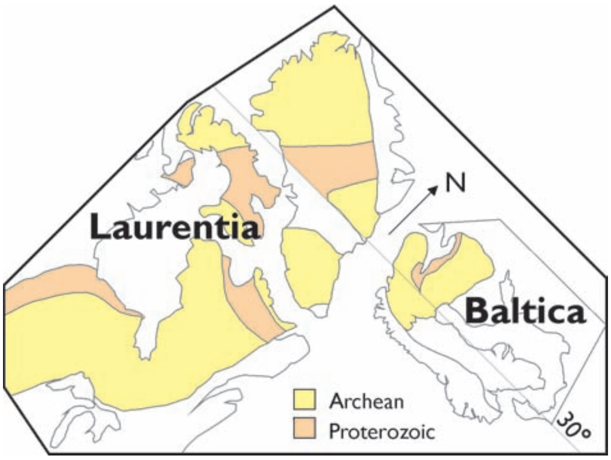

***Figure 1** Positions of Fennoscandian shield (Baltica) and Greenland (part of Laurentia) at 2.45 Ga.*

This review outlines and compares the main Archean tectonic units of Greenland and the Fennoscandian shields. Paleomagnetism does not tell whether these areas belonged to the same supercraton in the Neoarchean at 2.8–2.5 Ga, but similarities and differences between the cratons are important criteria when we are trying to understand the Archean plate tectonic framework and the existence and structure of possible supercontinents and supercratons. Both Greenland and the Fennoscandian shields record significant tectonic events coinciding with the globally recognized 2.7 Ga crustal growth episode. However, the earlier geological histories of these two areas differ in many respects. Eoarchean, 3.8–3.6 Ga supracrustal rocks are well documented in Greenland, but have not yet been found in the Fennoscandian Shield. Indeed, rocks of Paleoarchean (3.6–3.2 Ga) age are altogether relatively scarce in Fennoscandia, with the majority of plutonic rocks and greenstone assemblages being in the age range 2.9–2.7 Ga.

Greenland

Most of Greenland consists of a cratonic Archean core, which was extensively reworked by Paleoproterozoic collisional orogeny in its central and northern parts and is mostly covered by ice. The North Atlantic craton (Figure 2) in southern Greenland includes the intensely studied Godthåbsfjord/Nuuk region, which contains the Eoarchean Isua supracrustal rocks. Its crustal architecture, consisting of individual terranes, was defined during the 1980s (Friend et al., 1988). Prior to the opening of the Labrador Sea, the North Atlantic craton was contiguous with the Nain province in Labrador.

The North Atlantic craton mainly comprises 3.0–2.8 Ga mid-crustal, upper amphibolite to granulite facies rocks. Tonalitic orthogneisses predominate, with subordinate tholeiitic metavolcanic and gabbroic rocks and associated leucogabbro-anorthosite complexes, whereas clastic metasedimentary rocks are scarce. The craton therefore has previously been designated as representing a 'high-grade grey gneiss-amphibolite association' in contrast to the lower-grade granite-greenstone associations found in most other cratons. In addition to tonalite-trondhjemite-granodiorite (TTG) rocks, orthogneisses rich in P, Ba, Sr and light rare-earth elements (LREE) are also present and have been interpreted as containing a component of carbonatite-metasomatised mantle (Steenfelt et al., 2005). In the Nuuk region, some mafic metavolcanic complexes were formed in supra-subduction environments (Polat et al., 2008), and relicts of a large oceanic andesitic arc have recently been discovered (Garde, 2007). This suggests that the high-grade amphibolite-gneiss terrain simply represents the deeper part of a similar arc-type geodynamic setting as inferred in most other Archean cratons.

The North Atlantic craton forms a complex collage of individual tectono-stratigraphic terranes of different age which were amalgamated around 2.7 Ga, each having distinctive crustal components and geological histories. These terranes are best understood in the Nuuk region and have only been defined at reconnaissance level elsewhere in the western part of the craton (Nutman et al., 2005); the following account therefore mainly deals with the Nuuk region.

Eoarchean supra- and infracrustal rocks (3.86–3.6 Ga) occur in the Færingehavn and Isukasia terranes in the Nuuk region (Figure 2), and 3.7 Ga orthogneisses are exposed in the Aasivik terrane c. 200 km farther north. Eoarchean detrital zircons in younger sedimentary rocks in other parts of West Greenland may indicate that other very old terranes remain to be found. Whether the zircon ages of the early Archean orthogneisses record inheritance from earlier mantle-crust differentiation (Whitehouse and Kamber, 2005) or represent actual crystallisation ages of the rock units in which they are found (Nutman et al., 2000; Crowley, 2003), is a matter of vigorous debate. If the latter interpretation is accepted, the oldest rocks in West Greenland occur in the Færingehavn terrane as enclaves of supracrustal rocks within 3.86 Ga tonalitic orthogneisses, which were formerly known as the Amîtsoq gneisses (Figure 3). Eoarchean orthogneisses in the geographically separate Isukasia terrane (Friend and Nutman, 2005) host the Isua greenstone or supracrustal belt. This includes components with ages of both 3.8 and 3.7 Ga and is the largest known coherent area of Eoarchean rocks formed at the surface of the Earth. The supracrustal rocks have been metamorphosed and hydrothermally altered at least twice, at around 3.7 Ga and 2.8 Ga and are mostly intensely deformed, such that relict primary depositional features are rare. Important components of the Isua belt include boninitic and tholeiitic metabasalts, locally with well-preserved pillow structures, chemical metasedimentary rocks dominated by BIF, and metasedimentary schists with local disseminated graphite of probable biogenic origin (Rosing, 1999).

The Akia terrane northwest of Nuuk contains a 3.2 Ga granulite facies core surrounded by younger supracrustal rocks and the still younger, 3.05–2.97 Ga Nûk orthogneisses and related granitic rocks. A relict mafic-ultramafic complex south of Fiskefjord contains a platinum group element (PGE) mineralisation, while an extensive supracrustal belt north of Nuuk, interpreted as a 3.07 Ga andesitic island arc, hosts gold mineralisation. The recently defined 3.07–2.96 Ga Kapisilik terrane, to the east of Nuuk (Friend and Nutman, 2005) shares many features in common with the ≤ 3.07 Ga parts of the Akia terrane.

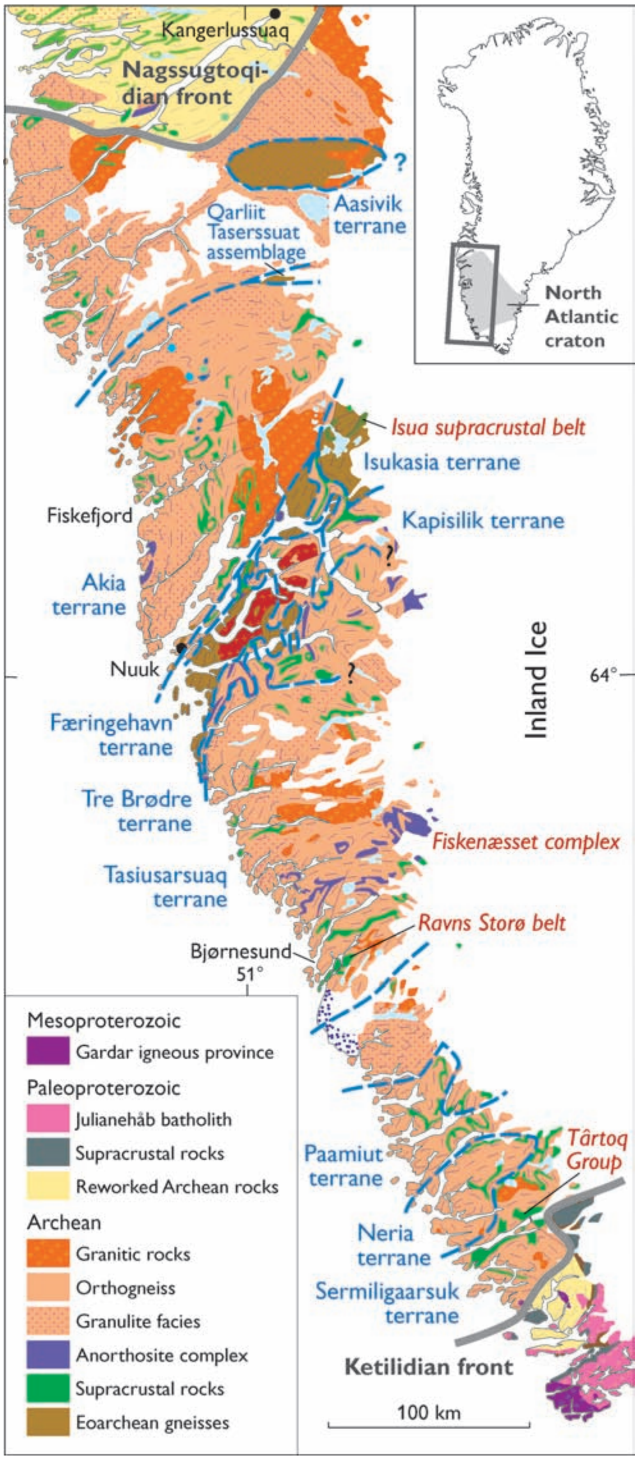

Figure 2 Archean terranes and rock units in the North Atlantic craton of southern Greenland.

The Tre Brødre and Tasiusarsuaq terranes east and southeast of Nuuk are composed of younger Mesoarchean rocks. The former consists of the 2.82 Ga amphibolite facies Ikkattoq granodioritic orthogneisses and a disrupted anorthosite complex. The tectonically overlying, but higher-grade Tasiusarsuaq terrane extends southwards for >100 km and contains 2.92–2.86 Ga orthogneisses (in part retrogressed from 2.795 Ga granulite facies metamorphism), a major granitoid body emplaced under granulite facies conditions (Ilivertalik granite), and also the Fiskenæsset anorthosite complex (Myers, 1985), notable for its occurrence of layered chromitites and metamorphic ruby. Large metavolcanic belts occur farther south at Bjør-

Figure 3 Eoarchean orthogneiss (Amîtsoq gneiss) of TTG-type, intensely migmatised and folded, and cut by undeformed, c. 2550 Ma pegmatite. Ameralik fjord, southern West Greenland.

nesund and Ravn Storø. Three or four additional terranes occur in the south towards the northern front of the Paleoproterozoic Ketilidian orogen in South Greenland. One of these terranes contains the >3.0 Ga metavolcanic greenstones of the Târtoq Group, with low-grade gold mineralisation. Metasedimentary units derived from contemporaneous continental crust and/or andesitic arcs predominantly occur in the boundary zones between terranes.

Archean rocks are also exposed along the eastern side of the North Atlantic craton in Southeast Greenland, within the Paleoproterozoic Nagssugtoqidian-Rinkian collisional orogenic complex in central–northern West Greenland, and as basement windows within the Caledonian orogen in East Greenland.

To conclude, each terrane in the North Atlantic craton typically comprises four main components: a) remnants of older, predominantly mafic crust and oceanic arcs derived from mafic oceanic or back-arc crust, or representing the mafic roots of andesitic volcanic arcs generated in subduction- related settings), b) orthogneisses, which form the bulk of the crust, c) granitic rocks formed by anatexis of the orthogneisses, and d) mafic dykes, which attest to younger episodes of crustal extension. Most terranes were metamorphosed in upper amphibolite to granulite facies, corresponding to relatively deep crustal levels.

Fennoscandia

Archean rocks comprise much of the eastern and northern parts of the Fennoscandian Shield and have been divided into five provinces, which were variably affected by Paleoproterozoic orogenic reworking—the Karelian, Belomorian, Kola, Murmansk and Norrbotten provinces (Figure 4). The Norrbotten province has not been studied in detail and is not discussed in this review. The Archean of the Fennoscandian Shield is dominated by the TTG association covering about 80% of the area, with subordinate greenstone belts, paragneisses, granulite complexes and migmatitic amphibolites.

Karelian province

In this paper, we follow Slabunov et al. (2006) in subdividing the Karelian Province into the Western Karelian, Central Karelian and Vodlozero terranes, each of which differ in terms of lithology, structure and ages of granitoids and greenstone belt volcanism (Figure 4). Large areas of the Western Karelian terrane and most of the Vodlozero terrane comprise Mesoarchean 2.8–3.2 Ga lithologies, while 3.5 Ga gneisses have been found in the Western Karelian terrane. In contrast, the Central Karelian terrane is mainly Neoarchean, both TTGs and greenstone belt volcanic rocks being 2.75–2.70 Ga in age. Subduction-related sanukitoids of age 2.74–2.70 Ga are common in the Central Karelian terrane and occur sporadically in the Western Karelian terrane. In contrast, the Vodlozero terrane is characterized by the absence of both sanukitoids and TTG granitoids of this age.

Except for some greenstone belts with lower or middle amphibolite facies peak metamorphic assemblages, most of the Karelian province record metamorphism under upper amphibolite facies and granulite facies conditions. U-Pb ages on titanites, monazites and zircons from granulites and migmatite leucosomes indicate that peak metamorphism coincided with protracted emplacement of monzogranites from 2.72–2.62 Ga (Käpyaho et al., 2007 and references therein). The highest grade rocks are the granulites in the western part of the Iisalmi complex, where thermobarometric results indicate crystallization at c. 800–850°C and 8–11 kbars.

Most parts of the Western Karelian terrane and the Belomorian province were reworked during Proterozoic tectonic events. In the Western Karelian terrane amphiboles and micas mostly yield K-Ar ages of c. 1.9–1.8 Ga (Kontinen et al., 1992). The Belomorian province yields Paleoproterozoic titanite and rutile ages of 1.9–1.8 Ga (Bibikova et al., 2001). Exposed Proterozoic igneous rocks are rare in the Karelian and Belomorian provinces, but lower crustal xenoliths from c. 500–600 Ma old kimberlites near the southern boundary of the Western Karelian terrane show that the Archean mafic lower crust has been repeatedly intruded by Proterozoic magmas, now consisting of Paleoarchean to Paleoproterozoic mafic granulites. Zircon ages of

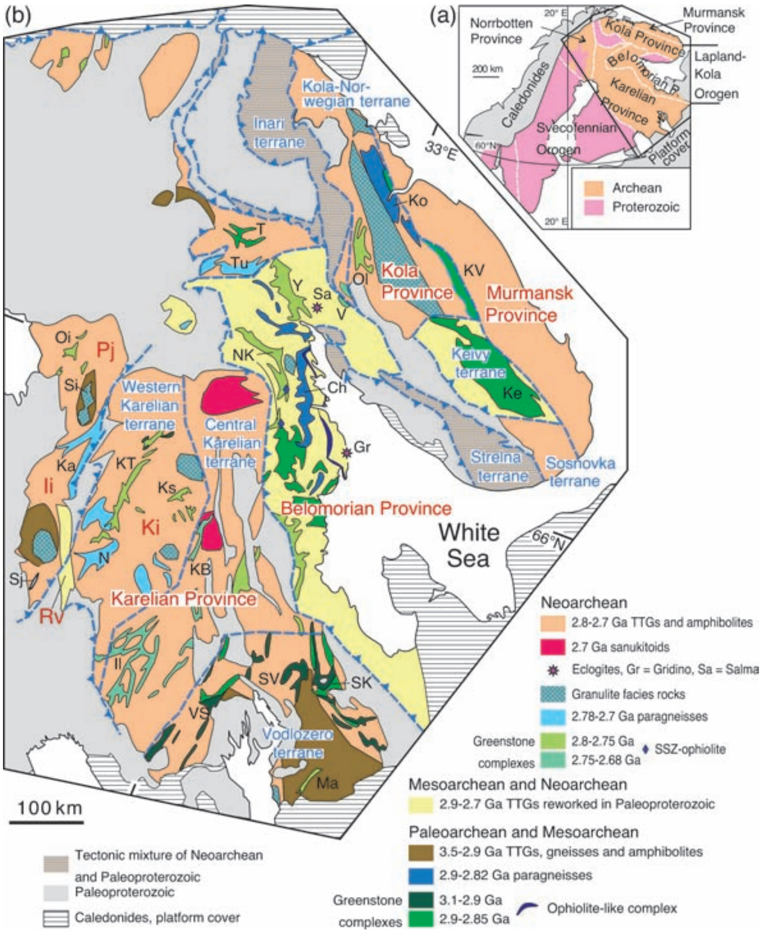

Figure 4 (a) Principal tectonic units of the Fennoscandian shield. (b) Geological scheme of the eastern Fennoscandian shield and representation of main Archean terranes, and greenstone, schist and paragneiss belts: Ch = Chupa; Il = Ilomantsi; KB = Khedozero-Bolsheozero; Ke = Keivy; Ko = Kola; Ks = Kostomuksha; KT = Kuhmo-Suomussalmi-Tipasjärvi; KV = Kolmozero-Voronya; Ma = Matkalahta; N = Nurmes; NK = North Karelian; Ol = Olenegorsky; Oi = Oijärvi; SK = Sumozero-Kenozero; SV = South Vygozero; Tu = Tuntsa; T = Tulppio; V = Voche-Lambina; VS = Vedlozero-Segozero; Y = Yena. Complexes of the Western Karelian terrane: Ii = Iisalmi; Ki = Kianta; Pj = Pudasjärvi; Rv = Rautavaara; Sj = Siilinjärvi carbonatite; Si = Siurua gneiss.

up to 3.5 Ga and whole rock Nd (TDM) model ages of c. 3.7 Ga of some xenoliths are equivalent to the age of the oldest gneisses in the Pudasjärvi area (Pj in Figure 4) in the northwestern part of the Western Karelian terrane.

Western Karelian terrane

The Western Karelian terrane, comprising much of eastern Finland and the westernmost part of Russian Karelia, is a diverse mosaic of rock units, although the nature and significance of boundaries between various subterranes are not yet adequately constrained. Migmatitic TTG orthogneisses and amphibolites predominate, with some medium to low pressure granulite areas in the western part of the terrane. Crustal architecture inferred from seismic data, as well as bedrock structural data, suggest thrust stacking and transpression during late orogenic deformation around 2.7 Ga. Tectonic transport was towards NE and SE, with evidence that the Western Karelian terrane was emplaced eastwards over the Central Karelian terrane, which generally has W-vergent polarity.

The oldest exposed rocks in the Karelian province—and indeed in Fennoscandia—are 3.5 Ga trondhjemitic gneisses (Mutanen and Huhma, 2003) at Siurua in the Pudasjärvi area (Figure 5). The Iisalmi area (Ii in Figure 4) contains 3.2 Ga TTG gneisses, with mafic intercalations that were derived from protoliths whose geochemical features resemble those of enriched mid-ocean ridge basalt. However, most of the region consists of 2.8–2.7 Ga orthogneisses, including 2.72–2.70 Ga enderbites and diorites with highly fractionated REE and high Sr/Y ratios, indicating that their parental melts were produced at high pressures in the garnet stability field. The youngest Archean igneous rock is the 2.61 Ga Siilinjärvi carbonatite (Figure 4), although the tectonic significance of this magmatic event is not clear. The Pudasjärvi–Iisalmi area also contains some supracrustal assemblages, including the Oijärvi greenstone belt (Oi in Figure 4), with amphibolite facies mafic and ultramafic oceanic plateau type volcanic rocks, and the Kalpio complex (K in Figure 4), which consists of migmatitic metasedimentary gneisses, including thin-bedded turbidites and quartzites.

The 3.2 Ga rocks of the Iisalmi area are juxtaposed sharply against the Rautavaara complex (Rv in Figure 4) from which the oldest known rocks are 2.75 Ga in age, suggesting that the boundary is of considerable tectonic significance. Supracrustal gneisses of the Rautavaara complex are characterized by cordierite-orthoamphibole mineral assemblages and Al-rich ultramafic rocks, indicating extensive hydrothermal alteration of protoliths. Their precursors were arc-type basalts and andesites which now form mafic interlayers in TTGs. Intrusive rocks include 2.74 Ga sanukitoids.

The Kianta complex (Ki in Figure 4), contrasts with the Rautavaara complex to the west and the Central Karelian terrane to the east in terms of the relative abundance of 2.85–2.78 Ga tonalitic gneisses, migmatites and volcanic rocks (Sorjonen-Ward and Luukkonen, 2005). The Kianta complex includes the Tipasjärvi, Kuhmo, Suomussalmi and Kostomuksha greenstones belts (KT and Ks in Figure 4). These 2.84–2.79 Ga greenstone belts include oceanic plateau type komatiitic and tholeiitic basalts, and sediments with BIF. The basalts are juxtaposed with arc type felsic associations. The youngest granites in the Kianta complex are dated at 2.71–2.68 Ga.

Figure 5 Paleoarchean Siurua trondhjemitic orthogneiss, cut by Neoarchean pegmatite dykes.

Much of the southern part of the Kianta complex consists of the metasedimentary Nurmes paragneisses, which are chemically identical to the global average for Neoarchean greywackes. The SHRIMP and TIMS U-Pb age determinations on zircon grains from mesosomes of migmatitic paragneiss and crosscutting granitoid plutons constrain deposition of the protolith wackes to 2.71–2.69 Ga. Trace element and U-Pb data suggest that the source terrains comprised mainly 2.75–2.70 Ga TTG and/or sanukitoid-type plutonic and mafic volcanic rocks. The presence of MORB-type volcanic intercalations in Nurmes wackes suggests they were deposited in a back- or intra-arc setting (Kontinen et al., 2007).

Central Karelian terrane

The Central Karelian terrane differs from the Western Karelian terrane in the west and from the Vodlozero terrane and the Belomorian province in the east on the basis of its somewhat younger age and the affinities of greenstone belt volcanism. The seismic structure of the terrane is characterized by subhorizontal reflections, which are interpreted to represent thrust-nappe system, with a northwestward tectonic transport during thrusting (Samsonov et al., 2001).

The oldest dated granitoids in the Central Karelian terrane are 2.76 Ga, although these contain xenocrystic evidence of crustal inheritance up to 3.3 Ga. In the Central Karelian terrane sanukitoid intrusions are strongly differentiated and vary in composition from ultramafic to felsic. They seem to be slightly older (2.73–2.75 Ga) than their counterparts in the Western Karelian terrane where sanukitoid intrusions formed mostly between 2.70–2.74 Ga and their compositions vary from diorite to granite (Lobach-Zhuchenko et al., 2005).

Volcanic rocks of the greenstone belts in the Central Karelian terrane are also younger than in the western and eastern parts of the Karelian province. Felsic volcanic rocks in the Ilomantsi and Khedozero-Bolsheozero greenstone belts are dated at 2.75–2.73 Ga. The presence of basalt-andesite-dacite-rhyolite series volcanic rocks and high abundances of greywackes in the Ilomantsi and Khedozero-Bolsheozero greenstone belts suggests that they represent arc type tectonic settings (Samsonov et al., 2001).

Vodlozero terrane

The Vodlozero terrane is poorly exposed, but several age determinations indicate that large areas of its core comprise 3.2–3.1 Ga granitoids, which include both migmatitic TTG gneisses and relatively homogenous intrusives. Granitoids and pyroxenite-gabbronorite-diorite intrusions of 2.98 Ga age, and coeval calc-alkaline amphibolite inclusions, which may represent mafic dyke remnants, are present in the central part of the terrane. Positive $\varepsilon_{Nd}(t)$ values for these mafic rocks and granitoids indicate that they represent juvenile material derived from a depleted mantle. The younger generations of TTGs in the area were intruded at 2.85 Ga, an event accompanied by regional metamorphism (Sergeev et al., 2007).

The sialic nucleus of the Vodlozero terrane is surrounded by three generations of greenstone belts. The first generation is 3.10–2.90 Ga in age and is charactertized by both oceanic plateau-type komatiites and basalts and island arc-type basalt-andesite-dacite-rhyolite (BADR) series volcanic rocks and adakites. The island arc system was formed during subduction of an oceanic plate under the western margin of the Vodlozero sialic continent, with concomitant back arc spreading setting, producing thick mafic and ultramafic lava units. Continuing subduction led to closure of the back arc basin, and the plateau-type volcanic rocks of the spreading center obducted onto the volcanic arc rocks. The second generation of greenstones is 2.90–2.85 Ga in age and represents continental margin-type volcanism with dacites, rhyolites and adakites; 2.85 Ga tonalites were also emplaced during this event. The third generation of greenstones erupted at 2.80–2.65 Ga, presumably in transpressional-transtensional pull-apart basins (Svetov, 2005).

The youngest (2.7–2.6 Ga) Archean rocks are granites and mafic dykes, which are tholeiitic and ultramafic in the NW part of the Vodlozero terrane and low-Cr, SiO_2-rich gabbronorites (e.g. the Shala dyke) in the central part. A mafic dyke yielded a Sm-Nd whole rock age of 2.61 Ga. Young granites have enclaves of enderbitic granulites and mafic and ultramafic amphibolites.

Belomorian province

The Belomorian province consists largely of Meso- and Neoarchean TTG gneisses, greenstones and paragneisses. The province is characterized by intense polyphase deformation and both Neoarchean and Paleoproterozoic high- and moderate-pressure metamorphic events. The province is dominated by granitoids which have U-Pb ages on zircon and Nd (T_{DM}) model ages with the range 2.93–2.72 Ga. The Belomorian province differs from other provinces of the Karelian and Kola cratons having ophiolites and eclogites that have not been discovered elsewhere in the Fennoscandian shield. Reflection seismic studies suggest that the Belomorian province is structurally formed of eastward plunging subhorizontal nappes and thrusts, being separated from the underlying Central Karelian terrane by a detachment zone (Mints et al., 2004).

Three greenstone generations are distinguished in the Belomorian province, dated at 2.88–2.82 Ga, 2.8–2.78 Ga and 2.75–2.66 Ga, with an additional 2.89–2.82 Ga paragneiss complex. The oldest, Mesoarchean 2.88–2.82 Ga greenstone complexes consist of arc-type BADR rocks and basalts-basaltic andesites with greywackes, oceanic plateau-type komatiites and basalts, the mafic-ultramafic Seriak complex with ophiolite-like compositional features and a metagreywacke unit interpreted as a fore-arc complex (Slabunov et al., 2006). The 2.8–2.78 Ga greenstones belts are represented by various arc type calc-alkaline and adakitic volcanic rocks, the suprasubduction ophiolites of the Iringora complex and metagreywackes and komatiitic-basaltic associations. The Iringora ophiolite sequence includes gabbro, sheeted dykes and massive and pillow lavas which belong to the boninite series (Shchipansky et al., 2004).

Neoarchean 2.72 Ga eclogites are known in two areas in the Belomorian province (Figure 6; Volodichev et al., 2004). Eclogites belong to a suite of rocks that is interpreted to have formed in a subduction zone. The 2.73–2.72 Ga granulite-enderbite-charnockite complexes and hypersthene diorite massifs of the Belomorian province were formed in a suprasubduction setting. Layered gabbro massifs and dykes of 2.7 Ga are considered to have formed at the initial stage of orogenic collapse (Slabunov et al., 2006).

The youngest greenstone complex is c. 2.66 Ga and comprises sediments with polymictic conglomerate lenses and a wide spectrum of volcanic rocks from rhyodacites to basalts, including subalkaline volcanic rocks and thus resembles molasse deposits. The youngest 2.68–2.64 Ga granitoids consist of small tonalite, trondhjemite and diorite veins and postkinematic granites in the northern Belomorian province. Coeval subalkaline granite massifs occur in the southern Belomorian province. Archean rocks of the Belomorian province were exposed at the present erosion level at around.1.8 Ga during the Paleoproterozoic Lapland-Kola orogeny.

Kola

The Kola area is a mosaic of Mesoarchean and Neoarchean tectonostratigraphic terranes, together with some Paleoproterozoic components, which consitute the Kola and Murmansk provinces (Figure 4; Kozlov et al., 2006; Slabunov et al., 2006, and references therein). These provinces reflect growth of continental masses from 2.9 Ga to 2.7 Ga, partly due to subduction of oceanic crust. They were first accreted to each other and subsequently collided with the Karelian Craton at 2.72 Ga, as indicated by high-pressure granulites in the intervening Belomorian Province. A mature intraplate setting developed at 2.67 Ga, and crustal growth continued until around 2.6 Ga.

The Archean crust of the Kola and Murmansk provinces is 36–43 km thick. Horizontal layering and listric seismic reflectors are characteristic of the upper part of the Kola-Norwegian terrane. This terrane records only slight Paleoproterozoic deformation, which enables good correlation between seismic reflectors and Neoarchean structures at the surface. Orthopyroxene-kyanite assemblages developed in Al-rich rocks at the very end of the Neoarchean and indicate pressures of 9–10 kbars in tectonically thickened crust at this time.

The individual Archean terranes consist of upper amphibolite to granulite facies supra- and infracrustal complexes which were variably reworked during the Paleoproterozoic Lapland-Kola collisional orogeny. Given its high metamorphic grade and the extent of reworking the Archean of the Kola region is distinct from the adjacent Karelian province but resembles the North Atlantic craton. Paleoarchean material is represented only by solitary 3.6 Ga detrital zircons in Mesoarchean and Paleoproterozoic granulite facies sediments, whereas the oldest preserved rocks are 2.92 Ga gabbro-anorthosites in a transitional zone between the Kola and Murmansk provinces. Whole rock Nd (T_{DM}) model ages from Archean rocks throughout the region are not older than 3.1 Ga, suggesting negligible input from Paleoarchean protoliths.

Figure 6 Eclogite layer in amphibolite, crosscut by pegmatite dike, Gridino, island of Stolbikha, White Sea.

Murmansk Province

The Murmansk Province comprises Neoarchean amphibolite facies TTG granitoids, diorites, enderbites and minor supracrustal rocks with 2.77–2.72 Ga zircon ages. The province is largely free of Paleoproterozoic deformational and thermal effects.

Kola Province

The Kola Province is a collage of Neoarchean terranes (Figure 4). The Kola-Norwegian and Kolmozero-Voron'ya terranes are almost unaffected by Paleoproterozoic events, whereas part of the Keivy terrane has been considerably reworked. The Kola-Norwegian terrane is made up of TTG granitoids, diorites, enderbites and peraluminous metasedimentary rocks typical of other Neoarchean granulite-gneiss regions. The metasedimentary rocks are interpreted as former greywackes and mudstones. The oldest metamorphic zircons in these rocks have ages of 2.8 Ga. The Olenegorsk greenstone belt is composed of basalts and rhyodacites dated at 2.76 Ga, paragneisses, and economically exploited BIF with gold mineralisation. TTG rocks of 2.8–2.9 Ga were formed by partial melting of mafic lower crust, with pressures varying over a broad range. Younger, 2.72–2.63 Ga granitoids are also present.

The Kolmozero-Voron'ya terrane is a Mesoarchean, c. 2.83 Ga collisional suture zone comprising mantle plume komatiitic rocks, arc-type tholeiitic basaltic-andesitic-dacitic metavolcanic rocks, and conglomerate-bearing terrigenous rocks, intruded by 2.73 Ga monzodiorites and granites.

The Keivy terrane contains 2.87 Ga felsic metavolcanic rocks resembling those formed in active continental margins, and a distinctive suite of alkaline granitoids, including aegirine-arfvedsonite and lepidomelane-hastingsite granites, together with gabbro-anorthosites and spectacular coarse-grained kyanite-, staurolite- and garnet schists, which are not known from elsewhere in Fennoscandia. These granites are the oldest anorogenic alkaline rocks in the world. Together with subsequent subalkaline series they yield ages of 2.67 Ga, identical to those from adjacent syenitic granites and gabbro-anorthosites and were derived from interaction between a mantle plume and continental crust under intraplate conditions (Mitrofanov et al., 2000; Vetrin et al., 2007).

The Sosnovka terrane is composed of poorly studied TTG rocks. Granitoids of 2.69 to 2.77 Ga occur in the Strel'na and Inari terranes located to south of the province (Figure 4).

Summary

Greenland and the eastern Fennoscandian Shield have some similarities in their Mesoarchean and Neoarchean crustal evolution. Large volumes of crust were generated in subduction-related settings in the Mesoarchean (3.1–2.8 Ga), and later in the Neoarchean (2.8–2.7 Ga). However, there are also clear distinctions. Eoarchean 3.8–3.6 Ga supracrustal rocks and granitoids, which are well known from Greenland have not been found in the Fennoscandia, or, if present, they are very scarce, because detrital zircons from paragneisses have not yielded Eoarchean ages. Paleoarchean (3.6–3.2 Ga) rocks are also relatively rare in Fennoscandia. During the c. 2.75–2.65 Ga period both cratons were intensely deformed and they underwent high-grade metamorphism during accretional and collisional processes. However, in contrast to Greenland, where igneous rocks are mostly 2.8 Ga or older, Neoarchean 2.75–2.67 Ga granitoids are common in Fennoscandia. These include mantle derived 2.75–2.70 Ga sanukitoids and related TTG rocks and even arc-type volcanic rocks in some greenstone belts, as well as large volumes of crustally derived 2.70–2.68 Ga granites. Extensive and rapid sedimentation occurred during or immediately prior to these events, recorded by widespread paragneiss suites throughout at least the western part of the Karelian province. The lack of these Neoarchean crust-forming processes in Greenland may indicate that Fennoscandia and Greenland were not parts of the same supercontinent at c. 2.7 Ga, or if they were, they were tectonically in a very different position.

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Paleoproterozoic evolution of Fennoscandia and Greenland

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The Paleoproterozoic evolution of Fennoscandia and Greenland can be divided into major rifting and orogenic stages. The Paleoproterozoic rifting of Fennoscandia started with 2.505–2.1 Ga, multi-phase, southwest-prograding, intraplate rifting. Both Fennoscandia and Greenland experienced 2.1–2.04 Ga drifting and separation of their Archean cratons by newly-formed oceans. The main Paleoproterozoic orogenic evolution of Fennoscandia resulted in the Lapland-Kola orogen (1.94–1.86 Ga) and the composite Svecofennian orogen (1.92–1.79 Ga). The Paleoproterozoic orogens in Greenland, from north to south, are the Inglefield mobile belt (1.95–1.92 Ga), the Rinkian fold belt/Nagssugtoqidian orogen (1.88–1.83 Ga) and the Ketilidian orogen (c. 1.8 Ga). The Lapland-Kola orogen, Inglefield mobile belt and the Rinkian fold belt/Nagssugtoqidian orogen are continent-continent collision zones with limited formation of new Paleoproterozoic crust, whereas the Ketilidian orogen displays a convergent plate-tectonic system, without subsequent collision. The composite Svecofennian orogen is responsible for the main Paleoproterozoic crustal growth of Fennoscandia.

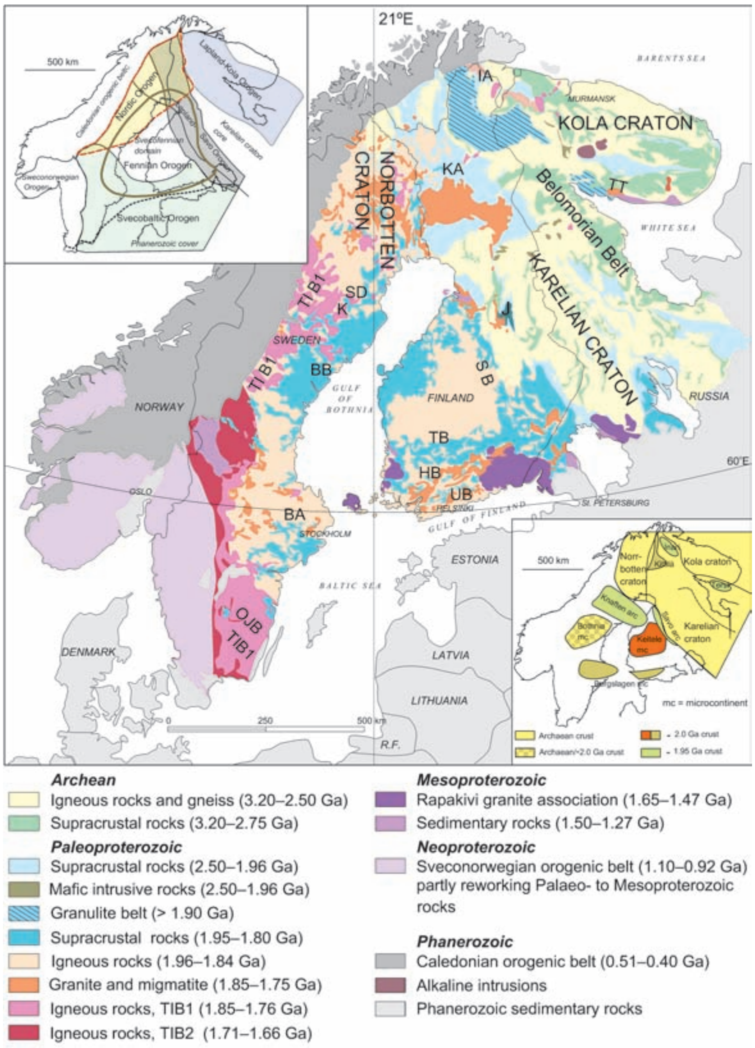


Figure 1 Simplified geological map of Fennoscandia based on Koistinen et al. (2001). Upper inset: Major Paleoproterozoic orogens of the Fennoscandia. Lower inset: Hidden and exposed microcontinental nuclei and arcs older than 1.92 Ga in Fennoscandia (based on Lahtinen et al., 2005). Paleoproterozoic units in Kola peninsula: IA = Inari area; TT = Tersk terrane. Paleoproterozoic units in Finland: KA = Kittilä allochthon; SB = Savo belt; TB = Tampere belt; HB = Häme belt; UB = Uusimaa belt; Paleoproterozoic units in Sweden: SD = Skellefte district; BB = Bothnian basin; BA = Bergslagen area; OJB = Oskarshamn-Jönköping belt; TIB = Transscandinavian igneous belt. Localities: J = Jormua; K = Knaften.

Introduction

Fennoscandia is a geographical term used to describe the Scandinavian Peninsula, the Kola Peninsula, Russian Karelia, Finland and Denmark. The Fennoscandian crustal segment of the East European Craton (Gorbatschev and Bogdanova, 1993) is a geological term and consists of the Fennoscandian Shield, a southern continuation of the Shield with Precambrian rocks covered by platform sediments, and the reworked Precambrian crystalline rocks within the Caledonides in the west (Figure 1). In the Fennoscandian Shield, Archean crust and its Paleoproterozoic cover dominate in the east, Paleoproterozoic Svecofennian crust in the center, and Mesoproterozoic rocks are found in the southwest.

Greenland (Figure 2) consists of a cratonic Precambrian core, Phanerozoic orogens along the northern and eastern sides, and a rifted margin in the west which separates Greenland from the main part of Laurentia in Canada. The Archean core was extensively reworked during Paleoproterozoic time, but juvenile additions were minor. This is in contrast with Fennoscandia where the Paleoproterozoic was the most important crust-forming era.

Fennoscandia and parts of Greenland belong to the world's best known Precambrian regions. Most of Greenland is covered by inland ice, but the coastal regions show almost continuous exposure. Fennoscandia is mostly covered by glacial deposits and the outcrop density is low, but nevertheless voluminous lithological, petrological, geochronological, aeromagnetic, gravity, deep seismic reflection and refraction, and geoelectric data are available and make it possible to understand its evolution in 3D. Our approach in this account is process-oriented and the focus is on major Paleoproterozoic events. We keep our usage of regional names to a minimum and only provide selected references.

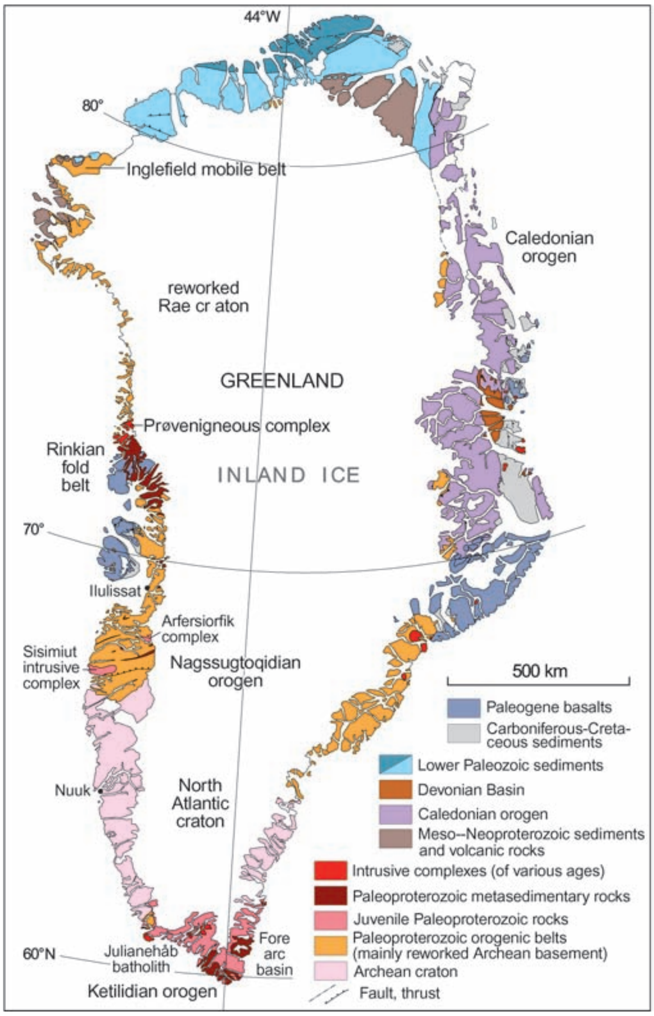


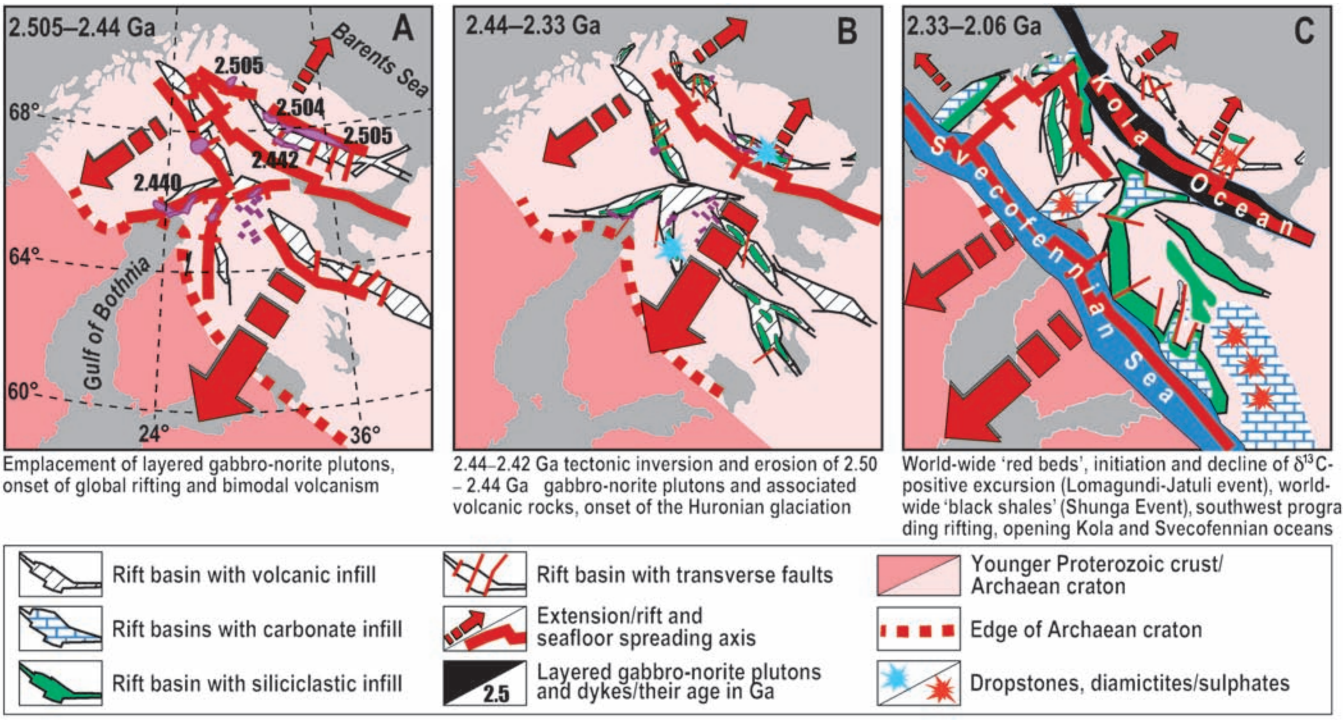
Figure 2 Overview map of Greenland with Paleoproterozoic orogenic complexes.

Paleoproterozoic rifting

The main Paleoproterozoic rifting events of Archean Fennoscandia comprise two stages of intraplate, southwest-prograding rifting between 2.505–2.1 Ga, and c. 2.1 Ga drifting and separation of the cratonic components by newly-formed oceans. Figure 3 provides a general guide through the geotectonic, palaeogeographic and environmental developments related to each stage of rifting, whereas Figure 4 displays rocks recording the most important features of the Paleoproterozoic rift evolution.

Incipient rifting began in northeastern Fennoscandia and became widespread after the emplacement of 2.505–2.440 Ga, plume-related, layered gabbro-norite intrusions and dyke swarms (for references see Melezhik, 2006). Sedimentation occurred mainly in lacustrine basins with a short-term invasion of seawater (Figure 4A). The mantle plume-driven continental uplifts led to the emplacement of voluminous continental flood basalts that were subsequently uplifted, dissected by rifting, and affected by erosion and deep weathering, eventually resulting in the onset of the Huronian glaciation (Melezhik, 2006). At 2.44 Ga, tectonic inversion was followed by repeated rifting. Incipient intraplate rifting at c. 2.35 Ga (Figure 4B) was characterised by predominantly subaerial volcanism (Figure 4C) and thick accumulation of polymict conglomerates (Figure 4D) including diamictites. Peculiar terrestrial products of the c. 2.2–2.1 Ga advanced rifting were highly oxidised, alkaline lavas (Figure 4E) and associated hot-water spring travertines (Figure 4F). Marine environments were marked by deposition of abundant calcium sulphates (Figure 4G) and diverse stromatolites on extensive carbonate platforms (Figures 4H-I). Red beds (Figure 2J) formed thick formations in both subaerial and marine environments, providing firm evidence of an O_2-rich atmosphere. All carbonate deposits were anomalously enriched in ^{13}C, signifying perturbation of the global carbon cycle during the Lomagundi-Jatuli Event (Melezhik et al., 2007).

Initial separation of the old, late Archean supercontinent, known as Kenorland, is roughly dated to 2.1 Ga (e.g., Daly et al., 2006). Formation of the Kola ocean and Svecofennian sea was marked by transition into marine conditions in most of the rifts fringing the continent (Figure 4K). Seafloor spreading was accompanied by voluminous submarine eruptions of MORB-like pillow basalts (Figure 4L), whereas thick turbiditic greywackes were deposited on the continental slopes (Figure 4M). The Lomagundi-Jatuli Event



Emplacement of layered gabbro-norite plutons, onset of global rifting and bimodal volcanism

2.44–2.42 Ga tectonic inversion and erosion of 2.50 – 2.44 Ga gabbro-norite plutons and associated volcanic rocks, onset of the Huronian glaciation

World-wide 'red beds', initiation and decline of $\delta^{13}C$-positive excursion (Lomagundi-Jatuli event), world-wide 'black shales' (Shunga Event), southwest prograding rifting, opening Kola and Svecofennian oceans

Figure 3 Rifting-related paleotectonic and paleogeographic evolution of the Fennoscandian Shield during the early Paleoproterozoic.

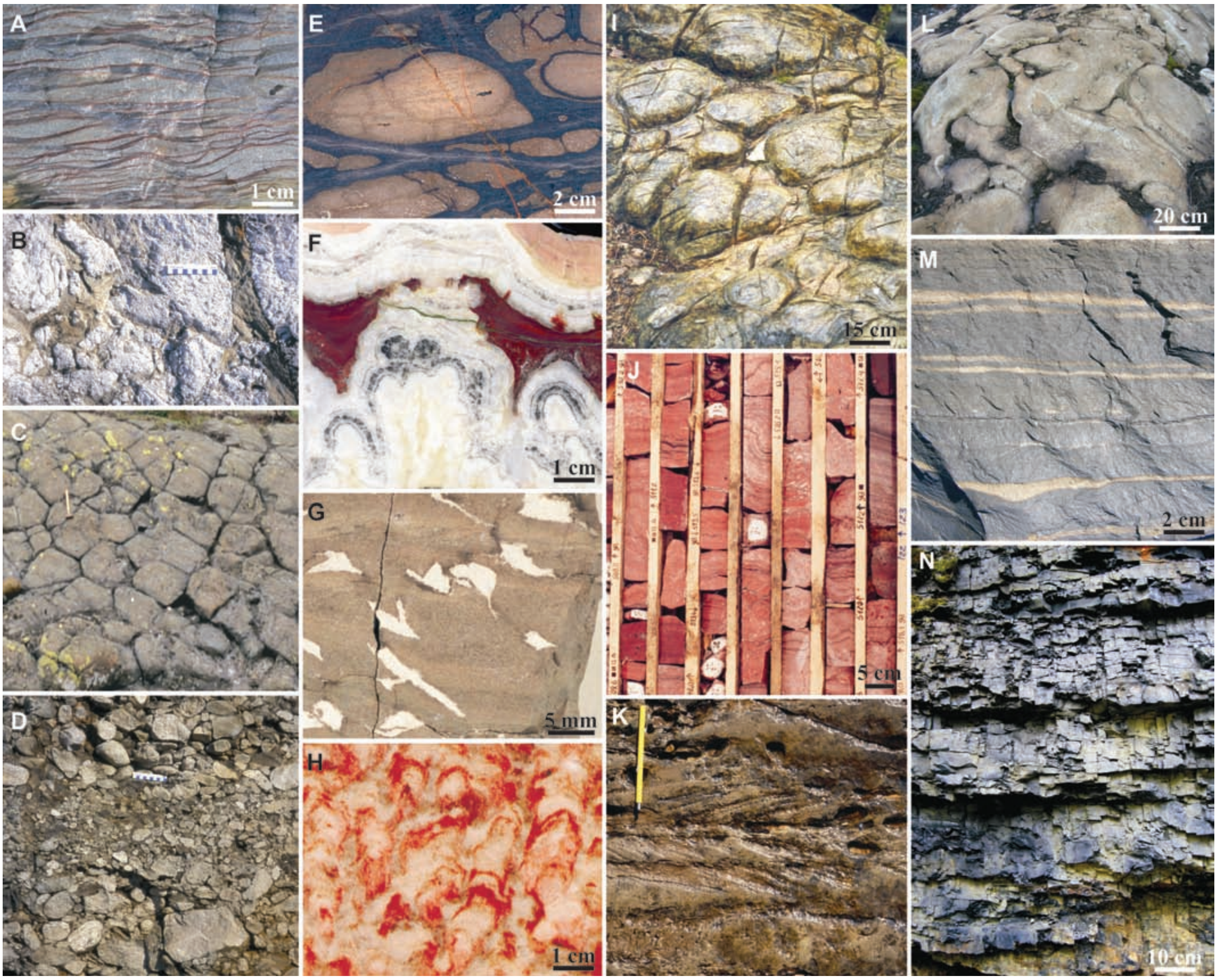


Figure 4 Rocks recording the most important features of Paleoproterozoic evolution.

A. Wavy bedding in mud-sandstone deposited on a mixed tidal flat - indication of a short-term invasion of seawater into a rift-bound lacustrine system; Seidorechka Sedimentary Formation, Imandra/Varzuga Greenstone Belt, Russia. **B**. Sand-filled fractures in Archean pegmatite recording incipient extension in the Pasvik palaeorift, Norway; scale bar 10 cm. **C.** Columnar jointing in Kuetsjärvi alkaline basalt—a typical feature of subaerially erupted mafic lavas, Pechenga Greenstone Belt, Russia; hammer 60 cm long. **D**. Basal, polymict, poorly sorted conglomerate of the 250 m thick Neverskrukk Formation, Pasvik Greenstone Belt, Norway; scale bar 10 cm. **E.** Highly oxidised alkaline dacite—an indicator of probable oxidation processes in the upper mantle; Kuetsjärvi Volcanic Formation, Pechenga Greenstone Belt, Russia. **F**. Laminated, red (oxidised), ^{13}C-rich dolostone overlain by ^{13}C-depleted travertine, the oldest by far in the Earth's record; the dolostone represents the Lomagundi-Jatuli isotopic event, whereas the travertine is a product of a rift-bound, subaerial, hydrothermal system carrying mantle-derived carbon; Kuetsjärvi Sedimentary Formation, Pechenga Greenstone Belt, Russia. **G**. Dolomite-pseudomorphed gypsum crystals in brown marine mudstone—indication of a sizeable seawater sulphate reservoir as a response to the oxic atmosphere; Tulomozero Formation, Onega basin, Russia. **H**. Pink (oxidised), ^{13}C-rich stromatolitic dolostone—an indication of perturbation of the global carbon cycle and oxic water; Tulomozero Formation, Onega basin, Russia. **I.** Exhumed stromatolite bioherm representing the subtidal facies of a carbonate platform; Peuranpalo, Tervola, Finland. **J**. Fresh drillcores of red beds representing a tidal carbonate flat and illustrating oxic depositional environments; Tulomozero Formation, Onega basin, Russia. **K.** Bimodal (herring-bone) cross-bedding in tidal channel sandstone; Kalix Greenstone Belt, Sweden; pencil 12 cm long. **L**. MORB-like, tholeiitic pillow basalt representing the 5 km-thick Pilgujärvi Volcanic Formation deposited during a transition from rifting to drifting; Pechenga Greenstone Belt, Russia. **M**. Rhythmically bedded, sulphide-rich (pale yellow) greywacke deposited from turbidity currents on a continental slope; Pilgujärvi Sedimentary Formation; Pechenga Greenstone Belt, Russia; **N**. Mudstone rich in organic carbon (55 wt%), representing an enhanced worldwide accumulation of organic matter (Shunga event); Zaonezhskaya Formation, Onega basin, Russia.

was terminated at 2.05 Ga, when previous 'red bed environments' were abruptly superseded by an unprecedented accumulation of formations rich in organic carbon (Figure 4N) representing the worldwide Shunga Event (Melezhik et al., 2005). The Jormua ophiolite (J in Figure 1), which either formed on a passive margin or in a continental rift setting at 1.95 Ga, is a unique example of Archaean subcontinental lithospheric mantle with a thin veneer of 1.95 Ga oceanic crust (Peltonen, 2005).

The last Paleoproterozoic rifting in Fennoscandia occurred at 1.65–1.54 Ga when the rapakivi granites formed. These granites both occur as large batholiths and smaller plutons; their genesis was caused either by deep mantle plumes or distant convergent plate-tectonic processes (Rämö and Haapala, 2005).

The onset of Paleoproterozoic rifting and continental breakup of the Archean in Greenland is documented by emplacement of the prominent, c. 2.04 Ga Kangâmiut dyke swarm in the Nagssugtoqidian orogen (Figure 2; Mayborn and Lesher, 2006) as well as several other, variably deformed and mainly undated dyke swarms throughout most of West Greenland. The extensional thinning of the Archean crust also gave rise to several continental margin basins that were later caught up in the Paleoproterozoic orogens.

Arc magmatism and orogenic stages

Fennoscandia

No subduction-related magmatism aged between 2.5 and 2.1 Ga has yet been found in Fennoscandia. The 2.02 Ga volcanic rocks in the Kittilä allochthon (Figure 1; Hanski and Huhma, 2005) are the oldest Paleoproterozoic arc rocks of oceanic affinity. Other examples that are older than 1.9 Ga include the island arc magmatism at 1.98–1.96 Ga in the Kola region (Daly et al., 2006), 1.95 Ga supracrustal rocks and granitoids in Knaften (Wasström, 2005), and the 1.93–1.92 Ga island arc rocks in the Savo belt (Figure 1). However, petrological, geochemical and isotopic data from intrusive complexes surrounded by juvenile crust indicate the existence of older (2.1–2.0 Ga) lithosphere (mc in Figures 1 and 6; Lahtinen et al., 2005). The 1.90–1.79 Ga age span records the most prominent magmatic activity observed at the present erosion level of the Paleoproterozoic of Fennoscandia.

The Paleoproterozoic of Fennoscandia can be divided into the Lapland-Kola orogen (1.94–1.86 Ga; Daly et al., 2006), the controversial Gothian orogen (c. 1.6 Ga; Andersson et al., 2002) and the composite Svecofennian orogen (1.92–1.79 Ga; Lahtinen et al., 2005). The last of these is divided into the Lapland-Savo, Fennian, Svecobaltic and Nordic orogens (Figure 1). Whereas the Lapland-Kola orogen shows only limited formation of new crust, the composite Svecofennian orogen forms a large volume of Paleoproterozoic crust. It covers c. 1 million km^2 and extends southwards, under the Phanerozoic cover, beyond the Baltic countries, as far as the Tornquist zone in Poland. The crustal cross-section of Fennoscandia shown in Figure 5 images collisional structures and the traces of inferred subduction zone in the Svecofennian orogen.

The Lapland-Kola orogen (Figure 1) is the orogenic root of a mountain belt comprising reworked Archean crust with only a minimum amount of juvenile material. An island arc accretion stage at 1.945–1.92 Ga (Inari and Tersk in Figures 1 and 6a) preceded transpressional continent-continent collision between the Kola craton and the Karelian craton at 1.93–1.91 Ga (Daly et al., 2006). Similarly, the amount of juvenile material preserved in the northern segment (Kittilä allochthon) of the Lapland-Savo orogen is minor (see below). Both of these orogens record collision between Archean continents, and only exhumed roots are preserved. However, Paleoproterozoic metasedimentary rocks (Figure 7A) are abundant in central Fennoscandia, and typically 60–70% of their detrital zircon populations are in the age range 2.1–1.92 Ga (Claesson et al., 1993; Lahtinen et al., 2002). The dominant 2.0–1.92 Ga zircons in the sediments could have their ultimate source in the former arcs in these orogens.

The Lapland-Savo orogen began to form in the north with collision of the Karelian craton with the Norbotten microcontinent at 1.92 Ga. Its main orogenic phase took place when the Keitele microcontinent collided with the Karelian craton at 1.92–1.91 Ga, followed by docking of the Bothnia microcontinent between 1.91–1.89 Ga (see Figures 6B–C). This latter docking terminated magmatism in the Knaften arc. The paleosubduction zone and associated accretionary wedge of the Knaften arc is seen as NE-dipping reflectors (C in Figure 5). The Karelian-Keitele continent-continent collision caused a change in the plate motions and led to a subduction reversal, with the onset of northward subduction at 1.90 Ga (TB in Figure 1). Subduction switchover occurred in the west, and N-directed subduction (B in Figure 5; Figure 6C) produced the Skellefte district volcanism (SD in Figure 1; Figure 7B) at 1.90–1.87 Ga (Allen et al., 2002). A doubly-plunging mantle reflector to the south of the Tampere belt, seen also further west in the BABEL 1 profile (B in Figure 5), indicates subduction also to the south under the Bergslagen microcontinent and attached island arc crust (HB in Figure 1).

The northward subduction under the Tampere belt itself ended at 1.89 Ga; this marked the beginning of the accretionary Fennian orogen (Figure 6C; Lahtinen et al., 2005). The N-directed subduction continued (reflector B in Figure 5, west of the proposed transform fault in Figure 6C), and produced 1.88–1.87 Ga back-arc volcanism in the Skellefte district. When the southern ocean had been consumed, the Bergslagen microcontinent was accreted to Keitele. This resulted in considerable shortening of the Tampere accretionary prism at 1.89–1.88 Ga (between TB and HB in Figure 1), and of the Häme and Uusimaa belts at 1.88–1.87 Ga (HB and UB in Figure 1). The Bergslagen area (BA in Figure 1) has a metamorphic peak at c. 1.87 Ga (Andersson et al., 2006). A second, younger peak at 1.86 Ga, dated from the southern part of the Bothnian Basin (BB in Figure 1) by Högdahl et al. (2007), prolongs the time window for the accretionary Fennian orogen to this date. Although it is widely

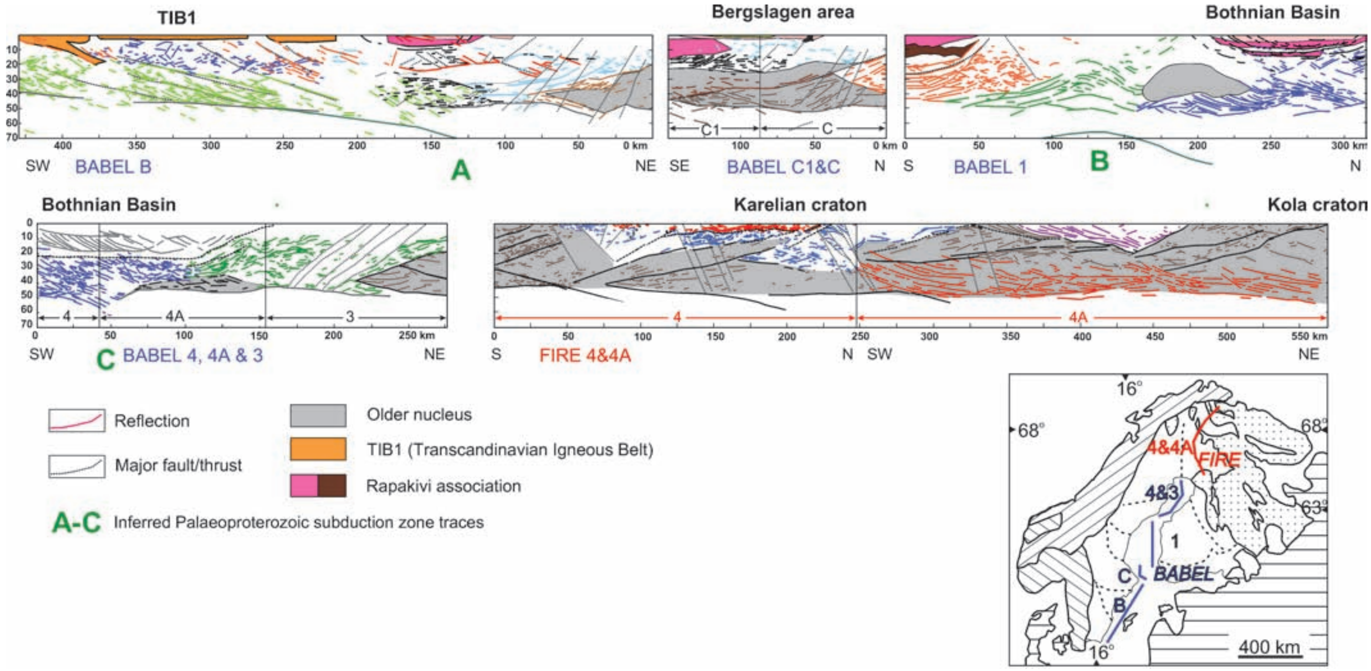


Figure 5 Simplified geological interpretation of the crustal structure of the Fennoscandian Shield along the BABEL and FIRE reflection profiles (after Korja and Heikkinen, in press). See Figure 1 for the geological map of Fennoscandia.

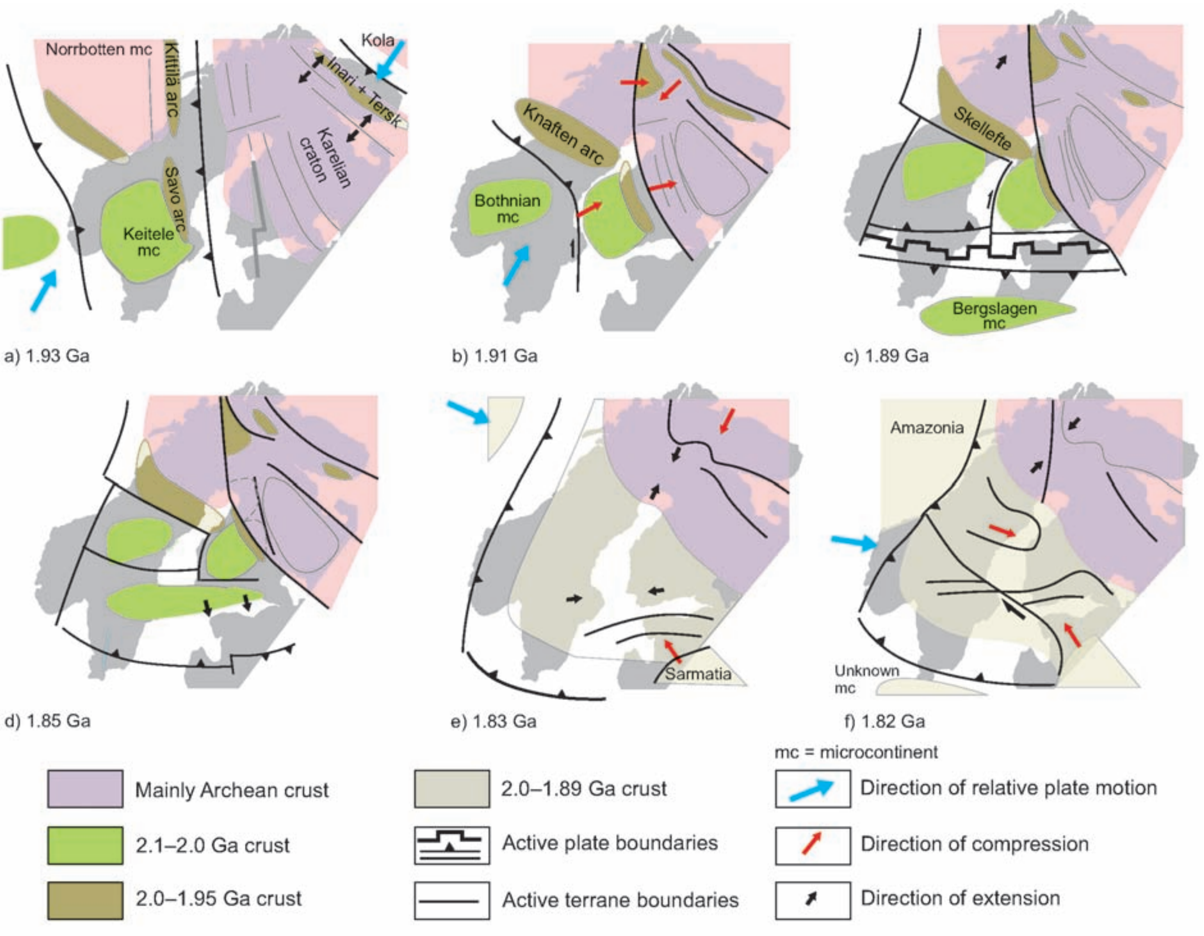


Figure 6 Selected stages of a schematic tectonic model for Fennoscandia between 1.93 Ga and 1.78 Ga (modified from Lahtinen et al., 2005).

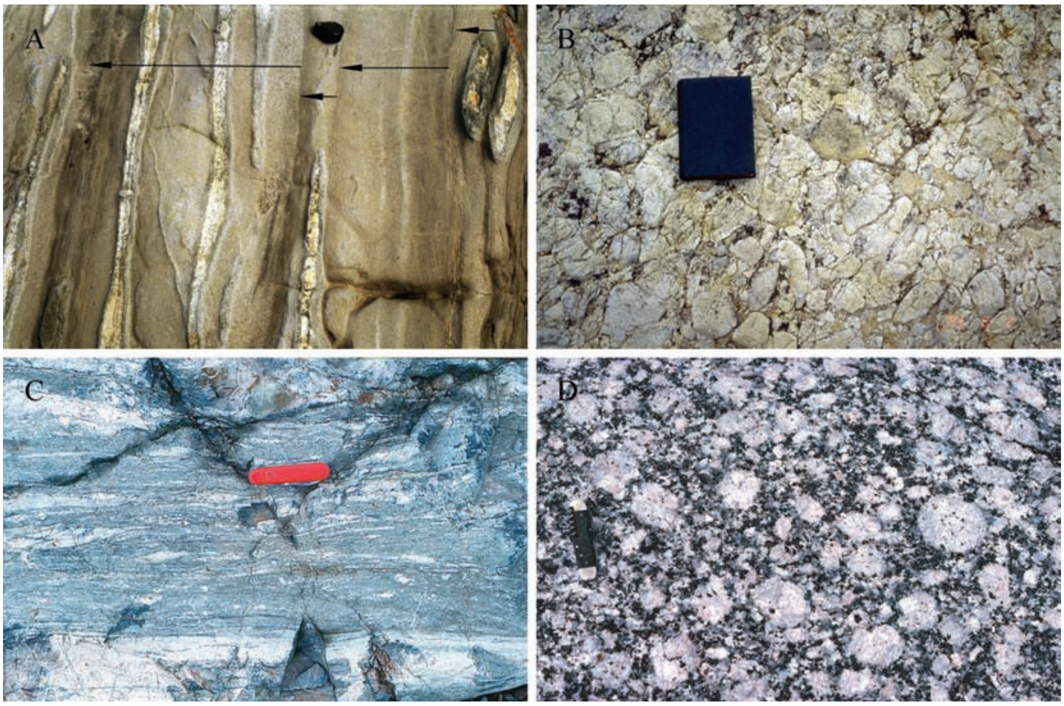


Figure 7 Rocks from the composite Svecofennian orogen.

A. Metagraywacke in Bothnian Basin; arrows indicate four turbidite beds. White bands and lenses are epidote-bearing calc-silicates. South of Boliden, northern Sweden. Photo: R. Kumpulainen. **B.** Rhyolitic volcanic mass flow, c. 1.9 Ga; Glommersträsk, Skellefte District, northern Sweden. Photo: B. Kathol. **C**. Strongly sheared, transposed and retrogressed migmatitic structures in a WNW-ESE-trending, dextral ductile shear zone; Strängnäs, south-central Sweden. Photo: M.B. Stephens. **D.** Microcline megacryst-bearing granite, c. 1.8 Ga. Stordalsberget, central Sweden. Photo: T. Lundqvist.

accepted that crustal growth of central Fennoscandia (the Fennian orogen in this paper) took place by arc accretion, this model has also lately been strongly questioned (e.g., Skiöld and Rutland, 2006 and references therein).

Högdahl et al. (2007) proposed that N-directed subduction (Figure 6D) caused continental margin magmatism at 1.86–1.84 Ga between the Bothnian basin and the Bergslagen area (BB and BA in Figure 1), and linked this magmatism with an inferred retreating subduction zone (trace A in Figure 5). Subsequent crustal extension (Figure 6D) led to the formation of intra-orogenic clastic sedimentary basins (Bergman et al., 2007). Hermansson et al. (2007) proposed a different tectonic model for areas surrounding the Bergslagen area (BA in Figure 1). In their model, the tectonic domains north and south of Bergslagen itself were formed along a single active continental margin at 1.87–1.85 Ga, and and were subsequently moved to their present positions.

The Svecobaltic orogen (1.83–1.80 Ga; Figure 6E) started as an oblique collision in the southeast affecting mainly the extended Fennian sequences. The transpressional tectonics can be observed as large-scale thrusting and margin-parallel E-W-trending shear zones (Figure 7C) in central Sweden and southern Finland. However, arc magmatism at 1.84–1.82 Ga (Mansfeld et al., 2005) is found in southern Sweden (OJB and BA in Figure 1). Thus, simultaneously with the collision in the southeast, a subduction regime was active at the southwestern margin (Figures 6E–F). A retreating Andean-type active margin at 1.85–1.80 Ga caused cyclic periods of subduction-type and marginal basin-type magmatism north (see above) and south of the Bergslagen area followed by terrane accretion (OJB in Figure 1) and final collision with an unknown microcontinent at 1.8 Ga (Figure 6F). One of the associated subduction zones is seen in BABEL B (A in Figure 5). The 1.81–1.77 Ga, NW-trending granitoids in southern Sweden, which belong to the older part of the Transscandinavian igneous belt (TIB1, Figures 1 and 5), are related to this stage.

The Nordic orogen includes the NNE-SSW-trending part of the 1.81–1.77 Ga TIB1 and related granitoids (Figure 1; Gorbatschev, 2004) and areas in central Sweden and Lapland affected by c. 1.8 Ga deformation. The granitoids resemble an Andean-type magmatic setting with an intruded batholith chain that presently occupies an area at least 800 km long and 100–200 km wide (Figure 7D). Lahtinen et al. (2005) proposed that the Nordic orogen resulted from a continent-continent collision between newly established Fennoscandia and Amazonia (Figure 6F). Another possibility is to interpret the Nordic orogen as an advancing Andean-type accretionary orogen, where the inboard deformation relates to retro-arc fold and thrust belts.

Younger TIB rocks occupy the western margin of Fennoscandia (TIB2 in Figure 1), where 1.71–1.67 Ga, N-S-trending batholiths and volcanic rocks discordantly truncate earlier WNW-ESE structural trends. Rocks of the Gothian orogen (c. 1.6 Ga) are present in the Sveconorwegian Province in parts of southwest Sweden and southern Norway. These rocks and parts of the TIB were heavily reworked during repeated orogenesis in the Meso- and Neoproterozoic (Andersson et al., 2002).

Greenland

Three roughly E-W-striking, Paleoproterozoic orogenies decreasing in age from north to south are found in Greenland (Figure 2). The deeply eroded Inglefield mobile belt, which straddles the north-western margin of Greenland and southeastern Ellesmere Island, is the northernmost and oldest of these orogens (Dawes, 2004). It is deeply eroded and mainly exposes intensely migmatised upper amphibolite to granulite facies paragneisses. A long-lived convergent orogenic stage accompanied by juvenile magmatism is documented by ≤ 2.0 Ga detrital zircon and syntectonic c. 1.95 Ga tonalites and diorites. Two late kinematic plutonic monzogranite and syenite complexes were emplaced at 1.92 Ga (Nutman et al., 2007).

The contiguous Rinkian fold belt and Nagssugtoqidian orogen in northern and central West Greenland, respectively (Figure 2), represent the northern and southern parts of a composite collisional orogen at ca. 1.88–1.83 Ga (Henderson and Pulvertaft, 1987; van Gool et al., 2002; Sidgren et al., 2006). The preceding arc magmatism is bracketed between 1.92 and 1.87 Ga. The northern part, the >600 km wide Rinkian fold belt, mainly comprises (meta)greywackes that were deposited unconformably on the Archean basement of the Rae craton (Figure 2; St-Onge et al., in press). The deformed unconformity can be used to trace large Paleoproterozoic structures in three dimensions: spectacular structures along steep fjord sides document first NE-, and then NW-directed tectonic transport by thrusting and recumbent isoclinal folding (Figures 8–9). The resulting flat-lying tectonic crustal structure favoured the development of huge late-stage, mid-crustal buckle folds during a final pulse of crustal shortening (Figure 10). The 1.87 Ga Prøven igneous complex in the central part of the Rinkian fold belt is a granitic laccolith with an Archean isotopic signature.

The 350 km wide Nagssugtoqidian orogen south of the Rinkian belt (Figure 2) consists of reworked Archean basement with some thrust and folded Paleoproterozoic rocks in its high-grade core. The c. 1.9 Ga Sisimiut and Arfersiorfik intrusive complexes have juvenile Paleoproterozoic isotopic signatures and were presumably fed from two parallel S-dipping subduction zones. The southern one is recognised as a suture in the core, and relicts of a northern suture probably occur in the transitional area between the Nagssugtoqidian and Rinkian belts around Ilulissat (Figure 2; Connelly et al., 2006).

The youngest Ketilidian orogen (c. 1.8 Ga), at the southern tip of Greenland, displays a convergent plate-tectonic system without subsequent collision (Garde et al., 2002). It mainly comprises a juvenile, c. 1.85–1.80 Ga, c. 30,000 km^2 calc-alkaline arc (Julianehåb batholith, Figure 2). The arc formed at the southern, rifted margin of the Archean North Atlantic craton during long-lived sinistral transpression due to northward subduction. A small relic of the oceanic plate may now be preserved as obducted tholeiitic pillow lava in the northwestern border zone of the orogen. Southeast of the Julianehåb batholith a fore-arc basin is preserved. Detrital zircon ages show that the basin was filled very rapidly at around 1.79 Ga

Figure 8 Tectonically stacked quartzite lenses of the lower Karrat Group in the central Rinkian fold belt, West Greenland, indicating top-NE tectonic transport. View northwest, north side of Kangilleq fjord. Cliff side approximately 250 m high.

Figure 9 Granulite-grade metasedimentary schist of the Karrat Group at Red Head (75°N) in the northern Rinkian fold belt, West Greenland. Asymmetric quartz pods viewed north, derived from boudinaged quartz veins, indicate top-W tectonic transport.

with immature detritus derived from the rising batholith. Immediately thereafter, the basin was deformed and subjected to HT-LP metamorphism and partial melting; numerous synkinematic, ultramafic to intermediate dykes in the fore-arc may represent a deeper heat source related to the subduction system. Continued heating of the lower crust resulted in crustal inversion whereby granites and syenites were extracted from the middle or lower crust and emplaced as huge, tabular rapakivi-textured bodies at c. 1.75–1.72 Ga, which were subsequently gently folded into crustal-scale domes and narrow cusps.

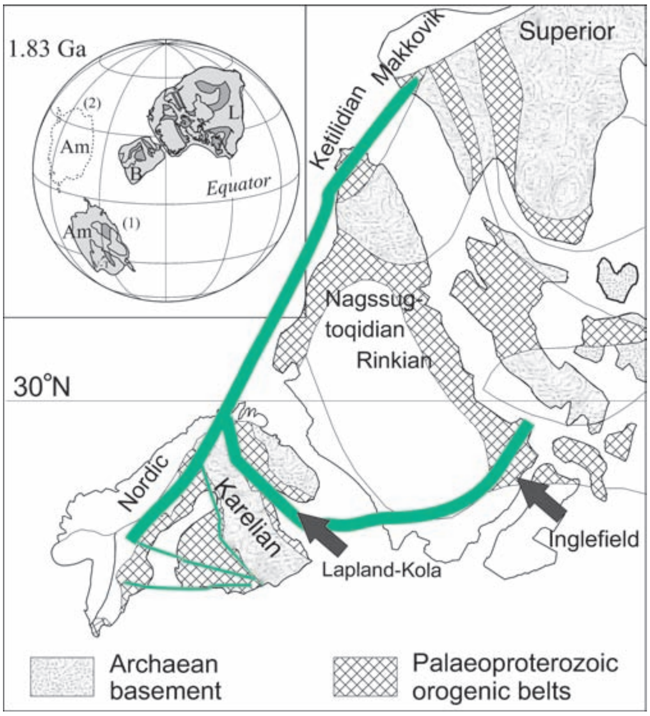


Figure 11 Correlation of Paleoproterozoic orogens in Greenland and Fennoscandia at the c. 1.8 Ga supercontinent stage. Thin green lines indicate the orogenic grains of the Lapland-Savo, Fennia and Svecobaltic orogens (see Figure 1). See St-Onge et al. (in press) for correlation between northeastern Canada and Greenland. The reconstruction of continents at 1.83 Ga is based on Pesonen et al. (2003). Am = Amazonia; B = Baltica; L = Laurentia.

Supercontinent stage

The global-scale network of Paleoproterozoic collisional orogens led to the formation of the Columbia/Hudsonia/Nuna supercontinent at c. 1.8 Ga (Zhao et al., 2002, 2004). Fennoscandia was located in the middle of this supercontinent and was surrounded by Laurentia in the northeast, Volgo-Uralia in the east, Sarmatia in the southeast, an unknown microcontinent in the southwest, and possibly Amazonia in the west (Lahtinen et al., 2005). Greenland is an essential part of Laurentia, and the Paleoproterozoic orogens in Greenland correlate well with Paleoproterozoic orogens in eastern Canada (St-Onge et al., in press). Correlations towards Fennoscandia are more problematic, not least due to the intervening Caledonian orogen. The Inglefield mobile belt and the Rinkian fold belt/Nagssugtoqidian orogen are both collision zones of Archean cratons, in which only a limited amount of Paleoproterozoic juvenile crust was formed and preserved. Similar collision zones in Fennoscandia are the Lapland-Kola orogen and the northern segment of the Lapland-Savo orogen. The collision age of the Inglefield mobile belt (c. 1.95–1.92 Ga) coincides with that of the Lapland-Kola orogen, and they are tentatively correlated with each other (Figure 11). The 1.88–1.83 Ga Rinkian fold belt/Nagssugtoqidian orogen is considerably younger than the Lapland-Kola orogen and partly overlaps in age with the Fennian and Svecobaltic orogens. However, the reworked Archean crust in the Rinkian fold belt/Nagssugtoqidian orogen, when compared with the major Paleoproterozoic accretionary crust in the two orogens in Fennoscandia does not favor correlation. The most obvious correlation is between the c. 1.8 Ga Ketilidian and Nordic orogens (Figure 11; Karlstrom et al., 2001), which both are characterized by linear Andean-type batholiths of similar age.

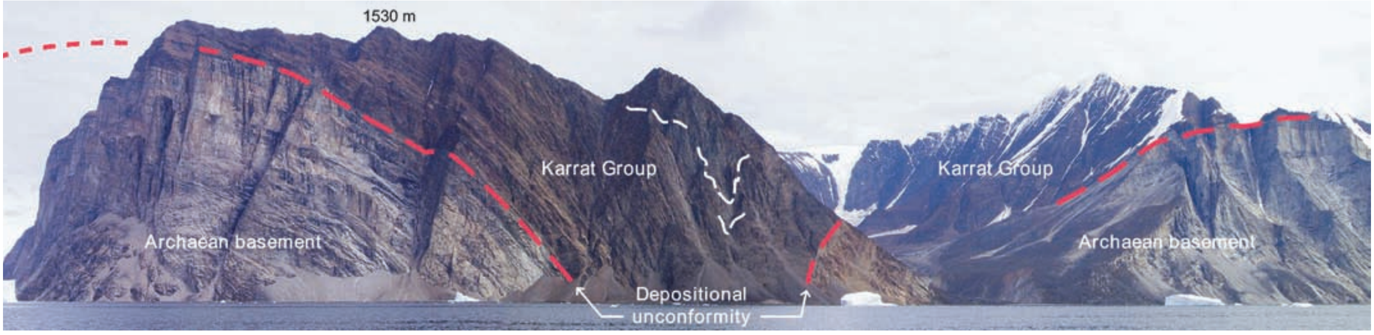


Figure 10 Dome-shaped anticlines and synclinal cusp of basement and cover ('Snepyramiden dome') in the central Rinkian fold belt, West Greenland: an example of crustal-scale, late-stage buckle folding of tectonically layered middle crust.

Conclusions

Fennoscandia and Greenland exemplify two major Paleoproterozoic events, the first of which is the prolonged rifting of Archean crust (part of a presumed supercontinent), which finally led to continental breakup at 2.1–2.04 Ga. The second event is formation of major new continental crust and reworking of older crust by accretionary and collisional orogens at 2.0–1.8 Ga, which finally led to formation of a new supercontinent at 1.8 Ga. The continental collision of Archean cratons in Greenland and northern Fennoscandia is characterised by large and wide orogenic roots which largely comprise reworked Archean crust and its cover, with only a minimum of juvenile material formed and preserved. Crustal growth in these cases is mainly seen in the derived sediment (e.g., Claesson et al., 1993; Kalsbeek et al., 1998; Lahtinen et al., 2002). The composite Svecofennian orogen forms a large Paleoproterozoic unit of new crust, covering c. 1 mill. km^2. It comprises 2.1–2.0 Ga microcontinents with unknown previous histories of evolution, juvenile arcs from >2.02 to ~ 1.8 Ga, and Andean-type vertical magmatic additions at 1.9–1.8 Ga, both in South Greenland and Fennoscandia. Subduction-related, folded rapakivi-textured granitoids at c. 1.75–1.72 Ga in South Greenland contrast with rifting-related rapakivi granites in Fennoscandia at 1.65–1.54 Ga.

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The Mesoproterozoic in the Nordic countries

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During the Mesoproterozoic, central Fennoscandia and Laurentia (Greenland) were characterized by a weakly extensional stress regime, as evident from episodic rapakivi granites, dolerite dykes, continental rift intrusives, sandstone basins and continental flood basalts. Along the southwestern active margin of Fennoscandia, the 1.64–1.52 Ga Gothian and 1.52–1.48 Ga Telemarkian accretionary events resulted in oceanwards continental growth. The 1.47–1.42 Ga Hallandian-Danopolonian event included high-grade metamorphism and granite magmatism in southern Fennoscandia. The pre-Sveconorwegian 1.34–1.14 Ga period is characterized by bimodal magmatism associated with sedimentation, possibly reflecting transcurrent tectonics. The Sveconorwegian orogeny involved polyphase imbrication of terranes between 1.14 and 0.97 Ga, as a result of a collision between Baltica and another major plate, followed by relaxation and post-collisional magmatism between 0.96 and 0.90 Ga. Recent geologic data support classical models restoring the Sveconorwegian belt directly to the east of the Grenville belt of Laurentia at 1.0 Ga. Fragments of Paleo- to Mesoproterozoic crust showing late Grenvillian-Sveconorwegian (1.00–0.92 Ga) magmatism and/or metamorphism are exposed in several tectonic levels in the Caledonides of Scandinavia, Svalbard and East Greenland, on both sides of the inferred Iapetus suture. Linking these fragments into a coherent late-Grenvillian tectonic model, however, require additional study.

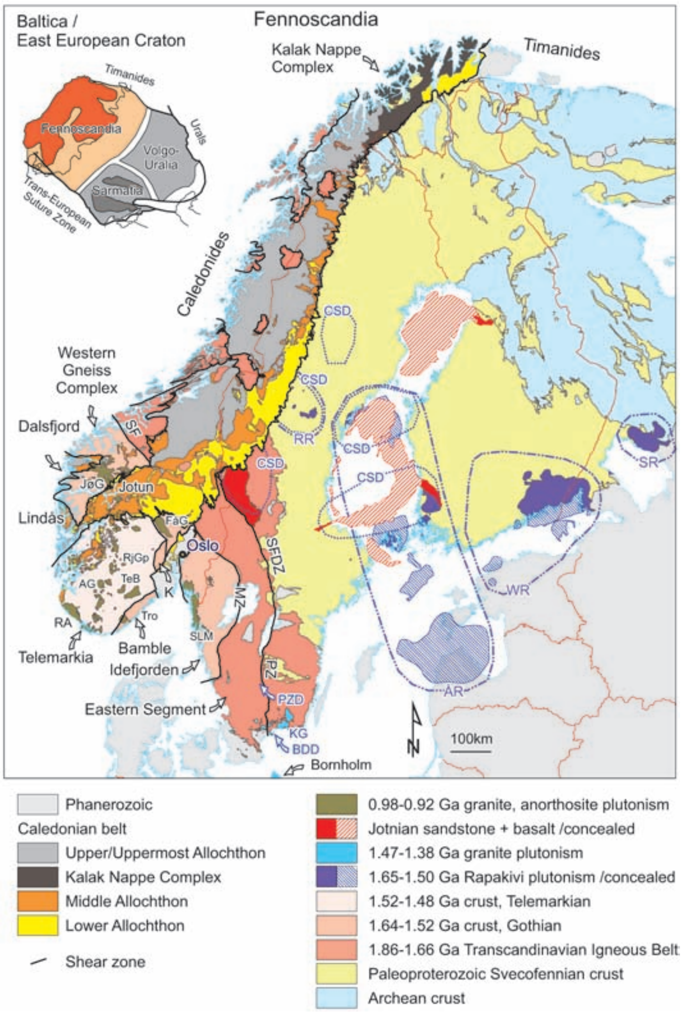

***Figure 1** Sketch map of Fennoscandia in a Mesoproterozoic context. Abbreviations: ÅR: 1.59–1.56 Ga Åland rapakivi suite. AG: 0.97–0.95 Ga Agder post-collision granites; BDD: 0.98–0.95 Ga Blekinge-Dalarna dolerites; CSD: 1.27–1.25 Ga Central Scandinavian Dolerite Group; FåG: 0.93–0.92 Ga Flå, Bohus post-collision granites; JøG: 0.96–0.93 Ga Jøstler, Hafslo post-collision granite plutons; K: Kongsberg terrane; KG: 1.45 Ga Karlshamn granite; MZ: Mylonite Zone; PZ: Protogine zone; PZD: 1.22–1.20 Ga Protogine Zone dolerite and granites; RA: 0.93 Ga Rogaland anorthosite-mangerite-charnockite complex; RjGp: 1.51–1.50 Ga Rjukan group bimodal volcanic rocks; RR: 1.53–1.50 Ga Ragunda rapakivi suite; SFDZ: Sveconorwegian Frontal Deformation Zone; SF: Sveconorwegian Front in Western Gneiss Complex; SLM: 1.57 Ga Stora Le-Marstrand formation; SR: 1.55–1.53 Ga Salmi rapakivi suite; TeB: 1.28–1.14 Ga Telemarkia bimodal magmatism; Tro: 1.20–1.18 Ga Tromøy gabbro-tonalite complex, Bamble; WR: 1.65–1.61 Ga Wiborg rapakivi suite.*

Principal Mesoproterozoic lithotectonic domains

Fennoscandia (the Fennoscandian shield) represents the northwestern part of Baltica or the East European Craton. At the start of the Mesoproterozoic, it consisted of Archean core (Karelia and Murmansk cratons) surrounded by Paleoproterozoic Svecofennian domains (sensu lato) intruded by the Transcandinavian Igneous Belt (TIB, Figure 1). During the Mesoproterozoic, the centre of Fennoscandia hosted episodic continental magmatism. The Timanian margin in the northeastern was passive, while the southwestern margin was active and the location of substantial continental growth. A regional metamorphic event, the Hallandian or Danopolonian orogeny is recorded in the southern part of Fennoscandia. Greenland was part of Laurentia. It is mainly made up of an Archean to Paleoproterozoic craton and contains only a minor Mesoproterozoic component.

At the end of the Mesoproterozoic, the southwestern margin of Fennoscandia was reworked during the Sveconorwegian orogeny, producing the c. 500 km wide Sveconorwegian orogenic belt (Figure 1). This belt is made up of five principal lithotectonic domains/segments, separated by Sveconorwegian crustal-scale shear zones. The easternmost domain, the Eastern Segment, exposes reworked lithologies of the TIB. West of the Mylonite Zone, a major Sveconorwegian lithotectonic terrane boundary, the Idefjorden, Kongsberg, Bamble and Telemarkia terranes are allochthonous and mainly the product of Mesoproterozoic continental growth (Bingen et al., 2005). Though most available evidence supports that they were marginal or attached to Fennoscandia during the Mesoproterozoic, models involving terrane accretion during the Sveconorwegian orogeny are plausible.

Late Grenvillian-Sveconorwegian overprint is detected in several units at different tectonostratigraphic levels in the Paleozoic Caledonides of East Greenland, Svalbard and Scandianavia (Figures 1, 2, 3). These rocks carry an important testimony for the understanding of the Mesoproterozoic, but are difficult to read, due to uncertainties in the Caledonian history.

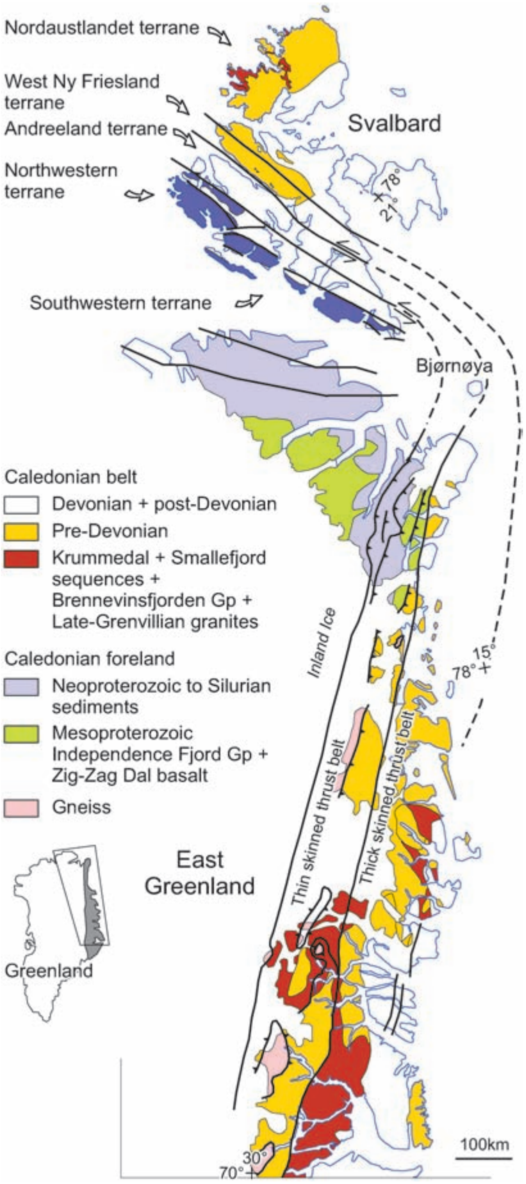

Figure 2 Sketch map of the Caledonian margin of Laurentia. Svalbard is reconstructed following Gee and Teben'kov (2004).

Mesoproterozoic events in Fennoscandia

1.65–1.50 Ga Rapakivi magmatism

Granite with a rapakivi texture, i.e. plagioclase mantling K-feldspar phenocrysts, are diagnostic of a number of shallow, non-foliated, dominantly felsic, plutons/batholiths intruded in central Fennoscandia (Figure 1; Haapala et al., 2005). Four rapakivi suites are distinct in time and space: from east to west, (1) the 1.55–1.53 Ga Salmi suite, (2) 1.65–1.61 Ga Wiborg suite, (3) 1.59–1.56 Ga Åland suite, and (4) 1.53–1.50 Ga comparatively small plutons of the Ragunda suite in central Sweden. Rapakivi plutonism overlaps in time with intrusion of dolerite dykes and sills in Sweden and Finland and a large anorthosite complex, the 1.53–1.50 Ga Mazury complex in Poland. The rapakivi granites and related magmatism reflects an intracontinental extensional setting.

1.64–1.52 Ga Gothian accretion

The Idefjorden terrane, and parts of the Bamble and Kongsberg terranes, west of the Mylonite zone (Figure 1), are made up of 1.64–1.52 Ga plutonic, volcanic and sedimentary rocks. The magmatic rocks have a juvenile calc-alkaline geochemical signature typical for an active margin setting. Some tholeiitic mafic metavolcanic rocks with oceanic volcanic arc signature and some metasediments showing a restricted zircon provenance pattern suggest that at least part of the island arc sequence formed off-board of a Paleoproterozoic continent.

The Gothian event relates to the 1.64–1.52 Ga geological evolution in the Idefjorden terrane (Figure 4) and can be classified as an accretionary event. The lithologies exposed in the Idefjorden terrane can be interpreted in the context of a single, progressively maturing, volcanic arc, variably-distal to Fennoscandia (Andersen et al., 2004), or as several volcanic arcs accreted shortly after formation. Due to Sveconorwegian overprint, structures related to the Gothian event prove difficult to trace at any large scale. Gothian amphibolite-facies structures are locally observed, but robust age constraints on Gothian metamorphism are lacking.

1.52–1.48 Ga Telemarkian accretion

The southwesternmost Sveconorwegian terrane, the Telemarkia terrane (Figure 1), can be divided into four sub-domains, the Telemark, Hardangervidda, Suldal and Rogaland-Vest Agder sectors. These sectors show distinct lithologies and metamorphic overprint, but share a common record of voluminous 1.52–1.48 Ga magmatism. This continental building event is here referred to as the Telemarkian (Figure 4). The geochemistry of the 1.52–1.48 Ga magmatic suites is poorly characterized, except for the Rjukan Group bimodal volcanics in Telemark, which show a continental rift signature. The magmatic rocks are overlain by quartzites, containing abundant Paleoproterozoic and Archean clastic material. This implies proximity of an evolved continent. Formation of the Telemarkia terrane at 1.52–1.48 Ga is probably best interpreted in the context of a continental arc.

1.47–1.42 Ga Hallandian and Danopolonian orogenies

In central Fennoscandia, rapakivi intrusives are unconformably overlain by an up to 800 m thick, cover of continental sandstone, the Jotnian sandstones (Figure 1). These are preserved in undeformed basins and interlayered with a c. 100 m thick tholeiitic basalt, showing geochemical similarity with rift-related or continental flood basalt. Some 1.46 Ga dolerites may represent feeder to the basalts.

Contrasting with the extensional regime in central Fennoscandia, the south-southwestern margin (southern Sweden, Bornholm and the concealed basement of Lithuania and Poland) was the loca-

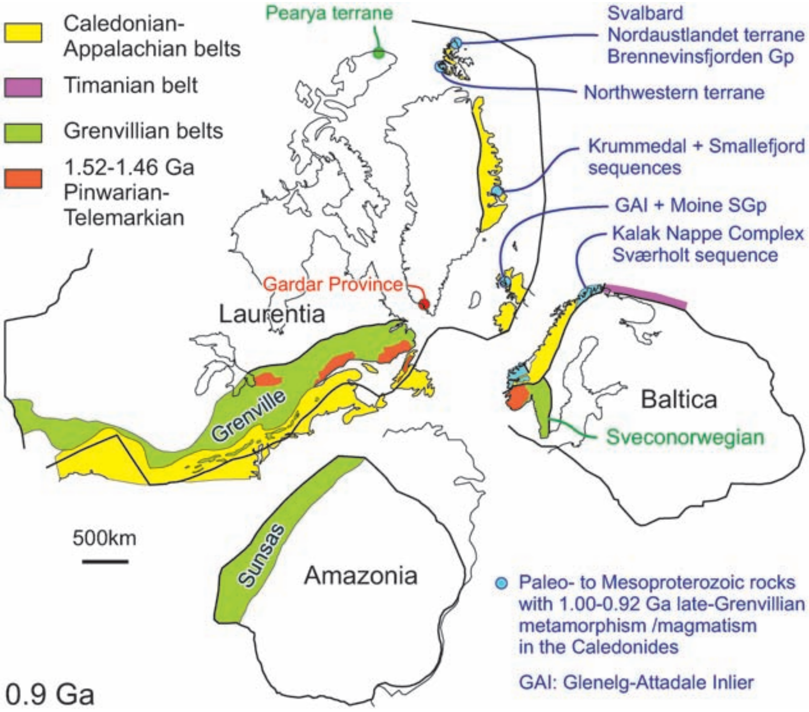

***Figure 3** Classical Baltica-Laurentia-Amazonia paleogeographic reconstruction at the end of the Mesoproterozoic, following Cawood et al. (2007).*

tion of volumetrically limited but widespread granite magmatism between 1.46 and 1.44 Ga, as well as an orogenic event, referred to as the Hallandian or Danopolonian orogeny (Figures 1, 4). The Hallandian is defined in the Eastern Segment of the Sveconorwegian belt and its eastern boundary, the Protogine zone. It is characterized by 1.46–1.42 Ga amphibolite-facies metamorphism, associated with regional scale migmatitization and locally gneissic layering (Möller et al., 2007). The Danopolonian is defined outside of the Sveconorwegian belt. Evidence for Danopolonian deformation includes syn-intrusion deformation in 1.45 Ga plutons in southern Fennoscandia and 1.49–1.45 Ga ^{40}Ar/^{39}Ar hornblende ages from drill cores in Lithuania possibly related to large E-W trending shear zones. The relation between the Hallandian and Danopolonian events and the significance of the Hallandian-Danopolonian as a large scale orogenic event are difficult to assess today. It may be related to a collision, reworking the south-southwestern margin of Fennoscandia, or to a change in subduction geometry in an active margin setting.

1.34–1.14 Ga Pre-Sveconorwegian interval

In central Fennoscandia, the extensive Central Scandinavian Dolerite Group formed around five magmatic complexes, formed in three distinct pulses between 1.27 and 1.25 Ga (Figure 1). It may record hotspot activity or back-arc extensional setting (Söderlund et al., 2006).

The allochthonous Sveconorwegian terranes are characterized by abundant pre-Sveconorwegian 1.34–1.14 Ga bimodal magmatism, variably interlayered with clastic sediments showing rapid lateral variation and local unconformities. The Bamble terrane hosts the 1.20–1.18 Ga Tromøy gabbro-tonalite complex (Figure 1). The geotectonic setting prevailing in the Sveconorwegian terranes before the Sveconorwegian orogeny is controversial. The tholeiitic Tromøy complex is interpreted as the remnants of an immature island arc accreted at an early stage of the Sveconorwegian orogeny. Bimodal magmatic suites associated with sedimentary basins can be interpreted in the context of an extensional or transtensional regime located in a continental arc, continental back-arc or Basin and Range environment. Large scale transcurrent movements of the Sveconorwegian terranes probably took place before and during the Sveconorwegian orogeny. This is compatible with the lack of evidence for Hallandian or Danopolonian overprint in these terranes.

1.14–0.90 Ga Sveconorwegian orogeny

Sveconorwegian high-grade metamorphism is dated between 1.14 and 0.90 Ga, defining the total duration of this orogeny. The Sveconorwegian orogeny is interpreted as a polyphase imbrication of terranes at the margin of Fennoscandia between 1.14 and 0.97 Ga, as a result of a continent-continent collision. Collision was followed by relaxation between 0.96 and 0.90 Ga. Syn- and post-collision magmatism increases dramatically towards the west.

Early-Sveconorwegian 1.14–1.08 Ga amphibolite- to granulite-facies metamorphism is observed in the Bamble and Kongsberg terranes (Arendal phase; Figure 4). These terranes form two tectonic wedges between the Idefjorden and Telemarkia terranes. The 1.14–1.08 Ga metamorphism may record early-Sveconorwegian collision between the Idefjorden and Telemarkia terranes, possibly involving accretion of the Tromøy arc. At 1.05 Ga, crustal thickening and deformation propagated towards the Idefjorden and Telemarkia terranes (Agder phase; Figure 4). The Idefjorden terrane is characterized by 1.05–1.02 Ga greenschist to amphibolite facies metamorphism, locally reaching high-pressure granulite-facies conditions and by several orogen-parallel shear zones interpreted as oblique thrusts. In the Telemarkia terrane, 1.05 Ga syn-collision crustal melting was followed by regional metamorphism between 1.03 and 0.97 Ga, peaking in granulite-facies conditions in the Rogaland-Vest Agder

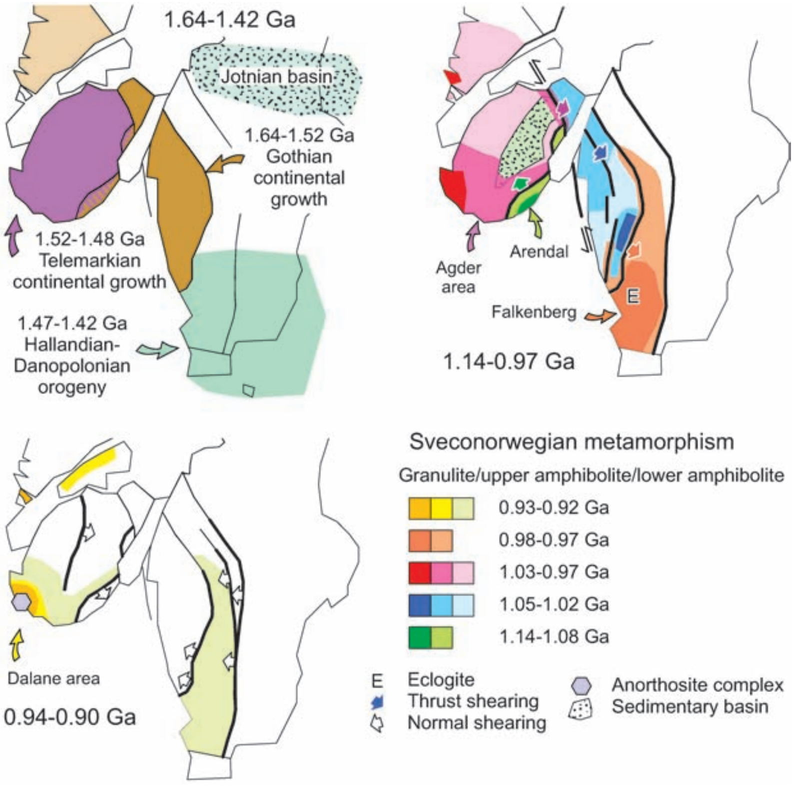

***Figure 4** Schematic distribution of orogenic and metamorphic events affecting the southwestern margin of Fennoscandia during the Mesoproterozoic.*

sector (Figures 4, 5). At 0.98 Ga, the orogeny propagated further towards the east to include the Eastern Segment (Falkenberg phase; Figure 4). In the core of the high-grade domain, high-pressure granulites and retrogressed eclogites attest to burial of large parts of the Eastern Segment to a depth of at least 35 km at 0.97 Ga, with simultaneous tectonic emplacement of an even deeper eclogite-bearing unit. Eclogite formation was shortly followed by exhumation.

After 0.97 Ga, the Sveconorwegian belt progressively collapsed probably in a dominantly extension regime (Dalane phase, Figure 4). The 0.98–0.95 Ga Blekinge-Dalarna dolerites intruded the foreland of the belt (Figure 1; Söderlund et al., 2005). The Eastern Segment is characterized by prominent folds reflecting crustal flow associated with exhumation of the high-pressure rocks (Möller et al., 2007). In the Rogaland-Vest Agder sector, Telemarkia terrane, 0.97–0.95 Ga post-collision granite magmatism is associated with regional decompression. A final voluminous pulse of plutonism, at 0.93–0.92 Ga, includes the Rogaland anorthosite complex (Figure 1) and spatially related high temperature-low pressure metamorphism. The Rogaland-Vest Agder sector can be interpreted as a large scale gneiss dome formed between 0.97 and 0.92 Ga, bringing hot ductile crust and plutonism to a shallow level (2–4 kbar) (Bingen et al., 2006).

Figure 5 Overview of the Knaben Mo-district in southern Norway, mined up to 1973. Widespread syn-collision granite magmatism took place during the Sveconorwegian orogeny in the Telemarkia terrane. In Knaben, intrusion of a 1.02 Ga granite plug is associated with deposition of molybdenite.

Mesoproterozoic events in Greenland (Laurentia)

1.38 Ga Zig-Zag Dal basalt magmatism

In North Greenland, Paleo- to Mesoproterozoic sandstones of the Independence Fjord Group overly a concealed crystalline basement (Figure 2). The sandstone sequence hosts numerous 1.38 Ga mafic intrusions known as the Midsommersø dolerites. The sandstone sequence is conformably overlain by an up to 1350 m thick tholeiitic flood basalt, the Zig-Zag Dal basalt. This basalt probably results from ascent of a mantle plume (Upton et al., 2005).

1.28–1.14 Ga Gardar province

The Gardar Province occupies a ENE trending rift structure in the Paleoproterozoic Ketilidian orogen of South Greenland (Figure 3). It consists of alkaline 1.28–1.14 Ga mafic dykes, syenite to nepheline syenite plutons and minor lamprophyre and carbonatite intrusions. The plutons are associated with a fault-bounded sediment and volcanic basin. An older 1.35 Ga intrusive phase is possible. The Gardar province is part of widespread evidence for Mesoproterozoic intracontinental extension in Laurentia.

Mesoproterozoic rocks in the Caledonides

East Greenland

In East Greenland, the Caledonides divide into two allochthonous belts (thin and thick skinned) transported westwards onto the Laurentia basement (Figure 2; Higgins et al., 2004). Each of them is made of several nappes, and both of them are regarded as endemic to Laurentia before the Caledonian orogeny. Psammitic paragneisses of the Krummedal and Smallefjord sequences are exposed in both allochthonous belts. They were deposited after c. 1.00 Ga and contain abundant Mesoproterozoic detrital zircons. They are affected by a 0.95 Ga late-Grenvillian medium to high-grade metamorphism, intruded by 0.94–0.92 Ga granitoids and overlain by a thick Neoproterozoic shallow-marine sequence (the Eleonore Bay Supergroup).

Svalbard

Svalbard is reconstructed north of Greenland before the Cenozoic opening of the North Atlantic. Following Gee and Teben'kov (2004), the Svalbard Caledonides represent the direct along strike extension of the East Greenland Caledonides (Figure 2). Svalbard's pre-Devonian bedrock divides into five terranes, from east to west, the Nordaustlanded, West Ny Friesland, Andréeland, Northwestern and Southwestern terranes.

In the Nordaustlandet terrane, the lowermost exposed stratigraphic unit is the metasedimentary Brennevinsforden group, deposited after 1.05 Ga, on top of an unknown basement. It is intruded by 0.96–0.93 Ga granites and overlain by 0.96 Ga rhyolites. The rhyolites are unconformably overlain by the Neoproterozoic Murchisonfjorden supergroup. The Brennevinsforden group correlates well with the Krummedal-Smallefjord sequence in East Greenland.

The Western Ny Friesland terrane consists of a Paleoproterozoic basement overlain by Mesoproterozoic quartzite hosting ca. 1.3 Ga dykes. It lacks Grenvillian overprint. The Northwestern and Southwestern terranes in Spitsbergen show a poorly characterized Mesoproterozoic basement intruded by 0.96 Ga granites. These terranes have affinity with the Pearya terrane exposed on Ellesmere Island, Arctic Canada.

Scandinavian Caledonides

The Scandinavian Caledonides (Figure 1) consist of four levels of thrust sheets, transported eastwards onto the Fennoscandia platform. They are referred to as the Lower, Middle, Upper and Uppermost Allochthons. The Lower and Middle Allochthons are generally considered endemic to Fennoscandia before the Caledonian orogeny. The lower part of the Upper Allochthon has a disputed origin (endemic vs. exotic), while the upper part of the Upper Allochthon and the Uppermost Allochthon are regarded as exotic terrains with an Iapetus Ocean or Laurentian ancestry.

The Western Gneiss Complex (Figure 1) is a large basement window in western Norway, interpreted as Fennoscandia Paleoproterozoic crust below the Caledonian nappes. The southern part of the Western Gneiss Complex is affected by a 0.99–0.95 Ga Sveconorwegian metamorphic overprint and 0.96–0.93 Ga granite magmatism (Figures 1, 3, 4). The front of Sveconorwegian reworking in the Western Gneiss Complex (SF in Figure 1) is approximately aligned with the Sveconorwegian Frontal Deformation Zone southeast of the Caledonian nappe front (SFDZ in Figure 1). Consequently the Western Gneiss Complex is commonly correlated with the Eastern Segment. In detail, this correlation nevertheless suffers from a number of shortcomings.

The crystalline Lindås, Dalsfjord and Jotun Nappes are located in the Middle Allochthon in western Norway (Figures 1, 3). They are made up of Paleo- to Mesoproterozoic crystalline rocks. They show late-Sveconorwegian 0.95–0.92 Ga metamorphism and 0.95 Ga anorthosite magmatism (Figure 4; Lundmark et al., 2007).

The Kalak and Seve Nappe Complexes are attributed to the lower part of the Upper Allochthon (Figure 1). The lower metasediment sequence in the Kalak nappes, the Særholt sequence, was deposited after 1.03 Ga and intruded by 0.98–0.97 Ga granite after a deformation phase (Kirkland et al., 2007). Metasediments of the Kalak and Seve nappes contains abundant populations of Grenvillian and older Mesoproterozoic detrital zircons. The Kalak and Seve Nappe Complexes are generally interpreted as part of the Neoproterozoic passive margin of Fennoscandia during opening of Iapetus. Recent data, nevertheless, underscore the similarities between the Særholt sequence in the Kalak Nappe Complex and the Krummedal-Smallefjord sequences and Brennevinsfjorden group in East Greenland and Svalbard (Figure 3). This rather suggests a common exotic origin for these three units.

On the road to Rodinia?

Classical paleogeographic models restore Baltica in a variety of configurations to the east of Laurentia for most of the Mesoproterozoic and Neoproterozoic (Figure 3). Large scale geotectonic interpretations picture a common long-lived active continental margin during the Mesoproterozoic for the two plates, facing the southeast for Laurentia and southwest for Baltica (Karlstrom et al., 2001; Cawood et al., 2007; Bogdanova et al., 2007). Periods of advancing subduction boundary, retreating subduction boundary or change in subduction geometry account for the diversity of tectonic regimes and rock assemblages along this margin. The summary presented in this paper shows that it is possible to interpret the Mesoproterozoic geology of Fennoscandia in this unifying model.

At the end of the Mesoproterozoic, the Grenville orogeny, sensu lato, involved collision of a number of continents at planetary-scale and allegedly resulted in assembly of the Rodinia supercontinent. The configuration of Rodinia is, however, speculative. Following classical models, the Laurentia-Baltica active margin collided with another major plate, presumably Amazonia, to form the Grenville belt, sensu stricto, in Laurentia, and the Sveconorwegian belt in Baltica. Formation of the Grenville-Sveconorwegian belt, extending from Texas to Sweden, by collision with the comparatively small Amazonia would, however, require large-scale transcurrent movement of Amazonia.

The classical Baltica-Laurentia-Amazonia reconstruction (Figure 3) for the Mesoproterozoic to Neoproterozoic is disturbing, as it features Baltica and Laurentia at almost exactly the same relative position at two occasions in the past, namely after the Grenvillian orogeny and after the Caledonian orogeny. Such a coincidence would imply a simple Wilson cycle between the two orogenies, a fact hardly compatible with the inferred large drift of Baltica during the Phanerozoic and with the complexity of the Caledonian orogenic belt. Nevertheless, as a matter of fact, recent geologic-geochronologic data support the link between the Grenville and Sveconorwegian belts, and thus support classical Neoproterozoic Laurentia-Baltica reconstruction. For example, (1) Voluminous 1.5 Ga plutonism, volcanism and clastic sediment basin formation are remarkably similar in the eastern Grenville province (the Pinwarian event) and the Telemarkia terrane (the Telemarkian event) (Figure 3). (2) The two belts and their foreland share a phase of continental, mainly mafic, magmatism, between 1.28 and 1.23 Ga (Söderlund et al., 2006). (3) While early Grenvillian metamorphic phases are diachronous in the two belts (1.24–1.22 Elzevierian, 1.19–1.14 Ga Shawinigan and 1.14–1.08 Ga Arendal phases), the main Grenvillian convergence-related metamorphic phases overlap. These are the 1.08–1.02 Ga Ottawan and 1.01–0.98 Ga Rigolet phases in the Grenville belt overlapping with the 1.05–0.98 Ga Arendal and 0.98–0.97 Ga Falkenberg phases in the Sveconorwegian belt. Especially significant is the coeval character of high-pressure 1.06–1.04 Ga metamorphism.

Late-Grenvillian in the Caledonides

Fragments of Paleo- to Mesoproterozoic crustal domains showing a late-Grenvillian metamorphic overprint and/or hosting late-Grenvillian intrusive rocks are detected along the whole length of the Caledonides, not only in the Nordic countries, as reviewed above, but also in Scotland (Glenelg-Attadale Inlier and Moine supergroup) (Figure 3). These fragments are situated on both sides of the main Caledonian (Scandian) suture zone, as defined by Iapetus related ophiolite complexes (Upper-Uppermost allochthons), and they are hosted in short- as well as far-travelled nappes. Two trends emerge though available data are sparse. (1) The timing of overprint in these fragments is typically in the interval between 1.00 Ga and 0.92 Ga and thus corresponds to the last increment of convergence and to the post-convergence relaxation in the Grenville and Sveconorwegian belts sensu stricto. (2) The Krummedal-Smallefjord sequences, Brennevinsfjorden group and the Særholt sequence (Kalak Nappe Complex), represent accumulation of thick sediment packages in late-Mesoproterozoic basins, overlain by thick Neoproterozoic sediment sequences. These features contrast with the scarcity of late-Mesoproterozoic to Neoproterozoic sediments in the Grenville and Sveconorwegian belts sensu stricto.

The different fragments of crust hosted in the Caledonides recording late-Grenvillian magmatism and/or metamorphism could be interpreted as the remnants of a coherent Grenvillian orogenic belt, branching northwards from the main Grenvillian-Sveconorwegian belt along the axis of the Caledonides (Figure 3). A northwards trending branch could result from final transpressional imbrication of Amazonia into Baltica, generating locally thick sediment sequences and magmatism. Nevertheless, several arguments prompt caution. The occurrence of late-Grenvillian rocks in Taimyr (Central Belt) and Ellesmere Islands (Pearya terrane) outside of the Caledonian belt may attest to an independent late-Grenvillian orogenic tract in the Arctic, possibly representing an alternative origin for these fragments. Also, the Kalak Nappe Complex shows evidence for Neoproterozoic magmatism and deformation, suggesting a possible link with the Timanian belt or peri-Gondwana terranes rather than the Grenville and Sveconorwegian belts sensu stricto. Further study of the Mesoproterozoic and Neoproterozoic sequences captured in the Caledonides and the relations between the Caledonian belt, Timanian belt and other orogenic belts in the Arctic is required to understand the significance of the late-Grenvillian record in the Caledonides.

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Neoproterozoic basin evolution in Fennoscandia, East Greenland and Svalbard

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Neoproterozoic successions of Fennoscandia, East Greenland and Svalbard are related to crustal extension and formation of sedimentary basins along the margins of northern Baltica (Fennoscandia) and eastern Laurentia (East Greenland and Svalbard), preceding final break-up of Rodinia. The early rift stage (late Tonian-Cryogenian) is characterized by up to 16 km thick sedimentary successions of deep-marine sandstones and conglomerates linked to rift and strike-slip basins. Pericratonic basins expanded during Cryogenian–Cambrian coastal onlap. Cryogenian tropical climate is reflected by carbonate and evaporitic formations, most of which predate Cryogenian-Ediacaran glaciations. Glacial units, collectively referred to the Varanger Ice Age, may be equivalent to the Marinoan (c. 630 Ma) and the Gaskiers (c. 580 Ma) glacial periods. The final stage in break-up of Rodinia commenced with the emplacement of dolerite dyke swarms along the Baltoscandian margin at c. 600 Ma and the opening of the Iapetus Ocean and other sea ways. No such dyke swarms have been recorded along the East Greenland segment of the Laurentian margin. Several Tonian-Cambrian tectonic and magmatic events recorded within the Kalak Nappe Complex in northern Finnmark make this unit an exotic terrane relative to the autochthonous Baltoscandian platform.

Introduction

The Neoproterozoic comprises the Tonian (1,000–850 Ma), Cryogenian (850–630 Ma) and the Ediacaran (630–542 Ma) of Gradstein et al. (2004). In northern Europe, the Russian terms Riphean and Vendian have previously been used, corresponding approximately to Mesoproterozoic+Tonian+Cryogenian and the Ediacaran, respectively. During the Cryogenian and Ediacaran, between c. 825 and 600 Ma, the supercontinent Rodinia broke up into several large and small plates. One of these, *Baltica,* includes the present Fennoscandian Shield (e.g., Pease et al., 2008). Major neighbouring plates were Laurentia and Amazonia (Li et al., 2008) (Figure 1).

The Fennoscandian part of Baltica was limited by the Timanian margin to the northeast and the Baltoscandian margin towards the northwest and west (referring to present coordinates); both margins hosted Neoproterozoic successions. Neoproterozoic strata in East Greenland and Svalbard were deposited along the eastern margin of Laurentia. These successions are correlated by achritarch stratigraphy (Vidal, 1985; Knoll and Walter, 1992). The Neoproterozoic rocks were variably affected by deformation and metamorphism within the Timanian and Caledonian orogenic belts. Reconstruction of the Neoproterozoic basin configuration requires restoration of Caledonian nappe displacements, strike-slip movements along plate margins and Cenozoic sea-floor spreading in the North-Atlantic and Arctic domains. Neoproterozoic successions in the Scandinavian Caledonides are described according to their tectonostratigraphic position as Autochthon, Lower, Middle and Upper Allochthons (Gee et al., 1985a). The objectives of this review are to emphasise basin evolution and controlling factors such as tectonics, climate and sea-level changes. The review starts at the Timanian margin in eastern Finnmark of Arctic Norway; it then proceeds from Autochthon to Upper Allochthon in the Caledonides and from north to south in Scandinavia, before describing the East Greenland and Svalbard successions (Figure 2). Summeries of the Neoproterozoic successions in the different areas and their correlations are shown in Figure 3. Discussion of Tonian orogenic and igneous activity within the Sveconorwegian (Grenvillian) orogenic belts in southwestern Fennoscandia and Svalbard and Eastern Greenland is beyond the scope of this paper and described elsewhere in this volume.

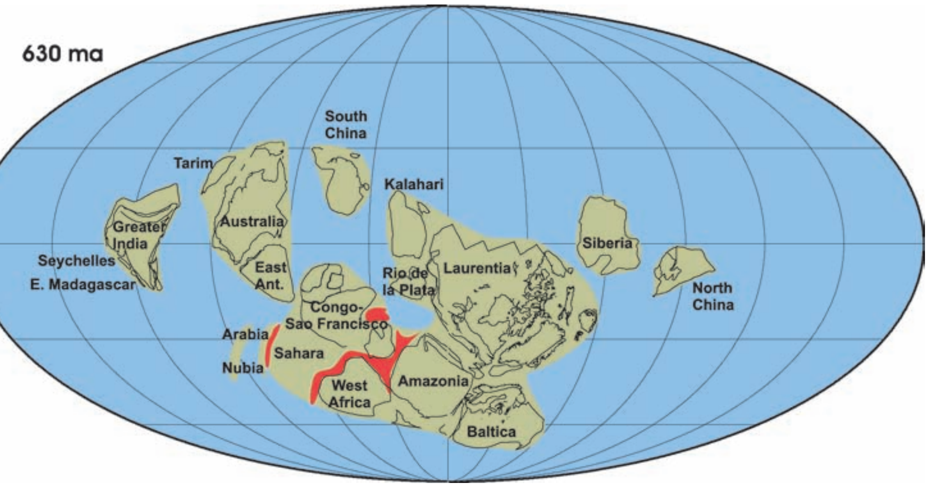


***Figure 1** Plate reconstruction showing relative position of Baltica and Laurentia at 630 Ma. From Li et al. (2008).*

Timanian margin: Eastern Finnmark

The Neoproterozoic sedimentary rocks at Tanafjorden and the Varanger Peninsula in eastern Finnmark (Figure 2) are important reference successions for the global Neoproterozoic stratigraphy. The strata were deposited along the Timanian margin of northeastern Baltica, from about 1000 Ma until the end of Ediacaran.

The WNW-ESE-trending Trollfjorden-Komagelva Fault Zone (TKFZ) divides the Varanger Peninsula into the Tanafjorden-Varangerfjorden Region (TVR) to the southwest and the Barents Sea Region (BSR) to the northeast. The fault zone continues into Russia along the northern coast of Kola Peninsula and the Pechora Basin, forming here the south-western margin of the Timanian Basin (c. 1000–630 Ma) and the foreland of the Timanian orogenic belt (c. 590–540 Ma). Towards the northwest, the TKFZ probably intersected the Baltoscandian margin in a triple junction (Siedlecka et al., 2004). Caledonian thrust tectonics and the Timanian orogeny affected the sedimentary succession on both sides of the TKFZ, the Caledonian deformation being most pronounced in the northwest. The Ediacaran strata at Tanafjorden close to the front of the Gaissa Nappe Complex (see below) pass into Cambrian beds. The successions beside Varangerfjorden rest on denudated Baltica basement rocks.

The Barents Sea Region, located NE of TKFZ, comprises the Barents Sea (c. 9,000 m) and the Løkvikfjellet groups (c. 6,000 m). These two groups are separated by a major unconformity. The substratum of the Barents Sea Group is unknown. The group commences with submarine turbidite fan sandstones (Kongsfjord Fm >2,500 m), continuing upwards into deltaic, coastal and fluvial beds. Subordinate platform carbonates with local stromatolites and traces of evaporites occur in the upper part of the group. Achritarchs (Båtsfjord Fm) provide evidence of a Cryogenian (late Riphean) age (Vidal and Siedlecka, 1983).

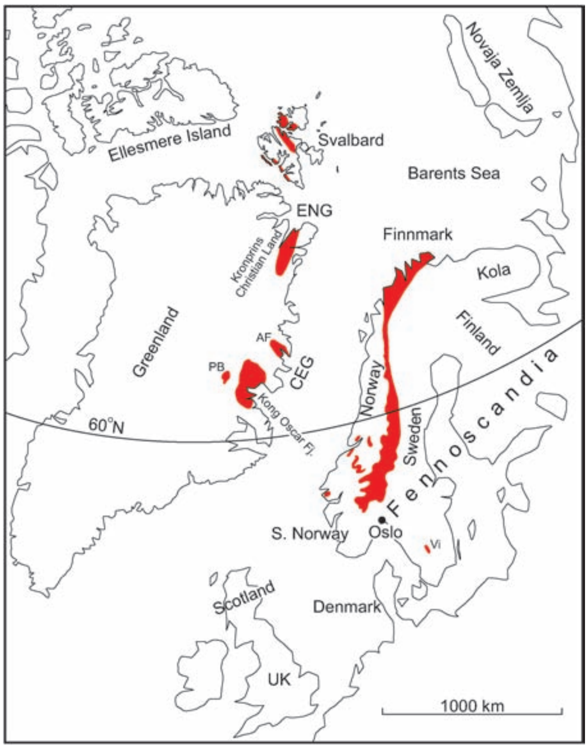


Figure 2 Northern Europe and Greenland in plate tectonic position in early Cenozoic time. Outcrop areas of Neoproterozoic successions in Fennoscandia, East Greenland and Svalbard are shown by grey shading. AF = Ardenaple Fjord, CEG = Central East Greenland, ENG = eastern North Greenland, PB = Peterman Bjerg, Vi = Visingö Group, Vättern Basin.

The Løkvikfjellet Group is entirely terrigenous and consists of predominantly shallow-marine and subordinate fluvial sandstone, mudstone and siltstone. No deposits of glacial origin are present in the succession. Metadolerite dykes, some of late Neoproterozoic age, penetrate the sedimentary successions of the Barents Sea Region (Siedlecka et al., 2004).

Rocks of the Barents Sea Region were displaced along the TKFZ towards the ESE at the end of the Timanian Orogeny and juxtaposed to the Neoproterozoic successions presently cropping out on the southwestern side of the fault zone. The succession preserved southwest of the TKFZ unconformably onlaps the Baltican crystalline basement, forming a pericratonic basin. The succession consists of the Vadsø (oldest), Tanafjorden and Vestertana groups, with an accumulated thickness of 3,000 m. Several unconformities and hiatus indicate tectonic activity during sedimentation. The Cryogenian (late Riphean) Vadsø and Tanafjorden groups are dominated by fluvial sandstone in the lower part and shallow-marine sandstone and mudstone in upper part, terminating with stromatolite-bearing dolomite (Grasdal Fm). A warm tropical climate prevailed at the end of Cryogenian in TVR, as well as in the BSR (Båtsfjord Fm). Carbonate platforms likely formed in response to rise in sea level in a late Cryogenian 'carbonate transgression' (Siedlecka et al., 2004).

The Cryogenian strata are cut by a low-angle unconformity, with increasing hiatus towards the south. Overlying Ediacaran successions consist almost entirely of siliciclastic deposits and commence with the Varangerian glacial deposits: the Smalfjord and Mortensnes tillite formations and the interglacial Nyborg Formation which is predominantly terrigenous, but with some marine carbonates, including the bottom bed. The tillite outcrops in TVR are among the world's most well-known and best studied Neoproterozoic glacial successions (Figure 4). The tillite-bearing formations may correspond to the Marinoan (c. 630 Ma) and Gaskiers (c. 580 Ma) glacial periods elsewhere, referred to as the Neoproterozoic III and IV glaciations by Rice and Hoffmann (2000).

The post-glacial Ediacaran record consists predominantly of various marine deposits and passes upwards into shallow-marine Early Cambrian to Tremadocian beds. Ediacara trace fossils are recorded on the Digermulen Peninsula (Siedlecka et al., 2004).

Stratigraphic correlations across the TKFZ between BSR and TVR show that the lower Barents Sea Group and the bulk of the Vadsø Group are correlative and indicate that the lateral translation of the BSR along the TKFZ is much less than the 500 km previously interpreted on geophysical grounds (e.g., Siedlecka and Roberts, 1992; Rice, 1994; Siedlecka et al., 2004).

Baltoscandian platform and margins

Cryogenian-Cambrian autochthonous successions along the Caledonian nappe front and in tectonic windows

Late Ediacaran-Cambrian successions rest on older Precambrian basement in outcrops along the Caledonian nappe front as the Dividal Group of central Finnmark, northeastern Troms and northern Sweden and correlatives further southwards to South Norway (Figure 5).

The Dividal Group begins with post-Varangerian accumulations and continues through Lower Cambrian beds with *Platysolenites antiquissimus* into the Middle Cambrian Alum Shale Formation. Fluvial sandstones and alluvial debris-flow conglomerates in the lower part are followed by coastal and shelfal terrigenous strata. Kulling (1972) found at Torneträsk *Kullingia concentrica*, the first discovery of Ediacara fossils in Scandinavia. The Ediacaran–lower Cambrian sandstone and shale beds along the nappe front locally starts with Varangerian tillite (Siedlecka et al., 2004).

Successions similar to those at the nappe front occur along margins of tectonic windows (antiformal stacks) in the nappe region; the strata rest with erosional contact on older Baltican rocks. Tillite-

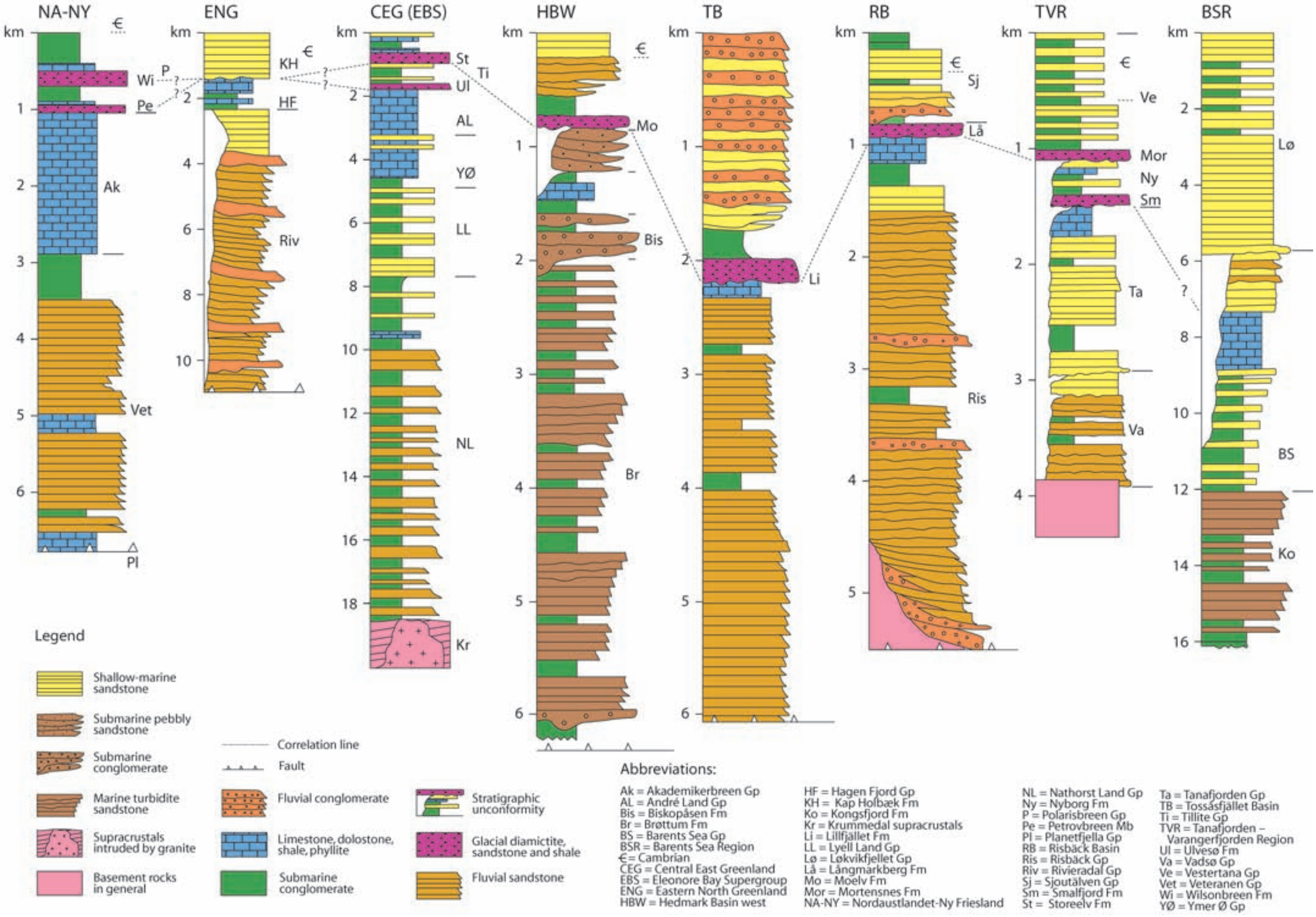


Figure 3 Neoproterozoic stratigraphy in Fennoscandia with Barents Sea Region (BSR), Tanafjorden-Varangerfjorden Region (TVR), Risbäck Basin (RB), Tossåsfjället Basin (TB) and western Hedmark Basin (HBW), East Greenland with central East Greenland (CEG) and eastern North Greenland (ENG), and Svalbard with Nordaustlandet and Ny Friesland (NA-NY).

bearing rocks of the windows in western Finnmark are correlatives of the upper Tanafjorden and Vestertana groups of East Finnmark, respectively. Discontinuous tillite units overlain by Ediacaran-Cambrian quartz conglomerate, quartz arenite, siltstone and shale rest directly on crystalline basement in a series of windows further south in the Scandinavian Caledonides (e.g., Siedlecka et al., 2004).

Figure 4 The Bigganjargga tillite at Oibaccanjarga in Varangerboth, East Finnmark, North Norway. Diamictite of the basal tillite facies of the Smalfjord Formation was deposited unconformably on a striated pavement of older quartzitic sandstone.

Neoproterozoic of the Lower Allochthon

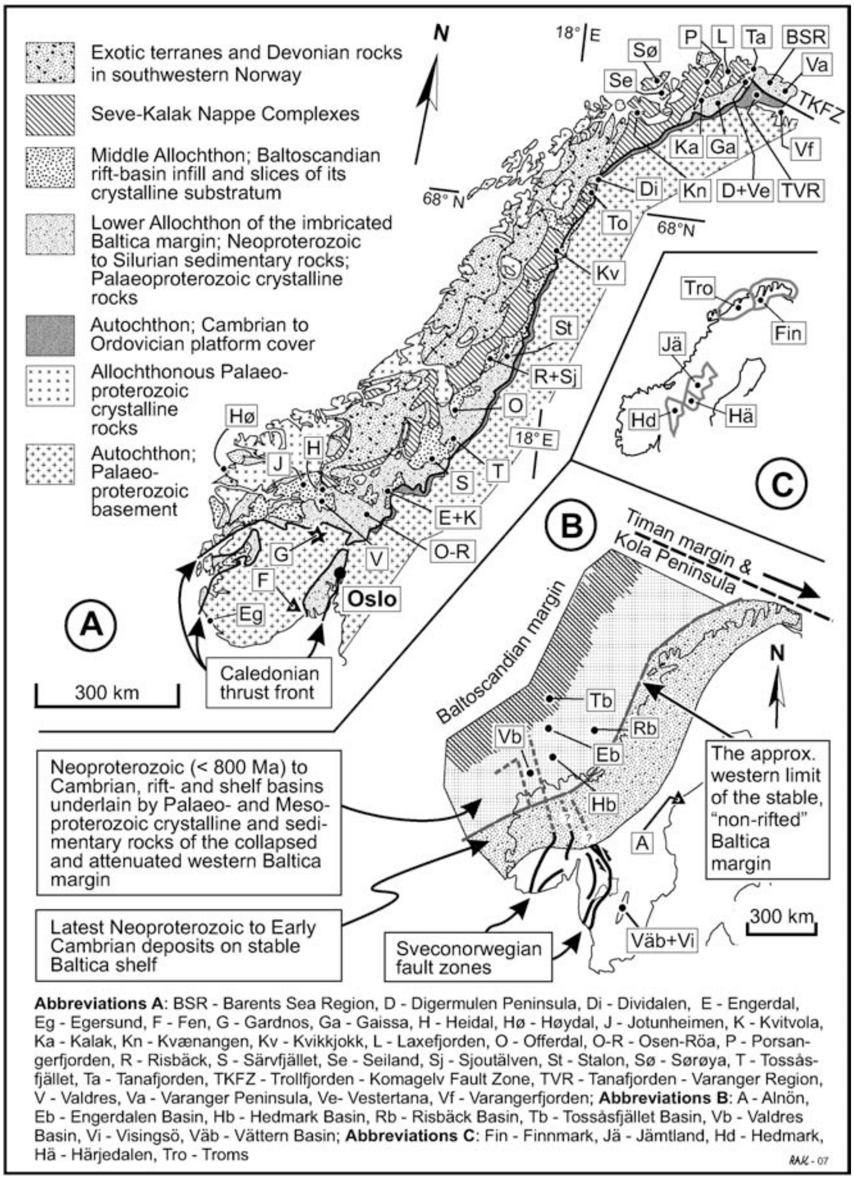
The Gaissa Nappe Complex

The Neoproterozoic pericratonic deposits of TVR continue westwards for a distance of about 200 km into the Porsanger area, as a part of the Gaissa Nappe Complex. Correlations indicate that these successions extend another 200 km southwestwards to Kvænangen. The lower, fluvially dominated parts of the succession occur southwest of the Porsangerfjorden. In the Porsangerfjorden area, marine sandstone and dolomite with evidence of evaporitic conditions correlate with sandstone and carbonate formations, respectively, in the Cryogenian Tanafjorden Group. Ediacaran rocks continue westward to the Laksefjorden area, while further to the west only scattered tillites occur (Siedlecka et al., 2004).

Jämtlandian nappes and the Osen-Røa Nappe Complex: the Risbäck and Hedmark basins

Attenuated thrust sheets of Lower Allochthon occur along the Caledonian nappe front in Arctic Sweden, thickening in the Central and Southern Scandinavian Caledonides. Besides the Neoproterozoic successions the nappe complexes contain slices of Baltican basement rocks (Gee et al., 1985a); tectonic transport exceeds 150 km (Kumpulainen and Nystuen, 1985).

Jämtlandian nappes in central-west Sweden carry a Neoproterozoic to lower Cambrian succession, the Risbäck and Sjoutälven groups. The pre-Varangerian Risbäck Group (c. 1,500 m), deposited in the Baltoscandian *Risbäck Basin*, consists of feldspathic sandstones and minor debris-flow conglomerates and shale units, includ-



Abbreviations A: BSR - Barents Sea Region, D - Digermulen Peninsula, Di - Dividalen, E - Engerdal, Eg - Egersund, F - Fen, G - Gardnos, Ga - Gaissa, H - Heidal, Hø - Høydal, J - Jotunheimen, K - Kvitvola, Ka - Kalak, Kn - Kvænangen, Kv - Kvikkjokk, L - Laxefjorden, O - Offerdal, O-R - Osen-Röa, P - Porsangerfjorden, R - Risbäck, S - Särvfjället, Se - Seiland, Sj - Sjoutälven, St - Stalon, Sø - Sørøya, T - Tossåsfjället, Ta - Tanafjorden, TKFZ - Trollfjorden - Komagelv Fault Zone, TVR - Tanafjorden - Varanger Region, V - Valdres, Va - Varanger Peninsula, Ve- Vestertana, Vf - Varangerfjorden; **Abbreviations B**: A - Alnön, Eb - Engerdalen Basin, Hb - Hedmark Basin, Rb - Risbäck Basin, Tb - Tossåsfjället Basin, Vb - Valdres Basin, Vi - Visingsö, Väb - Vättern Basin; **Abbreviations C**: Fin - Finnmark, Jä - Jämtland, Hd - Hedmark, Hä - Härjedalen, Tro - Troms

Figure 5 Main features of the Scandinavian Caledonides showing major outcrop areas of Neoproterozoic strata.

ing a dolomite at the top (Kalvberget Fm). The dolomite formation is unconformably overlain by the Långmarkberg tillite, followed by Ediacaran to lower Cambrian sandstone and shale in the Sjoutälven Group (Kumpulainen and Nystuen 1985).

Neoproterozoic-Cambrian rocks in the Osen-Røa Nappe Complex in southern Norway and Härjedalen of western Sweden have traditionally been named 'sparagmites', from the term *sparagmite* (feldspar-rich sandstone). The Sparagmite Region hosts the more than 5,000 m thick Hedmark Group, a reference succession of Neoproterozoic stratigraphy in southern Scandinavia, deposited in the *Hedmark* (rift) *Basin* (Kumpulainen and Nystuen, 1985). Fluvial sandstones form the initial deposits, followed by at least 4,000 m of thick deep-marine turbidite sandstones and black shales (Brøttum Fm) in the west and equivalent alluvial arkoses and conglomerates in the east. Achritarchs in marine shales indicate a late Cryogenian-early Ediacaran age (cf. Nystuen, 1999).

Tholeiitic basalt flows and deep-marine conglomeratic fans (Nystuen, 1999) are indicative of considerable crustal extension. The Biskopåsen conglomerate contains the first Precambrian fossil ever found in Norway, *Papillomembrana compta* (Spjeldnæs, 1967). Carbonate beds with local stromatolites interbedded with black shales (Biri Fm) formed during the 'carbonate transgression' of Baltica (Siedlecka et al., 2004).

The Varangerian glacial epoch in South Norway is represented by the Moelv tillite formation, correlated with the younger tillite formation in Finnmark (Siedlecka et al., 2004). Post-Varangerian time is characterized by siltstone, followed by latest Ediacaran-Cambrian deltaic and fluvial feldspathic sandstone and Early Cambrian shallow-marine quartz arenite (Nystuen, 1999).

Neoproterozoic of the Middle Allochton

The Laksefjord Nappe Complex

The Laksefjord Nappe Complex in central Finnmark includes Paleoproterozoic basement rocks with a Meso- to Neoproterozoic metasedimentary cover stratigraphically below the c. 8,000 m thick Laksefjord Group. The Laksefjord Group starts with diamictites formed in alluvial fans, grades upwards into braided stream feldspathic sandstones (psammites) and terminates with shoreline to shelfal mudstone and siltstone (phyllites) with local carbonate interbeds. The age of the Laksefjord Group remains unknown, though a Neoproterozoic age is a reasonable assumption with possible correlation with the Løkvikfjellet Group (Siedlecka et al., 2004). Dolerite dykes penetrate the Laksefjord Group (Gayer et al., 1987).

Särv, Offerdal, Stalon, Kvitvola, Valdres and other nappe complexes

A series of Neoproteozoic basin successions are present within the Middle Allochthon in the north-central to southern Scandinavian Caledonides. Baltican basement rocks occur as tectonic slices in several of the nappe complexes (Gee et al., 1985a) displaced about 400–600 km towards the east and southeast (e.g., Kumpulainen and Nystuen, 1985)

The Särv Nappe Complex is a major thrust unit within the central eastern Caledonides in Sweden and Norway, comprising the Neoproterozoic-Cambrian Tossåsfjället Group, deposited in the pericratonic *Tåssåsfjället Basin* (Kumpulainen and Nystuen, 1985). Pre-Varangerian strata consist of c. 2,000 m of fluvial feldspathic sandstones with minor lacustrine shale intercalations. A dolomite formation, supposed to correlate with other late Cryogenian transgressive carbonate units (above), occurs in the middle part of the Group and is unconformably overlain by the Lillfjället tillite. This inferred Varangerian formation is succeeded by c. 2,000 m thick Ediacaran-Cambrian shale and sandstone. The Tossåsfjället Group is penetrated by the Ottfjället dolerite dykes, correlated with the Sarek Dyke Swarm in northern Sweden, c. 610 Ma (Svenningsen, 2001). Psammitic successions, some with associated carbonate beds and intruded by dolerite dykes, are present in a number of thrust sheets of the Särv Nappe Complex northwards in Sweden and in south-central Norway.

The Offerdal Nappe of the Middle Allochthon in west-central Jämtland contains a Neoproterozoic succession of about 1,500 m strongly deformed, partly mylonitized conglomerates and sandstones. The succession has been correlated with the upper part of the Risbäck Group in the Lower Allochthon, derived from a rift basin supposed to have been located adjacent to the Risbäck Basin (Plink-Björklund et al., 2005). Sandy turbidites including conlomerates, probable correlatives of the Risbäck Group, occur in the Stalon Nappe in the Kvikkjokk area (Greiling and Kumpulainen, 1989).

The Engerdalen Group of the Kvitvola Nappe Complex, filling the *Engerdalen Basin,* is characterized by up to several thousand metres thick pre-Varangerian fluvial to marine sandstone. A formation of dolomite, with evaporitic magnesite, chert and black shale, is unconformably overlain by a glacial diamictite (Koppang Fm). A several hundred meters thick Ediacaran sandstone formation succeeds the tillite. The Engerdalen Group lacks dolerite intrusions, suggesting this basin was located in a more cratonward position than the Tossåsfjället Basin (Kumpulainen and Nystuen, 1985).

The Valdres Group and the lower part of the Mellsenn Group in the Valdres Nappe Complex, represents the *Valdres Basin,* a minor rift basin formed within a terrain of high-grade gneisses and gabbroic rocks now present as crystalline thrust sheets, similar to those in the overlying Jotun Nappe Complex. The Valdres Group is dominated by more than 4,000 m thick pre-Varangerian alluvial coarse-grained arkoses and conglomerates (Nickelsen et al., 1985). A marble unit probably corresponds to the pre-Varangerian 'carbonate transgression' level, and a tillite unit on top of the group is correlated with the Moelv tillite in the Hedmark Group. It is succeeded by the Mellsenn Group, containing in the lower part late Ediacaran-Cambrian green slate and fluvial to shallow-marine sandstone.

The Heidal and Høydal groups in central South and West Norway, respectively, are dominated of psammitic rocks, cut by mafic dykes and thought to represent Neoproterozoic successions derived from remote segments of the Baltoscandian margin, or from an outboard terrane. Except for small rift basin successions (Offerdahl, Stalon, Valdres) the majority of thick metasedimentary rocks in the Middle Allochthon have the character of being pericratonic basin successions (Siedlecka et al., 2004).

Neoproterozoic of Upper Allocthon: the Seve Nappe Complex

The Seve Nappe Complex (SNC) occurs along the eastern part of the Caledonides in Sweden and northeastern Troms County in Norway. In northern Sweden, the Neoproterozoic rock suite of the SNC is dominated by psammites, quartzites and various schists with marble beds, graphitic schists, evaporitic magnesite and diamictite horizons (Siedlecka et al., 2004); further to the south SNC also contains thick marble units (Kulling, 1972).

In the northern part of the Seve Nappe Complex, c. 850 Ma anatectic granite (Paulsson and Andréasson, 2002) postdate parts of the metasedimentary rocks; Rehnstöm et al. (2002) also inferred a 637 Ma deformational event in the Caledonides of northern Sweden. The sedimentary successions of the SNC are cut by the 615–550 Ma 'Baltoscandian dolerite dyke swarms' (Paulsson and Andréasson, 2002), including the Sarek Dyke Swarm (c. 610 Ma; Svenningsen, 2001).

Stretching lineations in the Seve Nappe Complex indicate transport towards the east-southeast, and the SNC is considered to be derived from a distant position of the peri-continental Baltoscandian margin (e.g., Gee et al., 1985b).

Middle and/or Upper Allochthon: The Kalak Nappe complex of northern Finnmark

In eastern Troms County of Norway, the Seve Nappe Complex appears to pass into the several thousand meters thick Kalak Nappe Complex (KNC) of northern Finnmark, ascribed to the Middle Allochthon by Gee et al. (1985a) and, in part, to the Upper Allochthon by Zachrisson (1986).

The Kalak Nappe Complex includes slices of Precambrian crystalline rocks and metasedimentary units dominated by psammites, and including muscovite-schists, marbles, calc-silicates and graphitic schists. The Complex is intruded by mafic dykes (amphibolites), granites, pegmatites, and the alkaline magmatic suite of the Seiland Igneous Province (570–520 Ma, Corfu et al., 2007).

Crystalline basement rocks and some of the psammites are intruded by c. 980 Ma granites. Granitic rocks and migmatites furthermore represent three main deformation events, c. 876–826 Ma, 710–680 Ma, and 602 Ma. Thus, the oldest part of the KNC is of early Tonian age, or even older, and the rock suit of the nappe complex has been affected be several Tonian–early Edicaran orogenic events (e.g., Kirkland et al., 2006; Corfu et al., 2007).

The KNC has been considered to be derived from a distant northwestern position of the Baltican margin (Siedlecka et al., 2004 and references therein). However, this has been contested by Kirkland et al. (2006) and Corfu et al. (2007).

Other Neoproterozoic rocks in southern Scandinavia

The *Vättern* Basin is a small Neoproterozoic rift basin in southern Sweden, running NNE-SSW along the Lake Vättern. The Visingsö Group (c. 1,000 m) consists of deltaic sandstone and marine shale, debris-flow and fluvial conglomerates followed by interchanging marine sandstone and shale beds and dolomitic limestone with stromatolites in the uppermost part of the Group. The dolomite is correlated with other pre-Varangerian carbonate formations in Fennoscandia, East Greenland and Svalbard (Vidal, 1985).

The *Gardnos Impact Crater* (French et al., 1997) in central-south Norway was likely formed in Neoproterozoic time when a bolide fell down in a shallow sea (French et al., 1997), perhaps an epicontinental sea formed during the pre-Varangerian 'carbonate transgression'.

The *Egersund dolerite dykes* (c. 616 Ma) in the Precambrian basement of southwestern Norway is interpreted to reflect intitiation of the Iapetus Ocean (Bingen et al., 1998). These dykes act as reference rocks for pre-Iapetus Neoproterozoic dolerite dyke swarms in the Caledonian nappes.

The *Fen and Alnö carbonatite complexes* in South Norway and central-east Sweden, respectively, originated at small volcanic centres for about 580 Ma ago and are thought to be related to continental crustal break-up at the end of the Precambrian (Meert et al. 2007).

Neoproterozoic of East Greenland

The Neoproterozoic deposits of East Greenland occur in several scattered outcrops in central East Greenland and eastern North Greenland (Figure 2). The strata occur in three different structural settings: (1) as relatively thin autochthonous to parautochthonous, Cryogenian-Ediacaran, pericratonic sandstone-carbonate deposits in the Caledonian foreland in the west, (2) as thin, local Ediacaran tillites, resting on Paleoproterozoic basement in tectonic windows in the nappe region, and as (3) up to several thousand metres thick ?uppermost Tonian to lower Paleozoic rift-basin successions within Caledonian thrust sheets (Higgins et al., 2001).

The outcrops around Kejser Franz Joseph Fjord and Kong Oscar Fjord in central East Greenland hold the most complete sections, with the Eleonore Bay Supergroup (Figure 6) as a reference succession for the Neoproterozoic in East Greenland (Sønderholm and Tirsgaard 1993).

Sønderholm and Tirsgaard (1993) subdivided the up to 16 km thick Eleonore Bay Supergroup, from base upwards, into the Nathorst Land (up to c. 11,000 m), the Lyell Land (up to c. 3,000 m), the Ymer Ø (900–1,500 m) and the Andrée Land (900–1,500 m) groups, overlain by the Tillite Group (c. 800 m).

A slight angular unconformity separates the Eleonore Bay Supergroup from the underlying latest Mesoproterozoic/Early Neoproterozoic Krummedal supracrustal succession. The lower boundary of the supergroup is, however, in most localities obscured by deformation, metamorphism and Caledonian granite intrusions, or by late- to post-Caledonian extensional faults.

The Nathorst Land and Lyell Land groups consist of alternating sandstone and mudstone. Both fluvial and marine settings have been proposed for the Nathorst Land Group, whereas marine shelf setting is suggested for the Lyell Land Group, dominated by fine-grained sandstone and mudstone (Sønderholm and Tirsgaard 1993). An about 6,300 m thick succession of sandstone and mudstone (Petermann Bjerg Gp) around Petermann Bjerg is variably metamorphosed and intruded by Caledonian granites. The succession is correlated with the two lowermost groups of the Eleonore Bay Supergroup.

Carbonate platform, slope and deep-marine basinal environments dominate the Ymer Ø and Andrée Land groups. A peritidal environment of arid climatic setting is inferred for carbonate beds in the upper part of Andrée Land Group, sharply overlain by the first glacial diamictite (Ulvesø Fm, c. 50 m) in the Tillite Group. The Ulvesø glacial formation is succeeded by offshore dolomitic shales and a sandstone-shale succession (Arena Fm, c. 200 m). The second glacial unit (Storeelv Fm, c. 200 m) is also capped by offshore dolomitic shale. Both glacial formations represent mixed terrigenous and glaciomarine deposits and are correlated with the Petrov tillite member (Elbobreen Fm) and the Wilsonbreen Formation, respectively, on northeastern Svalbard (Fairchild and Hambrey, 1995) (see below).

In eastern North Greenland, a Neoproterozoic rift basin, the *Hekla Sund Basin,* existed at the eastern Laurentian margin. The Hekla Sund Basin was bordered to the west by a down-to-the-E master fault. East of this fault, about 7 km of syn-rift deposits (Rivieradal Gp) make up the lower part of the basin succession. In the proximal, western part of the basin several upward-coarsening fan delta units occur. Sandstones, pelites, semipelites and calcareous pelites make up the eastern distal parts of the Rivieradal Group (Higgins et al., 2001).

The Rivieradal Group is overlain by the post-rift Hagen Fjord Group, in lower part composed of inter- to supratidal siltstones, sandstones, stromatolitic dolostones (Campanuladal Fm) and reddish brown limestone (Kap Bernhard Fm), and in upper part of dolostones of the Fyn Sø Formation. The carbonate formations record carbonate-platform settings. The post-rift succession is also identified in a pericratonic position on the autochtonous rift-shoulder west of the Hecla Sund Basin. A marked hiatus separates the Fyns Sø Formation from the overlying early Cambrian Kap Holbæk Formation. Glacial deposits are not recorded from the Hekla Sund Basin succession (Higgins et al., 2001).

The age of the Rivieradal and Hagen Fjord groups and their relationship to the Eleonore Bay Supergroup is uncertain. Higgins et al. (2001) proposed, as the most likely correlation, to link the change from the Rivieradal Group to the transgressive Hagen Fjord Group to the shift from siliciclastic facies of the Nathorst Land and Lyell Land groups to the carbonate dominated deposits of the Ymer Ø and Andrée Land groups in the Eleonore Bay Supergroup.

Neither rift-related dolerite dykes, nor volcanic or pyroclastic deposits have been identified in the Eleonore Bay Supergroup and its correlatives in the Hekla Sund Basin succession. This probably indicates that the Neoproterozoic basins of the eastern Laurentian margin in East Greenland were located in a cratonward position relative to the rift zone that later developed into sea-floor spreading and the opening of the Iapetus.

Neoproterozoic of Svalbard

Three terranes dominate the Caledonian bedrock of Svalbard—Northeastern, Northwestern and Southwestern, making up the pre-Devonian ('Hecla Hoek') basement.

Neoproterozoic sedimentary successions are present within two of these terranes (Northeastern and Southwestern Terranes). The most complete and best studied sections (Harland et al., 1993; Halverson et al. 2004, 2005; Maloof et al. 2006) occur within the Northeastern Terrane (Nordaustlandet and eastern Ny Friesland). Diamictites, of which some are interpreted to be glacial, are interbedded with a wide range of different lithologies in the Southwestern Terrane (Harland et al., 1997). Deciphering stratigraphy and depositional environments within the latter two terranes is difficult due to Caledonian deformation and metamorphism, as well as later Eocene contractional and extensional deformation.

Northeastern Terrane

The Northeastern Terrane exposes a 7 km thick succession of Neoproterozoic–Middle Ordovician strata. According to Harland (1997), the Neoproterozoic part consists, from base upwards of the Veteranen (3800 m), Akademikerbreen (1350–2500 m) and Polarisbreen (767 m) groups. An extensional fault separates the Veteranen Group from the underlying Planetfjella Group, a mixed sedimentary and volcanic unit of unknown depositional age and origin.

The Veteranen Group consists, in the lower part, of quartzite and subordinate limestone and in the upper part of quartzite, greywacke and shale. The Akademikerbreen Group is characterized by dolostones and limestones, partly stromatolitic; well preserved cyanobacteria in chert are correlated to the 700–800 Ma Bitter Springs biota of Australia (Knoll and Walter, 1992). The Polarisbreen Group, succeeding conformably the Akademikerbreen Group, is dominated by shale and carbonate beds with two distinct stratigraphic levels of glacial diamictites and shale with dropstones, interpreted to represent subglacial till and glaciomarine mud, respectively.

The glaciogenic Polarisbreen Group and its underlying Akademikerbreen Group have recently gained great interest with regard to age and dynamics of the Earth's Neoproterozoic glaciations (e.g,. Halverson et al., 2004). The lower, Petrovbreen Member (Elbobreen Fm) in the Polarisbreen Group is a thin glaciomarine diamictite that lacks a cap carbonate. About 350–400 m shale and siltstone separate this glaciogenic unit from the younger and thicker Wilsonbreen Formation which comprises terrestrial ice-contact deposits and is draped by a 3–18 m thick transgressive cap dolostone. The ^{13}C isotopic profile of the capping carbonate unit is identical to that of post-Marinoan cap carbonates elsewhere (Halverson et al. 2004). Halverson et al. (2004, 2005) interpreted the Petrovbreen and Wilsonbreen glacial units to represent the first and last phases of the Marinoan glaciation, respectively. Halverson et al. (2005) argued that the Sturtian glaciation might be present by the onset of the Polarisbreen Group, but this correlation is undocumented.

Maloof et al. (2006) suggested that the Veteranen Group repre-

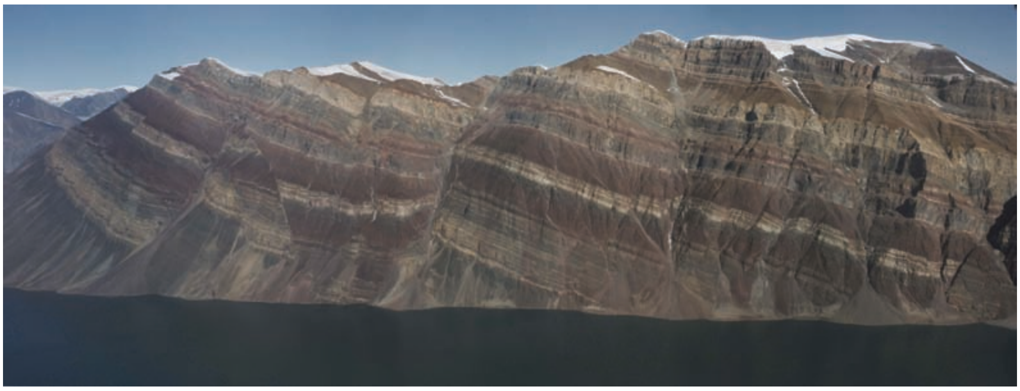


Figure 6 The Neoproterozoic Eleonore Bay Supergroup in the southeast-facing cliffs of Berzelius Bjærg (Segelsälskapets Fjord), East Greenland. The brownish weathering, cliff-forming lower part of the section with thin white sandstone beds represents the Nathorst Land and Lyell Land Groups. The change in slope in the upper part marks the transition to the carbonate dominated Ymer Ø Group. Height of wall c. 1,500 m.

sents syn-rift sediments linked to a rift phase in the time interval c. 850–825 Ma, an interpretation in agreement with 940 Ma U-Pb ages of basement granites of Nordaustlandet (Gee et al., 1995; Johansson et al., 2001).

Southwestern Terrane

Large areas of West-Spitsbergen and Prins Karls Forland are composed of intensely deformed, greenschist-grade carbonate-siliciclastic deposits with diamictites and pebbly siltstones. Two glaciogenic diamictite formations in the Kapp Lyell Group have been correlated with the Petrovbreen and Wilsonbreen glacial units in the Polarisbreen Group of NE Svalbard, respectively (Harland et al., 1993; Harland, 1997). Abrupt lateral variations in thickness and facies indicate that the rocks in the lower part of the succession were deposited in discontinuous, fault-bounded deep-marine basins. As neither cap carbonates, nor chemostratigraphic data exist from this part of Svalbard, correlation with other Neproterozoic successions in the North Atlantic region is uncertain.

Bjørnøya

Rocks believed to be Neoproterozoic in age (Russehamna Fm) also exist on Bjørnøya, but their depositional age is uncertain, although microfossils indicate an Ediacaran age for parts of the succession (Harland, 1997).

Discussion

Relative position of the segments of Baltica and Laurentia margins

The relative position between Baltica and Laurentia after the Rodinia break-up has been much debated; right-way-up and upside-down orientations (current coordinates) of Baltica have been suggested. The present data set appear to fit best the right-way-up model with the Baltoscandian margin juxtaposed the Scotland-SE Greenland segment of Laurentia (e.g., Cawood and Pisarevsky, 2006; Li et al., 2008). Within this paleogeographic framework (Figure 1), Svalbard's Southwestern Terrane was located north of Greenland in Neoproterozoic time (e.g., Fairchild and Hambrey, 1995). This terrane, with its deep-marine glacial debris-flow deposits, is today located geographically between Ediacaran shelf deposits in the Northeastern Terrane of Svalbard and in East Greenland. A possible original site of these western terranes on Svalbard might be to the east of present central East Greenland, representing a deep-marine trough east of the shelfal environment represented by the Ediacaran succession in the Eleonore Bay Group, as proposed by Andresen (2004). Later (Devonian) strike-slip movements may then have displaced Svalbard's western terranes to their present positions.

The Seve and Kalak nappe complexes: Baltican or non-Baltican origin?

The Kalak and Seve nappe complexes have long been considered of Baltican affinitiy, displaced 400 km or more from the northwestern Baltoscandian margin. The rock suites of the two nappe complexes have been inferred to be genetically related within a 'Seve-Kalak Superterrane' (Andreasson et al., 1998). A Baltican origin for the nappe complexes is argued by general similarity in lithology with the sedimentary successions of the well-known Neoproterozoic of the Baltoscandian margin, as well as from their dolerite dyke swarms (c. 600 Ma), typical of crustal segments of unquestioned Baltoscandian origin. Roberts (2007) argued from paleocurrent data from fluvial psammites in lower thrust sheets of the KCN that sedimentary transport was from south to north, thus linking a Baltic source to a KNC basin sink.

On the other hand, the Tonian to Cambrian complex depositional, deformational and igneous history encountered in KNC are exotic to the autochthon of central and northern parts of the Baltoscandian margin; for this reason a Laurentian or peri-Gondwanan ancestry has been suggested for the KNC and, perhaps the whole Seve-Kalak Superterrane (Corfu et al., 2007; Kirkland et al., 2006, 2007).

Siedlecka et al. (2004) suggested that the KNC, in terms of Cryogenian-Cambrian compressional and extensional events, might be related to a complexity of plate-tectonic movements along the distant northern Baltoscandian margin, similar to those along the Timanian margin.

Basin development

The several thousand metres thick Tonian to early Cryogenian successions along the Timanian and Baltoscandian margins and the eastern margin of Laurentia (Figure 3) reflect deeply subsiding *continental to marine basins*. Initial Tonian or early Cryogenian basins might have been pre-rift sag basins that later developed into rift or/and strike-slip basins. The enormous volumes of terrigenous clastic sediments reflect high hinterland relief, effective mechanical weathering and erosion with high runoff, likely in humid climatic conditions. One may speculate that montane glaciation at times may have contributed to the high sediment production.

Cryogenian *pericratonic basins* (TVR, Tossåsfjället, Engerdalen, East Greenland, Northeastern Svalbard and others) formed when rift basins were still active in more cratonward positions of Baltica (Risbäck, Valdres, Hedmark, Vättern basins). The 'carbonate transgression' took place within this stage; pre-Marinoan (Varangerian) carbonate platforms along the eastern Laurentian margin may be related to the same sea-level high-stand, as indicated by achritarch correlations (Vidal, 1985; Knoll and Walter, 1992). Evaporitic magnesite, dolomite and chert, together with very low siliciclastic sediment input indicate high-temperature conditions in an arid climatic region.

Cryogenian(?) to Ediacaran glaciations reflect a dramatic change in climate. Basal tills were deposited on glaciated cratons and upon pericratonic strata (TVR, Tossåsfjället, Engerdalen, East Greenland and Northeast Svalbard) and rift basin successions (Risbäck, Valdres, Hedmark). The Laurentian marine basins of Greenland and Svalbard still possessed space for infill of very thick accumulations of terrestrial glacial and glaciomarine deposits. Correlation of glacial units and their absolute ages remain very uncertain (cf. Meert, 2007).

Post-glacial Ediacaran to Cambrian basin development reveals similar trends along the Baltoscandian margin, East Greenland and Svalbard. In the Baltica domain, but not in the Arctic Laurentian domain, dolerite dyke intrusions (c. 590–615 Ma) are supposed to reflect the final break-up of Rodinia, leading to the birth of the Iapetus Ocean in the region. Shoreline retrogradation and flooding of the denudated continents took place. Compressional tectonics still operated along some margin segments, as within the Timanian margin. The Ediacaran-Cambrian magmatism in the Seiland Igneous Province and Fen and Alnö carbonatite volcanoes indicate localized high mantle heat flow accompanying final break-up and early Iapetus sea-floor spreading.

Concluding remarks

A series of problems are left for future studies of the Neoproterozoic in the region covered by this review. Better constraints are needed of (i) the break-up history of Rodinia, (ii) depositional systems, biostratigraphy and palaeoecology, and (iii) absolute age and correlation of the Neoproterozoic glacial units. Despite these major problems, we conclude that the Neoproterozoic of the northwesternmost Timanian margin in eastern Finnmark, Baltoscandian margin, central East Greenland, eastern North Greenland and Svalbard can be subdived into the following major stages of basin development:

1. Tonian to early Cryogenian (c. 900–850 Ma). Initial basin formation (sag-basins?) along northeastern Baltica and eastern Laurentia.
2. Cryogenian (c. 850–630 Ma). Initial break-up of Rodinia, with formation of rift- and strike-slip basins along future margins of northern Baltica and eastern Laurentia. Compressional tectonics along some plate margins. General overall shift in climate from humid to warm and arid. Development of wide epicratonic basins.
3. Latest Cryogenian to Early Ediacaran (c. 630–580 Ma). Main interval of overall climatic cooling and glaciations, generally referred to the Varangerian Ice Age in northern Baltica, central Eastern Greenland and Svalbard. The oldest Varangerian glacial units may correspond to the Marinoan (c. 630 Ma) and the youngest to the Gaskiers (c. 580 Ma).
4. Ediacaran (c. 615–542 Ma). Final break-up of Rodinia with Iapetus-related rifting and dolerite dyke swarms, magmatism in the Seiland Igneous Province and the intra-Baltica plate Fen and Alnö carbonatite volcanic centres. Compressional tectonics along the Timanian margin, possibly including the northernmost segment of the Baltoscandian margin. Pericratonic basins changed from continental and paralic to open-marine epicontinental seas in Cambrian times.

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From the Early Paleozoic Platforms of Baltica and Laurentia to the Caledonide Orogen of Scandinavia and Greenland

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The Caledonide Orogen in the Nordic countries is exposed in Norway, western Sweden, westernmost Finland, on Svalbard and in northeast Greenland. In the mountains of western Scandinavia, the structure is dominated by E-vergent thrusts with allochthons derived from the Baltoscandian platform and margin, from outboard oceanic (Iapetus) terranes and with the highest thrust sheets having Laurentian affinities. The other side of this bivergent orogen is well exposed in northeastern Greenland, where W-vergent thrust sheets emplace Laurentian continental margin assemblages onto the platform. Svalbard's Caledonides are disrupted by late Caledonian faults, but have close affinity with the Laurentian margin in Northeast Greenland. Only Svalbard's Southwestern terrane is foreign to this margin, showing affinity to the Pearya terrane of northern Ellesmere Island in arctic Canada. Between the margins of western Scandinavia and eastern Greenland, the wide continental shelves, now covered by late Paleozoic and younger successions, are inferred to be underlain by the Caledonide hinterland, probably incorporating substantial Grenville-age basement. In northernmost Norway, the NE-trending Caledonian thrust front truncates the NW-trending Neoproterozoic Timanide orogen of northwest Russia. Much of the central and eastern parts of the Barents Shelf are thought to be underlain by Caledonian-deformed Timanide basement.

Caledonian orogeny in Norden resulted from the closure of the Iapetus Ocean and Scandian collision of continent Baltica with Laurentia. Partial subduction of the Baltoscandian margin beneath Laurentia in the mid-late Silurian was followed by rapid exhumation of the highly metamorphosed hinterland in the early Devonian, and deposition of Old Red Sandstones in intramontane basins. Late Scandian collapse of the orogen occurred on major extensional detachments, with deformation persisting into the late Devonian.

Introduction

The Caledonide Orogen is preserved on both sides of the North Atlantic Ocean, in the mountains of western Scandinavia and northeastern Greenland; it continues northwards from northern Norway, across the Barents Shelf and Svalbard to the edge of the Eurasian Basin (Figure 1). The orogen is notable for its thrust systems, E-vergent in Scandinavia and W-vergent in Greenland. The width of the orogen, prior to Cenozoic opening of the North Atlantic, was in the order of at least 700–800 km, the deformation fronts on both sides of the orogen being defined by thrusts that, in the Devonian, probably reached substantially further onto the foreland platforms than they do today. Much of the Caledonide hinterland is hidden beneath the continental shelves offshore Scandinavia and Greenland, and the character of the crust beneath these margins that were attenuated during the late Paleozoic and Mesozoic prior to Cenozoic seafloor spreading, is poorly constrained. Minimum horizontal displacements on the thrust systems amount to many hundreds of kilometres and the shortening across the orogen may well have been comparable to the c. 1,000 km inferred for some of today's younger orogens (e.g., the Himalaya).

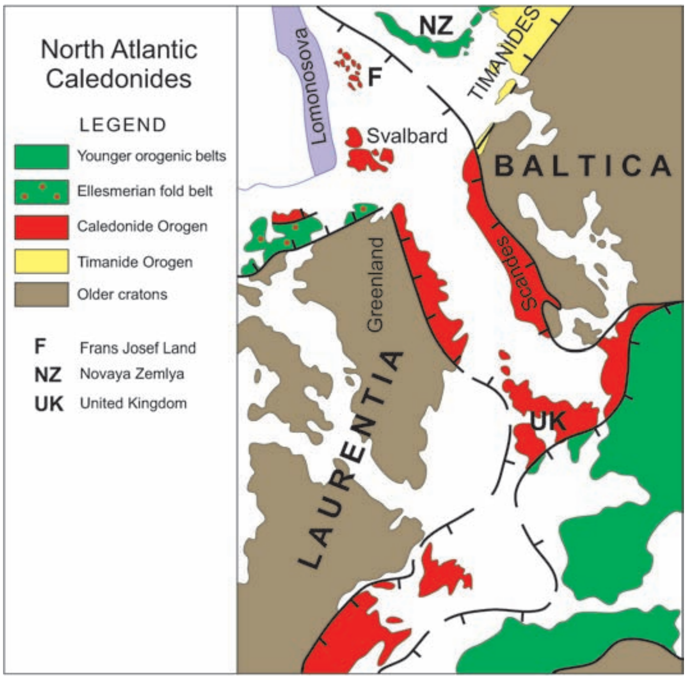

Figure 1 Outline of the North Atlantic Caledonides and relationship between Laurentia and Baltica.

Caledonian orogenesis around the North Atlantic started during the early Ordovician with subduction along both margins of the Iapetus Ocean and culminated with the collision of the continents of Laurentia and Baltica in the mid Silurian to early Devonian, Scandian orogeny. Underthrusting of Laurentia by Baltica is generally accepted to account for the different characteristics of the E and W-vergent thrust systems. Ocean-derived allochthons are preserved in the Scandes, comprising Cambro-Ordovician Iapetus sea floor, island arcs and back-arc basins. As in the Himalaya, continent collision resulted in partial melting of the underthrust (Baltica) margin and the resulting ductility had much influence on the geometry of the allochthons and the deep structure of the hinterland.

The Caledonian thrust front in northernmost Norway strikes northeastwards into the Barents Shelf, truncating the NW-trending Timanide orogen, a Neoproterozoic fold-and-thrust belt flanking the northeastern edge of the Fennoscandian Shield. The marked change in topographic expression of the orogen, from the Scandian Mountains of Norway and western Sweden to the Barents Shelf, coincides with this fundamental change in composition of the lithosphere. Northwards from the Barents Sea coast, the character of the Caledonide Orogen is obscured by late Paleozoic and Mesozoic sedimentary basins. Only on Svalbard, in the northwestern corner of the Barents Shelf, is the Caledonian bedrock well exposed and Laurentian affinity clearly defined. Thus, the Caledonian sutures that can be traced from the south through the Scandes into the Barents Shelf, lie to the east of the Svalbard archipelago beneath the Mesozoic cover and are poorly constrained.

Descriptions of the Caledonide Orogen in Scandinavia, Greenland and the Barents Shelf and its relationship to adjacent Paleozoic platforms follow below, along with an interpretation of the tectonic evolution. Presentations of the Precambrian crystalline basement and Neoproterozoic cover are found elsewhere in this volume.

The Paleozoic platforms

Paleoproterozoic and Archean crystalline crust dominates both Laurentia and Baltica in the Caledonian foreland regions, with younger (Mesoproterozoic) accreted terranes only present in southwestern Norway and Sweden. Grenvillian orogeny in eastern Canada and Sveconorwegian orogeny in Scandinavia were followed by a relatively stable interval (c. 900–600 Ma) with rifting of both the Laurentian and Baltoscandian margins and development of Neoproterozoic basins. Only in the far north, now largely beneath the Barents Sea, is the Caledonian foreland basement composed of Neoproterozoic Timanian terranes that were accreted to the East European Craton in the late Vendian.

A substantial part of the Caledonian hinterland is hidden beneath the late Paleozoic and younger successions of the continental shelves of Greenland and Scandinavia. Evidence contained in thrust sheets derived from these regions suggests that the Grenvillian-Sveconorwegian orogen may have continued along the axis of the Caledonides to the Barents Shelf (Andreasson et al., 1998).

Both the eastern margin of Laurentia in the northern Appalachian front and the western margin of Baltica provide evidence that the Neoproterozoic rifting culminated in the Vendian, with intrusion of mafic dyke swarms at c. 600 Ma; separation of the continents probably started at this time. Various lines of evidence suggest that these Laurentian and Baltoscandian margins were adjacent and part of a larger continental assemblage (Rodinia) prior to Vendian separation. However, this interpretation is not uncontroversial and other configurations are possible (Torsvik, 2003). Nevertheless, the Baltoscandian margin dyke swarms in the Särv and Seve Nappes (see below) suggest that, shortly after the deposition of the Vendian (Marinoan) tillites, perhaps during Timanian accretion, Baltica and Laurentia were established as independent plates.

Early Paleozoic successions deposited on the Laurentian and Baltoscandian platforms differ greatly in character, probably reflecting the low latitude location of the former and the moderate to high latitude of the latter. The Laurentian platform margin, from eastern Canada to eastern Greenland and Svalbard, is characterised by a thick Cambrian to mid Ordovician carbonate bank (Swett, 1981), underlain by late Vendian to early Cambrian siliciclastics. By contrast, the Baltoscandian platform is dominated by siliciclastics throughout the Cambrian, being characterised, in particular, by black shale deposition during the middle and late Cambrian and early Tremadocian (Andersen et al., 1986). Carbonate deposition dominated the Ordovician on both platforms and only along the Baltoscandian margin is there a change towards the west into turbidites, in response to early orogenic activity.

Along the Laurentian margin of the Caledonides, Silurian successions are well developed only in northernmost areas along the edge of the craton. The vast E-W trending Franklinian Basin of arctic Canada continues eastwards through northern Greenland and is cut by the Caledonian front in northernmost Northeast Greenland. Platform carbonates along the southern edge of this basin reach from the Cambrian through the Silurian and the shelf edge is marked by an abrupt change to deep water siliciclastics spanning the entire early Paleozoic and reaching into the early Devonian. Caledonian allochthons provided a source area in northeasternmost Greenland for Silurian–early Devonian turbidites (Peel and Sønderholm, 1991).

Along the Baltoscandian margin, as seen in the lower Caledonian nappes, the platform carbonate successions of the early Silurian give way westwards to turbidites with the onset of Scandian collisional orogeny further to the west. Late Silurian sandstones are preserved in the Oslo Graben and this facies has been inferred to have been present further to the north along the front of the orogen and subsequently removed by deep erosion. Within the mountain belt, Devonian sandstone and conglomerate deposits are preserved in intra-cratonic basins (Steel et al., 1985).

Scandinavian Caledonides

The Caledonides of western Scandinavia (Gee and Sturt, 1985) dominate the geology of Norway over a distance of nearly 2,000 km and include westernmost parts of Sweden (Figure 2). A deeply eroded section through this ancient orogen exposes a wealth of fragmentary information about what must have been a very complex and prolonged history of ocean opening and closure, culminating in continent collision (Stephens, 1988).

Cross-sections through the Scandinavian Caledonides show similarities with other orogenic belts, such as the Alps and the Himalaya: a classical foreland fold-and-thrust belt is developed in the eastern part, best preserved from later erosion in the Permian Oslo Graben. To the west, locally-derived nappes are overridden by successively more long-transported allochthonous units that are inferred to represent telescoped fragments of the pre-collisional Baltoscandian margin. Furthermore, windows in the orogenic wedge reveal that the Precambrian basement becomes gradually more reworked to the west, with paleotemperature and -pressure estimates increasing towards the Norwegian coastal areas; early Devonian high-pressure rocks such as eclogites, locally with coesite and microdiamonds (Dobrzhinetskaya et al., 1995) are found, consistent with crustal depths up to 125 km.

This evidence of deep depression of the western margin of the Baltica basement beneath the Caledonian allochthons has led to the generally accepted model of W-directed partial subduction of Baltica during Scandian collisional orogeny. The basement descended under the weight of an orogenic wedge of allochthonous units derived from the Baltican margin, from the Iapetus Ocean and, most likely, also from the Laurentian margin. The tectonic units are generally stacked with the most far-transported ones at the top. Gee et al. (1985), following Kulling (in Strand and Kulling, 1972), grouped the thrust sheets into the Lower, Middle, Upper and Uppermost allochthons, all resting on autochthonous crystalline basement with its late Neoproterozoic to Silurian metasedimentary cover (Figure 2).

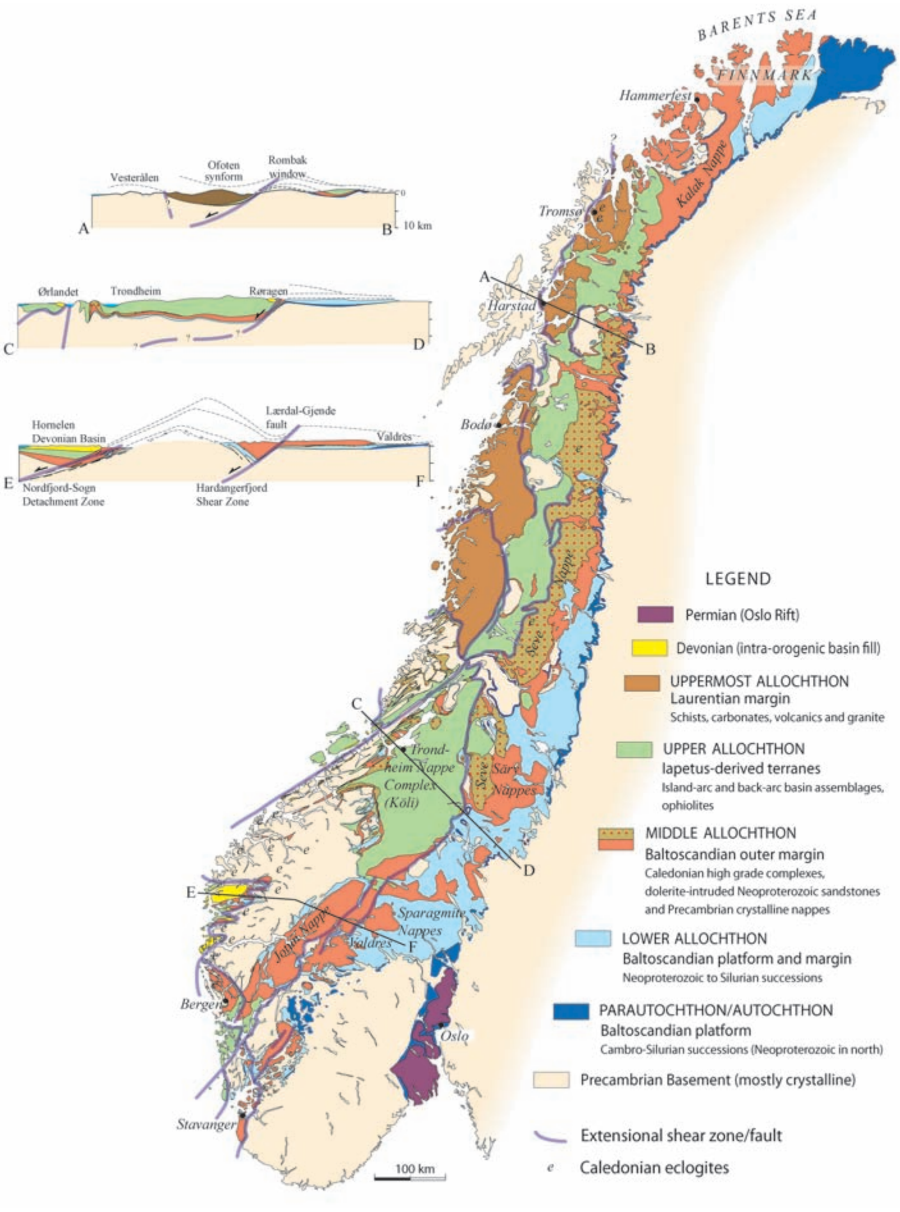

Figure 2 Geological map of the Scandinavian Caledonides.

The Lower and Middle allochthons represent the telescoped pre-collisional continental margin of Baltica. The Upper Allochthon is dominated by sedimentary and igneous rocks derived from the Iapetus Ocean and including ophiolites and island-arc complexes (Stephens, 1988). Previously, this major allochthon has also included a basal complex (the Seve Nappes) comprising metasediments, similar to those in the underlying Middle Allochthon, but metamorphosed to amphibolite, granulite and locally eclogite facies. Lithological affinity, in association with inversion of metamorphic isograds (the metamorphic grade decreasing downwards into and through the Middle Allochthon), favours the inclusion of these continental margin assemblages in the Middle Allochthon, as shown on Figure 2. The characteristic metasedimentary units of the Middle Allochthon, dominated by Neoproterozoic sandstones intruded by mafic dykes, along with the inverted metamorphism, can be followed westwards from the type areas in central parts of the Caledonides in Sweden to western Norway, implying that they must have been derived from west of the hinterland now exposed along the Norwegian coast, i.e., a distance of at least 300 km (Gee, 1975).

Within the overlying Upper Allochthon some of the ophiolites and arc complexes were derived from the Baltica margin; others initiated on the Laurentian side of Iapetus (Bruton and Harper, 1985). The Uppermost Allochthon also has affinities to the Laurentian margin, and thus represents the most exotic elements in the Scandinavian Caledonides. The oldest dated remnants of arc-related magmatism and ophiolites occur in the upper part of the Upper Allochthon and yield ages around 500 Ma (Dunning and Pedersen, 1988), while the youngest are around 430 Ma (Fossen and Austrheim, 1988). Between these two ages, there is evidence of seventy million years of convergence, recorded in the subduction-related magmatism, sedimentation and tectonometamorphic events preserved in the geological record of the Upper and Uppermost Allochthons.

Some of the most interesting clues about the complexity of the pre-Scandian history are found in early Caledonian (Ordovician) eclogites and related high P regional metamorphic parageneses in the Seve and related nappes. Whereas the granulite facies migmatites in the classical Seve areas of central Jämtland have yielded early Scandian ages (Claesson, 1987), similar to ages defined further south near Bergen in the eclogite-bearing Lindås Nappe, others, in northern Sweden (Essex et al., 1997) provide evidence of early Ordovician subduction along the Baltoscandian outer margin (490–470 Ma), perhaps related to collision with a volcanic arc or microcontinent. More recently, Brueckner et al. (2004) have published Sm/Nd isotopic ages of c. 450 Ma from similar high grade rocks in the Seve Nappes of northern Jämtland, defining an enigmatic late Ordovician high P and T episode.

Orogenic collapse, extension and Devonian basins

The present structure of the Scandinavian Caledonides is strongly influenced by extensional shear zones and fabrics indicating W- to NW-directed translations. In southern Norway, it seems clear that the Caledonian wedge underwent uniform W to NW translation around or shortly before 400 Ma, with the Caledonian basal thrust zone acting as a low-angle décollement (Fossen, 1992). This back-sliding of the orogenic wedge gradually gave way to more localized extensional shear zones that transected the Caledonian crust (Figure 2).

Although low-angle extensional shear zones were initially discovered in southern Norway, they have later been found to affect the orogen from Stavanger to Troms (Fossen and Rykkelid, 1992; Braathen et al., 2002). The change from contractional to extensional tectonics seems to have happened shortly prior to 400 Ma in the southern part of the orogen (Milnes et al., 1997; Fossen and Dunlap, 1998). Farther north, the relationship between extension and contraction appears more complex, with a likely overlap between Scandian contraction and the formation of major extensional detachments (Tucker et al., 2004).

Deposition of coarse siliciclastic sediments occurred during Devonian extension. Remnants of these intermontane basins are preserved onshore in southwestern Norway (Steel et al., 1985). Tectonic thinning, exhumation of the high pressure rocks and denudation of the Caledonian mountain chain was fast during the Devonian, causing the change from a very deep-rooted crust with high mountains during collisional orogeny to a more normal crustal thickness and a flatter and desert-type landscape towards the end of the Carboniferous.

Greenland Caledonides

The 1,300 km long Caledonide Orogen of Northeast Greenland (Figure 3) preserves a relict collisional geometry and comprises far-travelled foreland-propagating thrust sheets that were derived from the Laurentian margin and translated westwards across the orogenic foreland. Restoration of thrusting suggests that the site of collision between Laurentia and Baltica was several hundred kilometres east of the present day onshore part of the orogen (Higgins and Leslie, 2000). The over-thickened orogen then collapsed with extensional reactivation of many of the original contractional shear zones that had previously defined the major thrust sheets.

In central parts of northern East Greenland (72°–75°N), the youngest sediments are of middle Ordovician age (~ 460 Ma); there are no breaks in the depositional record between the Lower Cambrian and the middle Ordovician, and no evidence of tectonic activity corresponding to the Finnmarkian or Trondheim phases of Scandinavia (Roberts, 2003). The earliest known Caledonian granitoid rocks in the orogenic belt crop out in the southern part of the orogen and are I-type calc-alkaline granodiorites and quartz diorites dated at 466±9 Ma, with several ages of c. 432 Ma (Nutman A.P. and Kalsbeek F., personal communication, 2003). These older I-type granitoids can be interpreted as parts of an arc, formed during subduction of Iapetus oceanic crust beneath Laurentia, and corresponding in time to the Taconian/Grampian phase of arc accretion elsewhere along the Laurentian margin. Crustal thickening processes led to the widespread formation of S-type Caledonian granites at 435–425 Ma, that were formed by melting of metapelitic units in thick Upper Mesoproterozoic to Lower Neoproterozoic metasedimentary sequences (Kalsbeek et al., 2001a, b). These leucogranites cut across high-grade fabrics, presumed to be of both pre-Caledonian and Caledonian age. Granite emplacement was pre- to syn-thrusting; many of the swarms of more foliated sheets show geometries consistent with foreland-propagating transport.

The foreland-propagating thrust architecture is well preserved in the southern half of the orogen (70°–76°N), where two major thrust sheets are widely distributed. Net thrust displacement is estimated at 200–400 km. There is no evidence in East Greenland for early Paleozoic marginal arcs and basins that must have been associated with final convergence with Baltica and the subduction of Iapetus oceanic crust. The East Greenland Caledonides are entirely ensialic, with the highest structural levels of the East Greenland thrust pile comprising an up to 18 km thick Neoproterozoic to middle Ordovician sedimentary succession (Eleonore Bay Supergroup, Tillite Group, Kong Oscar Fjord Group) that is spectacularly exposed in the central fjord zone (72°–75°N) of East Greenland. The 4 km thick succession of the Tillite Group and overlying Kong Oscar Fjord Group represents basin accumulation on the western margin of the Iapetus Ocean, and these thick developments are in stark contrast to the <400 m thick partly equivalent succession preserved in foreland windows beneath the Caledonian thrust pile. In the extreme north of the orogen (80°–82°N), a complete transition is preserved from undisturbed foreland in the west, through a thin-skinned fold-and-thrust belt to allochthonous thrust sheets, which farthest east involve high-grade gneisses exhumed from deep levels of the orogen. Estimated displacement of the major thrust sheets here ranges from 35–50 km to >100 km displacement (Higgins et al., 2004).

Caledonian metamorphic patterns in the orogen are variously superimposed on Archean, Paleoproterozoic and early Neoproterozoic metamorphic histories in Precambrian crystalline complexes and Neoproterozoic to Lower Paleozoic sedimentary cover successions along the length of the orogen. North of 76°N, metamorphic grade increases eastwards in progressively higher thrust sheets suggesting that Caledonian metamorphic patterns are likely to have been evolving from the time of accretion and up to the onset of major thrusting during the Scandian orogeny. Early Carboniferous age ultra-high-pressure metamorphic conditions (eclogite facies) are preserved in Paleoproterozoic gneiss complexes over a wide part of the coastal region (Gilotti and Ravna, 2002; McClelland et al., 2006). South of 76°N, evidence for very low grade to non-metamorphic conditions is preserved in foreland windows. The lower major thrust sheet records greenschist to amphibolite facies conditions, and lacks Caledonian granites and migmatization. The lower levels of the upper thrust sheet are characterised by abundant Caledonian granites in a mid-crustal level migmatite complex recording high temperature amphibolite to granulite facies con-

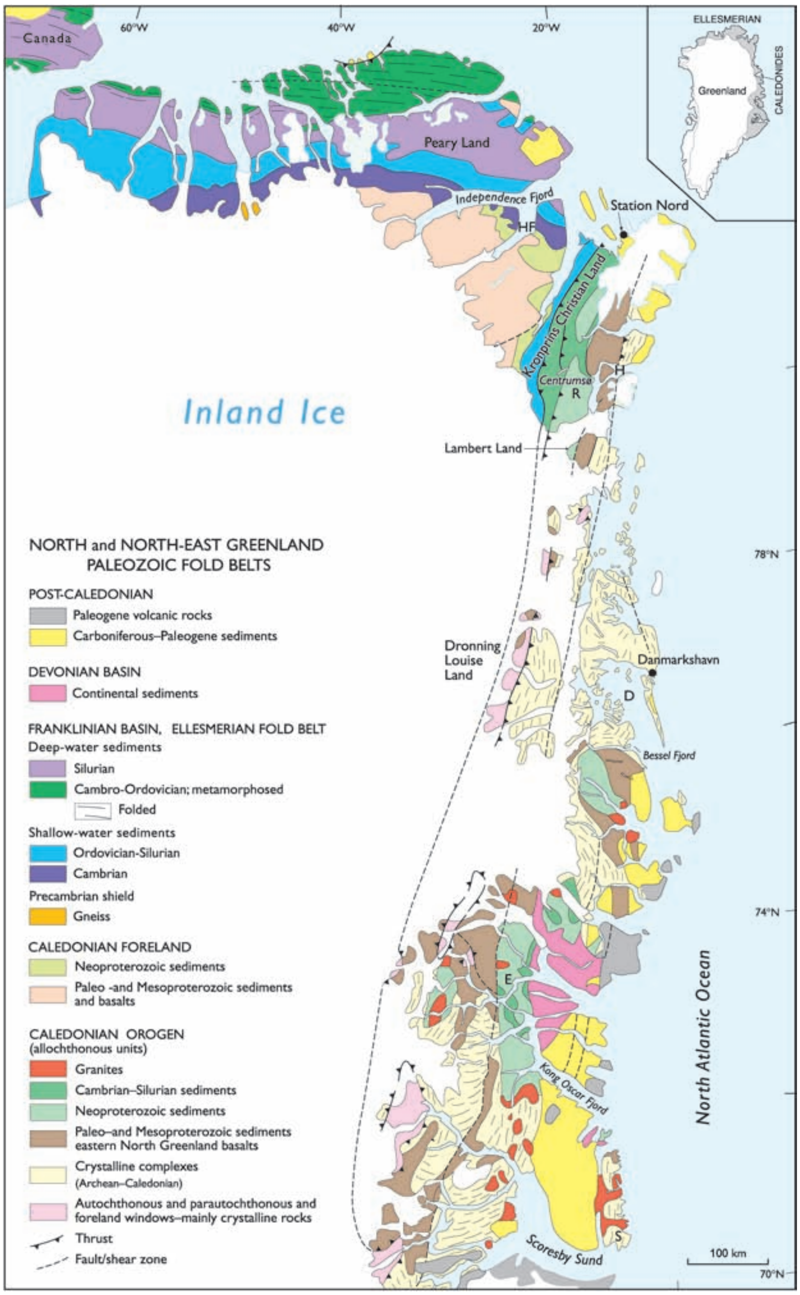

***Figure 3** Geological map of North and Northeast Greenland (from Higgins et al., in press), with the Silurian Caledonides in East Greenland and the early Devonian (?) Ellesmerian fold belt and its foreland in North Greenland. Place names: D: Dove Bugt, E: Eleonore Bugt, HF: Hagen Fjord, R: Rivieredal, S: Scoresbysund (town).*

ditions. The uppermost part of this upper thrust sheet comprises low grade to non-metamorphic Neoproterozoic to Cambro-Ordovician sedimentary rocks.

The outcrop pattern of geological domains in the East Greenland Caledonides is transected and displaced by a regional system of major late extensional faults, which essentially post-date emplacement and stacking of the thrust sheets. In the southern segment of the orogen, ESE-directed extension together with a N–S directed sinistral wrench component played a major role in extensional collapse of the East Greenland Caledonides and the initiation of the middle to late Devonian continental basins (Olsen and Larsen, 1993).

In the Caledonian foreland of northernmost East Greenland (north of 79°N) carbonate sedimentation on the Iapetus margin persisted into the late Llandovery (430 Ma). Silurian turbidites that brought carbonate deposition to a close are interpreted as debris flows derived from erosion of the rising Caledonian mountain chain. The youngest turbiditic sediments over-ridden by Caledonian thrusts are shales of the middle Wenlock (~426 Ma), and provide a maximum age for the frontal thrusts (Higgins et al., 1991).

The E–W trending Franklinian Basin that extends for 900 km across North Greenland, and further west into arctic Canada, was characterised from the early Cambrian until the early Silurian by a clear division into a southern carbonate shelf and a northern deep-water trough (Peel and Sønderholm, 1991). The trough accumulated turbiditic sediments of unknown derivation in the Cambrian, whereas most of the Ordovician was characterised by starved-basin conditions. In the Silurian (early Llandovery) the deep-water basin was flooded by vast quantities of turbidites, derived from erosion of the rising Caledonian mountains in East Greenland. During the Silurian the entire deep water trough was filled by turbidite flows, which then spread across the shallow carbonate shelf, bringing carbonate deposition to a close except in a restricted carbonate reef belt.

Sedimentation in the Franklinian trough ended in the early Devonian, and the Ellesmerian deformation that produced the E–W trending North Greenland fold belt took place sometime between the early Devonian and the late Carboniferous. In the north, up to three phases of folding are recognised in amphibolite facies schists. Deformation decreases southwards, with the limit of folding at approximately the former trough-shelf boundary and, in the south, typically of thin-skinned character; accompanying metamorphism decreases southwards from amphibolite facies through greenschist facies and into unmetamorphosed rocks. In contrast to the Caledonide Orogen of East Greenland, there are no granitic intrusions in the North Greenland fold belt, and gneissic rocks of the Precambrian basement are not exposed.

Svalbard and the Barents Shelf

The Caledonide Orogen of the Barents Shelf is exposed in the Svalbard archipelago (Harland, 1997), where generally N-striking Caledonian bedrock is exposed along most of the northern and western coasts of the main islands Spitsbergen and Nordaustandet (Figure 4). Old Red Sandstones, spanning most of the Devonian in age, occur in two N-trending grabens and are influenced by deformation in the early and late Devonian. These waning phases of Caledonian deformation involved both extension and shortening in sinistral transtensional/transpressional regimes. Related, major sinistral transcurrent faults divide the Caledonian bedrock into independent terranes (Gee and Tebenkov, 2004), which are described below.

Eastern terranes

Two Caledonian terranes have been distinguished in eastern Svalbard, the one (Nordaustlandet terrane) dominated by a late Grenville-age basement overlain by Neoproterozoic and early Paleozoic successions, and the other by a higher grade thrust complex of late Paleoproterozoic granitic basement and Mesoproterozoic cover (West Ny Friesland terrane), apparently uninfluenced by the Grenville-age orogeny.

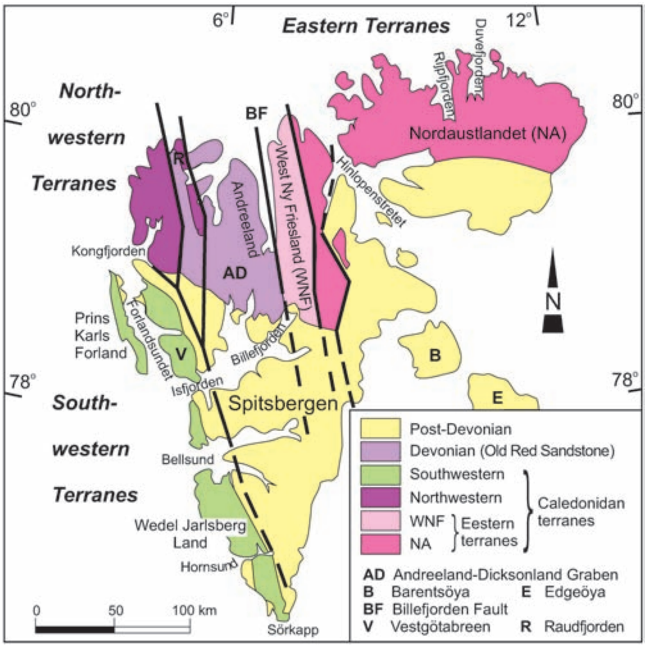

Figure 4 Svalbard's Caledonian terranes.

Nordaustlandet terrane

The Nordaustlandet Terrane, reaching from eastern Ny Friesland across Nordaustlandet to the isolated island of Kvitøya some 100 km further east, comprises the easternmost Caledonian bedrock on Svalbard. It is dominated by a thick Neoproterozoic siliciclastic and carbonate succession, the Murchisonfjorden Supergroup (also called Lomjorden Supergroup in eastern Ny Friesland), overlain by Vendian tillites and Cambro-Ordovician carbonates (Harland, 1997). This characteristic Laurentian margin Neoproterozoic succession rests with major unconformity on c. 950 Ma metavolcanic formations (andesites and rhyolites) and underlying metasediments (mainly turbidites) of latest Mesoproterozoic age. The metasediments were folded and intruded syntectonically by augen granites, also at c. 950 Ma, implying rapid intrusion, deformation, uplift and volcanic activity in the early Neoproterozoic. No basement to the late Mesoproterozoic successions has been recognised.

Northern parts of central Nordaustlandet and the areas further east (including Kvitøya) are dominated by migmatites, locally with augen granites. The latter have yielded c. 950 Ma ages, but zircons in the migmatites provide unambiguous evidence of Caledonian (c. 440 Ma) mobilization (Johansson et al., 2005) which also influences the lower parts of the Murchisonfjorden Supergroup and underlying metasediments. Caledonian deformation in the Nordaustlandet Terrane is dominated by W-vergent folds, which, at deeper structural levels, refold earlier recumbent folds and the intercalation of augen granites and gneisses.

West Ny Friesland terrane

The Neoproterozoic successions of the Nordaustlandet terrane are well preserved in eastern Ny Friesland, where they overlie an amphibolite facies complex comprising the West Ny Friesland terrane. These two eastern terranes are separated by a major normal fault, perhaps with a significant sinistral strike-slip component; they may previously have been juxtaposed by W-vergent thrusting.

The West Ny Friesland Terane (Witt-Nilsson et al., 1998) is dominated by a major fold, the Atomfjella Antiform, and composed of amphibolite facies granitic orthogneisses thrust together with psammitic metasediments. The orthogneisses, occurring at, at least, four levels in the antiform, yield c. 1750 Ma ages. Most of the intercalated metasediments are inferred to be Mesoproterozoic, based on the age of their detrital zircons and a metadolerite. The W-vergent thrusting, involving repetition of the late Paleoproterozoic granites and Mesoproterozoic cover, occurred during Caledonian high amphibolite facies metamorphism (Johansson et al., 1995).

Northwestern terrane

The Andreeland-Dicksonland Graben separates the Eastern from Northwestern terranes (Figure 4), with fluvial sandstones of Early Devonian and probably latest Silurian age (Friend et al., 1997) passing up into mid-Devonian marginal marine intertidal deposits.

The Northwestern Terrane (itself divided into two parts by a subordinate Devonian trough—the Raudfjorden Graben) is dominated in northwesternmost Spitsbergen by migmatites, extensively intruded by Caledonian granites (c. 430 Ma). The structure plunges gently southwards towards Kongsfjorden (Figure 4), where it gives way transitionally upwards into a thick succession of schists and marbles, the latter occurring as rafts deep in the migmatite complex. This metasedimentary succession is thought to be of late Mesoproterozoic or Neoproterozoic age (Ohta et al., 2002), and the migmatization Caledonian.

East of the Raudfjorden Graben, beneath the Old Red unconformity, the Caledonian bedrock, in southern parts, is similar to that further west, with schists and marbles passing down into migmatites within a major antiform. Locally, granites cutting the schists have yielded a 960 Ma age, implying that the northwestern Spitsbergen successions are potential correlatives of the late Mesoproterozoic successions in Nordaustlandet. In northern parts of this subordinate horst, on Biskayerhalvøya, an eclogite-bearing complex is exposed (Gromet and Gee, 1998), providing evidence of a Caledonian (c. 450–460 Ma) tectonothermal history that is in marked contrast to that in adjacent migmatite terranes.

Southwestern terrane

A major fault, through Kongsfjorden, separates the Northwestern from the Southwestern terranes. From Kongsfjorden southwards, the bedrock is influenced by the Cenozoic West Spitsbergen fold and thrust belt and the Caledonian history is more difficult to decipher. Nevertheless, a late Mesoproterozoic, Neoproterozoic and early Paleozoic record has been established that differs from the other Svalbard terranes; affinities with the Pearya terrane of northernmost Ellesmere Island in northern Canada has been favoured (Trettin, 1998; Harland, 1997).

North of Isfjorden (Figure 4), the Southwestern terrane is dominated by a variety of siliciclastic, greenschist facies metasedimentary formations, including thick diamictite-bearing units of inferred Neoproterozoic age. Early Ordovician blue-schists and eclogites of the Vestgötabreen Complex were thrust onto these older units and unconformably overlain by mid-late Ordovician conglomerates, limestones and Silurian turbidites (Ohta et al., 1989).

South of Isfjorden, a more coherent Neoproterozoic succession has been described (Birkenmajer, 1981), underlain by late Mesoproterozoic metamorphosed volcanic and sedimentary units. Vendian tillites are represented and, in southernmost areas, Cambro-Ordovician carbonates comparable with the successions further south on Bjornøya. Recently, remarkable evidence of a late Neoproterozoic (c. 640 Ma) amphibolite facies tectonothermal episode has been discovered (Majka et al., in press), providing additional evidence of the exotic nature of Svalbard's Southwestern terrane.

Barents Shelf, east of Svalbard

The evidence that Svalbard's easternmost terrane (Nordaustlandet) was subject to Caledonian migmatisation at deeper structural levels as far east as Kvitøya suggests that a substantial part of the Barents Shelf is underlain by Caledonian bedrock.

Deep drilling on Franz Josef Land (Figure 5) penetrated through an early Carboniferous unconformity into low greenschist facies turbidites reported to be of Vendian age, the small folding of which was inferred to be Caledonian (Dibner, 1998). Further east, on Novaya Ziemlya, early-mid Paleozoic successions, sourced from the west, locally include Devonian red beds, but no evidence of Caledonian deformation has been recorded. To the northeast on Severnaya Zemlya, folding and thrusting of Devonian Old Red Sandstone successions prior to the Visean (early Carboniferous) has been related to late Caledonian foreland deformation (Lorenz et al., 2007). The Caledonide Orogen has been inferred (Gee et al., 2006) to influence much of the Barents Shelf and it is has been referred to as the Barentsian Caledonides.

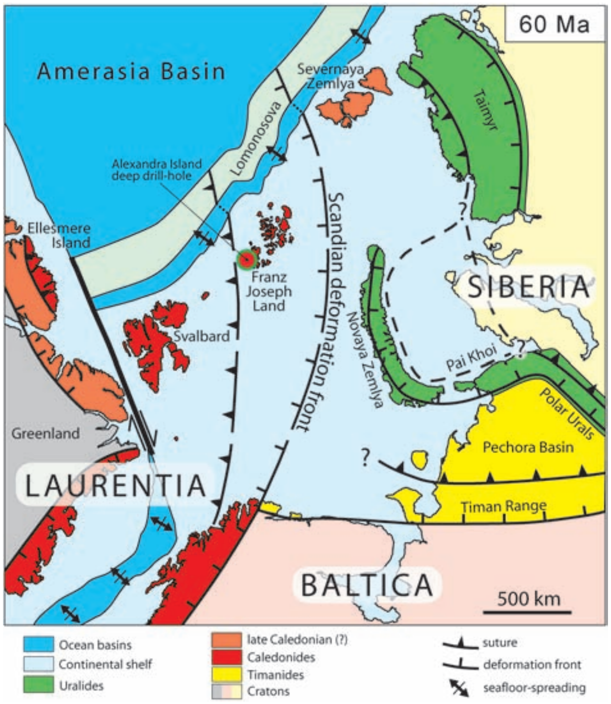

Figure 5 Arctic Caledonides, showing the relationships between the Caledonides, Timanides and Uralides and the cratons of Laurentia, Baltica and Siberia at the time of opening of the North Atlantic Ocean and the Eurasian basin (adapted from Gee et al., 2006).

Greenland-Svalbard relationships

The remarkable correlation of the Neoproterozoic Eleonore Bay Supergroup of central East Greenland and the Murchisonfjorden (Lomfjorden) Supergroup of eastern Svalbard, both overlain by similar Vendian tilllites and the Cambro-Ordovician carbonate bank, provides the basis for inferring that the East Greenland and Eastern Svalbard successions shared the same continental margin of Laurentia during the Neoproterozoic and early Paleozoic. The similarity between these successions has been interpreted to be the result of many hundreds of kilometres of sinistral strike-slip displacement of Svalbard's Eastern terrane along the Laurentian margin (Harland, 1997). Alternatively, Gee and Tebenkov (2004) have proposed that the sinistral displacements are subordinate and that Svalbard's Eastern terranes connected southwards through the continental shelf of northeasternmost Greenland to the mountains of central East Greenland. Svalbard's Southwestern terrane remains an enigma, being clearly exotic to the continental margin assemblages of the East Greenland Caledonides and the North Greenland Fold belt. Correlation with the Pearya terrane is favoured, but the evidence in both areas is too fragmentary to provide a coherent interpretation.

Summary of the tectonic history

The pre-Caledonian margins of Baltica and Laurentia, exposed in western Scandinavia and northeastern Greenland (with related parts of Svalbard), experienced a long history of Neoproterozoic rifting and extension prior to their separation from a larger continental assemblage, Rodinia, in the late Vendian. The relationship of these two margins of the Caledonide Orogen to each other in the Vendian remains poorly constrained and several alternatives have been proposed. Some favour juxtaposition, and a subsequent Wilson cycle of ocean opening and closing, with or without orogen-parallel strike-slip displacements; others require independence and invoke continent rotation prior to mid Paleozoic collisional orogeny.

Along the length of the Baltoscandian outer margin, the opening of an ocean was marked by widespread mafic magmatism at c. 600 Ma. By the Cambrian, passive margin successions of very different character and fauna were being deposited on the platforms, black shales dominating Baltica and carbonates Laurentia. The initial stages of ocean opening in the late Vendian were apparently accompanied by the accretion of Timanian terranes along the Baltica's northern margin, including what is now the eastern Barents Shelf; a passive margin was not established there until the late Cambrian, shortly before the start of Caledonian orogeny further west.

Within the Caledonide Orogen of northeastern Greenland, major W-vergent, long-transported thrust sheets dominate the structure, all derived from Laurentia's continental margin. Neither Vendian mafic dyke swarms, nor ocean-derived assemblages are present in these allochthon, which nevertheless involved deep underthrusting and local crystallisation of eclogites. By contrast, in Scandinavia the E-vergent thrust-sheets were transported from both oceanic and outer continental margin environments and emplaced many hundreds of kilometres onto the Baltoscandian platform. Laurentian margin and proximal island-arc terranes are inferred to comprise the highest allochthons in this part of the orogen. Closure of the ocean (Iapetus), separating Laurentia from Baltica, started in the earliest Ordovician (perhaps late Cambrian) and culminated in the early-mid Silurian with continent collision. About seventy millions years of subduction-related magmatism, sedimentation, deformation and metamorphism are recorded in the fragmented ophiolites, island-arcs and back-arc assemblages of the Scandinavian mountains. Scandian collisional orogeny (c. 430–390 Ma) involved underthrusting of Laurentia by Baltica and crystallisation of eclogites, locally with coesite and microdiamonds, in the deep hinterland. Eclogites and granulite facies migmatites are also present in some high grade allochthons (e.g., Seve Nappes) “extruded” from the outermost parts of the Baltoscandian margin onto the platform.

Caledonian collisional orogeny in both northeastern Greenland and western Scandinavia culminated in the latest Silurian and early Devonian with rapid exhumation of hinterland high grade complexes, deep erosion, deposition of Old Red Sandstones in intracratonic and foreland basins and major extensional faulting.

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by Bjørn T. Larsen[1], Snorre Olaussen[2], Bjørn Sundvoll[3], and Michel Heeremans[4]

The Permo-Carboniferous Oslo Rift through six stages and 65 million years

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The Oslo Rift is the northernmost part of the Rotliegendes basin system in Europe. The rift was formed by lithospheric stretching north of the Tornquist fault system and is related tectonically and in time to the last phase of the Variscan orogeny. The main graben forming period in the Oslo Region began in Late Carboniferous, culminating some 20–30 Ma later with extensive volcanism and rifting, and later with uplift and emplacement of major batholiths. It ended with a final termination of intrusions in the Early Triassic, some 65 Ma after the tectonic and magmatic onset.

We divide the geological development of the rift into six stages. Sediments, even with marine incursions occur exclusively during the forerunner to rifting. The magmatic products in the Oslo Rift vary in composition and are unevenly distributed through the six stages along the length of the structure.

Introduction

The Oslo Palaeorift (Figure 1) contributed to the onset of a prolonged period of extensional faulting and volcanism in NW Europe, which lasted throughout the Late Palaeozoic and the Mesozoic eras. Widespread rifting and magmatism developed north of the foreland of the Variscan Orogen during the latest Carboniferous and continued in some of the areas, like the Oslo Rift, all through the Permian period. We review the geological development of the Oslo Rift through its six stages of development (Ramberg and Larsen, 1978, Sundvoll et al., 1990, Olaussen et al., 1994), focusing on the four first—their lavas, sediments and tectonic structure, and briefly put it into the plate tectonic framework of NW Europe.

The Variscan orogeny, the Tornquist line and the Oslo Rift

The Oslo Rift sediments exhibit great similarities to the Lower Rotliegendes in the Northern European Permian Basin and in Kattegat and may be regarded as a prolonged northern arm of the Northern Permian Basin. The Skagerrak Graben is the southern part of the Oslo Rift and is the link between the two tectonic systems (Heeremans et al., 2004).

Recent reviews of post-Variscan tectonics in Western Europe (McCann et al., 2006; Ziegler et al., 2006) have described the genetic relations and the timing between the Variscan orogeny and subse-

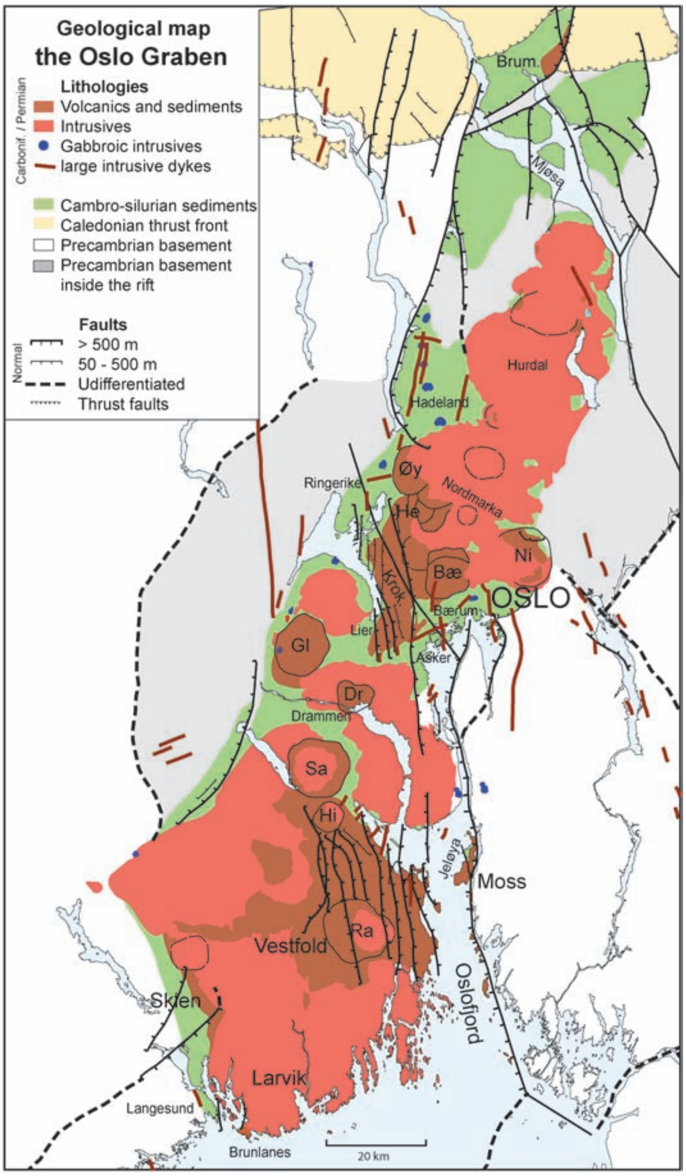

Figure 1 ***Simplified geological map of the Oslo Graben area. Brown—includes both volcanics, sediments and large dykes related to the Oslo Graben; Carboniferous-Permian age. Red—large Permian batholithic intrusions. Small blue dots—Permian gabbroic intrusions. Green—Lower Palaeozoic sediments. Yellow—the Caledonian thrust front. White—Pre-Cambrian basement rocks. Abbreviations for different areas: Brum. = Brumunddal, Krok. = Krokskogen, and for the caldera volcanoes; Øy = Øyangen, He = Heggelia, Ni = Nittedal, Bæ = Bærum, Gl = Glitrevann, Dr = Drammen, Sa = Sande, Hi = Hillestad and Ra = Ramnes.***

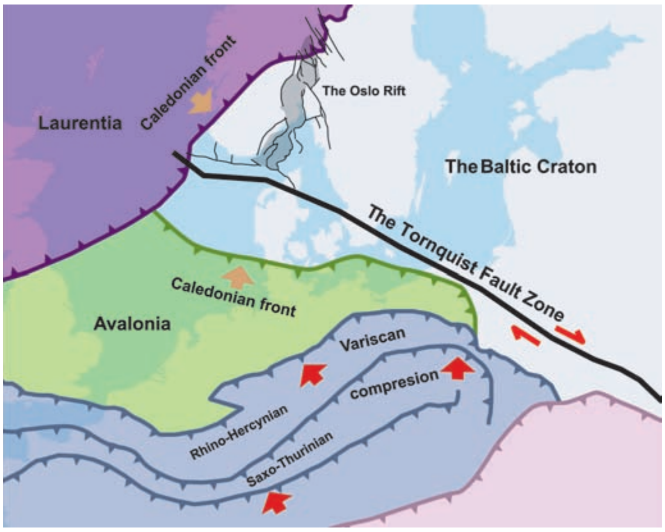

Figure 2 Simplified tectonic overview of West Europe with the Variscan front, the Tornquist fault system and the Oslo Rift. Also shown are the pre-rift configurations with the Caledonian structures and the boundary of the Fennoscandian Craton.

quent large, mostly NW-SE striking, wrench fault systems. The largest and northernmost is the Sorgenfrei-Tornquist Zone (Figure 2) that strikes across Scania (Skåne) into the North Sea (north of the Ringkøping-Fyn High), developing at least partly as a dextral strike-slip fault system. North of this fault, extensional stress fields developed widespread rifting, being linked to the late stages of the orogeny and to the strike-slip faulting (Heeremans et al., 1997). Rifts formed both inside the orogen and in the foreland to the north, even extending into the Fennoscandian Craton. The northernmost and the largest of these structures was the Oslo Rift.

Warr (2000) divided the development of the Variscan orogenic system in NW Europe into four phases, separated both in time and in different areas. The last of the four phases is named the Asturian phase and is generally Westphalian to Early Permian in age. Both Ziegler et al. (2006) and McCann et al. (2006) described it as the consolidation phase of the Variscan Fold belt and gave an age 305Ma as the critical decline of the Variscan orogeny and the onset of rifting. Latest Carboniferous to earliest Permian was the time for the onset of the Oslo Rift, leading up to its climax of both tectonic and magmatic activity (Sundvoll et al., 1990; Heeremans et al., 1997).

The Oslo Rift architecture and nomenclature

The architecture of the Oslo Rift is very much like that of other well known rift structures. Most have polarity off-set of grabens along the length of the rift axis, as described e.g. by Rosendahl (1987). The Oslo Graben (Figure 3) was subdivided into two rift segments with opposite subsidence polarity (Ramberg and Larsen, 1978). The Akershus Graben segment has an E-verging master fault (the Randsfjord-Hunnselv Fault) to the north, while the Vestfold Graben segment has a W-verging master fault (the Oslofjord Fault) to the south. These two half grabens have their accommodation zone around the city of Oslo, with a joining fault to the west of Oslo in the Kjaglidalen-Krokkleiva Transfer Fault (Heeremans et al., 1997). Today, we add the third Rendalen Graben segment to the north of the Akershus Graben, also with a west-verging master fault system, the Rendalen Fault (Skjeseth, 1963; Larsen et al., 2006). The accommodation, or transfer system, between the Akershus Graben and the Rendalen Graben is represented by the NE-SW trending Solberg Horst, beside lake Mjøsa.

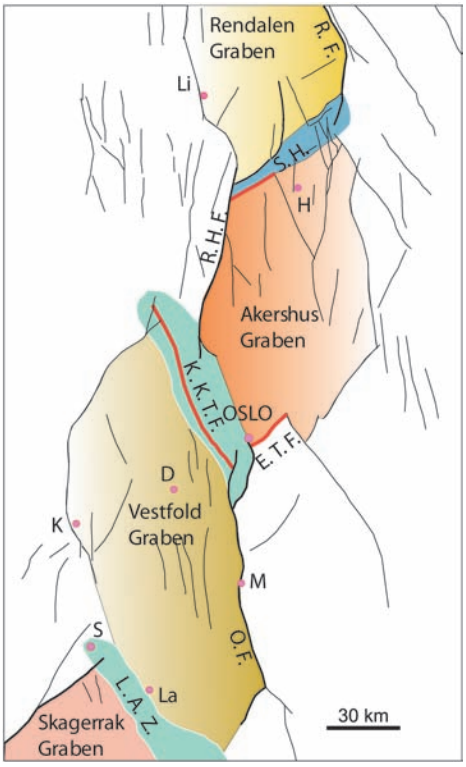

Figure 3 The graben segments and the graben polarity, the master faults, the accommodation structures and the transfer fault in the Oslo Rift. Abbreviations of the structural nomenclature: R.F. = Rendalen fault, S.H. = Solberg Horst, R.H.F = Randsfjorden-Hunnselv Fault, K.K.T.F. = Krokkleiva-Kjaglidalen Transfer Fault, E.T.F. = Ekeberg. Transfer Fault. O.F. = Oslofjord Fault, and L.A.Z. = Langesund Accommodation Zone. Li = Lillehammer, H = Hamar, D = Drammen, K = Kongsberg, M = Moss, S = Skien, La = Larvik.

Finally, the offshore Skagerrak Graben represents the southernmost part of the Oslo Rift, and abuts towards the NW-SE trending Sorgenfrei-Tornquist Zone in the south. The two Akershus and Vestfold graben segments form the classical Oslo Graben which is 220 km long and about 60 km wide. Adding the 100 km long Rendalen Graben in the north, and the 180 km offshore Skagerrak Graben in the south makes the total length of Oslo Rift about 500 km. The Skagerrak Graben is broader than the other segments to the north, and is composed of several more or less overlapping grabens (Heeremans et al., 2004). The rift axis here strikes NE-SW, perpendicular to the Sorgenfrei-Tornquist fault system.

The petrogenesis of a high volcanicity rift

Larsen and Sundvoll (1984) summarized the Oslo Graben part of the Oslo Rift as a north-south trending Permo-Carboniferous high-volcanicity continental rift system, much like the recent East African rifts of Kenya and Ethiopia. The high volume of volcanics filling the rift is a feature common to both, and distinguishes them from other continental low-volcanicity rifts such as the Baikal Rift and the Viking Graben. These two categories of rifts are useful descriptive end-members (Barberi et al., 1982).

A thorough analysis of the available data from the Oslo Rift was undertaken by Neumann et al. (2004). They discussed the magma origin and concluded that at least three mantle components have contributed to the petrogenesis of the basaltic magmas, the oldest apparently being derived from an enriched mantle source. This source was most likely located in the lithospheric mantle and might have been metasomatically altered by older carbonatitic fluid-rich melts (Anthony et al., 1989). The main mantle source for the basaltic magmatism was a prevalent depleted mantle. It may represent the composition of the base of the local lithospheric mantle, and the asthenosphere beneath, which partly melted in response to localized thinning of the lithosphere due to the extension. Anthony et al. (1989) also suggested an alternative scenario involving a mantle plume, with depleted characteristics, actively up-welling beneath the lithosphere. The most primitive lavas appear to involve low degree partial melting of one or more sublithospheric mantle sources. The rising mantle-derived magmas were modified by shallow-level processes, including magmatic differentiation, general fractional crystallisation, magma mixing and lithospheric contamination that masked the geochemical signature of the mantle source.

Large volumes of mantle-derived basaltic magma formed chambers near the Moho at c. 36 km depth. This also led to anatectic melting in the Precambrian host-rocks. Initial Sr isotopic ratios significantly above 0.7039 are typical of the syenitic and granitic rocks and imply influence of crustal contamination in the lower crust (Sundvoll et al., 1990). After 280 Ma, the rocks show a clear trend of increasing initial ratios; mantle signature is only present in the larvikites and the rhomb-porphyry and basalt lavas. Sundvoll et al. (1990) interpreted the Sr-initial ratios to reflect the relative importance of mantle- versus crustal-derived melts. At c. 280 and 275 Ma, the magmatism became dominated by melts (syenitic and granitic) containing a larger crustal component. The mantle source had slowly become inactive, but mantle-derived magmas were still undergoing fractional crystallisation in magma chambers in the lower crust giving rise to evolved rocks such as larvikites and late rhomb porphyry lavas, and to basaltic central volcanoes with shallower crustal magma chambers at c. 20 km depth. This termination of new mantle material into the Oslo Rift starts the mature stage of the rift. From this time, the slow tectonic and magmatic decay of the Oslo Rift started, and the rift segments developed differently. This long "aftermath" period towards the final termination lasted about 15 million years in the Vestfold Graben, but as long as 35 million years in the Akershus Graben. The transition from the "mantle melting" to the "mature stage" and further to the "aftermath" is also reflected in a change in magma-tectonic style: (a) the magmatism migrated towards the central part of the graben, and (b) fissure eruptions and normal faults gave way to central volcanoes and, finally, to explosive volcanism and caldera-collapse. Mantle derived melts appear to have been present somewhat later under the Akershus Graben than under the Vestfold Graben. This is in agreement with the proposed northwards propagation of the rift and its magmatism.

The asthenospheric mantle source of the most primitive magmas bears the signature of being plume-related. The discussion on the influence (if any) of a deep mantle plume on the magmatism in the Oslo Rift has been a controversy for about twenty years. Today, opinions seem to be swinging in favour of a plume, apparently supported by geophysical evidence (Torsvik et al., in press).

The six stages of development

Stage 1: The proto-rift forerunner to rifting

The Oslo Rift was initiated in the Late Carboniferous with deposition of a thin carpet of sediments in the southern two-thirds of what later was developed as the Oslo Graben. No record of sedimentary rocks from this forerunner stage are observed NE of the city of Oslo, suggesting non-deposition. These sedimentary rocks are named the Asker Group (Figure 4), which in the central part of the Graben is subdivided into three formations, of which the two first: the Kolsås Formation and the Tanum Formation belong to the proto-rift stage.

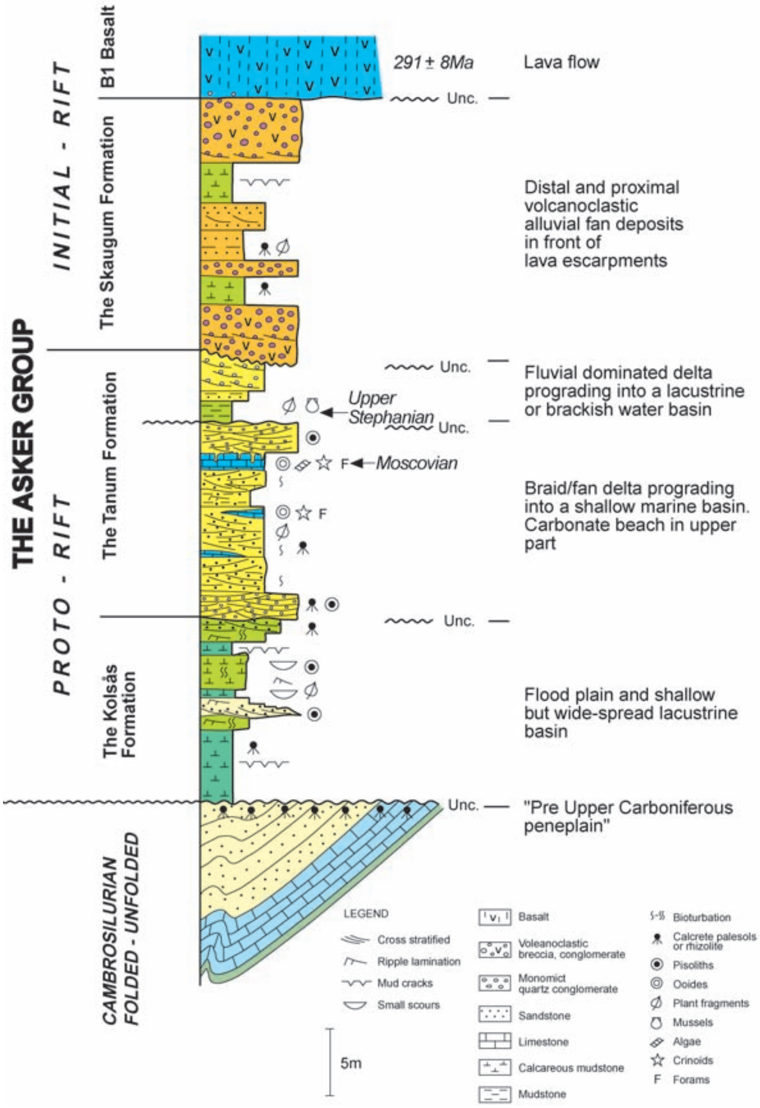

Figure 4 An overview of the stratigraphy of the two first stages of the development in the central part of the Oslo Graben.

In the central part of the Oslo Graben, the up to 20 m thick Kolsås Formation unconformably overlies the folded Cambro-Silurian sediments. The formation is dominated by red mudstones and sandstones with subordinate greyish to greenish conglomerates, limestones and rare anhydrite. The depositional environments have been interpreted as floodplain, fluvial stream channel fill and shallow lake (Dons and Gyøry, 1967; Henningsmoen, 1978; Olaussen et al., 1994). Immature to mature calcrete soil profiles (paleosols) are recognised in the red overbank and floodplain facies (Olaussen, 1981). This, together with evaporite minerals suggest that arid and semi-arid conditions must have prevailed during the deposition of the Kolsås Formation. A 30 m thick similar unit occurs in the southernmost part of the Vestfold Graben (Olaussen and Dahlgren, 2007).

The overlying 20 m thick Tanum Formation locally cuts down into the underlying Kolsås Formation. Also in the southern part of the Oslo Graben, an unconformity separates a lower finer grained unit from an upper 60 m thick coarser section. The Tanum Formation is well known for grey quartz conglomerate beds, which reach up to 5 m in thickness and are often large-scale cross-stratified and interbedded with medium to very coarse grained or pebbly sandstones. Grey and finer grained sandstones, green and less common red mudstone and limestone are other common lithologies. Dark greyish plant-rich, minor coaly, mudstones have been observed. The Tanum Formation has been interpreted as representing alluvial stream channels, floodplains and deltaic deposits (Dons and Gyøry, 1967; Olaussen et al., 1994). The coarser grained units are interpreted as braid plains and fan deltas deposits. Up to two meter thick calcrete profiles with hardpan and some silcretes show evidence of development of mature soil profiles in an arid to semi-arid climate. A thin marine limestone (sandy grainstone) overlies a fluvial or fluviomarine channel in the Kolsås area. This up to 2 m thick bed (Knabberud Limestone Member) is interpreted as a beach deposit (Figure 4). Clasts of this lithology are also recognised in other central parts of the Oslo Graben. Cross-stratified and horizontally laminated carbonate beds in Skien area resemble the same formation, suggesting a widespread marine incursion in the Oslo Graben (Olaussen, 1981). The scattered occurrence of foraminifers (fusulinids), e.g., *Novella evoluta mosquensis* (Rauser) in the limestone suggests a late Bashkirian (Westaphalian A+B) to late Moscovian (Westphalian D) age for the marine incursion. The fauna (freshwater mussels, fish and reptile remains) and flora in the uppermost part of the Tanum Formation and the overlying Skaugum Formation in the Asker area was suggested to be correlative with the Lower Permian in Northern Europe (Holtedahl, 1931; Höeg, 1936). It is suggested that this fossil-bearing unit in the Tanum Formation in Asker overlies the Knabberud Limestone Member. Eager (1994) reviewed the freshwater mussels and suggested a correlation with Upper Pennsylvanian in North America. The flora has also been reviewed and indicates a stage between Westphalian/Stephanian to Stephanian in northern Europe. The age of the Tanum Formation is also constrained by the radiometric age (291± 8Ma, Sundvoll et al. (1990) in the central Oslo Graben) and 300±1 Ma, Corfu and Dahlgren (2007) in the southern Oslo Graben) of the first overlying lava. The formation was deposited prior to the major outpouring of lavas.

The marine Knabbereud Limestone shows an affiliation with carbonate platform units of the same age beneath the Barents Sea, eastern and southern Europe. This implies that the Oslo area could have been flooded in the Late Carboniferous from both the east and the south. The variable lithologies and facies variations observed in the Tanum Formation are consistent with deposition during a period of major climatic and sea level changes, as recorded at the end of the Carboniferous, elsewhere.

Spread over most of the Oslo Region, we find sill intrusions that are radiometrically dated to the Late Carboniferous (308–305 Ma), which indicate a “mid” Pennsylvanian age (Sundvoll et al., 1992; Sundvoll and Larsen, 1994). This corresponds to the “key-age” for the start of magmatic activity, as also suggested by Ziegler et al. (2006). The sill intrusions are primarily of syenitic composition (maenaite), but also basic camptonites occur. The thickness of the sills varies from cm-scale to more than 10 meters.

Stage 2: The initial rift and first basaltic volcanism

Stage two (Figure 4) exhibits only basaltic lava flows and an up to 20 m thick volcaniclastic unit, the Skaugum Formation of the Asker Group. The basalts from this stage show the whole suite of compositions from highly silica undersaturated melilitites to oversaturated quartz tholeiites. The different basaltic lavas, however, are found in different areas or provinces during this very early development of the rifting.

In the southernmost province of Brunlanes (Figure 1), a total stratigraphic thickness of 800 m of basaltic lavas is located. The Brunlanes basalt flows are relatively thin (~5–0.5 m), and all are silica undersaturated melilitites and nephelinites. Recent U–Pb-dating has given the age 300 Ma for the earliest flows in the south (Corfu and Dahlgren, 2007). We therefore assume that these highly Si-undersaturated basaltic lavas are the oldest in the rift system. These most strongly alkaline and undersaturated basalts erupted in an initial rift setting and are similar to the proto-basalts in the Kenya rift (Williams, 1970 and 1971). In both rifts, they erupted closest to the potential “hot spot” and very early during the rift evolution.

To the northwest of Brunlanes, an equally thick suite of basaltic lavas are exposed in the Skien-Porsgrunn area called the Skien basalts. The flows are slightly thicker than in Brunlanes and vary in composition. These volcanic rocks are Si-undersaturated, mostly basanites in the lower part and more alkaline olivine basalts in the upper half. Thin volcaniclastic sediments and pyroclastic products are found between some of the lava flows. The Skien basalts, and most likely also the Brunlanes basalts, came from an enriched mantle source, potentially as a result of low degree partial melting within the garnet-bearing part of the mantle (Anthony et al., 1989). Thus, the earliest and southermost basalts in the Oslo Rift indicate a low degree of partial melting in an asthenospheric mantle source, subsequently modified by lithospheric mantle and crustal components (Neumann et al., 2004). A possible mantle plume or several smaller plumes have been inferred by Wilson et al. (2004).

The largest basalt province during Stage 2 is in the Vestfold/Jeløya area, in the central Oslofjord area and continues all the way to northwest of Drammen. The thickness of the Holmestrand/Jeløya basalts varies from 1500 m at Jeløya, close to the Oslofjord Fault, to about 100 m at places in central northern Vestfold. The composition of this basalt suite is ordinary alkaline olivine basalts, and the thickness of the individual flows varies from a few meters to c. 10 m. Some few flows of high-Ti basalts are found both at Jeløya and in Vestfold (Schou Jensen and Neumann 1985, Neumann et al., 1989). Many flows are aphyric, but flows with phenocrysts of olivine (mostly altered), augitic clinopyroxene and plagioclase are more common. The basalts erupted from a series of composite fissure volcanoes and from shield volcanoes, mostly as relatively thin compound lava flows, with nice examples of aa-lavas, pahoehoe-lavas and columnar jointing. Volcaniclastic sediments are frequent between the flows; they are mostly thin and varing from fine sand (wind blown) to well-rounded coarse conglomerates. Pyroclastic products are also found, but are not frequent.

North of the basaltic lava field in Vestfold, no alkaline olivine basalts are found north of Drammen. However, in Lier and Asker, we find sediments in this stratigraphic position. Alluvial debris flows were building out towards the north from the large basalt field in Vestfold. The sedimentary structures indicate a northward transport and all clasts are of alkaline olivine basalts. These, up to 30 m thick, red sediments are named the Skaugum Formation and occur only in the central part of the Oslo rift. The unit is dominated by volcaniclastics, varying from well sorted sandstones to coarse conglomerates. Although there is an abrupt change in composition and in colour from grey to red between the Tanum and Skaugum formations, no major unconformity is observed. Also some of the freshwater fauna and flora seen in the Tanum Formation continue into the Skaugum Formation. Inverse graded breccia occurs and is interpreted as deposition from debris flows. Together with similar continental depositional settings as in the Tanum Formation, this suggests a more proximal facies in the Skaugum Formation, probably representing an alluvial fan deposit (Olaussen et al., 1994). The Skaugum Formation also exhibits calcrete soil profiles, suggesting a semi-arid to arid climate during deposition.

In Lier and Asker, on top of the Skaugum Formation volcaniclastic sediments, there occurs a single aphyric basaltic lava-flow. It covers the whole of the central Oslo area, with a thickness varying from 5 to 20 m, and must have erupted as one simple flow from a fissure volcano. This flow, called the Kolsås basalt, has a quartz tholeiitic composition and is the only basalt in the Oslo Rift of this composition. North of this area, there is no indication of any eruption at this stage in the rift.

Stage 3: The rift climax, with rhomb porphyry fissure volcanoes

When the change to Stage 3 started, a new era opened (Figure 4), marked by the eruption of rhomb porphyry *(RP)* lavas. With this climax stage of the Oslo Rift, the volume of eruptions increased. The eruptions of alkaline olivine basalts did not stop, but continued into Stage 3. It continued and spread further to the north, but most likely decreased in volume and intensity. The earliest rhomb porphyry lavas had extremely large volumes. Together they covered an area of the southern and central Oslo Graben from well north of Oslo city and to the outer part of the Oslofjord, i.e. about 10,000 km^2. With an estimated thickness of at least 100 m, the total volume may have been as large as 1,000 km^3. But most subsequent RP-flows were much smaller than this first flow, varying in thickness from about 5 m to more than 100 m. Rhomb porphyry lavas are found all over the classical Oslo Graben, from Brumunddal in the north to Brunlanes in the south, a distance of about 220 km. They are today concentrated in two large and a number of smaller lava plateau areas. The two large provinces are the Krokskogen lava plateau (about 400 km^2) west of the city of Oslo and the Vestfold lava plateau (>1,000 km^2) in northern and central Vestfold. The stratigraphical thickness of the lavas in Vestfold is about 3 km, and about 75% are rhomb porphyries. At Krokskogen, the thickness is about 900 m with about 80% rhomb porphyries.

The production rate of RP-flows in the different areas varied. In Vestfold, about 50 flows erupted during about 10 million years giving a production rate of about one flow every 250,000 years. At Krokskogen, 20 flows erupted over 14 million years giving a production rate of about one flow every 600,000 years (Sundvoll et al., 1990). The eruptions continued longer at Krokskogen than in Vestfold. And the first of the four flows in Brumunddal, in the southern part of the Rendalen Graben in the north, is much later than the first RP-flows further south.

The rhomb porphyries have an intermediate composition with c. 55% SiO_2 and with relatively high content of Na and K. Feldspar phenocrysts constitute from c. 5 to 30% of the volume, and the feldspar crystals are mostly larger than 1 cm. The phenocryst feldspar is a ternary feldspar, zoned with a Ca-rich core and K-rich rim (Harnik, 1969). Such lavas, with a high content of Si and phenocrysts, would be expected to have a relatively high viscosity (Sæther, 1962). But the volcanological "performance" of the RP-lavas indicates that they flowed out quietly over large areas in "Hawaiian" style, accompanied by hardly any pyroclastic products. Consequently, the viscosity must have been relatively low. Two factors likely explain this behaviour. Firstly, the temperature must have been relatively high, being calculated to about 1050–1100°C (Larsen, 1978), i.e. about the same temperature as that of an evolved basalt with plagioclase phenocrysts. Secondly, there must have been a high content of dissolved gases. Dissolved water and other gases like halogens will decrease the viscosity. Recent analysis has shown that the content of Cl is low in the RP-lavas, but the content of F is very high, 0.25 to 0.5%. Calculations using USGS software "Conflow" (Mastin and Ghiorso, 2000) give viscosities of between 3 and 5 Pa·s in the southern part in the southern part using temperatures between 1050 and 1100°C, gas-dissolution of 1–3% and phenocryst content between 3 and 10%. This is only slightly more viscous than "Kilauea basalt" from Hawaii and explains the rhomb porphyry lavas volcanological behaviour.

Outside the lava plateau, large, mostly N-S striking RP-dykes occur over most of the area. Our impression is that the rare and huge RP lava flows erupted from large fissure dykes; the RP lavas are therefore classified as monogenetic fissure eruptions. Most of the RP-lavas have the appearance of simple flows; not compound flows like most of the basalts. By contrast, the basalts in Stage 2 probably erupted from polygenetic fissure and central volcanoes as compound and thin flow systems. Both at Krokskogen and in Vestfold, we find basalts interfingering with the RP-lavas. The basalts are mostly alkali olivine basalts, but also undersaturated basanites occur.

Apart from the extrusions, some sedimentary units are preserved as remnants of the original basin fill within the Oslo Graben (Olaussen et al., 1994). They can be grouped into two types: sedimentary rocks preserved between the lava flows, and thick (up to 1 km) units above the lava flows. The first group include fluvial and alluvial fan deposits and thin calcrete paleosols. Units with finer grained ripple-laminated sandstones and mudstones with stromatolithic limestone provide evidence for the development of ponds or smaller lakes. Up to 1 m thick, well sorted and rounded, large scale cross-stratified fine grained sandstones are interpreted as eolian dunes. A 400 m thick canyon-fill in the Krokskogen lava plateau, presumably terminated in an alluvial fan on the lowlands in the west. This, the Migartjern conglomerate, is uncomformably overlain by younger basalt and rhomb porphyry lavas (Larsen, 1978). In the second group, two major units are recognised: a minimum 1 km thick, coarse rhomb porphyry conglomerate (Brøgger, 1900; Størmer, 1935; Larsen et al., 1978), banked against the eastern master fault in the Vestfold Graben, and a 800 m thick dune and wadi deposit in the southern part of the Rendalen Graben in Brumunddal. The first of these represents debris flows, stream and sheet floods in an alluvial fan setting. The second, comprising the down-faulted red and yellow Brumund Formation, has both large scale, cross-stratified eolian dune deposits and fluvial stream channel and flood plain deposits (Rosendahl, 1929). Recent mapping and sedimentological studies of the Brumund Formation have also recognised lacustrine limestones and calcrete paleosols (Lothe et al., 1999). These authors recorded bedding to dip south-eastwards up to 60°, and to decrease upwards, and interpreted a syn-rift depositional environment. The sedimentary rocks which are preserved in the hanging-wall towards master faults are a response to increasing topography in the graben. These sedimentary rock units are compared with the Rotliegendes deposits in the North Permian Basin.

The end of the climactic Stage 3 was marked by the emplacement of major larvikitic batholiths.

Stage 4: The mature rift, with central volcanoes and caldera collapse

The volcanic processes and the products again changed when the rift-development approached Stage 4. Basaltic central volcanoes started to develop in many parts of the rift, which was now developed as a prominent structure with large faults bounding the grabens. Rhomb porphyries continued to erupt during this stage, but most likely with a decreased intensity and volume, together with the new formation of central volcanoes.

At tectonically strategic places all along the Oslo Graben, central volcanoes started to form. Most were basaltic with slight variation in composition. They were mainly alkaline olivine basalts, but also more Si-saturated transitional types occur as in the Glitrevann volcano, north of Drammen. The most prominent tectonic setting of some of these extrusions is a N-S trending string of volcanoes along the central axis of the Vestfold Graben, from Ramnes in the south to Glitrevann, NW of Drammen (Ramberg and Larsen, 1978). All central volcanoes did not necessarily start to form at the same time and it is possible that the southern ones started before those in the north.

The diameter of the calderas at the present erosion level varies between 12 km (e.g., at Ramnes and Nittedal) and 6 km (e.g., at Drammen). We infer from comparisons elsewhere that the original diameter of the pre-caldera volcanoes at their base was about three times the size, i.e. 36 to 18 km. Central volcanoes of similar setting with calderas are found in the Kenya Rift Valley e.g. the Silali, Suzwa and Menengai volcanoes (Williams, 1970; Baker et al., 1971). By analogy with the East African Rift, the heights of the central volcanoes in the Oslo Rift are estimated to have been in the order of 1–1.5 km above the rift valley floor. Apparently, the Kenya and the Ethiopian rifts are today in a situation similar to that in the Oslo Rift in the middle of Stage 4. The rift valley had formed, the central volcanoes were active and several of them had reached a mature explosive caldera-forming stage.

All the large central volcanoes inside the Oslo Rift seemed to have matured petrologically. Olivine, augitic clinopyroxene and plagioclase crystallized out of the basaltic magma leaving a felsic, mildly alkaline magma as the residual melt product. The latter was mostly trachytic in composition, but some also developed to alkaline rhyolites. The magma-products finally erupted explosively during the caldera formation. At the present erosion level in the Oslo Graben, felsic ring-dykes and central domes are exposed together with large and small remnants of ignimbritic effusives mixed together with basalts and other pre-caldera products. Only in Vestfold do we find thick and widespread ignimbrites in the upper part of the rhomb porphyry succession outside the calderas, most likely erupted from the nearest calderas. The age of these trachytic ignimbrites (T1 and T2) in inner Vestfold has been dated to 288 Ma and 285 Ma, respectively (Sundvoll and Larsen 1990). Even though these datings have limited precision, they indicate that the explosive eruptions in Vestfold are older than the ones further north, and that the different development stages distinguished in the Oslo Graben, were not synchronous, but started in the south. At Krokskogen, we lack significant dating among the caldera-related extrusive products, but the intrusions (ring-dykes and central intrusions) in the caldera cluster formed at c. 270 Ma, implying that the explosions from these calderas (e.g., the Øyangen caldera) most likely were significantly younger than in Vestfold. Since ignimbrites have not been observed in any part of the Krokskogen plateau, and the uppermost RP-lava was dated to c. 276 Ma, we have an interval of about 10 Ma between the first Vestfold caldera explosions and those at Krokskogen.

The youngest sedimentary units preserved inside the Oslo Rift calderas are red breccias, sandstones and thin laminated mudstones, often associated with pyroclastic rocks. These units are interpreted to be of alluvial and lacustrine origin, and the best preserved are inside the Nittedal caldera (Naterstad, 1978).

Small alkaline gabbros were intruded during Stage 4 at c. 265 Ma and are located along N-S tectonic lineaments like at Hadeland, and in clusters as in the central Oslofjord area (Neumann et al., 1985). They are only from 1 km to 100 m in diameter, sometimes exhibit layering and represent basaltic magma chambers that existed below smaller basalt volcanoes at the same time as the larger ones that developed to caldera volcanoes (Steinlein, 1981).

The large batholithic Drammen granite and a slightly smaller body further to the north, the Finnemarka granite, intruded into the northern part of the Vestfold Graben, slightly south of the transfer system that separates the latter from the Akershus Graben.

Stage 5: The magmatic aftermath, with major syenitic batholiths.

After the youngest intrusions related to the development of the Stage 4 calderas (c. 266 Ma, Sundvoll and Larsen, 1990), a set of large batholiths developed mostly in two areas—in inner Vestfold (west of the lava areas and north of the older larvikite batholiths) and in the Nordmarka and Hurdal areas, north of Oslo (Figure 1). Probably due to the present erosional level, no extrusions or sediments can be linked to this Stage 5 of igneous activity, which lasted from c. 265 to 255 Ma. These batholiths are mostly alkali syenitic to alkali granitic in composition and are called Nordmarkites and Ekerites. Several are intruded into the lava plateau, calderas and earlier batholiths, and partly destroyed these structures.

Stage 6: Rift termination, with the youngest small granite intrusions

This last stage of magmatic activity occurred in two separate areas, both north of the city of Oslo: in the Tryvann area in the northern hills of Oslo, and further to the north in Hurdal. The intrusions are granitic in composition with ages from 250 to 245 Ma (Sundvoll et al., 1990). Younger dikes also exist, primarily in the northern Oslo Graben (Torsvik et al., 1998, Heeremans et al., 2000).

Epilogue

The geological development of the high-volcanicity continental Oslo Rift is described through six stages in Late Carboniferous and all through the Permian. Such palaeorifts structures are rarely exposed due to post-rift cooling, subsidence and younger sedimentation. Though the Oslo Rift has been studied for nearly 200 years and has the easiest possible access, with the capital, Oslo, located in the middle of the structure, many questions remain unresolved, awaiting new investigations.

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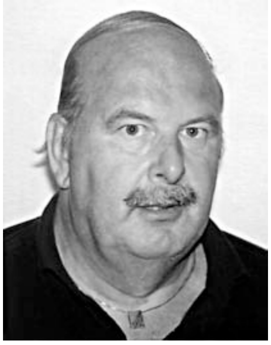

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The Mesozoic of Western Scandinavia and East Greenland

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Thick Mesozoic sediments are found offshore Norway and Denmark, and Mesozoic rocks are present and well exposed in Denmark, along the coast of East Greenland and on the arctic islands of Svalbard.

During the Mesozoic, Scandinavia and Greenland were subject to major extension in the Late Permian–Early Triassic and Late Jurassic–Early Cretaceous, prior to Cenozoic opening of the North Atlantic. Deep basins developed along the rift zones of the North Sea and between East Greenland and Norway, and were filled with sediments derived from mainland Scandinavia and Greenland. The marginal areas bordering the rift zones suffered less subsidence, as did the epicontinental Barents Sea.

Introduction—structural setting

In Late Paleozoic times, northern Europe and Baltica were located on the rim of the supercontinent Pangaea, bounded in the north, where Svalbard and the Barents Sea are located today, by the Boreal Sea. During the Triassic (Figure 1), Pangaea started to fragment and the Tethys Ocean opened in a westerly direction from the present-day Middle East and separated the new Europe from Africa (Ziegler, 1988; Torsvik et al., 2002). In the North Sea and Norwegian Sea, crustal movements that had begun in the Late Permian continued into the Early Triassic (Ziegler, 1982). Crustal extension and the formation of rift basins between Norway and Greenland attempted to divide Pangaea along a zone of weakness where the ancient Iapetus Ocean had closed at the end of the Silurian, resulting in formation of the Caledonian mountain belt.

During Early and Middle Jurassic times, the rift axis propagated progressively northwards, with formation of the central Atlantic Ocean. Following the intense rift tectonics of the Permian and Triassic, however, the North Atlantic and areas between Scandinavia and East Greenland were subject to a period of reduced tectonic activity. In the Late Jurassic, seafloor spreading in the Mid-Atlantic progressed northeastwards, leading to major rifting between East Greenland and Norway, and with a branch extending southwards into the North Sea. An elongate and continuous rift was formed extending from the North Sea to the Barents Sea. Late Jurassic rifting was superimposed on the older Permian–Triassic rift structure, after a period of quiescence of some 50 million years. Late Jurassic rifting resulted in deeper subsidence, and was localised within a narrower zone, in contrast to the much broader Permian–Triassic rift. Whereas the Permian–Triassic rift was essentially continental, Mid-, and especially Late Jurassic rifting thinned the crust to such an extent that the rift became submerged beneath the sea.

***Figure 1** Global reconstructions of the Mesozoic (From Torsvik et al., 2002).*

The Cretaceous was characterized by the transition from prolonged fragmentation of Pangaea to seafloor spreading, and formation of the Atlantic Ocean. Following the earliest Cretaceous South Atlantic opening, break-up and seafloor spreading progressed into the North Atlantic between Europe and North America in the Late Cretaceous, and culminated with continental separation and formation of the Norwegian and Greenland Seas in the Early Cenozoic. The break-up of Pangaea during the Mesozoic put an end to the last of the Earth's great supercontinents.

Palaeodrift and climate

At the onset of the Triassic, Baltica was situated in the sub-tropical zone between 25° and 40° north (Figure 1). In southern Baltica, the climate was arid and, at higher latitudes, there was probably more rain and more permanent vegetation cover (Scotese, 2001). During the Triassic, Pangaea drifted northwards and, at the same time, break-up of Pangaea and formation of the Tethys Ocean in the south led gradually to changes in patterns of global atmospheric circulation and climate. Humid air masses encroached further onto the continents, resulting in the break-up and shrinkage of the arid climatic zone that had covered most of Pangaea throughout the Permian.

The break-up in the central and southern Atlantic Ocean was associated with extensive volcanism, which released large volumes of CO_2 and SO_2. This promoted global warming which dramatically altered the basis for survival both on land and in the oceans, to the extent that it may have been a main cause for the mass extinction that occurred at the end of the Triassic. Some estimates suggest that up to 20% of the marine animals became extinct, and on land the great amphibians were almost wiped out, together with a major floral extinction. This event opened the way for the dinosaurs, which were eventually to dominate the terrestrial faunas during the remainder of the Mesozoic.

Baltica had drifted to between 45° and 60° north in the Middle Jurassic, but in the late Jurassic a change in pole of rotation caused it to rotate slightly southwards, to between 40° and 55° north. The climate was

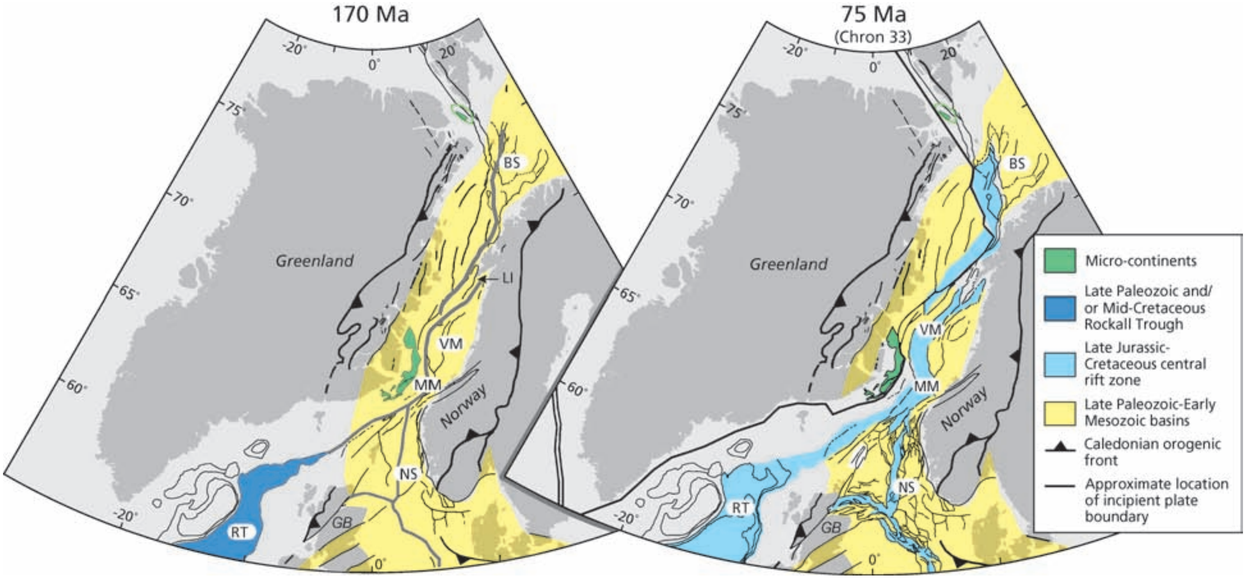

Figure 2 Plate reconstructions at 170 Ma and 75 Ma, based on total post Mid-Jurassic and pre-Cenozoic break-up stretching estimates. The Rockall Trough probably has a complex Late Paleozoic and/or mid-Cretaceous origin. RT = Rockall Trough, NS = North Sea, MM = Møre margin, VM = Vøring margin, LI = Lofoten Islands, BS = Barents Sea (Modified from Skogseid et al., 2001).

warm and humid, in the warm-temperate zone. This resulted in denser vegetation cover on land, increased chemical weathering, and the production of increased volumes of clay and quartz sand that were transported into the sedimentary basins. Minor seasonal variations allowed a diverse animal and plant life to stabilize during the Early Jurassic, somewhat after the mass extinction at the end of the Triassic. The combination of high temperature and elevated sea levels also resulted in increased biological productivity in the oceans. Superimposed on an irregular basin floor topography, with deep half-grabens, extensive water mass stratification and anoxia, this led to the formation of widely distributed, organic-rich mudstones in the Late Jurassic. Upper Jurassic mudstones form source rocks for oil and gas and represent some of the most organic-rich sediments ever deposited. Late Jurassic algae and plant remains have thus provided the source for some 25% of the Earth's oil and gas resources.

During the Cretaceous, Baltica drifted slowly northwards, to between 50° and 65°, in the temperate zone. In the Early Cretaceous, the Polar Regions had snow and ice during the winter months, but at no time were there permanent ice caps at the poles. Temperatures rose in the Late Cretaceous and remained above freezing throughout the year. In addition, cold, oceanic waters were not formed at the poles. As a result, there was very little density-driven exchange between the polar and equatorial water masses, and very little exchange vertically within the water column. This caused ocean-bottom temperatures to approximate those at the surface. No major ocean currents flowed from the poles as they do today, resulting in periodic oxygen deficiencies over large areas of the deep oceans.

Geological evolution

Very few Mesozoic rocks are found onshore Norway, Sweden and Finland, mainly as a result of Baltica being a stable craton undergoing erosion during much of this period and due to Late Pleistocene and Pliocene glaciations and erosion. Below the bordering North Sea, Norwegian Sea and Barents Sea to the south, west and north, however, a complete record of the Mesozoic is preserved (Figure 2). Mesozoic rocks are present and well exposed in Denmark, along the coast of East Greenland, and on the arctic islands of Svalbard (Figure 3).

Triassic

During the Triassic the central and northern North Sea became separated from the southernmost North Sea by the Mid-North Sea High. In the central-northern North Sea, crustal extension that had begun at the end of the Permian continued (Ziegler, 1982). Most of the Triassic faults are oriented approximately north–south and the structural grain is well demonstrated in the coastal regions of south-western Norway. The basins were commonly halfgrabens, 20–30 km wide and several tens of kilometres long. Basins and highs combined to form a rift valley between Norway and Britain that was up to 400 km wide (Figure 2). It was bounded to the west by the present-day Shetland Islands and to the east by the great Øygarden Fault, following the coast of south-western Norway. At the beginning of the Triassic the two basins were distinct, but towards the end of the Triassic they subsided to form a broad, continuous alluvial plain. The Danish Basin, covering most of present Denmark, was bordered to the south by the Ringkøbing-Fyn High, which is the eastwards continuation of the Mid-North Sea High.

Permian rifting between Norway and Greenland also continued into the Triassic (Ziegler, 1988; Seidler et al., 2004). During the Early Triassic, several deep marine rift basins were formed as a result of crustal extension and subsidence across these lowlands. During the earliest Middle Triassic, the rift zone became less active.

Triassic rifting did not affect the Barents Sea area. The Boreal Sea bordering the northern margin of Pangaea was already established during the Late Carboniferous and Permian, and was throughout the Triassic affected by global sea-level changes as a result of lithospheric plate movements. Islands emerged as a result of the crustal movements and served as major obstructions for westward sediment transport from the young Uralian mountain belt.

During the Triassic, continental conditions prevailed in the central-northern North Sea and the rift basins were filled with close to 2 km of alluvial sand, gravel and mud of the Hegre Group (Figure 4) (Steel, 1993; Fisher and Mudge, 1998; Goldsmith et al., 2003; Lervik 2006). Thick Permian salt deposits in the central North Sea became mobilized as a result of the Triassic overburden and faulting, and formed salt pillows and diapirs. These structures caused the sea floor to bulge upwards and controlled sediment distribution and depositional patterns within the basin. In the Danish Basin to the east, deposition, mainly of redbeds, took place in extensive floodplains in an arid desert. The Triassic succession in the basin is very

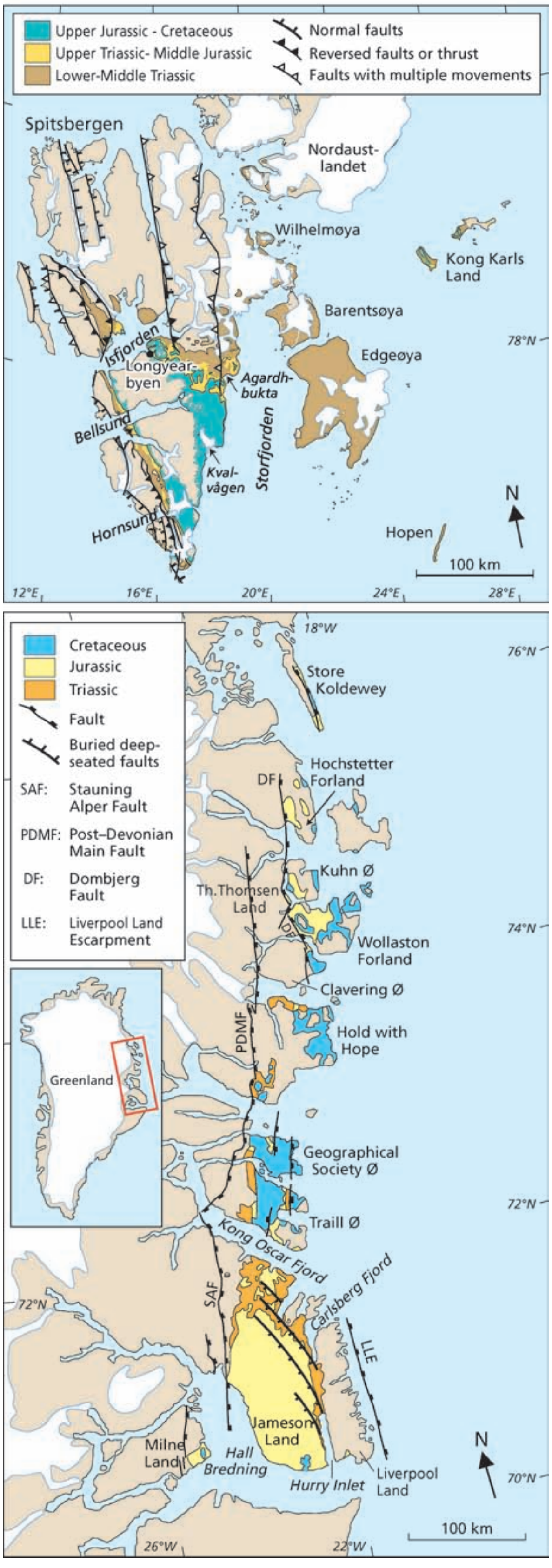

Figure 3 Geological maps of Svalbard (Dallman, Norwegian Polar Institute) and East Greenland (Surlyk and Ineson, 2003). Note that the map subdivision in Svalbard is based on stratigraphic groups (see Figure 4). Lower–Middle Triassic = Sassendalen Group, Upper Triassic–Middle Jurassic = Kapp Toscana Group, Upper Jurassic–Cretaceous = Adventdalen Group.

thick, reaching more than 6 km adjacent to the Fjerritslev Fault in northern Jylland. The Lower Triassic Bacton Group may reach up to 800 m in thickness. In the Middle Triassic the basin was flooded repeatedly by the sea and some 2,500 m of halite, anhydrite and clay of the Lolland and Jylland Groups were deposited in shallow coastal environments. In the Late Triassic a shallow brackish sea transgressed the low-lying area and sandy deltas of the Mors Group were formed along the north-eastern basin margin.

In the Norwegian Sea area and in East Greenland, the Early Triassic rift basins were largely marine and filled with marine sand and mud (Figures 3, 4) (Brekke et al., 2001; Seidler et al., 2004; Nystuen et al., 2006). The Triassic succession in East Greenland ranges from 1–1.7 km in thickness. The Boreal Sea gradually encroached southwards, forming an elongated arm between Norway and Greenland that extended to the northern boundary of the North Sea basin. Some faults blocks became elevated and emerged as elongated islands. The cessation of rifting in the Middle Triassic led to filling of the basins and an alluvial plain where sand and mud redbeds were deposited between Norway and Greenland. In the Late Triassic, crustal movements caused uplift in parts of mainland Norway, resulting in increased sediment transport to the Norwegian Sea basin. The area again became a shallow sea, and the lowermost Upper Triassic succession comprised marine mud and salt. These deposits were overlain by a thick mud succession, deposited in a vast lake. The Triassic ended with large parts of the present Norwegian continental shelf from north to south becoming dry land.

Lower Triassic deposits in the Barents Sea consist largely of mudstones belonging to the lower Sassendalen Group, varying from a few hundred metres to 1 km in thickness (Figures 3, 4) (Mørk et al., 1999). Sand was deposited along the basin margins, as observed in the eastern Barents Sea and on Spitsbergen (Mørk et al., 1982; Steel and Worsley, 1984). In the Nordkapp Basin, Permian salt began to move early in the Triassic, in the same way as in the southern North Sea area. It pierced into the overlying Triassic succession to form pillows and diapirs, which strongly influenced sediment distribution and deposition in the basin. Middle Triassic mudstones of the upper Sassendalen Group in the Barents Sea and Svalbard islands contain high proportions of organic material, up to 12% (Mørk et al., 1982; Nøttvedt et al., 1992). They form a very good source rock for oil and are also rich in phosphate. Middle Triassic source rocks contribute to the overall hydrocarbon play potential in the Barents Sea. During the Late Triassic, the Boreal Sea became shallower over large areas. In the southern Barents Sea, alternating beds of sand and mud were deposited in coastal plain and shoreline environments, reaching almost as far west as to the Loppa High. Sea-level changes caused the coastline periodically to retreat, resulting in deposition of well-sorted sand sheets. In the deepest parts of the northern Barents Sea and on Svalbard, the supply of mud continued unabated during the Late Triassic. The Upper Triassic sandstones and mudstones make up the Kapp Toscana Group, which is some 400 m thick on Svalbard and up to 2 km thick in the Barents Sea. Triassic deposits in the Russian sector of the Barents Shelf reach up to 7–8 km in thickness.

Jurassic

In many of the continental shelf basins the lowermost Jurassic succession is characterised by sandstones and mudstones with thick coal units, deposited on vast coastal plains (Figure 4). During the Early Jurassic sea level rose, however, and large parts of the North Sea, as well as the North Atlantic, East Greenland and Barents Sea regions, were flooded. The Shetland Platform, which had formed the margin of the Permian–Triassic rift basin, remained dry land during much of the Jurassic. The sea-level rise in the North Atlantic region eventually resulted in the development of a marine seaway between Greenland and Norway connecting the northern Boreal Sea and the southern Tethys Ocean. The Hammerfest Basin was the dominant basin in the Barents Sea during the Early Jurassic, and Lower Jurassic deposits are not found east of the Hammerfest Basin.

At the transition to the Middle Jurassic, the southern North Sea Basin drifted across a mantle hot-spot, resulting in thermal uplift of a

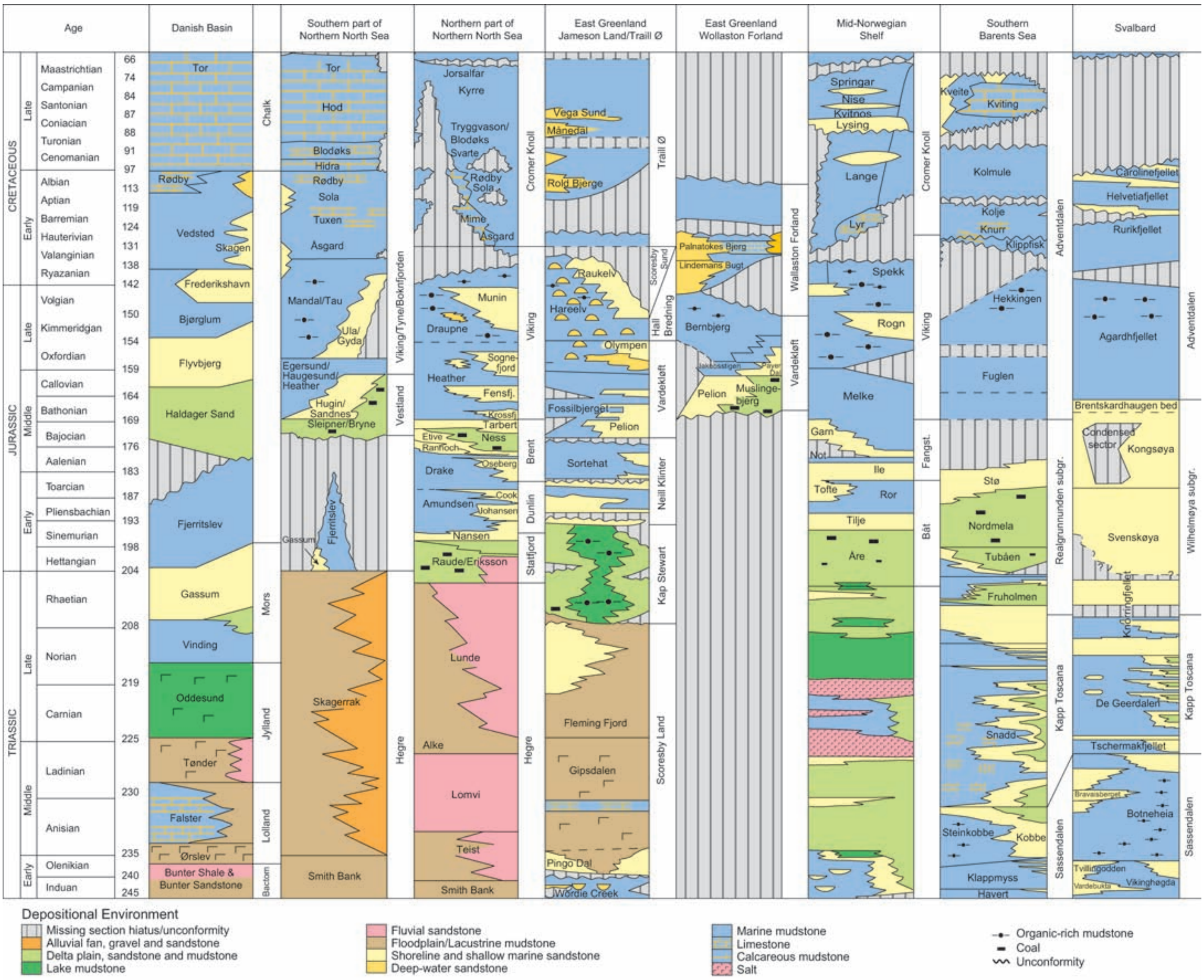

***Figure 4** Mesozoic stratigraphy of Denmark, offshore Norway, East Greenland and Svalbard. The names denote geological groups (vertical text) and formations. (Modified from Clemmensen, 1980; Surlyk and Noe-Nygaard, 2001; Michelsen et al., 2003; Surlyk, 2003; Brekke and Olaussen, 2006; Johannessen and Nøttvedt, 2006; Lervik, 2006; Nystuen et al., 2006; Nøttvedt and Johannessen, 2006).*

greater part of the southern North Sea area and the Ringkøbing-Fyn High of the Danish Basin. The uplift, which is commonly referred to as the North Sea Dome, became subject to significant erosion during the Middle Jurassic. As a result, Lower Jurassic sediments are today almost entirely absent from the southern part of the northern North Sea.

Jurassic rifting commenced in the North Sea in the late Middle Jurassic, but accentuated during the Late Jurassic. It resulted in the formation of the Viking Graben in the north and the Central Graben in the south (Figure 2). The rift is characterised by an axial, though discontinuous, rift valley. At some locations, the rift is defined along single faults or zones, comprising a few major faults. Elsewhere, the rift margin comprises fault terraces, like the Tampen and Oseberg terraces, consisting of series of rotated fault blocks. Fault blocks are typically several kilometres across and tens of kilometres long, and have their roots deep in the crust. Initially, the terraces were sloping very gently towards the axis of the rift valley. The present-day configuration, in which the terraces are tilted so that they link the shallow platforms with the deep rift valley, is a result of later thermal subsidence. The rift structure was largely submerged, but at some locations fault blocks emerged above sea level and formed narrow, elongate islands.

Between Greenland and Norway, the Late Jurassic rift structure is divided into the Halten-Dønna Terrace on the Norwegian side and the basins of East Greenland in the west (Figures 2, 3) (Blystad et al., 1995; Surlyk, 2003). The Nordland Ridge forms the northeastern extension of the Halten-Dønna terrace. The Trøndelag Platform is located east of the rift, together with the Helgeland and Froan Basins, and these all combine to form the eastern rift shoulder. The rift axis to the west lies deeply buried beneath several kilometres of Cretaceous deposits within the Rås Basin, and cannot be clearly resolved by seismic data. In the Wollaston Forland area in northern East Greenland, Late Jurassic rifting resulted in the formation of halfgrabens, whereas the wide Jameson Land platform in southern East Greenland was not broken up and was only gently tilted.

The rift structure extends into the Hammerfest and Bjørnøya Basins of the southern Barents Sea. From here it is linked to an embryonic spreading centre in the Arctic Ocean via a transverse fault separating Svalbard from North Greenland. The structure dies out in the eastern Barents Sea and the northern Barents Sea was mostly unaffected (Gabrielsen et al., 1990). Rifting in the Barents Sea commenced in the latest Jurassic, and intensified in the Early Cretaceous. The rifting typically led to fragmentation of the earlier Middle Jurassic basins of the entire shelf from the North Sea to the Barents Sea, and the faulted terrace provinces evolved into vast seas with elongated islands. Late Jurassic erosion of the fault blocks occasionally continued into the Early Cretaceous and resulted in the formation of a pronounced unconformity surface, the so-called "Base Cretaceous Unconformity".

The Lower Jurassic succession in the northern North Sea consists of fluvial sandstones and mudstones of the Statfjord Group, overlain by alternating coastal deltaic and shallow marine sandstones and mudstones of the Dunlin Group (Figure 4) (Steel, 1993; Husmo et al., 2002). The erosion of the North Sea Dome and Ringkøbing-Fyn High in the Middle Jurassic led to transport of large volumes of sand and mud towards the north, forming the great Brent delta and the deposits that now constitute the Brent Group (Graue et al., 1987; Helland-Hansen et al., 1992), as well as to the east, into the Danish Basin (Michelsen et al., 2003). The Lower and Middle Jurassic succession varies from less than 1 km along the basin margins to more than 2 km in the basin centre, as a result of compaction driven subsidence above the Permian–Triassic rift system. As the Late Jurassic seas encroached and eventually flooded the Middle Jurassic coastal plains of the North Sea, sedimentation changed into fine-grained, organic-rich mud. The resulting mudstones belong to the Viking Group, which may reach up to 1 km in thickness. Sandstones occur locally, however, resulting from deltaic progradation, such as across the Troll field, as well as from local sedimentation around emergent islands, such as in the northern Tampen area, and from submarine fan deposition along the rift structure (Nøttvedt et al., 2000; Fraser et al., 2002). The elevated inner shelf areas acted as sinks for the coarser sediments supplied from the Norwegian mainland. Similar processes were active on the rift's western flank where sands and gravels were trapped in smaller, marginal, rift basins. Consequently, the central rift provinces were supplied only with mud.

During the Early Jurassic, the coastal plains of the mid-Norwegian shelf were transgressed, resulting in a succession of fluvial to shallow marine mudstones and sandstones belonging to the 700 m thick Båt Group (Figure 4) (Gjelberg et al., 1987; Johannessen and Nøttvedt, 2006). Also parts of the East Greenland margin were flooded during the Early Jurassic, following a long interlude with lacustrine deposition across the Triassic–Jurassic boundary (Kap Stewart and Neill Klinter Groups) (Dam and Surlyk, 1993, 1998; Surlyk and Ineson 2003). As in the North Sea, associated coastal-deltaic sand wedges built out from mainland Norway and East Greenland. Early Jurassic marine basins in the North Sea and Norwegian Sea were shallow, commonly tidally influenced and rarely more than 100 m deep. However, continued subsidence across the underlying Permian–Triassic rift structure resulted in sediment thicknesses of several hundred metres, occasionally up to 1,000 metres above the rift axis. The Upper Triassic–Lower Jurassic Kap Stewart and Neill Klinter Groups in East Greenland reach up to 900 m in thickness in the central part of the Jameson Land Basin (Figures 3, 4). Along the basin margin of the Mid-Norwegian shelf, Middle Jurassic deposits reach only some few hundred metres in thickness. Middle Jurassic deposits in the Norwegian Sea and in East Greenland are very sand-rich as a consequence of advancing coastal plains and great delta systems, first on the Mid-Norwegian shelf, and later in East Greenland. Uplift, similar to that of the North Sea Dome, but slightly later, took place in East Greenland and was succeeded by onset of rifting, subsidence and influx of enormous amounts of pure quartz sand deposited in shallow marine, tidally influenced embayments (Surlyk, 2003). The Upper Jurassic succession of the mid-Norwegian shelf reaches up to 1 km in thickness and comprises mostly organic rich mudstones belonging to the Viking Group, but sandstones were deposited locally and around emergent islands such as the Frøya High. The halfgrabens in Wollaston Forland of East Greenland were filled with up to 3 km of deep marine boulder conglomerates, pebbly sand and mud, constituting the Wollaston Forland Group. In contrast, sedimentation in Jameson Land comprised about 300 m of marine coarse sandy high-angle clinoform beds of the Scoresby Sund Group, overlying and passing laterally into some 800 m of submarine sand and mud deposits of the Hall Bredning Group.

The alluvial plains of the Hammerfest Basin were flooded during the Early Jurassic, but with time, the deltaic coastline re-advanced into the western part of the Hammerfest Basin. This resulted in deposition of shallow marine sheet sandstones overlying fluvial mudstones and sandstones of the Realgrunnen Subgroup, some 500 m thick, in the western Hammerfest Basin (Figure 4) (Gjelberg et al., 1987; Mørk et al., 1999). A sea-level rise during the Middle Jurassic resulted in flooding of land areas in the eastern Barents Sea, including the Nordkapp Basin. Lower to Middle Jurassic deposits are preserved in Kong Karls Land in the east, and comprise interbedded tidal sandstones and mudstones, whereas they are very poorly developed and condensed on Spitsbergen (Figures 3, 4) (Johannessen and Nøttvedt, 2006). Widespread deposition of some few hundred metres of organic-rich mudstones belonging to the Adventdalen Group characterises the Upper Jurassic successions of the Barents Sea and Svalbard (Dypvik, 1985; Nøttvedt and Johannessen, 2006).

Cretaceous

Rifting in the North Sea ceased at the onset of the Cretaceous and the Cretaceous period was characterised by crustal cooling and thermal subsidence following the earlier periods of extension and crustal thinning. This process involved burial of the block-faulted terrace provinces along the rift margins, and continuous infilling of the extensive basins located along the rift axis (Figure 2). Within the platforms there are minor, restricted, saucer-shaped depressions such as the Farsund, Egersund, Stord and Helgeland Basins. It is possible that these basins represent an adaptive response to tensional crustal forces beyond the margins of the major rift structures, after the latter became inactive during the Early Cretaceous.

Rifting in the region between Greenland and Norway continued into the Early Cretaceous, along the extension of the Rockall Trough and sea-floor spreading took place in the Mid-Atlantic. The focus of rifting was transferred from the Halten-Dønna Terrace and out into the Møre and Vøring Basins. The magnitude of extension in these basins was great and beneath the Møre Basin, crystalline crust was reduced in thickness to only a few kilometres, corresponding to between 20 and 25% of its original thickness (Brekke, 2000; Skogseid et al., 2000). This suggests that the area came very close to the onset of seafloor spreading and formation of new oceanic crust. Deep, regional depressions such as the Møre, Vøring, Harstad, Tromsø and Sørvestsnaget Basins formed along the main rift axis where the crust was subjected to maximum extension and thinning. The extreme degrees of crustal thinning promoted several kilometres of thermal subsidence during the Late Cretaceous, while continuous sediment infilling from the basin margins kept pace with this subsidence. In East Greenland several phases of rifting and block faulting took place during the Cretaceous and were associated with deposition of coarse-grained gravity flow deposits which can be correlated with similar but larger deep-water sandstone bodies in the Vøring Basin (Surlyk and Noe-Nygaard, 2001; Fjellanger et al., 2004).

In the Barents Sea, rifting in the Hammerfest and Bjørnøya Basins accentuated during the Early Cretaceous (Gabrielsen et al., 1990). These basins represent two divergent rift arms, adjacent to the deep basins in the Norwegian Sea. On the marginal platforms in the Barents Sea, shallow depressions like the Sørkapp and Olga Basins developed. They resemble wave-like undulations of the platform interiors, but their exact formation mechanism is unclear, in that none of the smaller basins are superimposed on older clearly-defined rift structures. In the Late Cretaceous, isolated islands and large parts of the northern Barents Sea became uplifted, causing widespread erosion.

The Cretaceous was accompanied by a continuous global rise in sea level. Lowlands were progressively submerged and, in the Late Cretaceous, sea levels became higher than they have ever been, before or since, and more than half the continental landmasses were submerged, including large parts of mainland Scandinavia. High sea levels and low topographic relief resulted in extensive, shallow epicontinental shelf seas, which were completely different from our present-day marginal seas.

The Lower Cretaceous succession in the North Sea varies from a few hundred metres up to 1 km in thickness and is dominated by mudstones and marls of the Cromer Knoll Group (Figure 4) (Oakman and Partington, 1998; Copestake et al., 2003; Brekke and Olaussen, 2006). Adjacent to highs or close to prevailing coasts local deposition of sand occurred. In the Late Cretaceous, the sea-level rise resulted in drowning of much of mainland Scandinavia resulting in progressive cut-off of terrestrial sediment supply, leading to deposition of more than 1 km of mudstones and limestones of the Shetland Group. The southern North Sea and the Danish Basin received more than 2 km thick deposits of calcareous coccolith ooze forming the Chalk Group (Surlyk et al., 2003). The chalk deposits serve as major reservoirs for oil and gas, especially over salt structures.

On the mid-Norwegian shelf, some 700 m of shallow marine mudstones belonging to the Cromer Knoll Group were deposited during the Early through Late Cretaceous (Figure 4). In the Norwegian Sea, the deep Vøring and Møre Basins contain sedimentary successions between 6 and 9 km thick, and similar thicknesses are recorded in the Harstad, Tromsø, and Sørvestsnaget Basins further north (Skogseid et al., 2000; Brekke, 2000; Færseth and Lien, 2002). The Lower Cretaceous stratigraphy of the deep basins is not known, as no wells have been drilled through the succession, but sand-rich deltaic and fluvial deposits occur along the basin margins. East Greenland was the major source area for the sediments infilling the Early Cretaceous Norwegian Sea basins, notably the outer Vøring Basin. During the Late Cretaceous, thick units of marine mud were deposited in most of the Møre Basin and the southernmost part of the Vøring Basin, whereas in the northern part of the Norwegian Sea thick Late Cretaceous deep-water sandstones are encountered (Fjellanger et al., 2004; Lien, 2005). In East Greenland the Cretaceous succession comprises up to 1,300 m of marine mudstones of the Traill Ø Group, but with sandstone wedges occurring along the basin margins (Figures 3, 4). The warm Cretaceous ocean periodically became stagnant, or anoxic, resulting in the formation of organic-rich mudstones and fine-grained limestones. In the latest Cretaceous, anoxic conditions became much less common.

Early Cretaceous rifting in the Hammerfest and Bjørnøya Basins, led to increased subsidence and deposition of between 1–2 km of calcareous marine mud of the upper Adventdalen Group (Figures 3, 4) (Nøttvedt et al., 1992; Brekke et al., 2001). Sandy fans occur locally along the fault escarpment at the southern margin of the Loppa High. Some few hundreds metres of Cretaceous sediments are preserved in shallow, saucer-shaped, intra-platform depressions such as the Olga and Sørkapp Basins. In the Barents Sea, Upper Cretaceous rocks have been removed over large areas following uplift and subsequent erosion. Even though much of the erosion results from uplift of the entire Barents Sea during the last 2.5 million years, significant uplift and erosion also occurred during the Cretaceous. On Spitsbergen, a Lower Cretaceous succession, some 1.5 km thick, is exposed on land. At the onset of the Cretaceous, marine mud was deposited across the Svalbard area. Uplift and gentle tilting of the basin margin along the northwestern Barents Sea Platform led to erosion and progressive coastal advance from north to south, followed by relative sea-level rise and deposition of a transgressive fluvio-deltaic sandstone overlain by shallow marine sandstones and mudstones (Gjelberg and Steel, 1995). Volcanism associated with the opening of the Amerasian Basin led to eruption of lavas in the area from Franz Josef Land to Svalbard.

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The Tertiary of Norden

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This chapter provides a lithostratigraphic correlation and the present knowledge of the depositional history of the Tertiary succession of the Scandinavian countries. The succession records an initial phase of carbonate deposition in the early Paleocene. This was succeeded by deposition of deep marine clays with intercalation of sand-rich mass-flow deposits during most of the Paleocene and Eocene. Volcanic activity in the North Atlantic was extensive at the transition from the Paleocene to the Eocene resulting in widespread sedimentation of ash-rich layers in the North Sea area. During the Oligocene, the first prograding deltaic complex developed, sourced from the Fennoscandian Shield. Late Oligocene–Early Miocene inversion and uplift of Norway and the Shetland Platform resulted in major progradation of coastal and delta plain systems. At the end of the Tertiary most of the North Sea basin was filled and the Fennoscandian Shield was flanked to the west by a broad, coalesced coastal plain.

Introduction

The Tertiary period of northern Europe was characterised by tectonic movements related to the opening of the North Atlantic and the Alpine Orogeny in southern and central Europe. Vigorous flood basalt volcanism occurred at the time of continental separation, as seen on the Faroe Islands. The collision between Greenland and Svalbard resulted in strong folding along the west-coast of Svalbard. In the North Sea Basin, the limestone deposition that characterised the earliest Tertiary gave way to deposition of deep marine clays with intercalated sandy gravity flows (Figure 1). On Svalbard, a transgressional foreland basin accumulated coastal plain, shallow marine and deepwater deposits. There was distinct uplift of the marginal areas of the Fennoscandian Shield in the Neogene and major deltas and adjacent coastal plains prograded into the basins. Present Iceland formed from Middle Miocene to recent time by increased hot spot activity at the Mid-Atlantic spreading ridge. At the end of the Tertiary, the Fennoscandian area was tilted towards the west (Figure 2). The climate was sub-tropical to tropical in the early part of the Tertiary, not least during a series of early Eocene hyperthermal intervals but a marked climatic deterioration occurred at the end of the Eocene and of the Pliocene. In the Scandinavian land area's Tertiary deposits occur only in Denmark, southernmost Sweden and in a single, isolated locality in northern Finland. On Svalbard and the Faroe Islands Palaeogene sediments are known whereas only post Oligocene deposits occur in Iceland.

Early Paleocene: Chalk deposition in the south and coastal plain deposition in the north

The Cretaceous/Tertiary boundary event (c. 65 Ma) is represented in Denmark by the distinctive Fish Clay, well exposed in the cliff at Stevns. In Denmark and the North Sea the Danian succession consists of up to 350 m thick limestone and chalk. Two main facies are

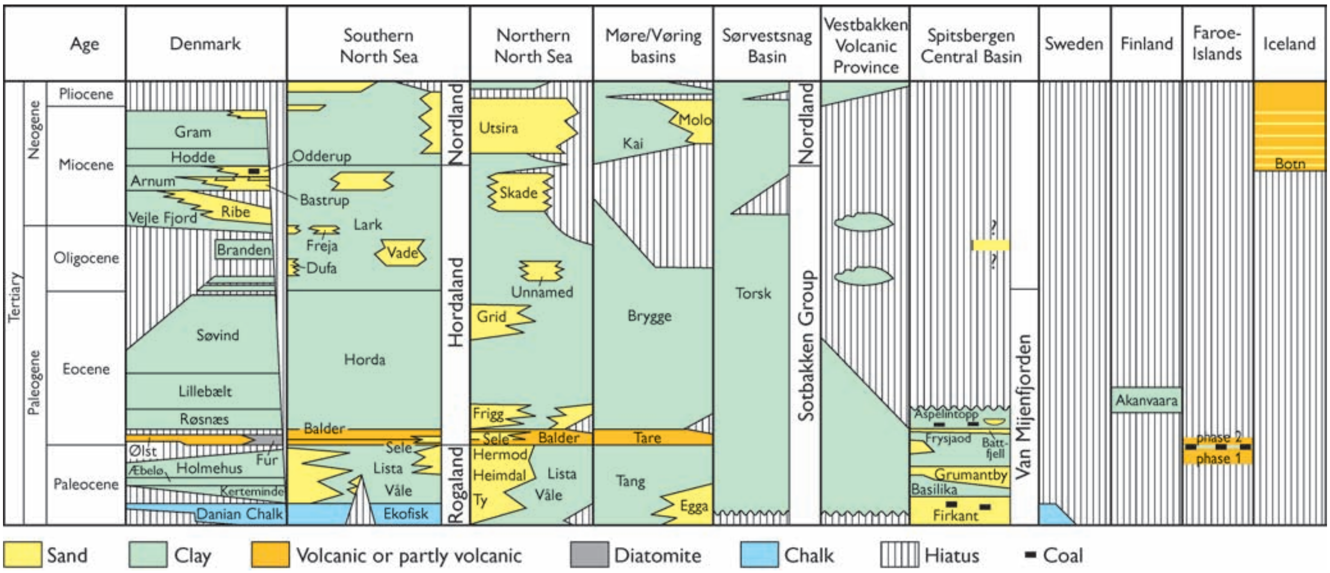

Figure 1 Lithostratigraphy of basins off the Fennoscandian Shield (partly based on Rasmussen, 2004; Martinsen & Nøttvedt, 2006; Eidvin et al., 2007).

recognized, 1) bryozoan limestones, often forming spectacular bioherms and including a few coral reefs and 2) fine-grained pelagic chalk composed mainly of coccoliths and planktonic foraminifera (Thomsen, 1995; Surlyk et al., 2006). In the Atlantic realm muds with some incursions of sandy gravity flows were deposited; locally up to 700 m of sand were deposited (Martinsen and Nøttved, 2006). On Svalbard the depositional environment was coal-forming delta plains, leading out to protected shallow marine basins (Steel et al., 1981; 1985). The water depth in the North Sea Basin decreased during the late Danian, and the easternmost parts may have been subaerially exposed. The relative sea level fall appears to have been primarily eustatic (Clemmensen and Thomsen, 2005), although thermal uplift caused by activity from the Proto-Islandic hotspot may also have been involved (Knox, 1996). The paleogrography is shown in Figure 3A.

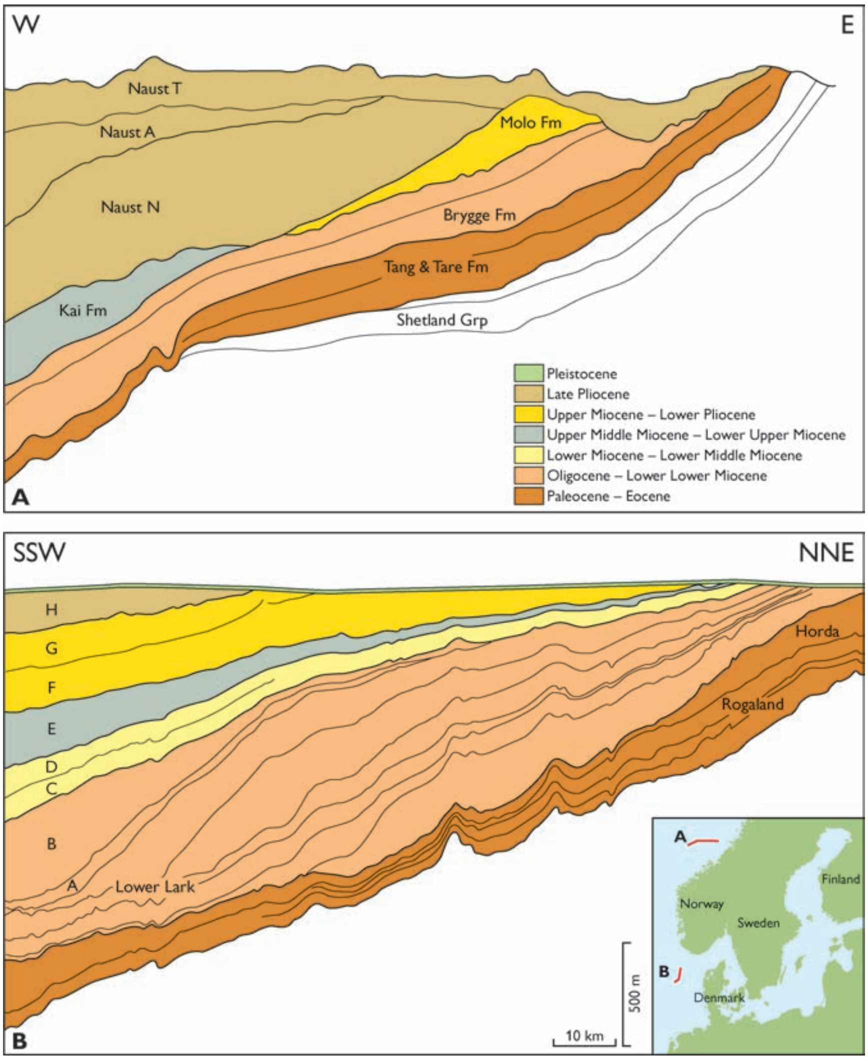

Figure 2 Tilted Tertiary successions from: A) North Atlantic and B) North Sea. Note that the same colour code has been used so it is possible to compare the two sections. For section A, Norwegian formations are indicated and for section B, sequences for the Neogene succession are indicated. Partly based on Eidvin et al., 2007.

Middle–Late Paleocene: volcanism, siliciclastic sedimentation and increasing water depth

In early Mid-Paleocene (c. 61 Ma), extrusion of flood basalts started almost simultaneously in a wide area extending from the British Isles, over the Faroe Islands, East and West Greenland to Baffin Island forming first phase of the North Atlantic Igneous Province (NAIP) (Figure 4) (Saunders et al., 1997). The lavas reach a total thickness of 3.3 km in the Faroe Islands and are underlain by > 1.2 km of hyaloclastites formed by magma-water interaction (Waagstein, 2006). The volcanism is usually taken to reflect a Proto-Icelantic hotspot, possibly the arrival of a mantle plume (e.g., White, 1989). However, some authors attribute the volcanism to extension during plate reorganisation (e.g., Lundin and Dore, 2005). At the same time, a profound change to the marine clay-regime took place in the North Sea Basin after nearly 40 million years of chalk-deposition. The cause for this shift is probably a combination of increased clay input from erosion of the uplifted Shetland Platform and the new basalt covered areas and severed connections between the North Sea Basin and the warm oceans to the south (Ziegler, 1990; Clemmensen and Thomsen, 2005). Later in the Middle Paleocene, a major inversion pulse took place in the narrow Sorgenfrei-Tornquist Zone, situated between the North Sea Basin and the Fennoscandian Shield, probably as a result of stress relaxation (Nielsen et al., 2005). During the Middle and Late Paleocene, progressively deeper water and more offshore marine environments are represented by successive formations, including in Denmark the Kerteminde Marl, Æbelø Formation and culminating in the Upper Paleocene Holmehus Formation which processes a *Zoophycos* ichnofacies (Heilmann-Clausen et al., 1985). The regional deepening may be due to subsidence during reduced activity from the Proto-Icelandic hotspot (Knox, 1996). In the North Sea very similar marine clays occur, but with incursion of sand-rich gravity flow deposits. These are known as the Våle, Lista and Sele formations representing the fine-grained deposits and as the sand-rich deposits of the Ty, Heimdal and Hermod formations (Schiøler et al., 2007). On Svalbard, more open, shallow-marine sediments were deposited, known as the Basilika and Grumantbyen formations (Steel et al., 1985, Johannessen and Steel, 2005).

Earliest Eocene: global warming event and rift-related volcanism

The Paleocene – Eocene (P/E) boundary (c. 55.8 Ma) coincides with the beginning of a thermal maximum, the PETM, an extreme global warming event lasting c. 200,000 years inferred to be caused by a huge carbon release to the biosphere and associated with profound biotic disturbances (e.g., Wing et al., 2003). The second phase of the NAIP peaked at about the same time along the final line of opening of the NE Atlantic extruding >5 km of flood basalts in E Greenland and >2 km in the Faroe Islands. The appearance of mid-ocean ridge type basalts appearing up-section suggests continental separation (Larsen et al. 1999; Storey et al., 2007). The carbon release referred to above may indirectly have been caused by the volcanism (Storey et al., 2007) or by rapid desiccation of a major epicontinental seaway and surrounding peat lands (Higgins and Schrag, 2006). Thus during the PETM the North Sea was reduced to a stagnant, lake-like water body (Figure 3B) (Knox and Harland, 1979). The major sea-level fall was probably caused by a new updoming of the entire NE Atlantic region in connection with the second phase 2 of increased hotspot activity (Knox, 1996; Jones and White, 2003). The PETM period is represented in Denmark by the c. 14 m thick, anoxic Stolleklint Clay (Heilmann-Clausen and Schmitz, 2000).

Numerous basaltic ash beds occur in the overlying succession all over the North Atlantic-NW European region as far away as the northern Tethys, 1,900 km from the assumed source within the North Atlantic rift zone (Egger and Bruckl, 2006). This ash series, the 'positive series' of Bøggild (1918) is best known from NW Denmark where it is well exposed in a 60 m thick diatomite, the Fur Formation (Heilmann-Clausen, 2006). The extremely violent volcanism suggests that the volcanic edifices were located in shallow water (Waagstein and Heilmann-Clausen, 1995; Larsen et al., 2003). The thickest of the ash layers are among the largest basaltic ash-falls known in geological history, and they may have contributed to the global cooling after the PETM (Egger and Brückl, 2006). The diatomite of the Fur Formation (Figure 5) probably formed in an upwelling belt south and south-west of Norway (Bonde, 1979). The mainly anoxic diatomite is rich in exquisitely preserved fossils including the world's best known early post-PETM faunas of insects, fishes and birds (Heilmann-Clausen, 2006 and references herein). During this period the locally sand-rich Balder Formation was deposited in the North Sea region and the Tare Formation off mid and northern Norway. On Svalbard, deepwater marine muds of the Frysjaodden Formation were deposited followed by the progradation of the Battfjell Formation shelf to deepwater slope system (Figure 6) (Steel et al., 1985).

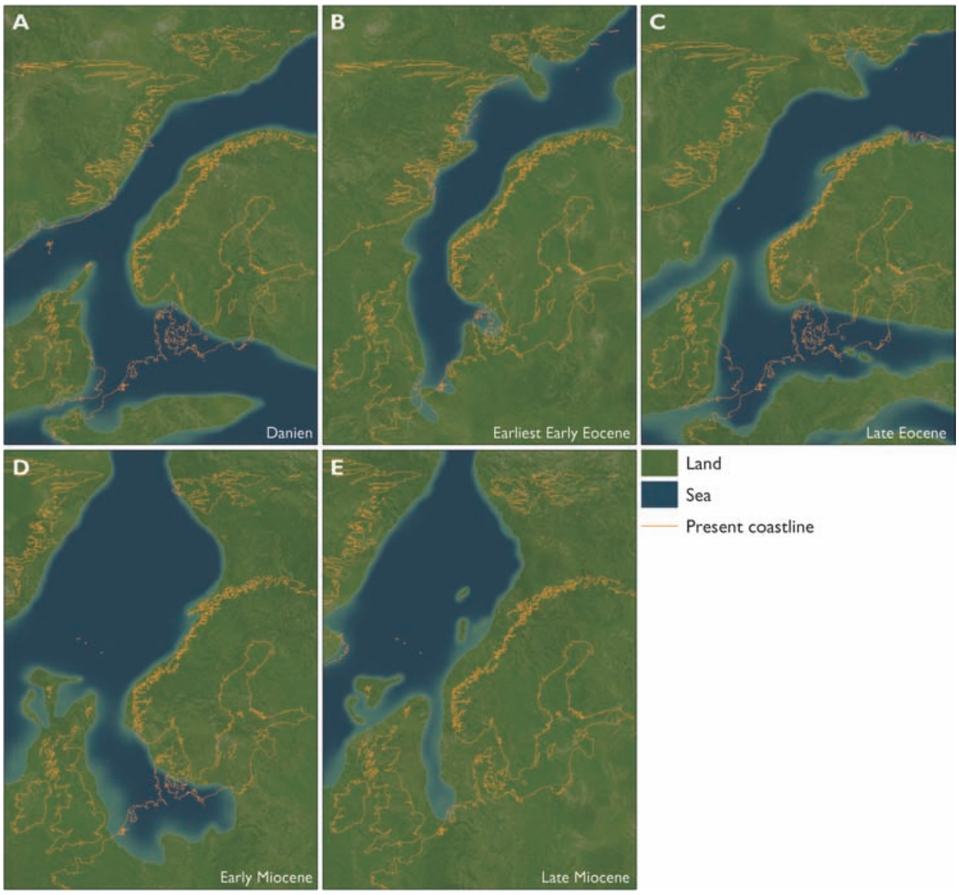

***Figure 3** Paleogeographic reconstruction of the area during the: A) Danian, B) Earliest Early Eocene, C) Late Eocene, D) Early Miocene, E) Late Miocene. Based on Rasmussen (2004), Stoker et al. (2005), Løseth and Henriksen (2005), Heilmann-Clausen (2006), Martinsen and Nøttvedt (2006).*

***Figure 4** Coastal exposure of the Kulagjógv lava flow at Fródba, Suduroy, Faroe Islands. The flow belongs to NAIP Phase 1. The boundary between magnetochrons c25n and c24r is at the top of the flow while compound flows of Phase 2 are seen in the mountain slope behind (top left). The Kulagjógv flow has bulldozed through underlying wet volcanoclastics resulting in rapid chilling af the magma. This is evidenced by the development of a prominent columnar jointing growing at a right angle from the irregular contacts towards the centre of the flow.*

Eocene bathyal, hemipelagic clays of the North Sea Basin

After the earliest Eocene (the Sparnacian Stage of Aubry et al., 2003), the major NW European Ypresian transgression occurred. In Denmark, a distinctly more offshore, mainly bathyal environment was established, with Ypresian water depths possibly reaching 600 m or more (Schmitz et al., 1996). A deep environment persisted for the entire Eocene, and up to 200 meters of extremely fine-grained clays (Røsnæs Clay, Lillebælt Clay and Søvind Marl formations) were deposited in western Denmark. These clays are very similar to the central North Sea succession, i.e., the Hordaland Group. As in the Middle–Late Paleocene, the large scale transgression may have been caused by reduced activity from the Proto-Icelandic hotspot (Knox, 1996). The transgression also affected the Faroes area where tuffeceous claystone and limestones were deposited on the Faroes platform before uplift in the Bartonian or Priabonian and later erosion (Waagstein and Heilmann-Clausen, 1995).

A climatically important *Azolla*-event at the Ypresian/Lutetian transition is recorded in the Polar Ocean and Northern Atlantic, and is suggested to represent a Polar Ocean freshwater overflow (Brinkhuis et al., 2006). The only onshore occurrence of this event is in Denmark.

The present limit of the Eocene deep water sediments towards the Fennoscandian Shield is erosional, caused by late Tertiary uplift and Quaternary glaciations. The position of the Eocene coastline is speculative, but it was possibly situated in Southern Sweden (Figure 3C). On Svalbard, the marine setting was successively filled and coastal plain and fluvial deposits eventually became dominant (Steel et al., 1985; Plint-Bjørklund, 2005). An isolated marine Eocene clay unit, the Akanvaara Clay, occurs in northern Finland (Fenner, 1988).

Figure 5 **The post-PETM 'positive ash series' (Lower Eocene) is seen as black, sandy layers in the light grey diatomite of the Fur Formation in NW Jylland. The folds and faults are caused by Quaternary glacial tectonics.**

Figure 6 **Coastal plain, shelf and slope clinoforms of the Frysjaodden and Battfjellet formations, Central Tertiary Basin, Spitsbergen. See also Johannessen and Steel (2006) for details (Photo: Frode Hadler-Jacobsen, Statoil).**

From Eocene greenhouse to Oligocene icehouse

Towards the Eocene–Oligocene boundary (c. 34 Ma) the greenhouse climate, prevailing since the Mesozoic, changed to the modern icehouse climate (Zachos et al., 2001). This led to a profound change of the depositional regime. A generally lowered, but fluctuating eustatic sea level was caused by growing and waning of ice caps primarily on Antarctica, but probably also in Greenland (Eldrett et al., 2007). In Scandinavia, the climate probably became cooler (Buchardt, 1978). From the latest Eocene distinctly pulsed and localized coastal and deltaic progradation occurred south of present day Norway, which replaced the previous, dominantly hemipelagic sedimentation pattern in the basin (Michelsen et al., 1998). During Oligocene time, sediments in the eastern part of the North Sea Basin were sourced from the present Norwegian land mass, which was undergoing considerable erosion. The Oligocene consists mainly of thick, geographically restricted units that were quickly deposited in neritic environments, such as the Viborg Formation and the Branden/Skive Clays (Heilmann-Clausen, 2006). The units are separated by considerable stratigraphic gaps, with most of the Rupelian absent. West of Norway muds of the Brygge and Torsk formations were deposited in more open marine environments. However, most of the Chattian has been removed in the Tampen area in the northern North Sea (Eidvin and Rundberg, 2001; Rundberg and Eidvin, 2005), and in most areas of the eastern part of the Norwegian Sea continental shelf (Eidvin et al., 2007). Close to the Early/Late Oligocene boundary conglomerates, sandstones and sandy clay were deposited in the Forlandsundet "graben" in north-western Svalbard (Eidvin et al., 1998). In Late Oligocene a warm climate dominated (Heilmann-Clausen, 2006; Pers. Comm. Linda Larson).

Miocene: Uplift and deltaic progradation from the Fennoscandian Shield

At the transition from the Paleogene to the Neogene (c. 23 Ma) prominent polar ice caps again built up primarily in Antarctica. This resulted in a global sea-level fall and the formation of a distinct erosional boundary. Superimposed on this, the Alpine tectonic event, the “Savian Phase”, resulted in flexural uplift of the Central Graben and along the Sorgenfrei-Tornquist Zone. Extensive erosion below Lower Miocene deposits in the Tampen area in the northern North Sea (Eidvin and Rundberg, 2001; Rundberg and Eidvin, 2005) and off Mid Norway indicate similarly marked changes, i.e., uplift, in these areas (Eidvin et al., 2007). Also the margins of the Fennoscandian Shield, the so-called Northern - and Southern Scanes, and the south Swedish Dome, were uplifted. During the Early Miocene, coarse-grained sediments were flushed into the surrounding basins and resulted in deposition of deltaic sediments of the Ribe, Bastrup and Odderup formations in the part of the North Sea basin which in the present day constitutes Denmark (Rasmussen 2004, Figure 3D and 7). Further north, in the Viking Graben area of the North Sea basin, the sand-rich Skade Formation was build up by sediments which were sourced from the elevated Shetland Platform (Rundberg and Eidvin, 2005, Figure 3D). Heavy mineral studies show that the source area for the sand-rich deltas in the present day Denmark were the present day Finland, Sweden and particularly Norway (Knudsen et al., 2005). The climate during most of the Early Miocene was changing from cool to warm temperate and frost was rare in the lowland areas.

A culmination in the uplift of the Fennoscandian Shield took place at the transition of the Early and Middle Miocene (Eidvin and Rundberg, 2001; Eidvin et al., 2007; Rundberg and Eidvin, 2005). In the Norwegian Sea, major compressional features, e.g., the Helland-Hansen Arch, formed (Ludin and Doré, 1996; Løseth and Henriksen, 2005). The uplift of the Fennoscandian Shield was accompanied by subsidence of the basins and flooding of former deltas and coastal plain environments. This flooding was partly tectonic and partly climatic in origin coinciding with the Mid Miocene climatic optimum (Zachos et al., 2001). South of the Fennoscandian Shield, the depo-

Figure 7 **Coarse-grained deltaic sediments showing braided fluvial deposits of the Billund fluvio-deltaic complex, Ribe Formation (Photo: Ole Rønø Clausen).**

sition of the clayey Hodde and Gram formations took place. In the western part of the Norwegian Sea continental shelf and in the Norwegian Sea the clayey and pelagic Kai Formation was deposited. In the Atlantic realm, the North Atlantic sediment drift that was initiated at the Eocene/Oligocene transition was intensified from the late Early to Middle Miocene (Wold, 1994). Major compression occurred around the Faroe Islands at same time (Boldreel and Andersen, 1993). The Iceland-Faroe and Iceland-Greenland ridges formed by increased Icelandic hot spot activity during the opening of the NE Atlantic and were probably above sea level initially. They were underlain by thick oceanic crust, like present day Iceland. Iceland itself was experiencing active sea-floor spreading and the oldest flood basalt exposures occur on the E and NW coasts dating back to Middle Miocene, when the island was vegetated by a temperate flora (Grimsson et al., 2006). The interbasaltic sediments include aeolian soils and various alluvial and lacustrine deposits, e.g., the Selardur-Botn Formation (Figure 1).

In the Late Miocene, the marked relief of the Fennoscandian Shield, accompanied by the general climatic deterioration (Utescher et al,. 2000; Zachos et al., 2001), resulted in pronounced out-building of coastal plains and deltas from the Fennoscandian Shield. On the Norwegian Sea, continental shelf sediments were deposited. These deposits were newly formal named the Molo Formation (Eidvin et al., 2007, Figures 1, 3E). In the transition area of the Viking Graben and the Central Graben, the Utsira Formation was deposited as submarine tidal bars in a narrow strait connecting the North Sea and the Atlantic Ocean (Galloway, 2002; Rundberg and Eidvin, 2005, Gregersen and Johannessen, 2007). The source was the Shetland Platform in the southern and middle part, and the Sognefjorden area in the northern part (Rundberg and Eidvin, 2005). South of the Fennoscandian Shield the deltas reached the Central Graben area, so the North Sea constituted a narrow gulf by the end of the Miocene (Sørensen et al., 1997; Rasmussen et al., 2005; Figure 3E).

Pliocene: Tilting of basins and climatic deterioration

In the early Pliocene, periodically warmer climate prevailed (Zachos et al., 2001; Utecher et al., 2000). Consequently, huge areas of coastal plain deposited during the Late Miocene were flooded. Resumed regression occurred in the Late Pliocene possibly associated with a falling sea level due to an overall climatic deterioration. In the Danish area this regression succeeded a tectonic event (Rasmussen et al., 2005). In the Atlantic area, a mid Pliocene tectonic event has also been documented (Stoker et al., 2005). The onset of more pronounced glaciation on the Fennoscandian Shield was initiated in the late Pliocene (c. 2.8 Ma; Fronval and Jansen, 1996). The Late Pliocene deposits that are the result of the regression and glaciations are named the Naust Formation in the Atlantic area (Eidvin et al., 2007). Similar huge packages of prograding units are seen in the North Sea (Eidvin and Rundberg, 2001; Rasmussen et al., 2005). However, it is in the southwestern part of the Barents Sea that the Upper Pliocene forms the most extreme sediment columns with depocenters close to 2500 m (Eidvin et al., 1998 and 2000). In most of these areas there are a pronounced hiatus below the Upper Pliocene glacial deposits (Eidvin and Rundberg, 2001; Eidvin et al., 2000 and 2007). Regional tilting of the area occurred in the late Pliocene (Figure 2) (Riis, 1996; Faleide et al., 2002; Japsen et al., in press). The distinct change in the structural pattern that occurred in the late Pliocene has been hotly debated during the last decade. The large amplitude of this phase may be related to movements within the upper mantle e.g. Japsen et al. (in press) and Stoker et al., 2005 or to changes in stress field, e.g., Cloetingh and Van Wees (2005). According to Riis (1996) the isostatic effect of onshore erosion and offshore deposition has contributed to amplify the vertical movements. A dominantly climate-driven origin of Cenozoic uplift has been suggested by Nielsen et al. (2002).

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Quaternary of Norden

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The Nordic countries have experienced multiple glaciations and intervening interglacials during the last ca. 2.5–3 million years. Although evidence from Greenland and Iceland shows that ice sheets started to expand some time before 3 Ma, little is known about the glaciations and intervening interglacials older than the last Glacial Maximum due to repeated phases of glacial erosion and reworking. The extensive Saalian glaciation (c. 140 ka BP) contributed to high sea levels in Greenland and in the Baltic area during the early part of the last interglacial (Eemian). Temperatures were about 5 °C higher during the Eemian than they are today and the Greenland ice sheet was reduced to about half of its present size, causing globally higher sea levels than we have today. Ice extent in Fennoscandia was restricted during early Weichselian stadials, but middle Weichselian ice advances in Scandinavia reached as far as Denmark. During the Last Glacial Maximum, large ice sheets were present in all Nordic countries and coalesced with neighboring ice sheets. Deglaciation commenced around 17–15 ka BP in most areas and was promoted by rapidly rising global sea level and glacial isostasy. The Younger Dryas cold event(c. 12.6–11.5 ka BP) is seen as a short-term re-advance, still-stand or fluctuation of land-based ice sheet margins. Around 7–9 ka BP ice sheets had disappeared or had attained their present size. While uplift is still going on in some regions, others are subject to submergence. The different stages of development of the Baltic Sea are an example of how the intricate interplay between glacial eustasy and isostasy influences sedimentation, basin size and drainage patterns.

Introduction

The Nordic countries have experienced multiple glaciations and interglacials during the course of the Quaternary time period, i.e. the last c. 2.5 million years (Ma). Ice sheets and glaciers shaped much of the present-day landscapes and isostatic rebound, combined with eustatic sea level changes left profound traces. The paleoenvironmental and paleoclimatic development during the early and middle part of the Quaternary, i.e. prior to the Last Glacial Maximum (LGM, c. 21 ka BP [thousand years before present]) is only poorly known since the ice sheets successively eroded and reworked older, underlying strata. In areas where the LGM ice sheet base was frozen to its bed, older glacial landforms are, however, well preserved and offer insight into earlier histories of ice sheet advance and retreat. The different parts in this review present the present state of knowledge regarding the Quaternary in the Nordic countries (Figure 1) and are organised and written by those most familiar with the regions (Greenland, Iceland, Finland) and/or topics (ice sheet behaviour and Baltic Sea development).

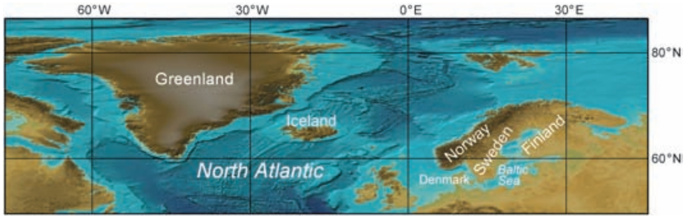

Figure 1 Map of the Nordic countries (reproduced with permission of Martin Jakobsson, Stockholm University).

Greenland during the Quaternary

The Greenland ice sheet, which now occupies 80% of the land, may have started to grow during Late Eocene times (Eldrett et al., 2007) and the glacial landscape with its fjords and glacial troughs was probably formed before the onset of the Quaternary. Till exposures on land, ice-rafted debris in the Greenland Sea, and seismic studies on the shelf show that the ice sheet expanded onto the shelf of northern and eastern Greenland at the beginning of the Quaternary. However, the trough mouth fans, which were built along the shelf break, are much smaller than their Norwegian counterparts (see chapter on Norway), which indicates that the hallmark of the Greenland ice sheet—its stability and inertia towards climate change—has prevailed throughout the Quaternary. The ice sheet apparently disappeared during Early Quaternary interglacials, as inferred from the sediment succession of the Kap København Formation (c. 2.4 Ma), a sequence with a unique record of terrestrial and shallow marine environments close to the northern tip of Greenland (Funder et al., 2001). This may have been the last time when Greenland was ice free, although DNA analyses of basal ice in a core from central Greenland indicate that this site and probably large areas in southern Greenland also were ice free, and covered by forest at some time between 0.4 and 0.8 Ma (Willerslev et al., 2007). Apart from this, very little information exists about Greenland's environment during the first 2 Ma of the Quaternary.

Glacio-isostatic uplift after the melting of the extensive Saalian ice sheet left wide-spread Early Eemian marine sediments on land in northwest and east Greenland. The rich marine faunas bear evidence of stronger than Holocene advection of warm Atlantic waters along the Greenland coasts. Terrestrial plant remains indicate summer temperatures, as much as 5°C warmer than present (Cape-Last Interglacial Project Members 2006). Melting of the Saalian ice sheet is estimated to have contributed 2–4 m to the Eemian high sea level, which was 5–7 m higher than during the Holocene and implies that the ice sheet was 33–50% smaller than at present (e.g. Otto-Bliesner et al., 2006) (Figure 2a). During the LGM the Greenland ice sheet covered an area of c. 3 million km^2, i.e. 40% more than today (Funder et al., 2004). In the north it merged with the Laurentide ice sheet of North America, and in the southwest, its margin was close to the western margin of the Icelandic ice cap (Figure 2b). Ice break up began c. 15 ka BP with the clearance of the shelves and may have been triggered by sea level rise. Large plough marks produced by ice bergs with a keel depth of 950 m off West and East Greenland testify to this phase of deglaciation (Kuijpers et al., 2007). Before the Younger Dryas (12.8–11.5 ka BP) the shelf and major inlets had apparently been cleared of ice. However, athough ice cores distinctly show the Younger Dryas cooling, the response of the ice margin is not clear. In some areas it may have advanced, while it retreated in others (Denton et al., 2005; Jennings et al., 2006). During the Early Holocene (c. 11.3 ka BP), retreat was under way in all parts, but the duration, amount, and rate varied from area to area (Bennike and Björck, 2002), as shown by the varying altitudes of the marine limits. Maximum altitudes of 160 m occurred in coastal West Greenland, while marine limits in the northwest and southeast were only 20-30 m above sea level (Funder and Hansen, 1996). Before 7.5 ka BP the present state of glaciation had been attained in most parts. After this, the margins withdrew behind their present location, possibly as much as 40 km in some areas (Weidick, 1993). The area uncovered during the first phase of deglaciation, i.e. the clearance of the shelf, amounted to c. 0.8 million km^2, while the second phase, i.e. melting and calving in fjords, uncovered only c. 0.4 million km^2. This is an expression of the ice sheet's remarkable stability.

Pollen and other climate proxies show that cooling began at c. 5.5 ka BP (Funder and Fredskild, 1989) and relative sea level curves show that at this time uplift changed to subsidence due to increased ice loading (Sparrenbom et al., 2006). The culmination was reached between c. 1880 and 1925 AD, although the event was not time-synchronous. Thereafter, glaciers began to retreat again in most parts and marked retreat phases occurred between 1925 and 1940 and since 1995 (Weidick, 1996; Wake et al., 2007).

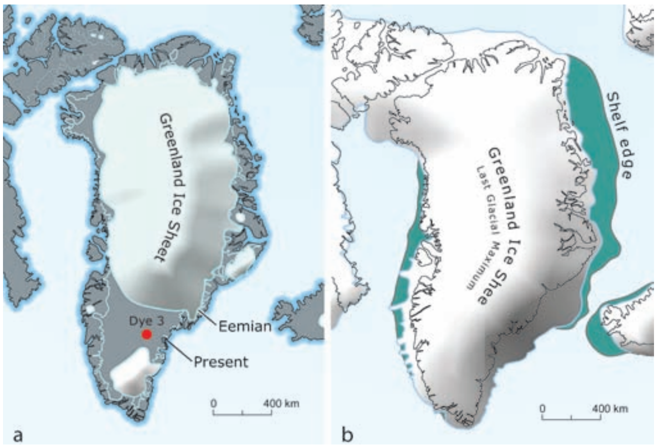

Figure 2 The Greenland ice sheet extent. (a) Minimum ice extent: among several models, this is the smallest-option for the Eemian. It is presupposed that 3.4 m of Eemian "excess sea level" came from Greenland. The site of the Dye 3 ice core (red dot) was earlier considered to have been ice free in the Eemian, but recent DNA studies indicate that it was ice covered; adapted from Otto-Bliesner et al. (2006). (b) Ice extent at the LGM (c. 15 ka BP), based mainly on field observations and bathymetrical, seismic and coring evidence from the shelf. The blue color denotes shelf areas which may have been dry land; adapted from Ehlers and Gibbard (2004).

Quaternary history of a volcanic island

Iceland has a Late Cenozoic record of glaciations starting in the Pliocene, more than 3 Ma ago. Signatures of at least 20 glaciations are preserved in Iceland's stratigraphy, due to continuous volcanism; during glaciations, till was deposited and during interglacials, sediments accumulated in basins and soils developped on top of till beds. Interglacial lava flows capped the sediments and preserved it from erosion. A key site at Tjörnes contains strata that span the Pliocene-Pleistocene transition. The 1,200 m thick sequence of lavas and sediments contains 14 glacial horizons of tills, as well as marine-to-littoral regression sediments, lake sediments and soils (Figure 3). The Tjörnes record shows that glacial conditions first occurred in coastal north Iceland about 3 Ma, and that ice sheets large enough to reach outside the present coast developed after 2.5 Ma (Geirsdóttir and Eiríksson, 1994; Buchard and Símonarson, 2003). Apart from the stratigraphical evidence for repeated growth of ice sheets since late Pliocene, the Icelandic landscape bears witness to the action of glaciers through time: glacially eroded valleys and fjord troughs characterize coastal western, northern and eastern Iceland, whereas hyaloclastite ridges and Table Mountains signify subglacial volcanism during periods of extensive Quaternary glaciations.

During the LGM Iceland was covered by an ice sheet that reached out towards the shelf break (Figure 4), as shown by a number of marine geological and seismostratigraphical studies (Andrews et al., 2000). It was drained by large ice streams entering major fjords and bays around the island (Hubbard et al., 2006). Ice thickness over the central highlands is not well known, but geomorphic and volcanologic data suggest maximum thicknesses of 1500±500 m. Nunataks occurred in coastal areas on northern and eastern Iceland. Available data indicate an onset of deglaciation starting before 16 ka

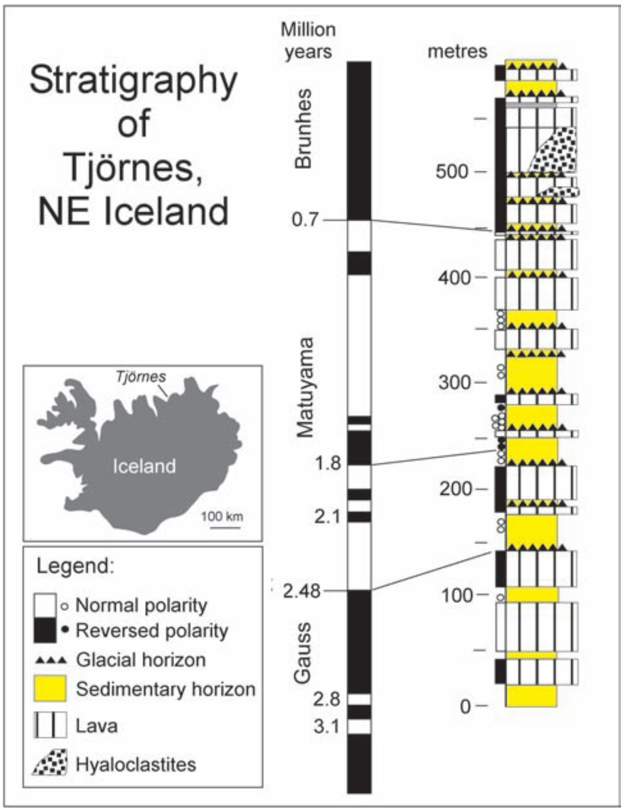

Figure 3 Stratigraphy of Tjörnes in northern Iceland showing 14 glacial horizons since 2.5 MA, modified after Einarsson (1968).

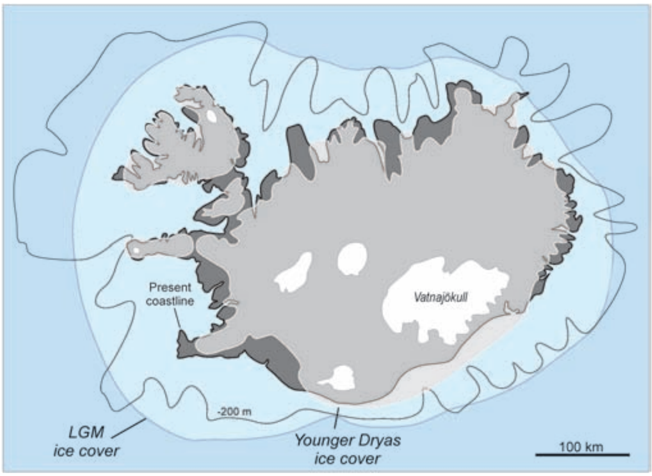

Figure 4 Extent of the Icelandic ice sheet at LGM and Younger Dryas modified after Hubbard et al. (2006).

BP off northern Iceland and c. 15.4 ka BP off western Iceland. After 15.4 ka BP deglaciation was extremely rapid, and probably controlled by rapidly rising global sea levels causing the ice sheet to destabilize and collapse (Syvitski et al., 1999; Ingólfsson and Norddahl, 2001). By 13.8 ka BP, the ice fronts were within the present coastline of Iceland. Relative sea level stood at the marine limit in western Iceland, at 150 m a.s.l. at c. 15 ka BP, but was followed by a rapid regression as Iceland's oceanic crust rebounded quickly in response to decreased glacial loading (Norddahl and Pétursson, 2005). Once inside the coast the ice sheet started growing again, culminating in a significant Younger Dryas advance. Ice sheet growth was accompanied by a transgression which culminated at c. 12.1 ka BP. After a brief early Preboreal (c. 11.2 ka BP) glacial advance, accompanied by a few meters of transgression in the coastal areas, the ice sheet disintegrated rapidly and glaciers were at or within present glacier limits prior to 9 ka BP (Björck et al. 1997; Rundgren et al., 1997; Norddahl and Pétursson, 2005). Due to the extremely rapid isostatic rebound, Iceland has been subject to a Holocene transgression since c. 10.2 ka BP (Ingólfsson et al., 1995).

Quaternary ice sheets formed the face of Scandinavia—examples from Norway

Quaternary glaciations formed the beautiful landscape in western Norway, including the spectacular deep fjords (e.g. Sognefjord, 1305 m b.s.l.). Including down-cutting above sea-level, the glacial erosion amounted to 2 km in several places along Norwegian fjords. Glacial erosion products were deposited as large wedges along the continental margin and as thick beds in the North Sea and Denmark–Germany. The Scandinavian Ice Sheet, which grew out from the mountain chain along the Norwegian-Swedish border, expanded some 40–50 times during the last 2.6 Ma (Mangerud 2004). During periods of maximum extent (Figure 5) it coalesced with the British, Barents Sea, Svalbard and Kara Sea ice sheets to form an Eurasian Ice Sheet, almost reaching the Black Sea (Svendsen et al., 2004).

Two types of major glacial depressions are recognized on the shelf (Figure 6). Transverse troughs, normally over-deepened to 400–500 m in their inner reaches, are most often seaward extensions of fjords. The longitudinal channels generally follow the boundary

Figure 5 The Eurasian Ice Sheet during the Saalian (white), the Last Glacial Maximum (red line), and maximum extension before the Saalian (stipled green), modified after Svendsen et al. (2004).

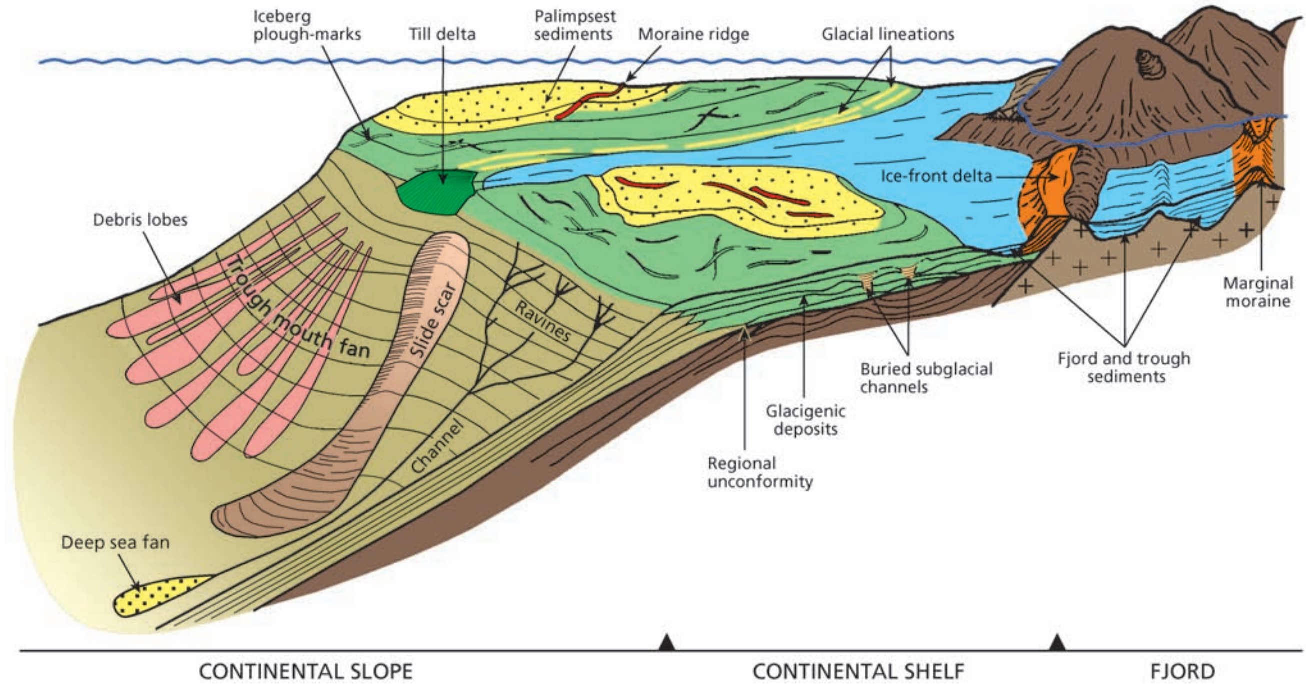

Figure 6 Model showing the main glacigenic morphological elements and lithofacies of the Norwegian continental margin, exemplified by the margin off of northern Norway; modified after Vorren and Mangerud (2006).

between sedimentary rocks on the shelf and crystalline rocks on the coast. Channels and troughs acted as drainage routes for ice streams (e.g., Vorren and Laberg, 1997; Sejrup et al., 1996; Ottesen et al., 2005). Mega-scale lineations, from hundreds of meters to several tens of kilometers in length, show former pathways for fast-flowing ice streams; the two largest were the Norwegian Channel ice stream and the Bear Island Trough ice stream, each 150–200 km wide at the mouth. Iceberg plough marks (normally at depths of less than 500 m) and iceberg turbate are found in many areas on the shelf, whereas morphological elements such as moraine ridges, lineations and glacitectonic forms (Figure 7) are similar to those found on land.

The thickness of glacigenic sediments varies between 0 and c. 300 m on the shelf. Much thicker prograding wedges were deposited along the continental margin, resulting in a shelf break migration of up to 150 km. Off mainland Norway, this growth was largely a response to Quaternary glaciations during the last c. 2.5 Ma. A major change in sediment transport routes is recorded at 0.8–1.1 Ma, reflecting larger Scandinavian ice-sheets. In the western Barents Sea an early phase of wedge growth was (glacio-) fluvial in character (Dahlgren et al., 2005). Particularly large accumulations are found in the trough mouth fans that contain up to 4 km-thick packages of glacigenic sediments, including glacimarine debris flow deposits of 2000 km^3, with a run-out distance of up to 200 km. The debris flows consist of remobilized sediments from till deltas/grounding-zone wedges deposited by ice streams at the shelf break. The long run-out distance might be due to hydroplaning. On the steeper continental slopes, the glacigenic sediments might have been transported directly to the deep-sea by turbidity currents, through channels, and accumulated in deep-sea fans and/or drifts.

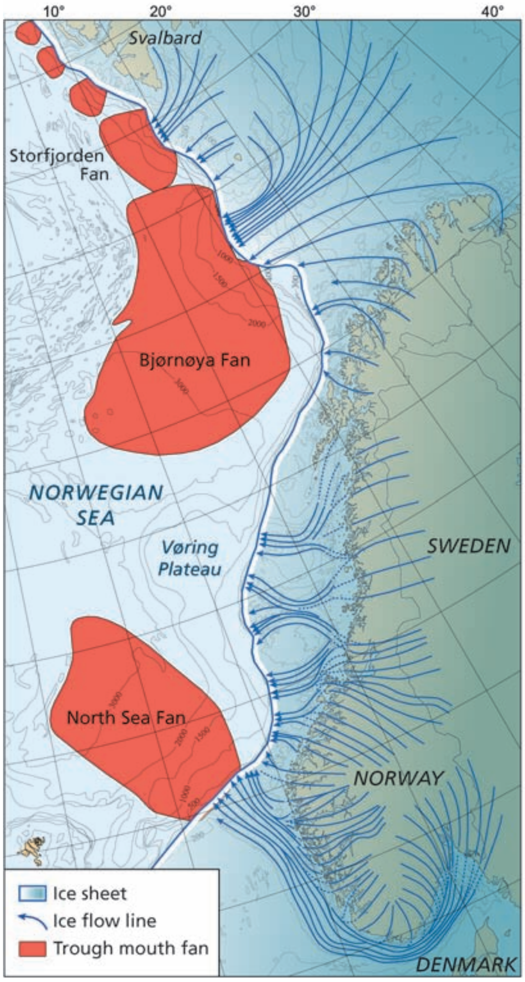

Figure 7 Inferred ice flow pattern, location and extent of trough mouth fans during large ice ages on the Norwegian continental margin, modified after Vorren and Mangerud (2006).

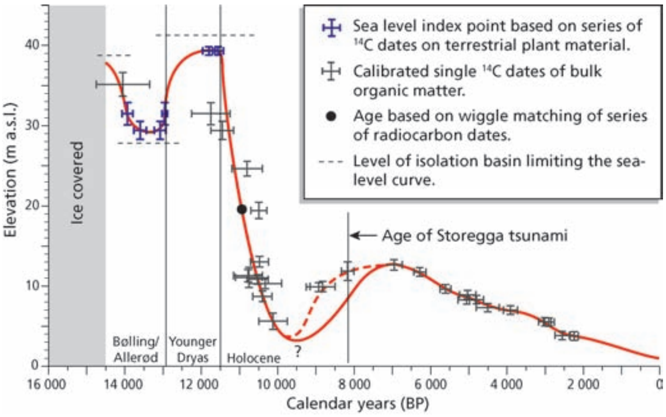

Figure 8 A sea level curve for the last 15 ka BP from the island of Sotra, west of Bergen showing 40 m emergence interrupted by two periods of relative sea level rise. Modified from Lohne et al. (2007).

The glaciations triggered a number of processes leading to sea-level changes. In Scandinavia, there are unique possibilities to describe these in great accuracy for the post-glacial period, because numerous lake basins have bedrock thresholds. When sea level was above the threshold, marine sediments were deposited in the basin; when high tides just reached the threshold, brackish sediments were deposited, and when sea level was even lower fresh water sediments were deposited. By coring the lake and dating the brackish sediments a sea level index point is obtained, i.e., the age and altitude of a certain sea level at the site, and by investigating lakes at different altitudes a relative sea- level curve can be constructed. An example from western Norway is shown in Figure 8 (Lohne et al., 2007).

Following the deglaciation, sea level dropped due to onset of glacio-isostatic rebound. Halt in rebound and rise in the local geoid level, both forced by a glacial re-advance, led relative sea level to move up during the Younger Dryas, followed by a fast drop at the onset of the Holocene. Many lake basins were inundated by the Storegga tsunami (8.2 ka BP) which was created by the huge Storegga slide on the continental margin off western Norway (Bondevik et al., 1997). The Tapes transgression, reaching its maximum level at 7 ka BP, was caused by deglaciation in Antarctica and/or North America, and subsequently glacio-isostatic rebound slowly caused regression to the present shore line.

Interstadial lakes and shallow arctic seas: gateways for ice streams in SW-Scandinavia

The Weichselian ice age repeatedly experienced rapid, high amplitude climatic changes between sudden warming events (interstadial conditions) followed by gradual cooling and a return to cold, stadial conditions. A number of so-called Greenland Interstadials which occurred at the beginning of longer cooling trends are registered during Marine Isotope Stage (MIS) 3 and have been correlated to the North European climate record.

In contrast to numerical models of the evolution of the Scandinavian Ice Sheet (SIS), stratigraphic evidence indicates at least four glacial advances between (MIS) 4 and 2 (Houmark-Nielsen, 2007, Houmark-Nielsen and Kjær, 2003). Clast provenances in tills indicate glacier flow twice via the Baltic Basin and twice via the Skagerrak-Kattegat trough (Figure 9). Rapid flowing ice in land based sectors of the SIS, which reached far south of the glaciated uplands, could have been initiated by the development of an expanded zone of basal melting beneath a steep gradient ice sheet. Instability, which was enhanced by melt water, caused ice-bed decoupling over large areas and may eventually have led to marginal collapse and surging through soft, water-saturated sediments bordering the SIS (Houmark-Nielsen, 2003; Kjær et al., 2003). Fine-grained freshwater

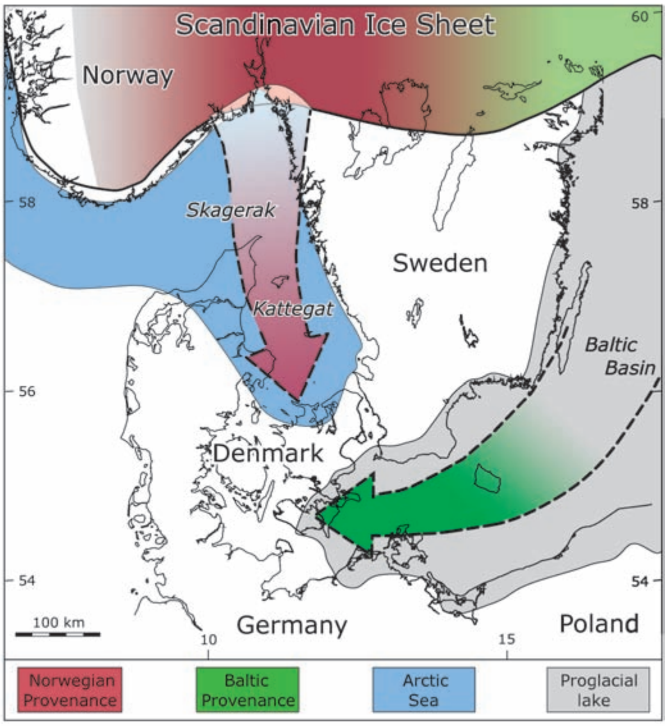

Figure 9 Distribution of shallow arctic seas and proglacial-interstadial lakes in southern Scandinavia. Arrows indicate ice streaming of Norwegian and Baltic provenance.

and marine sediments with an interstadial flora and fauna were deposited during MIS 3 in ice dammed lakes and narrow fjords in the Baltic Basin and the Kattegat trough. The regional distribution of former land-based ice streams in southern Scandinavia and in the North European lowlands seems closely related to the location of such an easily deformable substrate. The ice marginal collapse and out flow of streaming ice could have been triggered by abrupt warming, which was responsible for an ameliorated climate during MIS 3, when low arctic terrestrial biota and boreal-arctic marine waters occupied north-western Europe.

When Northern Hemisphere ice sheets experienced their largest expansion during MIS 4 and 2, slow and steady inter-stream flow was draining the SIS in central and southern Sweden, while prior to and just afterwards, rapid and canalized land-based ice streams were flowing along the Skagerrak-Kattegat trough and the Baltic depression respectively. Glaciation chronologies suggest that ice streaming occurred under relatively high glacio-eustatic sea level and ameliorated climate and that streaming episodes seem to have been out of phase with the global ice volume evolution, but might have been synchronous with regional climate trends. Alternatively, ice streaming could have been caused by internal ice sheet dynamics, which operated independently or out of phase with North Atlantic climate forcing.

Scandinavian Ice Sheet history in Finland and NW Russia

The bedrock of Finland consists almost entirely of Precambrian crystalline rocks upon which there is a relatively thin cover of mainly glacial Quaternary sediments. Stratigraphic and geochronological investigations of sediments deposited during the Eemian interglacial (c. 130–116 ka BP) and the following Weichselian (116–11.5 ka BP) make it possible to reconstruct a relatively detailed history of the major events that took place during the last interglacial/glacial cycle (Saarnisto and Lunkka, 2004). The extensive Saalian glaciation caused a strong glacio-isostatic depression which led to an open sea connection between the Baltic and White Sea basins during the Eemian interglacial (Figure 10). Marine Eemian clays beneath Weichselian till have been discovered in many localities. Their pollen and diatom content indicates that the passage between the White Sea and the Baltic Sea persisted for several thousand years (Ikonen and Ekman 2001, Miettinen et al., 2002), while mollusc data suggest only a short period of true marine conditions (Funder et al., 2002).

Figure 10 The extent of the Eemian Sea at around 120 ka BP between the Baltic and White Sea basins, modified after Saarnisto et al. (2002).

Subsequent to the Eemian Interglacial, ice began to build up in the Scandinavian mountains and the SIS eventually spread into adjacent areas to the east and northeast (Figure 11). It covered northern Finland and eastern Lapland at c. 90 ka BP (Lunkka et al., 2004; Helmens et al., 2007), while southern and central Finland remained ice free during the entire Early Weichselian (c. 116–74 ka BP) (Saarnisto and Lunkka, 2004). After the Odderade interstadial (MIS 5a), the ice sheet started to grow again and extended across Finland towards the east and southeast. It obtained its largest extent around

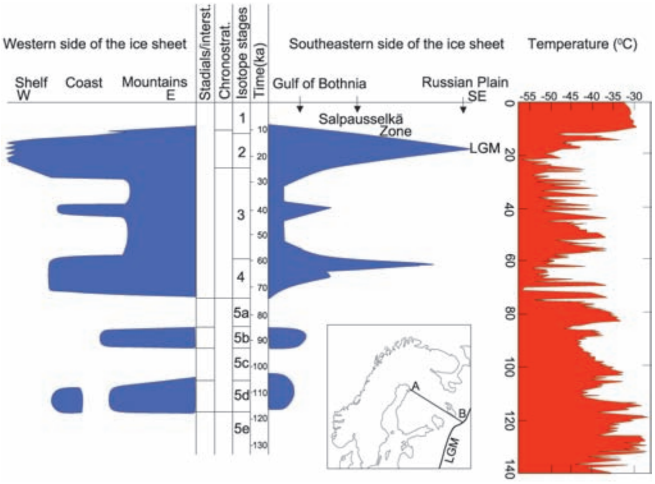

Figure 11 Time-distance diagram from the Gulf of Bothnia (A) to the Vologda area (B) and from the Scandinavian mountains to the Norwegian Shelf (see inset map) showing the fluctuations of the Scandinavian Ice Sheet during the Weichselian. Greenland ice core temperature reconstructions (according to Johnsen et al., 2001) are also shown for comparison; modified after Saarnisto and Lunkka (2004) and Mangerud (2004).

65–60 ka BP when present-day Finland was entirely ice covered (Saarnisto and Lunkka, 2004). Deglaciation commenced around 55 ka BP and periglacial conditions prevailed in southern and central Finland and even in eastern Finnish Lapland between c. 40 and 25 ka BP (Lunkka et al., 2001, 2004, Helmens et al., 2007). The final and relatively rapid advance of the SIS took place during the Late Weichselian, when Finland and an extensive area in northwest Russia became ice covered in less than 10 ka between 25 and 17 ka BP (Lunkka et al., 2001). Within the present dating resolution, the fluctuations of the eastern flank of the Scandinavian ice sheet were in phase with fluctuations that took place along the western flank of the ice sheet in Norway (Saarnisto and Lunkka, 2004).

Deglaciation of the eastern flank of the SIS was rapid and completed in less than 10 ka (Saarnisto and Lunkka, 2004). The deglaciation can be traced by an analysis of glacial landforms, especially end moraines and eskers. The most remarkable and distinct Younger Dryas (12.6–11.5 ka BP) end moraine zone comprises the Salpausselkä end moraines in Finland and their correlatives in Russian Karelia, the Keiva moraines on the Kola Peninsula and the end moraines around the Norwegian coast and in central Sweden (Andersen et al., 1995).

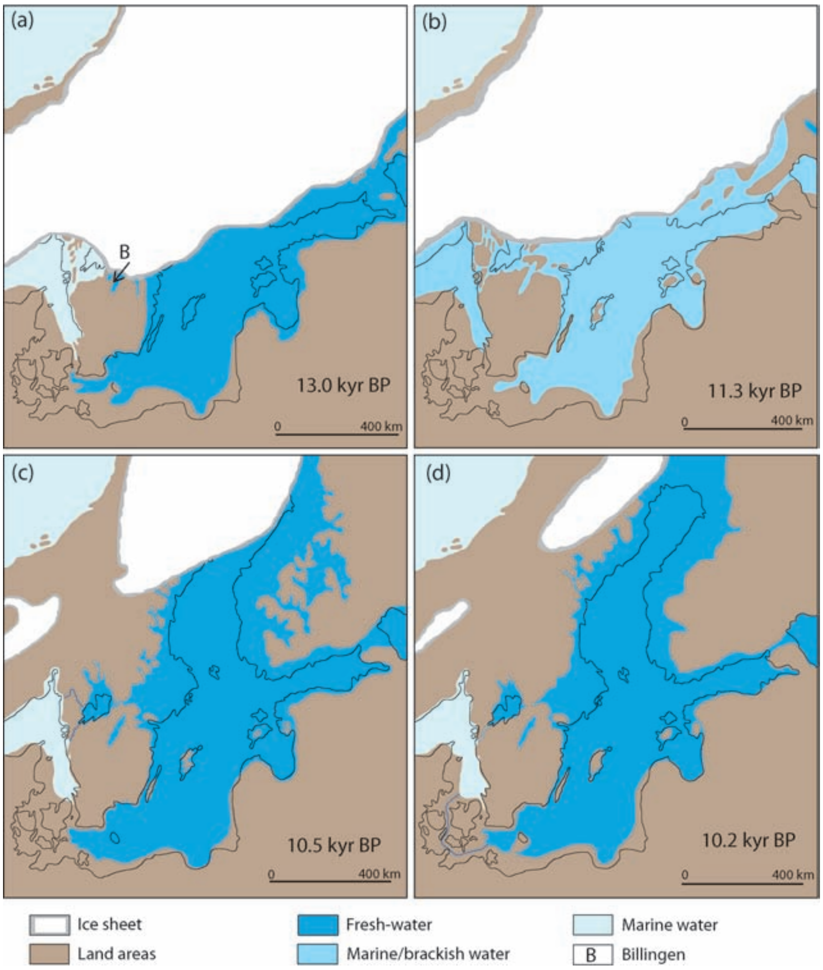

Figure 12 ***Baltic Sea stages and the extent of the Scandinavian ice sheet, modified after Björck (1995). The sequence of pictures illustrates (a) the time of the first drainage of the Baltic Ice Lake at c. 13 ka BP; (b) the Yoldia Sea stage at c. 11.3 ka BP, when southern Sweden and Denmark were connected by a land bridge, which facilitated a rapid immigration of plants and animals at the start of the Holocene; (c) the Ancylus Lake stage at c. 10.5 ka BP and (d) at c. 10.2 ka BP. The present-day shoreline is indicated by a full black line.***

The Baltic Sea development —a review

Nordic Quaternary geology is tightly linked with the development of the Baltic Sea because of an intricate interplay between glacial eustasy and isostasy. The Baltic Sea history is well known since the last deglaciation (Björck, 1995), but only little information exists for earlier time periods, with the exception of the last interglacial (Eem, 128–115 ka BP), when a connection, via Karelia, existed between the Baltic Sea and the White Sea during the initial part of the Eemian (Funder et al., 2002).

The first Baltic Sea stage, the *Baltic Ice Lake*, came into existence shortly after southernmost Sweden became ice free. It developed in front of the melting ice margin and received melt water from the decaying ice sheet as well as from large proglacial rivers. The outlet of the Baltic Ice Lake was situated in the Öresund region, where thick glacial deposits covered the chalk bedrock. The out-flowing water easily eroded the threshold and cut gradually deeper into the glacial deposits as the threshold kept rising. Around 14 ka BP, the out-flowing water had eroded most of the glacial deposits down to the flint dominated bedrock. The cessation of the erosion, combined with isostatic uplift in the Öresund region being larger than the sea level rise, led to a shallowing of the threshold. This caused a damming up of the Baltic Ice Lake, a transgression in the southernmost part of the Baltic, and a reduced regression in the remainder of the basin. At c. 13 ka BP, the ice margin was situated at the southern margin of the south-central Swedish low-land area (Figure 12a). The elevation of this area was, because of the isostatic depression, considerably lower than the threshold in the Öresund region, and the Baltic Ice Lake was dammed up 5–10 m a.s.l. Deglaciation of this southern margin at the water divide (Mt. Billingen) led to this first, poorly documented, drainage of the Baltic Ice Lake, with a new pathway for the waters towards the west. This may have lowered the level of the Baltic by 5–10 m and created a land bridge between Denmark and Sweden in the former outlet area in Öresund. The immigration of plants and animals to southern Sweden was facilitated, and the Baltic Ice Lake waters continued to drain westwards through the low-land area in south-central Sweden for another 300–400 years. Around 12.8 ka BP, at the start of the Younger Dryas cold period, the ice front started to re-advance and finally "closed" the connection between the sea in the west and the Baltic in the east. Meanwhile, the former threshold in the Öresund had risen even higher above sea level. The Baltic basin was once more dammed up above sea level. Towards the end of the Younger Dryas period, the level of the Baltic Ice Lake was 25 m higher than sea level, dammed up by the rising Öresund threshold in the south. A slight warming trend at around 12 ka BP caused the ice sheet to start retreating again. This led to a sudden and rapid drainage of the Baltic Ice Lake at Mt. Billingen through the south-central Swedish lowlands at 11.7 ka BP. Detailed studies have shown that the water level in the Baltic Ice Lake dropped by 25 m within only 1–2 years with the release of 7000–8000 km^3 of water (Jakobsson et al., 2007) producing large lobes of drainage deposits west of Mt. Billingen. The drainage led to distinct changes in the south western part of the Baltic, where the area around the former land bridge between Denmark and Sweden had increased in size. This land bridge facilitated a rapid immigration of plants and animals and humans into southern Sweden at the beginning of the Holocene. The rapidly melting ice sheet in south-central Sweden and the isostatically depressed areas in south central Sweden later allowed incursion of marine waters towards the east.

The second Baltic Sea stage (Figure 12b), the *Yoldia Sea* (11.6–10.7 ka BP) started once the Baltic had reached sea level; it is named after the glaciomarine shell *Portlandia (Yoldia) arctica*, which has been found in sediments in south-central Sweden. During a few hundred years in the middle of this stage, saline water reached as far as Finland and the southern Baltic. Rapid land uplift in south-central Sweden led to a shallowing of the connecting sounds and the Yoldia Stage came to an end. Drainage from the Baltic to the west coast was through Lake Vänern and further west through two river valleys. However, the rapid uplift of these outlets finally led to a new damming stage of the Baltic, the so-called Ancylus Lake Stage (10.7–9.8 ka BP), named after the freshwater snail *Ancylus fluviatilis* (Figure 12c, d). Since the Baltic level was regulated by uplift of the outlet area west of Lake Vänern, areas south of this isobase i.e. from southwestern-most Finland and southwards experienced a transgression; the further south the more extensive was the transgression, reaching a maximum of c. 20 m. The highest water level of the *Ancylus Lake stage*, which also marks the end of the Ancylus transgression, is today visible as distinct beach ridges on both sides of the Baltic. A sudden fall of the Ancylus Lake at 10.3 ka BP, the Ancylus regression, implies that erosion had created a new outlet, most likely through the German-Danish area, Darss Sill-Fehmarn Belt-Great Belt, where a large fluvial-lacustrine system was established around this time. The first signs of salt water in the Baltic, at around 9.8 ka BP, mark the end of the Ancylus Lake stage and show that marine water occasionally was able to penetrate through the long fluvial system in the Denmark, the so-called Dana River.

The last Baltic Sea stage, the *Littorina Sea*, named after the mollusc *Littorina littorea*, leads over to the present day Baltic Sea. From this time onwards, relative sea level changes were only governed by global sea level and local land uplift, but it would take at least another millennium before it became a truly brackish sea. During the early Littorina Sea stage land areas in the southern Baltic experienced a transgression, because there land uplift had ceased. Around 9.0–8.5 ka BP the sea level rise became more rapid than uplift in southern Sweden and coastal areas became transgressed, and transgression of the Öresund threshold (–7 m) allowed more marine water to enter the Baltic. During the following 3000 years five different transgression periods are recognized in the southern Baltic and have been related to global sea level changes as a consequence of melting of remaining ice sheets. The salinity of the Littorina Sea reached maxima during these transgressions and the concomitant high productivity led to oxygen deficiency in the bottom waters. Recurrent oxygen deficiency has been linked to increased salt water ingression and an often warmer environment, while colder conditions led to decreased salt content in the Baltic Sea waters. Since c. 5 ka BP the Baltic Sea level is only determined by the apparent uplift, highest today in northern Sweden with 8–9 mm/yr and lowest in the very south with –1 mm/yr.

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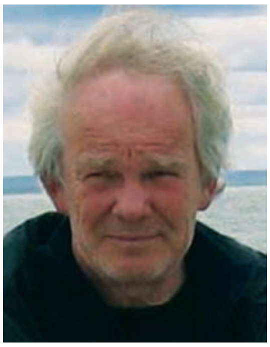

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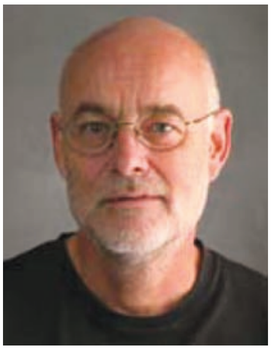

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Structure and evolution of the continental margin off Norway and the Barents Sea

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The Norwegian Margin formed in response to early Cenozoic continental breakup and subsequent opening of the Norwegian-Greenland Sea. There is a well-defined margin segmentation and the various segments are characterized by distinct crustal properties, structural and magmatic styles, and post-opening history of vertical motions. The sedimentary basins at the conjugate continental margins off Norway and Greenland and in the western Barents Sea developed as a result of a series of post-Caledonian rift episodes until early Cenozoic time, when complete continental separation took place.

Introduction

The Norwegian continental margin comprises the mainly rifted volcanic margin offshore mid-Norway (62–70°N) and the mainly sheared margin along the western Barents Sea and Svalbard (70–82°) (Figures 1 and 2). Physiographically, the Norwegian margin consists of a continental shelf and slope that vary considerably in width and steepness. The two adjacent shallow seas, the North Sea and the Barents Sea were, prior to the formation of the deep NE Atlantic ocean in early Cenozoic time, part of a much larger epicontinental sea between the continental masses of Fennoscandia, Svalbard and Greenland. The conjugate continental margins off Norway and Greenland (Brekke, 2000; Skogseid et al., 2000; Hamann et al., 2005; Tsikalas et al., 2005a), and the Barents Sea (Faleide et al., 1993; Gudlaugsson et al., 1998), experienced a long history of post-Caledonian extension (since Devonian) until breakup in early Cenozoic time. The margins are part of the North Atlantic Volcanic Province (NAVP) (Saunders et al., 1997). The voluminous igneous activity during breakup has left a distinct imprint on the rifted margin segments in terms of extrusive and intrusive magmatism at various crustal levels.

In this paper we synthesize and describe the regional structural and stratigraphic framework of the continental margin off Norway and the Barents Sea, emphasising on margin segmentation, tectonomagmatic style, sediment distribution and possible structural inheritance. The compilation builds on a large amount of integrated seismic reflection, wide-angle refraction and potential field data, and published scientific papers.

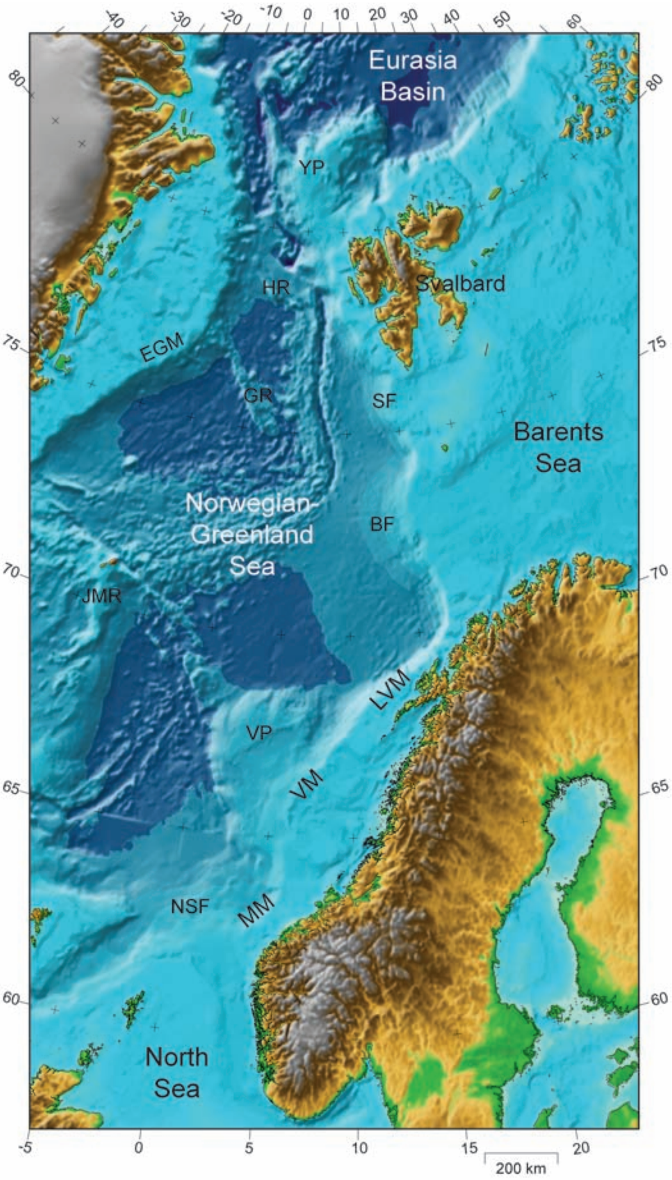

***Figure 1** Regional setting of the Norwegian continental margin, which formed in response to the Cenozoic opening of the Norwegian-Greenland Sea. Bathymetry/topography from the 1× 1' elevation grid of Jakobsson et al. (2000). BF: Bjørnøya Fan, EGM: East Greenland Margin, GR: Greenland Ridge, HR: Hovgård Ridge, JMR: Jan Mayen Ridge, LVM: Lofoten-Vesterålen Margin, MM: Møre Margin, NSF: North Sea Fan, SF: Storfjorden Fan, VM: Vøring Margin, VP: Vøring Plateau, YP: Yermak Plateau.*

Margin structure

The structural map (Figure 2) and a series of crustal transects (Figures 3 and 4) reveal an along-margin segmentation reflecting different geological provinces. The crustal thickness varies from 4–10 km in the oceanic Norway and Lofoten basins to about 30–32 km near the coastline and in the western Barents Sea, and is primarily governed by multi-phase extensional deformation and breakup-related magmatism. The transition from oceanic to continental crust differs considerably between the rifted and sheared margin segments.

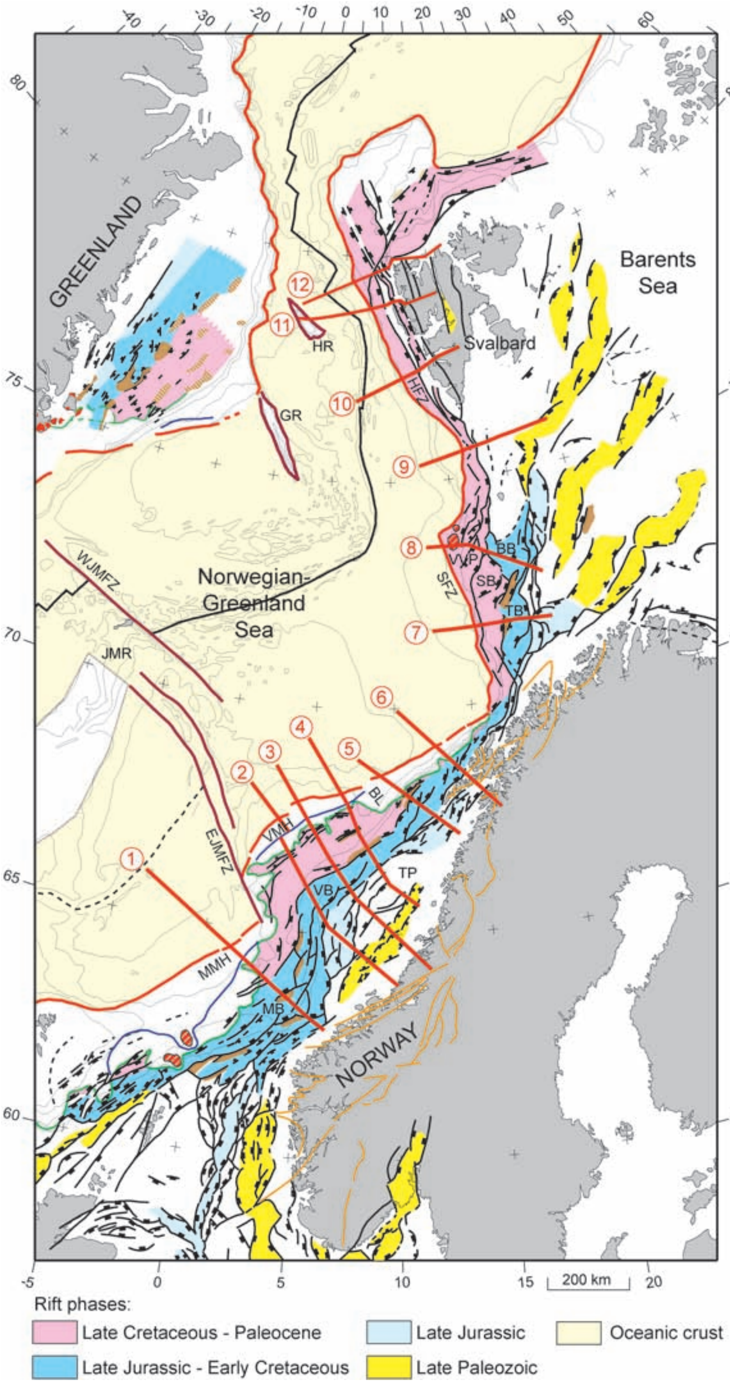

Figure 2   Regional structural map showing structural elements related to different rift phases affecting the NE Atlantic region. Location of margin transects in Figures 3 and 4 also shown. BB: Bjørnøya Basin, BL: Bivrost Lineament, EJMFZ: East Jan Mayen Fracture Zone, GR: Greenland Ridge, HFZ: Hornsund Fault Zone, HR: Hovgård Ridge, JMR: Jan Mayen Ridge, MB: Møre Basin, MMH: Møre Marginal High, SB: Sørvestsnaget Basin, SFZ: Senja Fracture Zone, TB: Tromsø Basin, TP: Trøndelag Platform, VB: Vøring Basin, VMH: Vøring Marginal High, VVP: Vestbakken Volcanic Province, WJMFZ: West Jan Mayen Fracture Zone.

Mid-Norwegian margin

The mid-Norwegian margin comprises three main segments (Møre, Vøring and Lofoten-Vesterålen), each between 400–500 km long, separated by the East Jan Mayen Fracture Zone and Bivrost Lineament/transfer zone (Figures 1 and 2). A lower crustal body (LCB) characterized by high P-wave velocities, 7.3–7.6 km/s, believed to be of breakup-related magmatic origin is characteristic for the outer parts of the volcanic margin off mid-Norway (Mjelde et al., 2005a). The LCB is best developed on the Møre and Vøring margin segments where it forms the lower part of the thickened crust beneath the marginal highs, with continuity to the exceptionally thick oceanic crust to the west. To the east, it continues below the crust that was extended and thinned prior to breakup (Figure 3).

The formation of the mid-Norwegian margin comprises the following tectono-magmatic evolution (Eldholm et al., 2002): (1) lithospheric extension during a rift episode in the latest Cretaceous-Paleocene leading to plate breakup and separation, (2) central rift uplift and increased igneous activity during late rifting and a few m.y. after breakup, culminating with voluminous outpourings of basaltic lavas in the Early Eocene, and (3) change to normal accretionary magma volumes with subsequent continental margin subsidence and maturation (Middle Eocene-Present).

The Møre Margin is characterized by a narrow shelf and a wide/gentle slope (Figure 1), underlain by the wide and deep Møre Basin (Figure 2) comprising a thick Cretaceous fill (Figure 3). The inner flank of the Møre Basin is steeply dipping basinward and the crystalline crust thins rapidly from >25 km to <10 km (Figure 3; profile 1). The sedimentary succession is the thickest along the western part of the basin; 15–16 km, decreasing to 12–13 km landwards. The deep Møre Basin comprises sub-basins separated by intrabasinal highs formed during Late Jurassic-Early Cretaceous rifting. Most of the structural relief was filled in by mid-Cretaceous time. Sill intrusions are widespread within the Cretaceous succession in central and western parts of the Møre Basin, and lava flows are covering the western part of the basin. A 2–5 km thick LCB with >7 km/s P-wave velocity is present under most of the Møre Basin. This body has been interpreted as breakup-related magmatic underplating (Olafsson et al., 1992; Raum, 2000). Seaward of the Faeroe-Shetland Escarpment, at the Møre Marginal High (Figures 2 and 3), thickening of the crystalline crust and shallowing of the pre-Cretaceous sediments and top crystalline basement occur near the continent-ocean transition (COT) (Breivik et al., 2006).

The ~500 km wide Vøring Margin comprises, from southeast to northwest, the Trøndelag Platform, the Halten and Dønna terraces, the Vøring Basin and the Vøring Marginal High (Figures 2 and 3). The Trøndelag Platform has been largely stable since Jurassic time and includes deep basins filled by Triassic and Upper Paleozoic sediments (Figure 3; profiles 2–4). Wide-angle seismic refraction profiles and deep MCS profiles constrain the Moho depth from ~30–32 km close to mainland Norway to ~25 km on large parts of the platform. The Vøring Basin can be divided into a series of sub-basins and highs (Figure 3), mainly reflecting differential vertical movements during the Late Jurassic–Early Cretaceous basin evolution. Moho is undulating at 20–25 km depth beneath the deep basin (Figure 3; profiles 2–4). In most parts of the area the velocity of the lower crust is very high, 7.3–7.6 km/s in a lower crustal body (LCB) created by magmatic underplating (Mjelde et al., 2003, 2005a).

Alternative interpretations of the LCB, including inherited high pressure granulite/eclogite rocks, melted continental crust or serpentinised mantle rocks, were discussed by Gernigon et al. (2004). The thickness of the body varies considerably laterally within the area, from absence to about 8–9 km. These strong lateral variations might be caused by variations in the pre-breakup structure and/or spatial variations in the magma distribution process.

The Vøring Plateau is a distinct bathymetric feature (Figure 1), and includes the Vøring Marginal High and the Vøring Escarpment (Figures 2 and 3). The Vøring Marginal High consists of an outer part of anomalously thick oceanic crust and a landward part of stretched continental crust covered by thick Early Eocene basalts and underplated by mafic intrusions. Densely spaced OBS data reveal a ~25-km-wide COT zone beneath the inner parts of seaward

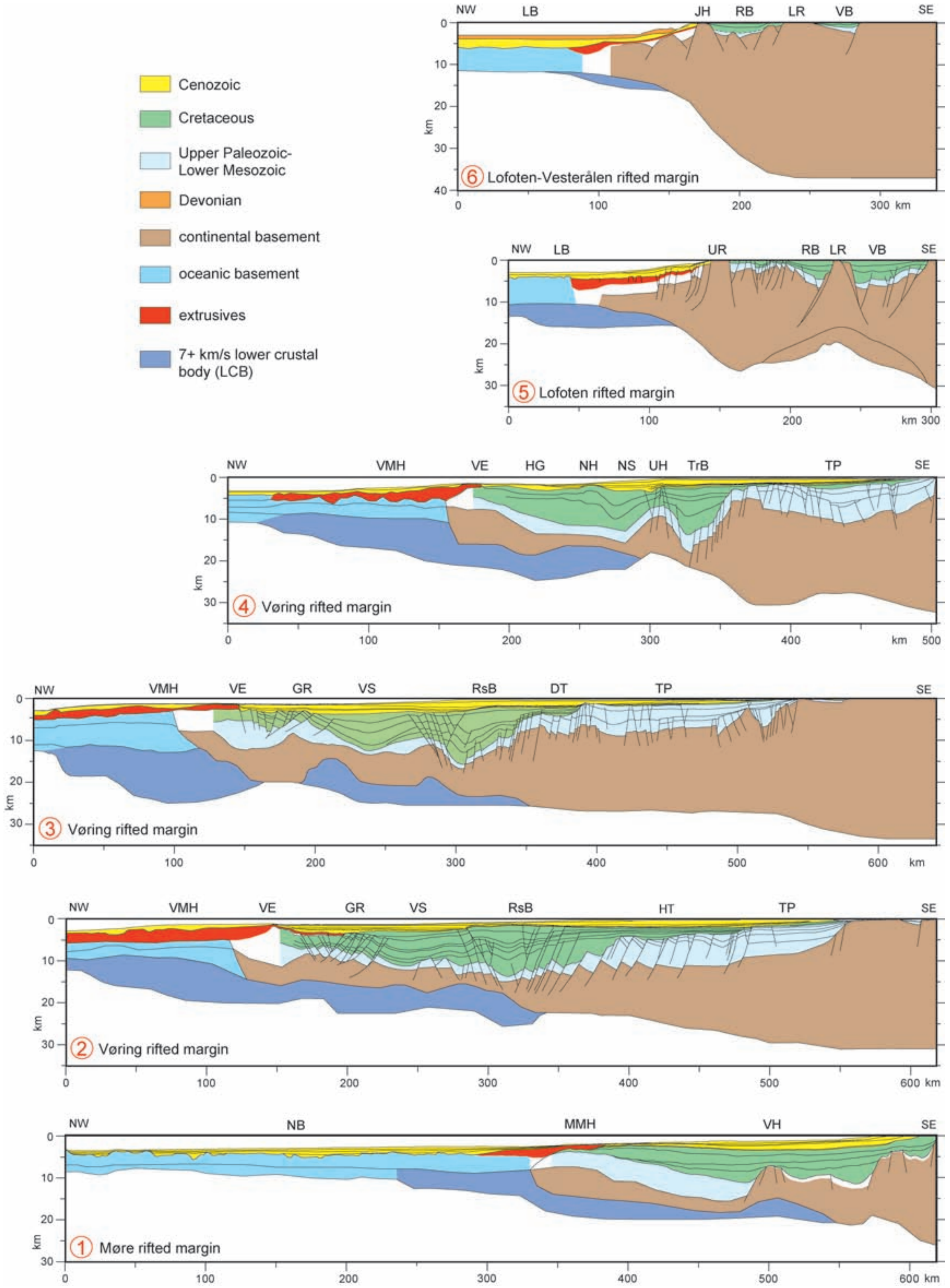

Figure 3   Crustal transects across the rifted continental margin off mid-Norway. Location of profiles in Figure 2. For references see text. DT: Dønna Terrace, GR: Gjallar Ridge, HT: Halten Terrace, HG: Hel Graben, JH: Jennegga High, LB: Lofoten Basin, LR: Lofoten Ridge, MMH: Møre Marginal High, NB: Norway Basin, NH: Nyk High,NS: Någrind Syncline, RB: Ribban Basin, RsB: Rås Basin, TrB: Træna Basin, TP: Trøndelag Platform, UH: Utgard High, UR: Utrøst Ridge, VB: Vestfjorden Basin, VE: Vøring Escarpment, VH: Vigra High, VMH: Vøring Marginal High, VS: Vigrid Syncline.

dipping reflector (SDR) sequences (Mjelde et al., 2005b). Landward of the COT, seismic velocities of ~6.0 km/s in the top of the main crustal layer are conformable with granitic basement, whereas corresponding velocities seaward of the COT (~6.9 km/s) indicate gabbroic, oceanic crust. The COT is characterized by intermediate, ~6.5 km/s, velocities, interpreted as heavily intruded continental crust that is underlain by a high-velocity LCB (Figure 3).

The Bivrost Lineament separates the Vøring and Lofoten-Vesterålen margins, marking the northern termination of the Vøring Plateau and the Vøring Marginal High, as well as the Vøring Escarpment (Figure 2) (e.g., Olesen et al., 2002). The Bivrost transfer zone is a major boundary in terms of margin physiography, structure, breakup magmatism, and lithosphere stretching; breakup-related magmatism is more voluminous south of it and the less magmatic Lofoten-Vesterålen margin was more susceptible to initial post-opening subsidence (Tsikalas et al., 2005b).

The Lofoten-Vesterålen margin is characterized by a narrow shelf and steep slope (Figure 1). The sedimentary basins underneath the shelf are narrower and shallower than on the Vøring and Møre margins (Figure 3, profiles 5–6). Typically they form asymmetric half-graben structures with changes in polarity bounded by a series of basement highs along the shelf edge. Beneath the slope, breakup-related lavas mask a sedimentary basin whose detailed mapping is hampered by poor seismic imaging (Tsikalas et al., 2001). Deep seismic profiles show ~30 km Moho depth in the coastal areas and a distinct thinning beneath the Lofoten Islands (Figure 3; profiles 5 and 6). The latter has been related to the development of a core complex in the middle to lower crust in the Lofoten Islands region, which has been exhumed along detachments during large-scale extension (e.g., Mjelde et al., 1993; Steltenpohl et al., 2004; Tsikalas et al., 2005b). The continental crust on the Lofoten-Vesterålen margin appears to have experienced only moderate pre-breakup extension, contrasting the greatly extended crust in the Vøring Basin farther south (Figure 3).

Western Barents Sea-Svalbard margin

Late Cretaceous–Paleocene rifting and subsequent breakup and initial seafloor spreading in the Norwegian-Greenland Sea was linked to the Arctic Eurasia Basin by the regional De Geer Zone megashear system. The western Barents Sea-Svalbard margin developed along this zone and is composed of two large shear segments and a central rifted margin segment SW of Bjørnøya associated with volcanism (Figure 2). Each segment is characterized by distinct crustal properties, structural and magmatic styles, and history of vertical motion (Figure 4), mainly as a result of three controlling parameters (Faleide et al., 1991): (1) the pre-breakup structure, (2) the geometry of the plate boundary at opening and (3) the direction of relative plate motion. The COT is confined within a narrow zone (10–20 km) along the sheared margin segments (Breivik et al., 1999), but is more obscure and partly masked by volcanics at the rifted margin segments.

The Senja Fracture Zone (SFZ), or Senja Shear Margin, marks the southern segment of the predominantly sheared margin along the western Barents Sea (Figure 2). Landward of the SFZ, the margin bounds a basinal province in which as much as 18–20 km of sedimentary strata cover a highly attenuated crystalline crust (Figure 4; profile 7).

The Vestbakken Volcanic Province (VVP) is located at a rifted margin segment southwest of Bjørnøya, linking sheared margin segments to the south and north (Figure 2). An east-stepping of the Eocene dextral shear margin (releasing bend) gave rise to basin formation in a pull-apart setting. The VVP structures are mainly extensional, but transpres-

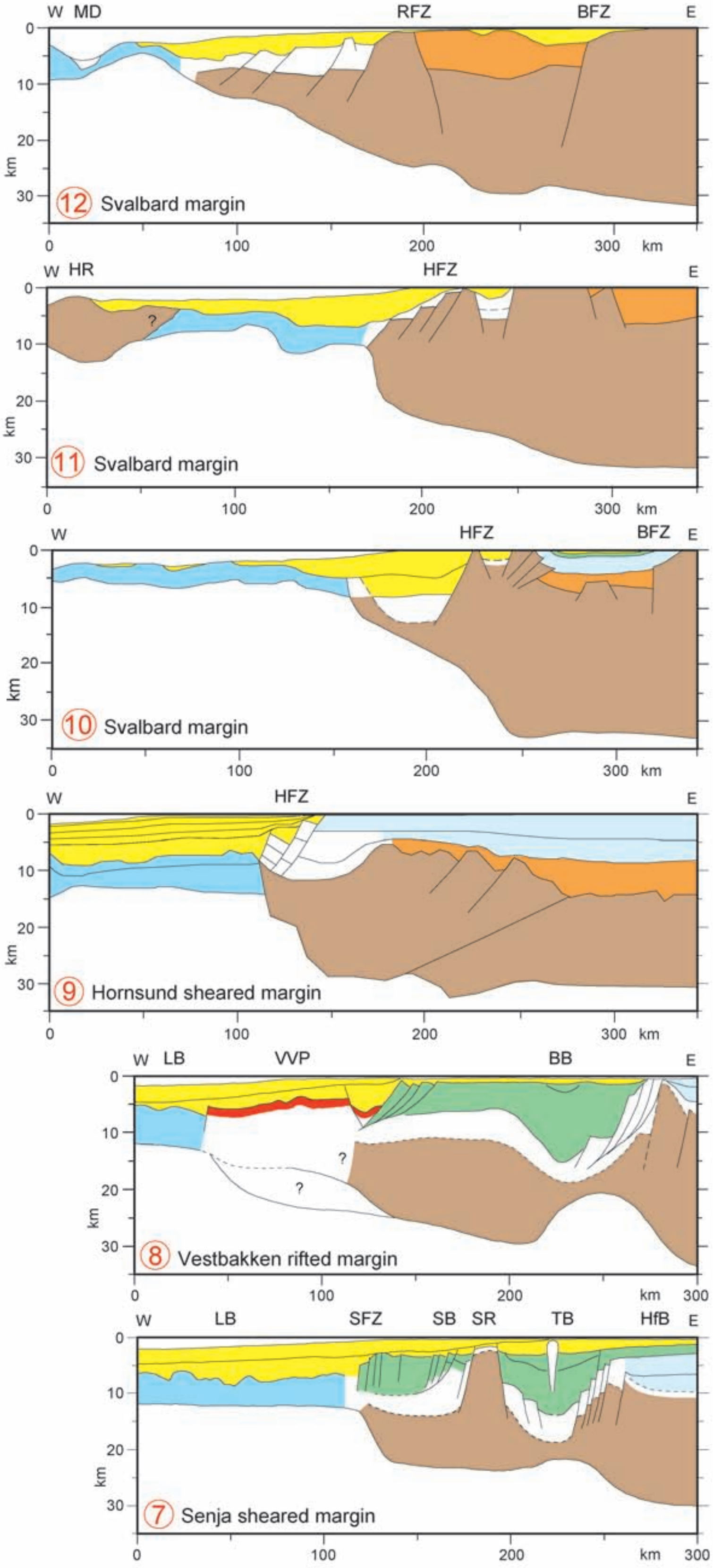

Figure 4 Crustal transects across the mainly sheared western Barents Sea-Svalbard margin. Location of profiles in Figure 2. For references see text. BB: Bjørnøya Basin, BFZ: Billefjorden Fault Zone, HfB: Hammerfest Basin, HFZ: Hornsund Fault Zone, HR: Hovgård Ridge, LB: Lofoten Basin, MD: Molloy Deep, RFZ: Raudfjorden Fault Zone, SB: Sørvestsnaget Basin, SFZ: Senja Fracture Zone, SR: Senja Ridge, TB: Tromsø Basin, VVP: Vestbakken Volcanic Province.

sional structures are observed locally. Prominent volcanoes as well as sill intrusions are observed at the outer margin (Faleide et al., 1988). Repeated tectonic activity in a pull-apart setting within the Vestbakken Volcanic Province reflects that the Cenozoic evolution of the NE Norwegian-Greenland Sea was complex, and as much as eight tectonic and three volcanic events have been identified (Jebsen and Faleide, 1998).

The continental margin north of Bjørnøya can be further subdivided into three segments (Figure 2): (1) a sheared margin from Bjørnøya to Sørkapp at the southern tip of Spitsbergen (74°30'–76°N), (2) an initially sheared and later rifted margin west of Svalbard between Sørkapp and Kongsfjorden (76–79°N), and (3) a complex sheared and rifted margin along NW Svalbard and SW Yermak Plateau associated with volcanism (79–81°N). The crustal thickness changes abruptly from continental crust more than 30 km thick on the Svalbard Platform, including the Svalbard archipelago, to oceanic crust 2–6 km thick in the Greenland Sea (Figure 4; profiles 9–12).

The continental margin between Bjørnøya and Sørkapp shows a narrow zone of crustal thinning dominated by two large rotated down-faulted blocks with throws of 2–3 km on each fault (Figure 4; profile 9), formed during the transform margin development (Breivik et al., 2003). The down-faulted terrace at the margin shows signs of periodic minor compression or wrench-tectonism (Grogan et al., 1999; Bergh and Grogan, 2003).

The Spitsbergen Fold-and-Thrust Belt formed between a restraining (SW of Sørkapp) and releasing (NW of Kongsfjorden) bend when Greenland slid past Svalbard during latest Paleocene and Eocene times (Figure 5) (e.g., Bergh et al., 1997; Braathen et al., 1999) (Figure 4; profile 10). West of the fold-and-thrust belt the continental crust thins rapidly across the Svalbard margin (Figures 2 and 4) (Ritzmann et al., 2002; 2004). The Hovgård Ridge probably represents a microcontinent rifted off from the Barents Sea-Svalbard margin (Figure 4; Profile 11) (Ritzmann et al., 2004). N-S trending grabens, up to 30 km wide, are present along the coast of NW Spitsbergen and SW Yermak Plateau (Figures 2 and 4). Profile 12 (Figure 4) shows a wider region of thin continental crust and a COT close to the present plate boundary at the Molloy Ridge (Ritzmann, 2003).

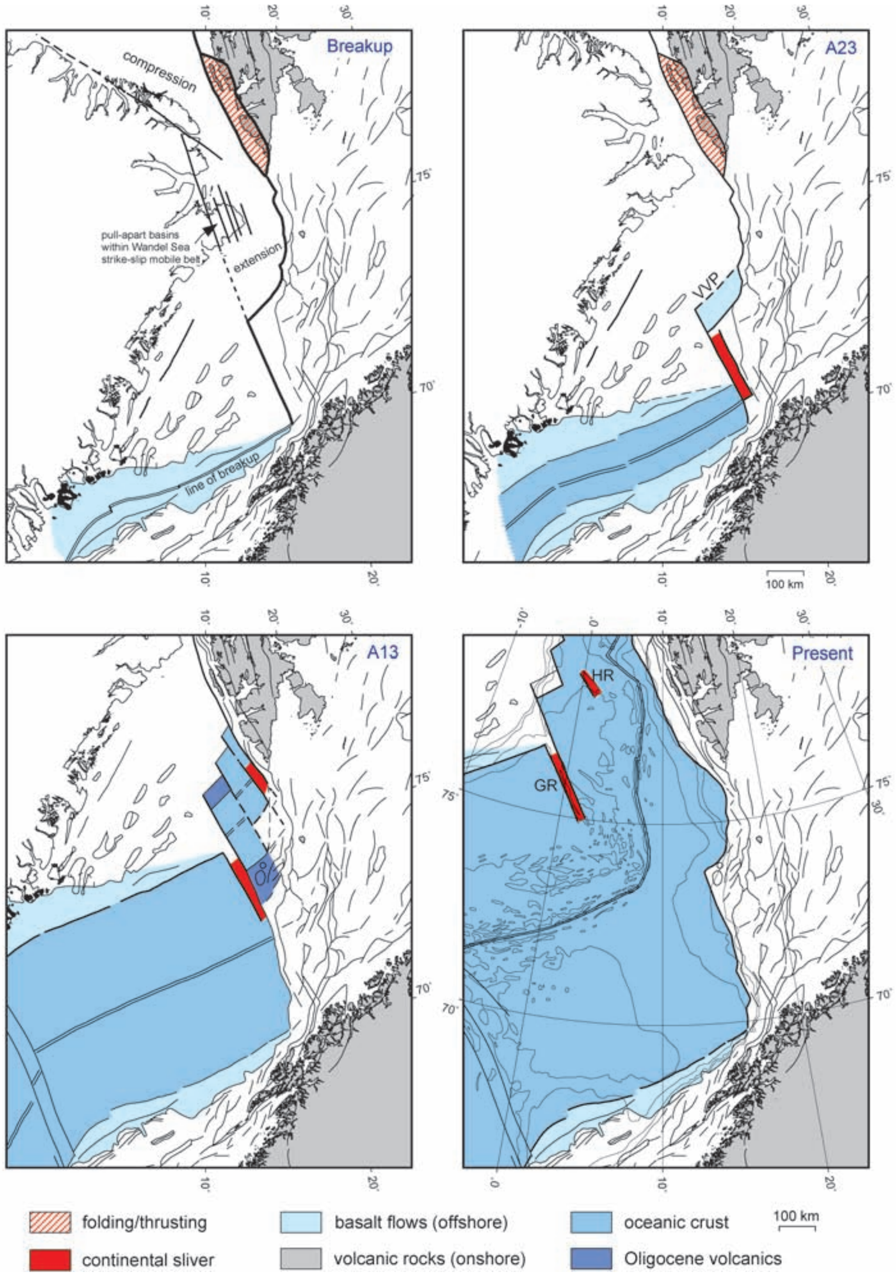

***Figure 5** Cenozoic plate tectonic evolution of the Norwegian-Greenland Sea. GR: Greenland Ridge, HR: Hovgård Ridge, VVP: Vestbakken Volcanic Basin.*

East Greenland margin

Opposite of the Norwegian margin, the conjugate Greenland margin has a narrow continental shelf in the south that becomes progressively wider northward (Figures 1 and 2). Integrated geophysical and geological studies have revealed pronounced differences in the crustal architecture of the East Greenland margin north and south of 72°N coinciding approximately with the landward prolongation of the West Jan Mayen Fracture Zone (WJMFZ) (e.g., Schlindwein and Jokat, 1999; Schmidt-Aursch and Jokat, 2005; Voss and Jokat, 2007). A lower crustal high-velocity body, interpreted as breakup-related magmatic underplating, is wider (190–225 km) and thicker (15–16 km) than previously thought (Voss and Jokat, 2007). Compared to the mid-Norwegian margin the dimensions of the LCB are considerably larger on the Greenland side contributing to a significant asymmetry in crustal architecture between the two conjugate margins.

The fairly good definition of early seafloor spreading anomalies and the continent-ocean boundary (COB) along parts of the NE Greenland margin (Figure 2) is deteriorated in character and definition towards the south, where the seafloor spreading anomalies trend obliquely with respect to the continental slope and there are alternative views to the COB/COT location (e.g., Scott, 2000; Tsikalas et al., 2002; Voss and Jokat, 2007).

Off NE Greenland, a series of prominent, elongate N to NNE-trending highs and basins (Figure 2) are recognized on the seismic data and are outlined on the gravity and magnetic anomaly fields (Hamann et al., 2005; Tsikalas et al., 2005a). Several of the basins appear locally to be very deep although extensive sill intrusions make it difficult to image the deep basin configuration. These basins correspond to the deep Mesozoic basins on the mid-Norwegian margin and in the SW Barents Sea (Figures 2 and 5).

Margin evolution

The conjugate NW European and East Greenland margins have a prolonged history of intermittent extension and basin formation, from post-Caledonian orogenic backsliding and collapse in Devonian times, to post-Early Eocene passive margin development governed by the widening and deepening of the NE Atlantic.

Pre-breakup basin evolution

The pre-opening, structural margin framework is dominated by the NE Atlantic-Arctic Late Jurassic–Early Cretaceous rift episode responsible for the development of major Cretaceous basins such as the Møre and Vøring basins off mid-Norway, and the deep basins in the SW Barents Sea (Figures 2–4). Prior to that, Late Paleozoic rift basins formed between Norway and Greenland and in the western Barents Sea along the NE-SW Caledonian trend (Figure 2).

It has been suggested that the main Late Paleozoic–early Mesozoic rift episodes took place in mid-Carboniferous, Carboniferous–Permian and Permian–Early Triassic times (Doré, 1991). Sediment packages associated with these movements are poorly resolved, mainly because of overprint by younger tectonism and burial by thick sedimentary strata. Carboniferous rift structures are widespread in the western Barents Sea (Gudlaugsson et al., 1998) (Figure 2) below an Upper Carboniferous–Lower Permian carbonate platform, which covered large areas of the present-day Arctic continental blocks. Thick evaporites were deposited in the Late Paleozoic rift basins on the SW Barents Sea margin, and off NE Greenland.

On the mid-Norwegian margin, the Trøndelag Platform (Froan Basin) and Vestfjorden Basin (Figure 3) record significant fault activity in Permian–Early Triassic time (Brekke, 2000; Osmundsen et al., 2002). Permian–Triassic extension is generally poorly dated, but is best constrained onshore East Greenland where a major phase of normal faulting culminated in the mid-Permian and further block faulting took place in the Early Triassic (e.g., Surlyk, 1990). The later Triassic basin evolution was characterized by regional subsidence and deposition of large sediment volumes. The Lower-Middle Jurassic strata (mainly sandstones) reflect shallow marine deposition prior to the onset of the next major rift phase.

A shift in the extensional stress field vector to NW-SE is recorded by the prominent NE Atlantic-Arctic late Middle Jurassic–earliest Cretaceous rift episode, an event associated with northward propagation of Atlantic rifting (Faleide et al., 1993). Considerable crustal extension and thinning led to the development of major Cretaceous basins off mid-Norway (Møre and Vøring basins, Figures 2 and 3) and East Greenland, and in the SW Barents Sea (Harstad, Tromsø, Bjørnøya and Sørvestsnaget basins, Figures 2 and 4). These basins underwent rapid differential subsidence and segmentation into sub-basins and highs.

In the North Atlantic realm, there is evidence for modest mid-Cretaceous extension in the Vøring Basin (Doré et al., 1999), Lofoten-Vesterålen margin (Tsikalas et al., 2001), onshore East Greenland (Whitham et al., 1999), and SW Barents Sea (Faleide et al., 1993). However, Skogseid et al. (2000) and Færseth and Lien (2002) argued that no distinct structures of this age are identified within the Vøring Basin. Biostratigraphic data from the Vøring margin reveal a change from neritic to bathyal conditions and an increase in sediment accommodation space in the Aptian-Albian, attributed to eustatic sea-level rise and regional tectonism (Gradstein et al., 1999). Aptian rifting is well constrained in the SW Barents Sea (Faleide et al., 1993). Farther north, there are few signs of Cretaceous extensional deformation, but magmatism of Barremian-Aptian age is widespread within an Arctic large igneous province (LIP) (Grogan et al., 1998; Maher, 2001). Regional uplift in the north gave rise to southward sediment progradation in the Barents Sea.

By mid-Cretaceous time, most of the structural relief within the Møre and Vøring basins had been filled in and thick Upper Cretaceous strata, mainly fine-grained clastics were deposited in wide basins. Pulses of coarse clastic input with an East Greenland provenance appeared in the Vøring Basin from Early Cenomanian to at least Early Campanian times (Færseth and Lien, 2002).

Breakup-related tectonism and magmatism

Breakup in the NE Atlantic was preceded by prominent Late Cretaceous–Paleocene rifting. At the onset of this rifting, the area between NW Europe and Greenland was an epicontinental sea covering a region in which the crust had been extensively weakened by previous rift episodes. Ren et al. (2003) suggested onset of rifting at about 81 Ma and that the main period of brittle faulting occurred in Campanian time followed by smaller-scale activity towards breakup. The Campanian rifting resulted in low-angle detachment structures that updome thick Cretaceous sequences and sole out at medium-to-deep intra-crustal levels on the Vøring and Lofoten-Vesterålen margins (Tsikalas et al., 2001; Gernigon et al., 2003; Ren et al., 2003).

Late Cretaceous–Paleocene rifting at the Vøring Margin covers a ~150 km wide area bounded by the Fles Fault Complex and the Utgard High on the east (Figures 2 and 3). Along the outer Møre and Lofoten-Vesterålen margins, most of the Late Cretaceous–Paleocene deformation is masked by the lavas, but the structures appears to continue seawards underneath the breakup lavas. On the Møre and Vøring margins, the Paleocene epoch was characterized by relatively deep water conditions. Depocentres in the western Møre and Vøring basins were sourced from the uplifted rift zone in the west (Hjelstuen et al., 1999). The northwestern corner of southern Norway was also uplifted and eroded, and the sediments were mainly deposited in the NE North Sea and SE Møre Basin (Martinsen et al., 1999; Faleide et al., 2002).

The Late Cretaceous–Paleocene extension between Norway and Greenland was taken up by strike-slip movements/deformation within the De Geer Zone (Figure 5). Pull-apart basins formed in the SW Barents Sea (e.g., Faleide et al., 1993; Breivik et al., 1998; Ryseth et al., 2003) and in the Wandel Sea Basin in NE Greenland (Håkansson and Pedersen, 2001). A relatively complete Paleocene succession was deposited under deep marine conditions in the Sørvestsnaget Basin and Vestbakken Volcanic Province (Ryseth et al., 2003).

Final lithospheric breakup at the Norwegian margin occurred near the Paleocene–Eocene transition at ~55–54 Ma (Chron 24r). It culminated in a 3–6 m.y. period of massive magmatic activity during breakup and onset of early sea-floor spreading. At the outer margin (e.g., Møre and Vøring margins), the lavas form characteristic SDR sequences that drilling has demonstrated to be subaerially and/or neritically erupted basalts (Eldholm et al., 1989; Planke et al., 1999). These seaward dipping reflectors have become diagnostic features of volcanic margins. During the main igneous episode at the Paleocene–Eocene transition, sills intruded into the thick Cretaceous successions throughout the NE Atlantic margin, including the Vøring and Møre basins. Magma intrusion into organic-rich sedimentary rocks led to formation of large volumes of greenhouse gases that were vented to the atmosphere in explosive gas eruptions forming several thousand hydrothermal vent complexes along the Norwegian margin (Svensen et al., 2004; Planke et al., 2005).

The evolution of the western Barents Sea-Svalbard margin was more complex due to the sheared margin setting. The SW Barents Sea margin, along the Senja Fracture Zone (Figures 2 and 5), developed during the Eocene opening of the Norwegian-Greenland Sea, first by continent-continent shear followed by continent-ocean shear, and has been passive since earliest Oligocene time. Deep marine conditions persisted in the SW Barents Sea (Sørvestsnaget Basin) throughout Eocene time, with deposition of significant sandy submarine fans during the Middle Eocene (Ryseth et al., 2003). Breakup-related magmatism in the Vestbakken Volcanic Province was followed by down-faulting and deposition of thick Eocene strata (Figures 2 and 4; profile 8).

The Bjørnøya-Spitsbergen margin segment experienced oblique continent-continent and partly continent-ocean shear with both transtensional and transpressional components during Eocene time (Grogan et al., 1999; Bergh and Grogan, 2003). On Spitsbergen, a foreland basin was sourced from uplifted parts of the fold-and-thrust belt in the west during latest Paleocene–Eocene times (Figure 4; profile 10) (Steel et al., 1985; Mueller and Spielhagen, 1990). At the end of Eocene, sea floor spreading had reached the margin off southern Spitsbergen and a narrow oceanic basin existed between the western Barents Sea and NE Greenland continental margins (Figure 5).

After a plate tectonic reorganization in earliest Oligocene time, Greenland (and North America) moved in a more westerly direction with respect to Eurasia (Figure 5). Significant marine shallowing took place at the Eocene–Oligocene transition in the Sørvestsnaget Basin (Ryseth et al., 2003). Early Oligocene rifting, related to the change in relative plate motion, reactivated faults in the Vestbakken Volcanic Province, in particular those with a NE-SW trend. This phase was also associated with renewed volcanism partly overprinting the breakup structures (Jebsen and Faleide, 1998). Transpressional movements west of Svalbard were replaced by oblique rifting and incipient seafloor spreading when relative plate motions changed in the earliest Oligocene, and narrow grabens developed along the Svalbard margin. The formation of these grabens was probably initiated within the Eocene wrench regime as indicated by minor compression observed in the deeper parts of the grabens (Gabrielsen et al., 1992; Kleinspehn and Teysser, 1992).

Post-breakup margin evolution

The mid-Norwegian margin experienced regional subsidence and modest sedimentation since Middle Eocene time and developed into a passive rifted margin bordering the oceanic Norwegian-Greenland Sea. The mainly sheared western Barents Sea-Svalbard margin had a more complex development and the different segments reached the passive margin stage at different times (see previous section).

Mid-Cenozoic compressional deformation (including domes/anticlines, reverse faults, and broad-scale inversion) is well documented on the Vøring margin, but its timing and significance are highly debated (Doré and Lundin, 1996; Vågnes et al., 1998; Lundin and Doré, 2002; Løseth and Henriksen, 2005; Stoker et al., 2005a). The main phase of deformation is clearly Miocene in age but some of the structures were probably initiated earlier in Late Eocene–Oligocene times.

The Miocene succession preserves a record of deep-water sedimentation that indicates an expansion of contourite sediment drifts (Eiken and Hinz, 1993; Laberg et al., 2005; Stoker et al., 2005b). Plate tectonic reconstructions indicate that the Fram Strait finally opened as a North Atlantic-Arctic Gateway in the Miocene (between 20 and 10 Ma; Engen et al., 2008) having major impact on ocean circulation. Deep water exchange was also enhanced through a southern gateway (the Faroe Conduit) and the general subsidence of the Greenland-Scotland Ridge (Stoker et al., 2005b).

There is increasing evidence on the Norwegian margin for Late Miocene outbuilding on the inner shelf (Molo Formation; Eidvin et al., 2007) indicating a regional, moderate uplift of Fennoscandia. At the western Barents Sea margin, a Late Miocene uplift event increases in amplitude eastwards within the Vestbakken Volcanic Province and may be related to pre-glacial tectonic uplift of the Barents Shelf (Jebsen and Faleide, 1998).

Over the entire shelf there is a distinct unconformity, which changes on the slope to a downlap surface for huge prograding wedges of sandy/silty muds sourced on the mainland areas around the NE Atlantic and the shelf (e.g., Barents Sea). This horizon marks the transition to glacial sediment deposition during the Northern Hemisphere Glaciation since about 2.6 Ma. Pliocene sedimentation is interspersed with ice-rafted debris signifying regional cooling and formation of glaciers. Large Plio-Pleistocene depocenters formed fans in front of bathymetric throughs scoured by ice streams eroding the shelf (Faleide et al., 1996; Laberg and Vorren, 1996; Dahlgren et al., 2005; Nygård et al., 2005; Rise et al., 2005). Plio-Pleistocene uplift and glacial erosion of the Barents Shelf and deposition of large volumes of glacial deposits in submarine fans along the margin resulted in a regional tilt of the margin (Dimakis et al., 1998). In terms of post-opening sediments, the glacial component constitutes more than half of the total volume deposited on the mid-Norwegian and western Barents Sea margins. The greatly enhanced Plio-Pleistocene deposition rates within the fans induced excess pore pressure and sediment instability resulting in a series of submarine slides of various sizes and timing (Bryn et al., 2005; Evans et al., 2005; Solheim et al., 2005; Hjelstuen et al., 2007).

Concluding remarks

The continental margin off mainland Norway and western Barents Sea-Svalbard, 62–82°N, evolved in response to the Cenozoic opening of the Norwegian-Greenland Sea as a mainly rifted and sheared margin, respectively. The margins exhibit a distinct along-margin segmentation reflecting structural inheritance extending back to a complex pre-breakup geological history. The lithospheric breakup was accompanied by massive, regional magmatism within the North Atlantic Volcanic Province. The breakup was preceded by a rift episode, clearly recognized by low-angle normal faulting on the outer margin during the Campanian. The fault activity continued toward breakup but appears to have been less frequent during the Paleocene. This is ascribed to focussing toward the incipient plate boundary, an area now covered by lavas, as well as to a more ductile lithospheric response when the thermal regime changed. After breakup, the passive margin evolved in response to subsidence and sediment loading during the widening and deepening of the Norwegian-Greenland Sea. Sedimentation was modest until the Late Pliocene when the Northern Hemisphere Glaciation led to rapid progradation and greatly increased sedimentation rates forming huge, regional depocentres near the shelf edge offshore Mid-Norway and in front of bathymetric troughs in the northern North Sea and western Barents Sea.

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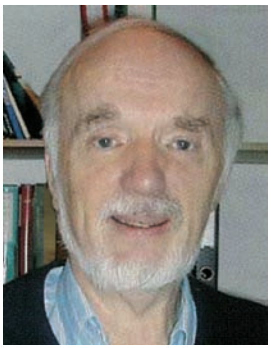

by Freysteinn Sigmundsson[1] and Kristján Sæmundsson[2]

Iceland: a window on North-Atlantic divergent plate tectonics and geologic processes

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Opening of the North Atlantic about 60 million years ago was associated with massive basaltic volcanism, now found on both sides of the Atlantic Ocean. Divergence of the North American and Eurasian plates since then has formed the ocean floor in the North Atlantic, with the Mid-Atlantic Ridge marking the present day plate boundary. Iceland is the only large sub-aerial portion of the ridge. These unique conditions provide a "window" on divergent plate tectonics and related geologic processes, some of the main features of which are described and explained in this paper. The geological record in Iceland reaches back into late Tertiary and is particularly notable for the interplay of rift-volcanism and glaciation during the last three million years of rapid climate change.

Introduction

The location of Iceland on the Mid-Atlantic Ridge provides unique opportunities for studying on-going geological processes related to sea-floor spreading and plume upwelling. This paper summarizes the main features of Iceland's geology and crustal structure, and compares them with geophysical observations of on-going crustal movements. Extensive studies of present day crustal movements have been conducted in Iceland using a variety of techniques, including levelling, precise geodetic measurements with the Global Positioning System, and interferometric analysis of satellite radar images (Sigmundsson, 2006). The volcanic activity is rather unique when compared to other areas above sea level, as it is more akin to activity on mid-oceanic ridges below sea level. The volcanoes of Iceland occur both within the main rift zones and also in off-rift flank zones where little or no spreading occurs. Many of Iceland's volcanoes are presently covered by ice, causing spectacular ice-volcano interaction. Rarely does such diverse volcanic activity as in Iceland occur in any one area on Earth. A more comprehensive treatment of Iceland's geology and tectonics is to be found in a special issue of *Jökull*, the Icelandic Journal of Earth Sciences (see e.g., Einarsson, in press, and other articles in the same issue).

Mantle plume–mid-ocean ridge interaction

The magnetic field in the Iceland region has been revealed in detail by extensive marine magnetic surveys, as well as aeromagnetic surveys conducted over Iceland (e.g., Kristjánsson et al., 1989; Jonsson et al., 1991). The geomagnetic field anomalies over Iceland are irregular, but parallel to the Mid-Atlantic Ridge to the south and north. Spreading has been restricted to a single axis south of Iceland, but a rift relocation has occurred north of Iceland. Spreading across the currently active Kolbeinsey Ridge began about 24 million years ago, but a prominent extinct ridge, the Aegir Ridge in the Norway basin, was active before. Magnetic anomalies are clear on each side of the Kolbeinsey Ridge (Figure 1), revealing a full spreading rate of about 2 cm/yr for the last 12 million years (Vogt et al., 1980). The spreading rate north of Iceland inferred from magnetic anomalies is one of the 277 globally distributed spreading rates used by DeMets et al.

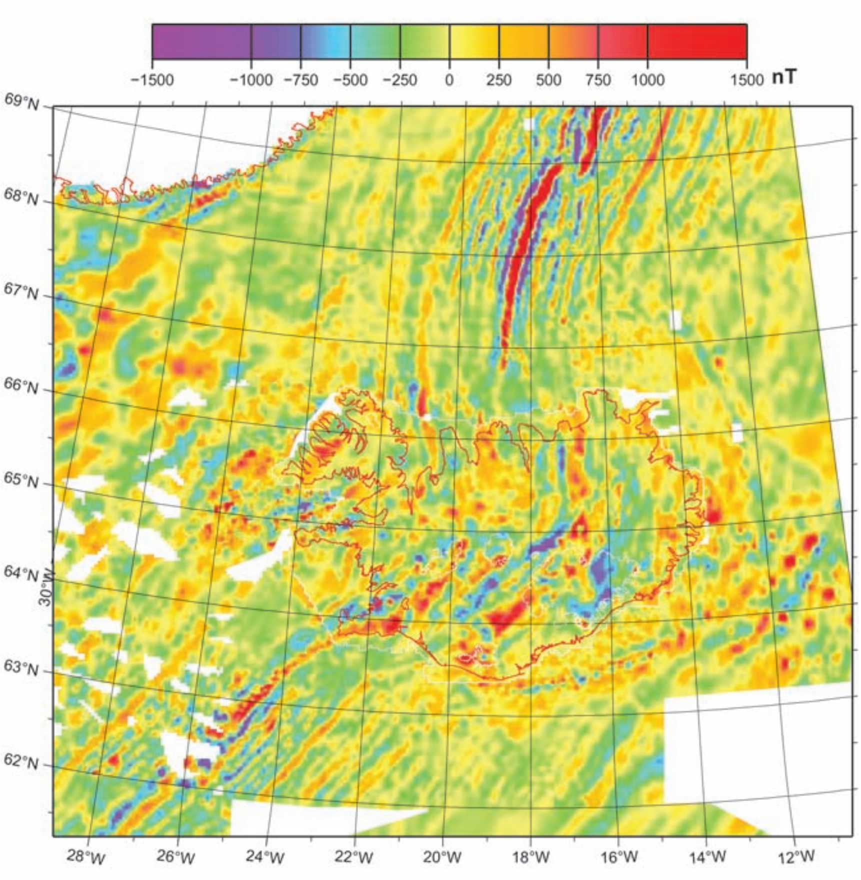

***Figure 1** Total magnetic field anomaly map of Iceland and the North Atlantic. After Eysteinsson and Gunnarsson (1995).*

(1994) to constrain the NUVEL-1 and NUVEL-1A plate motion model. According to the NUVEL-1A model, the inferred full spreading velocity in central Iceland (64.5°N, 18°W) is 18.3 mm/yr in direction N105°E. This estimate represents an average over a few million years time interval. The variation in spreading rate across Iceland, due to different distances from the pole of rotation, is less than 2 mm/yr.

An estimate of spreading rates, on a completely different timescale (years) can be inferred from precise geodetic measurements. Geodetic stations are needed on both sides of the plate boundary deformation zone, the central part of which is marked by extensive faulting and fissuring (Figure 2). The data have to be interpreted with care, as geodetic stations within plate boundary deformation zones in Iceland show spatial and temporal variation relating to various local processes. Only stations outside the main plate boundary deformation zone can directly give the divergence rate. A network of continuous GPS stations in Iceland (Geirsson et al., 2006) contains some stations outside these zones. Stations with the longest observation span are the REYK station in Reykjavík on the North American plate, and the HOFN station located in SE-Iceland on the Eurasian plate (Figure 3). The relative velocity between these two stations in 1999–2004 inferred by Geirsson et al. (2006) is 21.9 mm/yr in direction N102°E, slightly larger than the NUVEL-1A and REVEL velocities. The rates may reflect minor contributions from local processes, such as on-going glacio-isostatic movements (Pagli et al., 2007). The observed relative velocity between the REYK and HOFN stations allows, however, the conclusion that essentially all of the spreading across the Mid-Atlantic Ridge is accommodated within the width of Iceland.

The crustal structure of Iceland is fundamentally different from that of the adjacent Mid-Atlantic Ridge, being influenced by excessive melting attributed to the Iceland mantle plume. Seismic and gravity studies as well as mantle melting models provide insights. Recent seismic data argue for a thick relatively cold crust under Iceland, with crustal thickness increasing from c. 15 km in the coastal areas towards c. 40 km under central Iceland, with clear seismic reflections originating from a Moho. A fully three-dimensional study of the crustal structure of Iceland by Allen et al. (2002), based on a combination of surface wave and body wave data, as well as constraints from gravity data, gives a map of crustal thickness (Figure 4). There is little contrast in density between crust and mantle (Gudmundsson, 2003), and the large crustal thickness is consistent with high melt production in a mantle plume under Iceland. Various geochemical studies have been conducted to infer the style of mantle melting under Iceland, and the relation of melt generation to crustal structure and thickness (e.g., Maclennan et al., 2001a and b).

Figure 2 View from the plate boundary in Iceland at the Thingvellir site north of Lake Thingvallavatn in the western volcanic zone of Iceland. The photograph shows normal faults and tension fractures in a postglacial lava field, extending into a hyaloclastite mountain. To the right in the far distance is the Skjaldbreidur lava shield (Photo: Ágúst Gudmundsson, GEOICE).

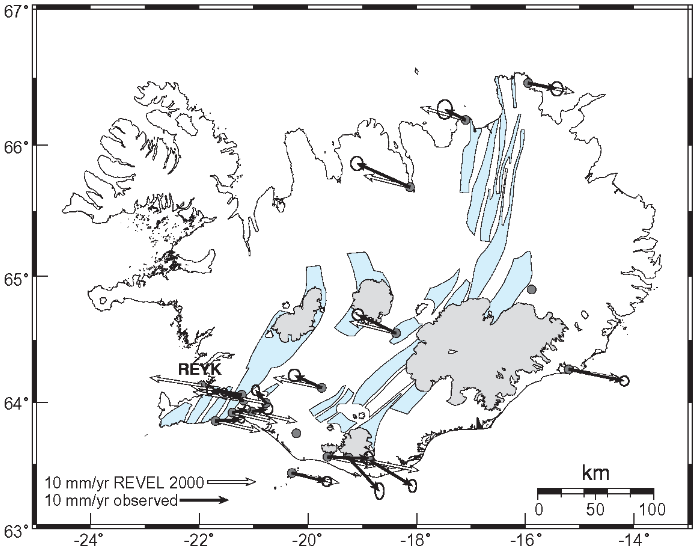

Figure 3 Velocities of continuous GPS stations in Iceland 1999–2004 (black arrows), assuming the REYK station moves at 10.5 mm/yr towards east and 1.6 mm/yr towards north. Confidence limits at the 2σ level are shown. The white arrows are velocities from the REVEL plate motion model (Sella et al., 2002), assuming stations on the North American plate move with a velocity equal to half of the inferred spreading across Iceland, and stations on the Eurasian plate move equally, but in opposite direction (movements relative to the central axis of the plate boundary). After Geirsson et al. (2006).

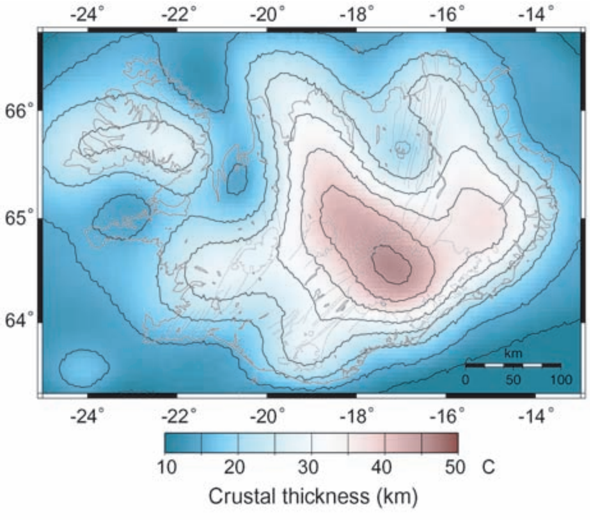

Figure 4 Crustal thickness model ICECRTb from Allen et al. (2002).

Geology

Rocks in Iceland are divided into four stratigraphic series based on climatic conditions at the time of formation, paleomagnetic field reversals, and radiometric age data. This division is somewhat modified from that used elsewhere and is shown on the geologic map of Iceland (Figure 5). An overview of the geology is given e.g. Saemundsson (1974, 1978, 1979, 1986) and Sigmundsson (2007). Iceland is mostly made up of basalts. They cover about 92% of the surface area of postglacial volcanic zones, whereas 4% are basaltic andesites, 1% are andesites, and 3% are dacite-rhyolites. The detailed geochemistry of volcanic rocks is complicated by the underlying mantle plume and rift relocations when new rift segments form in older crust (e.g., Oskarsson et al., 1985). The basic volcanotec-

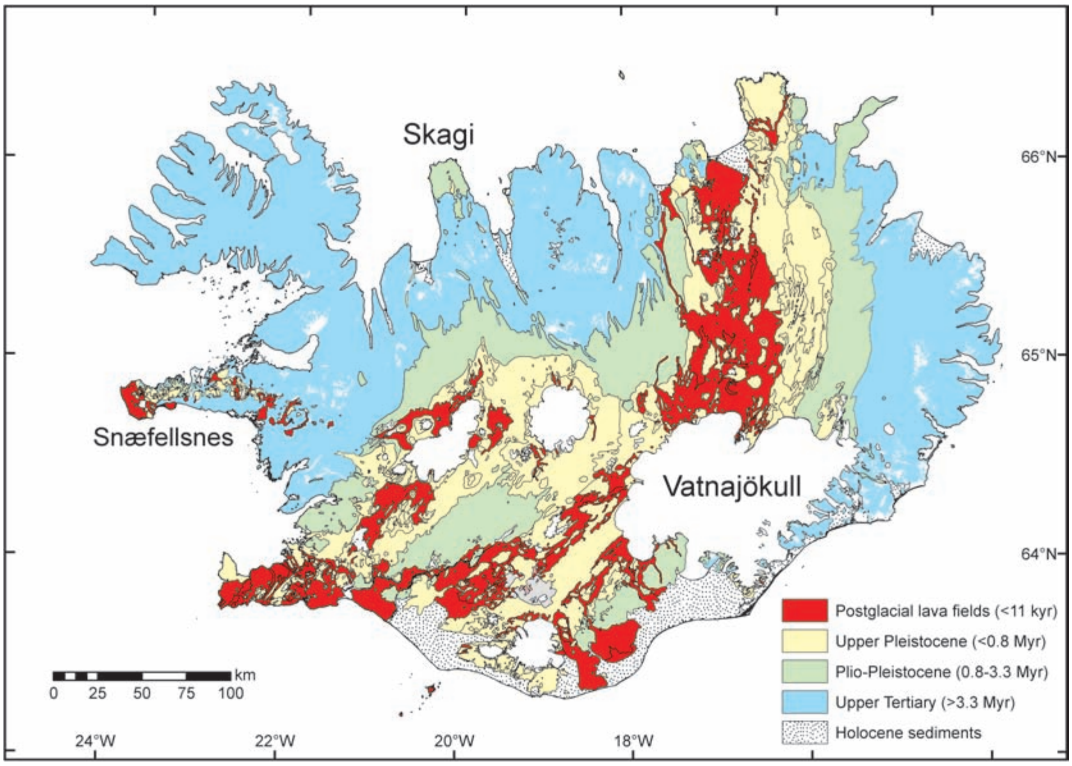

Figure 5 Geologic map of Iceland. Modified from Jóhannesson and Sæmundsson (1998).

tonic units forming the upper extrusive part of the crust are elongate volcanic systems. Each is active for a period of about 1 million years, during which a central volcano and an associated fissure/dike swarm is formed.

Rocks older than 3.3 Ma make up the Tertiary series covering about half of Iceland. It occurs in eastern, western and northern Iceland, with ages increasing with distance from extinct and active spreading zones. The oldest rocks, 14–15 Ma, are found in western and eastern Iceland, whereas rocks in north Iceland are up to 12 Ma. The Tertiary rocks formed prior to extensive glaciations on Iceland, so glacial deposits and subglacial volcanic products are rare. Most of the Tertiary series consists of a regular basaltic lava pile of slightly variable lithology. Subaerially erupted tholeiitic lavas about 5–15 m thick, separated by minor clastic interbeds of volcanic origin, form the bulk of the Tertiary lava pile. Within this lava pile, a vertical thickness of 1 km spans about 1 million years, on average. The corresponding lava deposition rate was low; about one lava flow per 10 000 years. However, these rates vary over a range from about c. 0.4–2 km per million years and only apply to areas outside of the volcanic centres. The interbeds between lava layers in the lava pile are, most commonly, thin layers of red or red-brown clayey or tuffaceous material. Thicker sedimentary beds commonly separate the main volcanotectonic units (Saemundsson, 1979). An integral part of the Tertiary lava pile are central volcanic complexes (central volcanoes). Where exhumed by erosion, they form structural irregularities with typically thin basaltic lava flows dominating and also silicic rocks as thick flows or pyroclastic sheets. The central part is characterized by collapse, clustering of intrusions and high alteration. Dike swarms, tens of km in length, are centred on the central volcanic complexes. The deepest level of erosion of about 2 km in SE-Iceland exposes a regional laumontite alteration zone and a local chlorite epidote cupola associated with the intrusive complexes. The eroded central volcanoes are analogues to the currently active volcanic centres in the neovolcanic zones, the dike swarms being the subsurface expression of fissure swarms. A characteristic feature of the Tertiary series is a regional tilting of the lava pile towards the volcanic zones in which they originated. The dips vary from near zero at the highest exposed levels to about 5–10° at sea level, the result of gradual loading from volcanic production (Figure 6). Anticlinal structures have formed in association with rift relocation, with lava loading occurring in two successively active rift zones.

The beginning of the Plio-Pleistocene in Iceland is somewhat arbitrarily set at the end of the Mammoth paleomagnetic event at 3.3 Ma. About this time, climate cooled with the onset of frequent glaciations. The change was not abrupt, as deposits of glacial origin, among them hyaloclastite ridges typical of subglacial fissure eruptions, are found in the Tertiary lava pile back to about 7 million years in southeastern Iceland. However, the changes at c. 3.3 Ma were drastic. Tuffs and volcanogenic sediments amount to only some 5% of the volume of the Tertiary series, whereas subglacial volcanics and glacially derived detrital beds gain in volume in later formations and may exceed 50% of its volume in the Quaternary. Rocks formed during the Plio-Pleistocene include extensive fluvioglacial and morainic deposits as well as hyaloclastites. The structure of this rock series differs from the more uniform Tertiary lava pile, being more irregular due to the subglacial volcanic activity. The erupted magma forms pillow lava, pillow breccia, or glassy tuff at the eruptive site,

Figure 6 Tertiary lava sequence in Reydarfjördur, Eastern Iceland. Tilt of lava varies from 5–10° close to sea level to almost zero near the top of the mountain (Photo: Freysteinn Sigmundsson).

commonly confined by the ice, causing the material to pile up rather than spread. Subaerially erupted lavas are found in between the subglacial formations, indicating that the Plio-Pleistocene was characterized by alternating warm and cold periods, with glaciation recurring every 100,000–130,000 years (Saemundsson and Noll, 1967; Geirsdóttir and Eiríksson 1994; Geirsdóttir et al., 2007). In southwestern Iceland, Kristjansson et al. (1980) found evidence for 13 glaciations between 3.1 and 1.8 Ma, in a 2.1 km thick succession of lavas separated by glacial horizons. Rocks from the Plio-Pleistocene epoch lie conformably above the Tertiary sequence. Exceptions occur on the Skagi peninsula in northern Iceland and on Snæfellsnes in western Iceland, where an unconformity exists between the Plio-Pleistocene sequence and the Tertiary lava pile. Erosion has cut over 1000 m deep into the lower part of the Plio-Pleistocene series revealing the same structural features that characterize the Tertiary series.

The boundary between the Plio-Pleistocene and the Upper Pleistocene is set at 0.8 Ma, at the reversal from the Matuyama magnetic epoch to the Brunhes magnetic epoch of normal polarity. As a rule the two are separated by a hiatus associated with a wide apron of non-tilted interglacial lavas at the margins of the Upper Pleistocene. The Upper Pleistocene rock series is characterized by more voluminous hyaloclastite formations than the Plio-Pleistocene, in addition to lavas erupted during interglacial times. The rather dominating hyaloclastite landscape features among the subglacially erupted volcanics of the Upper Pleistocence, in particular ridges and tuyas, gave rise to the collective term "Palagonite formation" (Móberg in Icelandic). The increased proportion of subglacially formed rocks relative to subaerially erupted rocks in the Upper Pleistocene indicates more extensive and longer lasting glaciations than earlier. Furthermore, glacial erosional features are in general insignificant in the Upper Pleistocene sequence as volcanic accumulation appears to have dominated over glacial or fluvial erosion (Saemundsson, 1979). In addition to being little eroded, the formations of the Upper Pleistocene can frequently be related to currently active volcanic systems. The Upper Pleistocene rock series, together with postglacially erupted rocks, are referred to as the neovolcanic zone of Iceland. Rocks from the Upper Pleistocene reveal a relationship between subglacial volcanic edifices and the ice sheets in which they formed, such that their height correlates with the ice thickness at the time of formation (Walker, 1965). Various studies (e.g., Walker and Blake 1966; Saemundsson, 1967; Werner et al., 1996) demonstrate that subglacial volcanic formations can be very complex, with superimposed or overlapping eruptive units formed in a number of eruptions under different environmental conditions.

The beginning of Postglacial time is not fixed as deglaciation procceded from the outer parts of Iceland towards the interior over a period of a few thousand years, beginning before the Younger Dryas. Extensive fresh lava flows and pyroclastics as well as sediments and soil formed after deglaciation, and characterize this epoch. Postglacial lavas are glacially uneroded and cover a large part of the neovolcancic zone of Iceland. The most extensive postglacial sediments occur along the south coast of Iceland, formed in repeated glacial outburst floods (jökulhlaup), associated with subglacial volcanic eruptions. Postglacial lavas are divided into prehistorical (older than 1100 years) and historical, a division based on the establishment of the first settlements in the country in the late 9th century. The intensity of volcanism during postglacial time has varied, with much more extensive volcanic production in the first millennia after deglaciation than is occurring now. This applies in particular to the lava shields, of which only two have formed during the last 3000 years; ten times more were erupted during the first three millenia after deglaciation.

The plate boundary and magma movements

The oldest part of the present-day plate boundary configuration in Iceland dates from 6–7 Ma. At that time a major eastward shift of the plate boundary occurred, leaving synclinal structures in western Iceland, at Snæfellsnes and west of Skagi as evidence of its former position. The shift has been explained as a response to gradual westward drift of the plate boundary away from the central plume upwelling under Iceland, because both Eurasian and North American plates have a westward component of movement in an absolute plate motion model, relative to fixed hot spots (Gripp and Gordon, 2002). Volcanism within the presently active zones on Iceland differs widely in character. Intense volcanism has built up a number of volcanic edifices through repeated eruptions. These foci of volcanic production along the volcanic zones are analogues to the eroded central volcanic complexes in the older series. Most of these central volcanoes are associated with silicic rocks, high-temperature geothermal areas, and many have developed a caldera. Crater rows formed in fissure eruptions, often grouped together with an array of normal faults, transect the central volcanoes. Accordingly, the neovolcanic zone is segmented into a number of volcanic systems (Figure 7). These differ in terms of volcanic production, proportion of silicic rocks, eruption frequency and tectonic character. They also have their own petrographic and geochemical differences which are most pronounced between volcanic systems in the spreading zone and those in the off-rift volcanic zones (Jakobsson, 1979a and b). The strike of the plate boundary varies and most of it is oblique to the spreading direction, causing en echelon arrangement of the volcanic systems. A similar arrangement is found for volcanic systems in the eroded Tertiary lava pile, with dike swarms extending away from central volcanoes into several million years older crust (Walker, 1974). Seismicity is mostly focused in two transform zones, the South-Iceland Seismic Zone and Tjörnes Fracture Zone, that tie the offset Iceland segment of the spreading zones up with the submarine

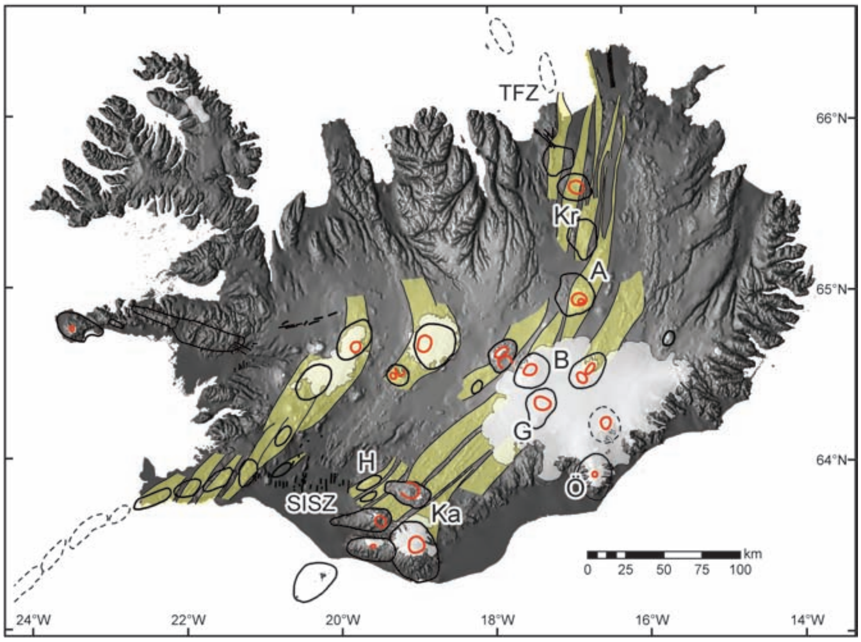

Figure 7 ***Volcanic systems in Iceland, as mapped by Einarsson and Sæmundsson (1987). Background map shows shaded topography. The volcanic systems consists of fissure swarms (yellow shading with outlines), central volcanoes (thick oval outlines), and calderas at some of the central volcanoes (red oval outlines). Names of selected volcanic systems are indicated: Askja (A), Bárdarbunga (B), Grímsvötn (G), Hekla (H), Krafla (Kr), Katla (Ka), and Öræfajökull (Ö). Locations of the South Iceland Seismic Zone (SISZ) and the Tjörnes Fracture Zone (TFZ) are also shown.***

Reykjanes and Kolbeinsey Ridges. In south Iceland, there are two subparallel spreading zones with different types of volcanism: lava shields of olivine tholeiite in the west and fissure eruptions of tholeiite in the east. There is evidence that the eastern zone formed later and is propagating to the southwest.

Throughout historical time, about 20–25 eruptions have occurred per century, with variable eruption styles (Thordarson and Larsen, 2007). Some of the volcanoes are subglacial (Figure 8) and in these cases, ice-volcano interaction is important (Gudmundsson et al., 1997). Large explosive eruptions include the 1362 eruption of the Mt. Öræfajökull stratovolcano, and a plinian eruption associated with caldera collapse at the Askja volcano in 1875. The volcanic production varies from one volcano to another, with the Hekla, Katla, Grímsvötn, and the Bárdarbunga volcanoes being the most active. The volumes of erupted products in individual volcano-tectonic episodes in Iceland span more than three orders of magnitude, from being less than 0.2 to c. 20 km^3, suggesting that widely different volumes of magma may accumulate in the crust prior to eruption. The largest lava producing eruptions were the Laki eruption in 1783–1784 (in the Grímsvötn volcanic system) and the Eldgjá eruption in c. 934 (in the Katla volcanic system), each with 15 km^3 or more of erupted material. The episodic nature of magmatic activity is not only reflected in intermittent volcanic activity; episodic events happen as well deep in the crust. Extensive studies of crustal deformation (e.g., Sigmundsson, 2006; Sturkell et al., 2006) and seismicity have revealed that the flow of magma through the lower crust towards shallow levels is highly episodic, resulting in periods of inflation and measurable ground deformation on the surface of the Earth. Recorded inflation episodes range in time from several months up to 15 years, with cumulative magma volumes ranging from c. 0.001 to 1 km^3. Only few of these episodes result in eruptions; often magma is emplaced at depth in the crust without an eruption at the surface (e.g., Pedersen and Sigmundsson, 2006). Between the relatively short periods of inflation, Icelandic volcanoes subside or show no signs of deformation. Because of limited magma inflow, shallow crustal magma chambers, typically at 3–7 km depth, are only found at the most active volcanoes in Iceland.

Various observations provide constraints on the crustal spreading process. The spreading leads to build-up of extensional stress in the uppermost part of the crust at a steady rate, and an associated decompressional melting in the mantle. Stretching across the fissure swarms prior to rifting causes subsidence of the fissure swarms as well. The stress is primarily released in large rifting episodes, when failure occurs on long segments of the plate boundary such as the entire length of a single volcanic system. The time between large rifting episodes is irregular, but on the order of 100 to 1000 years in each location along the plate boundary. The three most recent rifting episodes in the volcanic zone north of the Vatnajökull ice cap occurred in the Krafla volcanic system in 1724–1729, the Askja system in 1874–1875, and in Krafla system again in 1975–1984. The last one is the only one instrumentally recorded. The time intervals between rifting episodes are not only dependent on the amount of stretching since a preceding rifting episode. Availability of magma in the shallow crust appears to be critical, as magma allows "hydraulic fracturing" of crust at much lower stress levels than needed for faulting. The Krafla 1975–1984 rifting episode was associated with continuous inflow of magma towards a 3–7 km deep magma chamber under Krafla (Tryggvason, 1994; Brandsdottir et al., 1997). This was interrupted about twenty times by sudden deflation events when the chamber failed and dikes were expelled, with less than half of them reaching the surface. The 80 km long Krafla fissure swarm (spreading segment) widened on average by 4–6 metres. Diking events without eruptions were associated with formation of tension fractures and extensive normal faulting above them. Accommodation of plate movements thus appears to occur by different mechanisms throughout the crust. Widening by faulting and formation of tension fractures occurs in the near surface layer, whereas dikes dominate at greater depth. The dikes formed in the Krafla rifting episode have been estimated to extend to less than 10 km depth (Tryggvason, 1984; Árnadóttir et al., 1998), whereas in this location the crust is about 20 km thick. Ductile deformation mechanisms may be important in accommodating the plate movements in the lower crust.

Figure 8 The subglacial eruption of Grímsvötn volcano, Vatnajökull ice cap, in 2004. (Photo: Freysteinn Sigmundsson).

Conclusions

The divergent plate boundary in Iceland is complex because of an interplay between a mantle plume under Iceland and the spreading across the Mid-Atlantic ridge. The geology of Iceland reflects a complicated history of rift relocations, as well as variable climatic conditions that have shaped the environment and influenced volcanic activity. A number of tectonic and magmatic processes can be observed in Iceland with multiple techniques and approaches, and studied on different time scales. Volcanic activity is frequent, with variable eruption style. Magma intrusions and diking events associated with formation of the oceanic crust can be studied with modern instrumentation, and these observations can be compared to studies of eroded volcanic structures in the older parts of Iceland that provide a direct view of volcano interiors. All of these features make Iceland a unique "window" on North-Atlantic divergent plate tectonics and geologic processes.

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by Irina M. Artemieva and Hans Thybo

Deep Norden: Highlights of the lithospheric structure of Northern Europe, Iceland, and Greenland

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We present a review of geophysical models of the continental lithosphere of Norden, which includes the Nordic countries (Denmark, Iceland, Finland, Norway, Sweden), Greenland, and the adjacent regions of the neighbouring countries. The structure of the crust and the lithospheric mantle reflects the geologic evolution of Norden from Precambrian terrane accretion and subduction within the Baltic Shield and Greenland to Phanerozoic rifting, volcanism, magmatic crust formation, subduction and continent-continent collision at the edges of the cratons and at the plate boundaries. The proposed existence of a mantle plume below Iceland has not been uniquely demonstrated by the available seismic evidence. Its connection to the break-up of the North Atlantic Ocean c. 65 My ago is uncertain, but the >30 km thick crust in the strait between Iceland and Greenland may indicate the track of the plume. Using the results from seismic (reflection and refraction profiles, P- and S-wave, body-wave and surface-wave tomography), thermal, gravity, and petrologic studies, we review the structure of the crust and the lithospheric mantle of Norden and propose an integrated model of physical properties of the lithosphere of the region, including maps of lateral variation in crustal and lithospheric thicknesses and compositional variation in the lithospheric mantle.

Tectonic setting

The continental crust of Norden is chiefly of Precambrian age (Gaal and Gorbatschev, 1987), with large parts covered by Phanerozoic sedimentary sequences (the continental shelves and the North Sea area) and ice (Greenland). The topography is highly variable (Figure 1) with generally high topography in Norway (reaching c. 2,500 m in the peaks), gradually leveling eastwards to a constant value of a few hundred meters in the Precambrian shield of Sweden, Finland and Russian Kola-Karelia, and decreasing to about sea level in the sediment-covered areas around Denmark, the North Sea and Baltic Sea, and the continental shelves. The young (<16 Ma, Björnsson et al., 2005) crust around the oceanic spreading centre in Iceland is, surprisingly, above sea level, attaining surface elevations of up to 1,000 m. In the central parts of Greenland, where the ice cap reaches an elevation of c. 3,500 m above sea level, the bedrock topography is some hundred meters below sea level (Bamber et al., 2001), in contrast to the slightly elevated topography at the western coast and the generally high elevation (up to c. 2,500 m) along the eastern margin, where the topography is similar to the other side of the North Atlantic, in Norway. Negative bedrock topography in central Greenland may be explained by isostatic balancing of the load of the ice cap; the thickest ice sheet is found in those parts of Greenland where the bedrock topography is most depressed.

Due to the ice cover, the crust in Greenland is known only in a narrow rim at along the coast. Where it outcrops, it is mainly of Proterozoic age (Kalsbeek, 1993), although much of southern Greenland is Archaean and the Itsaq gneiss complex of southern West Greenland hosts some of the oldest rocks on Earth (c. 3.9 Ga, Baadsgaard, 1973; Nutman et al., 1993). Kimberlite dikes and pipes are also found in parts of western Greenland. The eastern parts of Greenland have been subject to the Caledonian orogeny, similar to the Norwegian side of the North Atlantic Ocean. The margins of Greenland and Norway were rifted apart during continental break-up and opening of the North Atlantic Ocean at about 65 Ma.

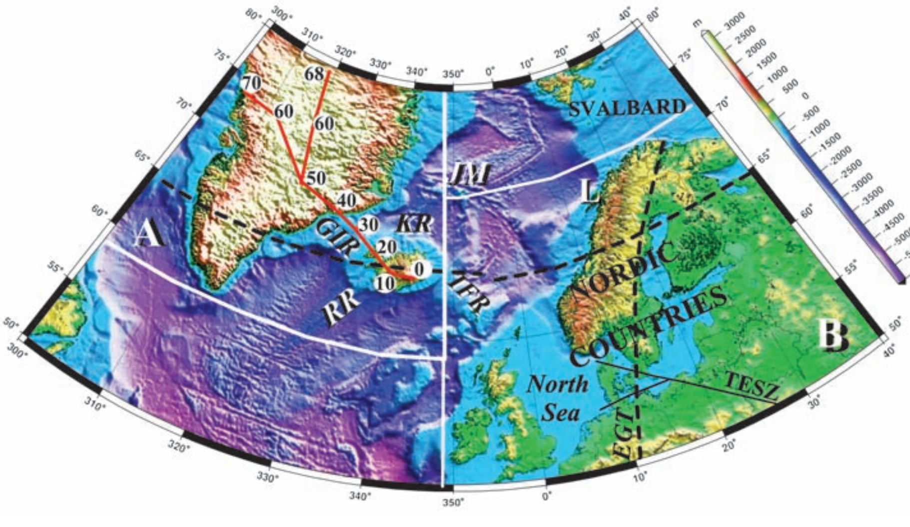

Figure 1 Topography and bathymetry of Norden (based on ETOPO2 data, NOAA, 2001). Dashed black lines—locations of 2 profiles (the European Geotraverse EGT and along 65°N) discussed in the text. White boxes labeled A and B—outlines of regions shown in other figures. Red lines—proposed tracks of Iceland hotspot (numbers—ages in My) (after Forsyth et al., 1986 and Lawver and Müller, 1994). Thin line—Trans-European Suture Zone (TESZ), which separates Precambrian East European craton from Phanerozoic Europe. Abbreviations: GIR—Greenland-Iceland ridge, IFR—Iceland-Faeroe ridge, KR—Kolbeinsey Ridge, RR—Reykjanes ridge, JM—Jan Mayen microcontinent, L—Archaean Lofoten block.

The Baltic Fennoscandian Shield in Norden includes an Archaean block (chiefly 2.9–2.7 Ga), located in the Kola-Karelian provinces of Finland and Russia, to which a series of terranes (Svecofennia) were accreted during the early Proterozoic (2.0–1.8 Ga) (Gaal and Gorbatschev, 1987). The southern part of the Baltic Shield has been significantly affected by the Sveconorwegian orogeny (1.1–0.9 Ga). The Caledonian orogeny (500–400 Ma) along the present western margin of the Baltic Shield and the eastern margin of Greenland resulted from collision of two main plates of Baltica and Laurentia. In the North Sea area, a micro-continent or a series of accreted terranes (Avalonia) formed a triple junction with Baltica and Laurentia (MONA LISA Working Group, 1997). On both sides of the North Atlantic, the Caledonian structures are identified in an up-to 200 km wide onshore zone. Further, on both sides of the North Atlantic, a 100–600 km wide continental shelf separates the land areas from the deep ocean. This shelf probably was also affected by the Caledonian tectonic events (Olesen et al., 2002).

The major geological boundary in Europe, the Trans-European Suture Zone (TESZ) marks the southwestern margin of the Proterozoic crustal domains of the Baltic Shield and the East European Platform. It came into existence during the accretion of a series of terranes during the Caledonian and the Variscan (430–280 Ma) orogenies (cf. Thybo et al., 2002, and references therein). The southwestern, Proterozoic and Palaeozoic part of Norden subsided during the late Palaeozoic and Mesozoic to form the North Sea basins. This basin formation followed intensive rifting episodes at, for example, the economically important Central Graben in the North Sea and the Oslo Graben (Ramberg and Smithson, 1975; Olsen, 1995).

The youngest (<16 Ma) onshore crust in Norden is located in Iceland, although Caledonian and older ages have been reported for the recycled crust (Korenaga and Kelemen, 2000). One of two major positive geoid anomalies on Earth (+60 m) peaks over Iceland. The positive free air gravity values and the elevated surface topography indicate significant dynamic support from the mantle in a wide zone around Iceland, which is situated above sea level at the intersection of two major tectonic structures: the oceanic spreading zone of the North Atlantic Ocean (that is the boundary between the American and European plates, diverging at the rate of 2 cm/y) and the Greenland-Iceland-Faeroe ridge of shallow bathymetry (Figure 1) and thick (25–35 km) oceanic crust (Figure 2). The ridge, transversing the North Atlantic, is interpreted either as a track of a semistationary (with respect to plate boundary) mantle plume (Lundin and Dore, 2005) or as major melting anomaly associated with a persistent volcanism centered at c. 65°N at the Mid-Atlantic ridge (Boutilier and Keen, 1999). In Iceland, the spreading ridge migrates eastwards; it was proposed that over the past 17 Ma (and perhaps as long as 26 Ma) spreading in Iceland has occurred along two parallel ridges (Foulger and Anderson, 2005). Tertiary flood basalts and shield volcanoes in the axial rift zone of Iceland are composed of primitive olivine-tholeiites generated at 20–40 km depth (Schiellerup, 1995). Icelandic basalts have a distinctive depleted component interpreted to be recycled oceanic crust (Chauvel and Hemond, 2002) and an iron-enriched component derived either from a chiefly eclogitic source (Foulger et al., 2005) or from an ancient OIB seamount structure (McKenzie at al., 2004). The source may also contain fragments of Caledonian and older continental lithosphere (Korenaga and Kelemen, 2000), e.g. the Jan Mayen microcontinent that separated from East Greenland c. 44 Ma or continental lithosphere delaminated during the opening of the North Atlantic.

Crustal thickness

The crustal thickness in the Nordic area is relatively well known, in particular in the Baltic Shield and in Iceland, from a series of controlled source seismological surveys (Figure 2). The thickest crust (>60 km) is observed in a localized area in the Archean and Proterozoic terranes of south-central Finland (Tiira et al., 2006). The Archaean Kola province and most of the Svecofennian province have crustal thicknesses of 40–50 km, similar to most of the East European Platform further to the southeast. The Caledonian deformed belt is characterized by a relatively thin crust (30–36 km), although values of c. 40 km have been reported for the southern part of Norway (Svenningsen et al., 2007). Most of this region has further been subject to the effects of ocean break-up along the Norwegian coast and to intensive rifting episodes with related crustal thinning in the North Sea area (Beach, 1986; Olsen, 1995). The TESZ marks a sharp transition from a thick (typically >40 km) Precambrian to a thin (28–32 km) Phanerozoic crust, although the Precambrian crust in the Tornquist Fan area of the North Sea basin has been significantly thinned (to c. 25–30 km) in-between thicker, more stable blocks during Paleozoic-Mesozoic rifting and basin formation (Thybo, 1997).

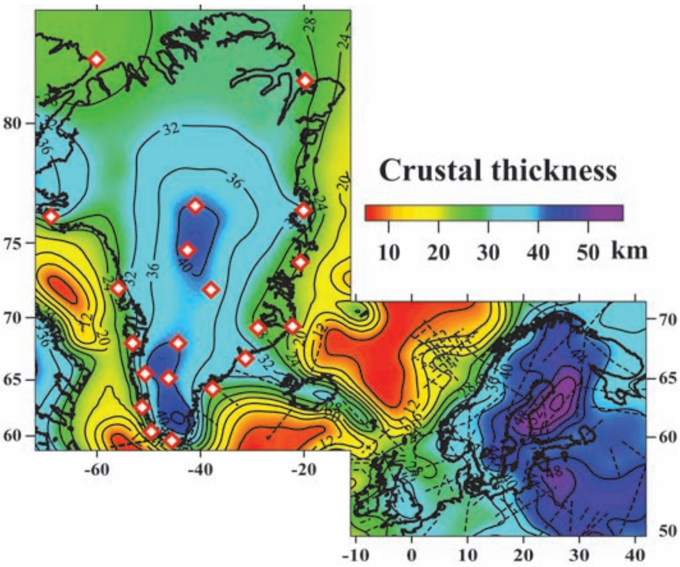

***Figure 2** Crustal thickness in Northern Europe, Iceland and Greenland (locations of major seismic profiles are shown by dashed lines, seismic stations in Greenland are shown by red diamonds). Data sources: see Artemieva et al. (2006) and Artemieva (2007) with additions from Korsman et al. (1999), Tsikalas et al. (2005), Hyvonen et al. (2007), Kelly et al. (2007), and Olsson et al. (2007) for Northern Europe; Kumar et al. (2007), Dahl-Jensen et al. (1998, 2003), Holbrook et al. (2001), and Chian and Louden (1992) for Greenland; Bott and Gunnarsson (1980) for Iceland-Faeroe ridge and Kodaira et al. (1998) for the Jan Mayen microcontinent.*

A substantial number of seismic and gravity studies have challenged estimates of the crustal thickness in Iceland. Two competing points of view exist: thin crust and thick crust (see e.g., Foulger et al., 2005 for overview). Both interpretations are based chiefly on similar or the same seismic data, which indicate a gradual increase in Vp seismic velocity from 6.5–7.0 km/s in the oceanic Layer 3 at depths above 10–20 km to Vp~7.0–7.6 km/s in Layer 4, that extends down to at least 60 km depth (Angenheistr et al., 1980). The major difference between "thin" and "thick" crustal models is in petrological and tectonic interpretations of Layer 4. In the thin-crust model, layer 4 is interpreted as anomalous peridotite mantle with a melt content of c. 2% (Schmeling, 1985). The thick-crust model interprets Layer 4 as gabbroic "lower crust" with some lenses of melt. Note that in both models partial melts are expected below 10–20 km depth.

According to the thin-crust model (Palmason, 1971), crustal thickness is 10–15 km under the main rifting axes increasing to c. 25 km in the oldest, Tertiary, eastern and western parts of Iceland. Thin crust is supported by electromagnetic studies (Björnsson et al., 2005), which indicate the presence of electrical conductor at <15 km depth below the active rift zones and at >25 km depth in Tertiary areas. The thick-crust model interprets the crust to be 35–40 km in central Iceland thinning to 30 km in the eastern and northern areas and to 20–25 km in the western and southern areas. This model is supported by the presence of deep seismic reflectors at 20–40 km depth (Gebrande et al., 1980; Bjarnason et al., 1993), which are commonly interpreted as the Moho (Menke and Levin, 1994; Staples et al., 1997; Darbyshire et al., 2000). However, the reflectors are fragmented and cannot be interpolated into a continuous interface (Kaban et al., 2002).

Gravity modeling (Darbyshire et al., 2000; Kaban et al., 2002; Fedorova et al., 2005) fails to discriminate between "thin" and "thick" crustal models: both crustal models can fit the data and explain the major Bouguer gravity low centered in east-central Iceland (Eysteinsson and Gunmarsson, 1995). They estimate the density of Layer 4 to be in the range of 3,030–3,150 kg/m^3, i.e., intermediate between the typical oceanic crustal densities (2,970 kg/m^3) and the typical uppermost mantle densities (3,300 kg/m^3). Thin-crust model implies hot lithosphere with a high percent of melt in Layer 4, not observed in seismic studies. In contrast, thick-crust model requires low mantle temperatures to keep a 20 km thick gabbroic Layer 4 below the gabbro solidus (Menke and Levin, 1994). Low temperatures are consistent with regional off-shore heat flow observations which do not show any heat flow anomaly (Stein and Stein, 2003). However, they contradict on-shore observations of a high temperature gradient in Iceland and temperature estimates based on the maximal earthquake hypocentral depths (Bjarnason et al., 1994).

The crust between Greenland, Iceland, and Faeroe Islands is surprisingly thick for oceanic crust (normal oceanic crust north and south of Iceland is 8–10 km thick). The Iceland-Faeroe ridge has a clear seismic Moho at a 30–35 km depth, and a similar crustal thickness was determined for the Greenland-Iceland ridge (Bott and Gunnarsson, 1980; Staples et al., 1997; Holbrook et al., 2001). The symmetric crustal structure to the west and east of Iceland has been used to argue against the plume origin of Iceland, unless it was semistationary with respect to the plate boundary (Lundin and Dore, 2005).

The crustal structure of Greenland is relatively poorly known. A recent broad band seismological experiment, GLATIS (Dahl-Jensen et al., 2003; Kumar et al., 2007) has provided estimates of the crustal thickness at about 20 locations by receiver function (RF) analysis. Most of the seismic stations were deployed close to the coast, but some of locations are within the central part of the ice cover (Figure 2). Further, some refraction seismic experiments provide profiles of crustal structure in the western and southeastern offshore parts of Greenland (Chian and Louden, 1992; Dahl-Jensen et al., 1998; Holbrook et al., 2001).

All onshore determinations of crustal thickness in Greenland are based on receiver function analysis of the depth to a seismic converter. They indicate that the crust below central Greenland is 40–45 km thick and that it thins towards the coasts, where values of some 30 km are estimated. It is remarkable that the highest bedrock elevation in Greenland (c. 2.0 km along the eastern coast) is apparently underlain by a relatively thin crust (c. 25–30 km). However, some of the values for eastern Greenland have been determined at locations close to the areas with extended continental crust. Therefore, it cannot be excluded that a high-velocity layer in the lower crust has not been identified as a part of the crust in the RF analysis. This is, in particular, very likely in the near-shore areas with extended crust, as exemplified by the significant discrepancy in the values reported by different groups: while the receiver function analysis gives values of around 30 km, seismic refraction profiles within a distance of less than 50 km from the shore indicate crustal thicknesses of c. 40–45 km along both the southwestern (e.g., Dahl-Jensen et al., 1998) and the eastern coasts (Chian and Louden, 1992). Along the coast of the North Atlantic Ocean, the lowest crust has extremely high seismic velocity (7.4–7.6 km/s which may be related to magmatic underplating, Dahl-Jensen et al., 1998) such that the strongest seismic converter may well be the transition from the middle to the lower crust, and *not* the Moho.

Seismic structure of the upper mantle

Interpretations of seismic reflection/refraction profiles, regional and global upper mantle seismic tomography, thermal, gravity, electromagnetic, xenolith, and elastic data (Artemieva et al., 2006 and references therein) provide an extensive database on the lithospheric structure of the Baltic Shield, whereas the information on the deep structure of Iceland and, in particular, Greenland remains sparse and, in some cases, controversial (e.g., Ritsema and Allen, 2003; Darbyshire et al., 2004; Foulger et al., 2005). In this situation, global tomographic models provide a means for a comparison of the deep structure of the upper mantle of the entire Norden, illustrated here by the variation in seismic S-wave velocity at a depth of c. 150 km (Figure 3). The resolution for the body-wave seismic tomography model is at least 500 km horizontally and no better than 50–100 km vertically.

At 150 km depth, high S-wave velocity (>4.6 km/s) is observed in the Precambrian terranes of the East European Craton (which outcrops in the Baltic Shield) and Greenland, where lithospheric keels generally extend down to at least 200 km depth (Artemieva and Mooney, 2001). Areas close to the cratonic edges have smaller velocity associated with the transition from lithospheric to sublithospheric mantle at c. 120–150 km depth. Within the regions with Precambrian crust in Northern Europe, the rifted area of the North Sea, where the lithospheric thickness is c. 100 km, shows a strong low velocity anomaly, with velocities smaller than 4.5 km/s. The transition from the cratonic to the Phanerozoic lithosphere in Northern Europe is marked by a pronounced decrease in seismic velocities at 150 km depth across the TESZ (Zielhuis and Nolet, 1994).

Like for the Precambrian Baltic Shield, high seismic velocities (>4.6 km/s) are observed for Greenland (Figure 3). Similar values have been calculated in surface-wave tomography models (Shapiro and Ritzwoller, 2002; Darbyshire et al., 2004), although their lateral resolution is lower than the resolution of the body-wave model (Grand, 2002). Seismic velocities in the tomography models (in particular, for surface waves) are sensitive to the corrections for the crustal structure, which is poorly known for the inland parts of Greenland. Thus, the velocity map for Greenland should be treated with some caution. The coastal areas of Greenland with extended crust towards the North Atlantic Ocean have low upper mantle seismic velocities. Similarly, low velocities are observed in the southernmost part of Greenland, which also may be an effect of the proximal continent to ocean transition. Part of the low-velocity anomaly

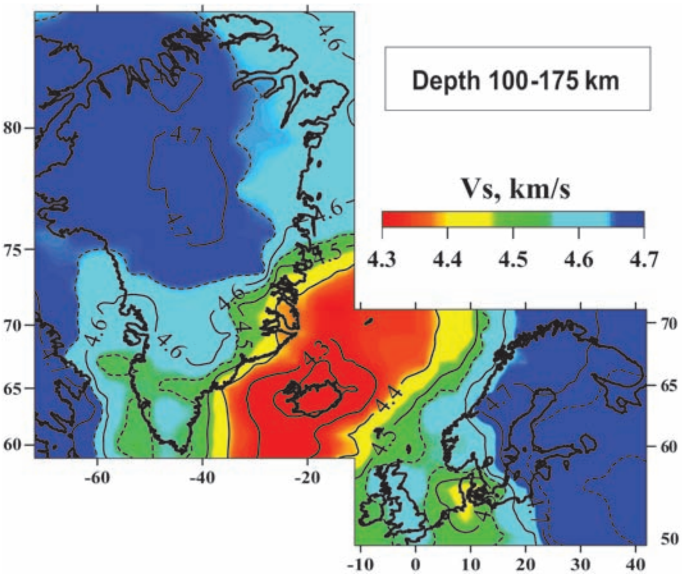

***Figure 3** S-wave velocities in Northern Europe, Iceland and Greenland at 100–175 km depth based on the global body-wave seismic tomography model of Grand (2002).*

at the southeastern coast can result from the smearing effect of the strong low-velocity anomaly around Iceland (Figure 3).

A layer below a depth of 100 km with slightly reduced seismic velocity has been identified by surface wave interpretation in the Baltic Shield and in Greenland (Bruneton et al., 2004; Darbyshire et al., 2004), thus confirming global analysis of body waves (Thybo and Perchuc, 1997). A recent interpretation by S-receiver function analysis of data from Greenland, Iceland and the North Atlantic shows a seismic interface at a depth of c. 100 km throughout the region (Kumar et al., 2006). Although these authors interpret this converter as the base of the lithosphere, it coincides with the top of the global, reduced-velocity zone in the upper mantle and in areas with a >200 km thick lithosphere this converter represents an intra-lithospheric feature. In Precambrian areas, typical seismic velocity anomalies above and below this layer are δVs ~+1+3% (with respect to the global continental reference model ak135), while within the layer they drop to δVs ~0+2%. In the high-velocity lithospheric mantle of the Baltic Shield, this layer is about 60 km thick with its thickness decreasing towards the oldest parts of the shield, generally with low heat flow. The nature of the reduced-velocity zone is still debated. Possible interpretations include: (a) high homologous mantle temperatures (c. 0.85*Tm, where Tm is wet solidus temperature) (Thybo, 2006) at which a sharp change in rheology and elastic properties of olivine-rich rocks (with a few percent drop in seismic velocities) is expected from laboratory experiments (Sato et al., 1989), or (b) petrologic heterogeneity in the lithosphere, e.g., associated with regional metasomatism (Artemieva, 2003). Note that neither thermal models (Artemieva, 2003), nor petrologic data on mantle-derived xenoliths (Kukkonen and Peltonen, 1999) require the presence of asthenospheric material in the upper 250–300 km beneath the Archean–early Proterozoic part of the Baltic Shield.

Surface wave tomography indicates that the upper mantle of Iceland exhibits a significant, isolated (c. 1,000 km in diameter), low S-wave velocity anomaly, which may extend to depths of at least 600 km (Figure 4a). This observation, together with a similar anomaly in the body-wave tomography model (Bijwaard and Spakman, 1999), where the P-wave anomaly persists below the transition zone, has been interpreted by some authors as evidence for a mantle plume (e.g., Bijwaard and Spakman, 1999; Ritsema and Allen, 2003). The observed S- and P-wave velocity anomaly (c. 5–10%) in the shallow mantle suggests a temperature anomaly of c. 50–100 ˚C and <1% of melt (perhaps as little as <0.1%) (Foulger et al., 2005 and references therein). Receiver function analysis of seismic data from Iceland (Vinnik et al., 2005) contributes to the on-going debate on the very existence of the Iceland plume (Foulger and Anderson, 2005) and challenges the conclusion of its existence (Figure 4b): it reveals the presence of a low-velocity zone in the shallow mantle only (centered at a depth of 100 km) and the normal thickness of the transition zone (a weak depression of the 410 km discontinuity can be explained by a c. 50˚C thermal anomaly, Presnall, 1995).

Courtillot et al. (2003) have proposed 5 criteria considered to characterize plumes (hot-spot track, large igneous province at one of the ends, high buoyancy flux, high ^{3}He/^{4}He ratio, and low seismic velocities in the mantle), and concluded that Iceland is a major hotspot, which satisfies at least 4 of the criteria. Anderson (2005) extended the number of "plume-criteria" to 12 (including the parameters which characterize seismic structure of the entire mantle and its thermal state) and concluded that Iceland equals on "plume" and "plate tectonics" scores, the major plume evidences being a low-velocity anomaly in the upper 400 km and ^{3}He/^{4}He ratios among the highest on Earth. We suggest that laboratory simulations of plume generation, evolution, and death in thermo-chemical convection (Davaille and Vatteville, 2005) provide an elegant resolution of the debate on the existence of the Iceland plume: in a dying plume, negative compositional buoyancy is no longer compensated by a positive thermal buoyancy, resulting in a downward flow along still hotter-than-normal "plume channel" seen in seismic tomography models for Iceland. Further, dying "*plumes start disappearing from the bottom up, sometimes even before reaching the upper boundary*", and "*they finally fade away by thermal diffusion. This sequence of events shows that time-dependence is a key-factor when interpreting present-day tomographic images of mantle upwellings. In particular, it could be erroneous to identify the depth of a present-day slow seismic anomaly with the depth of its origin, or to interpret the absence of a long tail as the absence of a plume*." (Davaille and Vatteville, 2005).

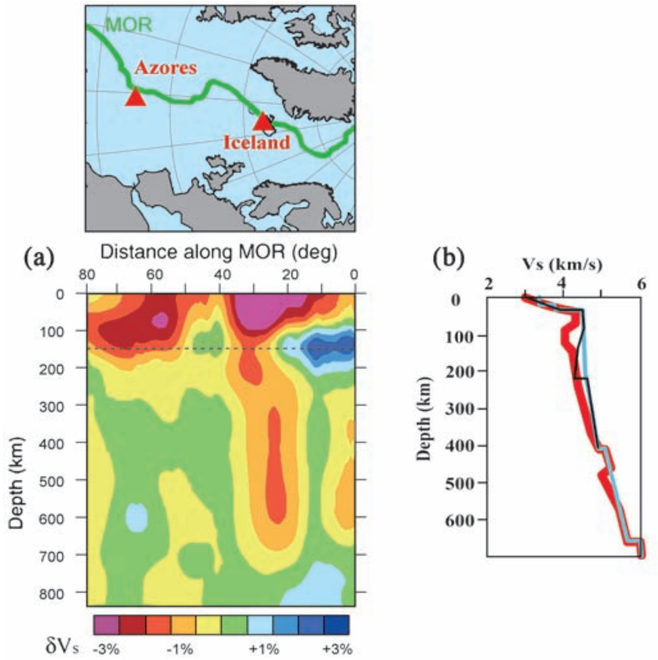

Figure 4 (a) Seismic tomographic profile along the Mid-Atlantic Ridge (MOR) (after Ritsema & Allen, 2003). Note the strong negative relative velocity anomaly around Iceland extending down to 660 km and interpreted as the signature of a mantle plume. (b) Seismic velocity model based on calculation of Receiver Functions for a station on Iceland (red line, after Vinnik et al., 2005). Note that, as compared to the velocity profile in (a), a velocity anomaly (red line) with respect to the global continental velocity profile (IASP91 model, blue line) is observed only down to a 400 km depth, with its amplitude decreasing with depth (global velocity model PREM is shown by black line). The receiver function interpretation shows seismic converters surrounding the low velocity zone below 100 km and at the 410 and 660 km discontinuities.

Global analyses of mantle-derived xenoliths indicate significant lateral and vertical compositional heterogeneity of the upper mantle, which reflects its tectonic and geological evolution. Since seismic velocities are sensitive to temperature of the mantle rocks (e.g. Jackson, 2000), variations in the thermal regime of the upper mantle can effectively mask velocity anomalies of a non-thermal origin caused by variations in composition, volatiles, as well as anelasticity, variations in grain size, and anisotropy. The Vp/Vs ratio is more sensitive to compositional than to thermal effects (Lee, 2003) and thus provides valuable information on the structure and compositional variations in the upper mantle (Figure 5). Since no high-resolution P-wave velocity model is available for Greenland, we limit the discussion to the Baltic Shield and the adjacent regions. Low values of Vp/Vs ratio indicate that a highly depleted (primarily in the basaltic component) mantle in the central part of the Baltic Shield, identified by geochemical studies of mantle-derived xenoliths (Peltonen and Brugmann, 2006), extends well into the Precambrian East European Platform. Gravity (Kaban et al., 2003) and buoyancy (Artemieva, 2003) modeling provide further evidence that lithospheric mantle of the Precambrian Europe is low-dense and thus depleted. The transition to the fertile Phanerozoic mantle of western Europe is marked by a sharp change to higher Vp/Vs values along the TESZ. The rifted areas of northern Europe with Precambrian crust, including the North Sea area and the Oslo Rift, show high Vp/Vs values indicative of a fertile mantle composition at sublithospheric depths.

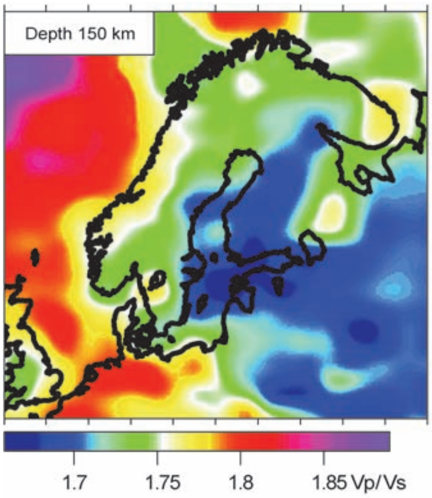

Figure 5 Compositional heterogeneity in the lithospheric mantle of Northern Europe, based on the Vp/Vs ratio. (Modified after Artemieva et al., 2006 and calculated using the S-wave surface-wave tomography model of Shapiro & Ritzwoller, 2002 and P-wave body-wave tomography model of Bijwaard & Spakman, 1999).

Lithospheric thickness

Geophysical data (primarily global seismic tomography models [e.g., Grand, 2002; Shapiro and Ritzwoller, 2002] and the global thermal model for the continents [Artemieva, 2006]) provide a unique possibility to construct a map of lithospheric thickness of Norden (Figure 6). Here, the base of seismic lithosphere is defined as a depth to (2±0.5)% velocity anomaly (with respect to continental reference model ak135 for continents and to global PREM model for oceans), while the base of thermal lithosphere is defined by a depth where mantle temperature reaches 1300 °C. Figure 6 provides an integrated interpretation of seismic and thermal data, since thicknesses of seismic and thermal lithospheres may differ by as much as 40–50 km in stable continental regions (Jaupart and Mareschal, 1999). The resolution of the map is effectively controlled by the heat flow and seismic data coverage, which is dense for the Baltic Shield and more coarse for Greenland and the western North Atlantic Ocean.

Thick lithospheric keels, extending to at least a 250 km depth, have been identified with certainty beneath the Archaean provinces of the Baltic Shield and the central and southern parts of Greenland (Figure 6). The existence of a high-velocity upper mantle down to a depth of 200–250 km beneath much of the EEC, including most of the Baltic Shield, is supported by regional dispersion analyses of long-period Rayleigh waves (Calcagnile, 1991) and by large-scale P- and S-wave seismic tomography models. However, most surface wave models loose resolution at depths below c. 250 km and cannot provide reliable constraints on the mantle structure below this depth. Lithospheric geotherms constrained by surface heat flow measurements (Artemieva, 2003) and mantle-derived xenoliths from central Finland and the Arkhangelsk region of northern Russia (Kukkonen and Peltonen, 1999) confirm the presence of cold thick (>250 km) lithospheric keels in these provinces of Baltica.

The region of the anomalously thick crust in the Baltic Shield (Figure 2) is located at the suture between the Archean and early Proterozoic blocks which formed during Proterozoic accretion of the Svecofennian provinces to the Archean Karelian block (Korja et al., 1993). Within the resolution of the crustal and upper mantle models, it may mark the edge of the thickest lithospheric keel in the Baltic Shield (Figure 6). Most of the crustal roots were only recently identified beneath Proterozoic western Finland (Hyvonen et al., 2007; Olsson et al., 2007) and their tectonic origin remains unclear. The small size of the region (c. 500×300 km), where both the crust and the lithosphere have anomalous thicknesses, suggests that the crustal and lithospheric roots could have formed during the same tectonic event and that they may represent a unique preserved remnant of an ancient continent-continent or continent-ocean collision zone (Artemieva, 2006). The geographical distribution of mid-Proterozoic rapakivi granite intrusions at the northwestern, western and southern sides of the region of thick lithosphere suggests that heat from the mantle has been deflected by the pre-existing lithospheric keel (Ballard and Pollack, 1987), causing magma generation along its rim. The deflection of heat from the mantle could further have assisted the survival of this thick keel during the mid-Proterozoic tectono-thermal activity in the region, which led to the formation of the Baltic/Bothnian Sea basin "embracing" the region of anomalously thick lithosphere in west-central Finland (Artemieva et al., 2006).

Similarly, both in central and southern Greenland the locations of the thickest crust and the thickest lithosphere are spatially close (Figures 2, 6). Due to the near-vertical wave propagation of teleseismic body-waves, the tomography model (Grand, 2002) used to constrain lithospheric thickness is only weakly sensitive to the crustal structure. Therefore, the spatial correlation between the maps of crustal and lithospheric thicknesses cannot be entirely attributed to incomplete crustal correction, although the lateral resolution of the seismic models is relatively low in Greenland. The thick lithospheric keel in the southern part of Greenland underlies Archean crust which outcrops along the coasts. The age of the lithosphere terrane in central Greenland is unknown. Here a (2±0.5)% S-wave velocity anomaly based on both body-waves (Grand, 2002) and surface-waves (Shapiro and Ritzwoller, 2002) tomography models extends deeper than 250 km. This observation may provide evidence for speculations about the age of the crust and lithospheric mantle in large parts of the ice-covered areas of Greenland. In southern Greenland, the northern margin of the region of anomalously thick crust and lithosphere (approximately at the latitude of the Arctic Circle) corresponds to the boundary between the Archean and early Proterozoic terranes, as evidenced by basement rock outcrops along the western and eastern coasts. While the thicknesses of the lithospheric keels in Greenland and the Baltic Shield are comparable, the maximum observed thickness of the crust is significantly smaller in Greenland than in the Baltic Shield (45–48 km versus >60 km). Nevertheless, the analogy to the Baltic Shield may indicate that the thickest crust and the thickest lithosphere in southern Greenland next to the Archaean-Proterozoic suture can be a remnant of late Proterozoic plate tectonic events. The situation in central Greenland is less clear

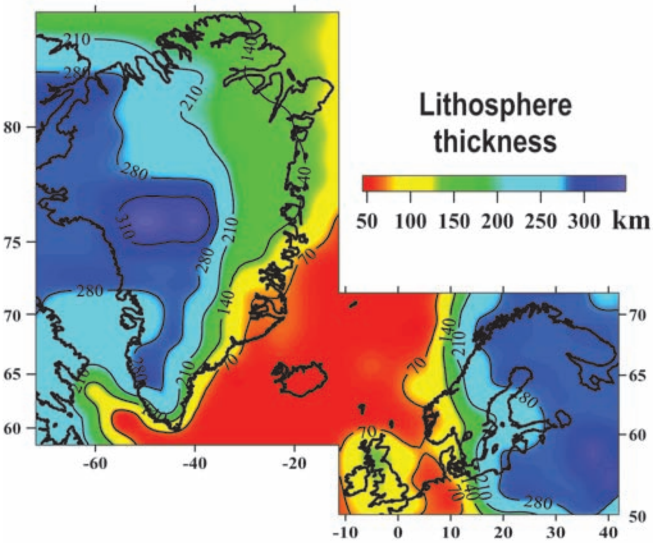

Figure 6 Lithosphere thickness in Norden, based on the global body-wave seismic tomography model of Grand (2002) and defined by a (2±0.5)% δVs anomaly with respect to the global continental reference model ak135 (Kennett et al., 1995) for the continents and with respect to PREM model for the oceans.

due to the lack of data on crustal ages. Below Iceland, where lithosphere stretching along the Mid-Atlantic Ridge leads to partial melting at shallow depth and magmatic formation of new basaltic crust, lithospheric thickness is, as expected, small (<50 km).

Profiles of lithospheric structure

Two profiles of the lithospheric structure (Figures 7a, b) summarize the above overview and illustrate lateral and vertical variations in physical properties of the crust and upper mantle in Deep Norden. The North-to-South trending profile across the Nordic countries (Figure 7a) follows the northern part of the EGT (European GeoTraverse, Blundell et al., 1992) and crosses the following structures from north to south:

(a) a region with very thick crust and lithosphere in the Baltic Shield with significant variation in crustal thickness between different Precambrian blocks;

(b) dipping structures in the lithospheric mantle, recognized in regional seismic surveys in the Bothnian Gulf of the Baltic Sea and interpreted as Proterozoic subduction zones within the cratonic lithospheric mantle (BABEL Working Group, 1990; Abramovitz et al., 1997). Magmatic intrusions within the Trans-Scandinavian-Igneous Belt (TIB) may be associated with the same tectonic events or younger features. Dipping structures in the lithospheric mantle further south haves been interpreted as evidence for the Caledonian subduction at the southern margin of the craton (MONA LISA WG, 1997).

(c) The transition from the cratonic mantle of Baltica to Phanerozoic mantle of the European plate (at the TESZ) is marked by a sharp change in seismic velocities and Vp/Vs ratio, which indicates a different composition of the mantle (primarily, the degree of mantle depletion). Gravity and buoyancy modeling require significantly different densities of Phanerozoic and Precambrian European lithospheric mantle and support this conclusion. The transition is further marked by a pronounced contrast in lithospheric and crustal thickness. The remnant of the Avalonia microcontinent is caught between the Baltica and the European plates; a dipping seismic reflector associated with the Paleozoic subduction zone marks its southern edge (near the Elbe River in Northern Germany) (Thybo, 1997).

The East-to-West trending profile along latitude 65°N (Figure 7b) illustrates variations in lithospheric structure from Greenland in the west, across the North Atlantic Ocean and Iceland, to the Baltic Shield in the east. Two zones of major contrasts in lithospheric struc-

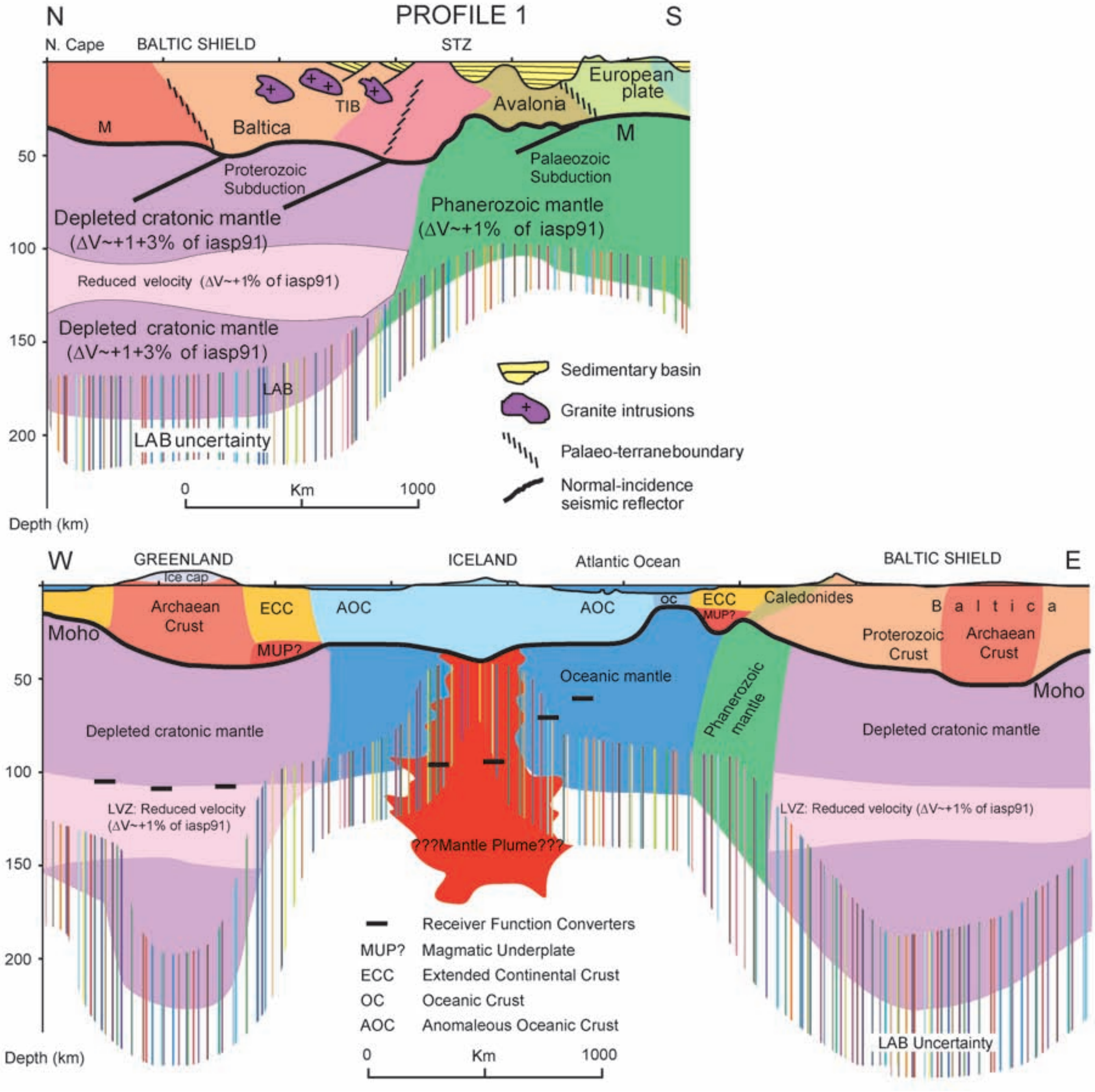

Figure 7 Two profiles through the lithosphere of Norden (see Figure 1a for locations): (a) N-S along the EGT profile (modified after Artemieva et al., 2006), (b) W-E along 65N latitude. The uncertainty of lithospheric thickness values is assessed to c. 50 km. Abbreviations: LAB—lithosphere-asthenosphere boundary, STZ—Sorgenfrei-Tornquist Zone (a part of the TESZ).

ture are associated with the craton-ocean transitions at the western and eastern coasts of the North Atlantic.

(a) The thickest crust with Moho at a depth of 60 km has only been observed in the central Baltic Shield, whereas the available seismic data indicate more moderate values of crustal thickness in Greenland.

(b) The extended crust along the continental margins of the North Atlantic, at the edges of the Caledonides, is thinned to c. 28–35 km and is underlain by intermediate thickness lithosphere (80–120 km). Several geophysical experiments have demonstrated the presence of a high-velocity layer in the lowermost crust of these regions, which probably represents a layer of magmatic underplating (e.g., Staples et al., 1997; Dahl-Jensen et al., 1998; Holbrook et al., 2001; Raum et al., 2002) brought into existence during the break-up of the North Atlantic Ocean.

(c) A remarkable feature is the belt of thick (30–35 km) crust extending from Greenland through Iceland to the Faeroe Islands, across the North Atlantic Ocean. The origin of this belt of thick (oceanic?) crust with a thickness comparable to continental crust, is enigmatic. The oceanic magnetic lineaments are indistinct or non-existing in this zone. The formation of this thick crust may be related to the passage of the proposed Iceland plume (e.g., Holbrook, 2001), which, in this case, should be semistationary with respect to the diverging boundary between the American and the European plates (Lundin and Dore, 2002). The depth extent and width of the mantle plume are unknown (seismic images of the region are highly controversial), and new high-resolution seismological data acquisition is needed before a conclusion can be made concerning its existence.

Conclusions

We have compiled the available geophysical data on the structure of the crust and lithospheric mantle of Norden, which may be summarized as the followings:

- Thick lithosphere (>200 km) underlies the Precambrian parts of the continents. In some areas, regions with anomalously thick crust and very thick lithosphere (>250 km) spatially correlate and are close to the Archean-Proterozoic suture zones. These may represent remnants of Precambrian collisional tectonic events.
- Sub-Moho seismic reflectors observed in the cratonic mantle of Baltica may represent paleo-subduction features preserved since the Proterozoic.
- Passive margins of the North Atlantic Ocean are underlain by magmatic underplated material in the lowermost crust.
- The crust below Iceland and the Denmark Strait in the North Atlantic is unexpectedly thick and may be explained by the "plume passage" model.
- The topography of basement rocks in central Greenland is negative; the load of the ice cap in Greenland may be kept in isostatic balance by the buoyancy of the lithosphere.
- Seismic evidence for the presence of the proposed mantle plume beneath Iceland remains controversial and its presence has not yet been uniquely demonstrated.

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Impact structures and events – a Nordic perspective

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Impact cratering is one of the fundamental processes in the formation of the Earth and our planetary system, as reflected, for example in the surfaces of Mars and the Moon. The Earth has been covered by a comparable number of impact scars, but due to active geological processes, weathering, sea floor spreading etc, the number of preserved and recognized impact craters on the Earth are limited. The study of impact structures is consequently of great importance in our understanding of the formation of the Earth and the planets, and one way we directly, on the Earth, can study planetary geology.

The Nordic-Baltic area have about thirty confirmed impact structures which makes it one of the most densely crater-populated terrains on Earth. The high density of identified craters is due to the level of research activity, coupled with a deterministic view of what we look for. In spite of these results, many Nordic structures are poorly understood due to the lack of 3D-geophysical interpretations, isotope- or other dating efforts and better knowledge of the amount of erosion and subsequent tectonic modifications.

The Nordic and Baltic impact community is closely collaborating in several impact-related projects and the many researchers (about forty) and PhD students (some seventeen) promise that this level will continue for many more years. The main topics of research include geological, geophysical, and geochemical studies in combination with modeling and impact experiments. Moreover, the Nordic and Baltic crust contains some hundred suspect structures which call for detailed analysis to define their origin.

New advanced methods of analyzing geophysical information in combination with detailed geochemical analyses and numerical modeling will be the future basic occupation of the impact scientists of the region. The unique Cretaceous/Tertiary boundary (K-T) occurrences in Denmark form an important source of information in explaining one of the major mass extinctions on Earth.

Introduction

Geological mapping and geoscientific investigation of Fennoscandia and Baltic countries started about two hundred years ago. The first geological maps were made more than 150 years ago. About the same time, national geological surveys and geoscience departments were established in several universities. These long-term activities are the main reason that the Nordic countries are generally well-mapped.

Impact craters came into the focus about 20 years ago and the interest among the Nordic communities has increased during recent years. The small *Kaalijärv* structure of Estonia was the first impact structure to be confirmed in northern Europe (Table 1; Figures 1 and 7). First described in 1794 (Rauch), the meteorite origin of the crater field (presently 9 craters) was proposed much later in 1919 (Kaljuvee, 1933) and proven as an impact crater in 1937 (Reinwald, 1938). As early as in the late 18th century and early 19th century, however, several of the presently recognized Fennoscandian structures were suggested to be of impact origin. Abels et al. (2002) state that the engagement of the two Swedish geologists F.E. Wickman and N.-B. Svensson in the early 1960s have been of great importance. The Nordic participation in impact research has increased through the years, in particular in Sweden, Estonia, and Finland as a consequence of the First Nordic Impact Crater Symposium arranged in Espoo, Finland, 1990. In Norway, the discovery of the Gardnos structure (Naterstad and Dons, 1992; French et al., 1997) triggered some activities, while in Denmark, impact-related research has concentrated on detailed studies of the Cretaceous-Tertiary boundary beds (e.g., at Stevns Klint, Figure 2), including the famous “Fish Clay” (Fiskeler Member in the lithostratigraphy proposed by Surlyk et al., 2006).

During the last 10 years, several important networks were organized through NorFa (coordinator H. Henkel; 1997–1999) and Nordforsk (coordinator H. Dypvik; 2006–2008). Before these Nordic network projects, a Swedish and Finnish initiative (together with French and German groups) for an European Research Group for Terrestrial Impact Phenomena (ERGTRIP) was coordinated by H. Henkel in the period from 1992 to 1995. The Nordic and Baltic countries were also well represented and active in the successful ESF IMPACT- programme (coordinator C. Koeberl) from 1998 to 2003.

In this first period, the international interdisciplinary cooperation of especially Alex Deutsch, Herbert Henkel, Maurtis Lindström, Victor Masaitis, Lauri J. Pesonen, Urs Schärer and Dieter Stöffler was of great importance. Their engagement was crucial for the great success in discovering new impact structures in Fennoscandia in the period between 1990 and 2003. The success reflects the detailed geological and geophysical mapping of the region, mineral and raw material exploration, drilling efforts and general background knowledge and interest of laymen in the theme of impacts. In addition, as in other shield areas such as Canada, the generally high age of the bedrock has implied that the area exposed for asteroid and cometary impacts has existed for a long time. It should also be noted that most parts of the Fennoscandian Shield are easily accessible through well developed networks of roads.

Presently, some 17 PhD students and 40 researchers are involved in impact-related research in the Nordic and Baltic countries.

Impact-related features in the individual countries

Denmark

In terms of surface geology, Denmark consists essentially of glacial debris, for the most part less than 20 kyrs old. Therefore the study of impact sites has little tradition, and very few circular to sub-circular topographic features have been noted. Mostly, they can be related to sub-surface structures, and in no case has a possible impact origin been investigated. Possible candidates for more recent impact sites are *Harre Vig* in the Limfjord area and *Stavns Fjord* on Samsø.

On the other hand, Denmark houses a unique series of outcrops constituting a formidable natural laboratory for the study of the long distal effects of the most famous terrestrial impact event, the 65 Ma old *Chicxulub* crater (Yucatan, Mexico), linked to the K-T boundary. Along the Danish Basin about ten outcrops expose the K-T boundary, from a basin margin setting in the SE to basin center conditions in the NW (Figure 1). The outcrops stretch over a distance of about 300 km—all with an unrivaled diversity of benthic invertebrates and a complete depositional record within the limits of biostratigraphic resolution. The overall global paleogeography at K-T boundary time, positions the Danish Basin several thousands of kilometers away from the *Chicxulub* impact site, in an ocean-land configuration essentially precluding any direct tsunami influence in the basin. Hence, the K-T boundary succession in the Danish Basin represents the distal ejecta blanket, as well as the results of global faunal turn-over, mixed with the effects of local, non-impact related processes.

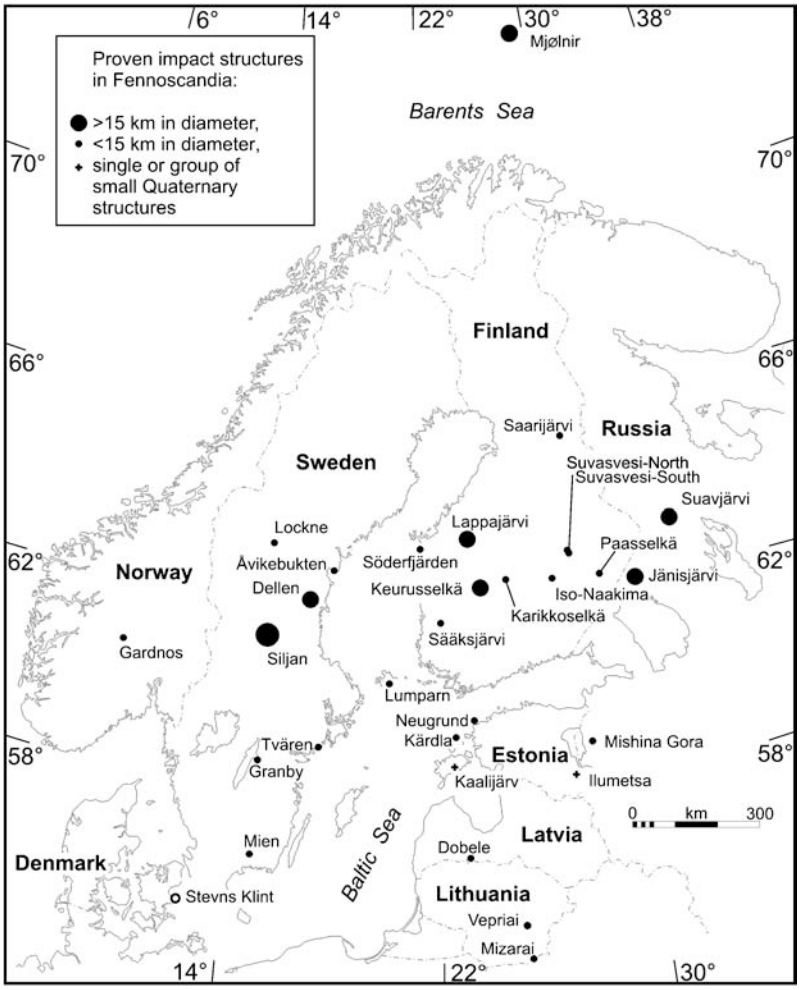

Figure 1 Recognized impact structures in Scandinavia and the Baltic states and the K-T location at Stevns Klint in Denmark (open circle signature). Based on the compilations of Abels et al. (2002) and Henkel and Pesonen (1992).

The classic and most intensely studied boundary succession in the Danish Basin is Stevns Klint (e.g., Alvarez et al., 1980; Hart et al., 2005; Rasmussen et al., 2005; Rosenkrantz, 1966; Surlyk and Håkansson, 1999), easily accessible some 65 km south of Copenhagen (Figures 1 and 2). It represents the marginal basinal setting, exposing the varied sedimentological development of the boundary succession in a sea-cliff over a distance of 12 km. The boundary itself is located at the base of the so-called 'Fish Clay' (Fiskeler Member) at the level of pronounced enrichments in Ir and other elements of the Platinum group (Schmitz et al., 1988). The boundary-related features also involve the “Grey Chalk” (Højrup Member) below and the “Cerithium Limestone” (Cerithium Limestone Member) above the “Fish Clay”. Due to the basin margin setting, several episodes of sea-floor cementation (hard-grounds) are encountered within the boundary succession of Stevns Klint.

Figure 2 Stevns Klint, displaying the classic K-T boundary near the church in Højerup. Note the contrast between the upper, overhanging “Bryozoan Limestone” (Stevns Klint Formation) of Early Danian age (Pal.) and the lower, recessive chalk of latest Maastrichtian age (Cret.). The prominent, horizontal nodular flint band in the chalk lies immediately below the boundary between the ordinary white chalk (Sigerslev Member) below and the topmost Maastrichtian “Grey Chalk” (Højerup Member) characterized by low Bryozoan mounds above. The undisturbed K-T boundary follows the (partly truncated) topography of these mounds. In this part of the cliff, the Maastrichtian–Danian succession totals about 15 m. The cliff is about 17 m in height and strikes NNE-SSW. (Photo: H. Dypvik).

More recently, also the distal basinal outcrops in northern Jylland have been investigated, displaying a more uniform depositional regime, with less pronounced boundary marls and reduced Ir contents. In particular, the Nye Kløv section has been in focus, providing most of the detailed paleontological information available from the basinal facies (Håkansson and Thomsen, 1999).

Norway

The *Gardnos* structure was the first impact structure recognized in Norway (Figures 1 and 3, Table 1). Though first described in 1945 as a “cryptovolcanic” structure, the discovery of shock metamorphic minerals by Naterstad and Dons (1992) disclosed its impact origin (French et al., 1997). The crater was probably formed at c. 600 Ma ago by an impact into a shallow shelf sea. The 5 km in diameter, complex crater is well exposed, easy accessible and conveniently located along the main road between Oslo and Bergen, just 170 km from Oslo. In addition, its great exposures offer a magnificent section through several different typical impact lithologies. The Gardnos structure is visited annually by about 20,000 tourists and geologists.

The *Mjølnir* crater was recognized just a couple of years after Gardnos. Mjølnir is a 40 km wide structure located offshore northern Norway, below 350 meters of water in the Barents Sea (Figure 1). Most petroleum geologists who studied the geophysical information interpreted this unfamiliar structure as volcano or salt diapir. Gudlaugsson (1993) launched the "crazy" idea that this structure demanded an extraterrestrial explanation (Dypvik et al., 1996). This triggered intense research activity on all available material from the Mjølnir region, along with the drilling of a new shallow core in the center of the structure in 1998, which confirmed the impact crater interpretation (Sandbakken et al., 2005).

The *Ritland* structure of Hjelmeland, outside Stavanger, has been investigated by geologist F. Riis in recent years. This structure is located in rugged west Norwegian terrain; 2.5 km in circular and 3–400 m deep. The presence of highly altered minerals (quartz, feldspar and mica) together with a good selection of breccias and intense fracture patterns, strongly indicate an impact origin, but no clear-cut impact features have yet been found in samples from the area.

Sweden

The Precambrian Shield of Sweden represents an ideal setting for finding impact craters. Seven confirmed impact structures (Figure 1, Table 1) with diameters from 2 to c. 60 km and ages ranging from 90 to 470 Ma (perhaps 600 Ma, Åvikebukten) are known (Henkel and Pesonen, 1992; Abels et al., 2002). In addition, about 7 probable and 30 possible astroblemes have been proposed for Sweden. In some regions, well preserved lower Paleozoic sedimentary strata display a record of environmental effects of impacts and variations in the flux of extraterrestrial bodies to Earth. Particularly notable has been the discovery (Schmitz et al., 2001) of more than 40 fossil meteorites (up to 20 cm in diameter) in the Ordovician limestones at Kinnekulle, southern Sweden (Figure 4).

The *Siljan* crater located in the Dalarna region of south-central Sweden (Figure 1) is Europe's largest impact crater and was formed in the late Devonian (Reimold et al., 2005). It is represented by a ring-formed lake structure. Its pre-erosional diameter is not well constrained and estimates vary from 65 km (Kenkmann and von Dalwigk, 2000) to as much as 85 km (Henkel and Aaro, 2005). Ar-Ar dating of melt breccias from the crater yielded an age of 377±2 Ma, which is identical, within uncertainties, to the age of 374.5±2.6 Ma for the Frasnian-Fammenian boundary (Reimold et al., 2005). The latter coincides with one of the five most severe extinction events of the Phanerozoic, suggesting a possible connection. However, distal ejecta from the Siljan impact have not been identified; hence it is difficult to relate the impact event directly to late Devonian bioevents.

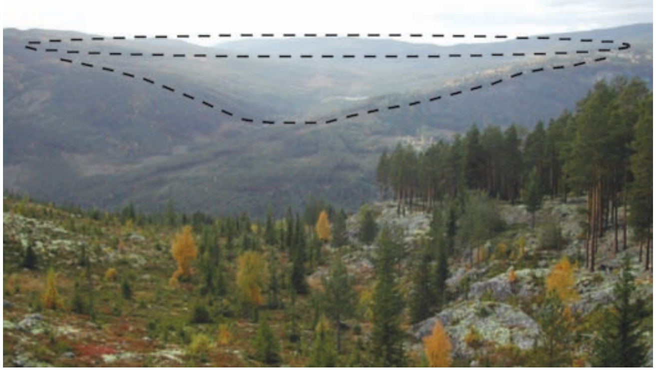

Figure 3 The Gardnos crater structure is located in Hallingdal (Norway) and has a probable late Precambrian origin. The 5 km diameter is indicated in this eastward-facing structure. (Photo: H. Dypvik).

Table 1 General characteristics of recognized impact structures in Scandinavia and the Baltic states. Data sources: see text and Abels et al. (1998; 2002), Henkel and Pesonen (1992), Pesonen (1996) and Puura and Plado (2005).

The table gives the age, the maximum present field diameter of the structure and information on crater morphology: C=complex crater, S=simple crater, e=exposed, m=submarine, l=lake, b=bay, tec=tectonically modified, bu=buried under sediment, r=rim exposed, u=central uplift exposed, f=crater field.

Name	Country	Latitude	Longitude	Diameter km	Age Ma	Morphology
Gardnos	Norway	N60°39'	E09°00'	5.0	600±10	C, e, u
Mjølnir	.	N73°48'	E29°40'	40.0	142±2.6	C, m, bu
Siljan	Sweden	N61°2'	E14°52'	65.0	377.8±2	C, e, l
Dellen	.	N61°48'	E16°48'	19.0	89.0 ±2.7	C, l, tec, r
Lockne	.	N63°00'	E14°49'	8	455	C, e, l
Granby	.	N58°25'	E14°56'	3.0	~470	S, b
Tvären	.	N58°46'	E17°25'	2.0	~455	S, b
Mien	.	N56°25'	E14°25'	9.0	121±2.3	C, l, r, u
Åvikebukten	.	N62°30'	E17°48'	9,5	600-1200	C, e, b, r, u,
Lappajärvi	Finland	N63°12'	E23°42'	23.0	73.3±5.3	C, l, r, u
Sääksjärvi	.	N61°24'	E22°24'	6.0	602±17	S, l, r
Söderfjärden	.	N63°2'	E21°35'	6.6	~560	C, bu, r
Iso-Naakkima	.	N62°11'	E27°9'	3.0	900-1200	S, tec, bu
Lumparn	.	N60°9'	E20°6'	9.0	~1000	C, tec, bu, r
Suvasvesi N	.	N62°42'	E28°10'	5.0	~260	C, tec, l, r
Karikkoselkä	.	N62°13'	E25°15'	1.5	~230	S. l. r
Saarijärvi	.	N65°17'	E28°23'	1.5	< 500	S, l, r, u
Paasselkä	.	N62°2'	E29°5'	10	<1800	C, l, r
Suvasvesi S	.	N62°40'	E28°10'	4,0	~280?	C, l, tec?
Keurusselkä	.	N62°8'	E24°36'	>20	<1800	C, tec
Kaalijärv	Estonia	N58°24'	E22°40'	0.11	0.004±0.002	S, e, l, r, f
Kärdla	.	N59°1'	E22°46'	4.0	~455	C, bu
Neugrund	.	N59°20'	E23°40'	7.0	~470	C, m, r
Ilumetsa	.	N57°58'	E27°25'	0.08	0.0066	S, e, r, f
Dobele	Latvia	N56°35'	E23°15'	4.5	205±35	C, bu
Mizarai	Lithuania	N54°01'	E23°54'	5.0	500±20	C, bu
Vepriai	.	N55°05'	E24°35'	8.0	160±5	C, bu
Jänisjärvi	Russia	N61°58'	E30°55'	16	700±5	C, l, r, u
Mishina Gora	.	N58°43'	E28°03'	2.5 × 4.0	350-250	C?, e
Suavjärvi	.	N63°07'	E33°23'	16	~2400	C, e

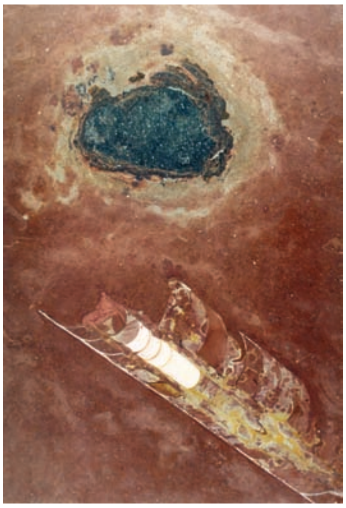

Figure 4 Middle Ordovician (470 Ma) fossil meteorite (6×8 cm) from the Thorsberg Quarry, southern Sweden. The meteorite with relict chondrule structures lies next to a nautiloid shell on a hardground surface. (Photo: B. Schmitz and M. Tassinari).

Both shatter cones and planar deformation features (PDFs) in quartz provide the proof for an impact origin of Siljan (Grieve, 1988). In the 1980s, the crater was drilled (two holes to nearly 7 km depth) in response to a proposal that an impact-induced fracture system below the crater would contain large amounts of "mantle-derived" hydrocarbons (Gold and Soter, 1980); no hydrocarbons of significance were found.

Three craters, namely *Lockne* (8 km), *Granby* (3 km), and *Tvären* (2 km) were formed between c. 470 and 455 Ma. This age clustering of the craters, together with a high abundance of craters of this age worldwide, indicates that they may have been related to an asteroid shower (Schmitz et al., 2001). Abundant relict L chondritic chromite grains dispersed in the mid-Ordovician limestone also provide empirical evidence for a higher flux (up to two orders of magnitude) of extraterrestrial dust and small meteorites at this time (Schmitz et al., 2001; 2003). On theoretical grounds it has been shown that the flux of asteroids may be substantially enhanced for 2–30 million years following a major parent body disruption (Zappalà et al., 1998). Further support for an asteroid shower comes from the discoveries of extremely abundant L chondritic chromite in the resurge deposits of the Lockne crater (Alwmark and Schmitz, 2007).

These three Ordovician craters formed by impacts into a vast epicontinental sea and contain excellently preserved breccia and resurge deposits. These sediments provide detailed information on the processes taking place during and after an impact into a shallow sea, such as tsunami generation, sediment disturbance and biota recolonisation on the sea floor (Lindström et al., 1994; Sturkell, 1998). Lockne hosts a crater museum.

The 19 km in diameter *Dellen* crater in central Sweden was formed at c. 89 Ma in the late Cretaceous (Deutsch et al., 1992). Because of severe post-impact erosion and two lakes filling a large part of the crater depression, impact-related rocks in the Dellen structure are difficult to access.

In the center of the *Mien* crater about 20–25 m of impact melt rocks have been drilled, but no sedimentary fragments are observed in the crater-fill breccias suggesting a continental impact on crystalline rock (Abels et al., 2002).

Recently the complex *Åvikebukten* structure (9.5 km in diameter), of uncertain age (600–1200 Ma?), has been found to contain quartz grains with PDFs (Henkel et al., 2005).

Finland

Eleven proven impact structures have so far been found in Finland (Figure 1, Table 1). These are (with discovery year in parenthesis): Lappajärvi (1967), Sääksjärvi (1969), Söderfjärden (1978), Iso-Naakkima (1993), Lumparn (1992), Suvasvesi North (1993), Karikkoselkä (1996), Saarijärvi (1997), Paasselkä (1999), Suvasvesi South (2001) and Keurusselkä (2003). The ages of formation vary from c. 1200 Ma (Iso-Naakkima) to about 73 Ma (Lappajärvi), but the majority is poorly dated. The present diameters vary from ~23 km in Lappajärvi to 1.4 km in Karikkoselkä (Abels et al., 2002). These diameters, however, are minimum estimates since the structures are moderately to strongly eroded (e.g., Keurusselkä).

Lappajärvi (Figure 1) is the largest impact structure (23 km) in Finland. It is situated in western Finland and Ar-Ar and U-Pb dating resulted in ages of 77.3±4 Ma to 71 Ma (Pesonen et al., 1992). Dark and dense impact melt rock, so-called kärnaite, occurs in Lappajärvi's central island Kärnäsaari and nearby smaller islands. The kärnaite layer is about 145 m thick and displays enrichments of Ni and Ir, possibly of meteoritic origin. Below the kärnaite, the few meters thick layer of suevite rests on a clastic impact breccia. PDFs in quartz are common. Lappajärvi hosts a "meteorite" museum.

Lake *Sääksjärvi* (U-Pb age 602±17 Ma, 6 km diameter) is situated in western Finland and displays a slight elliptical shape along NW-SE direction. In the late 1960s, shock metamorphic features in quartz were found in suevite boulders from the region. Later petrophysical studies by Elo et al. (1992) of drill core samples revealed abnormally low densities and high porosities consistent with a striking negative and nearly circular gravity anomaly and its second vertical derivative (Figure 5).

The *Söderfjärden* (~ 560 Ma, 5–6 km diameter) structure forms a distinct geomorphic depression. Drill core samples revealed mica gneissic basement composition, which is covered by 30–40 meters of Quaternary glaciogenic sediments. Topographic and aerial photographs show a somewhat conical structure (man-made), while the geophysical data demonstrate a more circular appearance (Abels et al., 2002).

The *Iso-Naakkima* (900–1200 Ma, 3 km diameter) impact structure is located in central East Finland. It was originally discovered by its distinct circular and negative gravity signature. The geophysical anomalies associated with the structure have a diameter of ~3 km. The basin is covered by 30–40 meters of Quaternary sediments.

The *Lumparn* structure (500–1200 Ma, 9 km diameter) is situated at the main island of the Åland archipelago. The geological studies of drill core samples display a minimum 50 m thick impact breccia unit with PDFs in quartz.

The *Suvasvesi-North* (5 km in diameter) and *Suvasvesi-South* (4 km in diameter) impact structures may form a doublet (Figures 1 and 6). The Suvasvesi-North is probably late Permian (260 Ma) in age, based on paleomagnetism and magnetic modelling (Pesonen et al., 1996), while the age for the Suvasvesi-South has not been determined. The Geological Survey of Finland drilled the Suvasvesi-North structure in 1992 in the center of a circular negative magnetic anomaly. It revealed an 80 m thick layer of impactites, including melt breccias and suevites, with PDFs present in quartz grains.

The small *Karikkoselkä* structure (230–530 Ma, 1.5 km in diameter) is represented by the nearly circular Lake Karikkoselkä. Well-developed shatter cones from a few centimeters to 2 meters occur around the lake. Quartz grains in a breccia boulder carry PDFs.

The *Saarijärvi* impact structure (<500 Ma, 1.5 km in diameter) is a drop-shaped lake located in Archean basement. The drill-core samples revealed PDFs in quartz from the impact breccias.

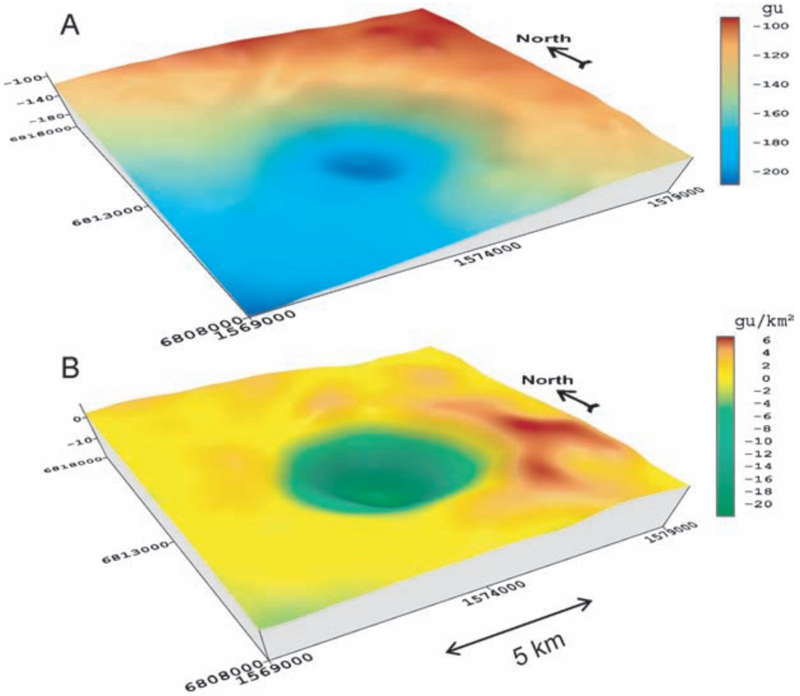

***Figure 5** Gravity anomaly maps of the Lake Sääksjärvi impact structure, SW Finland (Figure 1). (A): Bouguer gravity map as color coded surface presentation. The view is from southwest. Scale is in gravity units (1 gu = 0. 1 mGal). (B): the second vertical derivate of the Bouguer anomaly, in units of gu/km^2· Courtesy: Seppo Elo, Geological Survey of Finland.*

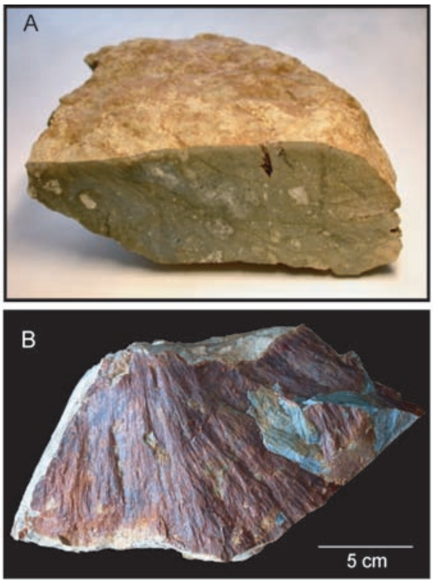

Figure 6 Examples of impact rocks in Finnish structures (for locations see Figure 1). A) Suevite-melt boulder from Mannamäki gravel pit, east side of the Suvasvesi South structure, central-east Finland. B) Shatter cone (from boulder) from the Keurusselkä impact structure, central Finland (Figure 1). The scale (5 cm) applies to both figures.

The *Paasselkä* structure (<1800 Ma) is an oval-shaped lake ~8–11 km in diameter, located in southeast Finland. The Geological Survey of Finland drilled two cores through the central magnetic "spikes" in 1999, which showed 20 m thick Quaternary deposits underlain by fractured mica schist down to 252 meters. Quartz grains in the breccia samples revealed well-developed PDFs.

The *Keurusselkä* structure (<1800 Ma) is located 32 km west from Karikkoselkä (Figures 1 and 6). Keurusselkä is most likely a deeply eroded impact structure. The preliminary estimate of the original diameter, based on shatter cone findings, points to >20 km.

The Baltic countries

In contrast to Norway, Sweden and Finland, the Baltic States (Estonia, Latvia, and Lithuania) are located in the Paleozoic platform area of the Svecofennian Crustal Domain. This circumstance is reflected in the ages and preservation of the impact structures; all are Phanerozoic in age and any older structures were likely destroyed during the 1300 to 600 Ma erosional epoch. The relatively well-preserved Paleozoic and Mesozoic impact structures have been preserved from erosion by burial immediately after impact. Most structures, therefore, have been found by indirect methods: drilling and geophysical analysis.

In **Lithuania**, two proven structures: *Mizarai* and *Vepriai* (Figure 1), were reported in 1978 (Motuza and Gailius, 1978). Both structures are complex: 5 and 8 km in diameter, with possible impact ages from 520 to 480 Ma (Middle to Early Ordovician) and 165 to 155 Ma (Jurassic), respectively. The structures are buried and were found by geophysical mapping and proven to be of impact origin by the occurrence of PDFs in quartz, shatter cones and impact glass in drill-core samples.

The *Dobele* structure is located in SE **Latvia**, near the border to Lithuania (Figure 1). The structure is 4.5 km in diameter and late Carboniferous to early Permian in age. It is buried below 75 m of variegated carbonate-terrigenous rocks of late Permian and early Triassic age, and sands and clays of Pleistocene age. The pre-impact sedimentary formations are highly crushed, and shatter cones, as well as PDFs in quartz are observed within the drill-core samples.

Estonia hosts two early Paleozoic (Kärdla and Neugrund) complex structures and two simple structures (Kaalijärv and Ilumetsa) which are Pleistocene in age (Figure 1). Applying strict rules of crater identification (see Henkel and Pesonen, 1992) only the Kaalijärv structure may represent a "proven" impact structure by the occurrence of meteorite fragments. Kaalijärv (Figure 7) was described by Pytheas from Massalia (Marseille) in 350–320 BC, and could be linked to Greek Mythology (Phaeton) and Nordic folklore (Finnish Kalevala and Estonian folk poems).

Figure 7 Inner view of the Kaalijärv impact structure as taken from the rim. The nine structures in Kaali (Estonia) are distributed within an area of 1 km^2, the photo illustrates the largest structure with a diameter of 105–110 m and height of the rim of 4–7 m. (Photo: J. Plado).

The Early Cambrian *Neugrund* structure (7 km) is located in the Gulf of Finland, about 10 km from the shore of NW Estonia. It was found in the course of integrated geological and geophysical mapping of NW Estonia in 1994–1995, when numerous brecciated erratic boulders were discovered and described in the onshore area by K. Suuroja (Suuroja and Saadre, 1995). This discovery prompted seismic reflection measurements, marine magnetic studies, and submarine sampling of the Neugrund Bank (e.g., with the discovery of shock metamorphic quartz). The shallow offshore plateau of post-impact sedimentary infill was protected against erosion by a well-developed surrounding crystalline rim.

The Ordovician *Kärdla* structure (4 km) was found in 1967 and confirmed in 1980 by identification of fracturing and planar features in feldspar and quartz (Figure 1). It is the most studied crater in Estonia due to an extensive drilling program (>300 wells) in the 1980s (see Puura and Suuroja, 1992). Kärdla was formed in a shallow Ordovician sea that covered older sediments and underlying crystalline basement. It is barely visible in the present topography, but displays a well-preserved complex subsurface structure.

The nine *Kaalijärv* craters are located within an area of 1 km^2. The main crater, which is 105 to 110 m in diameter, is water-filled, whereas the others (12 to 40 m in diameter) are only 1 to 4 m deep and dry. In the vicinity of the smaller structures, a total of about 3.5 kg of projectile remnants (coarse octahedrite iron meteorite) have been collected; the largest single fragment weights 30 g. The *Kaalijärv* crater has a visitor center and museum of meteoritics, which was established in 2005 and has thousands of visitors each year.

The *Ilumetsa* crater field hosts two structures, 70–80 and 50 m in diameter. Radiocarbon dating of samples from a peat layer with glassy impact spherules from the nearby (6 km) bog have yielded the age of 6,600 yrs BP (Raukas et al., 2001).

Two smaller possible impact structures—*Tsõõrikmäe* (40 m) and *Simuna* (8.9 m) are identified solely by morphological features. Some researchers have also proposed an impact origin of the recently (2004) discovered *Vaidasoo* structure.

Challenges in impact research

Finnish and Baltic challenges

Since the Baltic States are located in the Paleozoic platform area, the search for impact structures needs a slightly different approach compared to the Nordic countries (Figure 1). Analysis of the gravity, magnetic and seismic data, in particular, may give information on buried, circular structures (Figure 5). Studies of the old cores from the extensive Soviet drilling programs may give additional evidence in the search for distal ejecta layers and their host craters.

The most fascinating Baltic impact "mystery” is related to the theories of the age of the Kaalijärv event (Figure 7). Different researchers have proposed ages ranging from 6720 to 370 B.C. based on ^{14}C analysis of charcoal from within the craters and Ir- and spherule-rich layers in nearby bogs. The inner, unusual structure of Neugrund remains un-drilled; its broad central peak and post-impact sedimentary infill may give information on the age and setting at the time of impact (e.g., was the target wet or dry?).

In order to verify the impact origin of the small Pleistocene structures, unconventional approaches are needed, such as shallow seismic and ground penetrating radar analysis combined with other geophysical and geochemical methods. The first steps were made in 2005 during a summer-school for Nordic-Baltic PhD students focusing on the Ilumetsa structure.

Until 1990, only three impact structures had been found in Finland (Figures 1, 5 and 6). A recent impact search program (headed by L.J. Pesonen) has developed a new strategy with joint efforts involving impact scientists and universities, research institutes, exploration and drilling companies along with amateur geologists. This strategy resulted in the discovery of eight new impact sites during the period 1990–2004. Impact flux calculations suggest that numerous impact structures are still to be discovered. New geophysical techniques, including GIS and DEM analysis and mathematical algorithms, form the modern tools to find hidden structures. Additional problems are the poorly constrained ages of the impact events and the various levels of erosion; more modeling is needed of the impact processes by using sophisticated hydrocode softwares.

The recently founded joint co-operation between the universities of Oslo and Helsinki, the geological surveys of Norway and Finland, and ESA/ESTEC, will provide a new forum for scientific study of impact structures, and the discovery of new impact craters in Fennoscandia. These studies will gather information of interest for later application in extraterrestrial remote sensing analyses of the planets, Mars in particular.

The search for impact structures in Norway

The search for impact structures in Norway has been an important new initiative. Current projects also include: 1) the intensified mapping and the search for impact evidence related to the Ritland structure (headed by F. Riis). 2) The studies of the Mjølnir structure (Barents Sea) are progressing smoothly and an international effort to organize an IODP/ICDP coring program of the structure is underway (H. Dypvik). 3) In the Gardnos structure detailed mapping and sedimentological analyses have been finished recently and major efforts concentrate now on both U-Pb and paleontological dating of the impact event (E. Kalleson).

In 2005, a national program searching for circular structures in Norway was launched, first of all targeting the primary schools of Norway (~10 year olds). Based on the web site (*www.geo.uio.no/groper*) the students can search their own/home district in order to find possible circular structures with diameters between 2 and 7 km. Instructions on the web-site tell them what to look for and what the succeeding field studies should contain. This pilot project (run by S.O. Krøgli) formed the Norwegian base for the new Finnish, Norwegian, and ESA/ESTEC cooperative program mentioned above.

Understanding the K-T boundary in Denmark

While the biological effects of the K-T boundary event have been clarified to some extent, the sedimentological and geochemical signals still remain somewhat ambiguous.

The up to 4 m of “Grey Chalk” (Højerup Member) underlying the “Fish Clay” (Fiskeler Member) in Stevns Klint (Figure 2) owes its color to finely dispersed elementary carbon, allegedly of the same isotopic composition as the soot in the “Fish Clay” itself (Hansen, 1990), thereby seriously challenging the popular interpretation of the boundary soot as the result of impact-related wild fires.

The post-K-T-boundary “Cerithium Limestone” (Cerithium Limestone Member) has its peculiarities as well, containing an undetermined proportion of possibly chemically precipitated clay to silt-sized, euhedral calcite crystallites. In contrast to the soot mentioned above, these crystallites are abundant also in the “Cerithium Limestone” equivalents throughout the Danish Basin, whereas there seems to be no reports from other parts of the World.

In view of the apparent 'strangelove' (the alleged adverse ocean existing just after impact) conditions of the “Cerithium Limestone” sea, with basin-wide chemical precipitation of low-magnesium calcite, the changes in skeletal mineralogy of the benthos through the boundary succession becomes very intriguing. The “Grey Chalk”, like all chalk, is rich in species with all three varieties of skeletal $CaCO_3$ (low-Mg calcite [dominant], high-Mg calcite, aragonite). In contrast, the “Cerithium Limestone” and its equivalents in the Danish Basin are essentially devoid of benthic organisms with low-Mg calcite skeletons, in spite of the fact that low-Mg calcite is simultaneously precipitated directly in the sea water (Heinberg and Håkansson, 2000).

The numerous Swedish structures

A major future challenge in Swedish impact research will be to verify or falsify the proposed impact origin for the many structures in Sweden (Wickman, 1988; Henkel and Pesonen, 1992). Priority may be given to drill some of the six probable craters (Skedviken, Björkö, Hummeln, Landsortsdjupet, Trinddjupet, and Ledfat). Further reconnaissance field studies regarding the other 30 possible impact structures should also be given priority. Radiometric and biostratigraphical dating of craters and identification of the impactor types will enhance our overall understanding of the role of impact processes in the history of the solar system and the evolution of life. Analyses of platinum group elements and chromium isotopes and search for relict extraterrestrial minerals in impact melts or resurge deposits may give clues about impactor type.

Another important task will be to find sedimentary sections displaying distal Siljan ejecta (Abels et al., 2002). The large Siljan event has been claimed to be partly responsible for extinction events both in the middle and late Devonian. Consequently, locating ejecta in biostratigraphically dated sections would open up for studies of the effects of a major continental impact on the environment and biosphere.

The confirmed mid-Ordovician craters in Sweden were buried under sedimentary successions and their well-preserved resurge deposits may contain traces of the impactors. Coeval sedimentary strata outside the craters are widely distributed in Baltoscandia and have been studied in great detail during the last two centuries. These craters, consequently, hold a unique potential for studies of sedimentary processes and ejecta transport, and perturbations following marine impacts. The Paleozoic strata may, in addition, contain ejecta layers from impacts for which source-craters are unknown. Because of their condensed nature, they provide a unique flux record of various types of extraterrestrial matter to Earth through time (Schmitz et al., 2003).

Conclusions

It is evident that the field of impact competence is varied in the Nordic countries, underlining the need for close cooperation in order to improve our understanding of the impact events and their post-impact development. The Nordic and Baltic impact community is prospering and the many highly engaged researchers and PhD students promise that this activity level will be retained for many more years.

Impact structures form an important factor in shield research, since these rocks have recorded impacts for billions of years. Detailed geological, geophysical and geochemical studies of those old formations, in combination with modeling experiments and coupled with precise dating will give us a way to study the evolution of the shield in four dimensions.

Such new advanced analyses in combination with deep drilling programs will be the future basic occupation of the impact scientists of the region. In addition, the special K-T boundary occurrences in Denmark form a unique and important source of information in understanding one of the major mass extinctions of the Earth.

Impact structures globally, host economically valuable resources (ores, hydrocarbons, water). They have also become popular tourist attractions. Thus, it is hardly surprising that impact science has found its place in the curriculum of Nordic-Baltic universities.

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Petroleum geoscience in Norden – exploration, production and organization

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Offshore exploration in Norway and Denmark—in the North Sea, the Norwegian Sea and the Barents Sea—has involved drilling about 850 wildcat wells, resulting in about 300 oil and gas finds, of which 84 are fields with production. The recoverable resources of all these finds total about 65 billion barrels of oil equivalent. Almost all these hydrocarbons come from a Jurassic source and the main reservoirs and traps are Jurassic sandstones in fault blocks and Paleocene sandstones or Cretaceous chalks in gentle domes. The article describes four major fields—Ekofisk, Gullfaks, Ormen Lange and Snøhvit—to illustrate some of the many challenges in developing and producing the hydrocarbons.

Elsewhere in Norden, there has been much less exploration. Drilling results have mostly been negative in mainland Sweden, onshore Denmark, onshore Svalbard and on- and offshore West Greenland. Minor oil finds have been made in Palaeozoic rocks in the Baltic Sea. The first wells have recently been drilled off the Faroe Islands, resulting in one discovery. No drilling has taken place on- or offshore East Greenland.

As a result of the hydrocarbon activities in Norway and Denmark, petroleum geoscience there has flourished, with 2000 geoscientists currently employed in the industry, many technical innovations made, a wealth of publically available information and a great increase in the understanding of the geology.

Introduction

Norway and, to a lesser extent, Denmark have seen their economies transformed because of the discovery and production of oil and gas from below their continental shelves. These developments have been based on a huge amount of geoscientific work and have resulted in a revolution in the understanding of the geology of those regions. Thick sedimentary basins suitable for petroleum exploration also occur to the west and east of Greenland, on the islands and shelves of Svalbard, east of the Faroe Islands and in the Baltic Sea (Figure 1). This article aims to outline the petroleum geology of the basins, to give highlights of the production geoscience for four representative large fields and to summarize how that geoscience work has been organized.

Exploration

The modern phase of exploration in Norden started in the North Sea in the 1960's prompted by the discovery in 1959 in Holland of the giant Groningen gas field reservoired in Permian sandstones and sourced from Carboniferous coals. Although the early wells in Denmark and Norway were planned for such targets, the geology proved to be different. The first well offshore Denmark found oil in an Upper Cretaceous chalk (1966, Møller group). In Norway, the first find showed oil in Palaeogene sandstones (1967, Esso) and the first giant find was oil in the chalk at Ekofisk (1969, Phillips). These early wells were in water depths of less than 100 m but in the following decade exploration extended into the northern North Sea in waters up to 350 m deep. The most prolific play—Middle Jurassic sandstones in fault block traps—was discovered in the UK in the giant Brent Field (1971, Shell). Similar giant oil finds in the adjacent Norwegian sector were: Statfjord (1974, Mobil), Gullfaks (1978, Statoil), Oseberg (1979, Statoil). The largest field in the North Sea province, the super-giant Troll gas field, was found in Upper Jurassic sandstones (1983, Shell). Exploration north of 62°N in Norway started in 1980 and discoveries in Jurassic sandstones soon followed, opening up two new petroleum provinces: in the southwest Barents Sea (Askeladd, 1981, Statoil) and offshore mid Norway (Midgard, 1981, Saga).

These four regions—the Danish and Norwegian North Sea sectors, the Norwegian Sea and the Barents Sea—have seen the great majority of all the exploration in Norden (Table 1). In West Greenland, six wells were drilled offshore between 1976 and 2000 without discovery, and in the 1990's six onshore wells targeted oil seeps in a region of Palaeogene lavas, but made no commercial discovery. In the Svalbard Archipelago 15 wells were drilled onshore between 1963 and 1991, but most were based solely on surface geology and lacked seismic data, and no discoveries were made. In Sweden, wells were drilled onshore in southern Skåne and offshore in the Baltic in the 1970's without making discoveries, whilst drilling on the island of Gotland in the 1970's and 1980's resulted in many oil discoveries, but all with tiny resources. In the Faroes, drilling started in 2001 but targeted the same type of prospectivity as in the adjacent, prolific, West Shetland province of the UK; one oil discovery has been made (Marjun, 2001, Hess).

Petroleum systems, plays and resources

Almost all the discovered petroleum resources in Norden are in Norway and Denmark (Table 1). The petroleum system responsible for nearly all the discovered resources is derived from an Upper Jurassic source rock. Figure 2 shows that the Upper Jurassic source is known in all regions from the central North Sea to the southwest Barents Sea, and that the discovered hydrocarbons in these regions are proved to have come from this source. For example, in the central

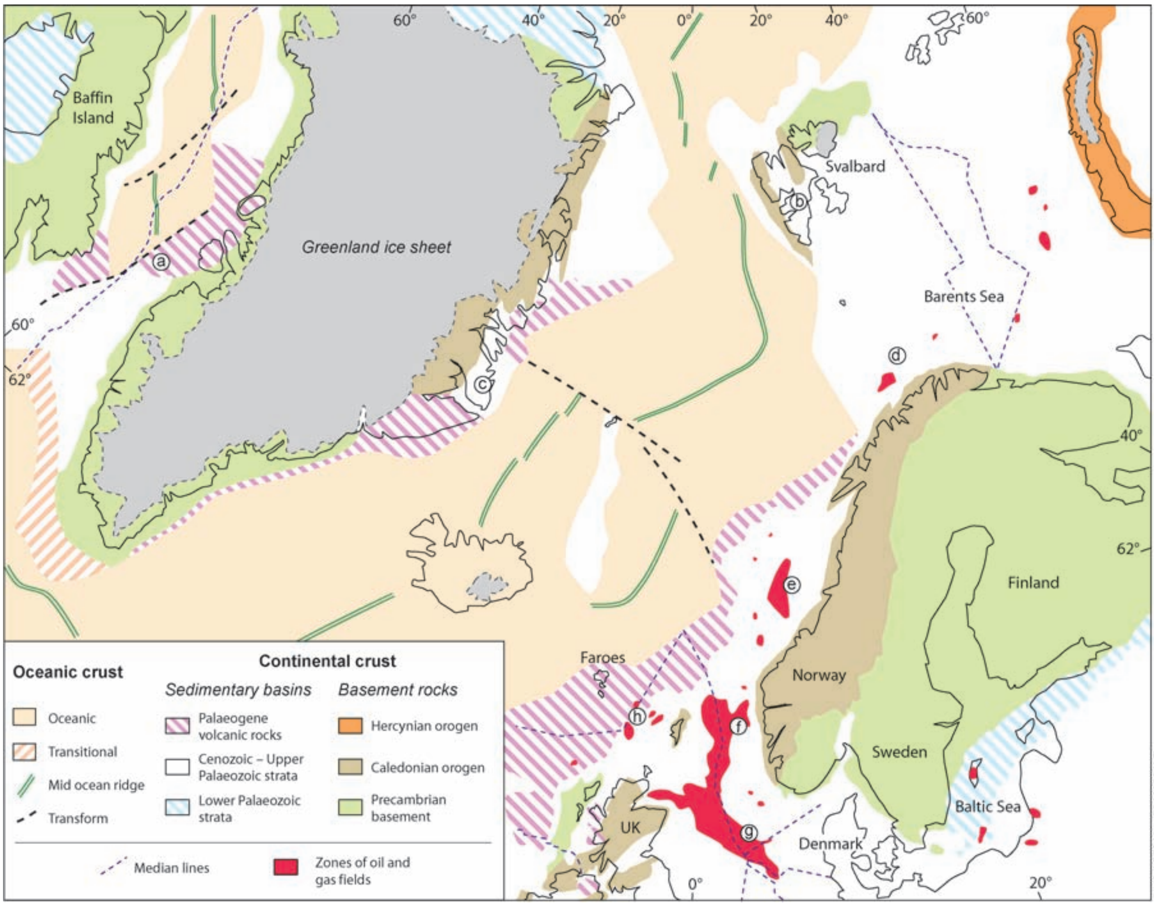

Figure 1 Outline map showing the setting of the sedimentary basins of Norden and the zones of discovered oil and gas fields. a–h: locations of stratigraphic columns in Figure 2.

North Sea this source has supplied hydrocarbons to nine different reservoir levels ('plays'), ranging from Devonian to Eocene. In Svalbard and the Barents Sea region, a Triassic marine shale source rock is known to be present and may have given rise to a petroleum system, but no link to the discovered hydrocarbons has yet been demonstrated. The oil finds in the Baltic Sea region, on Gotland and in the Polish sector there, are probably derived from a Lower Palaeozoic source. In Denmark, the main petroleum play is in the chalk, with smaller finds in Paleocene and Jurassic reservoirs. Below we describe the plays in Norway (Figure 3).

The Norwegian Petroleum Directorate (NPD) has defined 68 different plays on the Norwegian continental shelf, ranging from Carboniferous to Neogene and covering most of the Norwegian offshore areas, with 25 plays defined in the North Sea, 20 in the Norwegian Sea, and 23 in the Barents Sea. In the North Sea 18 plays are confirmed by oil and gas discoveries. Exploration is less mature in the Norwegian Sea, where nine out of 20 plays are confirmed, while in the Barents Sea six plays are confirmed. The rest of the plays are hypothetical, based on seismic and geological mapping. NPD estimates that 9.5×10^9 bbloe liquids and 11.5×10^9 bbloe gas remain to be discovered

Table 1 Petroleum exploration statistics of Norden.

Country	Region	Wildcat wells	Discoveries		Total discovered recoverable resources ($\times 10^9$ bbloe)	
			Oil	Gas	Oil	Gas
Greenland	West	12	-	-	-	-
	East	0	-	-	-	-
Svalbard		15	-	-	-	-
Norway	Barents Sea	61	3	16	0.4	1.1
	Norwegian sea	143	23	28	6.1	6.7
	North Sea	520	152	66	27.7	17.6
Faroes		5	1	-	-	-
Denmark	North sea	130	27	8	3.6	1.5
	Onshore & Baltic Sea	60	-	-	-	-
Sweden	Onshore, mainland	25	-	-	-	-
	Gotland, Øland	200	24	-	0.003	-
	Baltic Sea	17	-	-	-	-

Sources of discovery information: Denmark – Danish Energy Authority, as at January 1 2006; Sweden – IHS Iris 21 database; Norway – Norwegian Petroleum Directorate, as of January 1 2007.

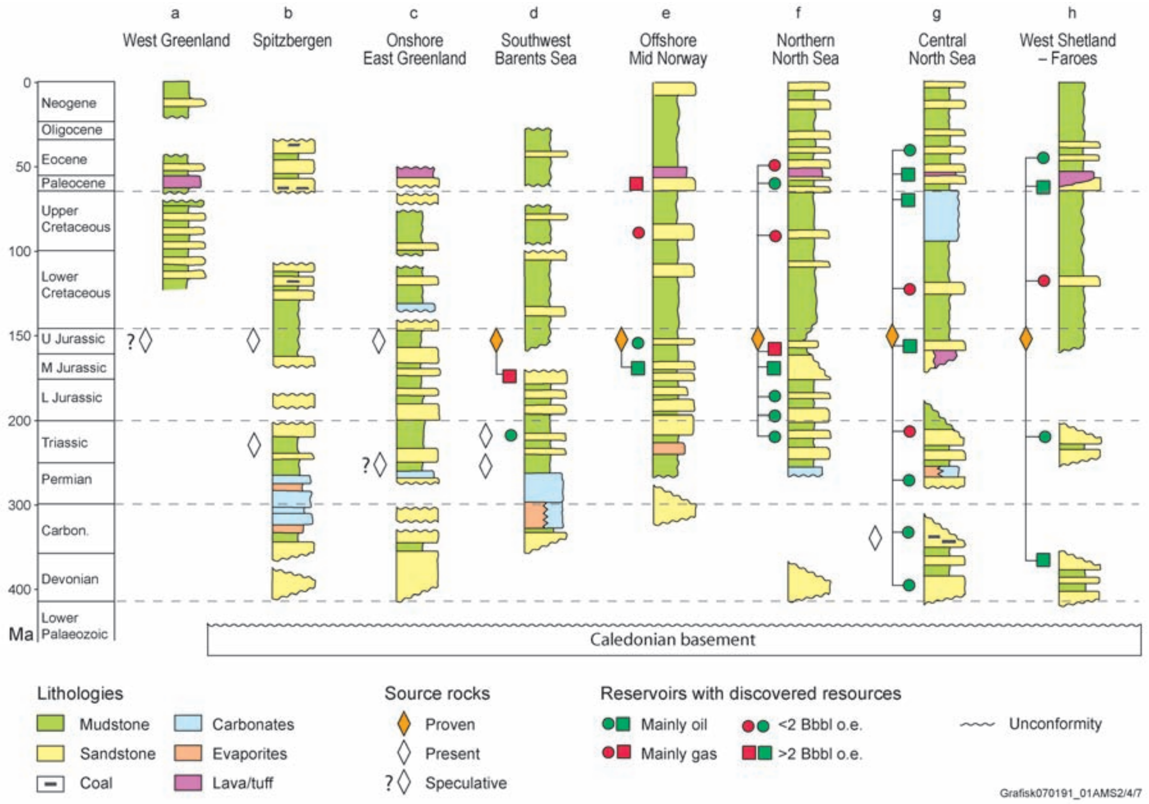

Figure 2 Stratigraphy of the main sedimentary basins of Norden, indicating the source rocks, reservoirs and resources. Compiled after Henriksen (2005), Harland et al. (1997), Ramberg et al. (2006), and Evans et al. (2003).

offshore Norway: 75 % of this lies in the proven plays. In this article petroleum resources are quoted in normal oil industry units: barrels (bbl), barrels of oil-equivalent (bbloe) and standard cubic feet (scf). Conversion factors are: 6.29 bbl = 1 Sm^3; 35.31 scf = 1 Sm^3.

Four plays contain the bulk of the resources in the Norwegian North Sea. They can be grouped in relation to the important Late Jurassic rifting. The pre-rift Upper Triassic to Middle Jurassic fluvial, deltaic and marginal marine sandstone play of the northern North Sea contains several major oil and gas fields (e.g., Gullfaks). This play alone contains 1/3 of the total Norwegian petroleum resources and more than half of the resources in the Norwegian North Sea. The NPD estimates that this play still has a significant undiscovered potential. Upper Jurassic plays occur both in the southern and the northern parts of the Norwegian North Sea. Norway's largest field, the giant Troll Field (47×10^{12} scf gas + 1.8×10^9 bbl liquids) belongs to this play. The post-rift chalk play of the southern Norwegian and Danish North Sea contains important oil fields (e.g., Ekofisk). As recently as 1997, a giant field (Halfdan) was discovered in a structural low between existing chalk fields in Denmark. The Palaeogene sandstones in the central part of the Norwegian North Sea contain several significant oil and gas fields.

The Norwegian Sea is well explored in parts but also contains large under-explored regions. The Upper Triassic to Middle Jurassic continental to marine sandstone play is dominant, containing two-thirds of the discovered resources and half of the undiscovered resources. The NPD estimates that marine sandstones of Late Cretaceous age have a significant potential in the Norwegian Sea. Paleocene sandstones are also important: the largest field discovered in Norway in the last 20 years, Ormen Lange, belongs to this play.

The Barents Sea is the least explored of the Norwegian offshore regions. The Hammerfest Basin is the only well-explored basin and contains most of the discovered resources. The Lower to Middle Jurassic sandstone play contains 75% of the discovered resources. The Snøhvit gas field belongs to this play. The NPD estimates that significant undiscovered potential also exists in sandstones and carbonates of Pennsylvanian and Permian ages and in Triassic sandstones, both in the south and in the area not yet opened for exploration in the north of the Barents Sea.

Fields and production

Since 1971 a total of 65 Norwegian fields and 19 Danish fields have started production. Most of the fields have sandstone reservoirs, but chalk reservoirs also occur. The sandstone reservoirs have generally good qualities and hydrocarbon flow is controlled by sedimentological, stratigraphic and large-scale structural heterogeneities. The chalk reservoirs usually have low matrix permeabilities and hydrocarbon flow is enhanced because of extensive natural fracture systems. We have selected four fields from different provinces and plays to illustrate the varied production challenges and technological phases in the oil and gas industry (Figure 4).

Ekofisk oil field

The Ekofisk Field in the south of the Norwegian North Sea is operated by ConocoPhillips. Production started from four converted exploration wells in July 1971. Permanent production facilities became operational in 1975 and the field has undergone continual development since then, with current production plans until 2028.

The Ekofisk field is the largest in the North Sea Chalk play. The structure is an elongated dome (Figure 5) at a crestal depth of 2900 m TVDss. Seismic quality is good on the flanks of the structure, but is severely degraded by a gas cloud over the crest, creating a seismically obscured area. The hydrocarbons are reservoired in originally overpressured Tertiary and Cretaceous chalks, up to 900 m thick. The productive pay interval is as much as 300 m thick. The original in-place resources are 6.9×10^9 bbl of oil and 10.7×10^{12} scf of solution gas, two-thirds of which are contained in the Danian age Ekofisk Formation reservoir. This is separated by a basal low poros-

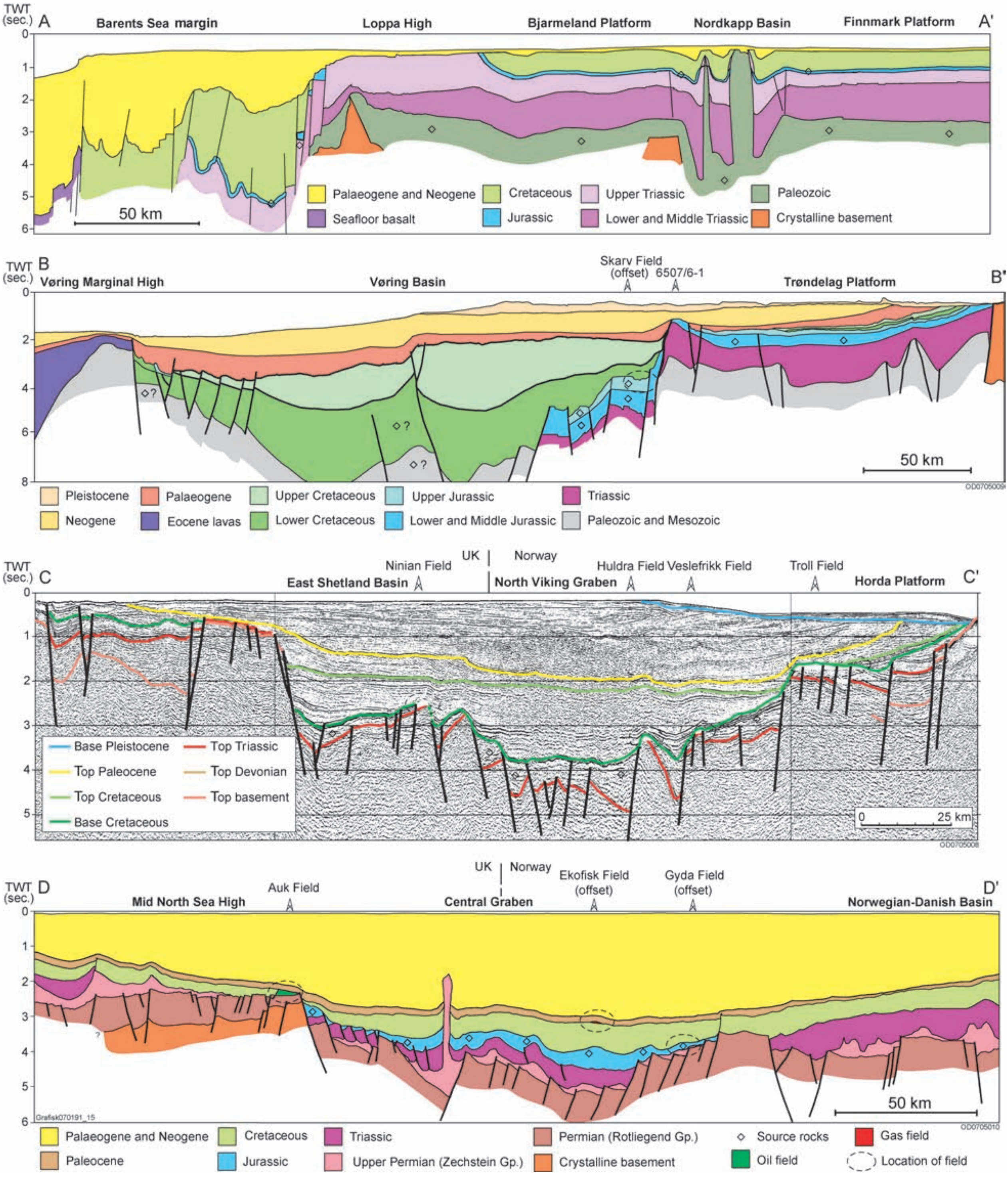

***Figure 3** Geological and seismic profiles across the petroleum provinces of Norway, modified from the following sources: A—NPD (1996), B —Blystad et al. (1995), C —Husmo et al. (2003), D—Zanella and Coward (2003). For locations see Figure 4.*

ity clay-rich interval (the Ekofisk Tight Zone) from the underlying Maastrichtian age Tor Formation reservoir (Figure 6). Both reservoirs consist of pelagic and redeposited coccolithophorid chalks, with average matrix porosities of 30% and matrix permeabilities up to 20 mD. Numerous low-throw faults are interpreted from seismic and well control. Extensive sub-seismic tectonic and stylolite-associated fracture systems enhance well permeabilities up to 200 mD.

The two reservoirs contain a 39°API black oil in pressure communication. Solution gas drive, partial gas injection and reservoir compaction were the primary drive mechanisms. The average field pressure was depleted about 2,500 psi over the first 16 years, with an accompanying decrease in production. Water injection was first started as a pilot project, since there was limited experience of water injection into a chalk reservoir. Full scale water-flooding commenced in 1987 and has been the dominant and highly successful secondary recovery strategy since then (Figure 7). Average field pressure has been pushed up by about 1000 psi and the oil production rate has increased significantly. Reservoir compaction has also acted as a significant drive mechanism, caused by initial reservoir

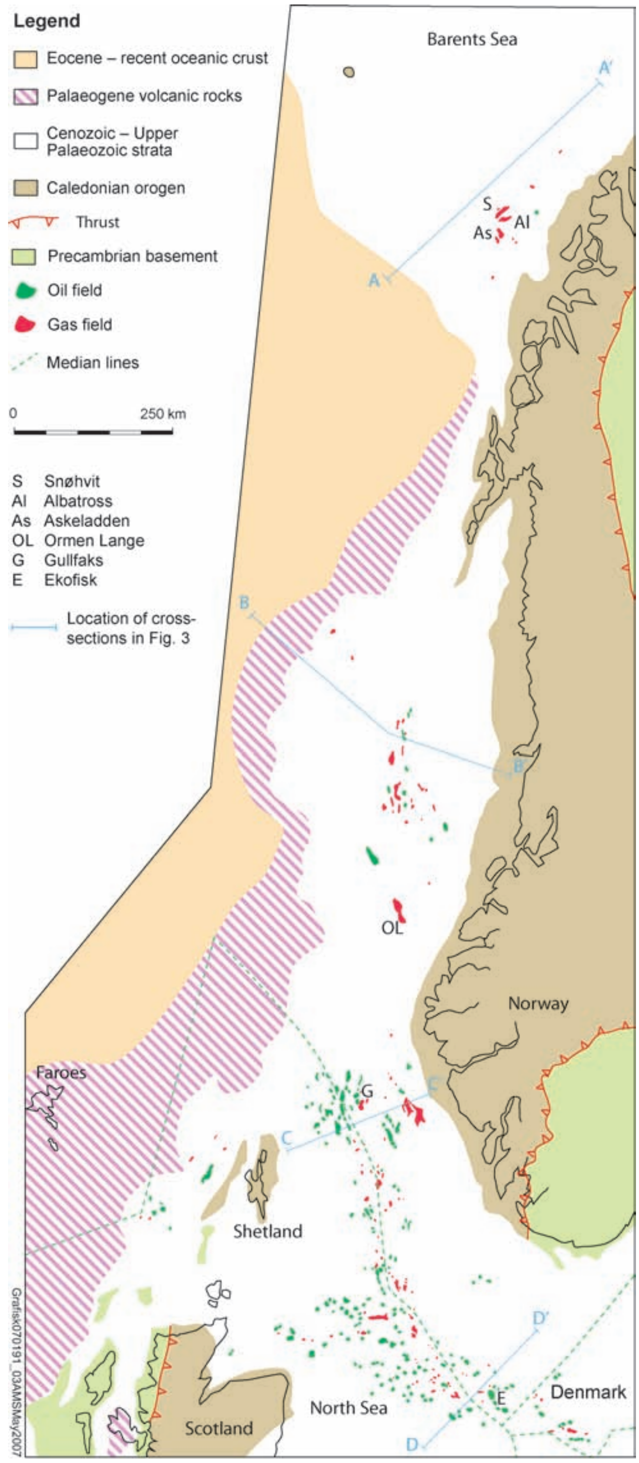

Figure 4 Oil and gas fields of Denmark and Norway.

pressure loss and porosity reduction, with further matrix weakening and compaction through water-flooding. As a consequence, the seabed above the field has subsided by a total of 9 m.

Geoscience work has focused exhaustively on understanding reservoir compaction and waterflood management, particularly the mechanical, drainage and imbibition properties of chalks under both oil and water-flooded conditions. Studies also continue to address the seismic and sub-seismic fracture systems that both aid water injectivity, yet also complicate prediction of water-flood movement. Current reservoir management strategy is focused on exceeding a 50% recovery factor, by exploiting 4D seismic data and extended reach drilling and completion technologies so as to enable optimal water injection management into the foreseeable future.

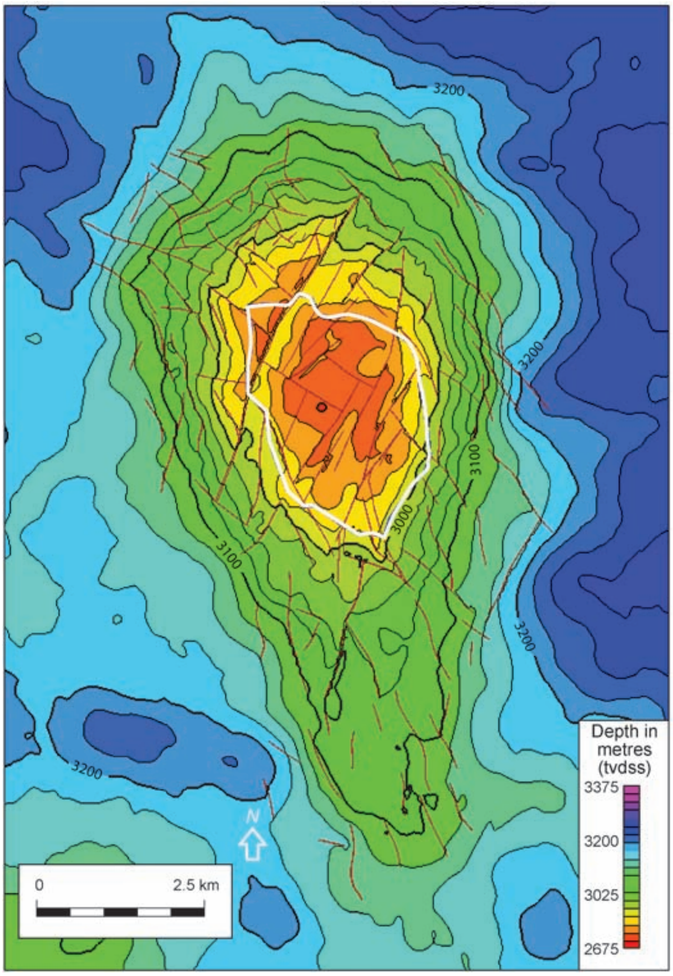

Figure 5 Ekofisk Field: depth map of the top of the Ekofisk Formation. The crest is at 2900 mss and vertical closure is about 350 m. The crestal area inside the white line has poor seismic imaging.

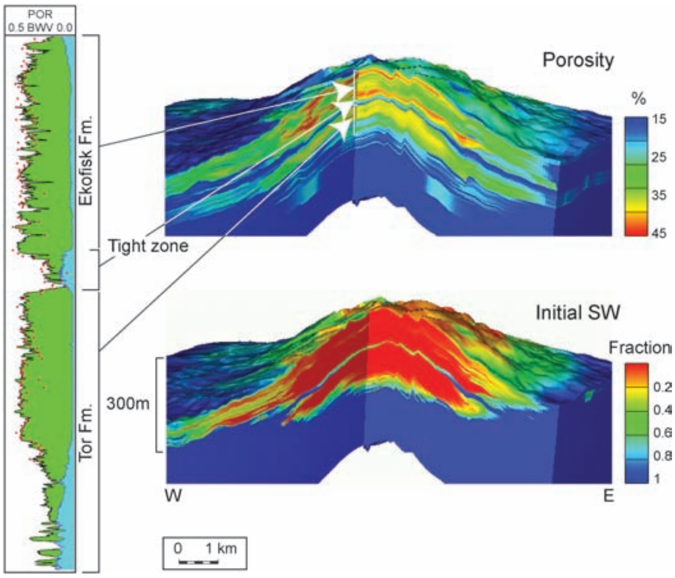

Figure 6 Ekofisk Field: cross section through the geomodel showing porosity and initial water saturation. The main reservoir (Ekofisk Formation) is separated by a tight zone from the underlying reservoir (Tor Formation). The oil-water contact is highly gradational due to the low matrix permeabilities and the high capillary pressure of the chalk.

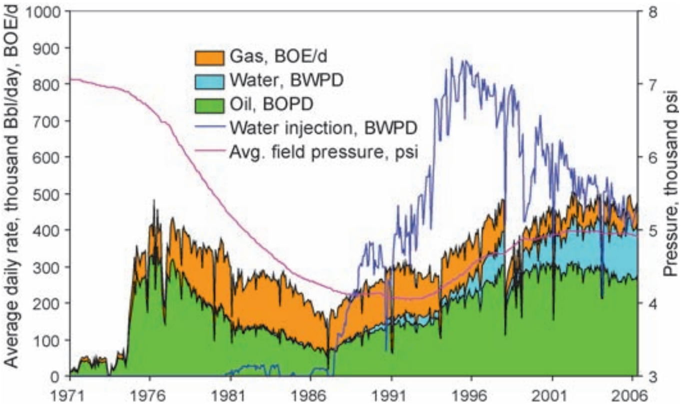

Figure 7 Ekofisk Field: production and water injection rates and average field pressure from 1971 to 2006. Note the decline in production rates and field pressure over the first 16 years, due to limited pressure support. The start of full-field water injection in 1987 reduced the pressure decline and increased oil production rates, while the reservoir was still compacting due to water weakening of the chalk. The subsequent build-up of field pressure increased the oil production, while reservoir compaction was reduced from 30–40 cm/yr to about 10 cm/yr after 1999. Total sea bed subsidence, due to reservoir compaction, amounted to 9 m by 2006.

Gullfaks oil field

Gullfaks is a giant oil field in the north of the Norwegian North Sea. The field came on stream in 1986 and the production up to June 2007 amounted to 2.09×10^9 bbl, which represents ca. 93% of the base reserves, assuming today's expected recovery factor of 61%. The ultimate goal is to achieve a recovery factor of 70%, and 4D seismic interpretation is a key element in locating the remaining oil to achieve this.

The field is trapped in a series of rotated fault blocks defined by major N-S trending faults, with throws up to several hundreds of metres (Figure 8). A secondary fault system trends E-W, with smaller throws of up to 100 m. The reservoirs consist of Cretaceous, Jurassic and Triassic sandstones. The sandy parts of the Cretaceous Kyrre Formation are interpreted to be a marine beach deposit fringing the Gullfaks structure. The Middle Jurassic Brent Group contains deltaic strata. The Cook Formation consists of marine to marginal marine deposits, while the Statfjord and Lunde Formations are mainly fluvial/alluvial. Most of the reserves are found in the Brent Group, within which the reservoir quality is generally good, with porosities up to 35% and permeabilities in the Darcy range.

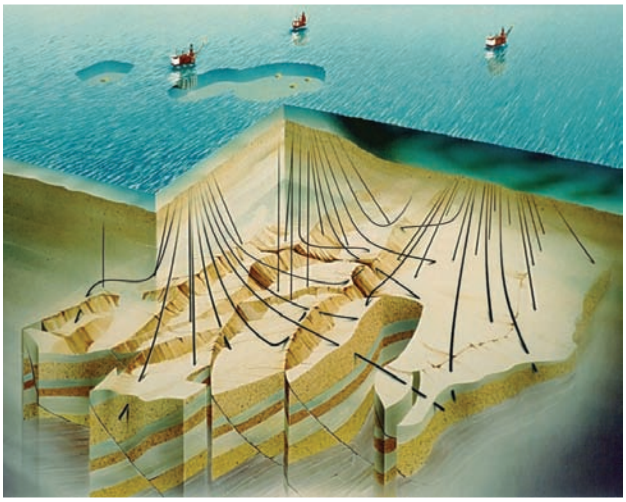

Figure 8 Gullfaks Field: production wells from three platforms target multiple intervals in the complex, faulted Jurassic reservoir.

The use of repeated seismic surveys (4D seismic/time-lapse seismic) has contributed significantly to improving oil recovery. Four repeated streamer seismic surveys have been acquired over the field, in addition to the baseline survey in 1985 prior to production start. Figure 9 shows a seismic line from 1985 and the corresponding geologic sketch illustrating the fluid contacts then. There is a strong seismic response from the top of the Brent Group reservoir when this contains oil and a very weak response down-dip when it contains water. There is also a strong reflection from the oil water contact. The corresponding seismic line acquired in 1996 shows significant changes in reflectivity on the dipping top reservoir surface; the earlier oil-water contact has more or less disappeared, whilst on the crest of the structure we still observe a strong response from the top reservoir level. Repeat saturation logs acquired from this location over the same time period show that water has displaced oil on the flank of the structure, with high initial oil saturations confined to the crest. Repeated saturation logs in numerous wells prove that changes in seismic response are often associated with changes in the saturation of different reservoir fluids. Sixteen development wells have now been drilled where interpretations based on 4D seismic data have played a major role in the decision making process.

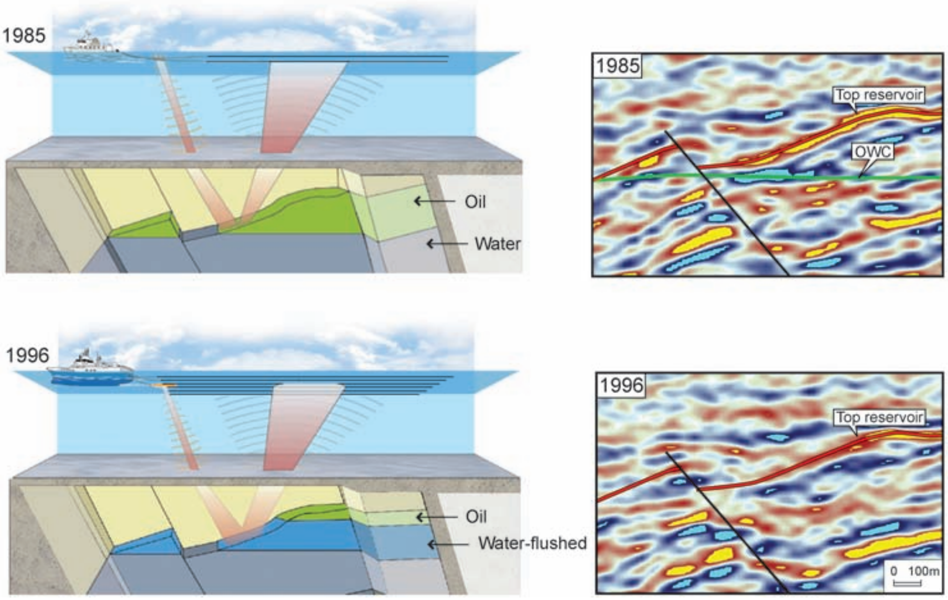

Figure 9 Gullfaks Field: time-lapse seismic, 1985 compared with 1996, and schematic illustrations of the changes in fluid content within the reservoir that have occurred over time—see text for explanation.

Ormen Lange gas field

The Ormen Lange Field lies 120 km west of the coast of mid Norway and is the second largest gas field on the Norwegian shelf, with estimated recoverable resources of ca. 14×10^{12} scf and an areal extent of 350 km^2 (Figure 10). The field was discovered in 1997 by Well 6305/5-1, finding gas-down-to (GDT) the base of the Paleocene Egga reservoir. In 1998, the southern part of the

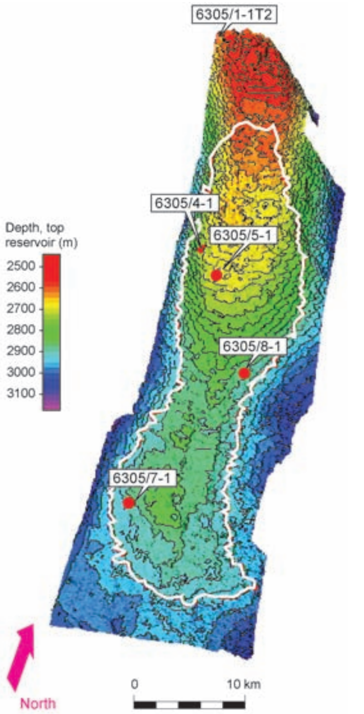

Figure 10 Ormen Lange Field: depth map of the top of the Paleocene reservoir. The white line outlines the area containing gas.

field was drilled by Well 6305/7-1, which penetrated a free water level (FWL). In 2000, Well 6305/8-1 penetrated a hydrocarbon contact and established a FWL. Finally in 2002, Well 6305/4-1, drilled 4 km to the northwest of 6305/5-1, revealed a GDT situation in the lower part of the Egga reservoir.

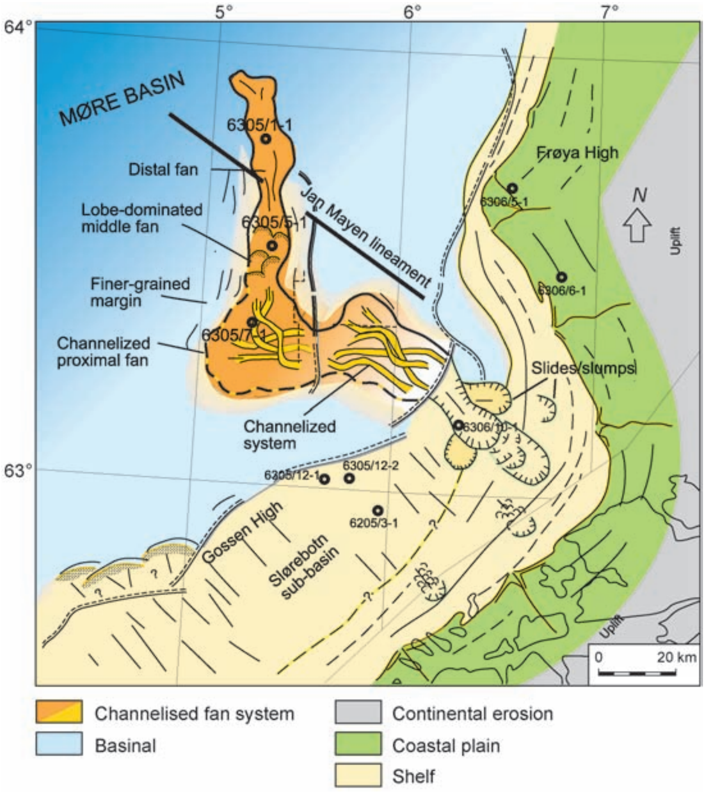

Figure 11 Ormen Lange Field: depositional model of the Paleocene submarine-fan reservoir.

The outline of the field is clear on seismic data from direct hydrocarbon indicators: a flatspot and frequency and amplitude changes. The field is heavily faulted and the faults generally juxtapose sand-rich reservoir rocks in the upper part against more clay-rich reservoir rocks towards the base. The Paleocene reservoir comprises the Egga Member, dominated by turbidite sandstones in a submarine fan (Figure 11). This sits upon an extensive shale, the “Våle Tight”, which overlies the sand/shale alternations of the “Våle Heterolithic” and the “Jorsalfare sands”. The Egga sandstones have good reservoir qualities and consist of upward-coarsening, massive, amalgamated or weakly separated sand/sandstone bodies, divided into three reservoir units.

The Ormen Lange Field is being developed as a subsea-to-land concept. This is challenging. The field is located beneath a depression on the sea bed left by an enormous submarine slide 8000 years ago (Storegga Slide). The sea bed is 800–1100 m deep and is very uneven, with 30–60 m high peaks. Also, the interface between the Gulf Stream and cold polar waters create exceptional currents that set particular demands on the installation work in the field. The same currents also cause below-zero temperatures in the water around the pipelines and installations for most of the year.

Two Templates (A and B) are currently installed on Ormen Lange. By May 2007, two pilot wells—one from each Template—and two production wells, in addition to the original exploration wells, had penetrated the reservoir section. So far the well results are in line with the geological interpretation of the field. The field has been operated by Hydro in the development phase, but Shell will take over as operator at production start-up, scheduled for October 2007.

Snøhvit gas fields

The Snøhvit development in the southwest Barents Sea comprises three separate discoveries (Figure 12). Albatross and Askeladden contain gas and condensate, whereas Snøhvit comprises a gas cap over a thin oil leg. The recoverable reserves of the three fields are estimated to a total of 6.8×10^{12} scf gas and 113×10^{6} bbl condensate (light oil). Gas production will commence in 2007, involving the drilling of 20 production wells over a planned 30 year period. Gas production will be driven by pressure depletion and the produced CO_2 will be re-injected below the hydrocarbon zone. Snøhvit is the first offshore development in the Barents Sea and is being developed with sub-sea wells remotely operated from land. Gas will be piped up to 200 km to the shore, to Europe’s first liquefied natural gas (LNG) export facility. Due to remoteness and complexity, it has taken 25 years from discovery to first production.

The hydrocarbon play comprises Lower–Middle Jurassic sandstones within rotated fault blocks and horsts of Late Jurassic– Early Cretaceous ages. Overlying marine shales form the seal, whereas Upper Jurassic organic-rich shale forms the principal hydrocarbon source. The central part of the basin (Snøhvit and Albatross) is characterized by E-W master faults; to the west (Askeladden), the structural grain is more N-S.

Three main sandstone reservoir units persist throughout the basin. The Tubåen Formation comprises fluvial and deltaic sandstones that will be used for CO_2 re-injection. The overlying Nordmela Formation comprises fine, micaceous tidal sandstones with limited reservoir potential. The Stø Formation is a transgressive, wave- and tide-influenced shoreface deposit; the principal reservoir zones are in the basal part; the overlying sandstones are extensively bioturbated, and related to the deposition in the lower shoreface and offshore transition zone; better sandstones occur in the upper part, recording new shallowing and possible shoreline regression. Abundant quartz cementation and common stylolites testify to extensive diagenetic alteration of the sandstones, involving exposure to high temperatures at depths exceeding 3–3.5 km. Subsequent Neogene to Recent uplift of 1.5–2 km has placed the reservoirs at their current depths (1.8–2.5 km). Accordingly the porosity in the main reservoir is low (12–18%).

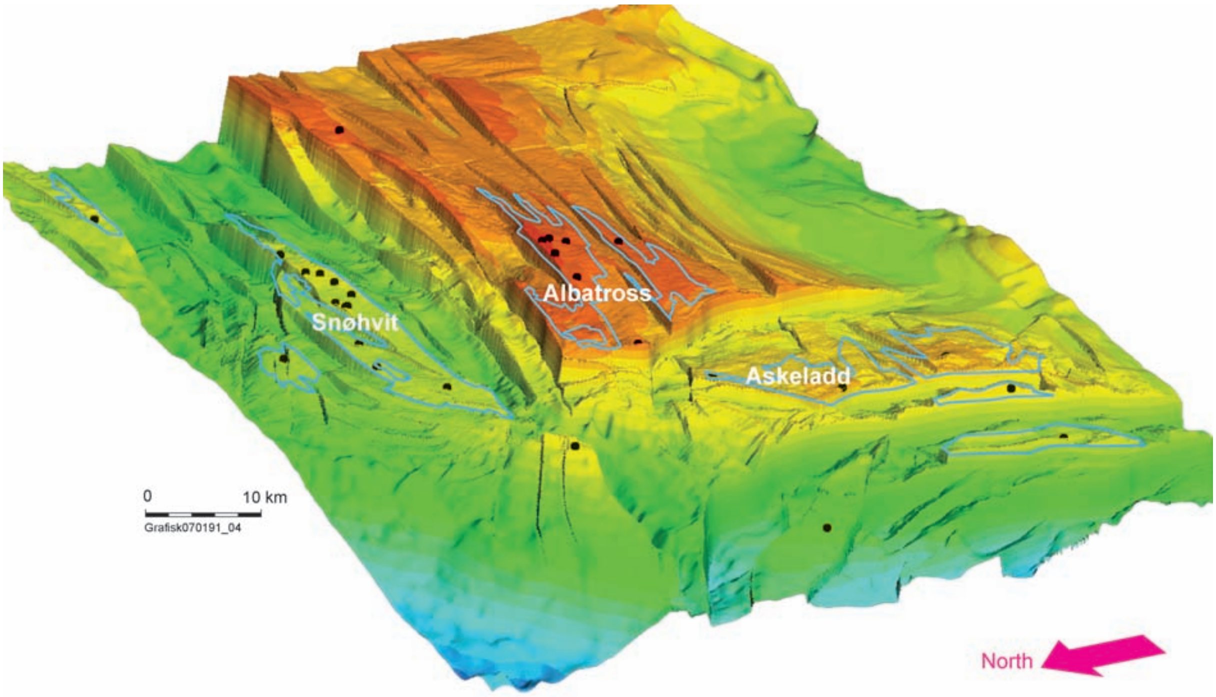

***Figure 12** Snøhvit Field: structure diagram at Middle Jurassic level. The blue lines show the outlines of the hydrocarbon pools.*

Organization

This article could have contained information just on geoscience. It would be wrong, however, to leave out all mention of the human side of the petroleum activities. The exploration and production work has led to the creation of a huge, highly talented work force, currently numbering about 2000 geoscientists. Here we briefly explain the ways in which the geoscience work has been organized, using examples mostly from Norway.

Authorities

In Norway, petroleum activities are the responsibility of the Ministry of Petroleum and Energy, a government department which oversees the work of the sector, making sure it is carried out in the best national interest (Bækken and Zenker, 2007) [*www.regjeringen.no/oed*]. Since 1973, the government has had a technical advisory division staffed by geoscientists, engineers and economists—the Norwegian Petroleum Directorate [*www.npd.no*]. It carries out independent assessments of the exploration and development, advises government on petroleum resources and on licensing round applications, oversees the oil companies' work on licenses and receives all technical information produced by the companies during that work. It currently has a scientific staff amounting to ca. 120. In Denmark, the equivalent work is undertaken by the Danish Energy Authority [*www.ens.dk*], which is a unit under the Ministry of Transport and Energy.

Oil companies

Most of the large international oil companies have had activities in Norway. The first well was drilled by Esso (1966), the first giant field was discovered by Phillips (Ekofisk, 1969), and the largest field in the province was discovered by Shell (Troll, 1983). Nevertheless, when it became clear in the late 1960's that major petroleum finds had been made, Norway decided to create a state oil company (Statoil, founded 1972) to ensure the development of native competence in all aspects of petroleum work. For long there was a restricted list of companies allowed to operate in Norway, mostly the super majors and majors and the native companies—Statoil, Norsk Hydro and Saga. In recent years, the authorities have recognized the importance of widening the mix of companies. Since 2000, about 50 companies have been 'prequalified' as operators or licensees, including completely new companies and companies entering the country for the first time.

Licensing

In Norway, there have been regular licensing rounds since 1965, and by 2006 some 540 licenses had been awarded. These have been based on 'blocks', of which there are 12 in each degree quadrant. Awarded licenses have had one company nominated as the 'operator', to carry out the technical work, and normally others as partners. Each license has had management and technical committees, with representatives from all the partners and the NPD: they are the fora in which the geoscience work has been planned, results discussed and further actions agreed. During their exploration period, licensees have carried out the agreed work programme in phases, each of several years duration, involving seismic data acquisition and drilling, followed by partial relinquishment, and then a new phase. Following a potentially commercial discovery, 'appraisal wells' have been drilled to more precisely estimate the recoverable resources and plan the optimum development scheme. Government approval, involving the NPD, has been needed before any field development could go ahead. Development and production of hydrocarbons from a field has involved a dedicated team of geoscientists in the operating company, monitored by others in the partner companies and reporting regularly to experts in the NPD.

Licensing in Denmark has followed a different pattern. In 1962, the onshore and offshore area was granted as a sole concession for 50 years to the ship owner A. P. Møller, who joined with oil companies to form a group which over the next 20 years discovered 13 chalk oilfields. In 1984, this license system was replaced by competitive licensing rounds for 'blocks', of which there are 32 in each degree quadrant.

How much geoscience work has been expended on a license? A license with only exploration work, e.g. seismic acquisition and interpretation and one exploration well, has only needed a total of a few man-years of geoscience work. At the other end of the scale is the Statfjord field. Work there has comprised 15 exploration and appraisal wells, 272 productions wells, a production history from

1979 to today, a total of up to 11 partner companies and—because it stretches over the Norway/UK median line—several major reviews of the resource distribution ('unitizations'). The geoscience effort of all organizations involved has probably reached 1000 man-years on this one field.

Contractors

The exploration and production work in the last 40 years has been achieved by cooperation between the authorities, oil companies and contracting companies. Great innovations have been made by contracting companies involved with seismic data. The first 2D seismic (single streamer, dynamite source) was acquired in the UK-Norway-Danish parts of the North Sea by Geophysical Service International in 1964. Since then, advances in acquisition technology have gone on continuously. 3D surveys began in the 1980's and have involved survey ships with more and more streamers. Repeated survey acquisitions over the same areas at different time periods ('time-lapse' or '4D seismic') have revealed changes in seismic reflections, caused by temporal changes in rock and fluid properties. Surveys involving permanent ocean bottom cables began in about 2000, giving the ability to monitor changes in reservoirs at intervals shorter than previously practicable.

The seismic contracting industry is worldwide in scope, but whilst in the 1960's there were no Norwegian companies involved, several have formed (e.g., Geco—now Schlumberger/WesternGeco; Petroleum-Geo Services; TGS-Nopec). Also, major technology breakthroughs have been made—for example, the development of 'sea-bed logging' to directly detect hydrocarbons below the sea floor by Electromagnetic Geoservices (*www.emgs.com*). Similarly, many geology-based contractors have developed in Norway—for mud logging, biostratigraphy, geochemistry, reservoir analysis, resource estimation (e.g., Geoknowledge—*www.geoknowledge.com*)—and even a geology-based exploration news magazine (Geo-expro—*www.geo365.no/geoexpro*).

Publications

Petroleum geoscientists in the North Sea have, since the early 1970's, had a tradition of publishing, to make available information that would otherwise be hidden away within company archives and official agencies. This publication effort has taken many forms. There have been six major conferences in London covering the North Sea and, later, northwest Europe (e.g., Doré and Vining, 2005). A five-year project involving societies, government institutes and companies resulted in the first consistent, published, overview of the central and northern North Sea petroleum provinces (Evans et al., 2003). The Norwegian Petroleum Society has arranged 22 conferences on petroleum geoscience themes since 1975 (e.g., Wandås et al., 2005) (*www.npf.no*). The Norwegian Petroleum Directorate has published data books on well stratigraphies, official overviews of stratigraphic and structural nomenclature (e.g. Gabrielsen et al., 1990; Blystad et al., 1995), assessments of petroleum plays and annual synopses of resources (e.g., NPD, 2007). The Geological Survey of Norway, although principally responsible for geoscience work onshore, has issued maps covering the structure and geology of the offshore basins (e.g., Sigmond, 2002) (*www.ngu.no*). The Geological Survey of Denmark and Greenland (GEUS) has issued compiled maps of the Danish on- and offshore areas (Britze, Japsen and Andersen, 1995) as well as major publications on Greenland (Ineson and Surlyk, 2003; Henriksen, 2005) (*www.geus.dk*).

Data

All well data become available for public inspection and purchase after two years in Norway and five years in Denmark. In Norway, this process is administered by the Diskos Database, currently operated by Schlumberger (*http://192.23.12.6/diskos/pex/default/index.html*). Summaries of well data are available from the NPD (*http://www.npd.no/engelsk/cwi/pbl/en/index.htm*).

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by Pär Weihed[1], Pasi Eilu[2], Rune B. Larsen[3], Henrik Stendal[4], and Mikko Tontti[2]

Metallic mineral deposits in the Nordic countries

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The Nordic countries, including Greenland, have a long tradition in mining. Documented mining dates back to the 8th century AD. Today this region is the most important metallic mining district of the European Union. Metals are produced from active mines in all countries except Iceland and related industries are thriving in all countries.

Important ore deposit types include: volcanogenic massive sulphide deposits (Cu, Zn, Pb, Au, Ag), orogenic gold deposits (Au), layered intrusions (Ni, PGE, Ti±V), intrusive hosted Cu-Au, apatite-Fe deposits, Cr- and anorthosite hosted Ti deposits. Besides these well-documented deposits, new kinds of deposits are being explored, e.g., iron oxide-copper-gold (IOCG), shale-hosted Ni-Zn-Cu and different types of uranium deposits.

Introduction

The Fennoscandian Shield, which forms a large part of the Nordic countries (see descriptions elsewhere in this volume), has historically been one of the most active mining areas in Europe. For example, archaeological evidence shows that copper was produced from the Falun mine in the Bergslagen province, Sweden, early in the 8th century AD (Eriksson and Qvarfort, 1996). Since the industrial revolution in the 19th century, numerous iron mines were exploited in Bergslagen and, during the 20th century, mining of both base metals and iron ore started in several new mining districts such as the Skellefte and Northern Norrbotten districts in Sweden, the Vihanti-Pyhäsalmi and Outokumpu districts in Finland, the Pechenga district in Russia, Tellnes and Sulitjelma in Norway, and Ivittuut (Ivigtut) in Greenland. However, Fennoscandia (the Precambrian Shield together with the Caledonides) can still be regarded as under-explored and having a good potential for major new discoveries, as shown by the discovery of metal, industrial mineral and natural stone deposits made every year in the region.

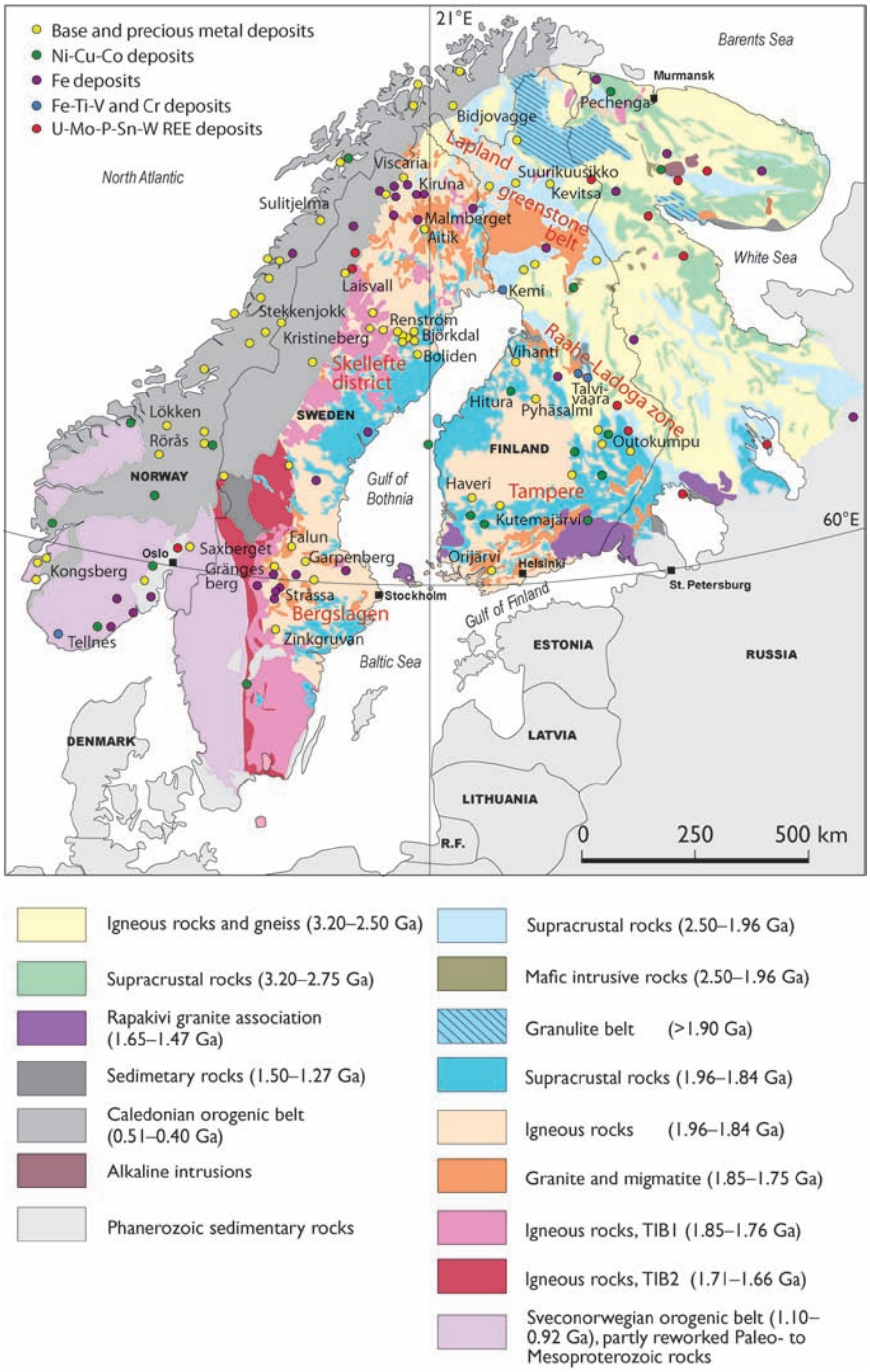

***Figure 1** Location of major ore deposits of the Nordic countries. Map from Lahtinen et al. (2005).*

Table 1 Data on major mineral deposits of the Nordic countries (Greenland included with Denmark).

	Type[2]	Size (Mt)	Cu %	Zn %	Pb %	Co %	Au ppm	Ag ppm	Fe %	Ni %	Cr %	V %	TiO_2 %	Status	Reference[3]
Fennoscandian Shield															
Bidjovagge	Cu-Au	2	1.2	-	-	-	3.6	-	-	-	-	-	-	Closed mine	Ettner et al. (1994)
Viscaria	Strat. Cu	12.54	2.29	-	-	-	-	-	-	-	-	-	-	Closed mine	Martinsson (1997)
Stora Sahavaara	Fe-Cu-Au	145	0.08	-	-	-	?	-	43.1	-	-	-	-	Prospect	Eilu et al. (2007)
Hannukainen	Fe-Cu-Au	170.7	0.2	-	-	-	0.1	-	35.5	-	-	-	-	Closed mine	Niiranen et al. (2007)
Aitik	Porph.	1600	0.4	-	-	-	0.2	4	-	-	-	-	-	Active mine	Wanhainen et al. (2003)
Boliden	VMS	8.3	1.4	0.9	0.3	-	15.5	50	-	-	-	-	-	Closed mine	Bergman Weihed et al. (1996)
Renström	VMS	12.6	0.8	7.3	1.5	-	2.8	155	-	-	-	-	-	Active mine	Allen et al. (1996a)
Petiknäs S	VMS	6.5	1.1	4.8	0.9	-	2.3	108	-	-	-	-	-	Active mine	Allen et al. (1996a)
Rakkejaur	VMS	20.7	0.3	2.4	0.2	-	1.0	45	-	-	-	-	-	Closed mine	Allen et al. (1996a)
Kristineberg	VMS	31.4	1.1	3.2	0.4	-	1.2	37.8	-	-	-	-	-	Active mine	Allen et al. (1996a)
Vihanti	VMS	37.1	0.48	4.0	0.36	-	0.44	25	-	-	-	-	-	Closed mine	Helovuori (1979)
Pyhäsalmi	VMS	71	0.79	2.47	-	-	0.4	15	-	-	-	-	-	Active mine	Weihed (2001)
Outokumpu region	VMS	42.1	3.4	1.1	-	0.22	0.6	8.3	-	0.12	-	-	-	Closed mines	Gaál 1985
Kylylahti	VMS	7.8	1.17	0.5	-	0.24	0.7	-	-	0.22	-	-	-	Prospect	Eilu et al. (2007)
Falun	VMS	28.1	~3	4	1.5	-	~3[4]	~20	-	-	-	-	-	Closed mine	Allen et al. (1996b)
Garpenberg	VMS	21.5	0.3	5.3	3.3	-	0.65	98	-	-	-	-	-	Active mine	Allen et al. (1996b)
Zinkgruvan	VMS	51	-	8	3.5	-	-	70	-	-	-	-	-	Active mine	Allen et al. (1996b)
Kiirunavaara	FeOx	>2000	-	-	-	-	-	-	>60		-	-	-	Active mine	Martinsson (1997)
Malmberget	FeOx	840	-	-	-	-	-	-	51–61	-	-	-	-	Active mine	Martinsson (1997)
Grängesberg	FeOx	227	-	-	-	-	-	-	58–64	-	-	-	-	Closed mine	Allen et al. (1996b)
Tellnes	Ti	408	-	-	-	-	-	-	-	-	-	-	18	Active mine	Charlier (2005)
Björkdal	Orog. Au	23.5	-	-	-	-	2.6	-	-	-	-	-	-	Active mine	Weihed et al. (2003)
Pahtavaara	Orog. Au	>3	-	-	-	-	3	-	-	-	-	-	-	Active mine	Eilu et al. (2003)
Kutemajärvi	Epith. Au	2.0	-	-	-	-	9	-	-	-	-	-	-	Active mine	Poutiainen and Grönholm (1996)
Suurikuusikko (Kittilä)	Orog. Au	24.3	-	-	-	-	4.75	-	-	-	-	-	-	Active mine	Patison (2007)
Kotalahti	Ni-Cu	13	0.27	-	-	0.03	-	-	-	0.72	-	-	-	Closed mine	Papunen and Gorbunov (1985)
Hitura	Ni-Cu	13	0.2	-	-	0.02	-	-	-	0.59	-	-	-	Closed mine	Papunen and Gorbunov (1985)
Ahmavaara	PGE	78.1	0.23	-	-	-	0.08	1.52 ppm PGE	-	0.09	-	-	-	Prospect	Weihed et al. (2005)
Kemi	Cr	158	-	-	-	-	-	-	-	-	17.1	-	-	Active mine	Alapieti et al. (1989)
Talvivaara	Ni-Zn	338	0.14	0.56	-	0.02	-	3	-	0.26	-	-	-	Active mine	Loukola-Ruskeeniemi and Heino (1996)
Kevitsa	Ni-Cu	207	0.46	-	-	0.01	0.13	-	-	0.3	-	-	-	Prospect	Mutanen (1997)
Mustavaara	Fe-Ti-V	43.5	-	-	-	-	-	-	21.5	-	-	0.2	5	Closed mine	Alapieti (1982)
Otanmäki	Fe-Ti-V	36.1	-	-	-	-	-	-	34	-	-	0.26	6.78	Closed mine	Eilu et al. (2007)
Björnevatn	BIF	140	-	-	-	-	-	-	31	-	-	-	-	Closed mine	Eilu et al. (2007)
Caledonides															
Løkken	VMS	30	2.3	1.8	0.02	-	0.2	19	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Stekenjokk-Levi	VMS	25.7	1.43	2.55	0.23	-	0.3	50	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Tverrfjellet	VMS	19.0	1.0	1.2	0.2	-	-	-	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Joma, Grong	VMS	22.5	1.49	1.7	tr.	-	-	-	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Skorovas, Grong	VMS	10.0	0.8	1.6	tr.	-	-	-	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Giken, Sulitjelma	VMS	9.5	2.25	0.70	tr.	-	-	-	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Bleikvassli	SEDEX	6	0.2	4.2	2.5	-	-	25	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Bruvann, Råna	Ni-Cu	7	0.1	-	-	-	-	-		-0.53	-	-	-	Closed mine	Grenne et al. (1999)
Ørtfjell, Rana	BIF	417	-	-	-	-	-	-	34	-	-	-	-	Active mine	Grenne et al. (1999)
Nordli	Porph	200	-	-	-	-	-	-	-	-	-	0.14 % Mo		Prospect	Eilu et al. (2007)
Laisvall	MVT	64.5	0.1	0.5	3.9	-	-	11	-	-	-	-	-	Closed mine	Grenne et al. (1999)
Greenland															
Black Angel	SEDEX	-	-	-	-	-	-	-	-	-	-	-	-	Closed mine	Thomassen (1991)
Citronen Fjord,	SEDEX	-	-	-	-	-	-	-	-	-	-	-	-	Prospect	van der Stijl & Mosher (1998)
Fiskenaesset	Cr	-	-	-	-	-	-	-	Chromium	-	-	-	-	Prospect	Stendal et al. (2005)
Isua	Fe	-	-	-	-	-	-	-	Iron	-	-	-	-	Prospect	Stendal et al. (2005)
Brogetdal	Cu	-	-	-	-	-	-	-	-	-	-	-	-	Prospect	Stendal et al. (2005)
Malmbjerg	Mo	-	-	-	-	-	-	-	-	-	-	-	-	Prospect	Stendal et al. (2005)
Nalunaq	Orog. Au	-	-	-	-	-	-	-	-	-	-	-	-	Active mine	Stendal et al. (2005)
Platinova Reef,	Ni-Cu	-	-	-	-	-	-	-	Gold, Palladium		-	-	-	Prospect	Stendal et al. (2005)

1)This table lists major deposits, in Norden where deposit data are available. Data for deposits 4, 5, 19, 20, 21, 22, 23, 35-55 from the Geological Survey of Finland deposit database, data for deposit 1, 2, 7-18 from Weihed (2001), data for deposit 6 from Boliden Mineral AB, data for deposits 24-27 from Allen et al. (1996), data for deposits 28-30 from Geological Survey of Sweden mineral deposit database and data for deposit 31 from Charlier (2005).

2)Abbreviations: Strat. Cu = Stratiform Cu deposits; Porph. = Porphyry type deposit; VMS = Volcanogenic massive sulphide deposit; FeOx = Fe-oxide deposit; Orog. Au = Orogenic gold deposit; Epith. Au = Epithermal Au deposit, BIF = banded iron formation.

3)There is only one reference for each deposit listed in the table. Where possible this is a recent reference containing more references to the deposit concerned.

4)Grade for epigenetic quartz vein hosted gold part of deposit.

The present economic mineral deposits (Figure 1) are largely concentrated in the Paleoproterozoic parts of the Fennoscandian Shield. Nickel-PGE, orogenic gold, and VMS (including some of uncertain classification), Pb-Zn, Cr and Fe-oxide deposits are the main types of economic interest in the Shield (Table 1). Large tonnage-low grade Cu-Au deposits (e.g., Aitik) are associated with intrusive rocks in northern areas. The latter have been described as porphyry style or as hybrid porphyry-IOCG style deposits (Weihed, 2001; Wanhainen et al., 2003). Also Fe-Ti oxides occurring in anorthosites and chromite in layered intrusions are major deposit types in the region. Besides these, mining of tungsten, molybdenum, REE and lithium has taken place during the last decades on smaller scales.

Greenland, with many terranes of Archean and Proterozoic age, is currently also being explored for similar commodities and the first gold mine is now in production. Also the Caledonian orogen hosts many major mineral occurrences in Norway and Sweden. This short review of ore deposit types in the Fennoscandian Shield and their geodynamic setting is chiefly derived from Weihed et al. (2005).

The main metal mining areas in Norden are described below and the metallogeny is put into a geodynamic context.

Greenland

Greenland's first gold mine, Nalunaq, located in the Nuuk region (Stendal and Secher, 2002) in southern Greenland, was officially opened in August, 2004 (Figure 2). Since the systematic exploration for minerals in Greenland started in the 1800s, moderate-size to major deposits of chromium, copper, gold, iron, lead, molybdenum, phosphorous, PGE, rare-earth metals, yttrium, silver, and zinc have been discovered but only a few have been mined (Table 1). Exploration for kimberlite pipes, with a potential for diamonds, is being carried out in west-central Greenland, and diamonds have been recovered in two areas (Jensen and Secher, 2004). Mining occurred in the last century at the Mestersvig lead-zinc deposit, the Maarmorilik (Black Angel mine) lead-zinc-silver deposit (Thomassen, 1991), and the Innatsiaq, Josva, and Lillian copper deposits in the Kobbeminebugt. A new exciting discovery, the Citronen Fjord lead and zinc deposit, occurs near the Navarana Fjord Escarpment in north Greenland (Van der Stijl and Mosher, 1998).

Greenstone belts in Greenland are found in both Archean and Paleoproterozoic terranes, where they are generally rather small in volume compared to similar belts in Canada, Australia, and the Fennoscandian Shield. The Greenland Archean gneiss complex, a part of the 3.8–2.5 Ga North Atlantic Craton, contains fragmented belts (maximum 10 vol. %) of supra-crustal rocks within the gneisses. In addition, within Greenland's granite-greenstone terranes, mafic to ultramafic magmatic intrusions occur hosting major deposits, such as chromitite (±PGE) in anorthosites, and gabbro complexes with V and Ti in magnetite and ilmenite.

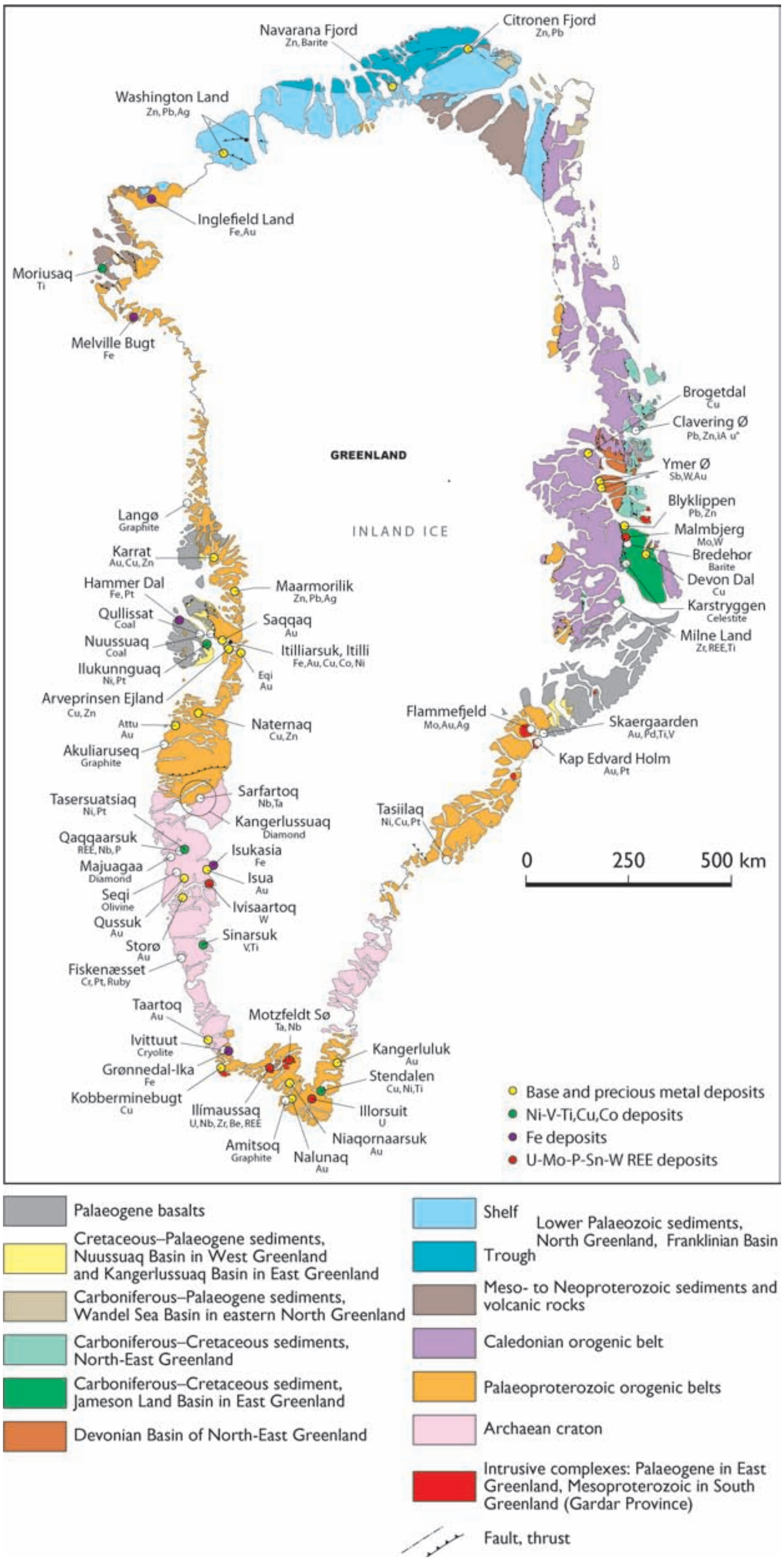

Figure 2 Major metallic mines and prospects in Greenland. Map from Greenland Mineral exploration letter (GEUS, 2007).

Banded iron formations (BIF), mostly Algoma type, and gold mineralizations are typical for the Archean greenstone belts in Greenland. BIFs occur in three main localities with the most famous in the Isua supracrustal belt (~3805 Ma), and the two others of rather large size, at Itilliarsuk (~2850 Ma) and Melville Bugt (2700 Ma). The latter locality can be correlated with similar deposits on Baffin Island, Canada, which are subject now to feasibility studies.

Gold is a potential commodity in most of the Archean and some of the Paleoproterozoic greenstone belts and other supracrustal sequences. Most of the known Archean gold occurrences in Greenland are older than 2.7 Ga, and they are all smaller than similar deposits in Canada and Australia. The favourable areas are the southwestern edge of the Mesoarchean block at Sermiligaarsuk fjord within the Tartoq Group greenstone belt, and the Meso-Neoarchean belts in the Nuuk region where there are two interesting areas: One is a Mesoarchaean arc-related system with a Cu-Au association (Qussuk), and the other is on Storø with a typical As-rich orogenic gold-style mineralisation. To the north of the Archean block, the Paleoproterozoic mobile belts contain large amounts of reworked Archean rocks and Proterozoic intrusions. Within this belt, a Mesoarchean block is preserved in the northeastern part of Disko Bugt area containing both stratabound and orogenic types of gold deposits (Stendal and Garde, 2005; Stendal et al., 2007).

The juvenile Ketilidian orogen is considered to be a gold province with several prospects in different settings and the only gold mine in Greenland. The gold is thought to be related to the later stages of a batholith intrusion (1800–1770 Ma), but is found both in supracrustal rocks and granitoids (Stendal and Frei, 2000). The greenstone belts in the Paleoproterozoic domains outside South Greenland are at present considered to have a low potential for gold deposits. Supracrustal suites in the northern Nagssugtoqidian orogen (1950–1920 Ma) contain syngenetic massive sulphide occurrences (Naternaq and Ataneq), and the Ataneq area contains prominent graphite deposits. The Karrat Group comprises the SEDEX-style Black Angel deposit (Thomassen, 1991) and sulphide-gold occurrences at Karrat Isfjord. In Inglefield Land gold mineralisation is related to shear zones and hosted by Paleoproterozoic deformed gneisses and supracrustal rocks (Stendal et al., 2005).

Mineral occurrences in Greenland's magmatic environments are very promising, with giant porphyry molybdenum deposits related to a Paleogene alkaline intrusion in East Greenland and associated vein systems with gold and silver. Another giant deposit is the Skaergaard gabbroic intrusion containing a world-class deposit of Au, Pd, Pt, V and ilmenite. Except around known deposits, the Paleogene alkaline and mafic igneous rocks in East and West Greenland are, in general, frontier areas, providing optimism for the discovery of new deposits.

The alkaline Mesoproterozoic intrusions in the Gardar province contain large deposits of niobium, tantalum, zirconium, rare earth elements, and cryolite. Of these, the eudialite (zirconium) deposit at Ilimaussaq ('Kringlerne') has been thoroughly investigated. Within Greenland's Mesoproterozoic magmatic province an equivalent to the Voisey's Bay deposit in Labrador has still to be found. The carbonatites of both Neoproterozoic and Jurassic age have a great potential for niobium, tantalum, REE and apatite. The Neoproterozoic kimberlite dykes and sills in the Kangerlussuaq area have promising diamond potential and are currently under exploration (Stendal et al., 2005).

Examples of sediment-hosted mineralizations are: (1) copper in Neoproterozoic and Triassic sandstones, (2) lead and zinc in shale/carbonate sequences, (3) fossil placer deposits and evaporite deposits and (4) lead-zinc veins in sediments in the Mesters Vig area in East Greenland, including the closed Blyklippen Pb-Zn mine.

SEDEX-type Pb-Zn deposits in shale sequences are found in the sedimentary basin in North Greenland. Carbonate-hosted Pb-Zn (MVT) is known from platform carbonates both in North and East Greenland. Celestite and barium deposits are related to basins with evaporites in East Greenland. Many of the sedimentary basins are situated in remote areas and are still frontier regions with respect to exploration. The geological setting in these remote areas is highly favourable for SEDEX- and MVT-type deposits (Stendal et al., 2005).

Fennoscandian Shield

Ni-Cu-PGE deposits

Ni-Cu±PGE deposits occur in several different settings within the Fennoscandian Shield (Weihed et al., 2005 and references therein). Nickel has been and still is mined on a large scale in northwestern Russia, (e.g., Pechenga) and Finland (e.g., Kotalahti, Hitura and Vammala) and to a lesser extent in Sweden (e.g., Lainejaur). The age and geodynamic setting of these deposits can be subdivided into: (1) Archean greenstone belts (2.74 Ga), (2) older Paleoproterozoic (2.49–2.45 Ga) mafic layered intrusions in Finland and Russia, also containing large Cr deposits and stand-alone PGE deposits, akin to Bushveld, (3) younger Paleoproterozoic (2.2 to 2.05 Ga) greenstone belts, (4) Paleoproterozoic ophiolite complexes (1.97 Ga), (5) rift-related ultramafic volcanism (1.97 Ga), (6) Svecofennian orogenic mafic-ultramafic intrusions (1.88 Ga), and (7) post-orogenic diabase dykes.

VMS deposits

Volcanogenic massive sulphide (VMS) deposits are currently the most exploited base metal ore type in the Fennoscandian Shield. Five deposits are currently mined in the Skellefte district in northern Sweden, one in the Pyhäsalmi area in central Finland and two in the Bergslagen region of south-central Sweden. However, it is unclear (as discussed below) whether or not some of the major deposits in the Bergslagen region should be classified as VMS deposits (e.g., Garpenberg and Zinkgruvan). Also an open question is whether or not the Outokumpu deposits (Kontinen, 1998; Sorjonen-Ward et al., 2004) really are VMS deposits *sensu stricto*. Significant VMS potential also exists in the northern Paleoproterozoic supracrustal belts, as shown by the now closed Viscaria and Pahtavaara Cu-Zn mines in Sweden and Finland, respectively.

Orogenic gold

Most of the gold occurrences of the Fennoscandian Shield belong to the orogenic category, following the terminology of Groves et al. (1998). These are present in practically all Archean and Proterozoic supracrustal belts. Some gold deposits have been described with alternative genetic models. For example, Enåsen (Hallberg, 1994) and Kutemajärvi (Poutiainen and Grönholm, 1996) have been interpreted as metamorphosed epithermal deposits. Today's largest gold deposit in the Fennoscandian Shield, Boliden, has also been described as a hybrid epithermal VMS deposit (Bergman Weihed et al., 1996). In the northernmost part of the Fennoscandian Shield, Cu-Au ores, such as Bidjovagge (Ettner et al., 1994), Pahtohavare (Lindblom et al., 1996) and Saattopora (Grönholm, 1999), have been described as orogenic gold deposits, although their high Cu content and saline mineralising fluids are more akin to IOCG deposits (Weihed, 2001; Eilu et al., 2003).

Almost all currently economic deposits are in the Paleoproterozoic domains (Sundblad, 2003). The apparent scarcity of Archean economic deposits may be due to the paucity of exploration for gold in the Russian part of the Shield, and that all gold exploration is recent within the region; also that the largest greenstone belt of the Shield (the Central Lapland greenstone belt) is Paleoproterozoic in age.

Age data on orogenic gold mineralizing events are scarce, but it is possible to constrain three major periods of mineralization: 2.72 to 2.67 Ga, 1.90 to 1.86 Ga and 1.85 to 1.79 Ga (Eilu and Weihed, 2005). The age data appear to define a rough zonation from northeast to southwest, which seems to be related to the southwestward growth of the Fennoscandian Shield with time.

Recent discoveries of orogenic gold deposits include the “Gold line” in northern Sweden with two active mines (Svartliden and Blaiken, currently in January 2008 the Blaiken deposit is put on hold due to technical and economic difficulties) and one deposit (Fäbodliden) in the feasibility stage. Suurikuusikko, in the Central Lapland greenstone belt of Finland, with a current *in situ* resource of 115 t gold, is the largest deposit in northern Europe and will start production in 2008 (Patison, 2007).

Fe deposits (including IOCG), porphyry Cu-Au and stratiform Cu±Au

The northern Paleoproterozoic part of the Fennoscandian Shield, including parts of Finland, Norway and Sweden, is an economically important metallogenic province dominated by Fe oxide and Cu±Au ores. Based on the style of Fe and Au-Cu mineralization and the extensive albite and scapolite alteration, the region has been regarded as a typical IOCG province (e.g., Martinsson, 2001; Williams et al., 2003; Niiranen et al., 2007). Four major types of deposits exist, namely skarn-like Fe±Cu±Au deposits, Kiruna type Fe oxides (apatite iron ores), and epigenetic and porphyry style Cu±Au and Au deposits. In strictly genetic terms, only some of these can be classified as typical iron oxide-Cu-Au (IOCG) deposits, whereas others only share a few characteristic features with this, rather loosely defined, ore class (cf. Hitzman et al., 1992; Hitzman, 2000). For example, the Kiruna-type deposits could also be interpreted as magmatic, or magmatic-hydrothermal occurrences (Nyström and Henriquez, 1994).

Economically, the most important deposit type for the region is the apatite-iron ore, presently with an annual production of about 31 Mt of ore from the Kiirunavaara and Malmberget mines and a total production of about 1,600 Mt from 10 mines during the last 100 years. Copper and gold have been mined on a large scale in Sweden (Aitik), whereas other Cu-Au mines (e.g., Bidjovagge, Saattopora) have been small. All of the sulphide deposits are hosted by Paleoproterozoic greenstones and are small- to medium-sized except for Aitik, which occurs in Svecofennian volcaniclastic rocks and is a world-class deposit with a total resource of >1,000 Mt and an annual production of 18 Mt. At present, Aitik is seen as a porphyry-style deposit possibly with a subordinate IOCG-style overprint (Wanhainen et al., 2003).

The Bergslagen region in south-central Sweden, and its extension in southwestern Finland, hosts a number of Fe deposits of various types. Currently there is no mining of Fe in this historically important iron province (e.g., major deposits like Grängesberg and Dannemora), but the recent increase in metal prices has led to a feasibility study to reopen the Dannemora mine. Also the Stora Sahavaara IOCG-style (?) Fe deposit in northern Sweden is currently being investigated, together with similar deposits in the neighbouring Kolari area in Finland.

Fe-Ti oxides in anorthosites

Magmatic ilmenite deposits are typically hosted by anorthosite massifs. The second largest deposit of this type in the world is the Tellnes ilmenite norite deposit which was intruded into the central part of the Neoproterozoic Åna-Sira anorthosite massif, in the Rogaland Anorthosite Province of southwestern Norway (Bingen and Stein, 2003). Smaller Fe-Ti occurrences are widespread in the area. Among them, the most important are Storgangen and Blåfjell (Duchesne, 1999), but mining activities are currently confined to Tellnes where the average grade is slightly above 18 % TiO_2 for >380 Mt of ore.

Other deposit types

Other types of metal occurrences in the Nordic countries include Cr, Li, Mo, Nb, REE, Sn, Ta, W and U. The Kemi chromite mine in Finland is one of the largest chromium deposits in Europe. Recent promising exploration results include the 340 Mt Talvivaara Ni-Cu-Zn deposits hosted by metamorphosed black shales in the Paleoproterozoic Kainuu Schist Belt, Finland (*www.talvivaara.com*; Eilu et al., 2007). Talvivaara is an example of a previously unexploited style of mineralization which may prove, globally, to be a major new source for base metals.

During the last decade, diamond exploration has been successful in delineating diamondiferous kimberlite pipes especially in the Archangelsk area in Russia, but also in the eastern Finland (see *http://en.gtk.fi/ExplorationFinland/Commodities/Diamonds.html*).

Uranium is known to occur in several mineralization types in both vein-type deposits in Precambrian rocks, primarily in Finland and in Paleozoic shales overlying the Precambrian basement in Sweden. Substantial low-grade reserves are known in Cambrian alum shales (Wilson, 1979; Andersson et al., 1985; Gustafsson, 2007). Many of these deposits are now being investigated, although it is uncertain whether or not mining of uranium will be permitted in Sweden or Finland.

Caledonide metallogeny

The Caledonide nappe complexes in western Fennoscandia contain several major ore deposit types, some of world-class dimensions. In the post-world war era, massive Cu-Zn-Pb sulphide deposits in both volcanic and sedimentary settings comprised the backbone of the mining industry in Norway. The last massive sulphide mine was closed in the mid-1990s and large-scale exploration for new deposits of any kind has been minimal since the 1980s. Currently, the Ørtfjell iron deposit is the only Caledonian metallic deposit being mined. Systematic exploration and research on Norwegian metallic deposits had a low priority since the mid-1990s, although the diversity of fertile geological terrains and large expanses of mostly unexplored territory provide an incentive for new exploration. Slowly, this situation is changing and currently there is active exploration in both the Fennoscandian Shield and the Caledonides of Norway, although far below the level now observed in Sweden and Finland. Most of the activities in the Caledonides concern hydrothermal gold deposits (e.g., Bindal and Mofjellet), but recently also polymetallic tungsten skarn deposits in the Nordland tungsten province and orthomagmatic Ni-Cu deposits in the Caledonides as well as the komatiite lithologies of Finnmark County in the Shield. According to Grenne et al. (1999), the Nordic Caledonian mineral deposits can be subdivided into:

- Stratabound, partly stratiform, massive to disseminated deposits of mainly Zn-Pb±Cu sulphides in mixed metasedimentary-metavolcanic successions (Bleikvassli, Mofjellet).
- Stratabound magnetite-hematite deposits in metasedimentary carbonate-pelite successions—so-called metasedimentary iron ores (Ørtfjell).
- Carbonatite-hosted Nb-Fe-P-REE deposits (Fen Complex).
- Organic-rich black shale deposits with concentrations of U, V, Mo, Ni.
- Stratabound, partly stratiform, massive pyritic deposits of Cu-Zn (±Pb) sulphides (VMS deposits, Stekenjokk-Levi, Lökken, Röros and Sulitjelma).
- Stratabound magnetite-(pyrite-chalcopyrite) deposits (volcanic-hosted iron ores).
- Orthomagmatic Ni-Cu-S and Cr deposits with locally high PGE (Bruvann, Råna).
- Minor Cu-Mo stockwork mineralisation in felsic magmatic rocks.
- Stratabound, disseminated to semi-massive accumulations of Pb±Zn sulphides in quartz-arenites (MVT, sandstone lead deposits, Laisvall).
- Various, small, vein- and replacement type deposits characterised by Au, Ag, Pb, Zn, Sb, As, W, Mo or U, in metamorphic and plutonic complexes.

Geodynamic settings from the Archean to the Paleozoic

Throughout the evolution of the Fennoscandian Shield, the orogenic gold deposits also reflect the orogenic younging of the Shield towards the southwest and west. Most orogenic gold deposits formed during periods of crustal shortening, and the mineralization processes peaked at 2.72–2.67 Ga, 1.90–1.86 Ga, and 1.85–1.79 Ga.

Between ca. 2.5 to 2.4 Ga, the Archean craton rifted on a large scale, possibly for the first time, facilitating the emplacement of extensive layered intrusions and mafic dyke swarms. At this stage and, to some extent, also during later rifting stages at 2.2 to 2.05 Ga, Ni-Cu±PGE deposits formed both as part of layered igneous complexes and associated with mafic volcanism in rifted basins with komatiite volcanism in the Karasjokk, Kautokeino and Central Lapland greenstone belts. However, small Ni±Cu±PGE deposits also occur in the Neoarchean greenstone belts of eastern Finland (possibly also in Russia), and also these may be related to rifting of the Archean crust. Synorogenic mafic-ultramafic intrusions formed during the peak of the Svecokarelian orogen at ca. 1.89 to 1.88 Ga. These host numerous Ni-Cu deposits and are confined to linear belts that slightly post-date the regional arc volcanism.

Nearly all VMS-style deposits in the Fennoscandian Shield formed between 1.97 and 1.88 Ga in extensional settings during basin inversion and accretion. The oldest, the Outokumpu-type Cu-Co±Au±Ni±Zn deposits were formed at 1.97–1.95 Ga in mantle rocks that were subsequently obducted onto the Archean continent during onset of convergence. The next, more typical VMS deposits formed at 1.93 to 1.91 Ga in an accreted, primitive, bimodal arc setting which formed during extension of only slightly older volcanic crust in the Pyhäsalmi area in central Finland. Their host rocks are tholeiitic basalts and transitional to calc-alkaline rhyolites, including high-silica varieties, and the deposits broadly fit within the "bimodal mafic type" classification of Barrie and Hannington (1999). The Skellefte VMS deposits are 20 to 30 million years younger and Allen et al. (2002) suggest that, in contrast to the deposits in the Pyhäsalmi area, the former district is a remnant of a strongly extensional intra-arc region that developed on continental or mature arc crust where the basement was only slightly older. The Bergslagen-Uusimaa belt, with a much more diverse metallogeny compared to the Skellefte and Pyhäsalmi areas, is coeval with the Skellefte area, but was formed within or at the margin of a microcontinent that collided with Fennoscandia at ca. 1.88 to 1.87 Ga. The Bergslagen region is interpreted as an intra-continental extensional or continental margin back-arc region developed on older continental crust (Allen et al., 1996b).

IOCG occurrences in the Fennoscandian Shield are diverse in style. At least the oldest mineralizing stages at ca. 1.88 Ga are coeval with magmatism having a monzonitic fractionation trend and calc-alkaline to alkaline subaerial volcanism more akin to continental arc, or magmatism inboard of an active arc. There also is evidence for multiple metal introduction or remobilization between ca. 1.80 and 1.77 Ga, related to late- to post-orogenic magmatism distal to an active N-S subduction zone further to the west (Weihed et al., 2002). Also, the interaction of magmas with evaporitic sequences in older Paleoproterozoic rift sequences could be significant for forming fluids able to carry large amounts of Fe, Cu and Au (Martinsson, 1997).

Large volumes of anorthositic magmas characterize the Sveconorwegian Orogeny, in the southwestern part of the Fennoscandian Shield. The best example of a major concentration of Ti associated with these anorthosites is the Tellnes deposit. The Tellnes ilmenite deposit belongs to the Mesoproterozoic (930 to 920 Ma) Rogaland Anorthosite Province in SW Norway. The rocks of this province were emplaced in the southwestern part of the Sveconorwegian orogenic belt under granulite facies conditions, ca. 40 million years after the last regional deformation (Bingen and Stein, 2003). Many massive, but small Ni-Cu sulphide occurrences also formed during emplacement of the anorthosite complexes associated with noritic melts (e.g., the Homsevatn deposit). Otherwise, more important orthomagmatic Ni-Cu deposits are associated with the early Sweconorwegian Iveland-Gautestad norite (1279±3 Ma) in Setesdalen comprising the Flåt Ni-deposit and several smaller occurrences. In addition, sub-economic Mo-occurrences are associated with Sweconorwegian granites, mostly in the southwestern part of this orogenic belt.

Ore deposits associated with the Scandinavian Caledonides may tentatively be divided into three groups: (1) formation during continental rifting and/or ocean floor spreading with emplacement as integral parts of the nappes during the Caledonian orogeny, (2) formation during plate convergence and ocean closure, or (3) formation during continent-continent collision and subsequent extensional orogenic collapse (Grenne et al., 1999). Accordingly, the deposits occur in the accreted Laurentia terrains to the west (now the Uppermost Allochthon), the outboard Iapetus oceanic sequences (Upper Allochthon), the outer continental margin sequences (Upper Allochthon, lower part) and the inner continental margin and shelf successions of Baltica (Middle and Lower Allochthon and Autochthon).

During Neoproterozoic to Cambrian pre-Caledonian divergent tectonics, massive to disseminated volcanosedimentary-hosted Zn-Pb±Cu and Cu-Zn sulphide deposits were formed in an Atlantic-type margin environment (Grenne et al., 1999). In the Shield, rift-type tholeiitic to carbonatitic magmatism gave rise to Nb, P and Fe mineralization in carbonatites of the Fen Complex. Late Cambrian epicontinental sedimentation deposited vast, but so far uneconomic resources of U, Mo, Ni and V in alum shales. Minor stratabound base metal sulphide and orthomagmatic Cr and Ni-Cu±PGE occur only in oceanic environments and continental margin and oceanic successions host many Cu-Zn sulphide ores in tholeiitic basalts. The earliest subduction-related sequences of major ore-forming importance are the Early Ordovician Stekenjokk-Fundsjö arc (ca. 490 Ma) and immature arc and ophiolitic assemblages formed between 500 and 480 Ma. In Early to Middle Ordovician times, magmatism gradually changed to a predominantly calc-alkaline character. Major granodiorites intruded the mature-arc sequences at an advanced stage of development (ca. 460 Ma), occasionally containing sub-economic vein- and stockwork-type Cu-Mo mineralisation. By the end of the Ordovician, obduction of the arc-and-arc-basin systems on to the edge of the Laurentian plate took place. Thick clastic sequences were intruded by rift-type, mainly tholeiitic to alkaline, magmas with Ni-Cu mineralization and stratabound sulphides associated with volcanic rocks. The final, collisional stage of the Caledonian orogeny (Scandian) is represented by MVT-type Pb-sandstone deposits and Au, Ag, Pb, Cu, Zn, Fe, As, Sb, W, Mo±U vein deposits (Grenne et al., 1999). Post-collisional magmatism is associated with a regional mineralization event in the western parts of the Uppermost Allochthon, characterised by polymetallic W-Mo-Au occurrences (Larsen, 1991; Grenne et al., 1999). Recent Re-Os dating of the Bjellåtinden W-Mo skarn has provided evidence of a long-lived mineralization stage from 430±5 to 401±3 Ma, i.e., beginning at Scandian peak metamorphism and continuing through lower-grade extensional shearing (Larsen and Stein, 2007). Also the Målvika W-Mo-Au and the Bindal Au-deposits (currently in test production) belong to this latest Caledonian mineralizing event.

Concluding remarks

The Fennoscandian Shield is one of the most intensely mineralized Paleoproterozoic areas in the world. Important ore deposit types include volcanogenic massive sulphide deposits, orogenic gold deposits, layered intrusions, intrusive hosted Cu-Au, apatite-Fe deposits, and anorthosite-hosted Ti deposits. Currently all these types of deposits are exploited and exploration expenditure is at an all time high level in 2007. Investment in exploration in the Fennoscandian Shield in 2007 will probably be close to 100 million euros. Besides the well documented deposit types, new kinds of deposits are being explored, e.g., iron oxide-copper-gold (IOCG) and shale-hosted Ni-Zn-Cu and different types of uranium deposits. Greenland is still a frontier area concerning mineral exploration and mining, however, present high activity of exploration is promising for the country. Two mines are in operation (gold and olivine) and feasibility studies are in progress for five deposits.

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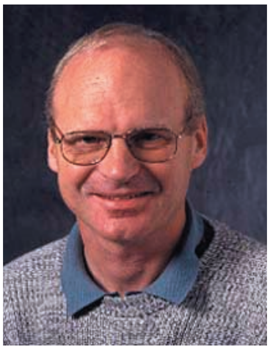

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Industrial minerals and rocks, aggregates and natural stones in the Nordic countries

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The Nordic countries, including Greenland, have a long tradition in mining. The industrial minerals sector is expanding in most Nordic countries and extensive development has taken place during the last few years. The main commodities mined are carbonate rocks, quartz, feldspar, apatite, olivine and talc.

A number of different types of dimension stones are quarried in all countries. Rock aggregates are increasingly important, replacing sand and gravel aggregate as construction materials in some countries due to the need to protect ground water supplies.

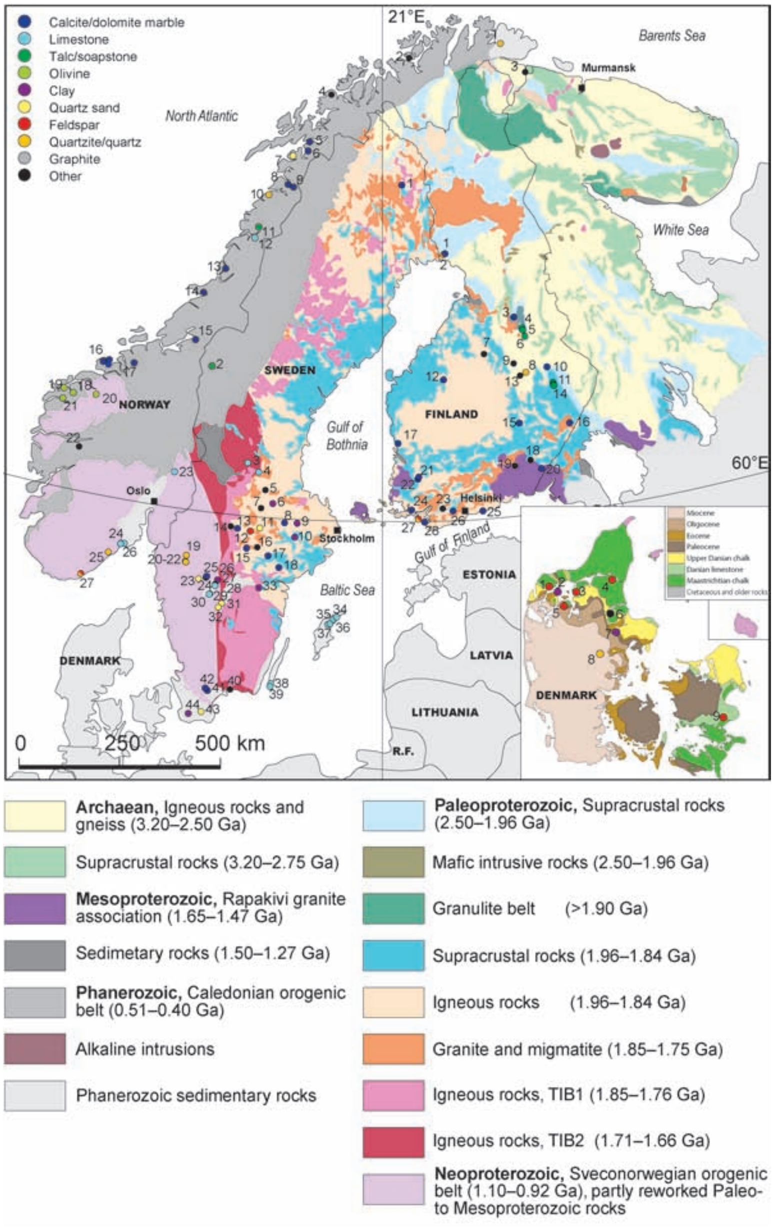

***Figure 1** Industrial mineral and rock mines and quarries of the Nordic countries. Geology from Lahtinen et al. (2005).*

Introduction

This paper presents a review of industrial minerals and rocks, aggregates and natural stones in the Nordic countries. Industrial minerals are mined in all Nordic countries (Figure 1 and Table 1). Major commodities include carbonate rocks, talc, olivine, apatite, quartz, feldspars and nepheline syenite, wollastonite, mica, clay, and diatomite. Today, the volume of the industrial mineral industry is increasing in all Nordic countries and extraction of industrial minerals is also expanding in Greenland (Figure 2).

Industrial rocks are rocks which, like quartzites used in ferrosilicon production or rocks in the stone wool manufacture, are used as such without any mineral processing. Natural stone is the oldest construction material and has been used by human beings since prehistoric times although modern quarrying, as we know it, started with the use of metal tools (Shadmon, 1996). Stone for architectural purposes in the Nordic countries was introduced with the Christianity, at around the year 1000 AD. The principal lithologies extracted are granite, gneiss, diabase/dolerite, schist, sandstone, quartzite, slate, marble, limestone and soapstone (Figure 3). The rock type names used by the stone industry are often different from normal geological nomenclature. Some of the Nordic stone varieties are well known and have become world brands (Nordic Stone, 2003). As natural stone is a durable, sustainable and often beautiful construction material, which can be fully recycled, its use has increased on a global scale.

The Nordic countries have vast resources of high-quality aggregates. Traditionally, in Finland, Norway and Sweden, the Quaternary deposits have been main source of supply. However, these resources are diminishing and the use of crushed bedrock has steadily increased. Thus, it has been decided in Sweden that, by 2010, gravel and sand will constitute only 12% of the aggregates. Furthermore, the use of recycled material is increasing. In Denmark marine sands are used, and in Iceland the young volcanic rocks. The Nordic countries, especially Norway, are exporting big volumes of high-quality crushed bedrock; these are much in demand in countries where soft sedimentary rocks dominate the bedrock, for example, in the North Sea and Baltic regions.

Industrial minerals

The Nordic countries have a very active industrial minerals industry (Table 1). The resources are described below by country, with most of the data from 2006.

Norway

Industrial mineral production in Norway had a turnover of USD 500 million in 2006 from 31 deposits throughout the country (Neeb and Brugmans, 2007). By comparison, the production of metals had

Table 1 Industrial minerals and rocks deposits in the Nordic countries (incl. Greenland). Numbers corresponds to deposit numbers in Figure 1 for Denmark, Finland, Norway and Sweden.

Denmark	
1. Thisted	Limestone
2. Mors and Fur	Diatomite
3. Løgstør	Chalk and limestone
4. Ålborg	Chalk
5. Batum, N Salling	Chalk
6. Mariager	Salt
7. Ølst, Randers	Clay
8. Silkeborg	Quartz sand
9. Faxe	Limestone
Finland	
1. Kalkkimaa	Dolomite marble
2. Ristimaa	Quartz (from quartzite)
3. Reetinniemi	Dolomite marble
4. Lahnaslampi	Talc (from soapstone)
5. Punasuo	Talc (from soapstone)
6. Uutela	Talc (from soapstone)
7. Pyhäsalmi	Pyrite (Sulphur)
8. Kinahmi	Quartz (from quartzite)
9. Joutsenenlampi	Ind. rock (Anorthosite)
10. Matara	Dolomite marble
11. Pehmytkivi	Talc (from soapstone)
12. Ryytimaa, Vesterbacka	Dolomite marble
13. Siilinjärvi	Apatite, mica, carbonates
14. Horsmanaho	Talc (from soapstone)
15. Ankele	Dolomite marble
16. Ruokojärvi	Calcite and Dolomite marble
17. Otamo	Dolomite marble
18. Vanhasuo	Ind. rock (Gabbro)
19. Lehlampi	Ind. rock (Olivine rock)
20. Ihalainen	Calcite marble, wollastonite
21. Punola	Dolomite and calcite marble
22. Matkusjoki	Dolomite and calcite marble
23. Sallittu	Ind. rock (Peridotite)
24. Skräbböle-Limberg	Calcite marble
25. Kalkkiranta	Calcite and Dolomite marble
26. Tytyri	Calcite marble
27. Ala-Aulis, Kyrkoberget	Feldspar, quartz
28. Förby	Calcite marble
Iceland	
1. Myvattn	Diatomite
Norway	
1. Tana	Ind. rock (Quartzite)
2. Stjernøy	Nepheline syenite
3. Bjornevann	Ind. rock
4. Skaland	Graphite
5. Hekkelstrand	Dolomite marble
6. Kjøpsvik	Calcite marble
7. Drag	Quartz
8. Hammerfall	Dolomite marble
9. Løgavelen	Dolomite marble
10. Mårnes	Ind. rock (Quartzite)
11. Altermark	Talc (from soapstone)
12. Seljeli	Dolomite marble
13. Velfjord	Calcite marble
14. Hestvika	Calcite marble
15. Verdal	Calcite marble
16. Fræna/Eide	Calcite marble
17. Glærum	Calcite marble
18. Steinsvik	Olivine
19. Åheim	Olivine
20. Stranda	Olivine
21. Lefdal	Olivine
22. Gudvangen	Ind. rock (Anorthosite)
23. Hamar	Limestone
24. Skien	Limestone
25. Kragerø	Ind. rock (Quartzite)
26. Bjørntvedt,Dalen	Limestone
27. Glamsland	Feldspar, quartz
Sweden	
1. Masugnsbyn	Dolomite marble
2. Bunnerviken	Talc
3. Kallholn	Calcitic marble
4. Jutjärns kalkbrott	Calcitic marble
5. Falu koppargruva	Iron ockre
6. Hamre (Bältarbo)	Clay
7. Styggberget	Other
8. Tistbrottet	Dolomite
9. Vittinge (Gillberga)	Other
10. Wappa	Clay
11. Broby	Quartz sand
12. N. Allmänningbo	Feldspar
13. Fanthyttan	Dolomite marble
14. Grythyttan	Ind. rock/natural stone (Slate)
15. Gåsgruvan	Calcitic marble
16. Latorp	Other
17. Björka	Dolomite
18. Forsby	Calcitic marble
19. Flåtungebyn	Ind. rock (Quartzite)
20. Ulerud	Ind. rock (Quartzite)
21. Kilane	Ind. rock (Quartzite)
22. Kilane	Ind. rock (Quartzite)
23. Råda	Quartz sand
24. Arnemossen	Other
25. Österplana	Calcitic marble
26. Horn	Clay
27. Billingsryd	Ind. rock (Diabase)
28. Våmb	Limestone
29. Berga	Limestone
30. Uddagården	Limestone
31. Baskarp	Quartz sand
32. Brogården	Quartz sand
33. Gärstad	Clay
34. Stucks	Limestone
35. Stora Vikers	Limestone
36. Västra brottet	Limestone
37. Rings i Hejnum	Limestone
38. Albrunna	Limestone
39. Ventlinge	Limestone
40. Sternö	Ind. rock (Diabase)
41. Ullstorp	Limestone
42. Ignaberga	Limestone
43. Fuglunda	Quartz sand
44. Böringekloster	Clay
Greenland	
1. Qaqqaarsuk	Phosphorus
2. Sarfartoq	Phosphorus
3. Seqi	Olivine

a turnover of USD 200 million from two operations. Economically, calcite-products from marble deposits comprise by far the highest production value (USD 320 mill.). This is followed, in decreasing order of value, by olivine, nepheline syenite, quartzite, talc, dolomite, feldspar and anorthosite. High purity quartz and graphite are examples of small, but growing products of strategic niche commodities (Neeb and Bruggans, 2007).

Most of the calcite is produced from Ordovician amphibolite-facies marbles situated in the Upper- and Uppermost Allochthons of the Scandinavian Caledonides. Ophiolitic mantle fragments in the Uppermost Allochthon also host the only operating talc deposit (Altermark). In addition, large talc resources have recently been documented in mantle fragments of the Upper Allochthon (Raudfjellet, Linnajavri). Olivine is chiefly produced from ultramafic intrusions emplaced in granulite-facies gneisses of the Western Gneiss Region (South Norway).

Granitic pegmatite comprises the most important resource of ceramic-grade quartz and feldspar in Norway. Quartz, sodium and potassium feldspars are produced from the Neoproterozoic Glamsland pegmatite in South Norway, and high-purity quartz from the Mesoproterozoic Drag pegmatite (Northern Norway). This type of quartz comprises less than 40 g/ton impurities; hence it may obtain world market prices beyond 1,000 USD/ton. Many of the Norwegian pegmatite occurrences, together with some hydrothermal dykes, comprise large resources of high-purity quartz (Larsen et al., 2004; Ihlen et al., 2004), in places matching the quality produced at Spruce Pine in USA, the largest high-purity quartz producer in the world. Potentially another emerging mineral resource is rutile in eclogitised oceanic lithosphere belonging to the Upper Allochthon. The Engebøfjellet rutile deposit (western Norway) is at an advanced stage of a feasibility study and comprises 386,000 Mt with 3.96 % rutile. It is aimed for the TiO_2 pigment market and as a raw material for the production of Ti metal. Traditionally, rutile is produced from ilmenite or leucoxene from beach placers, whereas the idea with the Engebø project is, for first time ever, to produce rutile directly by crushing and processing of a solid rock.

Finland

Industrial minerals and rocks were mined from 34 mines and quarries in 2006. These, excluding the natural stones, accounted for 24.4 Mt of mined rock and 80% (16.0 Mt) of all ore mining during that year. Crystalline limestones have been utilized by industry in Finland for well over 100 years, beginning with lime production and later the production of cement, fillers, and paper pigments. Large good-quality limestone deposits exist at Lappeenranta, Parainen (Pargas), Lohja and Kerimäki. Altogether, 4.28 Mt of carbonate rocks were mined from 17 mines and quarries (data from Ministry of Trade and Industry), as shown in Figure 1 and Table 1. Geologically, all of these Finnish carbonates are Paleoproterozoic (ca. 1.9 to 2.0 Ga) calcite and dolomite marbles.

In 2006, total quicklime production was about 710,000 tonnes, which is largely based on imported limestones, burned in Finland. The total cement production at Parainen and Lappeenranta was about 1.68 Mt. Dolomites and dolomite-bearing limestones, ~657,000 tonnes, were used for agricultural purposes. The large domestic paper and paperboard industry utilized about 3.3 Mt (dry) of pigment minerals. Of these, nearly 30 % derived from the bedrock of Finland. The "domesticity order" of these minerals was: talc and gypsum (100%), calcium carbonates combined (about 34 %), kaolin and TiO_2 (0%). Slightly more than a half of the 1.2 Mt (dry) of ground calcite (GCC) used by the domestic paper industry, was produced at Lappeenranta and Förby, both floating and micro-grinding domestic calcite marbles, whereas all production of precipitated $CaCO_3$ (PCC) in Finland (about 480,000 tonnes) was based on imported quicklime and limestone.

In 2006, there were 12 other open pit mines/quarries in operation for industrial minerals that produced ca. 11.46 Mt of ore (apatite, talc, quartz, feldspar, mica). By far the largest industrial minerals mine in Finland is hosted by the Archean (2609 Ma) Siilinjärvi carbonatite. This produced 9.81 Mt of apatite ore, from which 860,000 tonnes of apatite concentrate were recovered as the main product for fertilizer production. In addition, carbonate based by-products (135,000 tonnes) for other agricultural and environmental uses and mica concentrate (8,100 tonnes) and gypsum (103,000 tonnes) for pigment and other end uses, were also produced. Another resource of phosphorus (the Sokli deposit) is located in NE Lapland in a large regolith, which was formed by weathering of the surface parts of a Devonian (ca. 365 Ma) carbonatite.

Finland is the biggest talc producer in Europe; globally the fourth largest. Altogether, in 2006, 1.27 Mt of talc ore were mined from 5 open pit soapstone and talc schist deposits in East Finland. These soapstones are interpreted to be part of metamorphosed ophiolites, ca. 1.95–1.97 Ga in age.

Quartz and feldspar ores (ca. 337,500 tonnes) were mined in eastern and southwestern Finland, at Nilsiä and Kemiö (Kimito), respectively. Feldspar is also produced from the Lapinlahti anorthosite. Production of feldspar amounted to 56,000 tonnes and quartz production to 169,300 tonnes. The quartz deposits are mainly ca. 2000 Ma quartzites, but include by-product quartz from the island of Kemiö where the feldspar deposits include pegmatites and pegmatitic granite (1810–1830 Ma).

Other Finnish industrial minerals include wollastonite (16,200 tonnes concentrate), produced as a by-product of calcite flotation at Lappeenranta Globally, Finland is the fifth largest producer of wollastonite. Stone wool at Parainen, Oulu and Lappeenranta use anorthosite, gabbro, amphibolite, and diabase, and imported dolomite. The production of pyrite concentrate from Pyhäsalmi mine, mainly used for domestic sulphuric acid production, was 512,000 tonnes in 2006.

The main focus of the Geological Survey of Finland (GTK) in industrial minerals exploration, at present, is on a 500 km^2, Li pegmatite province in Ullava-Kaustinen area of western Finland. At Länttä (Ullava), the start-up of mining spodumene ore is planned for the autumn 2008, as is the production of $LiCO_3$ and by-products at Kaustinen. Towards the south from this Li province, at Kälviä and Halsua, GTK has previously explored and evaluated some ilmenite deposits, classified as mafic (gabbro or gabbronorite) intrusion-hosted magmatic titanium ores (Sarapää et al., 2001). For additional information on the industrial minerals and rocks of Finland, see Lehtinen (2006), and Pihl and Lehtinen (2007).

Sweden

In Sweden, the total production of industrial minerals was 10.9 Mt (excluding dimension stone) from 44 open pits in 2006. By far, the largest production was of carbonates (limestone, dolomite, marble) which contributed 9.7 Mt or c. 90% of the total production. Carbonates are quarried both from Paleoproterozoic limestone and dolomite marbles in Masungnsbyn, Tistbrottet, Fanthyttan, Gåsgruvan (underground) and Björka and from the younger Ordovician-Silurian limestones in Dalarna, Västergötland, Gotland, Öland and Cretaceous chalk and limestones in Skåne (Figure 1). The products are used as fillers, insulation, agriculture and water treatment and are burnt for the iron and steel industry.

The second most important industrial mineral produced in Sweden is quartzite and quartz sand, with a production of approximately 850,000 tonnes in 2006 (SGU, 2007). These are mainly produced from Paleoproterozoic and Mesoproterozoic quartzites in Bergslagen (Broby) and Dalsland (Flåtungebyn, Uleryd och Kilarne). Quartz sands are also produced from Phanerozoic sandstones in Västra Götaland (Baskarp, Brogården) and Scania (Fuglunda). The quartzite is used mainly in metallurgical, mechanical, chemical and refactory industries (Wik, 2002). Of the quartz sands, 50% are used in foundries, 30% as filters and 10–15% for concrete and some in sanitary ceramics (Wik, 2002).

Paleoproterozoic crushed schists are produced at Grythyttan in Bergslagen and diabase is mined for stone wool production in both Västra Götaland and Blekinge. The only feldspar production reported in 2006 was from Forshammar in Bergslagen. Talc and soapstone were mined in the Handöl quarry in the Caledonides of western Jämtland. Ground talc is used as a filler in roofing and soapstone is produced as block stone for interior fireplaces and heat-resistant cooking plates (Wik, 2002). The famous Swedish red ochre, used as pigment in the red paint from Falun, is still produced. This paint is used widely in Sweden and is seen in the characteristic red colour on many countryside wooden buildings throughout the country.

Denmark

The geology of Denmark is largely composed of sedimentary rocks of late Cretaceous to Neogene age, dominated by the Danian Limestone in the east and the Miocene deltaic sediments in the west. These are overlain by an extensive cover of Quaternary sediments, varying in thickness from a few to more than 200 m, mainly deposited during the glacial periods from 300,000 to 15,000 years ago. No underground mining is taking place in Denmark, except for the solution mining of salt from the Hvornum diapir at Mariager; this is the only salt mining in Scandinavia, with a yearly production of 600,000 tons. Figure 1 shows the location of occurrences. More information on production statistics can be found in Miljø og Energi (2006).

The exploitation of chalk and limestone amounts to 2.3 Mm^3, and the main part is used for the cement production located in Ålborg (Portland), northern Denmark. In eastern Denmark, the Danian limestone is excavated at Faxe for paper filling and the remaining chalk production is used for agricultural fertilization and in minor specialised industrial applications.

Plastic clay, exploited in the central part of east Jutland, is used for clinker. The production varies a lot and was, in 2005, about 330,000 m^3. It is foreseen that an additional need for bentonite will increase the exploitation of Palaeogene clays in the coming years. Clayey diatomite from ash layers in the Eocene Fur Formation form the basis for the production of cat litter granulate and insulation bricks on Mors and Fur in the Limfjorden region. The production is very stable with an average consumption of 225,000 m^3 moclay (moler, clayey diatomite).

During the last five years, the exploitation of quartz sand has increased to more than the twice the earlier production, to an average of 500,000 m^3 per year. The Miocene quartz sand was deposited in a coastal environment, which 10–15 million years ago was situated in the central part of Jutland. The sand is very pure, without flint and limestone, and with less than 1% heavy minerals. The main application is as filter sand and in high quality concrete. Furthermore, it is used for casting sand and for sports fields.

Sand and gravel from Pleistocene outwash-plain settings are excavated all over Denmark. In the western part of the country, they are obtained from glaciofluvial settings of Saalian age (300,000 years B.P.), with the source of the sediments located in southern Norway. In eastern Denmark, the glaciofluvial settings are mainly of Weichselian age (25,000 years B.P), with the source related to the ice advance in central Sweden and the Baltic Sea. In 1982 and 1993, the production was at a minimum of ca. 20 Mm^3, but in 1987, 1999 and at present the production amounts to 30 Mm^3.

The production of brick clay has for the last 20 years remained relatively constant at 700,000 m^3 per year. The exploitation is concentrated to a few glaciolacustrine settings of late Weichselian age, which are mainly regarded as ice-dammed lakes.

Greenland

A large, homogeneous resource of industrial olivine is in production at the Seqi deposit in West Greenland and mining occurred in the past century at the Ivittuut cryolite deposit, and the Amitsoq graphite mine. Greenland also has a good potential for phosphorous. Figure 2 shows the location of major deposits.

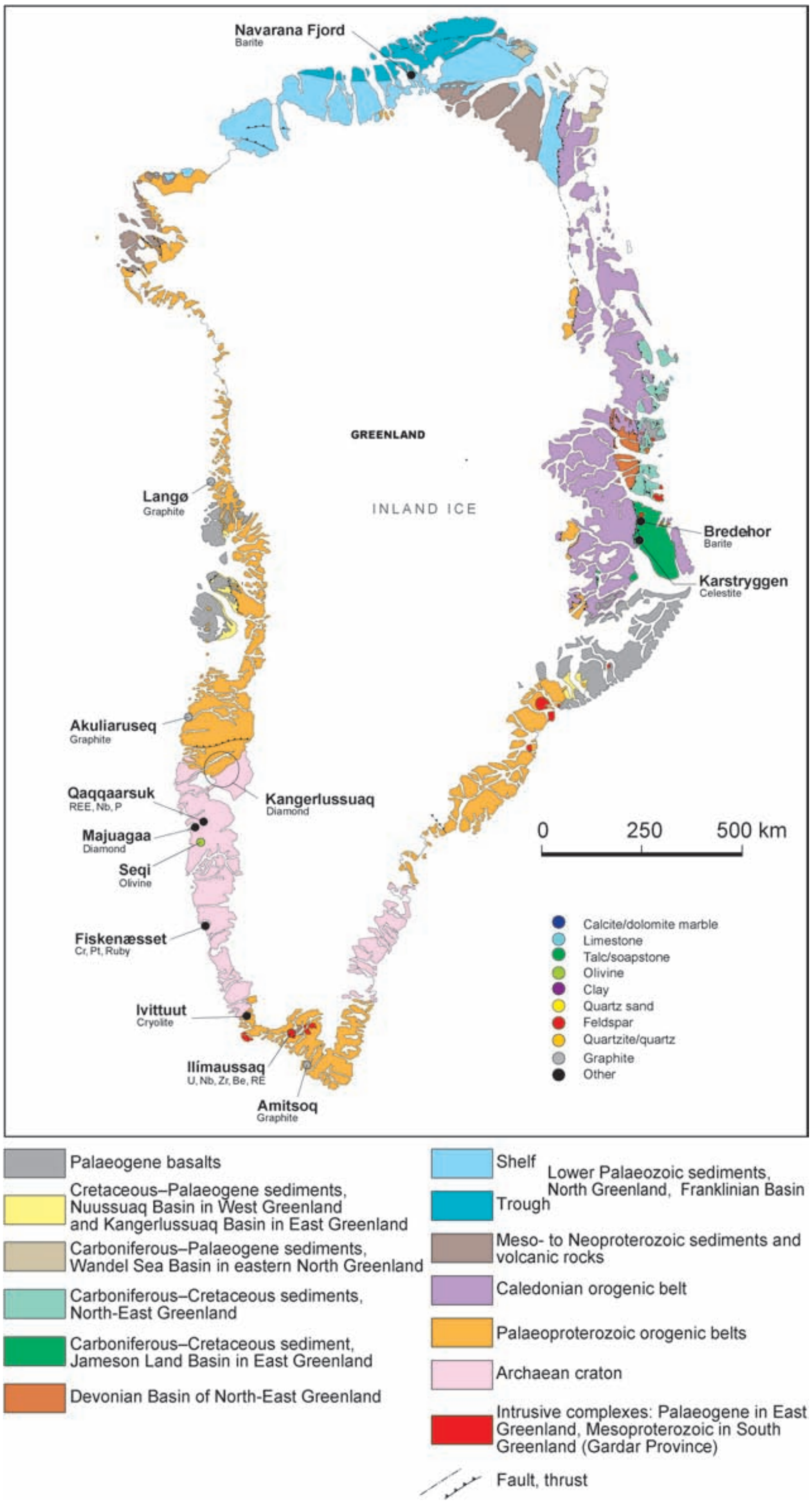

***Figure 2** Industrial mineral deposits of Greenland. Geology and deposits from Minex, Greenland mineral exploration letter 30 (2007).*

Iceland

Iceland has few identified mineral resources, although deposits of diatomite (Kuo, 2003) and hydrothermal silica are mined at Lake Myvatn, northern Iceland. In 2005, over 30,000 tonnes of diatomite and 120,000 tonnes of ferrosilicon were produced.

Aggregates and natural stones

The distribution of resources naturally reflects the geology. Natural stones quarried in Finland (mainly granites and soapstones) range from Proterozoic to Archean in age, whereas in Sweden and Norway (various rocks) the ages are from Proterozoic to Palaeozoic. In Denmark, natural stone (granites) is quarried on the island of Bornholm, south of Sweden in the Baltic Sea. On Iceland, the young volcanic rocks are used. Figure 3 shows the location of major deposits of natural stone in the Nordic countries.

For 2006, 57 quarries reported information about production (delivery) of dimension stone in Sweden. The main rock types are marble and limestone (64,000 tonnes), granite (318,000 tonnes), gneiss (212,000 tonnes), and diabase and gabbro (259,000 tonnes). The total production amounted 886,000 tonnes (SGU, 2007b). The aggregate production in Sweden in 2006 amounted approximately to 92 Mt, of which 20 Mt came from gravel and sand (SGU, 2007b). The total production has slightly increased since 2003, owing to increased infrastructure building; at the same time, there has been a decrease in the production of gravel and sand. In Norway, the 2005 production was 53 Mt of which 12 Mt tonnes (mostly crushed bedrock) was exported (Erichsen et al., in press).

Bedrock investigations are performed in Sweden in order to evaluate the bedrock resources. Bedrock quality is investigated by the Geological Survey of Sweden (SGU); they provide information for the construction industry about such characteristics as are relevant for construction material and for planning tunnels and other underground works. The latter has prompted the development of 3D bedrock models, providing geological and geotechnical information for underground excavations e.g., tunnels and caverns in Sweden, especially in the Stockholm metropolitan region (Persson, 2002).

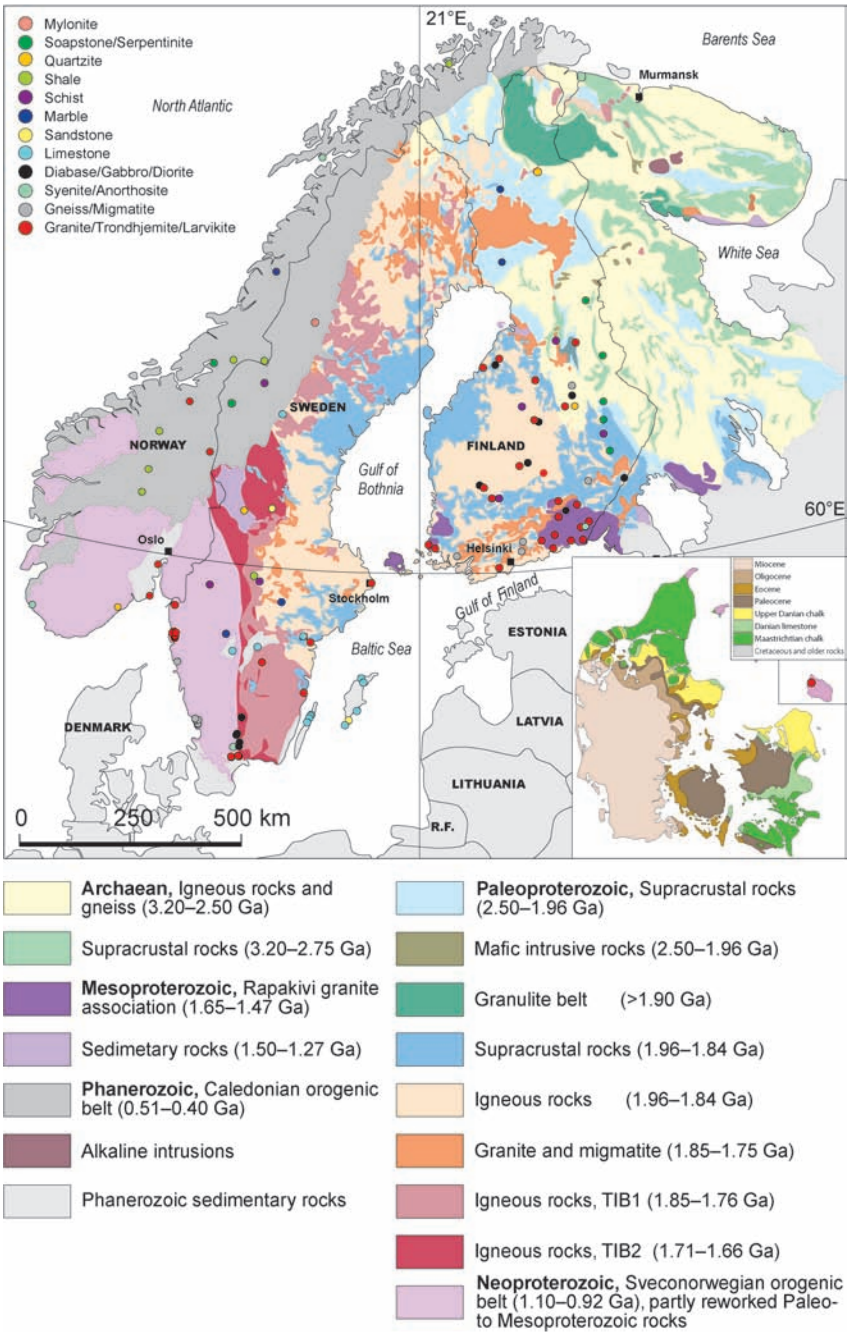

***Figure 3** Most important natural stone quarrying areas in the Nordic countries. Geology from Lahtinen et al. (2005).*

In terms of production, aggregates are the largest extractive industry in Finland, the total amount used annually being 95 Mt. Due to groundwater protection and reduced resources, the use of alluvial and fluvial aggregates is decreasing and other sources are needed. According to Rintala (2007), the potential use of rock aggregates has increased 35% since 1995, but glaciofluvial material still makes up over 60% of the total production. Presently, there are about 3500 active quarries in Finland, but the number of small quarries will probably decrease due to increasing need of high quality aggregates, and the introduction of standardised testing and productivity requirements.

In high latitudes, the cold climate places particular demands on the quality of the aggregates. Cars use studded tyres during winter to obtain more traction on the icy road surfaces and, therefore, asphalt aggregates need to have good resistance to abrasive wear. Frost may reach to a depth of 2.5 m, which affects the material choices in all layers of road construction. The quality requirements of an aggregate, which are based on the rock texture and modal composition, depend on how it will be used. For example, high-quality asphalt aggregates will not necessarily be appropriate in concrete or for gravel-road maintenance.

The Geological Survey of Finland has mapped ca. 24,000 sand and gravel deposits since 1970s in order to define both the quality and quantity of the country's aggregates and groundwater reserves. Inventories of rock aggregate outcrops have been made since 1989 (Härmä et al., 2006). This inventory has shown that less than 1% of the bedrock outcrops studied met the highest quality requirements, yielding aggregates suitable for motorway surfaces. The best rock types for this purpose are fine-grained felsic and intermediate metavolcanic rocks in which mineral grains are tightly interlocked, as well as strongly deformed plutonic rocks that have tonalitic and granodioritic composition. Lower quality aggregates can be produced from medium- and coarse-grained granitic rocks and gneisses containing abundant mica minerals. However, these aggregates are suitable for most common end-use applications. High-quality rocks are located mainly in the schist belts and their aggregates should be used only for applications where they are essential, because demand for such material will increase as reserves decrease. Knowledge of the distribution and quality variations of rock aggregates (Härmä et al., 2006) is becoming increasingly important.

Traditionally, the Finnish stone industry has been firmly based on the quarrying and processing of granites. The annual production is about 900,000 tonnes, of which granites account for 700,000 tonnes. Several worldwide famous commercial granite types (e.g., Baltic Brown, Carmen Red, Balmoral Red), from the Mesoproterozoic rapakivi granites (Figure 3), are quarried in the SE and SW Finland. A speciality of today's Finnish natural stone industry is the advanced production of soapstone products that represents approximately 50% of the total stone industry turnover (200 million euros). In 2006, soapstone was quarried from 4 Archean deposits in E Finland for oven and other fireplace manufacturing. The total output of usable soapstone was ca. 185,000 tonnes, of which 50,300 tonnes of soapstone products were manufactured (data from MTI). Altogether about 384,000 tonnes of natural stones, worth about 100 million euros, were exported from Finland in 2006, of which 66 million euros were from soapstone products. The main export countries of Finnish natural stones are Germany, China, Italy, Spain, Sweden, Belgium and Poland. Small quantities of natural stones are also imported, amounting to 13.8 million euros in 2006. The most important import countries were China, Norway, Portugal, Italy and Sweden (*http://www.nordicstones.org/finnish_natural_stone_associ.htm*, Leino, 2007).

Denmark has an aggregates industry which supports the domestic demand of sand and gravel (produced both onshore and offshore). The production of gneiss and granite aggregates from the Danish island of Bornholm varies a lot depending on the demand for new traffic constructions. The Øresund connection between southern Sweden and Copenhagen has been the most recent major aggregate consuming project. During its construction the annual production of granite from Bornholm amounted 400,000 m^3, but recently production has decreased to about 190,000 m^3. For protection of the coastal areas and the construction of harbour piers, sand and gravel are exploited from the sea-bed surrounding Denmark. This production varies a lot depending on the constructional activities, but in general it amounts to 6 Mm^3.

On Iceland, pumice, scoria, sand and crushed basalt are mined with a total production of 105,000 tonnes in 2005 (Kuo, 2003).

Concluding remarks

The non-metallic extractive industry in the Nordic countries is indeed an expanding industry with extensive development especially within the industrial minerals sector during the last few years. The main commodities mined today include carbonate rocks, quartz, feldspar, apatite, olivine and talc. Crushed rocks are to a large extent replacing sand and gravel as construction materials in Finland, Norway and Sweden due to the need to protect ground water supplies. The natural stone industry is diverse and includes some world famous commercial granite types quarried from Rapakivi intrusions in Finland and anorthosites (Larvikite) from southern Norway.

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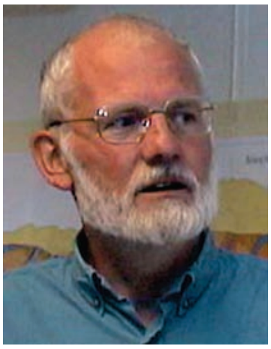

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Characteristics, development and utilization of geothermal resources – a Nordic perspective

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Geothermal energy is classified as a renewable energy source and it utilizes the heat generated in the earth primarily from the natural radioactive decay of isotopes of uranium, thorium and potassium. Heat is extracted from the earth to generate geothermal energy via a carrier, usually water occurring either in the liquid or steam phase. In the late 19th century and the early 20th century, the first developments of geothermal resources for power generation and household heating got underway successfully. Many of these geothermal fields are still being utilized today, proving their sustainability. Today geothermal energy is being utilized in more than 72 countries around the world and of the Nordic countries Iceland and Sweden have been in the forefront in each of their respective fields. While geothermal heat pumps are widely used for space heating in Sweden, geothermal energy covers 55% of the primary energy consumption in Iceland where it is used for space heating, power generation and industrial purposes. Future developments aim at expanding the range of viable geothermal resources by improving the capabilities to generate electricity from geothermal resources at temperatures as low as 100°C, as well as developing geothermal resources where water needs to be introduced, so-called hot dry rock resources. But the biggest expansion is expected to continue to be in the installations of geothermal heat pumps.

Introduction

Early humans probably used geothermal water that occurred in natural pools and hot springs for cooking, bathing and to keep warm. We have archeological evidence that the Indians of the Americas occupied sites around these geothermal resources for over 10,000 years to recuperate from battle and take refuge. Many of their oral legends describe these places and other volcanic phenomena. Recorded history shows uses by Romans, Japanese, Turks, Icelanders, Central Europeans and the Maori of New Zealand for bathing, cooking and space heating. Baths in the Roman Empire, the middle kingdom of the Chinese, and the Turkish baths of the Ottomans were some of the early uses of balneology, where body health, hygiene and discussions were the social custom of the day. This custom has been extended to geothermal spas in Japan, Germany, Iceland, and countries of the former Austro-Hungarian Empire, the Americas and New Zealand. Early industrial applications include chemical extraction from the natural manifestations of steam, pools and mineral deposits in the Larderello region of Italy, with boric acid being extracted commercially starting in the early 1800s. At Chaudes-Aigues in the heart of France, the world's first geothermal district heating system was started in the 14th century and is still in use. The oldest geothermal district heating project in the United States is on Warm Springs Avenue in Boise, Idaho, which came on line in 1892 and continues to provide space heating for up to 450 homes.

The first use of geothermal energy for electric power production was in Italy with experimental work by Prince Gionori Conti between 1904 and 1905. The first commercial power plant (250 kWe) was commissioned in 1913 at Larderello, Italy. An experimental plant was installed in The Geysers in 1932 and provided power to the local resort. These developments were followed in New Zealand at Wairakei in 1958; an experimental plant at Pathe, Mexico in 1959; and the first commercial plant at The Geysers in the United States in 1960. Japan followed with 23 MWe at Matsukawa in 1966. All of these early plants used steam directly from the earth (dry steam fields), except for New Zealand, which was the first to use flashed or separated steam for running the turbines. The former USSR produced power from the first true binary power plant, 680 kWe using 81°C water at Paratunka on the Kamchatka peninsula—the lowest temperature at that time. Iceland first produced power at Namafjall in the northern part of the country, from a 3 MWe non-condensing turbine. These were followed by plants in El Salvador, China, Indonesia, Kenya, Turkey, Philippines, Portugal (Azores), Greece and Nicaragua in the 1970s and 1980s. Later plants were installed in Thailand, Argentina, Taiwan, Australia, Costa Rica, Austria, Guatemala, Ethiopia, with the latest installations in Germany and Papua New Guinea. (See Cataladi, et al., 1999 for more background on the historical uses of geothermal energy.)

Types of geothermal resources

Geothermal energy comes from the natural heat of the earth primarily due to the decay of the naturally radioactive isotopes of uranium, thorium and potassium. Because of the internal heat, the Earth's surface heat flow averages 82 mW/m^2 which amounts to a total heat loss of about 42 million megawatts. The estimated total thermal energy above mean surface temperature to a depth of 10 km is 1.3×10^{27} J, equivalent to burning 3.0×10^{17} barrels of oil. Since the global energy consumptions for all types of energy are equivalent to use of about 100 million barrels of oil per day, the Earth's energy to a depth of 10 kilometers could theoretically supply all of mankind's energy needs for six million years (Wright, 1998).

On average, the temperature of the Earth increases with depth at about 30°C/km. Thus, assuming a conductive gradient and mean surface ambient temperature, the temperature of the earth at 10 km would be over 300°C. However, most geothermal exploration and use occurs where the gradient is higher, and thus where drilling is shallower and less costly. These shallow depth geothermal resources occur due to: (1) intrusion of molten rock (magma) from depth, convecting great quantities of heat upwards; (2) high surface heat flow, due to a thin crust and high temperature gradient; (3) ascent of groundwater that has circulated to depths of several kilometers and been heated due to the normal temperature gradient; (4) thermal blanketing or insulation of deep rocks by thick formation of rocks such as shale whose thermal conductivity is low; and (5) anomalous heating of shallow rock by decay of radioactive elements, perhaps augmented by thermal blanketing (Wright, 1998).

Geothermal resources are usually classified as shown in Table 1, modeled after White and Williams (1975). These geothermal resources range from the mean annual ambient temperature of around 20°C to over 300°C. In general, resources above 150°C are used for electric power generation, although power has recently been generated at Chena Hot Springs Resort in Alaska using a 74°C geothermal resource (Lund, 2006). Resources below 150°C are usually used in direct-use projects for heating and cooling. Ambient temperatures in the 5 to 30°C range can be used with geothermal (ground-source) heat pumps to provide both heating and cooling.

Table 1 Geothermal resource types (°C).

Resource Type		Temperature Range (°C)
Convective hydrothermal resources	Vapor dominated	≈240°
	Hot-water dominated	20 to 350°+
Other hydrothermal resources	Sedimentary basin	20 to 150°
	Geopressured	90 to 200°
	Radiogenic	30 to 150°
Hot rock resources	Solidified (hot dry rock)	90 to 650°
	Part still molten (magma)	>600°

Worldwide utilization of geothermal energy

The utilization of geothermal energy resources falls into two categories, energy for electric power generation and direct-use, where space heating is the principal constituent of the latter. The latest numbers based on reports at the World Geothermal Congress in 2005 (WGC2005) show that geothermal energy is currently used in 72 countries (Lund, et al., 2005; Bertani, 2005 and 2007). In Table 2 and 3 the figures of worldwide and regional geothermal electric and direct-use capacity is presented. Further details of the present installed electric power capacity and generation, and direct-use of geothermal energy can be found in Bertani (2005, 2007), and Lund, Freeston and Boyd (2005).

Table 2 Total geothermal use in 2005 (based on reports at the World Geothermal Congress 2005 and Bertani, 2007).

Use	Installed Power (MW)	Annual Energy Use (GWh/yr)(est.)	Capacity Factor	Countries Reporting
Electric Power	9,732	61,865	0.73	24
Direct-Use	28,268	75,943	0.31	72

Table 3 Summary of regional geothermal use in 2005.

Region	Electric Power		Direct-use	
	%MWe	%GWh/yr	%MWt	%GWh/yr
Africa	1.5	1.9	0.7	1.1
Americas	43.9	47.0	32.3	16.7
Asia	37.2	33.8	20.9	29.4
Europe	12.4	12.4	44.6	49.0
Oceania	5.0	4.9	1.5	3.8

Electric power generation

Geothermal power is generated by using steam or a secondary working vapor to turn a turbine-generator set to produce electricity. A vapor dominated (dry steam) resource can be used directly, whereas a hot water resource needs to be flashed by reducing the pressure to produce steam. In the case of a low temperature resource, generally below 150°C, the use of a secondary low boiling point fluid (hydrocarbon or water-ammonia mixture) is required to generate the vapor, in a binary or organic Rankin cycle (ORC) plant. Usually a wet or dry cooling tower is used to condense the vapor after it leaves the turbine to maximize the temperature drop between the incoming and outgoing vapor and thus increase the efficiency of the operation.

Currently electric power is being produced from geothermal energy in 24 countries over the world with the leading ones shown in Table 4 (Bertani, 2005 and 2007). Since 2000, the installed capacity in the world has increased by almost 1,000 MWe. This increase has been generated partly through installation of new plants as well as through a reinjection project to invigorate The Geysers field in northern California. One of the more significant aspects of geothermal power development is the size of its contribution to national and regional capacity and production of countries. The following countries or regions lead in this contribution with more than 5% of the electrical energy supplied by geothermal power based on data from WGC2005 and is shown in Table 5 (Bertani, 2005).

Table 4 Leading countries in electric power generation from geothermal energy (>100 MWe)(Bertani, 2005 and 2007).

Country	Installed Capacity MWe	Running Capacity MWe	Annual Energy Produced GWh/yr (est.)	Running Capacity Factor	Number Units of Operating
United States	2687	1935	16,200	0.95	209
Philippines	1970	1856	9,340	0.57	57
Indonesia	992	992	7,200	0.83	15
Mexico	953	953	6,280	0.75	36
Italy	811	711	5,430	0.87	32
Japan	535	530	3,470	0.75	19
New Zealand	472	373	2,570	0.79	33
Iceland	421	421	3,090	0.84	19
El Salvador	204	189	1,540	0.93	5
Costa Rica	163	163	1,150	0.80	5
Kenya	129	129	1,090	0.96	9

Table 5 National and regional geothermal power contributions.

Country or region	% of National or Regional Capacity (MWe)	% of National or Regional Energy (GWh/yr)
Tibet, China	30.0	30.0
San Miguel Island, Azores, Portugal	25.0	n/a
Tuscany, Italy	25.0	25.0
El Salvador	14.0	24.0
Iceland	13.7	16.6
Philippines	12.7	19.1
Nicaragua	11.2	9.8
Kenya	11.2	19.2
Lihir Island, Papua New Guinea	10.9	n/a
Guadeloupe (Caribbean)	9.0	9.0
Costa Rica	8.4	15.0
New Zealand	5.5	7.1

Since 2000, additional plants have been installed in Costa Rica, France on Guadeloupe in the Caribbean, Iceland, Indonesia, Kenya, Mexico, and Philippines. In 2004 Germany installed a 210 kWe binary plant at Neustadt Glewe and a 6 MWe plant has been installed on Papua New Guinea to generate electricity for the remote Lihir mine. Russia has completed a new 50 MWe plant at Kamchatka. More recently, a 200 kW binary plant using 74°C geothermal water and 4°C cooling water was installed at Chena Hot Springs Resort in Alaska (Lund, 2006).

Electric power generation from geothermal energy in the Nordic countries

Iceland

Iceland is located on the Mid-Atlantic Ridge, which transects the country from southwest to northeast along an active volcanic rift zone, where many high-temperature fields (>200°C at 1 km) are located. Iceland is therefore currently the only Nordic country where geothermal energy can be used to generate electricity. Electricity is generated from six power plants located on central volcanoes and systems within the active volcanic zone of Iceland (Figure 1). The first geothermal power plant in Iceland, a 3 MWe back pressure unit, was installed at Bjarnaflag on the Namafjall field in northern Iceland, and was put into production in 1969. In 1977, another two power plants were put into production, at Krafla and Svartsengi. At the Krafla central volcano in northern Iceland the National Power Company (Landsvirkjun) is operating a power plant with two 30 MWe double-flash condensing turbines (Ragnarsson, 2005). Electricity is produced from three well-fields in the Krafla geothermal system with temperatures of up to 320–350°C. The Svartsengi co-generation power plant is located on the Reykjanes peninsula. The plant utilizes geothermal brines at 240°C with a salinity two-thirds that of seawater. The power plant is owned by Sudurnes Regional Heating and has gradually been enlarged over the years so that currently the installed capacity is 200 MWt for hot water production and 45 MWe for power generation. Sudurnes Regional Heating commenced generating power in the new Reykjanes power plant in 2006. The power plant has an installed capacity of 100 MWe, which is generated from geothermal brine at a temperature of 280–310°C and with the salinity of seawater. Two power plants operated by Reykjavík Energy are located at Hengill central volcano in southwestern Iceland (Figure 1). Nesjavellir is a co-generation power plant, where fresh water is heated by geothermal steam in heat exchangers (Gunnarsson et al., 1992). The plant began production in 1990, initially providing hot water mainly for district heating in the capital of Reykjavik, but since 1998 has also been generating electricity. Today, the installed capacity is 120 MWe and 290 MWt. Electric power generation commenced at Hellisheidi power plant south of Hengill in 2006, which in the first stage has an installed capacity of 90 MWe, but drilling is currently in progress for further expansion of the power plant. Finally, among the first of its kind, a 2 MWe Kalina cycle binary generator was installed at Húsavík in northern Iceland in 2001. The plant is the only one located outside the active volcanic zone and utilizes 124–128°C hot water from the Hveravellir geothermal field, which heats a mixture of water and ammonia in a heat exchanger (Hjartarson et al. 2005). This power plant provides about two thirds of the electricity requirements of the community at Húsavík. With the launch of Reykjanes and Hellisheidi power plants in 2006 the installed capacity has almost doubled in Iceland bringing it up to 422 MWe (Björnsson, 2006). Further developments are expected in the coming years to meet increasing demands from the expanding aluminum industry in Iceland.

With the incentive to enhance the economics of geothermal energy, the Iceland Deep Drilling Project has been underway since 2000 and is expected to start drilling a well to a depth of 4–5 km in the Krafla geothermal system in 2008. The project aims to encounter fluids at supercritical conditions of 450–600°C (Fridleifsson and Elders, 2005). A successful outcome would give a unique opportunity to test the production and feasibility of utilizing supercritical fluids from the deep-seated parts of geothermal reservoirs.

Direct utilization worldwide

The main direct-use applications of geothermal resources are for heating and cooling. The main utilization categories are: (1) swimming, bathing and balneology; (2) space heating and cooling including district energy systems; (3) agricultural applications such as greenhouse and soil heating; (4) aquaculture application such as pond and raceway water heating; (5) industrial applications such as mineral extraction, food and grain drying; and, (6) geothermal (ground-source) heat pumps, used for both heating and cooling. Direct-use of

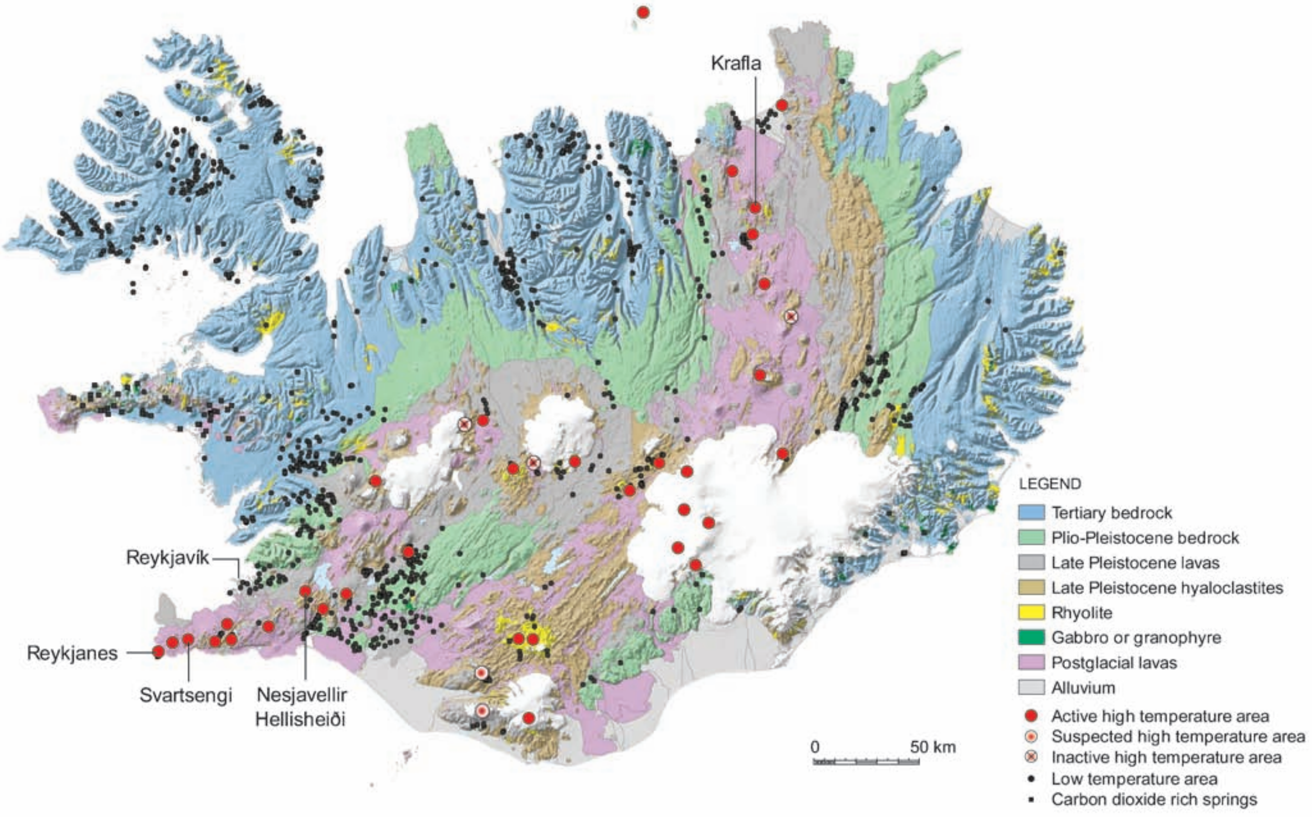


Figure 1 Geological map of Iceland with high and low temperature areas. Based on Geological map of Iceland (1:1 000 000) by Haukur Jóhanesson and Krislján Sæmundsson 1999, Icelandic Institute of Natural History.

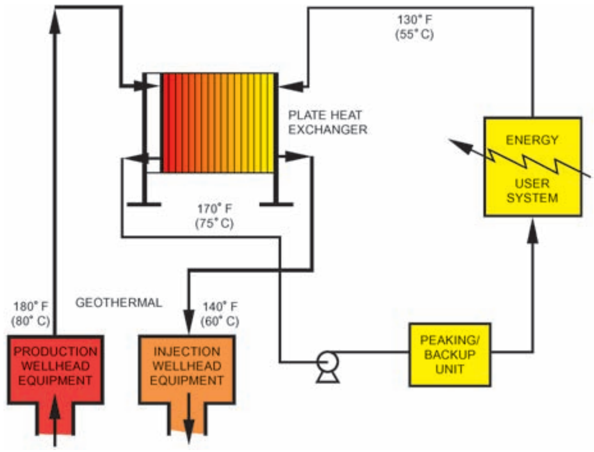


Figure 2 Typical components of a direct-use heating system.

geothermal resources normally uses temperatures below 150°C. The main advantage of using geothermal energy for direct-use projects in this low- to intermediate-temperature range is that these resources are more widespread and exist in at least 80 countries at economic drilling depths. In addition, there are no conversion efficiency losses and projects can commonly use conventional water-well drilling and off-the-shelf heating and cooling equipment (allowing for the temperature and chemistry of the fluid). Most projects can be on line in less than a year. Projects can be on a small scale such as for an individual home, single greenhouse or aquaculture pond, but can also be a large scale operation such as for district heating/cooling, food and lumber drying, and mineral ore extraction.

It is often necessary to isolate the geothermal fluid from the user side to prevent corrosion and scaling. Care must be taken to prevent oxygen from entering the system (geothermal water normally is oxygen free), and dissolved gases and minerals such as boron, arsenic, and hydrogen sulfide must be removed or isolated as they are harmful to plants and animals. On the other hand carbon dioxide, which often occurs in geothermal water, can be extracted and used for carbonated beverages or to enhance growth in greenhouses. The typical equipment for a direct-use system is illustrated in Figure 2, and includes downhole and circulation pumps, heat exchangers (normally the plate type), transmission and distribution lines (normally insulated pipes), heat extraction equipment, peaking or back-up plants (usually fossil fuel fired) to reduce the use of geothermal fluids and reduce the number of wells required, and fluid disposal systems (injection wells). Geothermal energy can usually meet 95% of the annual heating or cooling demand, yet only be sized for 50% of the peak load.

A summary of direct-use installed capacity and annual energy use are as follows: geothermal heat pumps 56.5% and 33.2%; bathing/swimming/spas 17.7% and 28.8%, space heating (including district heating) 14.9% and 20.2%; greenhouse heating 4.8% and 7.5%; aquaculture 2.2% and 4.2%; industrial 1.8% and 4.2%; agricultural drying 0.6% and 0.8%, cooling and snow melting 1.2% and 0.7%; and others 0.3% and 0.4%. District heating is approximately 80% of the space heating use. Figure 3 illustrates direct-use applications. The leading countries in the world are shown in Table 6.

In terms of the contribution of geothermal direct-use to the national energy budget, two countries stand out: Iceland and Turkey. In Iceland, it provides 89% of the country's space heating needs, which is important since heating is required almost all year and saves about US\$100M in imported oil. Turkey has increased it's installed capacity over the past five years from 820 MWt to 1,495 MWt, mostly for district heating systems. A summary of some of the significant geothermal direct-use contributions to various countries is shown in Table 7.

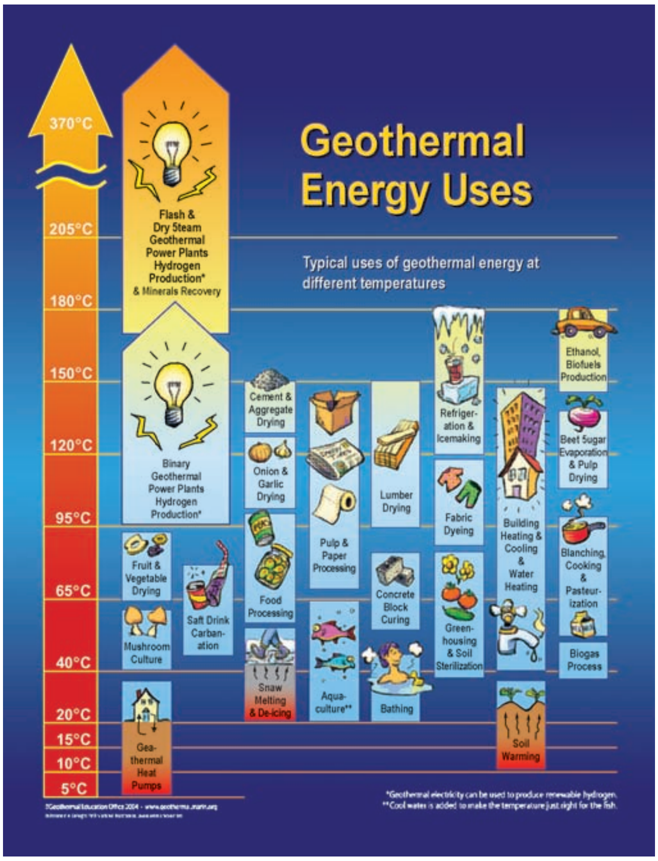


Figure 3 Examples of direct-use applications (Courtesy of Geothermal Education Office).

Table 6 Top direct-use countries (Lund et al., 2005).

Country	GWh/yr	MWt	Main Applications
China	12,605	3,687	Bathing
Sweden	12,000	4,200	GHP
USA	8,678	7,817	GHP
Turkey	6,900	1,495	District heating
Iceland	6,806	1,844	District heating
Japan	2,862	822	Bathing (onsens)
Hungary	2,206	694	Spas/greenhouses
Italy	2,098	607	Spas/space heating
New Zealand	1,969	308	Industrial uses

Table 7 National geothermal direct-use contributions.

Iceland	provides 89% of country's space heating needs
Sweden	Provides around 10% of the heating demand with geothermal heat pumps from 350,000 units
Turkey	space heating has increased 50% in the past 5 years, supplying 65,000 equivalent residences and 30% of the country will be heated with geothermal by 2010
Tunisia	greenhouse heating has increased from 10 ha to 100 ha over the past 10 years
Japan	over 2,000 hot spring resorts, over 5,000 public bath houses, and over 15,000 hotels, visited by 14.5 million guests per years use natural hot springs
Switzerland	has installed 30,000 geothermal heat pumps = one/two km^2, and 1,000 boreholes are drilled annually. Drain water from tunnel are used to heat nearby villages and they have also developed several geothermal projects to melt snow and ice on roads
United States	has installed 700,000 geothermal heat pump units, mainly in the midwestern and eastern states, with a 15% annual growth. Installation of these units is around 50,000 to 60,000 per year.

Direct-use in Iceland

Utilization of geothermal energy for direct purposes such as bathing, cooking and washing probably extends back to the first settlement of Iceland. However, it was not until the early twentieth century that general development of geothermal energy for purposes such as household heating took place. In 1928, the first extensive geothermal development for district heating got underway, when the first wells were drilled in the Laugarnes low temperature field in Reykjavik. By 1930, a three-km long pipeline was installed to transport the hot water into the center of the city to provide heating for a primary school, the national hospital, 60 households as well as hot water for a swimming pool (Gunnlaugsson et al., 2000). The Reykir low temperature field, approximately 17 km from the centre of Reykjavik, was developed in the 1930s and further research later led to the development of another field, Ellidaar, within the city boundaries. Today, these fields are providing water with temperatures ranging from 85–130°C from 52 wells. Reykjavik Energy is managing the district heating in Reykjavik and these three fields have a capacity of 2250 l/s and provide 74% of the hot water consumption for district heating in the capital, while heated water pumped from Nesjavellir high temperature field c. 30 km east of the capital provides the remaining requirements (Gunnlaugsson et al., 2000).

Geothermal energy is abundant in Iceland with more than 250 low temperature areas straddling the volcanic zone and more than 25 high temperature areas within the volcanic zone (Figure 1). Thus, in most communities around the country exploration and development of both low and high temperature geothermal fields has, through the years, been successful to such an extent that today 89% of the households in Iceland are heated with geothermal energy (Björnsson, 2006). Geothermal energy is used for a wide variety of purposes in Iceland such as greenhouse, industrial drying, carbon dioxide production, fish farming, swimming pools and snow melting, and amounts to a share of 26.8% of the total utilization of geothermal energy in Iceland, while space heating accounts for 57.4% and electricity generation the remaining part. In total geothermal energy covers 55% of the primary energy consumption in Iceland.

Geothermal (ground-source) heat pumps

Geothermal (ground-source) heat pumps (GHP) are one of the fastest growing applications of renewable energy in the world, with annual increases of 10% in about 33 countries over the past 10 years. Its main advantage is that it uses normal ground or groundwater temperatures (between about 5 and 30°C), which are available in all countries of the world. Most of this growth has occurred in the United States and Europe, though interest is developing in other countries such as Japan, China and Turkey. The present worldwide installed capacity is estimated at almost 15,400 MWt (thermal) and the annual energy use is about 87,500 TJ (24,300 GWh). The actual number of equivalent installed units (12 kW) is around 1,500,000, but the data are incomplete. Table 8 lists the countries with the highest use of GHPs.

GHPs come in two basic configurations: ground-coupled (closed loop) which are installed horizontally or vertically (Figure 4a), and groundwater (open loop) systems (Figure 4b), which are installed in wells and lakes. In the ground-coupled system, a closed

Table 8 Leading countries using GHP (Curtis et al., 2005).

Country	MWt	GWh/yr	Number installed
Austria	300	400	25,000
Canada	445	610	37,000
Germany	560	840	47,000
Sweden	4,200	12,000	350,000
Switzerland	530	790	44,000
USA	8,400	7,200	700,000

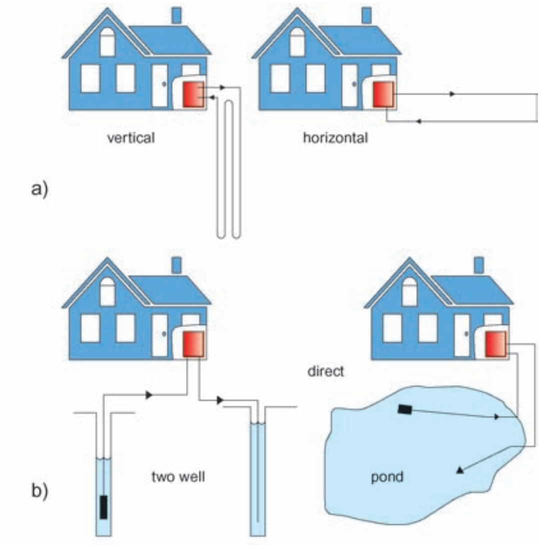


Figure 4 a) Closed loop heat pump systems (source: Geo-Heat Center); b) Open loop heat pumps systems (source: Geo-Heat Center).

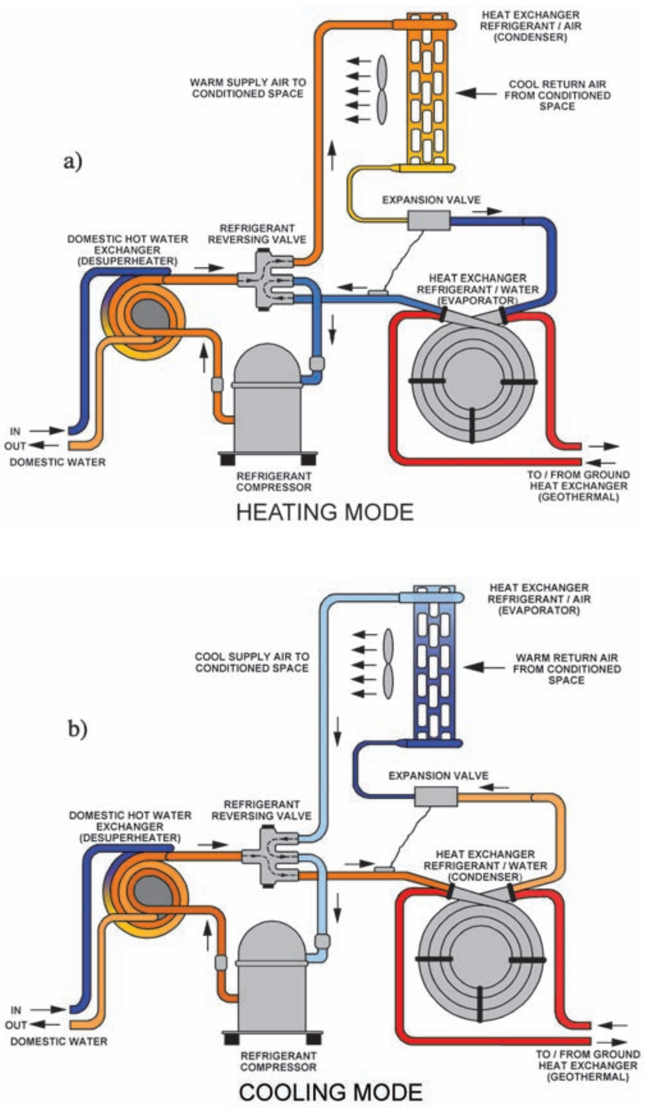


Figure 5 Desuperheater in heating (a) and cooling (b) mode (source: Geo-Heat Center).

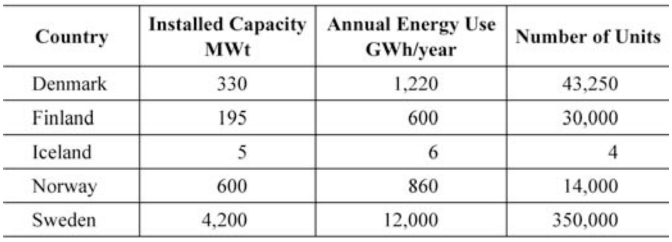
loop of pipe, placed either horizontally (1 to 2 m deep) or vertically (50 to 70 m deep) is placed in the ground and a water-antifreeze solution is circulated through the plastic pipes (high density polyethylene) to either collect heat from the ground in the winter or reject heat to the ground in the summer (Rafferty, 1997). The open loop system uses ground water or lake water directly in the heat exchanger and then discharges it into another well, into a stream or lake, or on the ground (say for irrigation), depending upon local laws. The type chosen depends upon the soil and rock type at the installation, the land available and/or if a water well can be drilled economically or is already on site.

A desuperheater can be provided to use reject heat in the summer and some input heat in the winter for the domestic hot water heating as shown in Figure 5. A small amount of electricity input is required to run a compressor; however, the energy output is in the order of four times this input. A desuperheater provides heat to the domestic hot water in the geothermal heat pump heating and cooling cycles. During heating (Figure 5a), heat can be removed for the desuperheater before it is provided to the normal heating system, however, with a loss in efficiency. During cooling (Figure 5b), heat can be rejected to the desuperheater before it is rejected to the ground or ground-water with no loss in efficiency. Unfortunately, a backup domestic hot water system must be provided, as the heat pump does not run 100% of the time, but does provide as much as 30 to 50% of the domestic hot water heating requirements which can be stored in a traditional insulated hot water tank. See Curtis et al. (2005) and Lund et al. (2003) for more background material.

Nordic countries

The obvious leader in geothermal heat pump installation is Sweden with many shallow bores and several very deep drillings, followed by Denmark with their two district heating plants. A summary of installations in the Nordic Countries is as follows (Table 9—based mainly of 2005 data; Sweden 2006 data).

Table 9 Geothermal heat pump installation data for the Nordic countries.



Country	Installed Capacity MWt	Annual Energy Use GWh/year	Number of Units
Denmark	330	1,220	43,250
Finland	195	600	30,000
Iceland	5	6	4
Norway	600	860	14,000
Sweden	4,200	12,000	350,000

Denmark

Denmark is noted for the two district heating plants using absorption heat pumps. The older installation, in operation since 1984, at Thisted in northern Jutland (Jylland), extracts heat from a 44°C, 19% salinity groundwater produced from 1.25 km depth (Mahler and Magtengaard, 2005). In 2000–2001, the plant was enlarged to 7 MWt capacity, producing 80 TJ/year (22 GWh/yr) of heat from 200 m^3/hr of water, which is then reinjected. The most recent installation, the Margretheholm plant in Copenhagen, started operation in the fall of 2004. Absorption heat pumps use water from a well. A deviated production well and a vertical injection well have been drilled to produce heat from a 73°C sandstone aquifer. The Margretheholm plant has a capacity of 14 MWt and energy use of 380 TJ/year (106 GWh/yr), utilizing 235 m^3/hr of 19% salinity water. A further 250 groundwater-based heat pumps and 43,000 other types of pumps (about 10 to 20% of which are vertical closed-loop) are also in operation. They extract approximately 3940 TJ/yr (1095 GWh/yr). The estimated installed capacity is 309 MWt (assuming 3,500 full-load operating hours/yr). The total for Denmark is therefore 330 MWt and 4,400 TJ/year (1,222 GWh/yr).

Finland

Based on limited information, approximately 10,000 geothermal heat pump units have been installed in Finland, producing 484 TJ/year (134 GWh/yr) from an installed capcity of 80.5 MWt, assuming 4,000 equivalent full-load hours per year based on 2000 data from Kukkonen. Based on data from the Finnish Heat Pump Association (Suomen Lampopoumppuyhdistys—*www.ivlampopumput.fi/eng.html*), heat pump sales (both air-source and geothermal types) have increased annually by 50–100% over the last five years, so that in 2005 the estimated number of installed units was 30,000 of which geothermal was 25,000 units (Hirvon, 2002). A standard Finish residence of 150 m^2 uses an average of 20,000 kWh/year, assuming a 5–8 kWt capacity unit (average COP of 3.1). Thus, the total installed capacity in Finland in 2002 was 162.5 MWt, using 1,220 TJ/year of geothermal energy (based on an average capacity of 6.5 kW). Extrapolating this to 2007, the estimated values are 30,000 geothermal heat pump units with an installed capacity of 195 MWt, using 2,160 TJ/year (600 GWh/year). Ground-source heat pumps in 2005 had captured 20 to 40% of the heating market shares in the country, increasing from less than one percent in 1995 and 13% in 2001. The average investment cost for a system is 16,000 Euros and the annual operating cost is 437 Euros. This compares to air source heat pumps of 9,000 Euros investment cost and 750 Euro annual operating cost. Air source units presently capture 10–30% of the heating system market.

Iceland

Geothermal heat pumps are utilized on a limited basis, with reports of only three locations: Akureyri, Grenivik and an unknown site in 2005. The total installed capacity is 4.0 MW producing 20 TJ/yr (5.6 GWh/yr) of space heating. Only two units are reported installed with a COP of 4.75 (Ragnarsson, 2005). Recent information (personal communication with Danielsson, 2007) indicates that few geothermal heat pumps have been installed in Iceland due to the readily available higher temperature geothermal resources used for space heating (there is little or no need for space cooling) and the low heat transfer coefficient of basaltic rock. One of note is a closed loop system using a 300 m deep well with an annual output of approximately 40,000 kWh and a COP of 3.3. Interestingly, about 15 air-to-air heat pumps have been installed since 2005, which are working extremely well. However, the geothermal and air-to-air units are relatively unknown in Iceland, and as a result not well accepted.

Norway

Norway is not considered a geothermal country; however about 150 geothermal heat pump systems sized for commercial or multi-family buildings have been installed (Midttrømme, 2005). Traditionally, these systems are used for heating only, but in some the exhaust ventilation is reinjected (stored underground) to provide additional heat for use in the winter. Increased interest in cooling in the commercial and industrial sectors is favoring ground-source heat pumps and underground thermal energy storage systems. As of 2003, there were 55,100 heat pumps installed in Norway, of which 5% were geothermal (i.e., 2,755). Norway has one of the largest geothermal heat pump installations in Europe, the system uses 180 boreholes to provide 9 MWt for heating and 6 MWt for cooling a school, shopping center, hotel offices and residential area covering a total of 180,000 m^2. In 2005, the total number of installed geothermal heat pump units was estimated at 14,000, with a capacity of 600 MWt. Over 90% of these installations are vertical boreholes of the ground-coupled type with a single U-type pipe installed. No figures are available on annual energy use, but using 2,000 full-load hours per years and a COP of 3.5, the annual energy use is estimated at 3,085 TJ/yr (857 GWh/yr).

Sweden

Sweden came in early with geothermal heat pumps for domestic heating. Already in 1985, there were some 50,000 units of ground-source heat pumps installed (Bjelm, 1983). Today, there are at least 350,000 units and the annual sale over the past 4–5 years has been around 40,000 units (Hellström, 2006). It is estimated that all these units produce about 10% of the heat demand in all single houses and official buildings in Sweden. The useful heat from the electric energy to the heat pump is not included here (Olof Andersson, personal communication, 2007). The annual energy use is estimated at 12,000 GWh/yr, making Sweden the largest GHP energy user in the Nordic countries and in the world in terms of GWh/yr.

Most of the geothermal heat pumps are small scale units for single houses but a few large ones with an installed capacity of 20 to 45 MWt are running. The largest is in Lund with an installed capacity of 47 MWt utilizing two heat pumps. It has been producing heat for the local district heating network since 1985 and the yearly production is around 235,000 MWh/yr. About 550 l/s is produced from four production wells with a temperature of around 20°C. The water is produced from about 700 m and re-injected in five wells some 1500 m away from the production wells. The project is a great success with very high availability and excellent economy. Production for domestic cooling is now becoming a new and more and more popular application of the use of ground source heat. It is estimated that at least 100 MWh/yr was produced during 2006 and a rapid increase is expected over the coming years.

Energy savings

Using geothermal energy in direct-use applications replaces fossil-fuel use and prevents the emission of greenhouse gases. Table 10 shows the savings brought about by the direct-use of geothermal energy assuming that it replaces electricity generated from fossil-fuels (conversion efficiency estimated at 0.35) If direct-use applications replace burning the fuel directly, then about half of this amount to fuel oil would be saved in heating systems (35% vs. 70% efficiency). Savings in the cooling mode of geothermal heat pumps is also included in the figures in Table 10. The savings in fossil fuel oil are equivalent to about three days (1%) of the world's consumption.

Table 10 Energy and greenhouse gas savings from geothermal energy production (after Goddard and Goddard, 1990).

	Fuel Oil (10^6)		Carbon (10^6 t)			CO_2 (10^6 t)			SO_x (10^6 t)			NO_x (10^3 t)		
	Barrels	Tonnes	NG	Oil	Coal	NG	Oil	Coal	NG	Oil	Coal	NG	Oil	Coal
Electric	96	15	3	13	15	12	51	59	0	0.3	0.3	2.8	9.6	9.6
Direct-use	174	26	5	24	27	16	67	78	0	0.5	0.5	3.8	12.4	12.4
TOTAL	270	41	8	37	42	28	118	137	0	0.8	0.8	6.6	22.0	22.0

It should be noted when considering these savings, that some geothermal plants do emit limited amounts of the various pollutants; however, these are reduced to near zero where gas injection is used and eliminated where binary power is installed for electric power generation. Since most direct-use projects use only hot water and the spent fluid is reinjected, the above pollutants are essentially eliminated.

Conclusions

Growth and development of geothermal electricity generation has increased significantly over the past 30 years approaching 15% annually in the early part of this period, and dropping to 3% annually in the last ten years due to an economic slowdown in the Far East and the low price of competing fuels. Direct-use has remained fairly steady over the 30-year period at 10% growth annually. The majority of the increase has been due to geothermal heat pumps. At the start of this 30-year period, only ten countries reported electrical production and/or direct utilization from geothermal energy. By the end of this period, 72 countries reported utilizing geothermal energy. This is over a seven-fold increase in participating countries. At least another 10 countries are actively exploring for geothermal resources and should be online by 2010.

Developments in the future will include greater emphases on combined heat and power plants, especially those using lower temperature fluids down to 100°C. This low-temperature cascaded use will improve the economics and efficiency of these systems, such as shown by installations in Germany and Austria and at Chena Hot Springs, Alaska. At the other end of the scale the Iceland Deep Drilling Project aims at testing whether it is feasible to extract supercritical fluids at 450–600°C from the deeper parts of the geothermal reservoirs. Also, there is increased interest in agriculture crop drying and refrigeration in tropical climates to preserve products that might normally be wasted. Finally, the largest growth will include the installation and use of geothermal heat pumps, as they can be used anywhere in the world, as shown by the large developments in Switzerland, Sweden, Austria, Germany and the United States.

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by Gert Knutsson

Hydrogeology in the Nordic Countries

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Hydrogeology in the Nordic Countries is characterized by many types of aquifers and great differences in groundwater recharge. Fracture aquifers in crystalline, hard rocks are the most common type of aquifer with, in general, low fracture porosity and low well yields. The most productive crystalline rocks are the basalts in Iceland and the rapakivi granite in Finland. The fracture and fault zones have mostly high conductivity. Porous aquifers are found in various types of geology. The most porous ones are the lava-fields and the pyroclastic rocks in the active volcanic zone of Iceland, but glaciofluvial deposits such as eskers and deltas in Finland, Norway and Sweden, outwash plains in SW Denmark and sandurs in Iceland are also very porous and good aquifers, as are some sedimentary rocks in Denmark. The glacial till has, in general, low conductivity. Fractured porous aquifers in consolidated limestones and sandstones have high well yields in relatively young formations in Denmark and Scania in southern Sweden, but medium or low yields in older strata. Karst aquifers have limited extension, but there are some well developed ones in the Caledonian mountain range in Norway and Sweden. Geothermal water with a lot of springs and even geysers are common in Iceland and of great economic importance. The groundwater chemistry of the crystalline, hard rocks is notable for bacteria, brines and mixed water at great depths (more than 500 m) as well as high contents of arsenic, fluoride and radon in drilled wells in certain regions.

Introduction

Hydrogeology in the Nordic Countries is very varied due to many types of bedrock and superficial deposits as well as great differences in groundwater recharge. Initially, hydrogeological investigations were focused on aquifers for water supply (especially in Denmark, where 98% of the supply is groundwater). Later, they involved acquisition of general data by mapping and monitoring, and nowadays, they mainly concern the requirements of the European Union Water Framework Directive and special environmental goals. Knowledge has improved greatly also for other reasons over the last decades: for example, acidification research in the 1970s–1980s in Finland, Norway and Sweden; the Danish Environmental Research Programme 1992–2004; the Environment of the Subsurface and the Groundwater Programme in Norway in the 1990s; and ongoing research for geothermal and fresh water in Iceland. A lot of data and experiences have also been obtained during construction works such as mining and tunnelling. As regards Finland and Sweden, intensive research on groundwater in crystalline rocks for the storage of nuclear waste has been carried out for the last 30 years (deep drillings, experiments such as tracer tests in underground laboratories, investigation of sites and modelling). New methods and advanced models have been developed in all these fields over the years. A challenge in the near future will be to manage the consequences of climate change on the hydrogeology (e.g. changes in recharge, flow, quality and sea-level).

Geology

The bedrock geology of the Nordic Countries (see other papers in this volume) is dominated by a large area of Precambrian, crystalline rocks—the Baltic Shield—in Finland, most of Sweden, S and SW Norway and the Danish island of Bornholm (as well as Karelia and the Kola peninsula in Russia). The Shield is flanked by the Caledonian mountain range in southwestern, central and northern Norway and the bordering areas of Sweden, and by sedimentary rocks in the east and south (above all in Denmark). Volcanic rocks occur in the Oslo Rift and further north-westwards on Iceland and the Faeroe Islands. On Spitsbergen (Svalbard), Caledonian rocks and most of the younger Phanerozoic formations are represented. Greenland is excluded in this short article.

Unconsolidated deposits of Quaternary age cover most of the glacially eroded bedrock, but there are widespread areas of bare rocks in the mountains and along the coasts, especially in Norway. The most common deposit is hard-packed sandy and silty till (moraine). The till cover is mostly only a few metres thick, but may be 50 m or more in some areas, especially in Denmark and parts of Scania in S Sweden, where the till is clayey. The most striking features from the Quaternary period are the elongated ridges of glaciofluvial deposits—the eskers, particularly in Finland, Sweden and SE Norway—as well as some vast deltas, the outwash plains in SW Denmark, the large sandurs in Iceland and the ice-marginal deposits, e.g. the Salpausselkä in S Finland and the Raerne in S Norway.

Sand and gravel deposits in river valleys all over the region and in the buried valleys in Denmark and Scania, S Sweden are also notable.

Climate and groundwater recharge

The Nordic Countries are situated in a border zone between different types of climate. Denmark, SW Norway and SW Iceland and the Faroes have a cold-temperate, maritime climate; S Sweden and Finland a cold-temperate continental climate and, further north, a boreal (or sub-arctic) climate. A great part of Iceland, Spitsbergen and some small areas of the high mountains in Norway and Sweden have a polar climate. All these climate types are characterized by higher annual precipitation than evapotranspiration, which means that the overall climate is humid. Precipitation is moderate (500–1000 mm/year) in most of the region, but high in a great part of Iceland and W and S Norway (1000–2000 mm/year) and very high in the western parts of the high mountains in Norway (2000–4000 mm/year) as well as in the southeastern parts of the glaciated, high mountains in Iceland (up to 8000 mm/year, Rögnvaldsson et al., 2007). The eastern parts of the mountains in Norway and Sweden, as well as the highland north of Vatnajökull in Iceland, lie in rainshadow with an annual precipitation of only 300–400 mm/year. Characteristic climate conditions during winter time mean that the lakes are ice-covered and that most of the precipitation accumulates as snow, which gives a period of intensive groundwater recharge during and after the snowmelt. The duration of the snow cover is one to two months in the southern parts of Norden, four to six months in the central parts, up to seven to eight months in the northern parts and still more in the high mountains, with the formation of glaciers, above all in Iceland, which has the largest glacier in Europe, Vatnajökull. Another significant feature of the winter climate is the frozen ground and even permafrost in small areas in the high mountains and in the extreme north. Permafrost increases the surface runoff and diminishes the infiltration capacity and the groundwater recharge. On Spitsbergen, permafrost with a depth of 100–400 m gives rise to confined aquifers and artesian conditions (Haldorsen et al., 1996).

A very important parameter for long-term groundwater recharge is the hydraulic conductivity of the soils, the unconsolidated deposits and the bedrock. The most permeable ground is the young lavas in Iceland, mostly covered only by moss. In contrast, almost impermeable areas with clayey soil and thick layers of clay on top of gneiss or schist can be found, for example, in central Sweden. Groundwater recharge in the Nordic countries has been studied in different types of climate, geology and topography, using various types of methods (Johansson, 1987; Englund et al., 1988; Olofsson and Knutsson, 2004). The methods used can be classified in three groups: recharge methods (e.g., tracers, modelling), response methods (e.g., groundwater level analysis, chloride balance, groundwater flow modelling) and discharge methods (e.g., isotope analysis and runoff measurements). Ideally, several independent methods have been tested in the same case. The highest figures of recharge are to be found in areas with high precipitation and very permeable ground, e.g., lava-fields in Iceland and gravel deposits in Norway (647 mm/year with P = 1703 mm/year in a glaciofluvial delta in N Norway; Storrö, 1990). Fairly high figures (390 mm/year) are reported from areas with moderate precipitation (700–800 mm/year) in sandy-gravelly deposits in S Finland (Lemmälä, 1990) and SE Norway (Jörgensen and Östmo, 1990). Some figures of groundwater recharge in Sweden can be mentioned: in E Sweden, 280 mm/year in sandy soil but only 20 mm/year in "mixed" crystalline rocks with 10 m thick overburden of compact sandy till and 1.6 mm to 5.7 mm/year at a depth of 500 m in crystalline rock in the same area; in SE Sweden, 170–200 mm/year in an area of shallow sandy till, 160 mm/year in a thick esker surrounded by fine-grained sediments, 150 mm/year in the upper part of a moderate fractured granite and 5 mm/year at a depth of 450 m in the same granite; in SW Sweden, 100–120 mm/year in a heavily fractured gneiss with a thin, coarse overburden—the figures at depth are calculated by modelling (Olofsson and Knutsson, 2004). The recharge figures in Denmark vary between 170–193 mm/year in W Jutland to only 15–60 mm/ year in E Denmark (Jacobsen, 1995).

Principal types of aquifers

Hydrogeology can be described in different ways. This short presentation focuses on the main types of aquifers.

Fracture aquifers

The hard crystalline rocks of the Precambrian, most of the rocks in the Caledonian mountain range and the basalts in Iceland and the Faeroes are typical fracture aquifers, where the storage and movement of water is restricted to fractures. Some types of compact limestone and quartzitic sandstones also belong to this type of aquifer. The total volume of these types of voids forms the fracture (secondary) porosity. This is dependent on the frequency, orientation and width of fractures and their mineral fillings, which in some areas stop up 70–80% of the conductive fractures (Hellä et al., 2005). Therefore, it varies strongly due to the composition, texture and structure of the rock and the geological history of the bedrock. The total fracture porosity is generally not more than 1% , but the effective (kinematic) porosity is still lower (0.1–0.0001%), as some fractures are disconnected or contain dead-end pits and therefore do not contribute to the groundwater circulation. Microscopic fluid flow inclusions (sometimes salt-rich) also exist and make up a closed system (Olofsson et al., 2001). In Iceland, the effective porosity of young, volcanic fractured rocks is generally very high, up to 5–10% (Einarsson, 2007).

There are hydrogeological differences between various types of crystalline rocks (Figure 1B). Granitic rocks with a high quartz content (acid) are often brittle and easily broken when stress conditions change, which results in well-developed, open fractures and a hydraulic conductivity (K) in the range of 10^{-7} to 10^{-5} m/s. The transport pathways in fracture networks have been studied in detail by tests with different types of tracers extending over 100 m at Äspö, SE Sweden (Winberg, 2007). Hydraulic connections have been established in fracture zones by interference tests stretching up to 1,600 m (by on-going tests almost 3,000 m) in the site investigations for the storage of nuclear waste at Forsmark, E Sweden (Gokall-Norman and Ludvigson, 2007). A very good example of an abundantly fractured rock is the rapakivi granite in SE and SW Finland, which locally disintegrates to gravel (Lahermo, 1971). The highest well output in this granite is reported to be 13.8 l/s (UNESCO, 1982). The normal yield of wells in granitic rocks is much lower, for example, 600–2000 l/h in large parts of Sweden (SGU, 1995), which is sufficient for the supply of farms and country houses. High-grade metamorphic rocks such as strongly folded gneisses are generally very compact with few fractures and low values of K (10^{-9} to 10^{-7} m/s, Olofsson et al., 2001). The same low values are common for basic rocks such as gabbro and diorite, which normally are tough and can withstand fracturing. The yield of wells is very low in metamorphic rocks such as amphibolite, phyllite and schist, e.g., 100–500 l/h in Norway (Henriksen and Nielsen, 2001), which is in contrast to that in interglacial basalts on Iceland, which have primarily very well developed fracture systems and thereby much higher K-values (10^{-4} to 10^{-2} m/s, Sigurdsson 1986). All values of K and T are, however, highly scale-dependent.

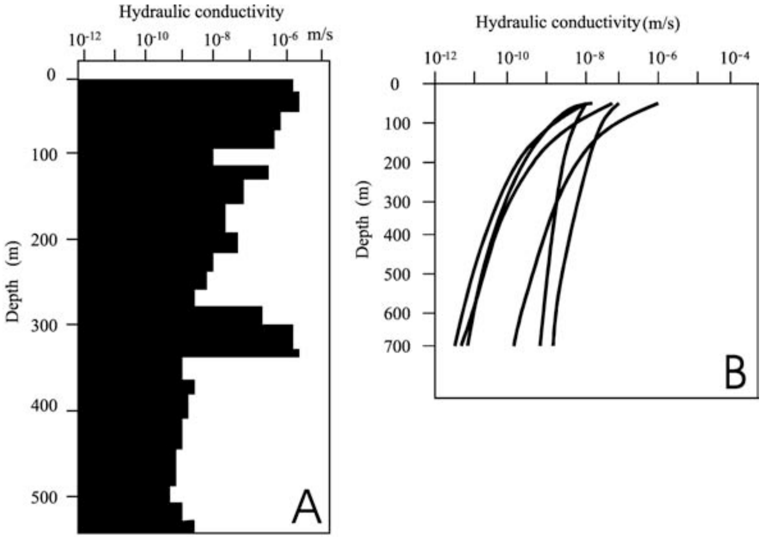

Figure 1 Hydraulic conductivity from drillhole measurements (injection tests) in granodiorite (A), and calculated hydraulic conductivity for different types of crystalline rocks (B); curves of granites on the right, and of gneisses and basic rocks on the left (from Olofsson et al., 2001).

A special phenomenon in these glaciated regions is that glacial pressure and frost activity have enlarged existing fractures to a depth of 15–20 m. Furthermore, new fractures and even faults developed or were reactivated during fast melting periods of the land ice with rapid changes in the vertical load, especially in northern Fennoscandia (Lagerbäck 1979). The on-going postglacial isostatic uplift has most probably reactivated old fracture systems and maybe also created new ones. There seems to be a relationship between the degree of uplift and the yield of drilled wells (Rohr-Torp, 1998). In general the fracture frequency decreases rapidly with depth. And the apertures become narrower due to increasing lithostatic stress. These factors result in lower values of K, which also differ between various rock types (Figure 1). The variability is, however, significant and highly permeable fractures and fracture zones can be found even at great depths (Figure 1 A). Fracture zones in hard rock areas may have K-values in a range from 10^{-6}–10^{-5} m/s up to 10^{-1}–10^{-0} m/s in Iceland (Knutsson, 1997; Sigurdsson, 1986). Such zones are, of course, of great importance for the regional groundwater flow and for the location of drilled wells with high yield. If the zones are continuous over longer distances, yields of 5–15 l/s are obtained and the wells are used for the water supply of villages in the countryside.

The capacity of wells and the volume of groundwater flow in rocks, for example, leakage in connection with construction work, are also due to the hydraulic contact between fracture zones and groundwater reservoirs in the overburden (Olofsson et al., 2001) or even surface water. The most extreme conditions as regards leakage were met during the construction of railway tunnels, one in SE Norway (Romeriksporten) which drained a small lake, and another through the Hallandsås horst in SW Sweden. The latter heavily tectonized horst is known to have the most productive wells in hard rock in Sweden (SGU 1995). The north entrance of the tunnel caused drainage of 35 l/s and a lowering of the groundwater level by 100 m, which influenced springs, brooks and hundreds of wells (Anderberg, 1998).

Porous aquifers

Porous aquifers are characterized by storage and circulation of water in pores. The most porous ones are the postglacial lavas, with bands of scoria (volcanic slag) and pyroclastics rocks of the active volcanic zones in SW Iceland having K-values of 10^{-2} m/s to 10^{-0} m/s (Sigurdsson, 1986). Almost all net precipitation infiltrates and there is no surface runoff. There are around 25 very big springs (>5 m^3/s) in Iceland (Figure 2). The largest spring area with a flow of 80–90 m^3/s is located on the north shore of lake Thingvallavatn. Spring-fed rivers have a very even, high discharge and almost constant temperature with a mean discharge of 100 m^3/s in Sog (Adalsteinsson et al., 1994).

Porous aquifers in more or less consolidated rocks are of considerable importance in Denmark and S Sweden (Scania). Tertiary sand deposits are the dominating aquifer in W Jutland. A loose, glauconitic sandstone (greensand) with overlying limestone, both of Cretaceous age, in Scania with high K-values and a transmissivity (T)-value about 5×10^{-3} m^2/s (UNESCO, 1979) forms the most extensive and productive aquifer in Sweden (well yields 17–55 l/s, Gustafsson et al., 2005). This resource is used for the water supply of a medium-sized town and several villages and for intense irrigation.

Figure 2 Spring discharge from a porous lava on a tight basalt at Hraunfossar, Iceland (photo by Knutsson, G., 2005).

Very important porous aquifers are found in coarse-grained, unconsolidated deposits of Quaternary age, such as sand and gravel deposits of glaciofluvial and fluvial origin. The glaciofluvial deposits are of different genetic types. The best aquifers are found in the subaquatic type, which were deposited in rather deep water (below the highest shoreline) at the margin of the land-ice, where an esker or a delta was formed (Figure 3). These deposits consist of well-sorted boulders, gravel and sand with K-values of 10^{-4} to 10^{-2} m/s. The eskers have a thickness of 10–100 m, a width of 500–1000 m and are continuous over long distances, 100 km or more, i.e. aquifers of regional size. Some rather large springs occur (Källakademin, 2006) along these eskers (50–330 l/s) in Sweden and in the distal parts of vast deltas, for example, the Romerike delta in SE Norway with a total discharge of 850 l/s (Jörgensen and Östmo, 1990), the Kaldvellfeltet delta in N Norway with a total discharge of 355 l/s (Storrö 1990) and the Brattforsheden delta in SW Sweden with a spring discharge of 200 l/s and a total discharge to a lake of 800 l/s (Källakademin 2006). Some large supraaquatic deposits such as the outwash plains in SW Denmark, the sandurs in Iceland and the ice-marginal deposits in Finland, Norway and Sweden are also very good aquifers (for example, Salpausselkä in Finland 450 l/s; UNESCO, 1982). The sand and gravel deposits along rivers with induced infiltration, especially in Norway, and in buried valleys in Denmark and

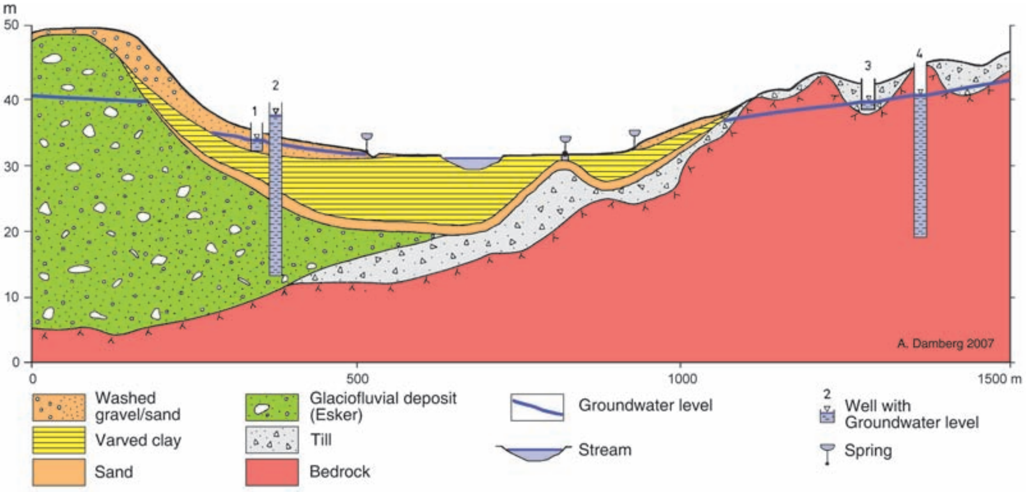

Figure 3 Conceptual figure of the geology and hydrogeology in a valley below the highest shoreline with a wave-washed, large esker (green) to the left, littoral sediments (orange) and glacial clay (yellow) in the valley and glacial till (light blue) on the slope of hard rock (red) to the right. Groundwater levels (lines), springs (glasses) and wells (shafts) are marked in different aquifers (Damberg, A., 2007; after SGU, 1975).

Scania are of great importance for the water supply of many small and medium-sized towns, e.g. flowing artesian wells in Jutland with a specific capacity of 20–30 l/s/m drawdown (UNESCO, 1979). Wells with high yield (several hundreds l/s) can be constructed in the coarse glaciofluvial deposits, but the natural recharge and/or the groundwater reservoirs are sometimes too small. Therefore artificial recharge is often arranged in Finland and Sweden. The steep and narrow eskers, formed supraaquatically above the highest shoreline, are not such good aquifers but, the resources are sufficient for the water supply of small villages.

The most frequent type of porous aquifer among the Quaternary deposits is various types of till. They are all more or less heterogeneous with a macrostructure of lenses or layers of sorted sand and gravel as well as bedding and fissility. Even clayey till in Denmark has deep fractures (6–8 m or more), which facilitate percolation down to the underlying aquifers, but thereby also the transport of nitrate and pesticides; this is creating a great pollution problem in Denmark (Björn, 2005). The bulk K-values of this fractured clayey till (Fredericia, 1990) are about the same as for the matrix of unsorted sandy or silty till (10^{-8} to 10^{-6} m/s). But the macrostructure and even the microstructure give a higher K in some parts of such till deposits or in special types of moraine terrain, especially in drumlins with spring discharge of 1–10 l/s. The highest discharges of springs in moraine terrain in Sweden have been found at the foot of large and high moraines, probably with sub-moraine layers of sand and gravel (e.g., in N Sweden 10–75 l/s; Källakademin, 2006). Such resources are, of course, of great interest for water supply and for mineral-water production, but normally the capacity of springs and dug wells in till is sufficient only for the water supply of farms and country houses.

Fractured porous aquifers

Consolidated limestones and sandstones, which have been slightly tectonized, develop a combination of fractures and pores, so- called “dual porosity”. The most productive aquifers of this type are the Tertiary (Danian) and Cretaceous limestones in Denmark and Scania. The Danian limestone is partly a calcarenite and partly a Bryozoan limestone, both containing chert. The K-values are low to medium, the highest values in the form of secondary porosity being due to fracturing (in the upper part) caused by glaciations (UNESCO, 1979). The median capacity of the wells is more than 17 l/s (up to 55 l/s) in some areas of Scania (Gustafsson et al., 2005). The aquifer is of utmost importance for the water supply of the capital region of Copenhagen, several towns and villages, and for irrigation. The Cretaceous White Chalk in N Jutland and some parts of Scania has very small interstitial pores, but has a high secondary porosity due to fracturing and karstification. So the K-values are high to medium and the T-values in the order of 10^{-2} m^2/s around the city of Ålborg, which means that the White Chalk is an important aquifer in the region (UNESCO, 1979). The Permian basalt and romb-porphyry (both with pores) in S Norway are good aquifers with well yields of normally 2–3 l/s, but up to 20 l/s. The Permian Brumunddal sandstone in the same region is a productive aquifer (20 l/s in one single well) as it has an effective porosity of 5% and is strongly fractured. It supplies the town of Brumunddal with water (Gaut and Ellingsen, 1992). Cambrian sandstones in S Sweden have K-values of around 10^{-6}–10^{-5} m/s and well yields of up to 15 l/s, and these aquifers are used for water supply of villages (SGU, 1995).

Karst aquifers

Karst is developed by chemical solution and erosion of carbonate rocks along bedding planes, fissures and fractures. The solution process is not favoured by the cold-temperate and boreal climate in the Nordic Countries. Therefore, most of the karst is of moderate size, but even slightly developed karst is of importance for the percolation of water, for example, in the flat, bare limestone areas (so-called Alvar) of the islands of Gotland and Öland in SE Sweden as well as for the secondary porosity and the K-values of carbonate rocks (see above). Typical features in karst are dolines and sink-holes on the ground, caves and tunnels underground and big springs at the out-let. These features form a very special hydrogeological system with fast drainage of great volumes of water during flood, but low flow of underground water during dry seasons. So the seasonal fluctuations in the discharge of springs are enormous (e.g., 1000 times higher after heavy snowmelt than during dry summertime in the Lummelunda karst system on the island of Gotland, Knutsson 1974). Small and moderate karst systems are found in very slightly tectonized limestone areas of Denmark, S Norway and S Sweden. In certain places, these aquifers are of importance for the local water supply and the karst springs for vegetation, especially fens with orchids. There are, however, some karst systems of larger size and of another type in the Caledonian mountain range. The host rock consists of regionally metamorphosed calcite and dolomite marbles in smaller and greater, steeply dipping bands, which are fractured. The karst is formed along the fractures in these bands. The largest karst region is found in Nordland county in N Norway, where the longest cave is more than 11 km and the deepest system 580 m. Most of the systems are active with flowing water, but there are also some fossil caves from the glacial time (Lauritzen, 1991). Rather large karst systems are found in the Swedish part of the mountain range. The river Bjurälven has a subterranean flow over a distance of more than 1 km just east of the border to Norway and an outflow in a spring with a discharge of several m^3/s. Some well-developed, active karst systems with caves and spectacular springs are found around Lake Torneträsk in N Sweden (Figure 4). An exceptional type of karst in carbonate rocks has been discovered on Spitsbergen, the so-called thermoglacial karst. The main recharge area for such a karst aquifer is melt-water from a superimposed glacier, but the water chemistry and the stable isotopes—as well as the water temperature—indicate, that some part of the water in the springs originates from a deep, thermal brine. Sulphate-reducing bacteria are also present in the water of these springs (Lauritzen and Bottrell, 1994).

Figure 4 Karst springs at different levels on a slope in the Caledonian mountain range, Vadvetjåkka National Park, NW Lake Torneträsk, Lapland, Sweden, close to the border to Norway (photo by Damberg, A., 1992).

Geothermal water

Water, which percolates to considerable depths, is heated in relation to the geothermal gradient of the region. This means that in a volcanic region such as Iceland the water will reach a temperature of +100°C or more (dependent on pressure), already at a few hundreds meters depth, and that it will have a high content of solids and gases. The high temperature areas with steam in fumaroles and solfataras are located only in the active volcanic zones. Hot springs (+70–100°C) and geysers (see figures in other papers of this journal) are found in low temperature areas, which are spread over Iceland. The recharge for the hot springs is either based on convection in fairly permeable regions or on long-distance flow along fracture zones, even from the high mountains. Isotope studies have shown, that the recharge area is sometimes a glacier (Arnason and Sigurgeirsson, 1967), as for the thermoglacial karst on Spitsbergen. There are 600–700 large- or medium-sized hot springs in Iceland, including the probably largest hot spring in the world (150 l/s, +100°C). This spring water is used for domestic heating of two small towns (Einarsson, 2005). Geothermal heat is of great economic importance in Iceland. Several hot springs can be used directly for heating, but most hot water and steam come from deep drill-holes. The entire capital city of Reykjavik is heated in this way and, in total, 85% of the households in the country. The heat is also used for greenhouse warming and the production of electricity. Hot springs are also very popular for bathing and washing throughout the country; some have a natural content of carbon dioxide.

Geothermal water with a lower temperature than on Iceland occurs in deep-seated sedimentary strata in Denmark and S Sweden and is utilized for heating by means of heat pumps. The most successful example is the district heating of 35% of the households in the medium-sized town of Lund in S Sweden. This is achieved by pumping of water (+16–21°C) in four 700–750 m deep wells in Cretaceous sandstone and reinfiltration of the used water in five other wells. The system has been in function for 22 years. Another system with two very deep (2300 m) wells in Triassic sandstone and fairly hot water (+82–83°C) has recently been established for heating in the capital city of Copenhagen (Bjelm, 2007).

Groundwater chemistry in the Nordic Countries: notable characteristics

Good knowledge of both the chemistry of groundwater and pollution problems exists in the Nordic countries. There are well documented examples of saline groundwater in coastal areas, chloride pollution by de-icing salt from roads, other types of pollution from roads, airfields and industries as wells as nitrate and pesticide pollution in agricultural areas. However, only some particularly noteworthy characteristics are mentioned here.

Bacteria, brines and mixed water at great depths

Intense investigations in connection with the underground storage of nuclear waste have mostly reached a depth of 500–700 m (maximum 1700 m). A few very deep holes have also been drilled for energy and scientific purposes to a maximum depth of 7,000 m in Sweden. And many drillings have been made for gas and oil in Denmark and Norway and for geothermal energy in Iceland.

Groundwater in the Precambrian crystalline rocks at depths below 1,000 m is saline (30,000–100,000 mg Cl/l) with a turnover-time of thousands to millions of years (Laaksoharju and Wallin, 1997). A very interesting discovery is that a special type of bacteria exists at these great depths. This type has carbon dioxide as a source of carbon and uses energy from hydrogen gas, which diffuses from very great depths (Pedersen, 2000). The microbes act as a catalyst for many of the inorganic reactions in groundwater, which would otherwise not take place. The groundwater down to a depth of 1,000 m and close to the Baltic Sea is a mixture of the old saline groundwater and water of other origins. The complex groundwater evolution at depth is a result of many factors such as: a) the present-day topography, water-table and proximity to the Baltic Sea; b) past changes in hydrogeology related to glaciation and deglaciation, land uplift and repeated marine and fresh water regressions and transgressions; and c) organic or inorganic alteration of the groundwater composition caused by microbial processes or water/rock interactions. The major discovery is that changes resulting from glacial rebound and land uplift (hence hydrogeology) seems to have a major influence on the groundwater chemistry at depth (Blomqvist, 1999; Laaksoharju 1999; Pitkänen et al., 2004).

Certain quality problems

Radon in groundwater has been observed in springs for more than 100 years, when radioactive water was supposed to be beneficial. Some information on radon in groundwater was gathered during the time of uranium prospecting in Sweden in the 1950s. However, most data has been collected during the last few decades for radiation-protection purposes. Today there is also an interest in the radium and uranium content in groundwater. The highest concentrations of radon have been found in water from drilled wells in Precambrian young granites and pegmatites (Knutsson and Olofsson, 2002), and in Norway also in a Permian granite around Oslofjord (Banks et al., 1998). The maximum values hitherto observed are 77,500 Bq/l in S Finland (Leveinen et al., 1998), 57,000 Bq/l in SW Sweden (Åkerblom and Lindgren, 1997) and 31,900 Bq/l in SE Norway (Banks et al., 1998). A regional study in the county of Bohuslän (SW Sweden) showed that 31% of the drilled wells had a radon concentration above 1,000 Bq/l (the mandatory limit for private wells in Sweden), while another study in the county of Stockholm showed that 11% of the wells had values above 1,000 Bq/l. However, great local differences were found, mostly related to the type of bedrock (Knutsson and Olofsson, 2002). The analysis of radium and uranium in groundwater in Sweden identified relatively high concentrations of uranium, but mostly low concentrations of radium. The highest values of uranium (100–300 μg/l) were found in drilled wells in the same type of bedrock as for high radon; 23% had values above the mandatory value 15 μg/l (Ek, 2005). The maximum value in Norway was recorded at 750 μg/l and 18% were above 20 μg/l (Frengstad et al., 2000), but the most extreme value of uranium in Nordic groundwaters was found in S Finland: 12,400 μg/l (Leveinen et al., 1998). The health risk for uranium is, however, not so much the radiation problem as the serious effect of uranium as a heavy metal on the kidney function.

Acidification is a natural process, which has gone on for a long time in poor, podsolic soil on acid overburden and bedrock, whereby shallow groundwater with low alkalinity also has developed low pH. However, the Nordic Countries (except in Iceland) have also experienced a period of increased acidification due to acid rain. Time-series indicate that some types of groundwater have changed their composition, as has been shown in the research catchment of Birkenes in Norway. Alkalinity and pH decreased significantly in drilled wells in sandy aquifers in SW Denmark during 1950–1986, as it did in some Finnish and Swedish shallow wells and springs in regions with acid deposits and rocks in the 1970s and 1980s; these changes were accompanied by increased concentrations of Al, Ca, Mg and SO_4 (Knutsson 1994). The reduction of acid precipitation has now stopped the acidification, and some groundwaters have even recovered.

Fluoride is a common component in groundwater from crystalline rocks and in volcanic areas, for example, in hot springs on Iceland. There are some similarities in the geologic distribution of fluoride and radon in crystalline rocks, especially to young granites. Lahermo et al. (1990) found the strongest correlation between fluoride and rapakivi granite in SE Finland, with the highest value of 5.8 mg/l, but in general 15–17% were above the drinking water limit of 1.5 mg/l (Leveinen et al., 1998). The highest value in Norway

(8.26 mg/l) is, however, reported from mafic rocks in W Norway. 16% of the drilled wells in Norway had values above the drinking water limit (Banks et al., 1998) compared with 25% of the drilled wells in Sweden (Aastrup et al., 1995).

Heavy metals such as As, Cd and Pb are observed in groundwater in crystalline rocks, especially those with pyrite and sulphide mineralizations. But heavy metals are also found in groundwater in volcanic and some sedimentary rocks, for example, alum shale. In SW Finland, 15% of the investigated drilled wells had a concentration of As above the drinking water limit of 10 μg/l, with values up to 1–2 mg/l (Leveinen et al., 1998). In Norway, 1.5 % of the drilled wells had values above the limit (Frengstad et al., 2000), and in Sweden 5%, but 2% had values above 100 μg/l and still higher values were recorded in a sulphide mine district in N Sweden (Socialstyrelsen, 2006). Surprisingly, arsenic has also been found in several production wells in sedimentary rocks and Quaternary deposits in Denmark. Heavy metals may also derive from pollution and it is possible to distinguish the real origin of some of these metals by means of analysis of the isotope ratios, for example, ^{206}Pb/^{207}Pb .

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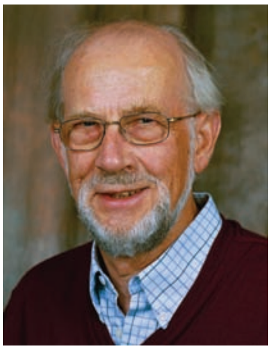

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Environmental Geology

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The mining environment, medical geology and urban geochemistry form a group of related scientific disciplines that have developed strongly during recent years in the Nordic countries. Modern legislation controls the environmental issues. Close co-operation of researchers and legislators has improved the quality and safety of life in the societies of the Nordic countries. In mining environmental studies, methods that are suitable in Arctic conditions have been developed; in medical geology, the input from the Nordic countries has made it an appreciated scientific discipline throughout the world, and in the case of the urban environment, methods developed by our geochemists have especially improved the health conditions, particularly of children.

Introduction

Environmental geology deals with many issues closely related to the life of human beings. Many disciplines of environmental geology are strongly developed in the Nordic countries. Sub-arctic conditions with long winters and thick snow cover provide special challenges in e.g. environmental management of mine wastes. On the other hand, environmental problems connected with volcanism and earthquakes hardly exist in the Nordic countries, except on Iceland. In this paper, we selected three special topics: the mining environment, medical geology and urban geochemistry to introduce some highlights of environmental research in the Nordic countries. In mining environmental studies, methods suitable in Arctic conditions have been developed; in medical geology, successful input from the Nordic countries has been a key issue, and applications developed by our geochemists have improved the health of citizens living in urban areas. Some other topics are discussed in other papers in the present volume.

Urban geochemistry

Urban soil is a key environmental topic considering the increasing urbanisation of our world. Processes that lead to urban soil pollution pose serious challenges to the management of urban environments. Cities and towns have been affected by the inward migration of large numbers of inhabitants during the last century, largely because of the concentration of goods and services that cities offer. Now, 70–80 per cent of the population in the Nordic countries lives in cities or towns. The urban environment is affected by a wide variety of anthropogenic activities (e.g., Berglund et al., 1994; Birke et al., 1992; Ahlgren, 1996; Mielke, 1999; Ottesen et al., 2000a; Mielke et al., 2005). In general, most products we use in our daily life pollute our environment during their production, use and disposal as waste. Typically, the urban soils are used and reused several times and a chemical imprint from each generation can be found.

Soil types within towns and cities vary greatly, ranging from relatively undisturbed natural soils, similar in some respects to their rural counterparts, to completely man-made products. Artificial landscaping and imported topsoil are a common feature within cities. For example, the inner city of Trondheim, Norway has, on average, two meters of man made soils (Ottesen et al., 2000b). Soils act as reservoirs for heavy metals and organic micro-pollutants from various sources. Human activity may create pathways from these reservoirs to the urban populations, thus, influencing human health.

Geochemical mapping, pollution sources and the dynamics of urban soil

Systematic geochemical mapping based on sampling and analysis of surface soils (0–2 cm) has been carried out in several Norwegian cities since 1994 (Ottesen et al., 1995); in other Nordic countries the systematic work started some years later (Salla, 1999; Peltola, 2005; Salonen and Korkka-Niemi 2007; Lax and Selinus, 2005; Ljung et al., 2006). Typically the soils in the oldest parts of the cities are polluted with metals (especially Pb) and polycyclic aromatic hydrocarbons (PAH). Surface soils in the younger suburban parts of the cities normally show lower concentrations of these compounds (Ottesen et al., 1999a; Jartun et al., 2002); however, polychlorinated biphenyls occur there (Andersson et al., 2004). The arsenic concentrations in soils at child day-care centres were often found to be higher than those in soil with other land use. Cu-Cr-As-(CCA) impregnated wood has proved to be the pollution source in day-care centres and play-grounds (Langedal and Hellesnes, 1997). A number of other sources, such as traffic, flaking paint, building wastes, city fires, waste incinerators, hospital incinerators, crematories, and industrial activity contribute to the pollution of the urban environment. The natural content of arsenic, metals and organic pollutants in the urban environment has been documented by analysis of 4–5 m deep soil samples (Ottesen et al., 2000; Langedal and Ottesen 2001), samples of bedrock (Ottesen et al., 1999b; Jartun et al., 2002), samples of overbank sediments (Ottesen et al., 1995), and by collecting samples from similar soil types around cities (Salla, 1999; Tarvainen et al., 2006; Salonen and Korkka-Niemi, 2007). The levels of the observed concentrations of contaminants in urban soils are of concern for human health.

Land use changes with time. It is now very common to develop dwelling areas in city centres and on old industrial sites. Changes in land use result in large volumes of surplus soils, after excavation. Ottesen and Haugland (2003) calculated the total volume of excavated masses from the polluted inner parts of four Norwegian cities in 2001 (Table 1). That year, 3.8 Mm^3 soil was re-dug up and moved in the four investigated cities. 1.2 Mm^3 were from older parts of the cities and therefore were probably polluted. Uncontrolled transportation of surplus soil is a very efficient method for spreading pollution.

Table 1 Data on volumes of excavated soil in four Norwegian cities in 2001.

Cities	Total amount of excavated masses (m^3)	Amount of polluted excavated masses from inner city (m^3)	Amount of polluted excavated masses delivered to approved landfill (m^3)
Oslo	1 612 000	850 000	16 000
Bergen	947 000	241 000	4 000
Trondheim	715 000	77 000	27 600
Tromsø	530 000	35 000	0

In addition to health risk evaluation, the urban geochemical data is used as background information in remediation of contaminated land sites. The Geological Surveys of Finland and Sweden have a programme in which they produce geochemical baseline data in the surroundings of the major cities.

Soil pollution in day-care centres and playgrounds

Studies of metal concentrations in playground dust ingested by children via the hand-to-mouth pathway have been carried out in a number of places (Calabrese et al., 1997). There is substantial evidence that a high Pb level in the environment can affect Pb levels in children's blood, thereby influencing their intelligence and behaviour (Mielke, 1991; Mielke et al., 2005).

Based on the results from systematic geochemical mapping, it was early realized that special focus must be directed towards soils in day-care centres and playgrounds. More than 75% of Norwegian children spend a long day in day-care centres. In four cities, a geochemical mapping and remediation program was initiated and conducted from 1996 until 2006. Surface soils (0–2 cm) were preferably collected from places where bare soil was visible, e.g., close to playing equipment, in areas where grass lawns had been worn down, in holes dug by the children, etc. The health risk evaluation was primarily focused on estimating the element exposure from soil through the three exposure routes: skin, oral and respiratory. To evaluate whether the soil pollution could contribute significantly to the children's health, the exposure from soil was compared with allowable intakes and background exposure levels from other sources (food and drinking water). Health risk evaluations have so far been carried out for As, Cd, Cr^{6+}, Hg, Ni, Pb, PAH_{sum16}, benzo(a)pyrene and PCB_{sum7} and the Norwegian Institute of Public Health has developed quality criteria for these components in soils in day-care centres and playgrounds.

The first project was carried out in Trondheim in 1996, where the CCA-impregnated wood in playing equipment was well documented. Later it was detected that the soil in all day-care centres in Tromsø was polluted with As due to use of CCA-impregnated wood. After these observations a process was initiated to ban this product and eventually it was banned in 2002 in Norway. In the inner city of Bergen, 45 out of 87 day-care centres were polluted to a degree that required remediation mainly due to concentrations of As, Pb and benzo(a)pyrene exceeding the recommended action levels. In Oslo, 34% of 700 day-care centres had to renovate the soils, due mainly to As, Pb and B(a)P, and to a smaller extent, Hg, Cd, Ni and PCB. Figure 1 illustrates the mean content of benzo(a)pyrene in 700 day-care centres in Oslo.

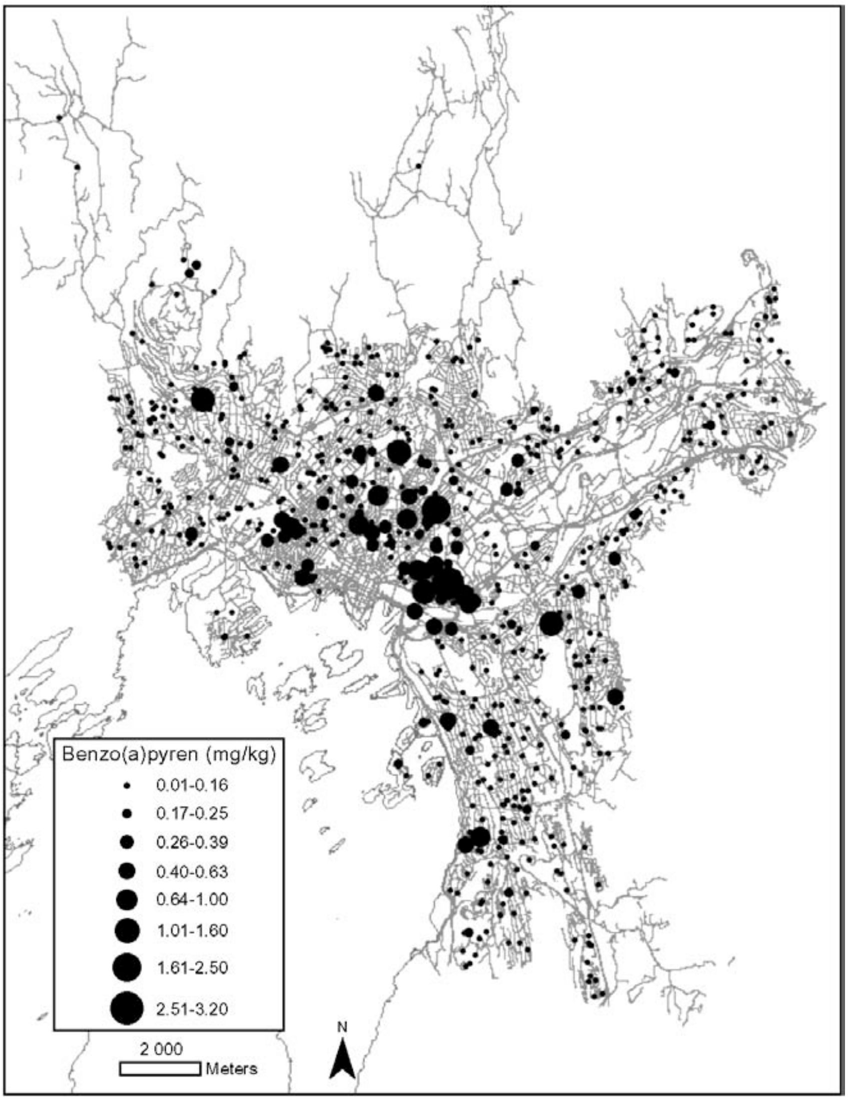

Figure 1 Content of benzo(a)pyrene in urban soils from day-care centers in Oslo, Norway. The symbol represents the mean value of 10 sample in each of 700 day-care centres (Geological Survey of Norway, unpublished data, 2007).

These projects convinced the present Norwegian government that soil pollution in day-care centres and playgrounds is an important health issue. The government presented an action plan in 2006, for mapping and, if necessary, remediation of all 6000 day-care centres and 40 000 playgrounds in Norway. The work started in ten cites and five industrial towns in 2007. Ten samples of surface soil (0–2 cm) are collected from each locality and analysed for As, metals, 16 PAHs and 7 PCBs. Samples from the industrial towns have an extended analytical program. The Geological Survey of Norway has developed routines for the mapping (field-, laboratory- and reporting- manuals) and is responsible for quality control. These ten cities and five industrial towns will be mapped during 2008 and necessary remediation completed before the summer of 2010. A proposal for an action plan to handle the day-care centres and playgrounds in the rest of Norway will be developed within the same time limit.

Urban geochemistry in land use planning

Concurrently with reorganizing the geological mapping programmes in the late 1990s, urban geochemistry projects were initiated in Sweden. The city planners and city environmental authorities are involved in urban geochemical projects and the results are adapted to the needs of the planners in Sweden and Finland. Typically these projects include sampling of surface soils, deeper soils, water, and other media. All types of geological information were mapped and used in this programme. In Gothenburg, the completion of the project was marked by the publication of an atlas (Selinus et al., 2001), which includes information on heavy metals, organic compounds, and natural background values in different sample media. Since then, Västerås and Stockholm have been completed and seven other large cities in Sweden will be covered before 2009. In Finland, a pilot project was carried out in Porvoo and the next target is the district surrounding Helsinki (Tarvainen, 2003; Tarvainen, 2006).

These programmes were largely focused on the analysis of soil by sampling within the cities and their nearest surroundings. A representative set of undisturbed, natural soils is sampled, both from the C-horizons (variable depth, mostly >0.6 m) and top soil samples (sampling depth, 5–25 cm). The parameters analysed are the same as in the regional mapping programmes, which facilitates comparison with samples collected from sites subject to no or extremely weak diffuse pollution. Sampling density is higher than for regional mapping and depends on the size of the urban area, the geology, and the sampling media. Topsoil samples are collected regardless of the type of Quaternary deposit, with a maximum sampling density of 1 sample/2.5 km^2.

Biogeochemical methods are also a part of the urban geochemistry programme in Sweden. Since natural vegetation usually is scarce or lacking in urban areas, transplants of *Fontinalis antipyretica* are used. Adapting a method recommended by the Swedish EPA (Naturvårdsverket, 1999), the transplants consist of sub-samples collected from an unpolluted site that have been stored in pure water for a few weeks prior to exposure to the water of investigated streams.

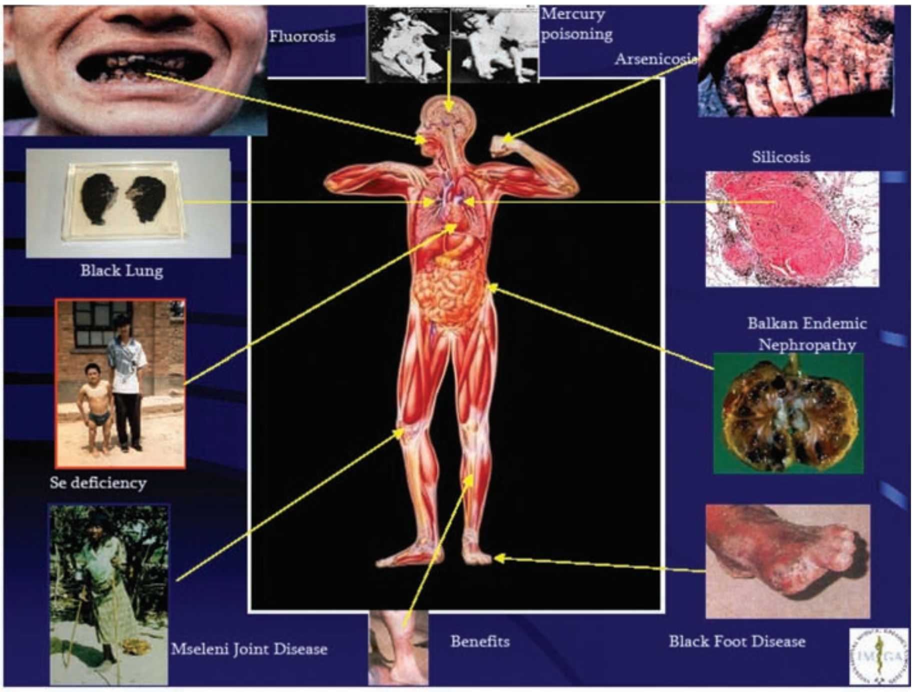

Figure 2 Examples of effects of geology on the human body (Finkelman, R. B.).

Site selection in urban areas is based on avoidance of known contaminated sites. Planning therefore involves contacts with relevant authorities, and most sampling is conducted in "green" areas, like parks, etc. Surrounding rural areas are also sampled to find the local natural background values of elements. The higher sampling density allows a statistical approach in order to verify visually interpreted diffuse pollution. Experience has shown that some samples have been subject to point source contamination; anomalous levels of element associations, typically not present in geological media, are sometimes encountered.

Geology and health in Scandinavia

Geologic factors play key roles in a range of environmental issues that impact the health and well-being of billions of people worldwide (Figure 2). But there is a general lack of understanding of the importance of these factors on animal and human health among the general public, the biomedical/public health community, and even within the geoscience community. The Scandinavian countries have been very active in this field for decades, have made important scientific contributions and have helped to raise awareness of these issues.

Two tracks in Scandinavia: medical geology and geomedicine

The first track is Medical Geology. In 1996, the IUGS commission COGEOENVIRONMENT established an International Working Group on Medical Geology led by Olle Selinus (Selinus, 2002a, b; Skinner and Berger, 2000; Bowman et al., 2003). In 2000, the International Geological Correlation Programme (IGCP) established a new project "IGCP 454 Medical Geology", chaired by Olle Selinus with co-chairs Peter Bobrowsky (Canada) and Ed Derbyshire (UK). This initiative was developed into the IUGS Medical Geology Working Group. Its main activity during the recent years has been to provide short courses on medical geology to developing countries where there are critical medical geology problems. These courses have now been presented on 33 occasions all over the world and have been attended by thousands of students and professionals. A textbook on Medical Geology (Selinus et al., 2005) with c. 60 authors, (about 50% geoscientists and 50% medics, veterinarians and other scientists) has been granted three distinguished international awards. The International Medical Geology Association (IMGA) was finally launched in January 2006 (www.medicalgeology.org) with councillors and regional divisions established all over the world (Finkelman et al., 2004).

The second track is in Geomedicine, defined as the relation between natural environmental factors and health. In addition to the composition of rocks, soils, and water, this field considers factors related to climate and radiation, and deals with human as well as animal health. This scientific discipline was first defined by Professor Jul Låg, Agricultural University of Norway, and is described in his book *Geomedicine* (Låg, 1990). In the Norwegian Academy of Science and Letters, the "Committee on Information and Research in Geomedicine" (*www.dnva.no/geomed*) has been active since 1984. Norwegian scientists (Jul Låg and Eiliv Steinnes) have promoted geomedicine as a subject in the International Union of Soil Sciences.

Examples of research

In Sweden, research started in the 1960s on coronary heart disease and hard water. Later, a large study was carried out on Diabetes type 1 in children, which resulted in evidence for a correlation between high contents of Zn in drinking water and this type of diabetes (Haglund et al., 1996). In the 1980s, when thousands of moose died in Sweden, close collaboration between veterinarians and geochemists showed that this disease was found to be the result of liming of acidified areas (Selinus and Frank, 2000; Selinus et al., 1996). The liming mobilizes molybdenum in bedrock and soils, causing a disturbed Cu/Mo ratio which is important for the health of ruminants. Much attention has also been focused on the health effects of radon and, in recent years, on the effects of natural arsenic in drinking water (Selinus et al., 2005). There has also been a focus on a serious genetic disease, Morbus Gaucher, with links to the old mining activities in the mountain areas of northern Sweden in the 17th century (Hillborg, work in progress). Research is also carried out on the effects of the Chernobyl disaster (Tondel, 2007) and currently on the links between geology and *Multiple Sclerosis* (Eliaeson, work in progress). These are just a few examples of research activities in medical geology in Sweden. It is important to stress that all this research has been undertaken as a close collaboration between geochemists and medical scientists, epidemiologists, toxicologists, veterinarians, etc.

In Norway, problems of geomedical character have been known for a long time in human as well as veterinary medicine. As an example, the connection between iodine deficiency and goiter, most prevalent in areas situated far from the ocean, was known already in the 1920s (Låg, 1990).

A number of investigations have been performed over the years on deficiency problems in animal husbandry related to low abundance of essential trace elements in pasture soils. Currently a large-scale geographical study is being carried out on the status of essential trace elements in grazing domestic ruminants in Norway, and the factors that determine this status (T. Sivertsen et al., work in progress).

At the Geological Survey of Norway, geomedical research has been carried out since 1971. This activity has included multi-element countrywide geochemical mapping and correlation of spatial distributions of geochemical and other types of natural data with the epidemiology of endemic human diseases. An example of this work is a comparison of the composition of drinking water from the main water works all over Norway with the geographical distributions of various types of cancer and other diseases (Flaten and Bölviken, 1991). Interesting regional distributions of elements were disclosed, although no strong correlations were evident between the chemical and corresponding epidemiological data. A novel method for spatially moving correlation has been developed. By the application of this method, several geomedical associations were revealed, including significant correlations for rates of the occurrence of *Multiple sclerosis* with Rn in indoor air (positive) and atmospheric deposition of marine salts (inverse) (Bölviken et al., 2003). By considering data in the literature, strong associations were observed in China for rates of *nasopharyngeal carcinoma* with the soil contents of Th and U (positive) and Mg (inverse).

In Finland, during the past few decades, studies of the effect of selenium, arsenic, radon and certain other substances such as asbestos, on human health have been carried out (e.g. Koljonen, 1975; Lahermo et al., 1998; Kurttio et al., 1999; Nikkarinen et al., 2001; Kokki et al., 2001; Kurttio et al., 2006; Piispanen, 2000; Szalay et al., 1981). There were also recent studies of environmental risk assessment and the spatial variation of certain chronic diseases in relation to the geological or geochemical environment (*http://www.eracnet.fi*; Kousa et al., 2004). GIS and geo-referenced data allow studies that benefit from a flexible geographical scale, for example grid cells instead of administrative boundaries. During the last ten years, the Geological Survey of Finland (GTK) and the National Public Health Institute (KTL) have carried out studies of the spatial variation of acute myocardial infarction (AMI) (Kousa et al., 2006) and the incidence of childhood type 1 diabetes (T1DM) in relation to the geochemistry of local groundwater (Moltchanova et al., 2004). Results of recent studies have suggested that water hardness, especially magnesium, in well water has an inverse relationship with geographical variation of AMI risk in Finland. The incidence of T1DM was not associated with the concentration of nitrate or zinc in well water at the population level.

Environmental risk assessment methods are increasingly applied to investigate small- and large-scale environmental problems and their impact on human health. GTK, KTL and the University of Kuopio have recently founded the Environmental Risk Assessment Centre (ERAC) to conduct scientific research and to develop new projects (*http://www.eracnet.fi*). The ERAC is based on multidisciplinary networking and co-operation, ranging from geochemistry, geology, biogeochemistry and ecology to environmental sciences, toxicology, epidemiology, risk analysis and the political sciences. One objective of ERAC, in co-ordination with The Finnish Cancer Registry, is to investigate relationships between cancer risk and exposure to natural elements in soil. Another multidisciplinary project, FINMERAC (Integrated Risk Assessment of Metals), improves risk analysis methodology using two selected metal industry areas and one mining target area as examples of environmental pollution, thus providing different challenges for risk assessment and management (*http://www.eracnet.fi*). Application of the Rapid Inquiry Facility (RIF), developed by Imperial College London together with international partners, operates with ArcGIS software, making possible the study of local and national scale health concerns, such as occurrence of cancer cases near particular industrial plants (or near all similar plants in the country). Partners of the FINMERAC project are GTK, KTL, the University of Kuopio, and the Finnish Environment Institute.

It can be concluded that the Nordic countries have been very active in research on geology and health for many years. This has resulted in close collaboration between geoscientists and the medical authorities, many publications including several books, as well as international recognition and leadership in this discipline.

Mining and the environment

Mining of metals has long and rich traditions in the Nordic countries, particularly in Finland, Norway and Sweden. Falun copper mine, in south central Sweden, where hard rock mining is thought to have commenced already during the Viking era around 800 A.D., is the oldest known metal mine in the Nordic countries; production continued until 1992. The mining industry is still very important for Finland and Sweden, where the European Union's most promising areas for finding new ore deposits are located.

Mining operations require large areas of land and associated conflicts arise that are primarily related to competing land use, fugitive dust, vibrations and, inevitably, large amounts of mine waste. The largest copper mine in Europe, at Aitik in northern Sweden (Figure 3), has an average copper concentration of c. 0.4 %; 99.6 % of the ore has to be deposited as waste after processing. Gold is mined in deposits with a grade as low as a few g/t., thus the major parts of the ores will be waste. During 2003, all the metal mines in Sweden together generated 58.9 Mt (million tonnes) of waste, 24.8 Mt of tailings and 34.1 Mt of waste rock (Höglund et al., 2004). However, the main environmental problem with mine waste is not the volume, but

Figure 3 The Aitik copper mine with the open pit, with waste rock dumps in the foreground and the tailings impoundment in the background (photo by Boliden Mineral).

the acid drainage waters (AMD) which often have high concentrations of dissolved metals.

The Swedish biologist Carl von Linné observed, already in the 18th century, that the Falu river was polluted by drainage waters from the Falun copper mine. However, it was not until a few decades ago that it was realised that AMD causes serious damage to the environment. Today, the Nordic mining industry and public organisations are in the forefront of the research concerning the mitigation of pollutants from metal mining, and the geosciences play a leading role.

Methods to mitigate the environmental impact of mine waste

Mine waste needs to be managed by using principles that control the environmental impact in both short and long term, the latter being a factor of particular importance. Neutralizing AMD by liming is common, but this generates a sludge rich in iron oxyhydroxides and heavy metals, thus generating a new type of metal-rich waste. The environmental authorities and the mining industry in the Nordic countries prefer remediation methods that will last for very long times (to the next glaciation) with a minimum of maintenance.

Actions to prevent the formation of acid drainage from mine waste deposits are usually directed towards reducing the amount of oxygen reaching the waste. The most common methods are to apply dry covers consisting of several different layers, usually including various soil types; alternatively, the waste can be covered with water (Figure 4). Both dry cover and water cover methods are based on the solubility and diffusivity of oxygen being much lower in water than in air. Soil covers therefore in most cases contain a sealing layer with low hydraulic conductivity, which is aimed at having a high degree of water saturation. The sealing layer then functions as a barrier against oxygen intrusion also in cases where the groundwater surface is far below the cover.

Various types of dry covers have been studied (e.g. Höglund et al., 2004). One conclusion is that, although dry covers may be effective, they are expensive to construct. A type of dry cover often used by the Nordic mining industry consists of a sealing layer of clayey till with low hydraulic conductivity, and a superimposed protective layer of unclassified till. Modelling based on extensive lab- and field studies has shown that the oxygen flux through this type of dry cover will be about one mole O_2/m^2 per year, implying a very strong reduction compared to the pre-remediation conditions (Höglund et al., 2004).

Other materials such as cement-stabilized fly-ash and organic waste (paper mill sludge and sewage sludge) have also been used as sealing layers. The organic waste is intended to function not only as physical barrier, but also by consumption of oxygen during decay of the organic matter. Sewage sludge is used for establishment of vegetation on covered waste and on tailings impoundments lacking cover.

Since 2000, the Geological Survey of Finland has investigated the environmental impact of mine waste, and has tested innovative remediation methods such as the use of magnesite tailings from a talc operation as the sealing layer in dry cover (Räisänen et al., 2005), and the utilization of natural reactions in wet-land treatments for collecting heavy metals from AMD (Räisänen, 2003). Geophysical methods have been used for characterizing tailings impoundments, related dam constructions, and underlying bedrock and soil structures (Vanhala et al., 2004).

Water cover reduces the rate of oxygen transport to a level that often is acceptable. Water coverage is achieved by underwater disposal of tailings during production, either in natural lakes or in tailings ponds that are deep enough. Conventionally operated impoundments, with discharge along a beach, may also be permanently protected by a water cover after mine closure by raising the dam walls along existing impoundments. Another possibility in complex mining areas is to deposit tailings in pit lakes, which may have anoxic bottom waters. Water cover is generally regarded as one of the most cost-effective methods for the mitigation of acid-generating mine tailings. Among the benefits of using water cover is the reasonably low maintenance required and beneficial side effects such as the prevention of dust formation. A major drawback of the method involves the construction of dams and dikes that often need maintenance and monitoring for long time periods. It remains to be proven that dams built at reasonable cost are effective for time scales of hundreds to thousands of years. This effectiveness includes both the geotechnical stability of the dam structures, and the long-term water balance for the water cover. According to the current policy of the Swedish Environmental Protection

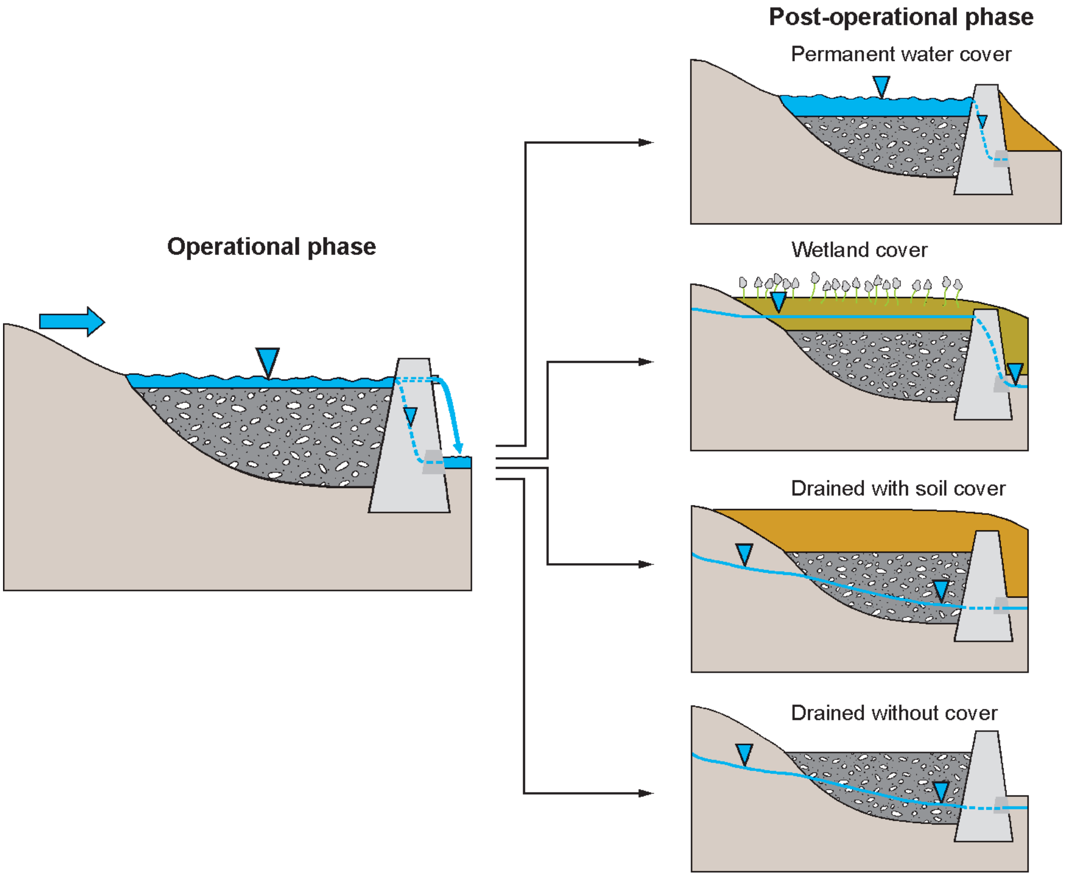

Figure 4 Illustration of some basic alternatives for remediation of mine tailings. The last alternative is not feasible if the tailings are potentially acid generating (from Höglund et al., 2004).

Agency, it is extremely difficult to get permission to use natural lakes for disposal of mine waste, which in many respects would be the best solution. They also consider it to be impossible to construct dams that will stand for very long time periods without maintenance, and therefore prefer dry cover as the remediation method for mine waste.

Norwegian researchers did some pioneering studies on the use of water cover (Arnesen, 1993; Arnesen et al., 1997). In the Hjerkinn tailings pond, sulphur-containing tailings from a Cu-Zn mine were deposited subaqueously between 1968 and 1993. The area of the tailings pond was 1 km^2. The minimum water depth was 1 m, which is considered not sufficient to prevent re-suspension. After deposition ceased, the water quality has been considerably improved. In another Norwegian tailings pond, situated at Løkken, tailings were deposited from 1974 to 1987. The minimum water cover depth was 1 m. Mine waste seepage was pumped into an underground mine, where heavy metals and suspended solids settled to the bottom. The Cu concentration in the outlet water from the mine was 99% lower than in the inlet water.

A well-known and well-studied mine site where water cover has been used is Stekenjokk, a stratabound volcanogenic Zn-Cu deposit of Caledonian age, situated in northern Sweden close to the Norwegian border. During the operations of Boliden Mineral from 1976 to 1988, 8.08 Mt were mined mainly by underground cut and fill operations. Mining left some 4.4 Mt of tailings containing about 20% sulphur, mainly occurring as pyrite (FeS_2). A decommissioning programme based on flooding was completed in 1991. Flooding was achieved by raising the water level in the tailings and clarification pond by raising the existing dykes. A breakwater system was built to prevent re-suspension from the tailings surface. The pond has an area of 1.1 km^2 and a water volume of about 2 Mm^3. Water depth is on average about 2 m. Field studies have shown that pond water is well mixed and oxic the whole year round, and has low metal concentrations. Layers rich in iron and manganese oxyhydroxides have been developed close to the tailings surface, and a layer of natural sediments rich in organic material has developed on the tailings surface since the flooding. The oxyhydroxides adsorb and/or co-precipitate metals and function as a trap for metals released at the interface between tailings and pond water. This illustrates that it is possible even in northerly areas for a deposit of flooded tailings to quickly reach a state when it functions almost as a natural lake, with Fe- and Mn-oxyhydroxide layers controlling the diffusion of metals into the overlying pond water (Holmström and Öhlander, 2001).

For very large deposits of mine waste, both dry cover with a sealing layer and water cover may be unrealistic. At the Aitik mine (Figure 3) in northern Sweden, operated by Boliden Mineral, the ore is mined in an open pit at a production rate of 18–19 Mt of ore per year, resulting in up to 36 Mt of waste (Lindvall, 2005). At a mean production level of 25 Mt/year, the mine will be in production at least to 2020. The depth of the final pit will be close to 600 m. Chalcopyrite ($CuFeS_2$) is the copper source, at an average concentration of 0.4 % Cu. The ore further contains Au (0.2 g/t) and Ag (3.5 g/t).

The waste rock is deposited in dumps with an area of c. 400 ha. Around 300 Mt of waste rock have currently been deposited. At the time of closure, at least 750 Mt of waste rock will have been produced. The dumps are located on c. 10 m thick glacial till with low permeability. Almost all water infiltrating through the dumps is collected as toe drainage in drainage ditches and used in the milling process. The tailings pond, occupying an area of 11 km^2, is delimited by the natural topography and four dams. The tailings are pumped as slurry from the concentrator to the discharge area along the upstream dam and distributed onto a 5 km long and 2 km wide beach. Tailings layers have reached the 40 m level. The free water volume in the tailings pond is normally around 2 Mm^3, covering 20% of the pond area. The 160 ha clarification pond has a holding capacity of 15 Mm^3 and constitutes the final water treatment step and a reservoir for mill process water. In a normal year, approximately 6 Mm^3 of water are discharged, resulting in a Cu load to the recipient typically below 50 kg. The concentrator operates exclusively on recycled water from the clarification pond.

About 20% of the waste rock is reactive (Lindvall, 2005). Old dumps containing so-called marginal ore, identified as the main metal source, have been removed and processed. Large quantaties of non-reactive waste rock are managed in a separate mass flow, allowing them to be a source for construction aggregates. Existing dumps of mixed waste rock, i.e., containing both reactive and non-reactive components, will be covered by a 0.5 m compacted till layer and a 0.5 m topsoil of till and some sewage sludge to establish vegetation and prevent erosion. The oxygen inflow is estimated to decrease to 1% of the level prior to application of the cover.

The future

The Nordic metal mining industry is very profitable, and there are still good possibilities to find new ores. Environmental standards are set high, and research aiming at development of cost-efficient technologies for prevention of environmental problems related to mining and remediation of mine waste is constantly going on. A new challenge facing the mining industry is that large areas with good potential in national parks and in other protected areas are excluded from industrial activities. National parks are completely protected, but in other restricted areas the environmental impact of mining should be compared with natural metal flows from mineralized bedrock to make it possible for society to take the right land use decisions.

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Climate change in the North – past, present and future

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The Nordic countries have produced famous polar explorers and researchers who have generated climate research schools at a variety of locations. The dependence of these countries with respect to the lifelihood of their societies, of their use of lands and seas, the exploitation of marine living and non-living resources have made climate research an eminent topic, and many outstanding discoveries of long- and short-term climate change have been made for the first time in Scandinavia. These include early contributions to our understanding of the geological effects of continent-wide glaciations during the ice ages, the complex postglacial history of the Baltic Sea and the varved sediment sequences preserved from lakes with an extraordinary seasonality in their sediment input, as well as the detailed records of temperature, ice texture and impurities and greenhouse gas variations of the last Glacial and of the Holocene preserved in the ice cores from Greenland. Iceland with its volcanic sequences and intercalated sediment layers not only preserved the history of this subaerial segment of the mid-Atlantic Ridge, but also easily datable paleoclimate records. The fate of the Vikings, who settled during the Medieval climate optimum on Iceland and later on Greenland and who lost their habitat on Greenland at the beginning of the Little Ice Age, illustrates vividly the climate-dependent subsistence of the indigenous and non-indigenous Scandinavian populations. Modern Scandinavian climate research institutions also include sophisticated modelling groups.

Why study the climate and its temporal variability?

Much of northwestern Europe and what is now Norden was buried under ice at the end of the last Glacial and Man could only migrate northwards after the Fennoscandian ice sheet receded. He did so early and with great success, but understood quickly that his well being depended on the climatic conditions. Medieval written records allow us to trace the build-up of relatively rich agricultural societies, which under the influence of the onset of the Little Ice Age and the Black Death in the 14th century, suffered severe losses. Fisheries along the west coast off Norway were dependent upon climatic and oceanographic conditions, and the possibilities to sail across the Norwegian-Greenland Sea were subject to sea-ice distribution.

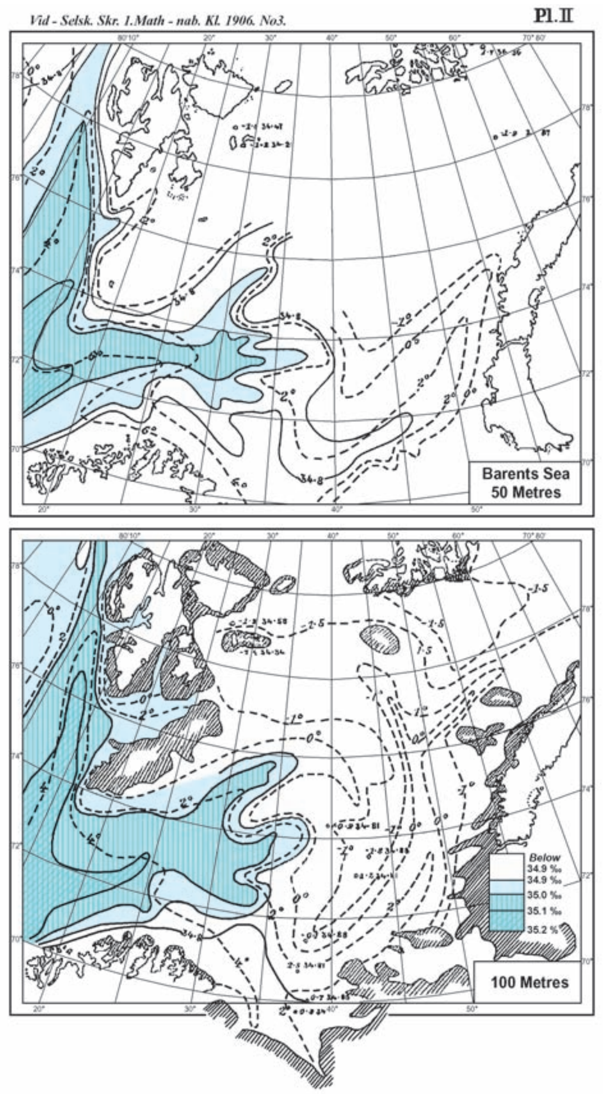

***Figure 1** Sea surface temperatures off Northern Norway and distribution of major water masses, published by Nansen (1906), based on the oceanographic observations of Amundsen during 1901.*

Nordic countries and academic institutions have therefore been a "Mecca" for climate and paleoclimate research from early on because the people concerned were keenly aware of the exposed geographic location of their countries in high northern latitudes, while enjoying relatively benign living conditions, extraordinarily comfortable as compared to other countries/continents like northern Siberia or North America at the same latitudes.

It was century-old knowledge that while the surface waters of the western Norwegian Sea and Greenland Sea off Greenland was cold and partly sea-ice covered, waters immediately off-shore Norway were much warmer and the home to important fisheries. Norwegian oceanographers soon began systematic investigations of the hydrographic properties of the major currents systems off Norway and they detected that an extension of the Gulf Stream System (now called the Norwegian Current) reached the Barents Sea and Svalbard (Nansen, 1906); hence, they understood that the regional extension of the temperate climate zones into high northern latitudes was closely linked to the atmospheric circulation over the northern hemisphere and the hydrography of the surface waters of the ocean basin adjacent to the Scandinavian peninsula (Figure 1). And it was also Nansen (1925) who speculated about the correlation of the impact of climate change on the fate of the Vikings who had settled on Greenland during the Medieval climatic optimum, but who had lost the ability for transoceanic voyages under the severe sea-ice conditions during the onset of the the Little Ice Age.

Meteorology and oceanography therefore developed early at a number of Scandinavian academic institutions because they were driven by the needs of shipping and fisheries. Successful polar expeditions such as those by Nordenskjöld, Nansen and Amundsen gave these disciplines a high public profile. The constructions of the Norwegian ships Fram and Maud, as the first dedicated purpose—built polar research vessels, represented milestones in this development because they provided for the first time state of the art, at that time modern scientific working platforms which at the same time guaranteed safety and healthy living conditions for their crews. It is therefore surprising that terrestrial paleoclimatology, in particular terrestrial Quaternary geology, emerged much earlier than its marine counterparts, namely paleoceanography and marine geology. The needs of weather forecasting and the increasing computing capabilities during the past 50 years created opportunities to model future climate scenarios, which are being continuously refined.

Terrestrial records of climate change

There is a substantial chapter devoted to the "Quaternary of Norden" by Wohlfahrt and others elsewhere in this volume which covers many aspects of climate change during the latest period of Earth history. But evidence for extreme climates over Scandinavia are not restricted to the Cenozoic, because outstanding discoveries have also been made to our understanding of glaciations older than the Cenozoic. Stratigraphic sequences with world famous outcrops of late pre-Cambrian tillites are known from the Varanger Peninsula in northern Norway and from the Sparagmite Basin near Oslo (Bjørlykke et al., 1976).

In countries like the Nordic ones, whose morphology was extensively reshaped during the Cenozoic glaciations and interglaciations, it was only natural that geoscientists tried to understand how and when this could have been happened. Studies of Paleogene sequences and their floras on Svalbard suggested long ago (Heer, 1876) that glaciations were relatively young and that widespread glaciations on the northern hemisphere only developed much later.

Esmark competed with his contemporaries on the nature and origin of glacial deposits and a rich culture of Quaternary research groups evolved in all of the Nordic countries (Wolfarth et al., 2008). They made contributions to the extent of the ice sheets, the nature of the interglacials, and the stratigraphy of Pleistocene and Holocene terrestrial and limnic deposits (Mangerud, 1982) based on a wide variety of techniques. Particular important were considerations of the interplay between isostatic and eustatic sea level changes and the extent of ice sheets. A particularly good example is the late Pleistocene and Holocene paleogeographic and paleoenvironmental history of the Baltic Sea basin (cf. Wohlfarth et al., 2008). Lately Scandinavian Quaternary geologists and paleoclimatologists have extended their studies to distant areas, mainly under the framework of international projects like PONAM (Funder et al., 1994) and QUEEN (Thiede et al., 2004; cf. Wohlfarth et al., 2008).

The probably most important contributions to Late Quaternary paleoclimatic studies come from the ice core research on Greenland, which started several decades ago in Copenhagen, under the leadership of Willy Dansgaard. By now, international teams are involved in collecting ice cores from all over world because they seem to provide excellent and, in part, very detailed records of temperature changes, of the historical variations of some of the most important greenhouse gases, as well as of impurities from a wide variety, but climatically often significant sources. In Figure 2, the most important features of the North Greenland Ice Core (North Greenland Ice Core Project Members, 2004) are illustrated; the glacial Dansgaard-Oeschger events display a series of short lived and dramatic climatic warming events interrupting the cold glacial climate over Greenland over very short spans of time, whereas the interglacial climates, in particular in the Holocene, are enigmatically stable. In Figure 2, the ice core record from Greenland is compared to data from the adjacent North Atlantic Ocean (Bauch and Kandiano, 2007) illustrating the intimate response of the paleoceanographic variability of ocean surface and bottom waters to the climatic changes observed over northern Greenland. The upper part of the Greenland ice core also clearly displays the early Holocene climatic optimum tending towards cooler temperatures afterwards. It will be highly exciting to trace the variabilities of tempartures and greenhouse gases in the youngest parts of ice cores, both from Greenland and from Antarctica.

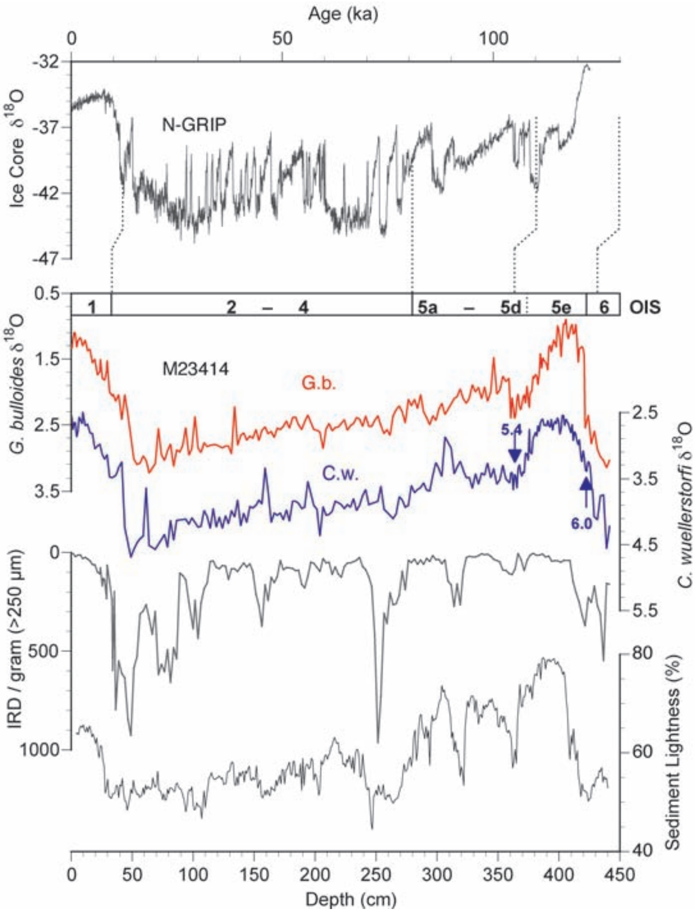

Figure 2 Comparison of Greenland ice core data (North Greenland Ice Core Project Members, 2004), in the upper panel, with proxy records from a North Atlantic sediment core M23414 (after Bauch and Kandiano, 2007, courtesy Dr. Henning Bauch, Kiel).

Paleoceanography and the history of seas in high northern latitudes

Despite the tradition in meteorology, oceanography and Quaternary geology, studies of the paleoenvironmental history of the Norwegian–Greenland Sea and of the Arctic Ocean only took off when Hans Holtedal (1955) studied the first sediment cores from the southern Norwegian Sea and detected the important changes in sediment composition at the transition from the last glacial maximum to the Holocene. He was preceded by the Swedish ALBATROSS expedition which circum-navigated the world and collected numerous sediment cores for paleoceanographic studies, mostly from tropical to subtropical seas (Olausson, 1996); these laid a foundation for many of the later stratigraphic studies of pelagic sediments. In the meantime, important research schools in several academic environments in high northern latitutes have risen from these early investigations.

Some 30 years ago, marine geophysicists succeeded to unravel the plate tectonic history of the Norwegian-Greenland Sea and of the eastern Arctic Ocean. The patterns of sea-floor spreading-type magnetic anomalies suggested that these ocean basins had started to open sometime between anomaly 24 and 25. Soon after these discoveries, the “Glomar Challenger” of the Deep-Sea Drilling Project visited the Norwegian–Greenland Sea during DSDP Leg 38, led by co-chief scientists Manik Talwani and Gleb Udintsev, to address four scientific questions, namely 1) the tectonic framework and evolution of the area, 2) the youngest times of the existence of land bridges between Eurasia and North America, 3) the date of initiation of northern hemisphere glaciations, and 4) to find Tertiary microfaunas and -floras. They succeeded splendidly and laid the groundwork for later legs of the “JOIDES Resolution” (Figure 3) which, under the framework of the International Ocean Drilling Program, visited the Norwegian–Greenland Sea during three expeditions (Leg 104—Dipping reflectors of the Vöring Plateau and history of the Norwegian Current, 151—North Atlantic Arctic Gateways I, 162—North Atlantic Arctic Gateways II). During Leg 151, the “JOIDES Resolution” even succeeded—accompanied by the icebreaker “Fennica”—to enter ice-free waters to the north of Svalbard, thereby bringing a scientific drill-ship for the first time into the Arctic Ocean. Lately, ECORD (the European Consortium of Ocean Research Drilling under the framework of the new Integrated Ocean Drilling Program) has organized a major drilling effort in the permanently sea-ice-covered central Arctic Ocean by sending a flotilla of three ice-breakers (including a drilling vessel) to the Lomonosov Ridge at a position very close to the North Pole (the ACEX expedition led by co-chiefs Jan Backman and Kate Moran). A host of new data addressing the four major themes already defined for DSDP Leg 38 have been collected as the results of these drilling efforts; contrary to common believe the Northern Hemisphere seems to have experienced widespread glaciations since Eocene times (St. John, in press).

Figure 3 JOIDES Resolution during ODP Leg 151 in the Fram Strait (Myhre, Thiede, Firth et al., 1995).

Modern arctic climates and their variability as expressed in the sea-ice cover and the oceanography of the Nordic Seas

Climate has a “memory” and modern climate scenarios can therefore only be understood, if we also have some knowledge of its historical variability, at various time scales. It has been clear for quite some time that the distribution of the Arctic sea-ice cover is a highly sensitive climate indicator. During the late 1970s, increased international interest led to new studies in the Marginal Ice Zone (MIZ) of the Nordic Seas. Several large international experiments took place such as the Norwegian Remote Sensing experiment in 1979 (NORSEX 79), the mega-science Marginal Ice Zone Experiment in 1983–1984–1987 (MIZEX 83, MIZEX 84, MIZEX 87), and the Seasonal Ice Zone Experiment in 1989 (SIZEX 1989), see Johannessen et al. (1992). The overall objectives of these experiments were to improve our understanding of the air-ice-ocean processes in the MIZ and to develop and validate remote sensing techniques. The concept and the strategy of all these experiments were to collect data from a three-level observational system—satellites, aircraft, and in-situ observations. Instruments on these varied platforms acquired a diverse suite of ice, ocean, and atmospheric data. From these experiments, we started to understand the mesoscale processes in the Seasonal Ice Zone (Figure 4). For example we learned that mesoscale ice-ocean eddies along the ice edge were very efficient in melting the ice edge. Furthermore that upwelling took place along the ice edge which is important for biological production during summer time.

Reviews of fragmentary observational evidence, taken together, provide a reasonably coherent picture of Arctic and subarctic change, indicating that the last 2–3 decades have experienced unusual warming over northern Eurasia and North America, reduced Arctic sea-ice, marked changes in Arctic Ocean hydrography, reduced glaciers and snow cover, increased runoff into the Arctic, increased tree growth in northern Eurasia, and reduced tundra areas and thawing (Johannessen et al., 2005). There have been fragmen-

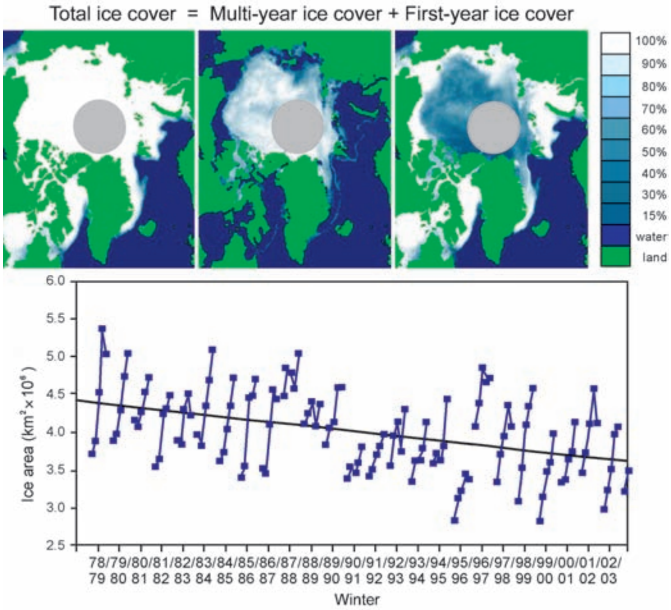

Figure 4 Upper three pictures—Arctic total sea-ice concentration (left) and its two components: multi-year (center) and first-year (right) ice, derived from satellite passive-microwave sensor data. The grey scale indicates the fraction (%) of each ice type (black = 0%, white = 100%). The lower diagram shows the variability and trend in multi-year ice area in winter, 1978–98. Source: Johannessen et al. (1999).

tary indications of unusual conditions in recent years, such as reduced ice concentration in the Siberian sector of the perennial ice pack in the 1990s and reduced ice thickness in parts of the Arctic since the 1970s (Johannessen et al., 1999). For example, Figure 5 infers the temporal evolution of the zonally averaged anomalies of annual mean surface air temperature from 30 to 90 degrees N. Two characteristic warming events stand out; the first from the mid 1920s to 1940 and the second starting about 1980 and still ongoing. Johannessen et al. (2004) inferred that the early warming was caused by natural variability and that the present warming was mainly caused by the increasing greenhouse gases of the atmosphere.

Complementary to the Arctic sea-ice and atmospheric changes, studied in the above-mentioned analyses, are changes in physical oceanography on similar time scales. This was studied through Norwegian–Russian collaboration (Bobylev et al., 2003). A similar early 20th Century warming was seen in the Atlantic Water (AW) temperature in the Arctic Ocean. Furthermore oceanographic data covering the period 1950–98 were compiled and used to determine interannual to decadal variations in the convective intensity and water mass structure in the Greenland Sea and adjacent areas. Extremely cold winters throughout 1965–70 intensified the vertical water exchange in the Norwegian–Greenland Sea. As a result, cold and fresh Greenland Sea Deep Water (GSDW) production was extremely high in the central Greenland Sea, while in the southern Norwegian Sea, warm and saline water spread downward. Long observational series obtained from Ocean Weather Station M confirmed the existence of layers with advection-driven high oxygen concentrations in intermediate and deep layers. A simultaneous rise in the NAO (North Atlantic Oscillation) index and GSDW temperature indicates a link between the atmosphere and the thermohaline circulation (THC).

The 21st century Arctic and European climate

In the beginning of the 1990s (Figure 5), when global warming started to be a major topic, the interest for studying the arctic climate increased. A consensus from coupled atmosphere-ice-ocean modelling studies of increasing greenhouse-gas (GHGs) scenarios is that anthropogenic global warming will be enhanced in the northern high latitudes, due to complex feedback mechanisms in the atmosphere–ocean–ice system. The predicted warming in the Arctic over the next 50 years is ~3–4°C or more than twice the global average. This suggests that the Arctic may be where the most rapid and dramatic changes (e.g., a shrinking sea-ice cover) take place during the 21st century.

The NAO, the major mode of atmospheric variability in the Northern Hemisphere, particularly in winter, is exerting a strong control on the extra-tropical climate, e.g., modulating the westerly jet stream and temperature from eastern North America into Eurasia.

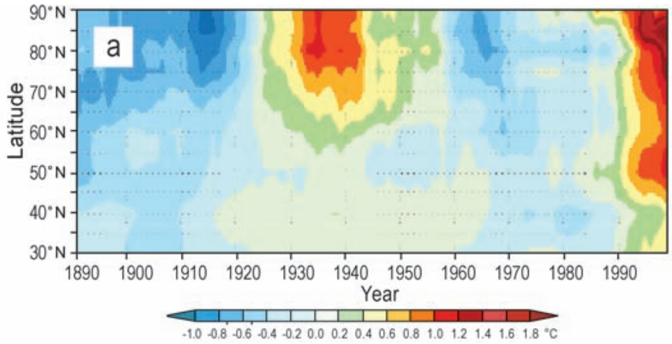

***Figure 5** Hovmöller diagram of the time-latitude variability of surface air temperature (SAT) north of 30°N from 1891 to 1999 (Johannessen et al., 2004).*

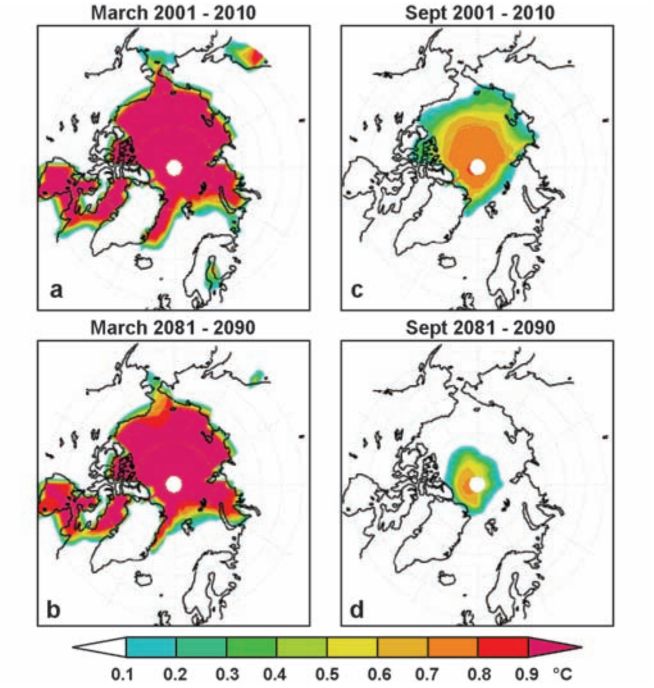

***Figure 6** ECHAM4-modelled Northern Hemisphere sea-ice concentration in late winter (March) from (a) 2001–10 and (b) 2081–90, and in late summer (September) from (c) 2001–10 and (d) 2081–90. From Johannessen et al. (2004).*

The NAO has exhibited a positive trend since the 1960s and it has been speculated that this may be linked to global warming. However, the observed variations in the NAO could also be caused by natural variations in the climate system. It has been difficult to uniquely state which of the two alternatives are most likely, as distinguishing natural versus anthropogenic variability in the NAO, based on observed surface-level pressure (SLP) alone, is challenging. There are also uncertainties in the theoretical response of NAO/AO (Arctic Oscillation) to enhanced greenhouse warming and our ability to model it realistically using numerical models.

The underlying causes of forced variability in the North Atlantic region are unclear. There are at least two candidate mechanisms to explain the recent trend of the NAO. The one involves an extra-tropical response to changes in tropical sea-surface temperature; the other appeals to stratospheric changes. The spatial distributions of the modelled sea-ice cover for the present decade (2001–10) and towards the end of this century (2081–90) are indicated in Figure 6. The results of models ECHAM4 and HadCM3 support each other, both predicting moderate reduction in winter ice extent and drastic reduction in the summer. The spatial distributions of the ECHAM4-modelled summer ice cover late in the 21st century (Figure 6 d) indicate essentially ice-free Arctic marginal seas, except north of Greenland and the Canadian Arctic Archipelago.

Broader impacts of climate research

The Nordic countries stretch from the benign climatic zones of southern Scandinavia to high latitudes well above the Arctic circle with true polar winters. The living conditions are intensively influenced by extreme environmental processes and their dynamics in the Arctic. Therefore, its indigenous as well as non-indigenous societies have developed special skills and technologies to live in the area and to exploit its living and other resources, and hence they also have a special interest in studying, exploring and understanding the high latitudes of our Earth including the temporal variability of their environments. Early polar explorers such as Nordenskjöld, Nansen and Amundsen organized audacious expeditions to the Arctic Ocean and to Antarctica. This situation changed dramatically close to thirty years ago, when the exploration of the Arctic Ocean gained more urgency and when Swedish scientists started using their large ice breakers for polar research. The highly successful YMER-80 expedition, marking the occasion of the 100th anniversary of Nordenskjöld's crossing of the Northern Sea Route (NSR), led to the ice-infested deep-sea regions to the north of Svalbard. Nowadays, the Scandinavian polar research organisations provide for rich possibilities to carry out sophisticated climate research and ambitious expeditions to marine and terrestrial regions in the high latitudes of both hemispheres.

The scientific and technical achievements resulting from climate research in Norden have strengthened the capacity to detect, understand and predict climate and environmental change, with focus on the high northern latitudes. The scientific and technological achievements of this research are also conveyable to European social objectives and policy. There is a strong need to improve our knowledge base and observation–prediction system for the following important societal issues:

1. Socio-economic and human impact of climate change. There is a need to assess the impact of climate change on a range of issues, such as environmental risk, industrial development, transportation and living conditions.
2. Ecosystems and fisheries: Improved understanding and preservation of the Arctic ecosystem is of high priority in Europe. Climate change can impact fisheries in the Nordic and Barents Seas, which are among the most important in the world.
3. Exploitation of hydrocarbon resources: Europe has significant interest in the exploitation of oil and gas, mineral and other resources in high latitudes, offering opportunities for the European energy and transport industry.
4. Sea transportation: The European shipping industry is preparing for increased use of the Northern Sea Route (NSR), which is a much shorter sailing route between Europe, the Far East and the west coast of North America.
5. Pollution. Europe is responsible for much of the pollution going into the Arctic regions. Improved understanding of the transport of pollutants, including radionuclides, is needed as well as the potential spreading of radionuclides from the Russian Arctic regions.

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Geoscience and high-level nuclear waste disposal: the Nordic scene

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In Norden, two countries, Sweden and Finland, are actively engaged in site investigations for the location of deep repositories for spent nuclear fuel from power-producing nuclear reactors. These investigations are being carried out in crystalline rocks of the Fennoscandian Shield. In Sweden, a long history of site selection has led to the identification and investigation of two sites, Forsmark and Laxemar/Simpevarp, based on a strategy of combining favourable bedrock with consent by the local population. Surface-based geoscientific investigations of the two candidates, with extensive deep drilling, are now drawing to a close. A proposal as to which of the sites would be most suitable for the development of a deep repository will be submitted to the governmental regulatory authorities in 2009. In Finland, the site selection process was shorter and less politically controversial, and led to a "Decision in Principle" by the Finnish parliament, in May 2001, to develop a deep repository at the Olkiluoto site. The access tunnel to an underground rock characterisation facility at 400–500 m depth is at present under construction, accompanied by extensive geoscientific investigations in the subsurface. An application for a construction licence for a deep repository will be submitted in 2012. Although all sites are located in Precambrian crystalline rocks, the Swedish sites both lie in relatively homogeneous granitic rocks, whilst the Finnish site is located in an heterogeneous migmatite complex. The Nordic approach to high-level nuclear waste disposal in crystalline rock will be the theme of a Topical Symposium at the 33rd International Geological Congress at Oslo, in August 2008, and the three sites mentioned above will be the focus of Congress Excursion no. 14.

Introduction

Nuclear wastes from nuclear power production occur in solid, liquid and gaseous forms and in a variety of isotopic compositions and radiation intensities, depending on reactor type, production strategy and processing method. They can be roughly subdivided into two main categories (Milnes, 1985): low-level waste (LLW) and high-level waste (HLW). This subdivision is based on an estimation of the long-term health hazard posed by the waste, which is roughly related to its content of long-lived radioisotopes, such as plutonium, which emit *a*-particles and are thus highly radiotoxic if inhaled or ingested. For the purposes of this brief overview, HLW will encompass various radioactive waste categories, including spent nuclear fuel, vitrified reprocessing waste, and intermediate-level waste (ILW, see Miller et al., 2000), which all contain long-lived radioisotopes. Waste has to be solidified and packaged prior to disposal in a repository. Emphasis is on the *geological aspects* of nuclear waste disposal, and these are similar for all the different categories of HLW.

To a first approximation, LLW can be regarded as material that is not initially heat-producing and which must be isolated from the biosphere for 100 to 1,000 years, after which it becomes innocuous from the point of view of its radioactivity. HLW, by contrast, must be isolated for much longer times, because of its content of long-lived radioisotopes. The period generally used as a guideline for developing appropriate disposal concepts for HLW is 100,000 to 1,000,000 years, which brings geology into the forefront of nuclear waste research. Based on our knowledge of human history, LLW management could include some degree of social commitment, i.e., disposal concepts depending on monitoring, surveillance, and, if necessary, remedial action. However, HLW remains potentially hazardous for times much longer than the life span of the most stable of human societies and must be managed accordingly, i.e., disposal must depend largely on engineered barriers and the behaviour of natural systems, although some degree of supervision is usually envisaged in the initial stages.

Geoscience, therefore, has been heavily involved in the problem of HLW disposal since the development of nuclear energy for peaceful purposes started in the 1950s. In Norden, Norway and Denmark decided not to develop nuclear power for electrical energy production and hence have not been directly involved in disposal-related geoscientific research. In contrast, Sweden built a total of 12 nuclear power stations during the 1970s and 1980s (now reduced to 10, but with retained capacity), and, since 1975, has played a leading role internationally in geoscientific research related to HLW disposal in deep repositories in fractured crystalline rock. During the same period, 4 nuclear power stations were built in Finland and a fifth facility is at present under construction. Since the 1980s, the problem of disposal within Finland has been the subject of intensive geoscientific research, in close cooperation with Swedish scientists due to the similarity of the disposal concepts in the two countries. Both Sweden and Finland have followed the "once-through" option for dealing with the HLW disposal problem, i.e., the spent nuclear fuel is considered as "waste", to be disposed of directly within the country boundaries and not to be transported abroad for reprocessing. In the following text, we concentrate on the present status of disposal-related geoscientific research for spent nuclear fuel in these two Nordic countries, after a short historical sketch of the site selection process in each case.

Historical sketch, Sweden and Finland

A large part of Sweden and all of Finland are underlain by the thick cratonic crust of the Fennoscandian Shield (Figure 1), which predominantly formed towards the end of the Paleoproterozoic and has been relatively stable ever since. However, the edges of the craton were affected by younger orogenic activity (e.g., Gothian, Hallandian, Sveconorwegian, Caledonian) and the craton itself was segmented by faulting in different periods (late Paleoproterozoic, Mesoproterozoic, Neoproterozoic, Paleozoic), as well as having been flexured by the growth and decay of continental ice sheets several times (Neoproterozoic, Pleistocene, and expected in the geologically near future). The fracturing and faulting related to this segmentation and flexuring are the focus of most of the geological, hydrogeological and rock mechanics investigations in the two countries, which both favour a deep repository (500 m below the surface), in combination with a multi-barrier disposal system. The aim of the necessary safety analyses is to show that the proposed systems guarantee isolation from the biosphere without supervision for 10^5 to 10^6 years. The repository concept also allows access, if necessary, by future generations. The locations of the Swedish sites and the Finnish site at present under investigation, which are described below, are shown in Figure 1. A more detailed summary of the geoscientific work carried out during the site selection process in both Sweden and Finland is to be found in Milnes (2002).

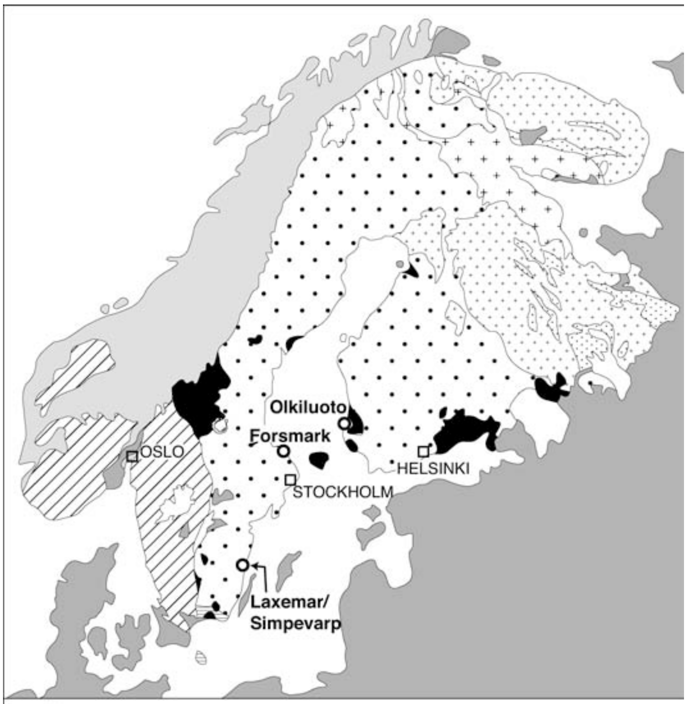

Figure 1 ***Overview geological map of the Fennoscandian Shield, showing the location of the three main sites which are being studied as potential repository sites for spent nuclear fuel in Sweden (Forsmark and Laxemar/Simpevarp) and in Finland (Olkiluoto).***

In Sweden, nuclear power and its future became one of the main political themes during 1976 and 1977, culminating in a change of government in the April 1977 elections. The new government immediately passed the "Stipulation Law" which coupled the further development of nuclear power to the demonstration of how and where "an absolutely safe final storage of high level waste … can be effected". As a consequence, the then nuclear waste company initiated the so-called KBS project, which aimed, among other things, at synthesizing geoscientific data on a national scale as a prerequisite to screening the country for suitable repository sites. However, controversy continued, compounded by an international review which came to the conclusion that a suitable site could probably be found, but that it had not yet been identified. At the same time, preliminary work relevant to siting continued, and studies in varying degrees of detail were carried out at several sites by various bodies. However, this work often provoked the local nuclear opposition and helped to create the polarized atmosphere which culminated in the 1980 referendum on the future of nuclear power in Sweden. Nevertheless, the geoscientific work carried out in this period contributed to an important report, the KBS-3 report, which was completed in May 1983 and laid the basis for the present HLW disposal research programme. In 1985, radioactive waste management in Sweden was reorganised, resulting in the founding of the Swedish Nuclear Fuel and Waste Management Company (SKB). From that point on, all disposal-related work was collected under one roof and there was a clear separation between SKB, as the implementing organization, and governmental control bodies (SKI, SSI, etc.), as the regulators.

The siting concept which had evolved up to 1985, and which was embedded in the KBS-3 report, was that Sweden could be subdivided into geological provinces, which are more or less favourable for a deep KBS-3-type repository. The province which was considered most favourable was the Precambrian basement complex in the Fennoscandian Shield, a vast area of crystalline, plutonic and metamorphic rocks. From 1985 to 1992, detailed investigations of individual study sites at different locations within this basement complex were carried out and final reports on all investigations, which had been carried out at six of the sites, were published in 1991–1992. In addition, a large amount of problem-oriented information from SKB-financed operations at several other localities became available. The main importance of the results from all these sites is that they consider not only surface conditions but also—and primarily—conditions at repository depth, several hundred metres below the surface. The main objective with the study sites was to obtain geoscientific information at depth in different geological settings, as well as to test and develop techniques, equipment, concepts, assessment methods, etc. This work was supported and complemented by results from the International Stripa Project, which was managed by SKB and located in the abandoned Stripa iron mine (SKB, 1993), and by pre-investigations for the construction of the Äspö Hard Rock Laboratory. In 1992, the Swedish government requested SKB to present a supplementary study to the current research and development programme, specifying in detail the planned scope and content of the siting programme, including the technical and other requirements on which site selection would be based (SKB, 1994). This strategy was later accepted by the Government and has since been the basis of the siting process in Sweden.

The starting point of the strategy is that no areas within the Swedish part of the Fennoscandian Shield can be excluded from consideration as a potential site for a HLW repository on general grounds, and that there is no way of distinguishing more favourable and less favourable areas without carrying out project-oriented investigations (feasibility studies). This standpoint was qualified by two general exclusion criteria within the Precambrian basement at the national scale: the avoidance of major deformation zones, and the avoidance of areas judged to be of high ore potential. Furthermore, the identification of an homogeneous bedrock was favoured. Overview studies were subsequently carried out over the whole country on a county-by-county basis, and feasibility studies in more detail, with field checks, in several municipalities. Local acceptance and local cooperation were taken as a prerequisite for carrying out a feasibility study at the municipality level ("strategy of consent"). In all, feasibility studies were carried out in eight municipalities between 1993 and 2000. These feasibility studies identified many favourable areas, both at county and municipality level. Following a control by the regulatory authorities and a "strategy of consent" from the respective municipalities, specific site investigations, including deep drilling, were started during 2002 at two identified favourable areas, Forsmark and Laxemar/Simpevarp, as outlined below.

In Finland, there has been close cooperation between the Swedish implementing body, SKB, and the corresponding Finnish implementing body, Posiva (and its forerunners, TVO/IVO), for many years. At an early stage, Finland chose to base its programme on the KBS-3 concept and to run research and development activities closely coordinated with those of SKB, often as cooperative efforts. However, the siting process diverged considerably from that of Sweden (see McEwen and Äikäs, 2000). Already in 1983, the Finnish government established the objectives and timetable for the siting process, with Phase 1 (1983–1985) consisting of a site identification survey, Phase 2 (1986–1992) encompassing preliminary site investigations at a number of sites identified during Phase 1, and a third and final phase, Phase 3 (1993–2000), envisaged as involving the detailed site characterisation of some or all of the sites studied during Phase 2, and culminating in a "Decision in Principle" by the Government as to the future Finnish deep repository site.

During Phase 1, about 85 potential investigation areas were identified on the basis of regional geology, satellite imagery and aerial photograph interpretation (rock blocks), together with a consideration of environmental and societal factors. After discussions with the relevant municipalities, five sites inside these areas were chosen for the preliminary site investigations in Phase 2. These included detailed geological and geophysical surveys, the drilling of numerous deep boreholes with continuous coring, and extensive hydrogeological sampling and testing at each site. After review by the authorities in 1993, three of these sites were retained for more detailed study (Olkiluoto, Kivetty, Romuvaara), including a second series of deep cored drillholes. Later, a fourth site was added after a positive feasibility study (Hästholmen), and a crash investigation programme was initiated there, to bring investigations up to the same level as the other three sites by the year 2000. These efforts culminated in the TILA-99 safety assessment, which was based on the data variations from all four sites, and which was submitted to the Government, supported by a favourable international review, in late 1999, with the request for a positive "Decision in Principle". However, the municipality in which the Olkiluoto site lies had already agreed to allow it to be developed as a potential deep repository site over the next 10 years, if the decision was positive. Hence, Posiva had published a preliminary RDD plan (research, development, technical design) for underground investigations at Olkiluoto, which would lead to the application for a construction licence around 2012. The Government made a positive "Decision in Principle" at the end of 2000, and the decision was ratified by the Finnish parliament, almost unanimously, in May 2001. Afterwards, Posiva concentrated its efforts on Olkiluoto and underground investigations started in 2004, with the start of excavation of the access tunnel to the planned underground research and characterisation facility, ONKALO, as outlined below.

Present status and future outlook, Sweden

The prime objective of the site characterisation at Forsmark and Laxemar/Simpevarp (Figure 1) is to locate a repository for spent nuclear fuel at c. 500 m depth in crystalline rock, which fulfils the safety requirements established by the governmental regulatory authorities. Both sites are composed of Paleoproterozoic rocks and are situated in the western part of the Fennoscandian Shield (Koistinen et al., 2001 and Figure 1).

As far as geological aspects are concerned, the following tasks have been completed during the period 2002–2007:

- Geological mapping of the crystalline bedrock and Quaternary cover at the surface.
- Acquisition of airborne (helicopter) and higher-resolution surface geophysical data.
- Acquisition of high-resolution reflection and refraction seismic data at the surface.
- Extensive cored drilling down to c. 1000 m depth, and percussion drilling down to c. 200 m depth with associated geological and geophysical logging work.
- Vertical seismic profiling along selected cored boreholes.
- Acquisition of mineralogical, geochemical, petrophysical, structural geological and geochronological analytical data, both at the surface and along boreholes.

The acquisition and evaluation of fracture mineralogical and geochronological data have been completed in the framework of four Ph.D studies at the Universities of Göteborg and Lund.

Following the acquisition of data at each data freeze, analytical and modelling work has been completed. These tasks comprise the iterative steps of identification, control and evaluation of primary data, descriptive and quantitative modelling in 3-D space and an assessment of uncertainties. A site descriptive model (SDM) is an integrated model for geology, rock mechanics, thermal properties, hydrogeology and hydrogeochemistry, and a description of the surface system.

The geological models at both sites address rock domains and deformation zones in a deterministic manner. Aspects of penetrative ductile deformation at the Forsmark site are included in the rock domain model. By contrast, the fractures inside the bedrock between deformation zones are addressed in a stochastic manner. At Forsmark, the strongly anisotropic character of the bedrock has provoked the need for its division into fracture domains, prior to the execution of the stochastic modelling procedure (Olofsson et al., 2007). In order to address the problems encountered with variable data resolution in different volumes, models at different scales have been constructed at both sites. The site descriptive models for Forsmark and Laxemar, version 1.2 (SKB, 2005, 2006a) formed the basis for a preliminary repository layout at each site (SKB, 2006b,c). Furthermore, both these site descriptive models and the respective preliminary layouts provided a basis for the first evaluation of the long-term safety for potential KBS-3 repositories at Forsmark and Laxemar (SKB, 2006d).

In essence, two contrasting types of geological process have affected the bedrock at the two sites. Tectonic activity occurred at different time intervals, predominantly during the Proterozoic, and produced the compressional structures with a conspicuous component of strike-slip deformation as described below. As the effects of tectonic activity, for the most part, waned, the effects of loading and unloading in connection with the deposition and uplift/erosion, respectively, of sedimentary material during, for example, the Phanerozoic increased in significance.

Forsmark

The Forsmark site is located along the eastern coast of Sweden, approximately 120 km north of Stockholm (Figure 1). It lies within a major deformation belt which extends several tens of kilometres across the WNW to NW strike of the rocks. In this belt, rocks show high ductile strain anastomosing around tectonic lenses, within which the bedrock is folded and generally affected by lower ductile strain. The ductile deformation, which formed under amphibolite-facies metamorphic conditions at mid-crustal levels, has contributed to the development of a strong bedrock anisotropy (Figure 2).

The potential repository is situated inside one of these tectonic lenses, directly to the southeast of the nuclear power station at Forsmark (Figure 2). Regionally important, discrete deformation zones occur solely within the broader, high-strain rocks around the tectonic lenses at the site (Figure 2). They dip steeply and are retrograde in character with both ductile and polyphase brittle strain. The bedrock is dominated by granitoids with subordinate ultramafic, mafic and

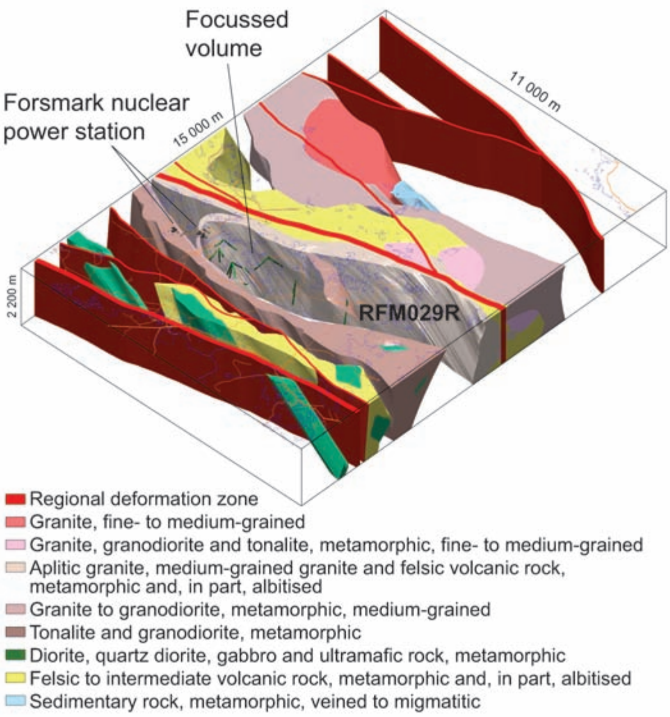

***Figure 2** 3-D regional model (stage 2.2) for selected rock domains and steeply dipping, regional deformation zones at Forsmark. View from the south. The focussed volume for the potential location of a repository is situated in rock domain 29 (RFM029. R indicates regional model), directly to the southeast of the nuclear power station and in the hinge of a major synform that plunges moderately to steeply to the southeast.*

intermediate rocks (Figure 2). An older plutonic suite of meta-intrusive rocks, dated to 1.89–1.87 Ga, was affected by penetrative ductile deformation under amphibolite-facies metamorphic conditions prior to the intrusion of a younger granitoid suite, dated to 1.86–1.85 Ga (Hermansson et al., 2007, in press). The latter intruded during the waning stages of and after this major compressional tectonic event. Younger ductile strain at lower metamorphic grade was concentrated along the regional deformation zones and culminated with a regional uplift at c. 1.80 Ga. The bedrock was able to respond to deformation in a brittle manner prior to 1.70 Ga.

Metagranite with a high content of quartz (24–46%), which is partly altered to a finer-grained, quartz-plagioclase rock, dominates the focussed volume inside the tectonic lens that has been selected for the potential location of a repository. Steeply dipping fracture zones strike ENE to NNE across the potential repository at c. 500 m depth (Figure 3a). The damaged and core parts of these predominantly strike-slip zones are up to a few tens of metres thick and contain a high frequency of sealed fractures. Only two of these zones (ENE60A and ENE62A in Figure 3a) show a trace length at the ground surface that is greater than 3 km. Some gently, south- and SE-dipping, hydrogeologically conductive fracture zones (e.g., A2 in Figure 3) occur in the rock volume above 500 m depth, but such zones are far more conspicuous to the southeast of and outside the potential repository volume (Juhlin and Stephens, 2006 and Figure 3a). The gently dipping zones show evidence for reverse dip-slip and strike-slip displacement.

The bedrock above the potential repository, down to a maximum depth of c. 200 m (see base of fracture domain FFM02 in Figure 3b), shows a relatively high frequency of sub-horizontal and gently dipping fractures with apertures, and is hydrogeologically conductive. It is suggested that unloading of younger sedimentary material resulted in the reactivation of especially sub-horizontal and gently dipping fractures in the form of extensional failure and the development of joints (Juhlin and Stephens, 2006). Newly formed fractures in the form of sheet joints may also have formed in connection with unloading.

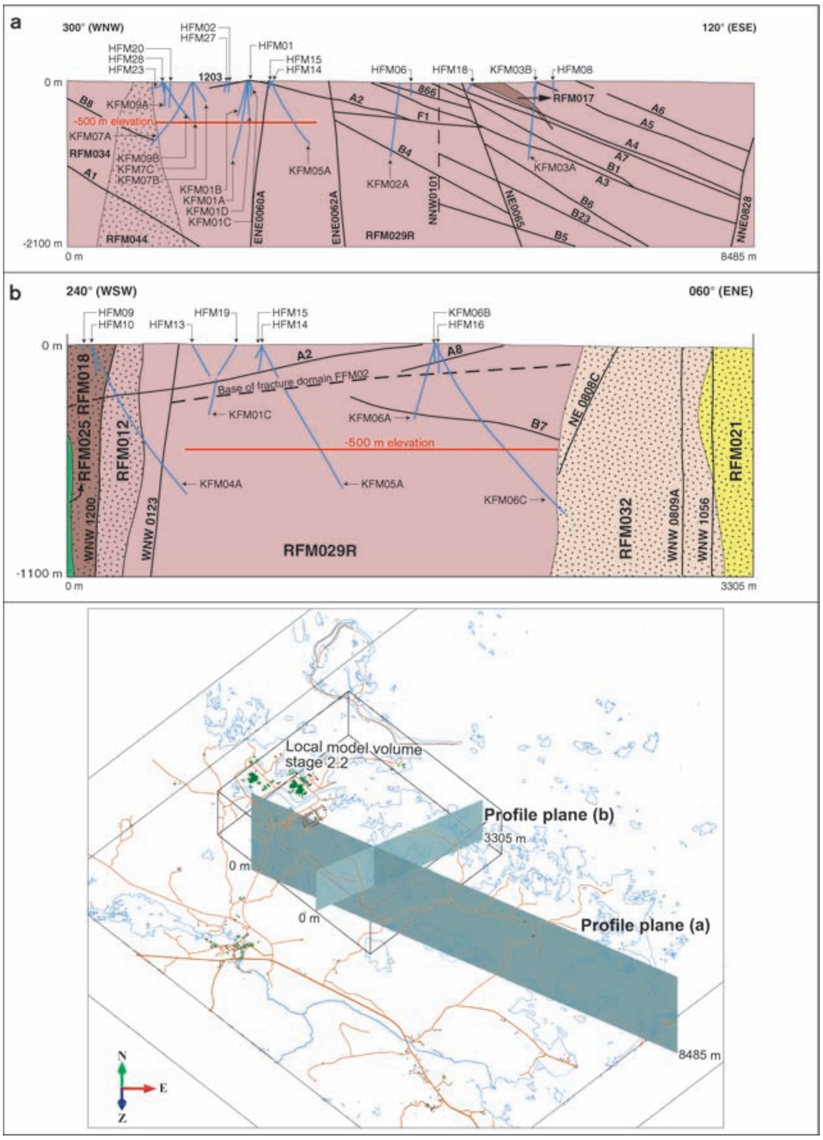

***Figure 3** 2-D cross-sections in the crystalline bedrock at Forsmark, based on regional model stage 2.2. The lines of section and the local model volume stage 2.2, where the potential repository is situated, are shown in the lower part of the figure. Yellow = felsic metavolcanic rock, dark green = metagabbro (1.89 Ga), dark brown = metatonalite (1.88 Ga), dark brown with black dots = strongly foliated metagranodiorite and metatonalite (1.88 Ga), pale brown = metagranite (1.87 Ga), pale brown with black dots = strongly foliated metagranite (1.87 Ga), beige with black dots = strongly foliated metagranite partly altered to quartz-plagioclase rock. Continuous black line = fracture zone, dashed black line in section (a) = fracture zone situated outside section line and included only in local model, dashed black line in section (b) = base of the more strongly fractured domain FFM02, continuous blue line = borehole. The c. 500 m elevation level inside the focussed volume is shown by a red line.*

This phenomenon is coupled with a release of stress in the bedrock and is most conspicuous close to the surface interface and in the vicinity of the geologically ancient, gently dipping zones. For this reason, the bedrock above c. 200 m depth in the modelled repository volume forms a separate fracture domain from the bedrock at repository depth.

Laxemar/Simpevarp

The Laxemar/Simpevarp site is located along the southeastern coast of Sweden, approximately 230 km south of Stockholm (Figure 1). The bedrock is dominated by a 1.80 Ga suite of granitic, granodioritic, monzodioritic and gabbroic rocks belonging to the 1.86–1.65 Ga Transscandinavian Igneous Belt (Figure 4). Furthermore, two 1.45 Ga old granites occur, both north and south of the focussed volume (Figure 4). In contrast to the Forsmark site, the bedrock is mainly composed of well preserved igneous rocks, with little sign of ductile deformation, except for some low-grade ductile high-strain zones of mesoscopic to regional nature. These deformation zones are interpreted to have formed shortly after the emplacement and crystallization of the parent magmas, i.e., shortly after 1.80 Ga.

The focussed area for the potential location of a repository is situated in the southern part of the Laxemar subarea, west of the nuclear power station along the Simpvarp peninsula. The dominant rock types comprise equigranular quartz monzodiorite and finely porphyritic quartz monzodiorite to granodiorite ("Ävrö granite"). They show a conspicuously lower content of quartz (10–25 %) relative to the dominant rock types at Forsmark. Important subordinate rock types are smaller bodies of diorite to gabbro, and dykes, lenses and irregular small bodies of fine-grained granite, pegmatite and fine-grained mafic rock. The latter commonly occur as composite intrusions together with fine-grained granite.

Deformation zones strike NE, NW and NS, and dip steeply or are vertical (Figure 5). They include both ductile structures reactivated in a polyphase manner in the brittle regime and zones that are essentially brittle in character. By contrast, zones with EW strike are inclined (40–60°) with both northerly and southerly dips (Figure 5). The most prominent ductile deformation zones with NS to NE strike and sub-vertical dips show sinistral, strike-slip kinematics. One of the NE-striking zones, the so-called Äspö shear zone, separates the Laxemar and Simpvarp sub-areas. Ductile deformation zones with E-W strike are compressional and, if inclined, show reverse displacements. The kinematics of the brittle deformation along the zones has so far not been resolved.

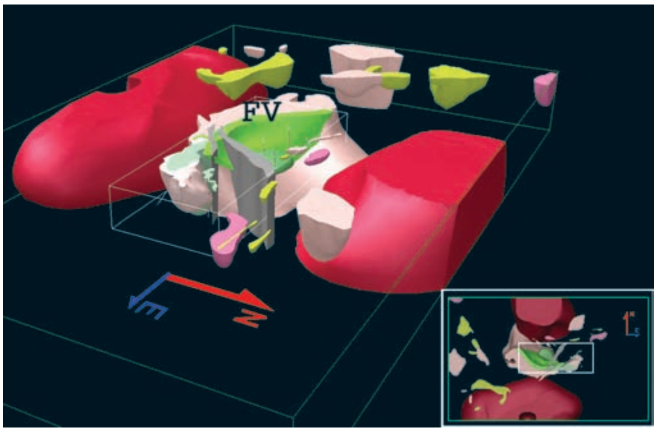

***Figure 4** 3-D regional model (version Laxemar 1.2) for rock domains at Laxemar/Simpevarp. Apart from some granite dated to 1.45 Ga, all rocks are 1.80 Ga in age. Red = granite (1.45 Ga), pink = quartz monzodiorite, purple = fine-grained granite, yellowish green = diorite to gabbro, dark green = "Ävrö granite" mixed with frequent diorite to gabbro, light green = fine-grained dioritoid, grey = high frequency of ductile shear zones. The transparent domain (black) is composed of "Ävrö granite". The inset map provides a top view. FV = focussed volume.*

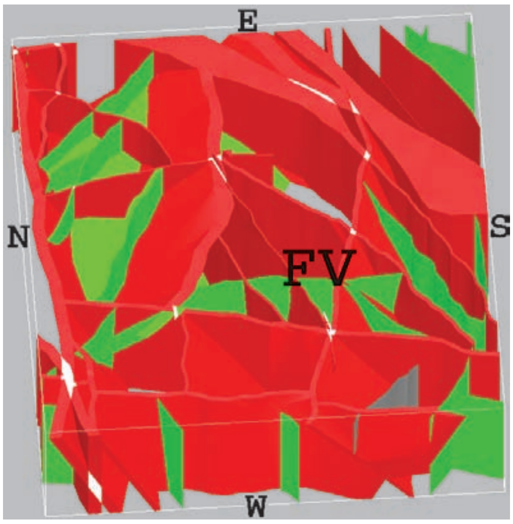

***Figure 5** Deformation zones in the local model volume in the Laxemar sub-area. Red = zones with a high confidence of existence, green = zones with a medium confidence of existence, grey = zones with a low confidence of existence. FV = focussed volume.*

Future outlook

At the time of writing of this paper, multidisciplinary work, in connection with model stages 2.2 and 2.3, are in progress at both sites. The models produced during this work will form the basis for the final repository layout. The final site descriptive models for the two sites, as well as the final assessment of their long-term safety, will be completed during 2008–2009. The selection of a repository site will be decided and the motivation documents submitted to the governmental regulatory authorities during 2009.

Present status and future outlook, Finland

As described above, the nuclear waste disposal organization in Finland, Posiva, was granted a "Decision in Principle" in May 2001 by the Finnish parliament. Even though the work continued following submittal of the application, this democratic support provided a major impetus for drawing up detailed plans for the underground activities at the Olkiluoto site. A report on baseline conditions (Posiva, 2003a) and a detailed plan of the proposed underground investigations (Posiva, 2003b), based on the earlier site report (Anttila et al., 1999), were finalised before the construction of the access tunnel to the planned underground research and characterisation facility, ONKALO, was started in August 2004. The ONKALO access tunnel is located in the central part of Olkiluoto island and in the central part of the well-investigated area (Figure 6).

ONKALO

The ONKALO access tunnel is constructed for investigation purposes, but it is anticipated that it will probably be included in a licence application as a part of the repository access tunnel. It is constructed with the traditional drill and blast method. However, for better control of the excavation disturbed zone (EDZ), emulsion charging was adopted in 2006. The tunnel advances approximately 30 m per week, and the blasting takes place in about 5 m rounds. The construction work is scheduled for tunnelling to reach the main investigation level at about 420 m by the end of 2009. The first lesson learnt was that it always takes time, in this case, about half a year, before the parallel construction work and systematic geoscientific investigations can proceed smoothly.

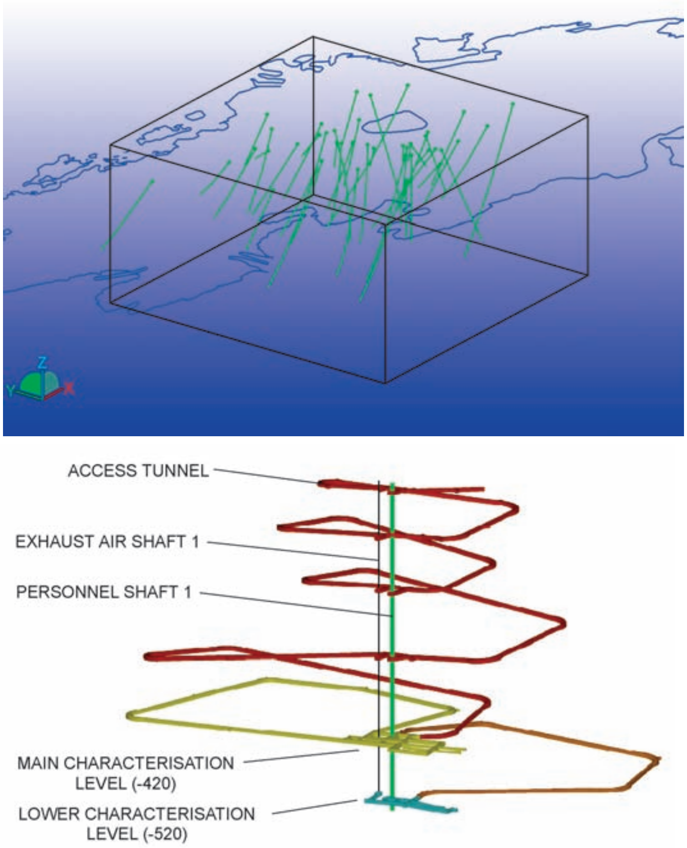

Figure 6 Upper: Olkiluoto island with existing drill holes, the ONKALO access tunnel and the cube defining the nominal volume of the Olkiluoto site area, which also represents the well-investigated area. Lower: Proposed layout of ONKALO facility and the access tunnel. View from the southwest.

In constructing the access tunnel, pilot holes are drilled within the tunnel perimeter to check the existence and the exact location of predicted deformation zones and other features, and to assess the rock quality. These pilot holes are subsequently excavated away. The length of the drillholes varies between 100–200 m. These cored boreholes are used for design, construction and investigation purposes, e.g., the layout design can be adjusted if a really significant feature is encountered. Furthermore, pre-grouting planning is based on pilot hole information and the investigations along, as well as the information from, these boreholes are used especially for prediction-outcome studies and for updating the ONKALO area model.

The mapping of walls and roof along the tunnel proceeds together with the construction work. The tunnel is mapped for construction and work safety purposes, i.e., reinforcement and grouting needs, after each round. However, systematic geological mapping is carried out approximately 100 m behind the face, due to time limitations and working safety. The grouting of the tunnel is a very important part of the construction work. The tunnel needs to be as dry as possible to avoid the up-coning of saline water from deeper levels. At the moment, the limiting value for the water leakage into the tunnel is set at 2l /100 m tunnel, and, so far, this has not been exceeded. Furthermore, Posiva is developing low-pH cement for the grouting purposes deeper down in the repository level to avoid the high-pH plumes caused by usual grouting material, which could affect the isolation capacity of the bentonite buffer.

Investigations both on the surface and underground proceed at the same time as the construction work along the tunnel. The number of drillholes is optimised in order to provide enough information, but to avoid too many holes from the surface to the repository level. At the present time, no deep investigation holes (length 500–1000 m) are now drilled in the central part of the investigation area. Surface investigations are focussed on an extension of the investigation area towards the east. In the ONKALO area, the surface investigations are complemented by characterisation holes drilled from underground locations along the ONKALO tunnel.

Olkiluoto

The latest interpretation of the geology of the Olkiluoto site is presented in Andersson et al. (2007). The bedrock at Olkiluoto mostly comprises supracrustal rocks, metamorphosed under upper amphibolite-facies conditions, the source materials of which are epiclastic and pyroclastic sediments. These rocks are variably migmatitic and contain abundant veins and irregular masses of pegmatitic granite. The whole complex has undergone multiple deformation (several phases of folding, some coeval with migmatisation), and is cut by a few, narrow, post-tectonic, mafic dykes. In terms of their mineral composition, texture and migmatite structure, the rocks of Olkiluoto can be divided into four major classes: 1) migmatitic gneiss, 2) TGG gneiss, 3) gneiss and 4) pegmatitic granite. The migmatitic rocks can further be subdivided into stromatic gneiss, veined gneiss and diatexitic gneiss on the basis of their migmatite structures. Radiometric age dating indicates that the migmatisation took place between 1.89 and 1.87 Ga., i.e., coeval with the formation of the older meta-intrusive rocks at Forsmark (see the Forsmark section). Comprehensive petrographic and geochemical description of the lithologies is presented in Kärki and Paulamäki (2006) and the methodology of treating the anisotropy and heterogeneity of these rocks is described in Milnes et al. (2006).

Based on the 2006 site description (Andersson et al., 2007), the Olkiluoto bedrock has a more fractured and, hydrogeologically, more conductive part, containing meteoric (depth of 0–30 m) and brackish water (TDS < 10 g/l), in the upper 100 to 150 m. These features are also present in the ONKALO tunnel. Below this depth, down to the –300 m level, the rock is clearly less fractured. At the -300 m level, a group of sub-horizontal deformation zones, with clearly increased hydraulic conductivity and fracturing, are inferred to be present. At the repository level, between 400 and 500 m, the rock is expected to be clearly less fractured and less conductive than in the zone above, but to contain saline groundwater (TDS > 10 g/l). The repository block is expected to be limited by the large, hydraulically conductive, sub-horizontal to gently SE-dipping deformation zone at a depth of approximately 600 m in the ONKALO area. The highest salinity met in Olkiluoto of 84 g/l is encountered close to 1000 m depth.

With regard to the modelling of deterministic structures, the latest published version is the Geological Site Model, version 0 (Paulamäki et al., 2006). The model consists of four sub-models, the ductile deformation model, the lithological model, the alteration model and the brittle deformation model, which, although closely interdependent, are distinguished for practical reasons. A new version of the model, version 1.0, is already constructed and the main advances are the integration of the different sub-models, the inclusion of conceptual models and the increased understanding of the geological history of the site. As an example of the integration of the sub-models, the site-scale sub-horizontal deformation zone underneath the repository block is associated with large bodies of illite alteration (Figure 7), indicating that the faults have acted as pathways for the circulation of hydrothermal fluids. In addition, major improvements in the sub-models for alteration, ductile deformation and brittle deformation have been included, compared to the 2006 model. An extensive amount of detailed kinematic data from fractures in all the drill cores was collected between 2004 and 2005. These data have now been applied to reconstruct the kinematic history of the main fault zones.

One of the main developments during the modelling work has been the application of prediction-outcome studies. Before the construction of each tunnel segment, different characteristics of the bedrock, i.e., geological features, rock mechanical behaviour and hydrological characteristics, are predicted based on existing models, and available data and pilot holes. After the excavation of the tunnel

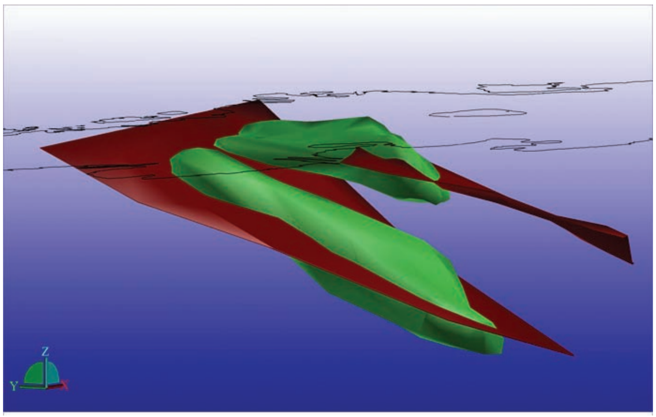

Figure 7 Illitisation in relation to the main faults of the Olkiluoto site area. Illitisation is shown as green volumes and faults as brown surfaces. View from the east.

segment, the actual observed relationships ("outcome", mainly based on tunnel mapping) are compared to the predictions. With this method, the predictive capacity of the models as well as the degree of site understanding is continuously tested. The method is planned to be developed further, to be used in future at the repository level to define suitable areas for the deposition tunnels and canister holes.

Future outlook

In the future, Posiva is heading towards the licencing process, to demonstrate the long-term safety capability of the whole repository system, together with an application for a construction licence for the repository around 2012. The operation of the repository is planned to be started at 2020.

Concluding remarks

The title of this short paper, geoscience and high-level nuclear waste disposal, has two sides. Here we have concentrated on one of these: the significance of geoscientific research for providing insights and solutions relevant to one of the most burning current environmental problems—one for which, because of the long time intervals involved, geoscientists are particularly qualified to address. However, the other side of the coin should not be forgotten, and may be equally important. Nuclear waste disposal and the history and politics of nuclear energy have provided a background against which a vast amount of human and material resources have been invested in geoscientific investigations, which would otherwise not have been carried out. The detailed knowledge of the petrology, structural geology including brittle deformation, hydrogeology and geophysics of selected areas and sites, both surface and subsurface, of the Fennoscandian Shield, together with the techniques and methodologies, which have been developed and subject to continuous scientific scrutiny, will provide a permanent contribution to geoscience of enormous value in the future. Both SKB and Posiva follow a policy of transparency with regard to geoscientific data: all recent technical, progress and working reports can be downloaded free of charge from the company web sites: *www.skb.se and www.posiva.fi*, which also instruct how to order free hard copies of earlier reports.

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Natural hazards in Nordic Countries

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Compared to many areas of the world, the human losses caused by natural hazards are smaller in Nordic countries. This is mainly due to the low population density in the exposed areas. However, the economic losses are significant and the geohazards picture varies among the countries. The predominant natural hazards in Nordic countries are floods, landslides, and, with the exception of Denmark, snow avalanche. Volcanoes and earthquakes are major geohazards in Iceland, and parts of Norway are susceptible to seismic activity. Slide-triggered tsunamis also represent a threat to parts of the coastal areas of Nordic countries and Greenland.

Introduction

The paper gives a broad overview of the natural hazards situation in the different Nordic countries. The main focus of the paper is on "geohazards", i.e. natural hazards that are driven by geological features and processes. Geohazards pose severe threats to humans, property and the natural and built environment. Earthquakes, floods, landslides, volcanoes, avalanches and tsunamis are typical examples of such events. Landslides, caused by heavy rainfall, flood, earthquake, erosion, and human activities, are the most common geohazards on land. Near-shore and offshore, various geological processes, earthquakes and human activities, for instance in connection with petroleum exploration and production, can trigger slides and large mass flows.

During 2005, geohazards accounted for about 100,000 deaths worldwide, of which 84% were due to October's South Asia earthquake. In that year, natural disasters affected 161 million people and cost around US$ 160 billion—over double the decade's annual average. Hurricane Katrina accounted for three quarters of this cost. From 1996 to 2005, disasters were responsible for the deaths of over 934,000 people—nearly double the figure for the previous decade, affecting 2.5 billion people across the globe (World Disaster Report 2006, *http://www.redcross.ca*). Over the decade, 51 people died per natural disaster event in countries of high human development (as defined by UNDP), compared to 573 deaths per event in countries with low human development (Centre for Research on the Epidemiology of Disasters, Belgium). When the trend of fatalities due to natural hazards is studied over the last 100 years, it appears that the increase in the number of deaths is solely due to the increase in the exposed population in this time scale, not an increase in the frequency and/or severity of natural hazards.

Compared to other areas of the world, the human losses caused by natural hazards are small in Nordic countries. This is mainly due to the low population density in the exposed areas. However, the economic losses are significant and the geohazards conditions vary among the countries.

Norway

The main natural hazards in Norway are landslides, snow avalanche, floods and, to a lesser extent, earthquakes (Solheim et al., 2005a). Statistically, 10 large slides can be expected to occur in Norway in the next 50–100 years, each with possibly 20–100 associated deaths. The number of deaths caused by all types of slides in Norway over the past 150 years exceeds 2,000 individuals. Most of these casualties are due to snow avalanche (Figure 1).

Rockfalls and rockslides are among the most serious geohazards in Norway, mainly because of their tsunamigenic potential (Blikra et al., 2002). The three natural disasters causing the largest number of deaths in Norway in the 20th century involved large rock slides in bodies of water generating a tsunami (Loen in 1905 and 1936; Tafjord in 1934, Figure 2).

About 5,000 km^2 of Norway is covered by soft marine clay deposits; nearly 20% of this area consists of highly sensitive or quick clay. Landslides in quick clay represent a common and serious geohazard in Norway and Sweden. They frequently initiate without warning and turn into a flowing liquid in minutes. Statistically, large quick clay slides involving several million m^3 occur in Norway at intervals of about 4 years (Aas, 1981). The largest quick clay slide in Norway in the 20th century occurred at Rissa near Trondheimsfjord in 1978 (Figure 3). It covered an area of 330,000 m^2 and 5–6 million m^3 of clay poured out of the slide area. The largest historical quick clay occurred in Norway in 1893 in Verdal, north of Trondheim. It involved 55 million m^3 of clay and caused 116 fatalities, making it the most destructive natural catastrophe in Norway.

A typical quick clay slide is a combination of a minor initial slide and a progressive failure developing very rapidly in all directions from the first slide. For example, the Rissa quick clay slide started with the failure of a small fill at the lakeside. The initial slide involved only 200 m^3 of sediments. It grew to about 6 million m^3 in a few hours through a retrogressive sliding process.

The seismicity of Norway and adjacent areas is moderate and, even though it is the highest of north-western Europe, it is still lower than in many other 'stable' continental (intraplate) regions (Bungum et al., 2005). Seismicity rates over the 20th century suggest that the region experiences, on average, one magnitude 5 earthquake every 10 years and one M 7 earthquake every 1,100 years. An overview of the data behind these numbers is given in Figure 4, including a frequency-magnitude distribution that is reasonably stable except for the largest events where the time period covered naturally is too short. Earthquakes during this period included two earthquakes with magnitude greater than 5 offshore western Norway in 1988 and 1989, one M 5.4–5.6 earthquake in the Oslofjord region in 1904, in addition to a few offshore earthquakes in the same magnitude range. The largest historical earthquake onshore in Norway, with magnitude 5.8, occurred in 1819 in the Rana region (Muir Wood, 1989).

The average annual cost of flood damage in Norway is about 200,000,000 NOK. After a major flood in south eastern Norway in 1995, the governmental commission gave several recommendations

Figure 1 Left: Snow avalanche in Norway. Right: The Riise snow avalanche in 1968.

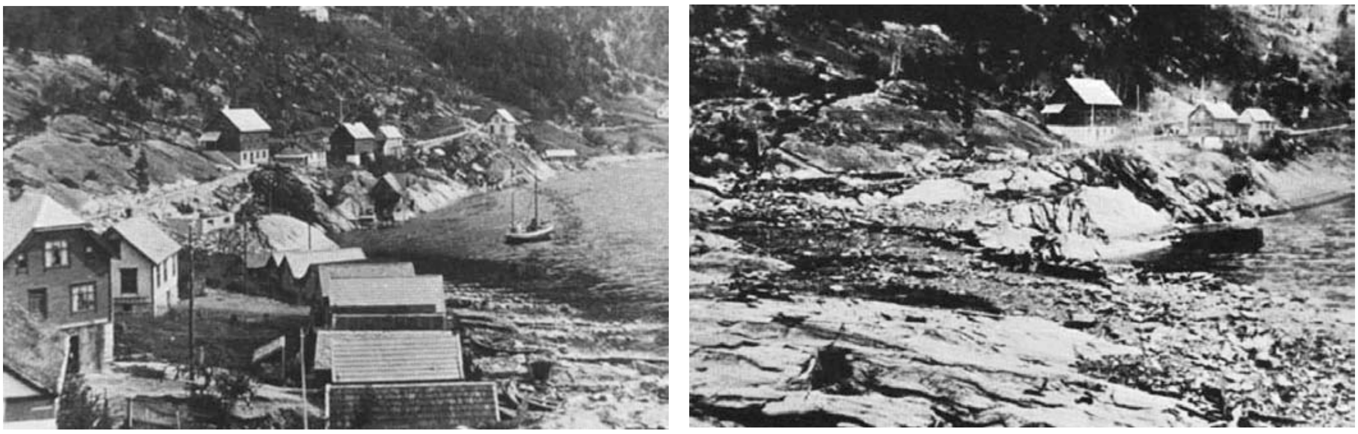

Figure 2 Municipality of Fjøra in Tafjord, Norway, before (left) and after (right) the tsunami triggered by a massive rockslide into Tafjord in April 1934.

Figure 3 Quick clay slides in Norway. Left: The Rissa quick clay slide of 29 April 1978. Right: The Trøgstad quick clay slide of 1967 (1 million m^3, 4 fatalities).

in order to reduce flood damage in the future. The cost of the damages caused by the 1995 flood amounted to about 1.8 billion NOK (230,000,000 €). One of the recommendations of the commission on flood protection measures was to produce flood inundation maps for the areas with the largest damage potential. This is now an ongoing activity of the Norwegian Water Resources and Energy Directorate (*www.nve.no*).

The exploitation of offshore petroleum resources, development of oil and gas pipeline corridors, fishing habitat protection, and protection of coastal communities, have contributed to a growing interest in offshore geohazards, in particular seafloor mass movements and their consequences, in Norway. In particular, the ongoing development of the Ormen Lange field, which is the second largest gas field on the Norwegian Continental Shelf, has contributed greatly to the understanding of the offshore geohazards in Norway. The field is located in the Norwegian Sea in water depths of about 800 to 1,100 m, approximately 120 km from the coastline, within the scar of the prehistoric Storegga slide (Figure 5). The Storegga slide, which took place 8,200 years ago, is one of the world's largest known submarine slides with an estimated slide volume in excess of 3,000 km^3 (e.g., Solheim et al., 2005b). Evidence of a major tsunami generated by the Storegga slide has been found along the coasts of Norway, Scotland and the Faeroe Islands. Considering the enormity of the Storegga slide and the potentially catastrophic consequences of a similar event today, it was essential to clarify and quantify the risks associated with submarine slides in the area to obtain approval for field devel-

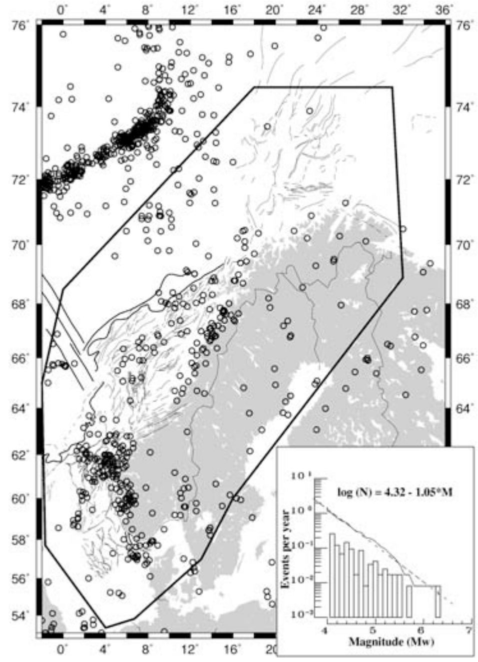

***Figure 4** Left: Evidence of a large prehistoric earthquake on the Stuoragurra (Masi) fault in North Norway, which is part of the Mierujavr'i-Sværholt fault zone. Right: Earthquake distribution in Norway and surrounding regions since 1900 (events > magnitude 3). Inset shows an annual cumulative frequency-magnitude (Gutenberg-Richter) distribution for the area within the polygon (Bungum et al., 2005).*

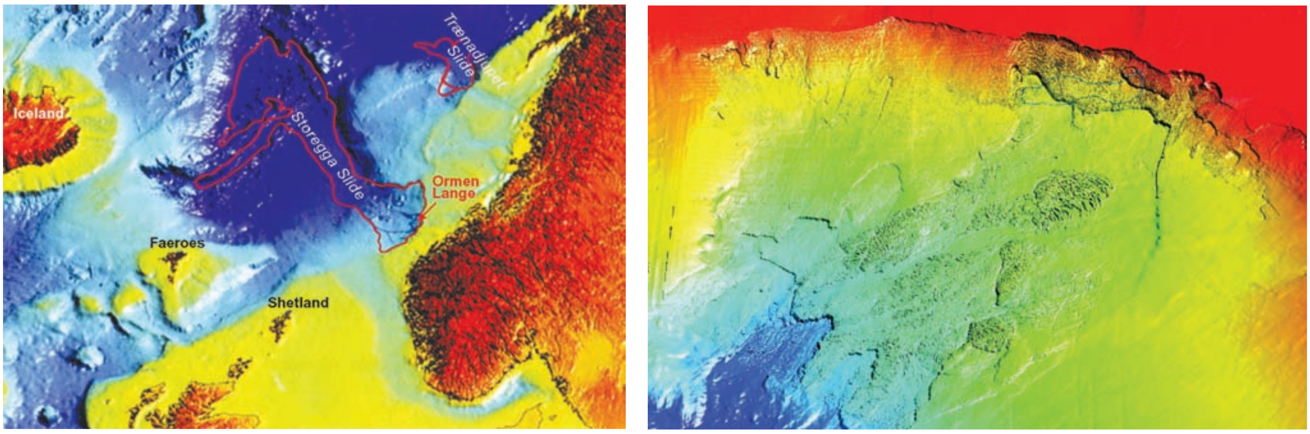

***Figure 5** Left: Location and extension of the Storegga slide. Right: The central and deepest part of Storegga slide scar (the Ormen Lange gas field in blue).*

opment from the authorities. A major effort was therefore undertaken to evaluate the stability situation of the slopes in the Ormen Lange area today, and quantify the potential risks associated with the field development in the future. The numerous studies carried out in the Ormen Lange offshore geohazards study were summarised in a special volume of Marine and Petroleum Geology journal in 2005.

Finland

Finland is located in the path of westerly cyclones, and a large number of stormy days occur especially in winter. The geographical location to the east of the Scandinavian mountain range protects northern and eastern Finland from many major storm effects, exposing mostly southern Finland to related hazards. The rather small size of the Baltic Sea and the structure of large parts of Finnish coastal morphology protect the country from larger storm surges, exposing the coastal areas to flood events by rising water tables during storms (*www.gtk.fi/slr*). The number of stormy days, as weather extreme events, is likely to increase with climate change. When a winter storm front coincides with a risen sea-level, coastal floods can be a significant threat, as occurred in January 2005. An online description of the effects of this winter storm can be found under *www.astra-project.org*.

The European-wide natural hazard maps developed by the ESPON 1.3.1 Hazards project (*www.gtk.fi/projects/espon*) clearly convey the impression of Finland being a country with few natural hazards. The dominant geohazards in Finland are avalanches, landslides, storm surges and winter storms (Schmidt-Thomé, and Kallio 2006). Landslides occur especially on river shores in southern and western parts of Finland among thick clay areas and in the hilly areas in northern Finland. Zooming into the hazard maps on a national scale reveals that river floods are also a prominent natural hazard (Jarva and Virkki, 2006). Finland is characterized by different landscapes, roughly divided into the Finnish Lakeland, west-coast Bothnian and northern Finland riverine areas and southern coastal areas. The water level in large lakes in Finland today is largely controlled leading to a low flood hazard in general terms. Nevertheless in the Bothnian region, spring floods are frequent annual phenomena. In northern Finnish rivers, climate change effects on temperature, ice cover thickness and duration, and changing precipitation patterns might have significant effects on runoff patterns and thus increase the flood risk in the future (Schmidt-Thomé et al., 2006). A national estimate on Finnish major flood hazards showed that the damages caused by an extreme flood with return period of 250 years could cause damages of up to some 550 million Euros (Ollila et al., 2000). Regarding earthquakes, Finland is located on a tectonically very stable craton, so that seismic hazards play only a minor role.

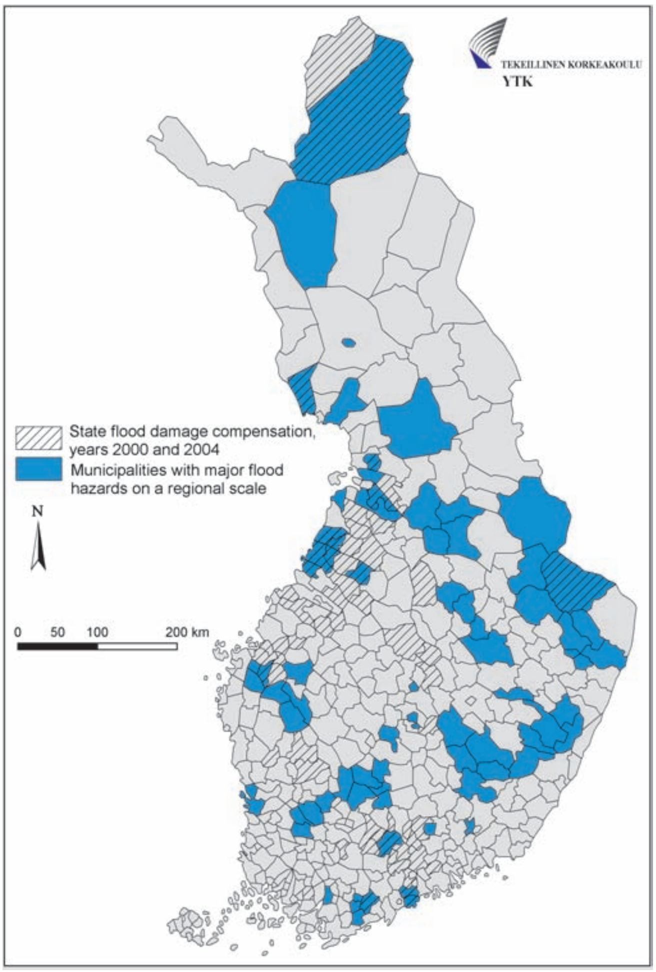

Figure 6 Finnish municipalities with major flood hazard on a regional scale (blue) and municipalities receiving national flood damage compensation (hatched) in period 2000–2004 (After Timonen et al., 2004; source: Schmidt-Thomé et al., 2006).

Denmark

Denmark is a lowland (the highest point about 170 m a.s.l.), with the peninsula Jutland and a number of islands between the Baltic Sea and the North Sea. The country is formed by Quaternary deposits, mainly deposited during the glacial periods 300,000 to 15,000 years ago. The Quaternary deposits have an average thickness of about 30 m, but can reach thicknesses of more than 200 m, which overlie Upper Cretaceous to Neogene sedimentary rocks, dominated by Danian Limestone to the east and Miocene deltaic sediments to the west.

Denmark is not seriously affected by geohazards. There is no volcanic activity and earthquake activity is of minor importance. The last time serious damage due to an earthquake was recorded in 1842, but the event did not cause any casualties. There is no documented damage to the coastal areas of Denmark by tsunami either.

The main geohazard problem in Denmark is landslides, which occur frequently along the cliffed coasts (Pedersen, Foged, and Frederiksen, 1989). The landslides in Denmark can be differentiated into rock falls and mud-dominated landslides (rotational slides). The rock falls are related to the chalk cliffs mainly located at Møns Klint and Stevns Klint at the easternmost coast of Denmark (Figure 7). Møns Klint is one of the key localities of chalk cliff collapse known from northern Europe, which occur at steep coastal cliffs where Upper Cretaceous chalk is exposed (Hutchinson, 2002). In general, cliff collapse takes place in the late winter to early spring, when the ground water saturation is highest and the action of freeze and thaw triggers the rock falls. This type of rock fall characterised the most recent chalk cliff collapse at Møns Klint in the spring 2007 (Pedersen, 2007), where two large falls took place (the larger one is shown in Figure 8).

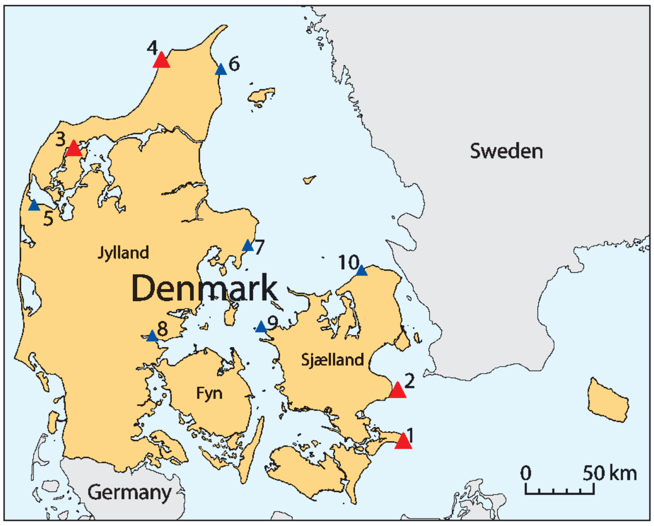

Figure 7 Location of major landslides in Denmark (1) Møns Klint, Cretaceous chalk, cliff 100 m high; (3) Western Limfjorden Region mud-landslides; (6–10) mud-landslides.

Figure 8 Upper: The chalk cliffs of Møns Klint. Lower: The most recent landslide at Møns Klint, which collapsed in January 2007 (100,000 m^3 chalk created a peninsula 300 m out into the sea) (© SASP).

Mud-landslides are common along the coastal cliffs in Denmark (Figure 7). They develop by progressive back-stepping of crescent-formed décollement surfaces. The formation of the landslides is controlled by three factors: 1) Steep sloping surface; 2) High pore-water flow (generally depending on the lithology); and 3) Erosion of the toe of the slide. The mud-landslides cause constructional problems, but so far no human casualties. These landslides create a problem in parts of the attractive coastal environments. However, the cost of private property is not regarded high enough compared to the cost of coastal protection, thus no active protection or mitigation is provided by the public services.

Greenland

Greenland is the largest island in the world with an area of 2,166,000 km^2, of which 410,000 km^2 are bedrock, and the remaining area is covered by the inland ice reaching a thickness of more than 3 km. Very few geohazard problems have affected the Greenland population, which consists of about 60,000 inhabitants. There is no recent volcanic activity in Greenland; and earthquakes, caused mainly by the displacements in the inland ice, are only of minor importance. However, landslides and rock falls can cause serious problems.

The landslides in Greenland are influenced by permafrost, glacial ice, high topographic relief, and repeated freezing and thawing (Pedersen, 1987; Pedersen et al., 1989). In most parts of Greenland, however, where gneiss and granite dominate, slides are rare. In contrast, the Nuussuaq Basin in central part of West Greenland comprises weakly consolidated sedimentary rocks overlain by a thick pile of dense volcanic rocks. This stratigraphical succession is favourable to the generation of slides. Consequently, large parts of Disko, Nuussuaq and Svartenhuk Halvø are strongly affected by landslides (rock falls, disrupted slides and avalanches), especially along the coasts (Figure 9). It is not the landslides themselves that have been disastrous, but the tsunamis related to landslip out into the deeper parts of the sea. These dangerous landslide and tsunami events appear with a frequency of one per 50 years.

The latest event occurred in November 2000, which was investigated in detail by the Geological Survey of Denmark and Greenland (Pedersen, 2002). Late in the afternoon November 21,2000 the coast at the settlement Saqqaq was flooded by a series of giant waves triggered by a 90 million m^3 landslide from a cliff (1,400 m a.s.l.) (Figure 9). Ten boats were destroyed, but luckily no humans were killed. About 30 millions m^3 of the landslide flowed seawards, triggering the tsunami. The velocity of the tsunami was calculated to be 240 km/h, corresponding to the depth of 450 m in Vaigat and to the time interval between the landslide-induced tsunami initiation and the registration of the waves in Saqqaq.

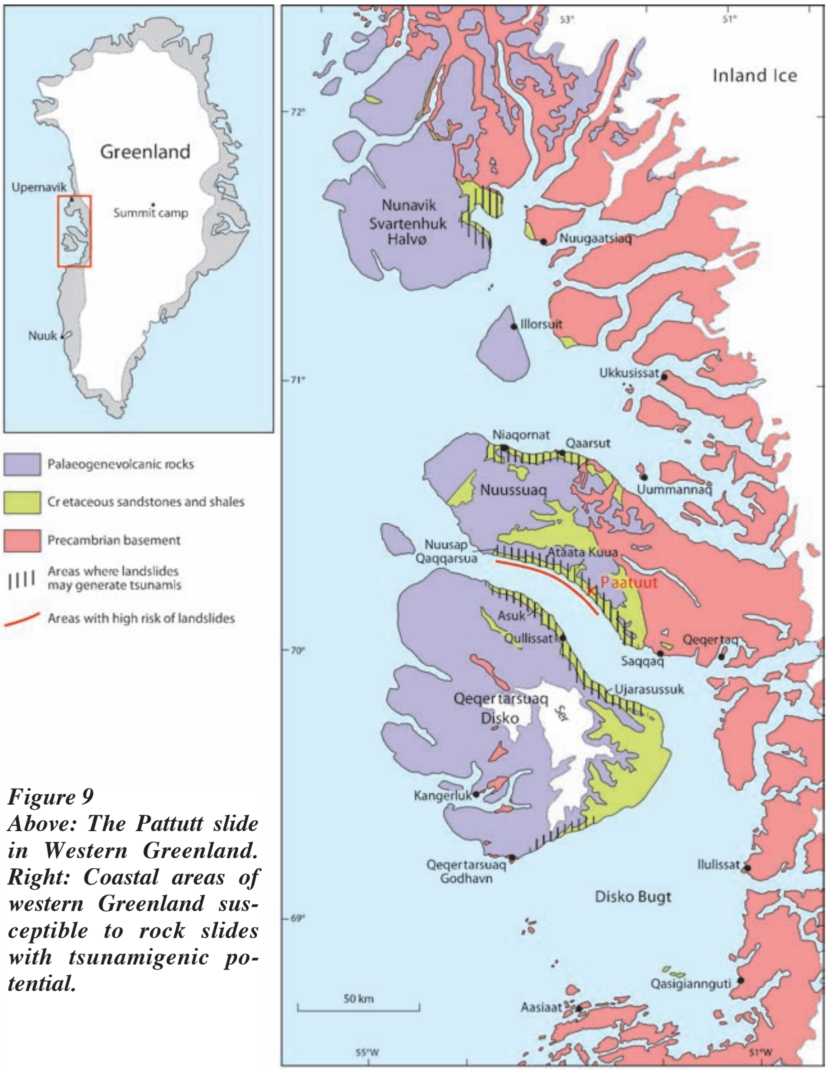

Figure 9
Above: The Pattutt slide in Western Greenland. Right: Coastal areas of western Greenland susceptible to rock slides with tsunamigenic potential.

Iceland

Among the Nordic countries, Iceland is the one that is most exposed to geohazards. Volcanic and seismic activity is pronounced in Iceland due to its location on the Mid-Atlantic Ridge. Frequent earthquakes and eruptions occur along the boundary between the North-American and Eurasian plates that runs through Iceland as a series of seismic and volcanic zones (e.g., Einarsson 1991; Sigmundsson, 2006). A comprehensive record extending over 1,100 years as well as present-day good instrumentation and extensive research have revealed the nature of the hazards. In addition to volcanic and seismic hazards, Iceland has major avalanche hazards due to its northerly latitude and rapidly changing climatic conditions.

The volcanic zones of Iceland are comprised of about 35 main centres of volcanic activity. In historical times there have been about 20 eruptions per century, or one eruption about every 5 years on average (e.g., Thordarson and Larsen, 2007). Three volcanoes, Hekla (Figure 10), Katla, and Grímsvötn, are by far the most active in Iceland. The first post-settlement eruption of Mt. Hekla in 1104 A.D. was a major explosive eruption that produced about 2.5 km^3 of rhyolitic tephra, blanketing large parts of Iceland and causing complete destruction of the nearby inhabited areas. Through historical time, one or two major eruptions occurred each century at Hekla until 1947 (Thorarinson, 1967). Thereafter, the eruptive pattern changed to more frequent and smaller eruptions. The initial phase of many Hekla eruptions is explosive and has spread tephra over large parts of Iceland. At Hekla, soluble fluorine adheres to erupted tephra particles, leading to lethal fluorosis in grazing animals even in areas of minor tephra fallout (Óskarsson, 1980). Other volcanoes with large explosive eruptions include the Askja volcano in 1875, and in 1362, a large explosive eruption of Mt. Öræfajökull devastated large areas in SE-Iceland.

A number of Iceland's volcanoes are subglacial, including the Katla and Grímsvötn volcanoes. Eruptions at these volcanoes can cause rapid melting of huge amounts of ice (e.g., Gudmundsson et al., 1997). Major glacial outburst floods associated with such eruptions, volcanic jökulhlaups, are more frequent in Iceland than elsewhere in the world and are a particular hazard. Katla eruptions, once or twice each century throughout Iceland's history, have produced large quantities of airborne tephra, as well as major huge glacial outburst floods with estimated peak flow rate

Figure 10 Left: Eruption of Krafla Volcano in 1980. Right: Eruption of Hekla Volcano in 2000.

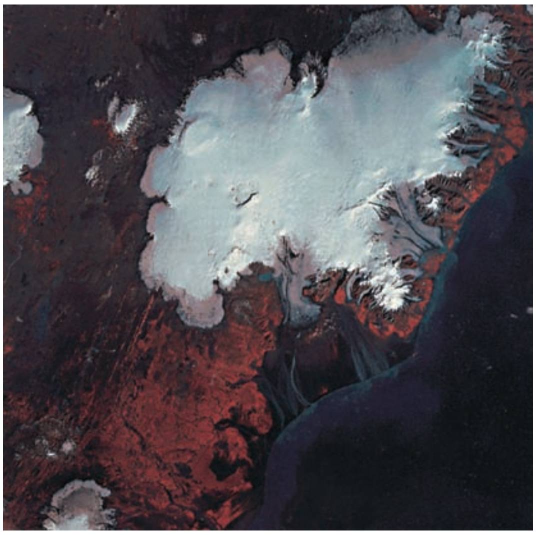

Figure 11 Satellite photo of the Vatnajökull ice cap.

exceeding 100,000 m^3/s (Larsen, 2000). The Grímsvötn volcano under the Vatnajökull ice cap (Figure 11) has the highest eruption frequency of all volcanoes in Iceland and produces frequent jökulhlaups. However, only a fraction of them are associated with eruptions as many of them are due to storage of water and melting of ice by geothermal heat within the subglacial Grímsvötn caldera. Jökulhlaups originating from the Katla and Grímsvötn volcanoes have produced large outwash plains downstream from the affected glaciers. These outwash plains, termed "sandur" in Icelandic, have been greatly augmented in historical time in Iceland. They are zones of particular hazards in the case of subglacial eruptions.

In addition to hazards from tephra and jökulhlaups, large quantities of lava have been erupted in effusive eruptions during historical time in Iceland. Whereas most of the lava forming eruptions are small in volume (on the order of 0.1 km^3), two exceptionally large volume eruptions have occurred, including the largest historical lava flow on Earth (witnessed by man). The Eldgjá eruption in 934 A.D. has an estimated volume of 19.6 km^3 (Thordarson et al., 2001) and the1783–1784 Laki eruption produced 15 km^3 of lava (Thordarson and Self, 1993). Both eruptions mark major rifting episodes consisting of a series of eruptions associated with dike intrusions accommodating plate spreading, and their environmental effects were tremendous. Widespread air pollution associated with the Laki eruption lead to the death of livestock by fluoride poisoning and subsequent famine in Iceland. The population of Iceland decreased from about 50,000 before the eruption to about 40,000 in the years after, and the eruption also had an impact on living conditions in Europe. Smaller lava flows provide a threat as well. A small volume eruption on the Heimaey Island in 1973 had a major influence, as it occurred within a village, causing temporary evacuation and considerable destruction of the village.

Seismicity in Iceland is concentrated in two transform zones, the South Iceland Seismic Zone and the Tjörnes Fracture Zone, each associated with a lateral shift in plate spreading (Figure 12). They experience persistent micro-earthquake activity and earthquakes as large as magnitude 7–7.5 (Ms) occurring in a series, typically about once each century. Dates of the largest earthquakes in South Iceland are known back to the 12th century, pointing to sequences of major damaging earthquakes in the South Iceland Seismic Zone at average intervals of 80–100 years (e.g., Einarsson, 1991). A country-wide seismic network in Iceland, composed of three-component digital seismic stations run by the Icelandic Meteorological Office (*http://www.vedur.is*), records well the present day seismicity in Iceland (e.g., Jakobsdottir et al., 2002). Within the volcanic zones, background seismicity is focused at the central volcanoes where elevated earthquake activity is there often associated with magmatic movements that cause temporarily high local stresses. Such magmatic movements are most frequent at the central volcanoes, but major seismic activity also occurs in the fissure swarms during rifting events. Extensive crustal deformation studies have revealed how magma moves in the crust (e.g., Sturkell et al., 2006; Sigmundsson, 2006).

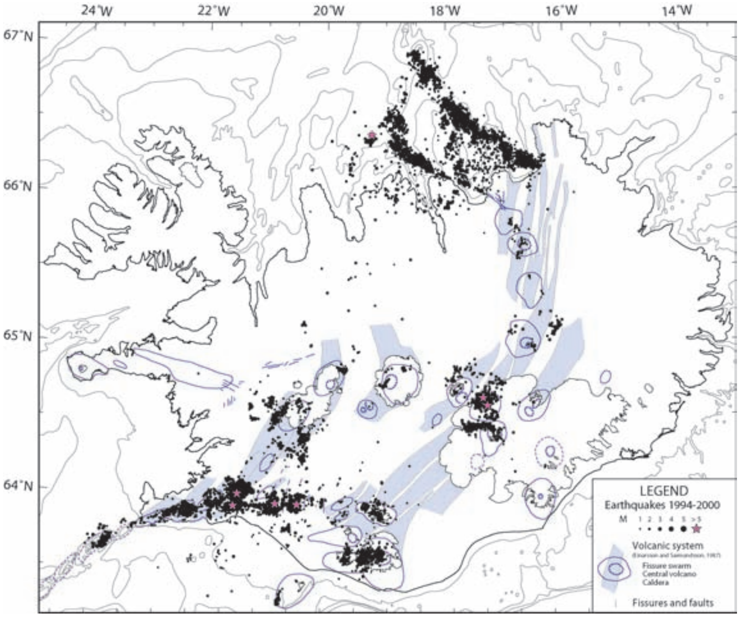

Figure 12 Tectonic map of Iceland.

The last decade includes some significant tectonic and magmatic events in Iceland, including a major earthquake sequence in South Iceland in 2000, with Ms 6.6 events occurring on June 17 and June 21. Maximum fault slip was 2.5–3 meters (e.g. Pedersen et al., 2003) and triggered seismic activity followed the initial seismic event occurred farther to the west along the plate boundary (e.g., Arnadottir et al., 2003). Significant earthquake activity immediately precedes most eruptions in Iceland (in association with a formation of a feeder dyke), changing at the onset of eruptions to volcanic tremor that continues throughout the eruption as long as magma flows to the surface (e.g., Vogfjörd et al., 2005).

Snow avalanches are a major geohazard in Iceland and have claimed over 600 lives throughout Iceland's history (Bjornsson, 1980). In the period 1901–2000, landslides claimed 27 lives and snow avalanches 166 lives (Jóhannesson and Arnalds, 2001). The main avalanche areas are in the steep coastal areas outside the seismic and volcanic zones. Presently, the avalanche risk is most pronounced in threatened coastal villages and a major avalanche protection plan is being carried out (Haraldsdottir et al., 2006). In recent decades, the largest natural disasters in Iceland were two snow avalanches in Northwest Iceland in 1995 that claimed together 34 lives.

Landslides, in particular debris flows on slopes in fjord environments, occur regularly and cause considerable damage in Iceland. The slopes are glacially over-steepened, and are typically covered with shallow regoliths comprised of till and colluvium. The main source of debris is the rapidly weathered basaltic cliffs that form the upper parts of the slopes and the inherited glacigenic material still available on the intermediate benches. Debris flow activity in Iceland has been recorded all year round, but the activity level is higher in late spring, late summer and autumn.

There are some regional differences in the meteorological factors for debris flow initiation (Decaulne and Sæmundsson, 2007). Snowmelt is the most common triggering factor in North Iceland (35%), while it represents the third most common one in Northwest Iceland (19%), and is hardly represented in East Iceland (4%). Snowmelt associated with rainfall controls around 24% of the debris flow releases in both the Northwest and North fjords. It also represents the largest proportion of triggered nival debris flows in East Iceland (14%). Long-lasting rainfall is the most common pluvial triggering factor in all fjord areas. It controls almost 50% of the debris flow events in East Iceland; it is the primary cause of debris flows in Northwest Iceland, and the third most important triggering factor in North Iceland. Intense rainfall is the second most important triggering factor in East Iceland, causing more than 30% of the pluvial debris-flows.

Sweden

The major geohazards in Sweden are landslides, floods and snow avalanches. Most of the Swedish Quaternary deposits and minor terrain configurations are a result of the deglaciation of the latest continental ice sheet. Due to the pressure of the weight of the inland ice, lowlands were submerged during the deglaciation. Marine conditions prevailed in southwestern Sweden while fresh water or water with low salinity occurred in the Baltic basin up to Bothnian bay. As soon as the pressure of the inland ice started to lighten, the crust began to slowly rebound. The highest traces of the shoreline are at different altitudes throughout Sweden, depending on how far the crust had been depressed, how much the local sea surface had transgressed, and the time at which the area became deglaciated. The highest shoreline is at 286 m a.s.l. on the coast of central northern Sweden. In the south, the highest shoreline coincides almost with the present shoreline. The rate of the present land uplift is almost 9 mm per year along the coastland of northern Sweden.

Figure 13 Munkedal landslide (2006) affecting the Oslo-Gothenburg traffic.

Most common types of mass movements in Sweden are found in areas below the highest shoreline. They are formed in connection with snowmelt and the thawing of frozen ground, as well as intense or prolonged rainfall, i.e. when the water pressure in the ground is high, or when there are sharp fluctuations in the groundwater level. Large landslides have become increasingly common during the past century, most likely as a result of anthropological interference, e.g. by construction activity that undercuts or overloads dangerous slopes. The landslides in Sweden mostly occur in relatively gentle slopes made up of glacial silt and clay, mainly in quick clay. Most of the dangerous slopes are bordered by open water—a river or a lake. About 4% of the land surface consists of clay and silt. Based on known landslide scar frequency (Figure 14, left), about one per cent of the land surface is highly susceptible to spontaneous landslides.

Many of the largest and most costly landslides in Sweden have taken place in the River Göta älv valley and its surroundings between Lake Vänern and Gothenburg. The total volume eroded by landslides and gullies in that valley is calculated to be roughly 500 million m^3. The latest large landslide with significant casualties

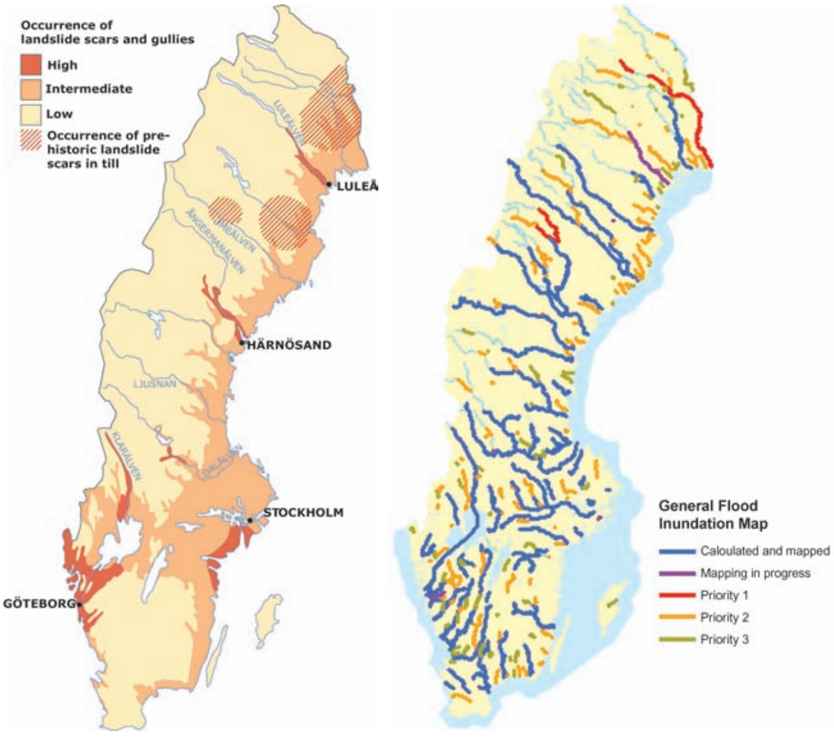

Figure 14 Sweden: Most susceptible slide areas (left) (www.sgu.se) and flood risk map (right) (www.srv.se).

occurred at Tuve on 30 November 1977. The slide severed seven electric cables and completely destroyed 65 single-family houses, killing nine people. The consequences of a landslide are not always proportional to its size. On 1 October 1918, a small landslide with disastrous consequences occurred at Getå on the slope to Bråviken Bay. A train with about 300 passengers crashed at full speed into the slide. Fire broke out in the wrecked wagons. Some 40 victims were identified, but the exact number of casualties is not known.

Landslides represent a major threat to the communication infrastructure in parts of Sweden. For example, as recently as 20 December 2006, part of Highway E6 near Munkedal in Bohuslän in the west of Sweden collapsed in a landslide (Figure 13). The E6 is the main road between Oslo and Gothenburg. The landslide caused major disruption to traffic as the 15,000 vehicles that passed the collapsed section of road every day had to be rerouted for several weeks. The site of the landslide was the most recently opened section of the E6, which has been undergoing rebuilding work. The cause of the landslide is not known, but there is speculation that the construction activities and unusually heavy rain that had recently hit the area could have triggered a quick-clay slide. The Bohusbanan railway line, which runs parallel with the E6 road, was also affected. The landslide destroyed the railway embankment and cut an electricity line leaving the railway without power.

Almost every year Sweden is affected by floods resulting in damage. Damage can be limited through prevention planning and effective response operations during flood emergencies. For this purpose the SRSA (Swedish Rescue Services Agency) compiles and maintains general flood inundation maps (Figure 14, right). These are created as basic data for prevention work with the help of a watercourse model for those areas close to watercourses that are at risk of flooding. The maps are intended for use during the planning of emergency and rescue services work and as a foundation for land use planning by municipalities. They can also be used as basic data for various risk and vulnerability analyses.

Concluding remarks

The predominant natural hazards in Nordic countries are floods, landslides, storms and cyclones, and, with the exception of Denmark, snow avalanche. Volcanoes and earthquakes are major geohazards in Iceland, and parts of Norway are susceptible to seismic activity. Quick-clay slides pose a major threat in Norway and Sweden. Slide-triggered tsunamis also represent a threat to parts of western Norway and the coastal areas of Greenland and Iceland.

However, compared to many areas of the world, the human losses caused by natural hazards are smaller in Nordic countries. This is mainly due to the low population density in the exposed areas. The economic losses, on the other hand, are significant and the societal risks posed by natural hazards vary significantly from country to country in Norden. The results of recent research projects imply that the temporal and spatial distribution of natural hazards in Nordic countries might increase significantly in the coming decades because of climate change. Adapting to the new situation will require a proactive approach from the politicians, geoscientists and decision makers.

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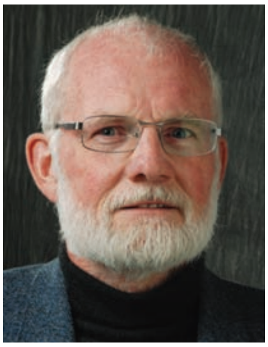

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History of Geology in Norden

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The Nordic countries of Denmark, Finland, Iceland, Norway, and Sweden have been closely connected for many centuries, not least from a geological point of view. Scientific cooperation as well as contentions have been common. The earliest known records of "geological" treatises are from the 16th century, but especially in the 18th century, when the natural sciences flourished all over Europe, Nordic scholars were in the forefront in geochemistry, mineralogy, and paleontology. This was also the century when "geology" started to be taught at the universities, and science academies were founded in Norden, adding greatly to "geological" studies. In the 19th century, like in so many other countries, national geological survey organizations and geological societies were founded. In Norden, geological research has long traditions within mineralogy and ore geology, paleontology and stratigraphy, tectonics and structural geology. During the last century, focus has turned also to Quaternary and glacial geology, igneous and metamorphic petrology, geochemistry, micropaleontology, petroleum geology, sedimentology, marine geology, geophysics, geochronology, and research related to geothermal energy and deposition of radioactive waste products. In many of these research areas, Nordic geoscientists have contributed greatly over the years to the development of the science of geology.

Introduction

Geology as a science was established around 1800. It was the fruit–however unripe–of many centuries of efforts, experiences, failures, and successes by precursors. Fundamental for geology to evolve as a science was the realization that the Earth had a history that went back long before Man, and that the order and fossil contents of sedimentary rock strata could reveal that history. Geology was a new science, building on the advances made in chemistry, physics and biology, but adding to them an "incomprehensible" time dimension. But also instrumental achievements were basic for important parts of the practical accomplishment, mainly the development of the microscope in the 1830s. In addition, an array of early cumbersome problems had been solved or put aside, e.g., the earth was not a divine gift, the earth was not a few thousand years old, Man was not the crown of Creation, fossils were not *lusus naturæ* but the remains of living creatures.

This brief chapter on the history of geology in Norden will cast light on some problems and endeavours engaging people—natural scientists, as well as physicians and clergy in the early days—in the Nordic countries contributing to this process.

A brief outline up to 1800

Basic knowledge about rocks, ores and soils were of course achieved from generations of experience in mining and agriculture. An early account of mining, minerals, rock carving and agriculture by a Northerner was given by Petrus Magni (c. 1465–1534; a Swedish monk, later bishop), written partly independently, in the early 16th century. Olaus Magnus (1490–1557; exiled Catholic archbishop of Sweden living in Rome) in his *Historia de gentibus septentrionalibus* ("History of the Nordic peoples"), published in 1555, also wrote on mining and natural conditions. Even the Icelandic sagas tell us about former climate conditions. Although not scientific, these books are important sources for understanding the level of knowledge and the mysticism that was linked to many natural objects at that time.

In the 17th century there appeared so-called "*physicæ*", i.e., general treatments of the entire visible nature and its characteristics; the heavenly bodies, the earth and its mountains, rivers, organisms, rocks and minerals. In Finland, Sigfrid Aronus Forsius (c. 1555–1624; vicar and astronomer) wrote *Physica* (1611, published 1952!) and *Minerographia* (1613, published 1643), summarizing the knowledge about rocks, minerals and metals. In Denmark, there was an early interest in the earth sciences. Caspar Bartholin the elder (1585–1629) wrote *Systema physicum* (1628) and Ole Worm (1588–1654), Thomas Bartholin (1616–1680) and Ole Borch (1626–1690) treated geology-related matters, minerals, metals, fossils. In the year 1669 two pioneering books written by Danes were published; Niels Stensen's (Nicolaus Steno, 1638–1686) *De solido intra solidum naturaliet contentum dissertationis prodromus* (published in Florence) and Erasmus Bartholin's (1625–1698) treatise on the bi-refringency of Iceland spar (published in Copenhagen).

In the 18th century, landscape descriptions became more frequent, many of which were carried out by clergymen publishing on the natural and cultural history of their parishes. But also scholars contributed to this genre. In Sweden, Urban Hiärne (1641–1724) was the first to investigate the nation's geological conditions by sending, in 1694, an inquiry to officials around the country asking for information. The results were published in the following decade. Carl von Linné (Linnaeus, 1707–1778) in his travel descriptions made many remarks on geological findings, and Daniel Tilas (1712–1772), a grandson to Hiärne, published on occurrences of ores and petroleum in central Sweden. In Denmark, the writer and playwright Ludvig Holberg (1684–1754) published a description of Denmark and Norway, and so-called natural histories were published on Norway by, e.g., Erich Pontoppidan (1698–1764). The seashore exposures and their fossil contents at Stevns Klint and Møns Klint in Denmark were described by Søren Abildgaard

(1718–1791), and Hans Strøm (1726–1797) wrote on Norwegian landscapes as well as on fossils. Early investigations of the natural conditions of Iceland were carried out by Eggert Olafsson (d. 1768) and Biarni Pálsson (1719–1779), and in their printed description of 1772 was also a chapter on the island's geological structure.

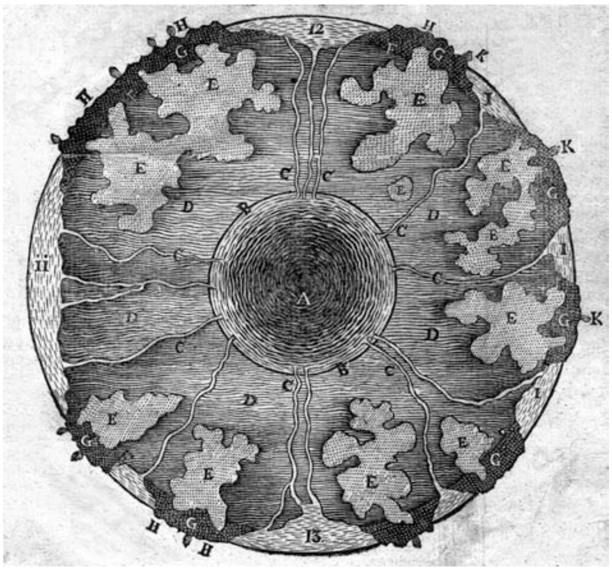

***Figure 1** Earth's interior according to an early 18th century view. Ocean waters enter through canals (C) into the center of the earth (A) which is filled with fermenting mud. From there the rising steam is purified when passing through the porous earth (D), entering the "linia trivialis" (F) and eventually the surface. E marks "hydrophylacia", major cavities filled with water and fine sand. (From U. Hiärne, 1706: Den beswarade och förklarade anledningens andra flock, om jorden och landskap i gemeen, facing p. 150.).*

Academies of sciences were founded in 1739 in Sweden, in 1742 in Denmark, and in 1760 in Norway. These came to have a great influence on the development of natural science in Norden. Two universities had been established in the 15th century, in Uppsala (Sweden) in 1477 and in Copenhagen (Denmark) in 1479, and two in the 17th century, in Turku (Åbo, Finland) in 1640 and in Lund (Sweden) in 1666. But is was not until the 1720s that mineralogy and paleontology began to be taught at universities in Norden. In Turku, for instance, teaching in this field was initially conducted by professors of medicine and economics, and from 1761 by Pehr Gadd (1727–1797) and later by Johan Gadolin (1760–1852), professors of chemistry, who also supervised a number of master dissertations on mineralogical and geological topics.

Rock classifications and mineral analyses, mainly by blowpipe, were strongly developed during the 18th century. In Sweden, so-called *Mineralogiæ* were published by well-reputed scientists like Magnus von Bromell (1679–1731), Johan Gottschalk Wallerius (1709–1785), Axel Fredrik Cronstedt (1722–1765) and Torbern Bergman (1735–1784), contributing greatly to the science, many of which ran through many editions and were translated into several languages. Even Linnaeus in his *Systema naturæ* (1735) included a "Regnum lapideum". Paleontological treatises began to appear, by, e.g., Magnus von Bromell and Kilian Stobæus (1690–1742) in Sweden, Hans Strøm in Norway, Morten Thrane Brünnich (1737–1827) and Peter Christian Abildgaard (1740–1801) in Denmark.

An issue that concerned many scholars in Sweden and Finland, e.g., Emanuel Swedenborg (1688–1772), Linnaeus, Anders Celsius (1701–1744), and Wallerius in Sweden, and Johan Browallius (1707–1755) and Per Kalm (1716–1779) in Finland, was the so-called "diminution of the sea". Already Hiärne had called attention to the observations that the shore of the northern Baltic Sea had moved seaward for centuries; old landing-stages were now far inland. This phenomenon was regarded as due to a diminishing amount of sea water, and it was not until the 19th century it was explained as due to the elevation of that region—later construed as being due to isostatic rebound following deglaciation.

Geology in Denmark and Greenland after 1800

Early in the 19th century a young naturalist and mineralogist, Henrik Steffens (1773–1845), made his spectacular entrance to Copenhagen. Under great public attention, he gave a series of lectures on European science and poetry. Together with, e.g., Alexander von Humboldt and the great German author and naturalist Johann Wolfgang von Goethe, Steffens had studied geology under Gottlob Werner. Through Steffens' friendship with Goethe the knowledge about the growing Romantic literature spread to Danish authors and leading cultural personalities such as N.F.S. Grundtvig and the national icon and poet Adam Oehlenschläger. These events are generally considered to mark the onset of the Romantic Movement in Danish poetry, painting *and science*, where the discoverer of electromagnetism, H.C. Ørsted (1820) together with Steffens became a leading figure with his Romantic thoughts and writings on 'The Spirit in Nature'.

However, the Norwegian-born Steffens soon left Copenhagen to take up a position as professor of geology in Kiel in Holstein. (Both Norway and Schlesvig-Holstein were united with Denmark until 1814 and 1864, respectively.) Soon thereafter the first professorship in geology (i.e., mineralogy and chemistry) was established at Copenhagen University, and Johan Georg Forchhammer (1794–1865) was appointed. Forchhammer was of a more specific scientific school than Steffens and Ørsted, and his geological studies were based on the methods of another Dane, Nicolaus Steno (1638–1686), who already in 1667 and 1669 had made important contributions to the foundation of the science that we now call geology. Forchhammer met Charles Lyell, and together they studied the chalk formations of eastern Denmark. They agreed that the

***Figure 2** Stevns Klint at the east coast of Sealand is the international type locality of the Cretaceous-Tertiary (Maastrichtian-Danian) boundary. At the base of the Danian the boundary is marked by the so-called 'Fish Clay' containing a high concentration of the rare element iridium. At a conference in Copenhagen in 1979 lead by geology professor Tove Birkelund a major controversy started to evolve on the interpretation af the Ir-content. The geologist Walter Alvarez claimed that the Ir-deposition was caused by a large bolide impact also causing the mass extinctions at the K-T boundary, while others—especially people from Copenhagen University—claimed the Ir-deposition to be caused by the Deccan Trap volcanism in India 65 m.y. ago.*

Danian limestone at Stevns Klint is younger than the Upper Cretaceous chalk. However, they disagreed on the formation of the large floes of white chalk piled up and interbedded with 'dilluvial' deposits in Møns Klint. Lyell suggested that Møns Klint, which is now a classic example of glaciotectonics, was formed by drifting masses of sea ice and icebergs. Forchhammer doubted Lyell's explanation and considered the large dislocations to be of volcanic origin associated with crustal earth movements.

In 1874 geology professor F. Johnstrup argued for a glacial origin of the surface deposits in Denmark. The zoology professor Japetus Steenstrup (1813–1897) confirmed Johnstrup's ideas about a glaciation in the recent past by studies of bogs in Northern Zealand where immigration of more and more warmth-demanding species followed the arctic species found at the base of the bogs. In 1888 the Geological Survey of Denmark (DGU) was founded with Johnstrup its first Director. Thereafter Quaternary geology and environmental history studies became a prominent part of Danish geology. In particular, during the first half of the 20th century Johannes Iversen's (1904–1971) development and use of pollen analysis provided a modern understanding of past climatic changes, the immigration and settlement of Man, and the temperate vegetation's migration into Denmark and Northern Europe.

During the first part of the 20th century the geology of Greenland also became a prominent part of Danish earth sciences subsequent to expeditions led by H. J. Rink, J. F. Johnstrup, K. I. V. Steenstrup, and N. V. Ussing to West Greenland. Most conspicuous were 'The Danish Expeditions to East Greenland' from 1926 to1958 including the 'Three Year Expedition' to North East Greenland (1931–1934). These dangerous expeditions were led by the charismatic geologist Lauge Koch. He worked directly under the Danish Government, and invited many foreign colleagues to join his expeditions. In the 1930s, however, after Koch had published his *Geologie von Grönland* and *Geologie der Erde*, a major controversy divided Danish geologist into two groups, respectively *pro et contra* Koch. At a meeting in the Geological Society of Denmark, Koch was seriously accused by eleven prominent Danish geologists to have stolen or misinterpreted their results. Koch took the accusers to court, and after a long and bitter trial he partly won the case after appealing to the Supreme Court. In 1934 Koch won another important trial as Danish delegation leader, namely the trial between Denmark and Norway at the International Court in The Hague about the High Supremacy over East Greenland.

Shortly after the Second World War the Geological Survey of Greenland (GGU) was founded. The first task for GGU concerned the geological mapping of West Greenland, where the population is concentrated. From 1970 to the end of the century the geological mapping progressed to East and North Greenland, mainly supervised by Niels ("Oscar") Henriksen.

In the late 1960s the Danish Underground Consortium (DUC) made the first oil discovery in the North Sea under the geological leadership of Theodor Sorgenfrei (1915–1972). Soon after, oil discoveries were also made in Norwegian and British parts of the North Sea. In 1981 a law on the exploration of the Danish 'underground' opened the Danish North Sea sector for other oil companies. This led to a considerable growth in oil and gas exploration in the Danish North Sea sector, and at the time of writing Denmark is Europe's third largest producer of hydrocarbons.

This work also stimulated the oil geology at the universities and at DGU. DGU's chief geologist Arne Dinesen made important decisions for the benefit of geological research and economic geology. A large geophysical division was established at DGU and important basic research in the sedimentology and dynamics of chalk reservoirs was undertaken by groups at DGU and Copenhagen University.

In 1971, the Danish Government appointed the world's first minister of the environment, and simultaneously environmental geology became an increasingly important issue in Danish geology with state geologists Lars Jørgen Andersen (hydrogeology) and Svend Thorkild Andersen (environmental history) from DGU, and professor Henning Sørensen (geochemistry) from Copenhagen University as leading personalities. At Århus University environmental geology culminated with Kurt Sørensen's outstanding development of geophysical methods for groundwater mapping.

In 1995, the DGU and GGU were merged to form one institution (the GEUS) working equally in Denmark and Greenland. On top of that, GEUS and the geological and geographical institutes at Copenhagen University formed a 'Geocentre Denmark' together with the Geological Museum and in 2007 also including the geological institute at Århus University.

Geology in Finland after 1800

After the 1808–1809 war between Russia and Sweden, Finland became part of the Russian Empire as an autonomous Grand Duchy. Governor-General Fabian Steinheil (in office 1811–1823) was deeply interested in mineralogy and emphasized the role of mining industry and exploration in pursuit of domestic raw materials for the country's iron works. The mining office was reorganized and Nils Nordenskiöld (1792–1866) was appointed superintendent. As the result of active and enthusiastic prospecting, several new minor iron deposits were discovered. Nordenskiöld urged systematic geological mapping as the basis for successful prospecting. In 1877, a ten-year budget was allocated to the "Geological Expedition" and in 1885 the Geological Commission (Geological Survey of Finland) was founded. The Geological Society of Finland was founded in 1886.

In 1828, the Academy of Turku was moved to Helsinki, later to become the University of Helsinki. A professorship of geology and mineralogy was established there in 1852, but it remained without a permanent incumbent for many years, as the young and talented mineralogist Adolf Erik Nordenskiöld (1832–1901) had to flee to Sweden for political reasons. In 1877, Fredrik Johan Wiik (1839–1909) was appointed to the post.

In the early and mid-19th century, Finland had several famous mineralogists, e.g., the above-mentioned persons and Axel Gadolin (1828–1892). The granite pegmatites and skarn deposits of southern Finland provided rewarding research opportunities for these scientists who mastered crystallographic and mineral-chemical research methods. The modern study of the Precambrian crystalline bedrock was, however, only made possible by the advent of the petrographic microscope. In Finland this was first used by Wiik, and for his students Jacob Johannes Sederholm (1863–1934) and Wilhelm Ramsay (1865–1928), as well as for Ramsay's student Pentti Eskola (1883–1964), it served as a basic research instrument.

Sederholm was Director of the Geological Survey from 1893 to 1933. In the 1890s, he applied the uniformitarian doctrine to the origin of the Precambrian bedrock of southern Finland, and later he made pioneering studies of the petrology of granites and migmatites.

Figure 3 Geological excursion to Skogböle (Kuovila), Pohja, southwestern Finland, on May 16, 1908. From left: P. Eskola, R. Stenberg, B. Frosterus, Miss E. Holmberg, J.J. Sederholm (with hammer), O. Trüstedt (discoverer of the Outokumpu deposit), W. Ramsay. Photo: W.W. Wilkman, Geological Survey of Finland, VK05671.

Wilhelm Ramsay followed Wiik as professor of geology and mineralogy. He discovered and studied the alkaline rocks of the Kola Peninsula and, subsequently, focused on the Finnish Quaternary geology and the history of the Baltic Sea. Ramsay's successor Eskola introduced his doctrine of regional metamorphic facies in 1915 and developed it in subsequent works. His studies on petrographic-tectonic classification and origin of granitic rocks were classics in their fields. The discovery of the large and rich Outokumpu copper ore in 1910 and the Petsamo (Pechenga) nickel deposits in the 1920s and 1930s enhanced the possibilities of exploration and mining industry in Finland.

The theory of a continental ice sheet gained support in Finland in the 1860s. Studies of Quaternary geology made rapid progress in the late 1880s and 1890s and, by the early 1900s, Ramsay and Sederholm, together with Finnish and Swedish colleagues, had outlined the history of the Baltic Sea as well as the origin of the Salpausselkä marginal formations and eskers. In 1924, Ramsay explained the Baltic Sea shore displacement as the result of postglacial isostatic rebound and water level fluctuations resulting from the melting of the continental glacier. Ramsay's work was continued by Matti Sauramo (1889–1958), professor of geology and paleontology, who also applied the varved clay method and microfossil studies. The prominent lakes of Finland and their discharge channels were studied by Ramsay and Väinö Auer (1895–1981) among others.

The decades after World War II were a period of steady progress for both mining industry and geological research. The staff of the Geological Survey increased from about 25 in 1935 to 900 in 1985. The bedrock and soils of the country have been mapped to the scale of 1:400,000, and more detailed mapping (1:100,000) covers most of the country. Airborne geophysical mapping was initiated by Aarno Kahma (1914–2004) and Maunu Puranen (1914–1999) in 1951 and completed in 1972, and a low-altitude survey is near completion. Other study and research objects of the Geological Survey have included geochemistry, isotope-geochemistry, mineralogy, marine geology, peat bogs, and nuclear waste disposal in hard rock.

For many years, the Department of Geology at the University of Helsinki was the only institution of its kind in Finland. A chair of geology and mineralogy was founded at the Swedish-language Åbo Akademi University in Turku in 1918. The universities of Turku and Oulu got chairs of geology and mineralogy and Quarternary geology in the late 1950s and in the 1960s. Currently, the departments of geology at the universities of Helsinki, Turku, and Oulu have 4–6 professorships, Åbo Akademi has two. Helsinki University of Technology has a chair of economic geology and Tampere University of Technology has a chair of engineering geology. The departments have produced important contributions to the geology of Finland and beyond. The Institute of Seismology at University of Helsinki has played an important role in the study of the deep structures of the lithosphere.

In the 1940s and 1950s, Thure Georg Sahama (1910–1983) and Kalervo Rankama (1913–1995), both professors of the University of Helsinki and authors of *Geochemistry*, rose to world fame as geochemists. In the 1950s, Sahama focused on mineralogy, and Rankama wrote and edited comprehensive books on isotope geology and Precambrian geology.

Between 1940 and 1980, thirty new base and ferrous metal mines were opened in Finland. Later, successful exploration has been focused more on precious metals. In recent years, the discovery of diamond-bearing kimberlites with deep crustal and mantle xenoliths has initiated cutting-edge studies on the nature and composition of the lithospheric mantle in eastern Finland.

During recent decades, the bedrock research have included plate tectonic modelling of the origin and evolution of the Finnish Precambrian and the origin of intracratonic igneous complexes. In Quaternary geology, the work of Sauramo has been continued by his students and younger geologists. New field data and dating methods have produced a great deal of information on the final stages of the Ice Age and postglacial climate evolution. Paleolimnological investigtion methods have been used successfully to gauge the state of the environment and its changes.

Geology in Iceland after 1800

The geology of Iceland is so radically different from that of the Continent that for most of the 19th century foreign geological interest centered mostly on the island's hot springs and volcanoes. However, a general description of Iceland had appeared in 1772, "Eggert Olafsson and Bjarni Palsson's *Travels Through Iceland*", based on an expedition (1750–1757) that was planned by the Royal Danish Academy of Sciences and Letters and funded by the Crown. This large illustrated book was duly translated into German (1775), French (1802) and English (1805) and remained the chief general source of information about Iceland's ethnology, geology, zoology and botany for over a century.

In 1839 Japetus Steenstrup (1813–1897) and Jonas Hallgrimsson (1807–1845) were sent to Iceland by Danish authorities to investigate the country's natural resources. Lignite samples they collected were later investigated in Zürich by Oswald Heer (1809–1884) who found them to be Miocene in age. Jonas Hallgrimsson intended to replace Olafsson and Palsson's book with a new description of Iceland to accompany the topographic map being made by the mathematician and surveyor Björn Gunnlaugsson (1788–1876). Hallgrimsson's plans were never realized due to his untimely death but Gunnlaugsson's map appeared in 1846 and remained the basis for geological work in Iceland until superseded by the Danish Geodetic Survey maps in the 20th century.

The 1845 Hekla eruption attracted a number of foreign scientists to Iceland the following year, including R. W. Bunsen and W. S. von Waltershausen. They visited Hekla and Geysir and traveled around southwest Iceland collecting rock samples which Bunsen subsequently analyzed, finding that intermediate lava compositions were more scarce than silicic; and in 1851 he postulated that there were two magma types beneath Iceland, basaltic and silicic, with the intermediate rocks being mixtures of the two. Waltershausen, having studied "palagonite" (he coined the term) in Sicily, suggested that the Icelandic palagonites were formed in submarine eruptions.

C. W. Paijkull (1836–1869) traveled about parts of Iceland in 1865 and produced the first geological map of the country. Also, the Plio-Pleistocene sedimentary and volcanic sequence of the Tjörnes peninsula attracted renewed attention. Eggert Olafsson had described it in his *Travels* and found fossils of shells not living around Iceland at the time, indicative of a different climate.

The 19th century ended in a grand crescendo with Thorvaldur Thoroddsen's (1855–1921) expeditions between 1882 and 1898 to explore and describe the whole of Iceland. A prolific writer, Thoroddsen produced a continuous flow of books and papers from about 1880 till his death. With his work he put Iceland, literally speaking, on the map, and for a long time no geological research could be undertaken without first consulting Thoroddsen. An overview of his geological work was contained in a geological map (1901) and his book *Island, Grundriss der Geographie und Geologie* (1906).

Thoroddsen's 19th-century view that the Ice Age was a single, long cold spell was challenged in 1900 by Helgi Pjetursson (1872–1949) who, in both terrestrial and marine sequences, including Tjörnes, found evidence of at least three warm/cold cycles during the Ice Age. The Tjörnes peninsula is now a type locality for the Pliocene-Pleistocene transition, where almost 20 cold/warm cycles can be discerned.

In the 20th century, and especially after 1970, growth in earth-science activity has been exponential and only a few milestones can be pointed out here. Inspired by Wegener's continental-drift theory, Arthur Holmes (1918) suggested that Iceland must be underlain by sialic crust, thus explaining both the country's elevation above sea level and the relative abundance of silicic rocks. This idea prevailed until 1965 when it was disproved by isotope geochemistry. Increasing exploitation of geothermal energy in the 1930s engendered

Figure 4 Ice-carved Tertiary landscape. View to the NE across the fjord Breiddalsvik, E Iceland, showing typical westward-dipping basalt sequences. Photo: Oddur Sigurdsson.

increased geothermal research and in 1943 geophysicist Trausti Einarsson (1912–1986) postulated that geothermal fluids are in fact recycled meteoric water. Icelandic geothermal know-how is now being exported to all corners of the world.

The Hekla eruption 1947–48 was the first eruption thoroughly researched by Icelandic scientists. The Iceland Science Society (founded 1918) published a four-volume collection of articles about the eruption, edited by T. Einarsson, G. Kjartansson (1909–1972) and S. Thorarinsson (1912–1983), all of whom were very active in the research. Having started his tephra studies ten years before, Thorarinsson now continued to develop his tephrochronology as well as being active in other volcanological and glaciological research. When the Natural History Museum in Reykjavík was taken over by the State in 1947, Thorarinsson became a permanent member of staff.

The Iceland Glaciological Society, which became a mainstay of glaciological research in the country, was founded in 1950 and a year later founded the journal *Jökull*, which is now the main Icelandic earth-science periodical.

After 1950, Trausti Einarsson and Thorbjörn Sigurgeirsson (1917–1988) started paleomagnetic mapping in southwest Iceland, and in 1955 George Walker began systematic geological mapping of the Tertiary plateau basalts in eastern Iceland. This work has been actively continued to the present day, assisted by radiometric datings. After 1970, plate-tectonic theory has been central to the understanding of Icelandic geology.

Before the Second World War, Icelandic geologists (except Thoroddsen), were either gymnasium teachers or had professions other than geology. But in the 1940s, earth science in Iceland gradually became 'institutionalized' and the number of earth scientists grew. Founding members of the Iceland Geoscience Society in 1966 were thirteen—now the Society counts about 270. The energy sector increased greatly in the 1970s and 1980s owing to the development of geothermal and hydroelectric projects. Geology and geophysics were taken up at the University of Iceland in 1968. Sigurdur Thorarinsson was first professor, supported by staff from the University Science Institute. In 1973 the Nordic Volcanological Institute was founded with Gudmundur E. Sigvaldason (1932–2004) as first Director. The Institute has been particularly active in petrology and in geophysical monitoring of crustal movements. The Meteorological Office runs a seismic monitoring network, employing a number of geoscientists; the Natural History Museum is responsible for the publication of geological maps, and a number of more specialized research and service institutions have earth scientists in their employ.

Geology in Norway after 1800

The development of geological science in Norway has to a substantial degree been determined by the fact that the capital is situated in the middle of an extremely geodiverse area—the Oslo paleorift (also known as the Oslo graben or Kristiania territory)—exhibiting Paleozoic sedimentary rocks that are very rich in fossils, a great variety of igneous rocks mostly of Permian age, and abundant Quaternary deposits and geomorphological features created by ice ages.

A Norwegian university was established in Christiania (now Oslo) in 1811, and the mineral collections, library, models and instruments from the Kongsberg *Berg-Seminarium* were transferred there in 1813–1814. One of the lecturers from Kongsberg became the University's first geology professor: Jens Esmark (1762–1839), a student of Abraham Werner in Freiberg. Esmark established the new mining science school at the university; which remained the only centre of natural science study in Norway until the 1850s. In 1824 Esmark published evidence of a former large scale glaciation of Norway, and thus became an early advocate of Ice Age theory.

The first comprehensive national survey and map of the geology of Norway was published by Baltazar M. Keilhau (1797–1858) in his 3-volume *Gæa Norvegica* (1838–1850). His successor as professor, Theodor Kjerulf (1825–1888), revolutionized Norwegian geology by introducing biostratigraphical methods, new laboratory methods in the study of rock chemistry, and ice age theory. He founded the Geological Survey of Norway in 1858. His pupil Waldemar C. Brøgger (1851–1940) made significant contributions to the study of the mineralogy of pegmatites, and Paleozoic paleontology and stratigraphy. In 1881 he established the mineralogical institute of Stockholm University in Sweden. Brøgger's students from Stockholm afterwards filled a number of geology chairs in the Nordic countries. After succeeding Kjerulf in the Oslo professorship in 1890, Brøgger concentrated on the origin of igneous rocks, developing theories of magmatic differentiation inspired by biological evolutionary theory in his seven-volume *Die Eruptivgesteine des Kristianiagebietes* (1895–1933). Brøgger was also one of the initiators of the Natural History Museum building complex at Tøyen in Oslo, including the mineralogical-geological and paleontological museums. The physico-chemical theory of magmatic differentiation was further explored in a series of benchmark works by Johan H. L. Vogt (1858–1932), who also contributed many studies of ore-bodies and marbles in Norway, providing knowledge for commercial developments.

Figure 5 The building of the mining academy – Det Kongelige Norske Berg-Seminarium – at Kongsberg, Norway. The academy, one of the first of its kind, was established in 1757 and associated with the Royal Silver Works. The building is from 1786 and is today part of the Norwegian Museum of Mining. Photo: Norsk Bergverksmuseum, B. I. Berg.

The beautifully developed contact metamorphoses between sedimentary and igneous rocks in the Oslo region had been studied by Keilhau, Kjerulf, and Brøgger, but it was for Victor M. Goldschmidt (1888–1947) with his comprehensive *Die Kontakt-Metamorphose im Kristiania-Gebiet* (1911) to make the region and its geological phenomena a classic area for the study of metamorphism. A pupil of Brøgger and the son of a professor of chemistry, Goldschmidt became one of the founders of geochemistry, exploring the principles of the quantitative distribution of the elements in his nine-volume *Geochemische Verteilungsgesetze der Elemente* (1923–1938). His *Geochemistry* appeared posthumously in 1954. Tom F.W. Barth (1899–1971) combined the research traditions of Brøgger and Goldschmidt in several influential works and textbooks.

In parallel with this focus on rock origins and chemistry, the phenomena of Quaternary geology, so prominent in the Norwegian landscape, were explored by Amund Helland (1846–1918) in pioneer works on the glacial erosion of fjords and lakes, and through his studies of glacier movement in Greenland. In Finnmark in 1889, Hans H. Reusch (1852–1922), Kjerulf's successor as Director of the Geological Survey, discovered traces of ‘an ice age long before the ice ages’, today known as the Varangerian ice age (c. 650 Ma). Reusch was the main initiator of the Norwegian Geological Society in 1905, which continues to publish the *Norwegian Journal of Geology*.

Throughout the 19th century a number of prominent foreign geologists visited Norway, providing impetus to the local scientific community, e.g., Leopold von Buch, Friedrich L. Hausmann, Carl Naumann, Alexandre and Adolphe Brongniart, Charles Lyell, Roderick I. Murchison, James D. Forbes, Harry Rosenbusch, Georg Williams, Joseph Paxton Iddings, and Archibald Geikie. This flow of visiting geologists continued in the 20th century, when Norwegian geologists also increasingly participated in large international projects, including the Deep Sea Drilling Project.

Paleontology was professionalized by Johan A. Kiær (1869–1933), a pupil of Brøgger and von Zittel in Munich. In his steps followed Leif Størmer, Olaf Holtedahl, Anatol Heintz, Ove Arbo Høeg, Gunnar Henningsmoen and Niels Spjældnes, with studies on the Oslo region Paleozoic and more recent formations on Svalbard which became part of Norway by international treaty in 1920.

The advent of methods for the absolute dating of rocks revolutionized the understanding of the evolution of the geology of Norway, a country which, outside the Oslo-region and Svalbard, is almost devoid of fossils, and dominated by a complex patchwork of more or less heavily metamorphosed rocks of Precambrian or Paleozoic age. The theory of plate tectonics contributed greatly to the reconstruction of the history of Norway, where a main feature has been the Caledonian orogeny and large overthrusts created by continent collision.

The Polar explorer Fridtjof Nansen (1861–1930) did pioneering work on the continental shelf in the Barents Sea and along the Norwegian coast. The discovery of oil on the continental shelf in the North Sea in 1969 (Ekofisk Field) brought radical change to Norway's economy and industry. Geology departments in the universities experienced an explosion in the number of students, and curricula were hastily remodelled. The majority of Norwegian geologists are today employed in the oil industry. Norway has been in the forefront among nations to secure that natural energy resources should primarily benefit the citizens; oil revenues have been a significant contribution to the welfare state. The state has shareholder control of the major companies StatoilHydro and Petoro. The extraction of oil has spurred sophisticated scientific and technological innovation, computer software for ‘visualizing’ reservoirs, supply vessels, drilling platforms, equipment for deep drilling and oil exploration in Arctic waters.

Recent years have seen an increased focus on industrial minerals, and with the development of infrastructure in a modern society there has also been an increased demand for applied engineering and environmental geology.

Geology in Sweden after 1800

One might say that while the earth in earlier centuries was the subject of much theorizing, mainly about its origin and interior, the 19th century was the beginning of its close and extensive investigation. Minute studies of rocks and rock sections were commenced. Stratigraphies were established for different places and regions, and correlations were elaborated, even world-wide. Rudimentary stratigraphies had been recognized in the 18th century, in which development Swedenborg, Linnaeus and Bergman in Sweden had taken part. But with the recognition in the early 19th century that sedimentary rock strata could be characterized by their fossil content, work in the field expanded and biostratigraphy developed.

Among those who made extensive field work, Wilhelm Hisinger (1766–1852) should receive specially mention. His series of descriptions of the geology of various parts of Norway and Sweden from the late 1790s to 1840 were pioneering endeavours. Another giant in the 19th century natural sciences was Sven Nilsson (1787–1883), who published primarily in zoology, but also in paleontology, geology, and archaeology. Nils Peter Angelin (1805–1876), the first holder of the chair in paleozoology at the Swedish Museum of Natural History in Stockholm, published descriptions of several hundred trilobite species, and was the first in Sweden to make use of biostratigraphy.

During the 19th century geology and geological investigations were organized and institutionalized in various ways. A school of mining was established at Falun in central Sweden in 1819, in 1868 replaced by mining technical departments in Stockholm, and later in Luleå. The school in Falun came to be a breeding ground for generations of geologists later to take leading positions at universities and the Survey.

Another important centre for geological reasearch in Sweden was the Swedish Museum of Natural History in Stockholm. With roots in the 18th century, it was formally established in 1819 with departments of, among others, mineralogy (1841), paleozoology (1864), and paleobotany (1884). At the turn of the century, outstanding researchers like Alfred G. Nathorst (1850–1921) in paleobotany, Gerhard Holm (1853–1926) in paleozoology, and Hjalmar Sjögren (1856–1922) in mineralogy, were professors at the Museum, making it a stronghold for geology in Sweden.

The first chair in geology (with mineralogy) in Sweden was established at Uppsala University in 1852 (Lars Peter Walmstedt, 1782–1858), and a second (with paleontology) was established at Lund University in 1867 (Otto Torell, 1828–1900). In Uppsala, the professorship grew from the mineralogical-chemical part of science, while in Lund it grew from the zoological-biological. Stockholm University was established in 1878, and its first professor of geology and mineralogy was the great Norwegian geologist Waldemar Brögger (1851–1940), appointed in 1881. The University of Gothenburg was founded in 1891, and geological research begun there in the 1950s.

A third important establishment in the 19th century for the development of geology in Sweden was that of the Geological Survey. On the initiative of Axel Erdmann (1814–1869), the Survey was founded in 1858 with Erdmann its first Director. For more than a century the Survey had a strong research activity, producing about a thousand papers and treatises in pure science, in addition to ordinary maps and map descriptions. In later decades the Survey has become a central government agency responsible for matters relating to the geology of Sweden and the management of mineral resources.

A fourth important establishment was that of the Geological Society of Sweden in 1871, and the start, in 1872, of the publication of a scientific journal, still today published (under the name of *GFF*). This new publication became the most important forum for Swedish geologists for more than a century.

The debate about the nature of the “dimunition of water”, which had started in the early 18th century, was revived with the finding that striations on bedrock surfaces and eskers were orientated in certain directions. Various explanations were presented, but it was not until the idea of a former extensive ice cover that it was found that these were parts of one and the same phenomenon; the Great Ice Age. This issue interested not only geologists but also scholars like the chemist J. Jacob Berzelius (1779–1848) and the botanist Göran Wahlenberg (1780–1851). The leading figure in Sweden on glacial geology was Otto Torell, who developed Agassiz' theory and successfully convinced colleagues about its validity. In the late 19th century Gerard De Geer (1858–1943) came up with the idea that the varves in glacial clay deposits represented annual deposits, and he developed his clay varve chronology, later elaborated to give an age in absolute years for the last deglaciation in Norden. The pollen analysis, developed by Lennart von Post (1884–1951) in the 1910s, was of great importance for the reconstruction of the migration of plants into formerly glaciated areas, as well as for dating of soils.

Another field of major concern was the structure and development of the Caledonide mountains in Scandinavia. Swedish and Norwegian geologists had for long debated its geology, but the complex tectonics involved made conclusions about its origin vague. It was not until the 1880s that Alfred E. Törnebohm (1838–1911) suggested that huge nappes had been transported from the west, overriding the Lower Paleozoic sedimentary rocks and basement by some 100 km. The idea of nappe tectonics was not new, but movements of that magnitude had not been demonstrated previously. Törnebohm was also one of the pioneers in Sweden who made use of the petrographic microscope for regular research.

Arctic expeditions started in the mid 19th century and continued for many decades into the 20th century. People such as Torell, Nathorst, Adolf Erik Nordenskiöld (1832–1901), and De Geer carried out pioneering studies in paleontology and Quaternary geology. Around the year 1900, there were also expeditions to Antarctica, led by Otto Nordenskjöld (1869–1928) and others.

During the first seven to eight decades of the 20th century, geological research developed strongly in Sweden. The number of professorships increased and research became more specialized. The main fields of research have been in mineralogy, petrology, paleontology and micropaleontology, Quaternary geology, marine geology, geochronology, isotope geology, tectonics, and ore geology.

Concluding remarks

Studies in the Earth Sciences have a long tradition in the Nordic countries; early accounts are from the 16th century. Scientific research started there in the 17th century, and in the following century reached international fame primarily by works in chemistry, mineralogy, and paleontology. The 19th and 20th centuries marked the break-through for geology as a science, in Norden as well as internationally. State geological surveys were founded, geological societies, journals, and university chairs were established.

From an international point of view, Nordic geoscientists have contributed greatly to geology, and in some disciplines directed its development, particularly regarding the petrology, mineralogy, and geochemistry of igneous and metamorphic rocks, glacial and Quaternary geology, paleontology and stratigraphy, and structural geology and nappe tectonics. Also, expeditions to the Arctic areas were significant endeavours.

In later years, geology related to the energy issue has been much in focus in the Nordic countries. The discovery of oil on the continental shelf in the North Sea in the late 1960s brought radical change to, in particular, Norway's and Denmark's economy and industry, as well as to geological and geophysical research and university curricula. In Iceland, an increase in exploitation of geothermal energy in the 1930s engendered increased geothermal research. Icelandic geothermal know-how is now being exported to all corners of the world.

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A note on "Norden"

Norden is a collective term, used for some 300 years, denoting the Nordic countries of Denmark (incl. Greenland and the Faroe Islands), Finland (incl. Åland), Iceland, Norway, and Sweden. The Nordic countries have since early medieval times been closely connected to each other by trade, political treaties, royal marriages, and in part language. Modern Danish, Norwegian and Swedish are very similar written languages. Iceland and the Faroe Islands retain languages closer to Old Norse (the language of the Vikings), while Finnish is a very different language, closely related to Estonian, more distantly to Hungarian. Finland, Norway and Sweden have groups of indigenous people speaking several Sami languages, and Greenland has an indigenous population speaking the official Inuit language Greenlandic (Kalaallisut).

Borders and political unions between the Nordic countries have changed much through history, and wars have been frequent, particularly during the 16th, 17th and early 18th centuries. Finland in the 13th century became part of Sweden, and so remained until 1809, when it was joined to the Russian Empire as an autonomous Grand Dutchy, and eventually, in 1917, became an independent republic. Iceland, for several centuries an independent republic founded by Norwegian emigrants, was in 1262 forced to recognize the Norwegian king. In 1380 Greenland, Iceland and the Faroe Islands came under joint Danish-Norwegian rule, after Norway, through royal marriages, had been joined in union with Denmark to constitute the dual Kingdom Denmark-Norway. The latter remained until 1814 when Norway was forced into a union with Sweden. Iceland remained under Danish rule until 1918 when it was united with Denmark; this lasted to 1944 when Iceland again became an independent republic. The union beween Norway and Sweden lasted until 1905 when Norway again became an independent kingdom.

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The Nordic geological surveys: Geology for society in practice

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Since the mid-nineteenth century, when the first of the Nordic Geological Surveys were established, they have generated a substantial amount of information on the Earth's crust, its natural resources, its processes, and on the geological history of Nordic areas. The collective mission of the geological surveys is to carry out "Geology for Society", by doing research and providing services, and by making geological information and data easily accessible to all the varied end users in industry, government agencies, government institutes, public administrations, technical offices, academia and research institutes, as well as for private individuals. The present paper gives a brief overview of a few, selected, research areas and projects currently undertaken by the Nordic geological surveys. These serve as practical examples of how the Nordic geological surveys address important societal problems and challenges that require geological input for their solution.

Introduction

Most countries in the world have a Geological Survey with a mission to carry out services for the benefit of Society. The Nordic geological surveys (Centers shown in Figure 1) have long traditions of providing, and applying, geological knowledge and data for multiple purposes and needs. The history of the surveys reflects the political and social situation of their host countries over the past 150 years. The oldest, the geological surveys of Norway (NGU) and Sweden (SGU), were established by 1858, followed by the Finnish survey (GTK) in 1885 and the Danish survey (GEUS) in 1888. The late 19th Century was characterized by notable industrialisation, urbanisation and the development of efficient and modern farming. The surveys were established to meet the rapidly developing needs for more knowledge about national mineral resources, materials for construction and space for agriculture. In contrast to the older surveys, the Iceland GeoSurvey (ÍSOR) was established in 2003, by taking over the responsibilities of the former GeoScience Division of Orkustofnun, the National Energy Authority of Iceland.

When NGU was established in 1858 it was argued to the "Ministry of the Interior" that a national geological survey would be "practically useful, scientifically important, and to the honour of the country" (Børresen and Wale, 2008). The mapping of bedrock, surface deposits and mineral resources has traditionally been the main task of the geological surveys. However, today, they are dealing with almost all aspects related to the need for geological knowledge and information in society, focusing on mineral, water and energy resources, land use and protection, engineering geology, geohazards, environmental and climatic changes, pollution and waste management, as well as geotourism. The Finnish, Icelandic, Norwegian and Swedish surveys are placed under the national ministries of Industry (and Trade), while the Danish survey is responsible to the Ministry of Environment. The present paper gives a brief overview of a few, selected, research areas and projects currently undertaken by the Nordic geological surveys. These serve as practical examples of how the surveys address important societal problems and challenges by conducting geology research for society.

The growing need for minerals

The markets for minerals and mineral products are to some extent global, particularly those relating to ores and concentrates. There are also local markets for minerals, mainly those of lower value such as aggregate, although these may be transported very long distances. Between these, many minerals, particularly industrial minerals, span regional, national and global markets, being driven, for example, by the building of new infrastructure in emerging economies.

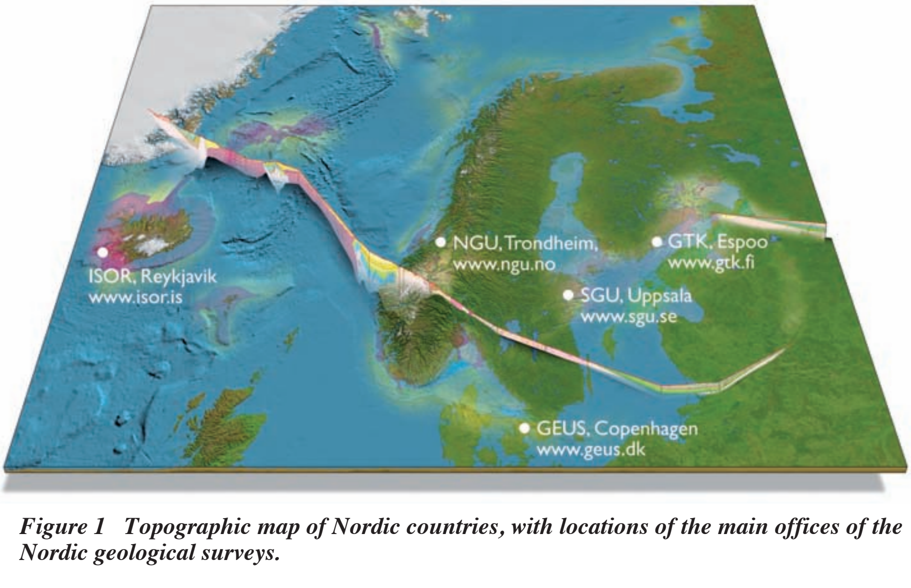

***Figure 1** Topographic map of Nordic countries, with locations of the main offices of the Nordic geological surveys.*

The geological conditions for mineral extraction differ between the Nordic countries. In Denmark the products extracted are mainly industrial minerals such as chalk, limestone, clay, quartz sand, expanding clays and moler (diatomaceous minerals), whilst in Greenland the production of olivine is important. Icelandic mineral production includes diatomite, pumice and basalt; the last of these is mainly used for mineral wool production. Thermal energy is a large contributor to Icelandic power supply; it is utilised in the downstream mineral industry for production of aluminium and ferroalloys (ferrosilica), but also for heating. Norway is a major supplier of ilmenite, olivine, nepheline-syenite and quartz, as well as limestone and dolomite (Neeb, 2006). In Finland, the major industrial minerals produced include carbonates, apatite, talc, quartz, feldspar and wollastonite. Swedish industrial mineral production includes carbonates and dolomite, dolerite, quartz, feldspar and clay. Ores mined include those of iron, lead, zinc, copper and gold in Sweden (Figure 2); copper, zinc, nickel and chromite in Finland and iron in Norway.

The use of dimension stone on a global scale has increased steadily. The principal materials extracted in the Nordic countries include granite, schist, sandstone, quartzite, flagstone, marble, limestone and soapstone. Some Nordic stones are internationally famous and include varieties such as Balmoral Red, Baltic Brown, Blue Pearl, Emerald Pearl, Bohus, Vånga and Ebony Black (Selonen and Suominen, 2003).

On-going exploration activities for the future supply of mineral commodities are intense, and mostly undertaken by mining and exploration companies. The Finnish Geological Survey is the only Nordic survey carrying out exploration itself. The role of the other geological surveys is traditionally supportive; they are the national authorities that stand for the geological knowledge and collection of data, which are presented on geological maps and databases. Geophysical and geochemical data are also collected, stored and made available; airborne geophysical data are highly valuable for exploration (Airo, 2005). Some of the surveys have dedicated rock stores where drillcore from exploration is archived and where researchers and exploration geologists can examine core material. Commonly, exploration reports have been archieved and give direct access to information from past exploration operations. Internet services have been developed for the mining sector, and international companies use them actively for fact-finding and data mining (e.g., *http://en.gtk.fi/ExplorationFinland/*, *http://www.prospecting.no* and *http://www.sgu.se/sgu/en/naturresurs/mininfo/index.html*). Information of more common geoscientific interest is made available at the libraries of the geological surveys and at the surveys internet webpages.

Figure 2 Mineral production at Vitåforsgruvan, Malmberget in Lappland, Sweden (Photo: Anders Damberg).

Geology and land-use

The surveys have undertaken several studies assessing the suitability of different areas for construction, particularly associated with the planning of geological resources in densely populated areas—for instance where water supply is essential (Neeb, 1996; Nikkarinen et al., 1996; Ojala et al., 2006). The investigations are based on the existing geological mapping data produced by surveys. In Finland, the surficial deposits have been classified according to their known geotechnical properties. Map data are commonly integrated with information on slope steepness, thickness of the fine-grained deposits, clay and silt content, and sometimes with information on bedrock topography as well. The data collected by geological mapping, drilling, airborne electromagnetic measurements, and gravimetric profiling of surficial deposits provide information on the suitability for construction purposes.

Underground construction is of increasing importance because of on-going urbanization; infrastructure, caverns, storages, offices, etc. commonly are built underground. The demand for bedrock investigations, including information on weathering, fractures, joints and faults, is considerable. Bedrock material is increasingly used in infrastructure development as aggregates for roads, railways, concrete and airport runways. SGU has developed so-called Bedrock Quality Maps, now covering large parts of urban areas in central and south Sweden, such as the Stockholm, Lake Mälaren and Göteborg regions. The methodology for production of these is described by Persson and Schouenborg (1996), cf. Persson (2002). A quality classification of bedrock materials is necessary to ensure the correct usage for different purposes. In Scandinavia the use of gravel and sand is to be reduced on environmental grounds, whereas the demand on other materials, such as crushed bedrock, will consequently increase.

Geological maps are being used increasingly in land-use planning. The standard geological map provides regional information on the thickness of surficial deposits—based on boreholes along road and railway lines, and sounding data from shallow surveys. The maps are generally accompanied by written descriptions of the properties of the soils in the area, and tables illustrating soil and groundwater qualities (Neeb, 1996; Nikkarinen et al., 1996). Despite these features, however, the maps are often not readily adaptable for detailed planning purposes. For example, the standard 1:20,000 Finnish geological map (*http://geokartta.gtk.fi/*) has a grid that makes generalizations unavoidable.

The need for more detailed maps, for specific purposes such as construction suitability assessments, has increased. For example, since the 1990s, geological and geotechnical soil maps for building purposes and geological risk evaluation have been made available on the 1:10,000 and 1: 4,000 scales in Central Finland and near Helsinki in connection with geotechnical investigations (Neeb, 1996; Nenonen et al., 1999; Ojala et al., 2006). Information relating to soil distribution, for instance geotechnical soil maps at 1:10,000 and 1:2,000 scales, are available for land-use planning purposes in each of the Nordic countries. The geological surveys have produced construction suitability maps, based largely upon slope angles, overburden depths and soil types (Idman et al., 2006). The data collected provide information on suitable foundation types and foundation depths (pile lengths). In Finland, a cost-benefit analysis has shown that piling is economic to a depths of c. 13 m. Geophysical methods (gravimetric measurements and the airborne electromagnetic) allow delineation of local areas, where deep and/or unfavourable foundation conditions occur (Puranen et al., 1999; Ojala et al., 2006) and building costs are greatest. The methodology for producing "suitability maps" for construction purposes is most usefully employed in areas of new construction. Only sparse geotechnical drilling data are needed to evaluate the overall foundation costs of different regional and town plans (Figure 3). One service provides maps that enable planners to evaluate areas susceptible to geological hazards, such as

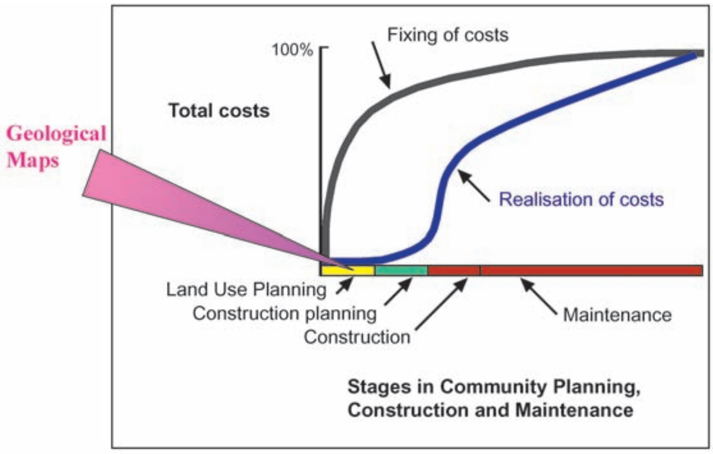

Figure 3 The figure illustrates the overall costs of a construction process. They are firmly fixed in the initial stage of the process, where geology based land-use planning may lead to substantial reduction of construction costs, thus maximizing the impact of geodata for citizens, constructors and society (Idman et al., 2006).

landslides, rock-falls, flooding, erosion, compressive or frost-affected swelling soils, radon risks, etc. In Sweden and Norway, the most detailed regular maps of this type produced by the surveys are at the scale of 1:20,000. The work of both surveys in collaboration with geotechnicians, has resulted in examples of landslide thematic maps (Viberg et al., 2002; see also *www.skrednett.no*).

The internet has become an increasingly important tool in providing geological information to planners and developers. In the Helsinki area, a completely new geological information system (GeoTIETO) for land use planning is being developed (Wennerström et al., 2006). The basic idea has been to offer users continually maintained and updated geological data and supporting material within any area at the desired scale, directly through an open and free Internet-based portal. The datasets will include geological maps (bedrock maps at 1: 50,000 and Quaternary deposit maps at 1: 20,000 scales), geological models and uniform geological databases such as those based on soils, bedrock drilling, rock aggregates, geophysical data, relief models, topographic maps, aerial photographs and land use information. Users will be able to easily combine and display several data sets, make searches and interpret geological information using a Web browser.

Data from sites have been collected and stored in databases at the geological surveys and are commonly used to develop models or products. In some cases (for example, at SGU) the information from tunnels and caverns has been presented in 3D models (cf. Morfeldt and Persson, 1997; Persson, 1998). Storage of geological and engineering geological information from new sites has to be maintained to ensure the models remain up-to-date.

Developing geothermal energy

The Nordic countries rely on a diverse spectrum of sources of energy that reflect both the natural resources each country has at hand, as well as what has been developed through political motivation. The national geological surveys have been central in the exploration, development and management of energy resources, including: the large oil and gas reserves in the Nordic seas that Norway and Denmark have been able to develop; coal deposits that are mined on Svalbard; water resources for hydropower which are abundant in Iceland, Norway and Sweden; and geothermal resources that are especially abundant on Iceland.

The geological surveys actively promote and develop new knowledge and technologies for effective and extensive use of geothermal energy; in all countries there is increasing use of geothermal energy, both in the public and the private sectors. Iceland is in an unique position owing to its active volcanism, and is leading the development; already more than 70% of the primary energy use in Iceland comes from hydropower and geothermal energy.

The geological setting of Iceland is unique with a sub-aerial exposure of the Mid-Atlantic Ridge, manifested by active volcanic rift zones extending from northeast to southwest of the island. The active volcanism produces a high heat flow to the surface, caused by magmas emplaced in the upper crust. This heat is extracted from both ‘high temperature fields’ within the active volcanic zones and ‘low temperature fields’ outside these zones. The heat is extracted as hot water and steam and is used for district heating, industrial purposes and power generation, offering a cheap and environmentally benign source of energy for the Icelandic society.

From the early stages of exploration to eventual development and production from a geothermal field, the geological survey’s involvement is manifold. At the exploration stage, the geological survey makes geological and geothermal maps and conducts geochemical surveys to produce a preliminary model of the geothermal field, the geological and the tectonic setting in order to estimate the temperatures and fluids that may be expected to be found at depth. Complementary geophysical surveys and studies of seismic activity are used to map reservoir boundaries and to outline active tectonic features that may be associated with permeable zones (Eysteinsson et al., 1994). When drilling commences, data from drill cuttings, cores, geophysical logs, fluid samples and flow tests are collected from the wells. These data provide the basis for evaluating the geothermal characteristics and production capacity of each well. Furthermore, they are integrated into a conceptual model of the reservoir that forms the basis for numerical modeling to assess the generating capacity of the field as well as to improve the positioning of new production and injection wells. With production, changes in the geothermal reservoir are continually monitored and evaluated in order to optimise production and enhance the lifetime of the geothermal reservoir (Stefansson et al., 1995; Kristmannsdottir and Armannsson, 1996). Examples of ongoing projects are the Hellisheidi (Figure 4) and the Reykjanes fields in south-western Iceland, where two new geothermal power plants with installed capacity of 90 and 100 MWe, respectively, began production in 2006. Drilling is still on-going in the Hellisheidi field to encourage further expansion, while exploration drilling is well underway in northern Iceland in the fields of Krafla, Námafjall and Theistareykir. Meanwhile, exploration and development in the ‘low temperature’ areas, whilst at a smaller scale, is continuing to increase the percentage of households (currently 89%) in Iceland heated by geothermal energy.

With increasing demand for renewable energy, the Nordic geological surveys have in recent years become involved in research and exploration into new resources of geothermal energy through international projects, for example the on-going ENGINE project (ENhanced Geothermal Innovative Network for Europe, *engine.brgm.fr*). Another major project, IDDP (Iceland Deep Drilling Project, *www.iddp.is*), is exploring whether supercritical fluid can be extracted economically from geothermal fields in Iceland (Fridleifsson and Elders, 2005).

The knowledge and experience from exploration and development of geothermal fields in the surveys is extensive and goes back more than 70 years. It is passed-on through scientific training and workshops across the world in order to advance the development of geothermal energy. Since 1979 the United Nation University has been conducting a geothermal training programme in Iceland for professionals from developing countries (Fridleifsson, 2005). By 2006, 359 students from 40 nations had graduated from this programme.

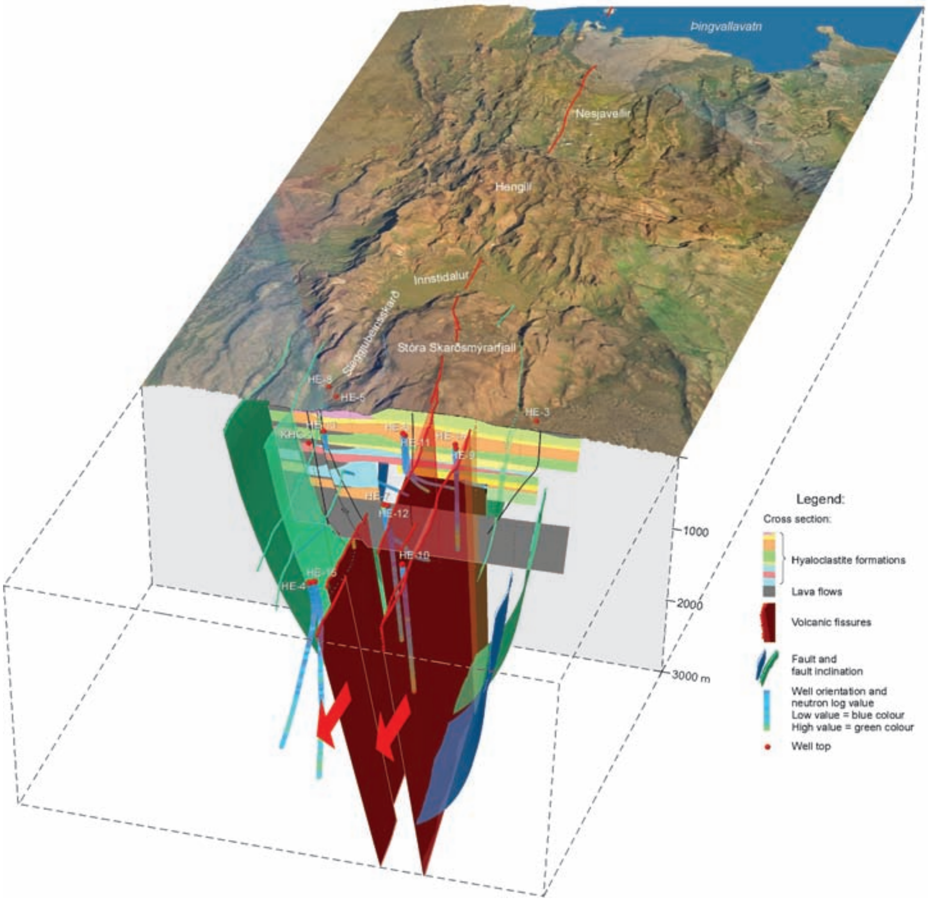

***Figure 4** 3D geological model of the Hellisheidi geothermal field. The flow of hot geothermal fluids is believed to be mainly towards the northeast and southwest, out from the Hengill central volcano along two eruption fissures, that are, respectively, 2,000 and 5,000 years old (Franzson et al., 2005).*

Exploring the sea-floor

The Nordic countries include extensive coastal and shelf areas with large abiotic and biotic natural resources. The Nordic marine "landscapes" comprise a variety of environments from the intra-cratonic Baltic Sea, via the extensive Norwegian Sea margin, to the deep ocean with active sea-floor spreading in the Norwegian-Greenland-Iceland Sea, and on to the glaciated shelves and coasts of Greenland and Svalbard. For decades the geological surveys have mapped and studied the sea-floor and subsurface, providing key information on the geological history, geological processes and properties of the Nordic coastal and shelf areas (Holtedahl, 1993; Longva and Thorsnes, 1997; Ottesen et al., 2005; Smelror et al., 2007). As exploitation for resources in the Nordic seas increases, there is a rapidly growing need for more knowledge about the natural and human-influenced state of the marine environment—particularly with regard to biological diversity and the state of contamination. The geological surveys provide basic knowledge to ensure that the marine resources are managed in an effective and sustainable way, by providing data on the spatial distribution, quantities and qualities of the resources in the sea and on and below the sea-floor and important knowledge about the natural and man-made processes affecting the marine environment.

One important task is to produce detailed topographic databases and models of the sea-floor (Figure 5). These bathymetric maps, combined with information about the sea-bed geology and environment, have multiple applications for the identification of marine habitats (e.g., soft- and hard-ground communities, coral mounds), the exploitation of marine mineral resources, and the planning and installation of sub-sea infrastructures (e.g., pipelines, cables, aquaculture installations and hydrocarbon installations). Examples of on-going projects are the international GeoHab-project (*www.ngu.no/geohab/*), the EU Inter-regional Balance project (*www.balance-eu.org/*), the Finnish Inventory Programme for the Underwater Marine Environment (VELMU) in the sea areas of Finland, and the Norwegian Mareano-program in the Barents Sea and the northern Norwegian Sea (*www.mareano.no*).

In recent years, the geological surveys have also focused on studies of the interaction between changes in the Quaternary climate, sedimentary processes and ocean circulation in the Nordic and North Atlantic waters (Rise et al., 2005; Nyberg et al., 2007). Other climate-related research projects deal with both Arctic and low-latitude marine environments and the possible role of climate change in these areas for forcing NW European climate.

The marine geology research of the Nordic surveys also includes investigations of

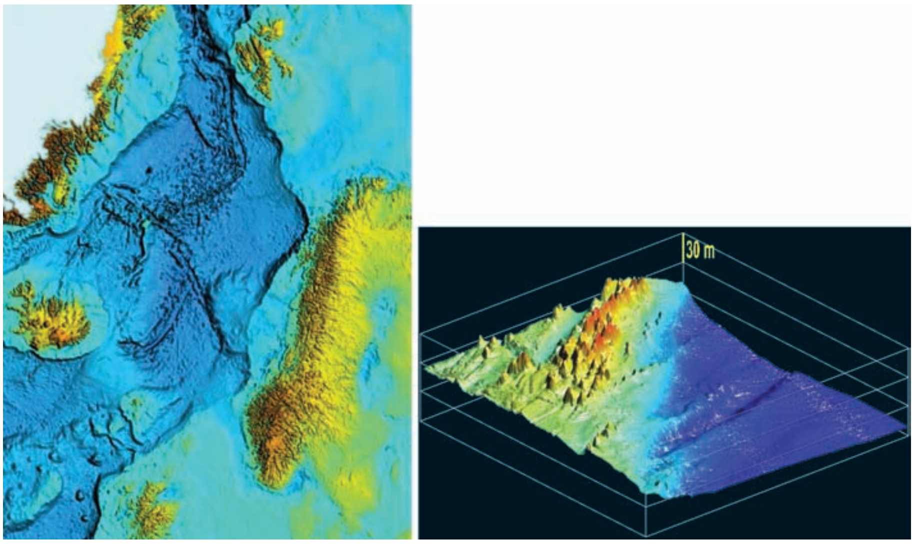

***Figure 5** The Sula reef is one of the many large cold-water coral reefs that in recent years have been mapped on the Mid-Norwegian shelf (Thorsnes and Fosså, 2004). The coral reefs are amongst our richest marine habitats, and for several commercially important fish stocks, the reefs are very important spawning and breeding grounds. Significant amounts of coral reefs and other habitats are already damaged by human activities, in particular trawling with heavy equipment.*

coastal erosion processes, shelf stratigraphy, and potential geohazards in the fjords, on the shelf and in deep-water areas of interest for offshore hydrocarbon exploitation (Rise et al., 2006). One key project has been on developing a geological model for the Ormen Lange area; i.e., an integrated geological and geotechnical study for the safe development of the Ormen Lange gas field within the giant Storegga submarine slide complex.

On unstable ground

Natural hazards, including geohazards, pose constant risks to human life and infrastructure. Landslides, rockfalls, avalanches and flooding represent the most common types of natural hazard in those Nordic countries where the bedrock is dominated by the tectonically stable Baltic Schield. Whilst on Iceland, with its position on the Mid-Atlantic spreading zone, earthquakes and volcanic eruptions also comprise serious threats. The vulnerability of populated areas to natural disaster is partly a consequence of decades of neglect by planning authorities of the dangers of natural hazards. Therefore, it is important to characterize the land areas that potentially are subject to geohazards, and to develop efficient methodologies to incorporate natural disaster reduction into land-use planning and management. In recent years, the Nordic geological surveys have participated in EU-funded projects dealing with geological and technological hazards, such as ESPON, researching natural and technological hazards and risks affecting the spatial development of European regions *http://www.espon.eu/* (Schmidt-Thome, 2006) and ARMONIA applied multi-risk mapping of natural hazards for impact assessment *http://www.armoniaproject.net* (Jarva and Virkki, 2006; Schmidt-Thome et al., 2006).

One task of the Nordic geological surveys is to develop national databases that include hazard maps, risk maps, geological data, historic volcanic eruptions, earthquakes, avalanche and slide events, geotechnical data and localization of different types of protection work and monitoring. The database is served on the Internet, providing an easy access to digital maps, information on previous hazard areas as well as to hazard assessments.

Landslides, rockfalls and avalanches are important geological processes in the Nordic landscape. Slow displacements through time may cause instabilities and bedrock failures. If large rockfalls and landslides run into narrow fjords or alpine lakes they may trigger tsunamis, damaging near-shore settlements and infrastructure (Bøe et al., 2004; Braathen et al., 2006; Harbitz et al., 2006) (Figure 6).

Fine-grained marine sediments cover large lowland areas of middle and eastern Norway, and large areas in southwestern and middle Sweden (also northern Sweden in some valleys) and Finland. Dilution of salt by groundwater flow leads to the formation of quick clay. Such processes may lead to highly unstable conditions and fatal quick-clay slides can occur. Glacial tills on steep mountain slopes may collapse during periods of intense precipitation, triggering debris flows. With changing climatic conditions and more extreme rainfalls in some exposed regions, the frequency of such natural hazards is expected to increase in the years to come.

Earthquakes occur in response to stress-release due to movement of the Earth's lithospheric plates, and are particularly abundant in the plate-boundaries. The divergent plate boundary between the North American and Eurasian plate (the Mid-Atlantic Ridge) transects Iceland from southwest to northeast, forming an active volcanic rift zone, where seismic activity occurs on a daily basis, and where volcanic eruptions take place every few years (Figure 7). Large destructive earthquakes fortunately are rare and far between; the other Nordic countries are located within the Eurasian plate and, consequently, earthquakes are relatively rare and occur mainly at magnitudes that create little damage. The daily monitoring of seismic activity is the responsibility of different national agencies (for example, the Metrological Office on Iceland and NORSAR in Norway); however, the geological surveys' expertise is more concerned with risk assessment. Evaluation of the risks from geohazards such as earthquakes and volcanic activity is based principally on reconstruction of previous events, their magnitude and rate of recurrence. Through geological mapping and the dating of such events the record of large destructive earthquakes and volcanic eruptions can be reconstructed. On the foundation of such data, the geological surveys provide estimates of the risk of forthcoming events, their possible magnitude and impact. In societies, where the vulnerability of living on a dynamic earth is well understood, geohazard risk assessments have priority. When making decisions concerning where to plan developments and how to construct or reinforce them, there always has to be a viable balance between the risks, on the one hand, and the social and economic gains, on the other hand.

Figure 6 Installation of radar reflectors for monitoring movements of unstable mountains in Storfjorden, western Norway. Rockfalls into fjords and lakes may create large tsunami that will damage the settlements and infrastructure (Photo: Lars H. Blikra).

Figure 7 Krafla geothermal power plant during the Krafla fires, 1975–1984. The eruptions slowed down the development of the field for more than 20 years due to volcanic gas contamination of parts of the geothermal field (photo: O. Sigurdsson).

The melting Arctic

The Arctic constitutes an important region for the Nordic countries. Consequently, studies of climate and environmental change in the Arctic are among the key research areas of the geological surveys. Nordic mythology and cultural identity is closely tied to the vast northern expanse, originally populated by the Inuit in Greenland and the Sami in Northern Scandinavia. The cold Arctic regions are also home to numerous glaciers and ice caps as well as the second-largest body of ice on Earth, the Greenland ice sheet. This mass of ice covers 1.7 million square kilometers and would cause a global sea-level rise of nearly 7 meters were it to melt away completely.

Instrumental temperature records over the last 100 years indicate a global average rate of warming of 0.74 ± 0.18ºC. The Arctic seems to be much more sensitive to climate change, as the average arctic temperatures have increased at almost twice the global average rate over the same period (Trenberth et al., 2007). Such a warming has a profound impact on the mass balance of glaciers being associated both with more precipitation and more melting (Figure 8). Understanding the response of glaciers and ice caps to climate change is important to the Nordic geological surveys for several reasons: the contribution of Arctic ice masses to global sea level rise is potentially very large, the changing run-off from glaciated catchments may affect existing or planned hydropower production significantly and, finally, the changing position of the glacier margin may cover or reveal valuable mineral resources. All these aspects are currently under investigation in Greenland by GEUS.

Within the last five years, the Greenland ice sheet has experienced a dramatic loss of mass to the ocean. Observations of elevation change, gravimetrical change and outlet glacier acceleration have all provided strong indications of accelerated loss of ice volume. However, reports on the estimated current mass loss varies from less than 100 cubic kilometers a year to more than three times that value (Alley et al., 2007). This uncertainty means that the accelerated mass loss of the Greenland ice sheet was not explicitly included in the last climate change assessment of the United Nations (the IPCC Report from 2007), but only noted as requiring clarification; a suspected feedback mechanism between increased surface meltwater production due to warming and outlet glacier acceleration was mentioned. A new programme for monitoring of the Greenland ice sheet has now been launched in order to quantify the mass loss on a regular basis (Ahlstrøm et al., 2007). The programme aims at providing the policymakers with the necessary scientific knowledge to make decisions regarding carbon-emissions.

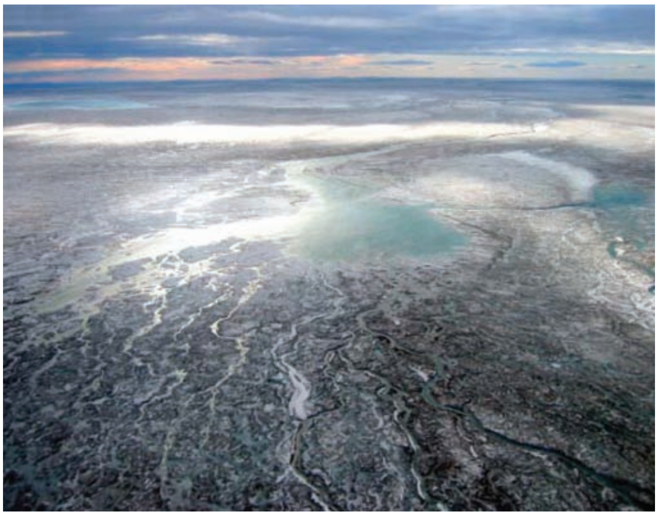

Figure 8 Meltwater lakes forming on the surface of the Greenland ice sheet near Ilulissat, West Greenland. The areal extent of the melting surface has increased over the last two decades (photo: A.P. Ahlstrøm).

The Inuit of Greenland pursue the dual goals of becoming self-supplying with energy and reducing their carbon dioxide (CO_2) emissions. This has made hydropower an attractive solution in Greenland, which is currently meeting the CO_2 emission reduction goals specified in the Kyoto-protocol (Mai, 2007). Planning hydropower investments demand some degree of certainty as to the future variations in the availability of water. In Greenland, water is often glacial meltwater, and the hydropower feasibility is thus tightly linked to the fate of glaciers or ice sheet margins within the catchment. Several sites with hydropower potential in Greenland are currently being surveyed with respect to their future sensitivity to climate change, including one near the town of Ilulissat next to the famous Jakobshavn Isbræ, recently listed as a UNESCO World Heritage Site (Ahlstrøm, 2007).

Some mineral occurrences have been located just at the margin of the Greenland ice sheet, even extending beneath the ice. Given the history of extensive ice-marginal change in Greenland, prospective mining companies wish to know what risks they might be taking if they attempt to exploit such an occurrence. Specifically, they are interested in the expected ice-marginal increase in retreat rates as a function of climatic change and likely changes in the glacial meltwater routing that they will have to deal with.

The melting Arctic ice masses are clearly of global as well as regional concern. The Nordic geological surveys thus have an important role to play in assessing the impact of climate change on these and the assessing the consequences for society. Current projects connected with International Polar Year 2007–2008 address some of these issues (i.e., “Arctic Natural Climate and Environmental Changes and Human Adaptions”; *www.ngu.no/SciencePub*).

Geological data for society

During the period of their existence, the Nordic geological surveys have generated a substantial amount of information on the Earth’s crust, its natural resources, its processes, and on the geological history of Nordic areas. Their collective mission is to make this geological information and data easily accessible to all the varied end users in industry, government agencies, government institutes, public administrations, technical offices, academia and research institutes, as well as for private individuals. Traditionally, geological maps and technical reports have been the main products, but today the products provided by the surveys cover a large spectrum of geological, geophysical and environmental databases, maps, models, cores and geological samples, literature and internet-based news- and service-pages.

The formats and distribution protocols of geological data products have been jointly developed by the Nordic national communities and the EU (INSPIRE) spatial information community. Data distribution policy varies between the countries; consequently, in some of the surveys supply of selected information or materials is chargeable by law. Others have made the information available on an open access basis. The internet is currently being developed as the main distribution channel as it gives easy access to key information for all users. The accessible databases are updated continuously. Over the history of the Nordic surveys, and at present, securing the growing volumes of geological and environmental information has consistently proved to be efficient and economically advantageous for society.

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