CHAPTER 3

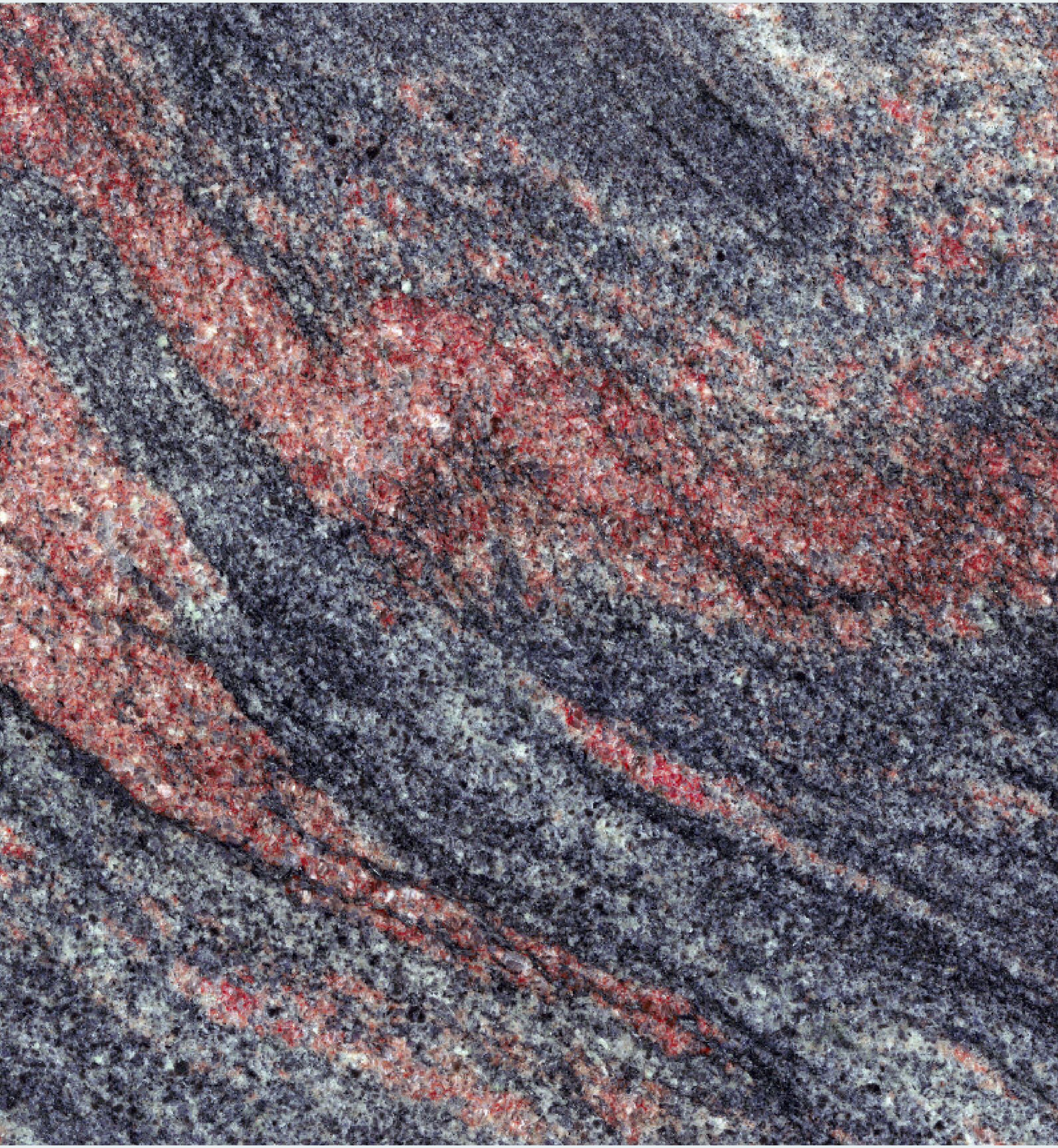
Øystein Nordgulen
Arild Andresen

Illustration: Bogdan Bocianowski. Photo: P. Aas, both NHM, Univ. of Oslo.

The Precambrian

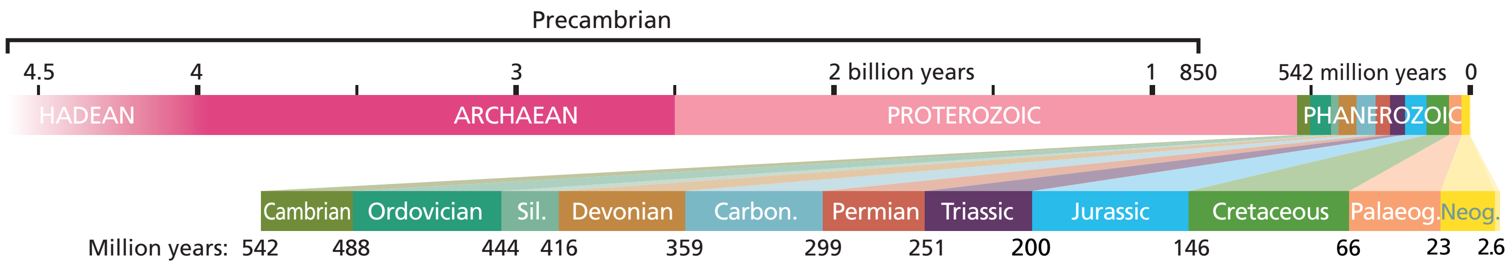
The oldest rocks are formed: 4600–850 million years

In its infancy, the Earth was a red-hot ball exposed to a shower of impacts from space. Slowly, the planet cooled, water vapour was converted into oceans, and a stable crust developed on the surface. A billion years later, the oldest life forms known emerged in an environment poor in oxygen. Another billion years passed, and sufficient oxygen was present in the atmosphere to enable the evolution of the first feeble signs of the life we now know on the Earth.



Introduction

Precambrian is the collective term for the Hadean, Archaean and Proterozoic Eons, which account for seven eighths of Earth's history. In this long period, the Earth developed from a cloud of dust and gas to become a planet with stable continents, large oceans and an atmosphere that provided the basis for the evolution of the Earth's enormous profusion of animal and plant species from the beginning of the Cambrian.



(Illustration: R.W. Williams)

The universe arose in the "Big Bang" 14-15 billion years ago. Only nine billion years later, in one of the spiral arms of the Milky Way Galaxy, our solar system arose from a cloud of compacted dust and gas which was the remains of long-dead giant stars (supernovae) that had slung enormous quantities of matter out into space. This matter contained all the elements that build up the Earth. Directed by the powerful gravitational force of the Sun, everything from ice to metal was gathered in eight planets that orbit the Sun. The four planets closest to the Sun (Mercury, Venus, Earth and Mars) consist of rock and metal, while the outermost four are much larger and are mostly composed of gas.

For the first billion years, which is called the Hadean Eon, the Earth was a melting pot whose surface was covered by large and small seas of lava. The heat generated by the compaction of matter, meteoritic impacts and the decay of radioactive elements led to the melting of iron and nickel. These metals sank towards the centre of the Earth and formed the core. Heavy minerals rich in iron and magnesium accumulated outside the core and formed the mantle with a thin skin of lighter crust on the surface. The primaeval atmosphere was formed from gas (water vapour, nitrogen and carbon dioxide) that poured from volcanoes.

No traces can be seen of the first 200-300 million years of the evolution of the Earth. A solid crust only formed 4.4 billion years ago. The temperature gradually dropped, water vapour condensed to water which filled depressions between the first continental areas. At the same time, the destruction wrought by meteors impacting from space declined, and the stage was set for the blue planet to slowly evolve.

FACING PAGE: Photograph of a polished surface of 2800 million-year-old gneiss from Grasbakken on the south side of Varangerfjorden, Finnmark. The rock has a tonalitic composition and contains reddish veins of quartz and feldspar which have given the rock its commercial name of "Barents red". (Illustration: NGU)

The Earth is formed – the earliest development

New continental crust was continuously being formed through the interplay between internal and external forces. Changes in these processes and the evolution of life forms over the ages led to changes taking place in the physical conditions in the interior of the Earth, on the Earth's surface and in the atmosphere.

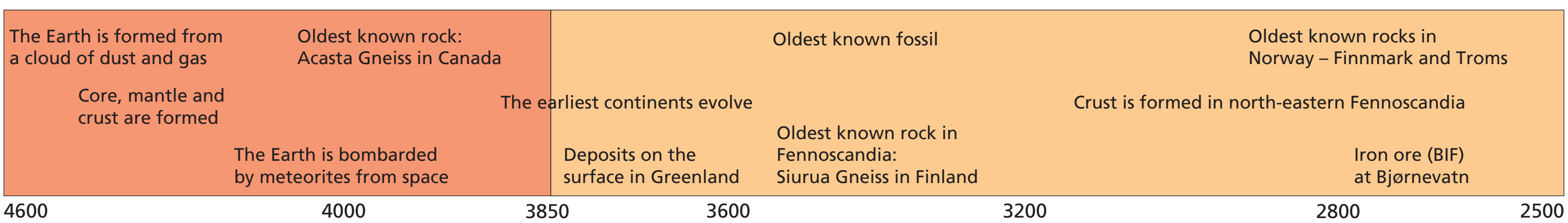
Rocks from the Archaean Eon (older than 2500 million years) make up the core of most of the larger continents. The oldest known crustal rock, the Acasta Gneiss in north-western Canada, is an approximately 4000 million-year-old metamorphosed plutonic rock, whereas the oldest rock in Norway is a 2900 million-year-old gneiss in Sør-Varanger, north-eastern Norway. However, the oldest remains of continental crust are ancient zircon crystals, all of 4400 million years old, found in sedimentary deposits in Australia. These crystals were formed when the oldest plutonic rocks on the Earth solidified from a melt.

Well-preserved sedimentary strata deposited in water are also found among the earliest Archaean rocks. These strata are particularly interesting because water is a very important precondition for the evolution of life on the Earth. The oldest known sedimentary rocks are found at Akilia and Isua in West Greenland. Minute particles of carbon, which some scientists believe have a biological origin, have been found in these 3800 million-year-old deposits.

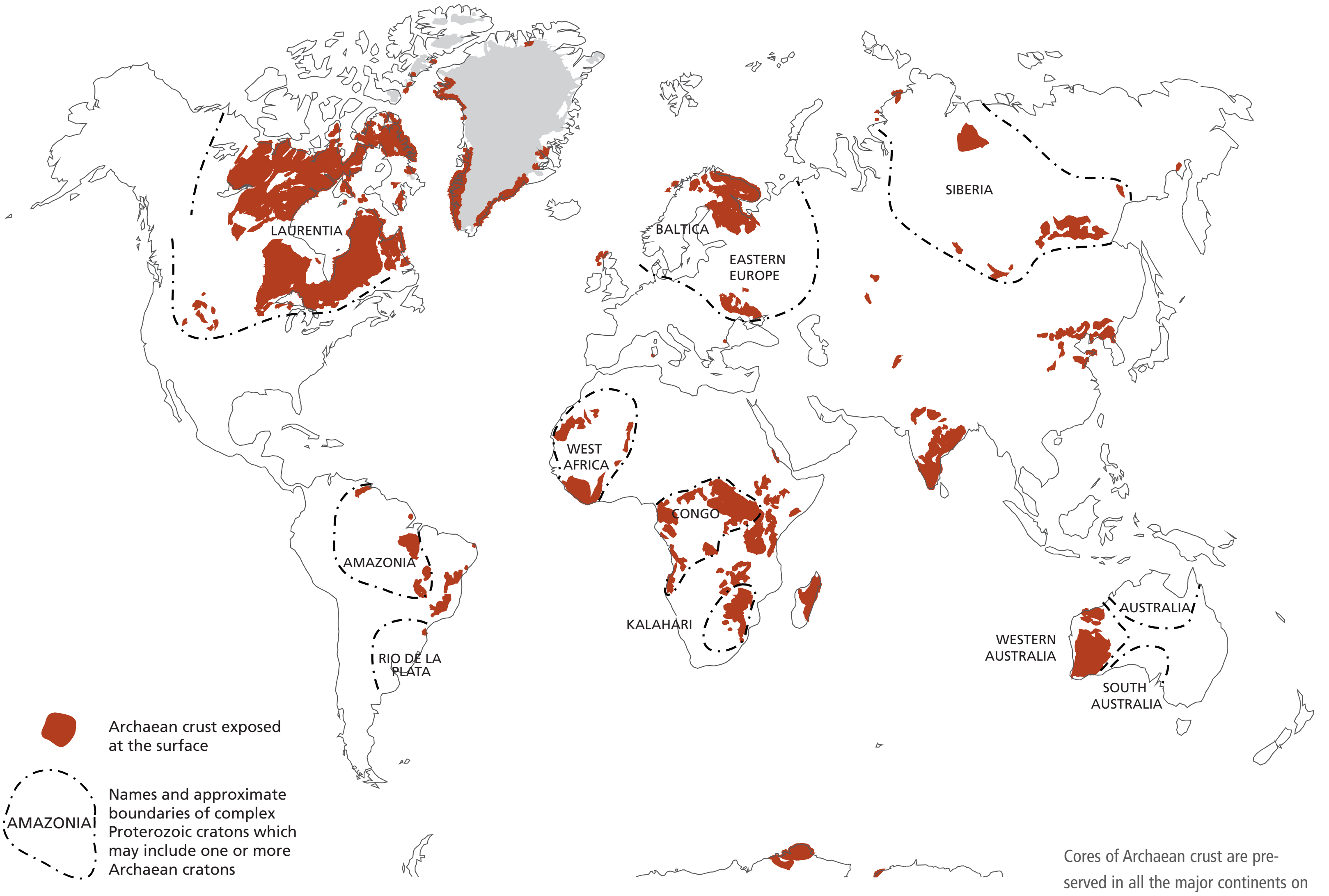
Initially, the Earth had an outer layer of basaltic rock whose composition was not unlike that of present-day oceanic crust. In the early Archaean, the crust and mantle had a higher temperature gradient than today, and the early Archaean lithosphere therefore had comparatively low density, perhaps so low that it could not sink into the mantle like the lithosphere does today (Chapter 2). Subduction zones, as we know them today, may therefore not have developed before the end of the Archaean. This agrees with the observation that certain types of rock that predominate in Archaean areas become less common in the Proterozoic Eon.

The uppermost part of the crust in the Archaean was composed of basalts and sodium-rich plutonic rocks formed by partial melting in the lower parts of a thickened basaltic crust. The lightweight melts forced their way upwards and solidified in large, massive bodies closer to the surface. Gradually, they formed more or less continuous areas that are generally referred to as tonalite-trondhjemite-granodiorite (TTG) gneisses and which differ clearly from the more potassium-rich rocks that became common after the Archaean.

Tonalite, trondhjemite and granodiorite are all quartz-rich plutonic rocks with varying proportions of sodium-calcium feldspar (plagioclase) and potassium-sodium feldspar (alkali feldspar), tonalite having



The most important events in the Precambrian from the formation of the Earth to nearly 4000 million years later, at the beginning of the Proterozoic.



Cores of Archaean crust are preserved in all the major continents on the Earth. The earliest rocks that were formed may have been destroyed by meteorite impacts, tectonic processes, surface weathering and erosion, or they may be covered by younger strata. Rocks that are older than 3500 million years are only preserved in a few areas.

most plagioclase feldspar and granodiorite least (Chapter 2). Trondhjemite is a tonalite whose predominant dark mineral is biotite. Characteristic successions also developed on the surface. These are usually called *greenstone belts* because they are mostly made up of metamorphosed basaltic lava, which generally has a greenish colour. Archaean greenstone belts contain two major associations of volcanic rocks. The first is komatiite and tholeiitic basalt. Komatiite is a rare, characteristic magnesium-rich rock that, together with basalt, probably formed by partial melting in mantle plumes. The second association comprises basalt and dacite that are more like rocks formed nowadays. Basalt is a volcanic rock whose composition corresponds to gabbro, and dacitic lava has a similar composition to granodiorite. Greenstone belts also contain several kinds of sedimentary rocks (shale, conglomerate and quartzite) that were deposited in shallow-marine basins together with the volcanic rocks. In Archaean terranes, the rocks are usually metamorphosed and highly deformed, and the greenstone belts are found as saucer-shaped troughs or narrow, down-folded lenses or belts in the tonalitic gneisses.

Global glaciation (Huronian)
Free oxygen in the atmosphere
Major changes in the Earth's geochemical cycles
Eukaryotes & multi-cellular organisms arise on the Earth
Rodinia merges to a supercontinent
Large granites in Southern Norway
Rodinia breaks up
Rifting and volcanism in Finnmark and Troms
Svecofennian mountain chain in northern Fennoscandia
Gothian mountain chain in southern Scandinavia
Sveconorwegian mountain chain in southern Scandinavia
Ediacaran fauna
Uplift & erosion of Archaean crust in east Finnmark
Kola Ocean closes
Trans-Scandinavian Intrusive Belt
Volcanism & sedimentation in Telemark (Rjukan & Vindeggen groups)
Bandak and Heddal groups
Extensive glaciations (Varangerian Ice Age in Norway)

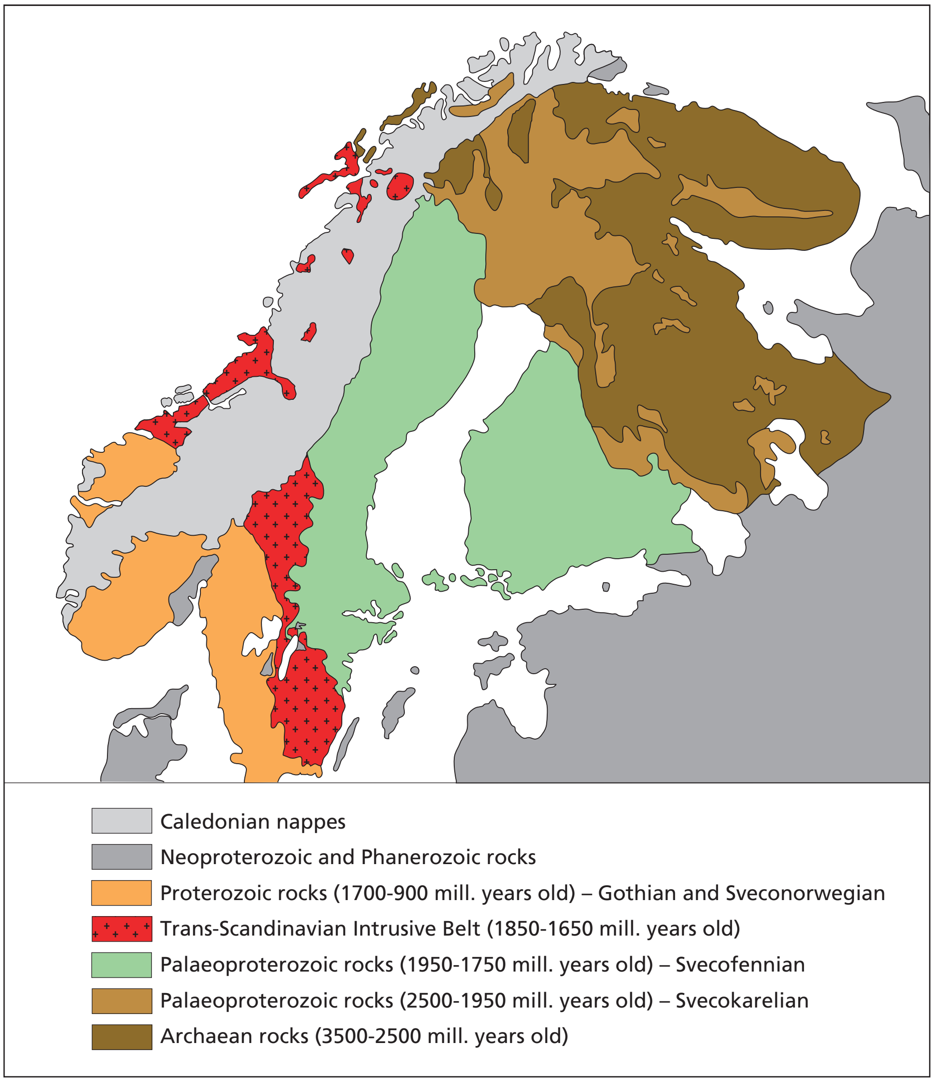
2500 2000 1600 1000 850 542

The transition from Archaean to Proterozoic – an environmental disaster?

The transition from Archaean to Early Proterozoic time was perhaps the most dramatic in the history of the Earth. Many fundamental processes changed character, and a development began where geological and biological processes functioned more or less as they do today. The first extensive glaciation of the Earth's surface occurred at the beginning of the Proterozoic and is generally referred to as the Huronian Ice Age. The most significant change took place through the evolution of an oxygen-rich atmosphere between 2450 and 2320 million years ago.

During the rest of the Proterozoic, conditions on the surface of the Earth as regards water and the atmosphere were largely as they are today. Even though large, multi-cellular organisms and plants did not evolve until much later, the biogeochemical processes on land and in the sea were based on the conditions being *aerobic*, that is, oxygen existed as the most important carrier of energy in the biosystem. In contrast to this, oxygen-rich environments in Archaean time were limited to local "oases", and weathering by oxidation usually did not occur.

Simplified geological map of the Fennoscandian Shield. The map shows the broad divisions of the bedrock according to its age and the types of rock.



The evolution of life is best known from the beginning of the Cambrian, particularly because of the enormous wealth of species found in richly fossiliferous Cambrian lithologies in various parts of the world. Apart from the Late Precambrian Ediacaran fauna (Chapter 4), most of the fossils found in Precambrian strata are of micro-organisms. Well-preserved micro-organisms are very rare in Early Proterozoic and Archaean rocks. Interpretations and models for the origin of life and its earliest evolution are partly based on biochemical markers in material of assumed biogenic origin.

In the Proterozoic, the plate tectonic cycle functioned more or less as it does today (Chapter 2). The Earth was continuously changing. Rift systems, collision zones and mountain chains arose and were destroyed. Continental crust formed throughout this period, and more and more new crust was gradually added to the ancient Archaean cores. The Norwegian basement provides a good impression of how these processes acted over a long period. The oldest rocks, up to 2900 million years old, are preserved in northern Norway. The Precambrian bedrock in southern Norway is largely younger, and formed between 1700 and 900 million years ago.

The Fennoscandian Shield – an overview

The Precambrian rocks in Norway are part of the Fennoscandian Shield. Mapping and numerous age determinations of rocks over the last 20 years or so have provided a fairly detailed picture of the geological composition of the shield and the history of its development. From its origin 3500 million years ago, the shield has grown through periods of volcanism, deformation and mountain chain formation alternating with erosion and sedimentation.

Plate tectonic reconstructions are uncertain for most of the Precambrian, and information on where the shield was located on the Earth is extremely sparse and uncertain. From the mid-Proterozoic (about 1300 million years ago), the shield became incorporated in the supercontinent of Rodinia. In the same way as the huge Pangaea continent, which existed towards the end of the Precambrian, Rodinia comprised virtually every piece of continent that was found on the Earth. The fragmentation of Rodinia into several smaller continents began towards the

LIFE IN THE PRECAMBRIAN *By Jørn H. Hurum and David L. Bruton*

The oldest rocks known to have traces of life are 3.8 billion years old and occur in Greenland. They do not contain fossils, but the composition of isotopes in some elements suggests that there really was life so early. It is also possible to find layers in such old rocks that were formed by "fossilisation" of siliceous or carbonate-rich mud, and animals have even drilled holes in pillow lavas in this period.

Bacteria

The oldest fossil bacteria are cyanobacteria found in 3.5 billion-year-old siliceous rocks in Western Australia and southern Africa. Like plants today, they could manufacture their own food by photosynthesis and simultaneously produce oxygen. Carbonate dust adhered to the slimy cyanobacteria mats that spread over the sea floor, eventually covering them completely. The bacteria grew up between the carbonate grains and formed a new slimy mat on the top. Over many thousand years, this developed into layered mounds several metres thick, called stromatolites. Cyanobacteria cannot have been the first; more primitive forms (archaeobacteria) must have existed earlier, but they have left no trace in the fossil record.

Eukaryotes

All animals, plants and fungi, and also innumerable micro-organisms, are *eukaryotes*, that is to say they are living organisms consisting of cells that are divided into compartments, one of which is the nucleus which contains most of the genes as long strings of DNA. We can now recognise at least 60 different types of eukaryotes based on the internal structure of their cells.

One of the great enigmas in the evolution of the eukaryotes is that they were already present more than 1.7 billion years ago but did not make their presence felt in either numbers or forms before 600 million years ago. This may indicate that something prevented them from evolving. Stromatolites appeared more than 3.5 billion years ago and became the dominant organisms in the seas in the course of the next hundred million years. They covered the floor of the shallow seas surrounding the continents and formed the first carbonate reefs. Such stromatolites are still found on the west coast of Australia. These bacterial mats are toxic, and other life avoids them. Perhaps it was these poisons that resulted in the eukaryotes only living in limited areas or in the deep oceans that were not dominated by the bacterial mats? However, the stromatolites disliked the cooler climate 850-550 million years ago, and many forms died out. This gave the eukaryotes the opportunity to evolve in the shallow seas.

Chemical traces of eukaryotic cells have been found in Australia in rocks that are more than 2.7 billion years old. It thus seems that it took at least one billion years to evolve the first eukaryotic cell after the first bacteria were formed.

Multicellular life

A multicellular animal consists of several cells that depend upon one another. They can move and can eat other living organisms. Many theories have been put forward for how the single-celled animals combined to form multicellular ones. The colony theory, which most people favour today, states that many unicellular creatures gathered in a ring where they began to co-operate. Perhaps they did this to defend themselves from others. Gradually, some of the cells became specialised for specific tasks and were increasingly dependent on the other cells. This was how a genuine multicellular animal may have evolved.

The oldest fossils of multicellular life are rather insignificant. They are minute, black lumps of carbon found in rocks that are 1.8-2.1 billion years old. These fossils measure only a couple of millimetres, but consist of several cells. We do not know whether they are animals, plants, algae or fungi. The first definite multicellular animal fossil was found in southern Timan in Russia and is called *Parmia*. It is one billion years old. Parmia were up to 6 cm long and resembled earthworms, but we still know very little about them.

Bilateral animals

All bilateral animals have two sides along an axis, and one side is a mirror image of the other; hence, the name *bilateralia*. The majority of present-day animals belong to this group. One of the very first was *Dickinsonia* from the White Sea. It is thought to be one of the most primitive bilateral animals and represents part of the very well-known Ediacaran fauna from Australia. Similar impressions are found all over the world, also in rocks from Finnmark. These fossils, and traces of excavation undertaken by multicellular animals, occur in sediments immediately before the "Cambrian explosion" of fossilised animals that evolved hard components in the form of shells or skeletal supports to their body tissue.

The chemistry of the oceans changed following the worldwide glaciation at the end of the Precambrian. Warmer climate with an associated rise in sea level and flooding of continents succeeded this ice age. New, extensive, shallow-marine environments formed and are thought to explain the "explosion" of new, bilateral life forms in the first 10 million years of Cambrian time. This is described in more detail in the coming chapters.

Dickinsonia from the White Sea. The fossil is 75 mm across. Museum of Natural History, Tøyen. (Photo: J.H. Hurum)

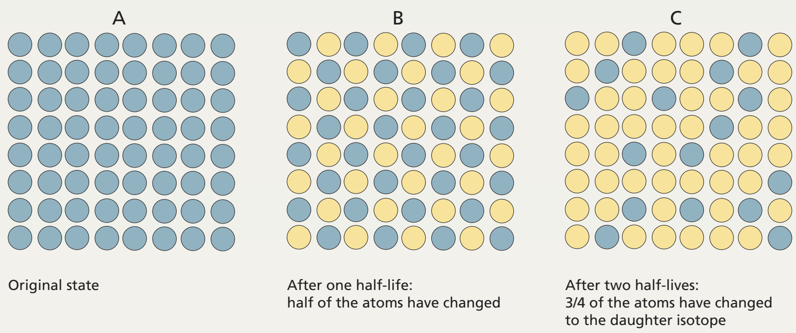
HOW DO WE DETERMINE THE AGE OF THE ROCKS?

Most people have an intuitive understanding of time. Time comes and goes without pausing, and is divided into years, days, hours and minutes. If we are going to study the evolution of the Earth, time is generally a matter of tens and hundreds of millions of years. The term "Deep Time" is often used to distinguish this concept of time from the everyday understanding of time.

There are historical reasons why time on the geological time scale is divided into units with exotic names like Proterozoic, Devonian and Cretaceous. Time was first measured in relative units on the basis of stratigraphy, with divisions determined by changes in the fossil content of the strata. Since there are very few fossils in Precambrian beds, this work concentrated on successions that are Cambrian or younger.

The Scottish scientist, William Thomson (later Lord Kelvin), calculated the age of the Earth on the basis of an assumed rate of cooling, and found that it could not be more than a few tens of millions of years old. It was therefore too young to fit Lyell's theory of gradual geological change and Darwin's theory of evolution. What was not known then was that the Earth has its own heat sources at depth.

Radioactive decay of elements was discovered at the end of the 19th century. This process takes place at a specific rate that can be measured in the laboratory. It is stated as the half-life, which is the time taken for half of the unstable isotopes of an element to convert to other types of elements (isotopes) with the generation of radioactive radiation and heat. This discovery swept away the basis for Lord Kelvin's age estimation and at the same time cleared the way for radiometric age determinations that were developed early in the 20th century. For the first time, the absolute age of minerals and rocks could be measured. Slightly simplified, this is achieved by determining the ratio between the amounts of mother and daughter isotopes (see the figure).



The principle of age determination. The ratio between mother and daughter isotopes in a mineral or rock is measured. Their known half-life is then used to calculate the length of time that has ensued since the process started from the original state, and this gives the age of the mineral or rock.

The uranium-lead method of age determination, based mainly on the minerals zircon, titanite and monazite, is most used for Precambrian rocks. These minerals usually contain some uranium, which gradually breaks down to lead. The ratios between the various uranium and lead isotopes are determined in a mass spectrometer, which can measure minute differences between the mass and the charge of atoms. It is usual to determine the age of minerals that crystallised when magmatic rocks cooled. Zircon, titanite and monazite may also crystallise when the rocks are subsequently metamorphosed, and thus record the age of important metamorphic events during an orogeny.

Zircon has a hardness of 7.5, and tiny grains of the mineral can withstand erosion and repeated episodes of long-distance transport in rivers. Small numbers of zircon crystals, which occur in the majority of sand deposits, will therefore be erosion residues derived from older rocks in the source area of the sediments. If the age of the individual zircon grains is known, this may provide valuable information on potential source areas. In addition, the age of the youngest zircon in a sand deposit will give the minimum age of the sedimentation.

Some zircon crystals have an old core surrounded by a younger growth rim formed during a metamorphic event. In such cases, dating the older and younger parts of the zircon will provide new data on the geological history of the bedrock.

During the past decade, zircons from several Precambrian sandstones and quartzites, particularly in southern Norway, have been investigated. The results show that important source areas contained rocks with ages of 1500-2000 million years. Many sandstones also carry Archaean zircons with ages up to 3400-3500 million years. This indicates that Proterozoic sandstones in southern Norway derive from the breakdown of older rocks now found in the eastern part of the Fennoscandian Shield.

end of the Precambrian. That was when the Fennoscandian continent was succeeded by Baltica (Chapter 4).

The oldest bedrock in the Shield, extension and rift formation

Large areas composed of several fragments of Archaean crust are found on the Kola Peninsula, in Russian and Finnish Karelia and in the northern parts of Finland, Sweden and Norway. Most of this bedrock formed between 3100 and 2500 million years ago, but still older rocks are found in a few places. Some greenstone belts in Russian Karelia are probably more than 3200 million years old. By far the oldest rock so far found in Fennoscandia is the Siurua Gneiss in northern Finland. It has a cooling age of about 3500 million years, but contains 3730 million-year-old zircons, implying that the crustal evolution of the Fennoscandian Shield is still older.

The Archaean continents suffered extension from 2500 to 1950 million years ago (the Early Palaeoproterozoic), and several northwest-southeast trending rift zones gradually formed. Stratified mafic intrusions and mafic dyke swarms composed of dark, heavy, igneous rocks cut the Archaean rocks, and were emplaced in the early rifting phase. Volcanic and sedimentary successions testify to the development of rift zones over a long period. In some places, the shield was divided and the Kola Ocean arose along this rift axis. Subsequent changes in the plate tectonic setting led to this ocean closing and a mountain chain being formed when crustal blocks collided about 1900 million years ago.

The Svecofennian mountain chain

An important period of crustal formation occurred from 1960 to 1860 million years ago. Several island arcs and intervening sedimentary basins developed along the western margin of the ancient continent. Folding and metamorphism of plutonic, volcanic and sedimentary rocks took place during the formation of the *Svecofennian* mountain chain (also called the Svecokarelian); these terms mean "Swedish-Finnish" and "Swedish-Karelian", respectively. (The term Svecokarelian is also generally used for events in the Early Palaeoproterozoic in Finnmark, Finland and western Russia.) The new fragments of crust had been welded together with the older core in the northeast about 1860 million years ago. Metamorphism and the intrusion of large plutons of granite continued until approximately 1760 million years ago. Rocks from this period are particularly well preserved in Sweden, where they have formed the basis for an important mining industry, for example in Kiruna and the Skellefte field in Norrland. Corresponding rocks are little evident in Norway.

The Trans-Scandinavian Igneous Belt (TIB)

The next phase of crustal accretion in Scandinavia took place when large volumes of granitic plutonic rock invaded the western margin of the Svecofennian province about 1850-1650 million years ago. These rocks are found along a 1500 km-long belt from Skåne in south-eastern Sweden to Lofoten in north-western Norway, occasionally emerging through windows in the cover of younger Caledonian nappes (see the map on Page 68). Volcanic rocks of the same age are also found in Sweden and in Trysil in southeast Norway. This belt of igneous rocks is called the Trans-Scandinavian Intrusive Belt (TIB). The various plutonic rocks in the northernmost part of the Western Gneiss Region in southern Norway and in the Lofoten-Vesterålen district are generally considered to be part of this belt. Characteristic rapakivi granites, as well as intrusions of gabbro and anorthosite, are also found in the Svecofennian area. Rapakivi granites have feldspar crystallised in several-centimetre-sized, round grains, often with a core of alkali feldspar and a rim of plagioclase. Anorthosite is a plutonic rock that is related to gabbro but lacks the dark minerals (pyroxene) found in gabbro and therefore consists almost entirely of plagioclase. This group of rocks is 1650-1470 million years old and is concentrated in a belt extending from Russian Karelia westwards through central Scandinavia.

Crustal development in southern Scandinavia

Precambrian rocks which formed over a long period of time from about 1750 to 900 million years ago occur in a large area of southern Norway and the adjacent part of southern Sweden west of the Trans-Scandinavian Intrusive Belt. They comprise a wide variety of rocks formed in different plate tectonic settings and deformed and metamorphosed during two orogenies, the *Gothian* about 1700 to 1500 million years ago and the *Sveconorwegian* (Swedish-Norwegian) about 1130 to 900 million years ago. The present appearance of these rocks is mostly a result of deformation and metamorphism during the last of these two orogenies. Many large bodies of granite with ages ranging from about 975 to 925 million years mark the end of the Sveconorwegian orogeny and the Precambrian evolution of the basement in southern Norway.

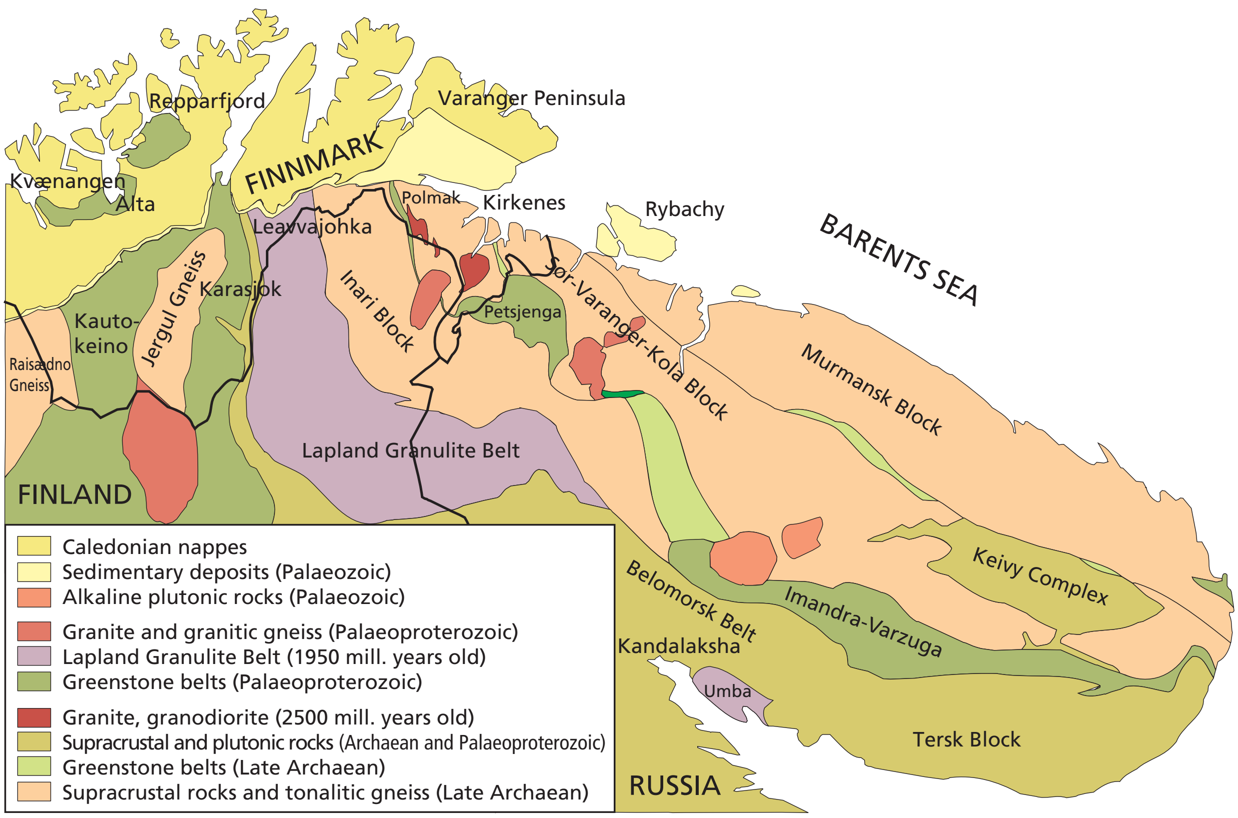
Precambrian rocks in Sør-Varanger and on Finnmarksvidda

The oldest parts of the basement are found in north Norway. A journey in time and space through Norway's geological history will therefore have its natural starting point in eastern Finnmark, where the core of the Norwegian basement is located.

The rocks in east Finnmark and adjacent parts of the Kola Peninsula and Finland include part of a large block of crust formed in the Late Archaean (about 3100 to 2500 million years ago). This crustal block probably continued to Troms and Lofoten in the west and to Kiruna, in northern Sweden, in the south.

The rocks in this northern part of Norway bear evidence of repeated orogenic episodes, rifting, ocean-floor spreading and new mountain range formation, events that recurred in slightly different ways at intervals of several hundred millions of years. The Precambrian crust gradually grew in extent and thickness.

Large rift zones, oriented approximately northwest-southeast viewed in relation to present-day compass points, segmented the Archaean crust in the Early Proterozoic. Volcanic and sedimentary deposits that filled the rift valleys are now found as greenstone belts. Along the centre of the Finnmarksvidda highland plateau, the Archaean Jergul Gneiss separates the Kautokeino and Karasjok greenstone belts. In Sør-Varanger, the Archaean rocks are divided into two blocks by a greenstone belt stretching from Polmak to Pasvik and continuing onto the Kola



Geological map of the Kola Peninsula and eastern Finnmark showing the distribution of the most important geological units and how they correlate with adjacent areas on the Kola Peninsula and in Finland. On Finnmarksvidda, Neoproterozoic to Cambrian strata rest with an angular unconformity on the basement. These deposits are overlain by nappes belonging to the Caledonian mountain chain which conceal the ancient basement rocks in the fjord districts of Troms and Finnmark.

Peninsula. The Sør-Varanger or Kola block is situated northeast of the greenstone belt and the Inari block southwest of it. The Levajok (Leavajohka) Granulites occur between Finnmarksvidda and Sør-Varanger. Granulites are gneissose rocks characterised by non-hydrous, "dry", dark minerals like pyroxenes. They are thought to have been metamorphosed at particularly high temperatures and pressures deep in the Earth's crust. This is the northern end of a broad belt of strongly metamorphosed gneissic rocks (the Lapland Granulite Belt) that continues 300 km southwards and eastwards through Finland and into Russia. The granulites formed about 1900 million years ago in the Lapland-Kola mountain chain, in response to the extensive Svecofennian or Svecokarelian orogeny in the Fennoscandian Shield.

Norway's oldest rock

Many rock types in Sør-Varanger are typical for the Archaean, and the area offers good opportunities for studying Late Archaean crustal evolution. The oldest rock so far identified in Norway is an approximately 2900 million-year-old orthogneiss (igneous rock metamorphosed into gneiss) occurring in the area east of Jarfjorden in Sør-Varanger. It was metamorphosed at a high temperature deep in the crust (in the granulite facies) and consists of layers of hypersthene-bearing tonalite and granodiorite alternating with thin amphibolites. Hypersthene ($(Mg,Fe)SiO_3$) is a pyroxene that is rich in magnesium and iron. It has an orthorhombic crystal structure and therefore belongs to the orthopyroxene group. This rock is older than the approximately 2800 million-year-old tonalite-trondhjemite-granodiorite gneisses (TTG) that crop out over large parts of Sør-Varanger and

Boulder of water-polished Varanger gneiss on the shore west of Bugøynes, Sør-Varanger. (Photo: Samfoto)

Monzonitic plutonic rock intruded the gneisses in Sør-Varanger 2750 million years ago. The monzonite has angular fragments of dark rocks and is transected by a pale-pink pegmatite dyke. Skallvåg, Sør-Varanger. (Photo: Ø. Nordgulen)

are typical for early crustal development in Archaean regions of the Earth. Similar rocks are found in the middle of Finnmarksvidda, where the Jergul Gneiss (ca. 2800 million years) crops out as an elongate body. The Raisædno Complex, west of the Kautokeino Greenstone Belt, contains corresponding gneisses. The TTG gneisses are migmatitic in some places and are traversed by several generations of granitic and pegmatitic hypabyssal rocks. The migmatisation is assumed to be a result of partial melting of the gneiss, with subsequent crystallisation. In addition to homogeneous tonalitic gneiss, some areas have numerous zones of banded gneiss, micaceous gneiss and amphibolite.

The iron ore near Bjørnevatn

The plutonic rocks in Sør-Varanger were exposed to erosion before forming the substrate for several types of younger volcanic rocks from the latest part of the Archaean Eon. The greenstone belt containing the valuable magnetite iron ore near Bjørnevatn, a village south of Kirkenes, is of special interest. The Bjørnevannet Group is a greenstone belt that consists of several formations of conglomerate, greenstone and amphibolite (metamorphosed basaltic lava), metarhyolite (metamorphosed lava with a granitic composition), quartzite and mica schist. These rocks occupy a north-south trending, downfolded structure (synform) with strongly deformed rocks along its boundaries with the tonalitic gneisses. The Pesktind conglomerate contains cubic-metre-sized, rounded boulders of the tonalitic gneiss on which the succession was deposited.

The iron ore near Bjørnevatn occurs in the middle of the Bjørnevannet Group and consists of alternating layers of quartz and magnetite that are 2-10 mm thick. It occurs in two thick zones in an amphibolite that was originally basaltic lava. In some places, the amphibolite has characteristic pillow-shaped structures which show that the lava solidified in water, probably a lake or a bay of the sea, where the stratified iron ore was precipitated as fine-grained, iron-rich mud alternating with thin layers of sand. Such b*anded iron ore* is typical of many Early Proterozoic sequences around the world. Similar greenstone belts on the Russian side of the border, at Oleneogorsk, contain a major, haematite-rich, quartz-banded iron ore. Sør-Varanger also has other areas with assumed Late Archaean supracrustal rocks (rocks that overlie the basement). The Jarfjorden Gneiss, which corresponds to the Kola Gneiss in Russia, covers large areas and continues eastwards across the border to Pechenga and onwards over the Kola Peninsula. It consists of mica schist with subordinate layers of metamorphosed sandstone, rocks rich in calc-silicate minerals and, in several places, amphibolite with thin lenses of quartz-banded magnetitic iron ore, corresponding to the Bjørnevatn ore body. At Bugøyfjord, the supracrustal rocks occupy trough-shaped synforms that overlie tonalitic gneisses of the Varanger Complex. In western Sør-Varanger, the Garsjøen Complex consists of various types of highly deformed tonalitic gneisses alternating with mica schist, quartzite and amphibolite. These amphibolites also contain scattered lenses of quartz-banded iron ore. Even though the precise depositional age of the various sedimentary and eruptive rocks is not known, the close relationship between these successions and the grey TTG gneisses in Sør-Varanger suggests that they were formed approximately simultaneously, during the Late Archaean.

Late Archaean migmatites and plutonic rocks

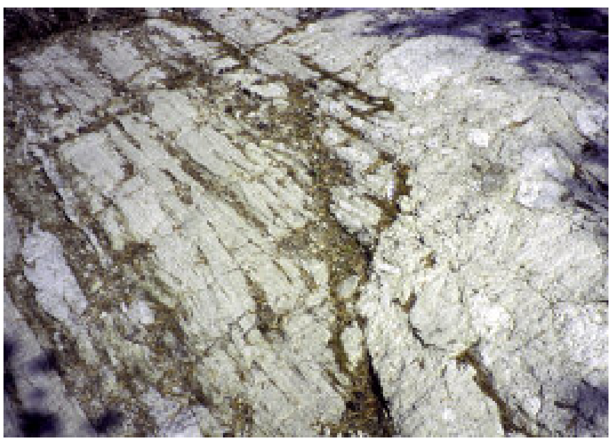
After a stable Archaean crust had formed, processes began approximately 2750 million years ago that helped to change its character; it was exposed to high pressures and temperatures in the roots of a mountain chain. The rocks in the easterly areas, near Grense Jakobselv, were metamorphosed at a high temperature (granulite facies), and the Jarfjorden Gneiss is partly transformed to migmatite by partial melting. Here, there are numerous garnet-rich granite bodies that were probably formed by melting of crustal rocks. Completely different kinds of plutonic rocks also occur in the same area. These are relatively quartz-poor granodiorites, monzonites and syenites which are younger than the Jarfjord Gneiss.

These rocks are comparatively rich in magnesium, showing that they probably formed by melting of mantle rock. Similar small bodies of rock have recently been recognised in the Archaean areas in Russia and Finland, and are assumed to have formed when oceanic crust sank into the mantle. These rocks are between 2750 and 2700 million years old, approximately corresponding to when the high-temperature and high-pressure metamorphism and the formation of migmatites ceased in this area. Large bodies of granite, dated to about 2500 million years, mark the end of the Archaean Eon in east Finnmark. The most notable are the Geahoaivvit Granite southeast of Polmak and the Neiden Granite south of Kirkenes. The Neiden Granite is little deformed and cuts the gneissic banding and lithological boundaries in the older Archaean rocks.

Rifting of the Archaean continent

At the transition from Archaean to Proterozoic time, several large bodies of layered gabbro, with ages ranging from about 2505 to 2440 million years, formed in the Fennoscandian Shield. These intrusions mark the beginning of a long period of crustal fracturing and the formation of several major rift zones. One of these rift zones crosses the southern part of the Pasvik valley where there is an area of little-deformed and metamorphosed volcanic and sedimentary rocks (the Petsamo Supergroup). This succession belongs to the Polmak-Pasvik-Pechenga Greenstone Belt, which is more or less continuous from Polmak, through Finland, across Pasvikdalen and over the Russian border to Nikel and Pechenga. Further east, similar rocks can be followed via the Imandra-Varzuga Greenstone Belt all the way to the east coast of the Kola Peninsula. The Archaean crustal block was therefore split along a rift zone that extended 700-800 km.

What kind of conditions existed when these huge rift zones developed? One answer is found in the Pasvik valley where a very well-preserved unconformity separates conglomerate and sandstone in the Neverskrukk Formation from underlying, older Archaean gneisses. At several localities, the gneisses beneath the conglomerate display a several-metre-deep zone of weathering, called a *regolith*. The regolith contains rounded blocks of gneiss in a groundmass of coarse sandstone, clearly showing that the Neverskrukk Formation was deposited on an eroded and weathered surface of Archaean rocks.



Unconformity at Skrukkebukta in Pasvik. Conglomerate has filled in an uneven surface where erosion has cut down into foliated Archaean gneiss. (Photo: V. Melezhik)

OXYGEN AND THE EVOLUTION OF THE ATMOSPHERE

Breathe in! About a fifth of the air you breathe consists of oxygen. Yet this has not always been the case. If we go sufficiently far back in the history of the Earth, to the Archaean, the atmosphere had scarcely any oxygen. The simple life forms that existed were adapted to a mixture of nitrogen and carbon dioxide, mixed with sulphurous gases from active volcanoes. Where did the oxygen come from, and when was it formed?

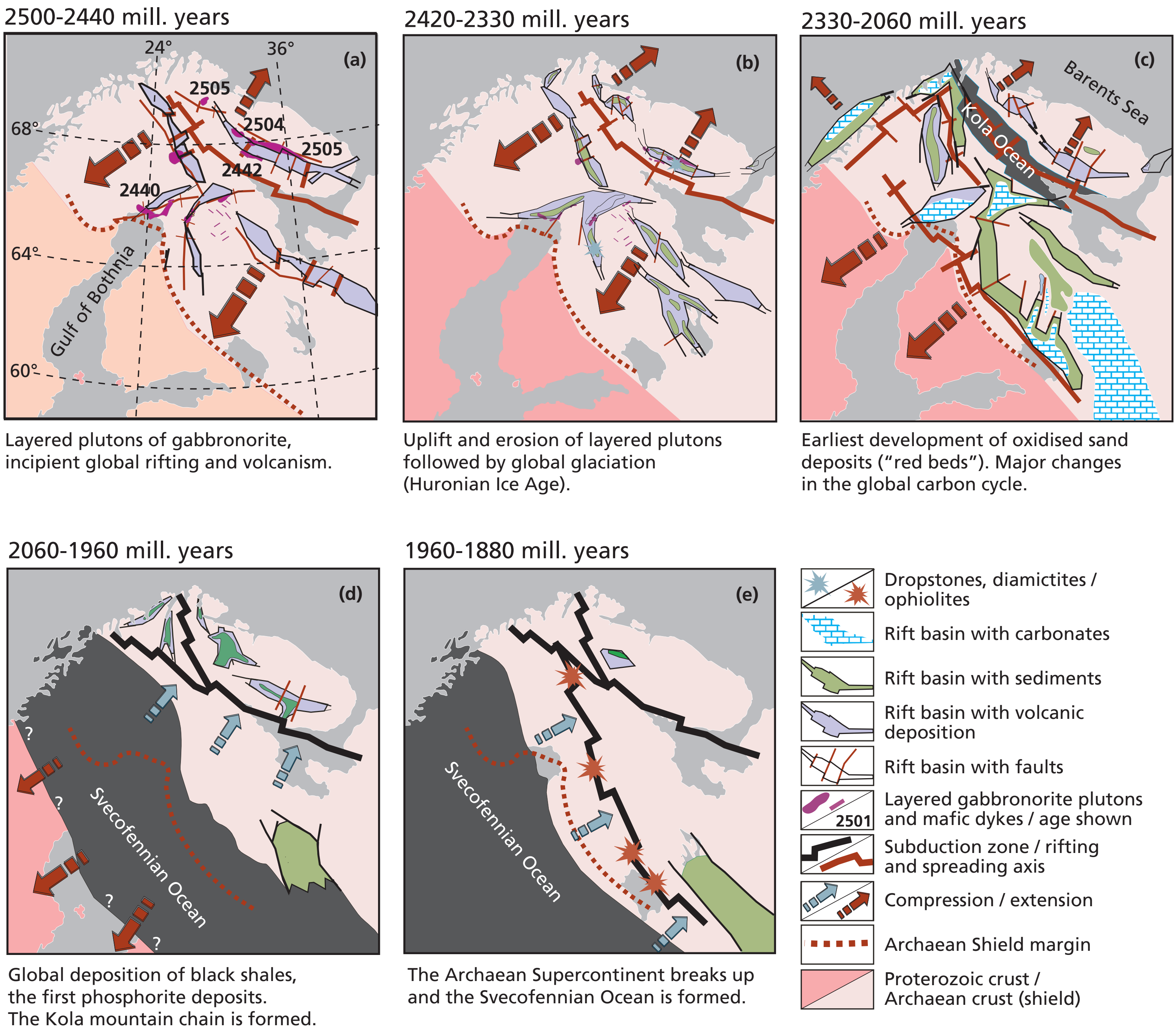
The first organisms that produced oxygen were primitive bacteria (cyanobacteria). Powered by sunlight, these bacteria grew on water and carbon dioxide and emitted oxygen as a by-product of photosynthesis. Traces of such organisms have been found in deposits that are at least 3.5 billion years old. Nevertheless, little suggests that the content of oxygen in the atmosphere had risen significantly before sometime in the Early Proterozoic, probably around 2.35 billion years ago. How do we know this? Valuable knowledge is gleaned from studies of fossilised weathering zones of Late Archaean age. If the atmosphere had contained free oxygen at that time, any iron present in the rock would have been converted to insoluble iron hydroxides, which would have remained in the rock. We can also find fluvial deposits that are rich in iron pyrites and uraninite. In contact with oxygen, these minerals would have been rapidly replaced, but deposits are found in Archaean successions where these minerals have not been affected by contact with oxygen-rich air. An oxygen-rich atmosphere is also essential to develop the ozone layer that has protected life on the Earth from harmful radiation from space.

The quartz-banded iron formations (see box: The iron ore in Sør-Varanger) are further evidence of former oxygen-poor conditions on the Earth's surface. Iron in sea water bonded to itself the oxygen which bacteria produced and built up iron formations. Only when the supply of free iron was reduced could sufficient oxygen be released to bring about a marked change in the atmosphere. These deposits are mainly older than 2.3 billion years, but some iron formations are as young as 1.8 billion years. They probably formed at comparatively great depths in the ocean, where there was little access to free oxygen at that time.

The Polmak-Pasvik-Pechenga Greenstone Belt overlies the Neverskrukk Formation. It is composed of an alternating sequence of volcanic and sedimentary rocks deposited in a rift basin over a long period of time, possibly as much as 400-500 million years. This greenstone belt has its greatest extent in the area between Pasvik and Pechenga. The world's deepest borehole, the 12,262 metre-deep "Kola Superdeep Borehole", was drilled east of Nikel. It penetrated approximately 6.7 km of Early Proterozoic rocks before reaching the Archaean basement. On the Russian side of the border, huge nickel-bearing sulphide ore deposits, associated particularly with the dark plutonic rocks, are worked in the well-known mines at Nikel and Zapolarnyj, for example. The rocks along the rift display a development from the deposition of sand ("red beds") in a continental environment with an oxygen-bearing atmosphere, followed by deposition of carbonate sediments in shallow-marine basins. Broad rift zones with oceanic crust formed as time went by, creating the Early Proterozoic Kola Ocean that divided the Archaean continent.

Andesitic lava and other rocks that characterise volcanic island arcs were deposited along the margin of the rift zone about 2000 million years ago. This took place where oceanic crust in the Kola Ocean sank into the mantle, probably along the margin of the Inari block. Andesitic lava is named after the Andes Mountains in South America. It corresponds to the plutonic rock, diorite, and is characteristic of volcanic mountain chains associated with subduction zones. The areas of ocean gradually closed, and the continents that had been drifting apart for a long time collided and formed a mountain chain which stretched through Lapland and the Kola Peninsula about 1900 million years ago.

The Levajok Granulite Belt is situated west of the Inari block and differs in several ways from the other Precambrian rocks in the border area between Norway and Finland. It contains metamorphosed micaceous sandstones, mica gneiss and metavolcanic rocks that were deposited later than 2000 million years ago. These supracrustal rocks were subsequently intruded by plutonic rocks that are approximately



The figures illustrate the geological evolution of the north-eastern part of the Fennoscandian Shield in the Early Proterozoic.

1950-1900 million years old. Several models have been proposed for how these rocks originated. One interpretation is that they formed in an island-arc setting close to or along the western border of the Inari block. They were strongly deformed, including partial melting and migmatite formation in the micaceous gneisses in Svecokarelian time. When the Kola Ocean closed, the Inari block was fused with the granulite belt and was thrust westwards over the eastern part of the Karasjok Greenstone Belt. The rocks throughout the granulite belt are strongly banded, and this banding generally dips steeply eastwards. Laminated mylonites in the western part of the granulite belt testify to strong plastic deformation in the thrust zone.

Volcanic activity on Finnmarksvidda

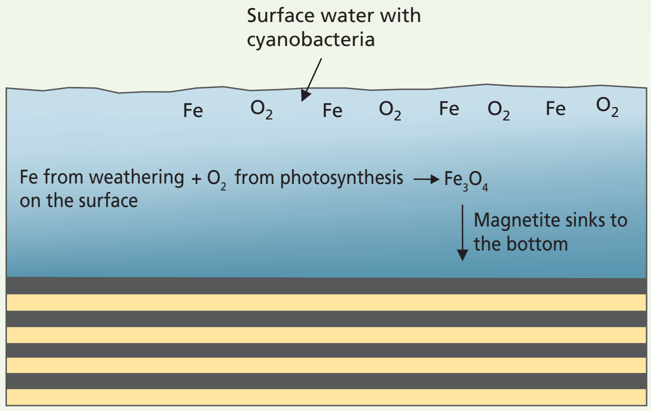
Finnmarksvidda is flat, and extensive areas are covered by basal till or bog. Rock outcrops therefore have to be sought along rivers and on hills to reveal what the overburden may be concealing. Geophysical surveys may be particularly valuable in such areas. If a dense network of profiles is flown over the area, information can be gathered on such aspects as variations in the magnetic and electrical properties of the rocks. This gives a good impression of how the rock types are distributed beneath areas covered with overburden. Geologists can compile bedrock maps in such areas by comparing geophysical information with field observations.

THE IRON ORE IN SØR-VARANGER

The iron ore near Bjørnevatn was discovered by Tellef Dahll, a superintendent of mines, when he was broadly surveying the area in 1866. Following its thorough mapping, the deposit began to be worked in 1906. Through the 20th century, hundreds of millions of tonnes of iron ore were blasted out and shipped abroad from Kirkenes. The mining had its golden age for a period after the Second World War, but the availability of cheap, high-quality ore from other parts of the world gradually made the mines uneconomical, and they closed down in 1997. Enormous open workings and dumps of waste rock dominate the landscape for several square kilometres in the vicinity of the village of Bjørnevatn, south of Kirkenes, and show that the mining company, A/S Sydvaranger, was one of the giants in Norwegian mining.

The iron ore deposits in Sør-Varanger belong to a worldwide group of sedimentary ore deposits, generally termed *Banded Iron Formations* (BIF), which formed over a comparatively short space of time from the Late Archaean up to about 1800 million years ago. Iron (Fe) was liberated by the breakdown of rocks on the continents. Since the atmosphere contained little oxygen, the iron was transported to shallow-marine basins as ions. Primitive cyanobacteria, which produced oxygen (O_2) as a by-product of photosynthesis, lived in the surface water. The free oxygen was able to bond to the iron ions and form the iron oxides, magnetite or haematite, which sank to the sea floor. With increasing blooms of cyanobacteria, a surplus of oxygen gradually built up in the sea water, and this led to the widespread death of the bacterial flora, which was favourable for precipitation of silicon dioxide in the form of jasper. After some time, conditions once more became favourable for new blooms of bacteria, and a new iron-rich band formed.

The iron formations were deposited in partially isolated, shallow-marine basins close to continents. They may comprise sequences up to a hundred metres in thickness and may extend laterally for several hundred kilometres. The economically workable iron ores usually contain between 30 and 70 % Fe, and the largest deposits are found in Brazil, Australia, India and South Africa. This type of ore accounts for approximately 90 % of the world production of iron ore, which amounts to about 1 billion tonnes. Hence, it is one of the most important kinds of ore in the world, in terms of both volume and value.

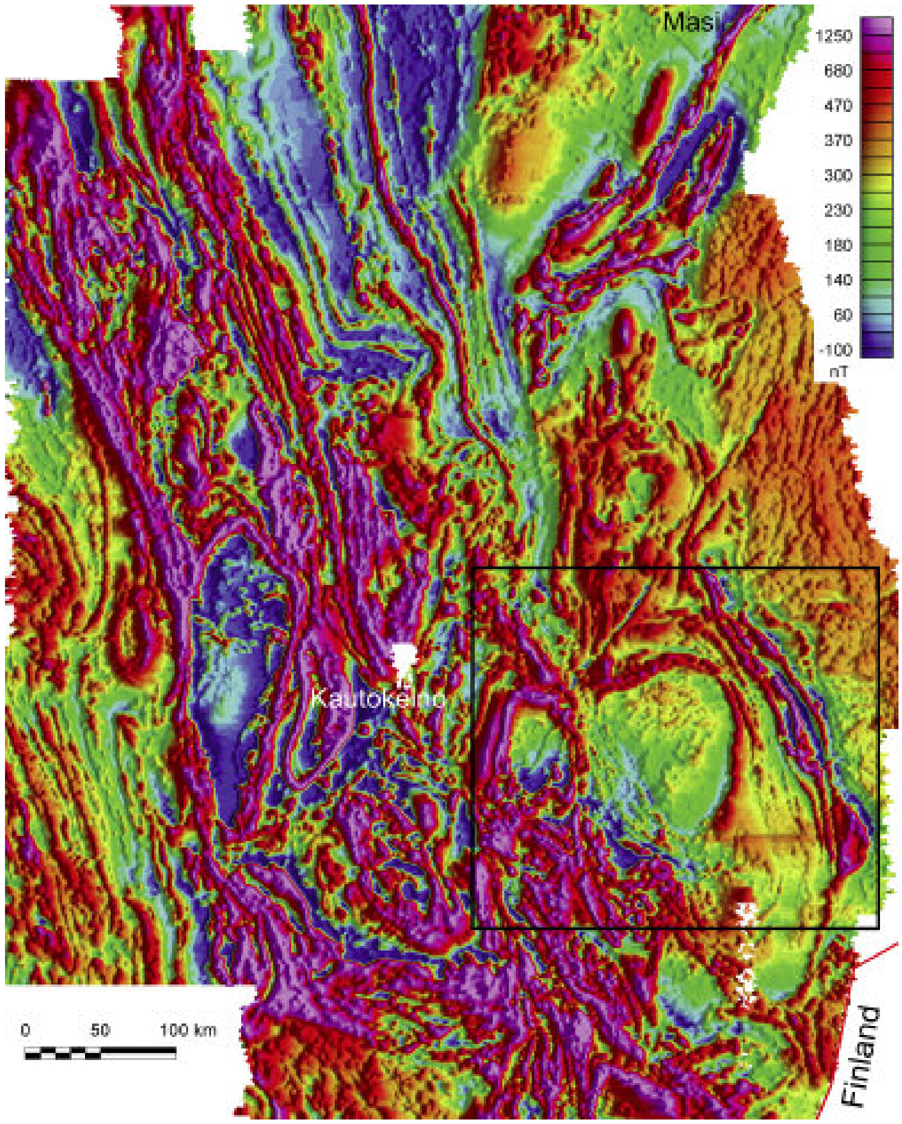


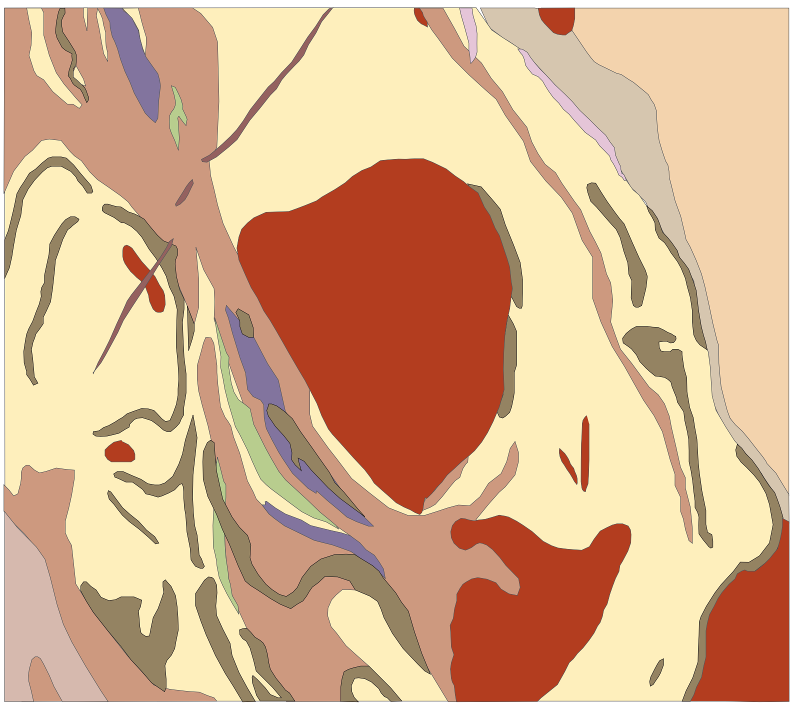
Schematic drawing showing how the quartz-banded iron ore in Sør-Varanger probably formed. Free oxygen (O_2) and iron ions formed the iron oxides, magnetite (Fe_3O_4) or haematite (Fe_2O_3) (dark bands in the figure). These are separated by layers of precipitated jasper (yellow bands). Each band may be from one millimetre up to a few centimetres thick.

The iron ore, which consists of alternating bands of quartz and magnetite that are 2-10 mm thick, occurs in the middle of the Bjørnevann Group. (Photo: Ø. Nordgulen)

The Karasjok Greenstone Belt is 20-40 km wide and can be traced from Lakselv about 300 km south to Kittilä in Finland. It consists of a sequence that alternates between several types of volcanic and sedimentary rocks formed in an elongate rift basin like that in Pasvik. The commonest rocks are amphibolite and metamorphosed lava with a high content of olivine and pyroxene (komatiite), quartzite, metasandstone, mica schist and marble. There are also some small bodies of gabbro and pyroxenite, a particularly dark plutonic rock. The rocks have been metamorphosed at moderate temperatures and pressures and have undergone plastic deformation with multiphase folding. This took place in Svecokarelian time when the Levajok Granulite Belt was thrust westwards over the eastern part of the greenstone belt.

Similar rocks also occur in the Kautokeino Greenstone Belt west of the Jergul Gneiss. This belt narrows towards the Finnish border in the south and disappears beneath the Caledonian nappe pile in the north. The same rocks appear again near Alta and Kvænangen, where erosion of the overthrust Caledonian nappe pile has formed a “window” revealing the basement (see below). The Kautokeino Greenstone Belt mostly comprises metamorphosed basalt and lithified volcanic ash, tuff, which was deposited in marine basins.





KAUTOKEINO GREENSTONE BELT

Palaeoproterozoic rocks

- Granite and granodiorite
- Albite dolerite, magnetite-rich
- Dolerite with remanent magnetism
- Metamorphosed dolerite
- Greenstone and greenschist
- Mica schist and micaceous gneiss
- Amphibolite
- Ultramafic metavolcanic rock
- Quartzite and metasandstone

Late Archaean rocks

- Amphibolite and ultramafic metavolcanics
- Granitic to tonalitic gneisses (Jergul Complex)

A geophysical map (above) showing the total magnetic field and a bedrock map (below) of part of Finnmarksvidda (the Kautokeino Greenstone Belt). The bedrock map illustrates part (framed) of the geophysical map. It shows how the geophysical properties of the bedrock can be used as a valuable aid when mapping areas covered by superficial deposits. (Figures: O. Olesen and J.S. Sandstad)

GOLD IN FINNMARK – FEVER, MYTHS AND REALITY

By Morten Often

Autumn 1990, in the Sargejåk goldfield on Finnmarksvidda. A digger and a huge wheeled loader have spent several days excavating a 16 m-deep crater in layer upon layer of till, sand and gravel, and a 250,000 year-old gyttja containing flattened branches and leaf impressions. The underlying bedrock is finally laid bare. After six seasons of investigations, there is great excitement because just here must be the source of the gold in the largest and best-known goldfield on the plateau. Many people earned a great deal of money here for a few years at the end of the 19th century.

Searching for gold in the bedrock beneath a thick cover of till requires heavy-duty equipment. Sargejåk 1990. (Photo: M. Often)

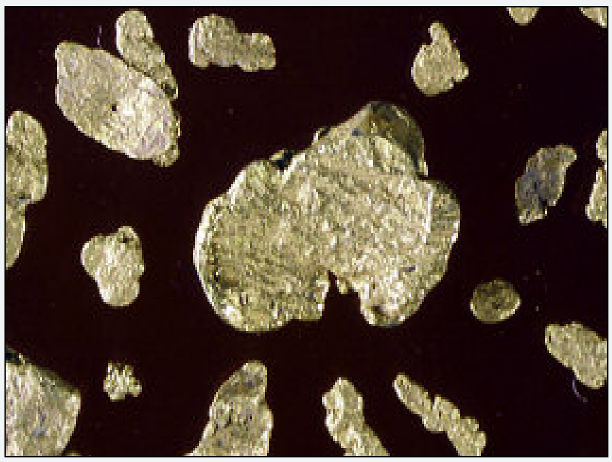
Two men jump down into the pit to scrutinise the rock and take samples. Curiosity wins over the fear that the walls may collapse, and there on the bottom they find something they had not seen anywhere else in the goldfield; a layer of alluvial gravel beneath the basal till, the gold-bearing till that geologists from the Geological Survey of Norway (NGU) had traced backwards towards the source of the gold. Samples were taken, and sent up to be washed. The answer came. The ancient gravels were rich in gold! The source of the gold had been found, but there was no cause for rejoicing. It was gold in the bedrock they were after, not an uneconomical, buried river bed; a success for methodology, but an economic fiasco. The primary source of the gold at Sargejåk has still not been found.

The fairy story of gold on the North Calotte really started some 140 years ago, in 1866, when Tellef Dahll found a grain of gold in his pan in the Niitusjohka, a small tributary of the Karasjohka, just outside the village of Karasjok. The North Calotte gold rush began.

Washing gold in the Gossejåk in 1901. (NGU's photo archive)

Tellef Dahll, one of the two geologists employed by the recently-started Geological Survey of Norway, journeyed to Finnmark that year to start preparing a geological map of northern Norway, a formidable task! He also had to survey the mineral resources, and one of the first things he did was to find out whether there could be any truth in old rumours that gold had been found in the River Tana. He was successful at his first attempt, and in the course of a couple of summers, he found gold in alluvial gravels over a large area south of Karasjok, including the Øvre Anarjohka area on the Finnish side of the border.

A gold rush started in Finland that is still continuing, and several tonnes of gold have been extracted. In Norway, a big gold rush was feared, only 17 years after the huge one in California. The Norwegian Parliament therefore passed an emergency resolution to amend the Mining Act to make alluvial gold the property of the landowner and no longer open for stakes to be claimed. The State owned all the land in Finnmark, which placed an effective damper on prospecting on the Norwegian side of the border.



Gold from Finnmark. The largest grain is about 2 mm wide. (Photo: B.M. Messel)

Many people still look upon Finnmarksvidda as *the* place in Norway where gold is found, even though the official statistics show that only a few tens of kilograms of gold have been extracted, at any rate from superficial deposits. We must not forget the Bidjovagge Mine, however. It opened as a copper mine in 1970, but the smelting plant in Spain paid a surprisingly high price for the gold content in the copper ore. The mine was subsequently run as a financially successful gold mine until it closed down in 1992 after extracting some 6.2 tonnes of gold.

Gold prospecting is again taking place in Finnmark, on the western part of the plateau near Bidjovagge, in the Karasjok district and in Pasvik, far to the east. Promising finds have been made on the Finnish side of the border, in corresponding geological units. The Palaeoproterozoic greenstone belts in Finnmark no doubt have more waiting for those who can find it.

The gold and copper deposits at Bidjovagge (Biedjovágge), west of Kautokeino, occur in such a volcanic succession. Exploration for gold has taken place on Finnmarksvidda for more than a century, and more than six tonnes of gold, in addition to copper, were extracted from the mines at Bidjovagge in 1985-91. This greenstone belt also includes valuable sedimentary rocks, like the Masi Formation, a several hundred-metre-thick quartzitic sandstone containing layers of conglomerate. The quartzite is known for its content of chrome-rich mica (fuchsite), which gives it a distinctive green colour that makes it popular for building purposes.

The youngest deposits in this greenstone belt make up the Caravarri Formation, north of Kautokeino. It is composed of some 4000 m of eastward-dipping sandstones and conglomerates. Such quartz-rich rocks erode slowly and produce poorer soil than the volcanic strata in the greenstone belt. The formation therefore forms a 25-km long, north-south trending ridge rising some 300 m over the flat plateau. Why was such a sequence deposited above volcanic strata in a rift basin? One explanation is found by studying sedimentary structures in the sandstones and conglomerates, structures formed by currents in rivers carrying sand and gravel westwards from a mountainous area in the east that was undergoing strong erosion. This area was probably located on the margin of the mountain range formed when the Kola Ocean closed and the Levajok Granulite Belt was thrust westwards some 1900 million years ago. The gravel and sand deposits constituting the Caravarri Formation would thus have been deposited in a foreland basin west of the Early Svecokarelian mountain chain.

Tectonic windows

On the north-western part of Finnmarksvidda, the Precambrian rocks are concealed beneath Caledonian nappes containing younger metamorphic rocks. In Kvænangen, Alta and Komagfjord, the bedrock has been uplifted and the overlying nappes have been removed by erosion, thus giving us a chance to peep down into the Precambrian basement through what are called tectonic windows.

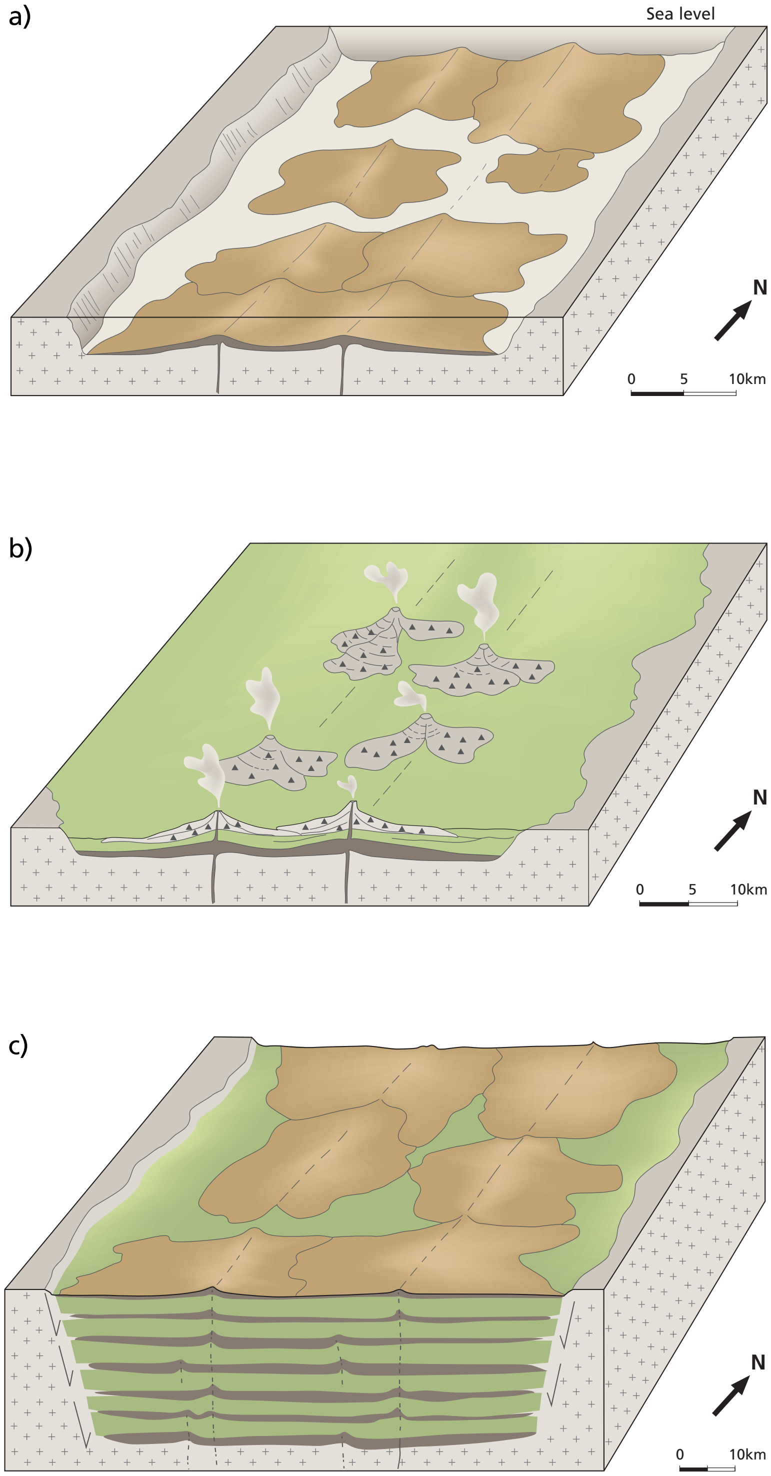
Early Proterozoic volcanic and sedimentary rocks belonging to the Raipas Group are exposed in the Alta-Kvænangen and Komagfjord windows. Even though they lie immediately beneath the Caledonian nappes, the rocks are surprisingly little metamorphosed and deformed. The oldest part of the succession is volcanic and consists of up to 1500 m of recurring gabbro, basalt, pillow lava and tuff (the Kvenvik Greenstone). The pillow lava and tuff derive from eruptions of lava in a shallow-marine basin that arose in an early rifting phase, or in an initial development of a rift zone in the Archaean basement. Because lava came into contact with water, pillow structures formed, like those in the amphibolitic lava near Bjørnevatn in Sør-Varanger. Together with the lava, there are also explosively expelled pyroclastic products like ash and volcanic bombs, now appearing as tuff and volcanic breccia, respectively.

Ore deposits, formed by precipitation of metalliferous solutions that poured out of the sea floor, are found in the volcanic rocks. Kåfjord Kobberverk (1826-1909) worked copper pyrites in what was the first important mining activity in Finnmark. In the mid19th century, this was the largest copper mine in the country and the largest workplace in north Norway.

Shales and various types of limestone and dolomite are found in the middle of the succession. The most distinctive rock is the Storviknes dolomite, which sometimes contains laminated structures assumed to have originated as stromatolites. Stromatolites are formed when fine carbonate mud adheres to sticky mats secreted onto the sea bed by cyanobacteria and algae. The possible stromatolites in the Raipas Group may be among the oldest traces of life identified in Norwegian bedrock, apart from the indirect indications of life shown by the stratified iron ore in Sør-Varanger. Stromatolites are still more common in the Late Precambrian, Neoproterozoic beds in east Finnmark and are described in more detail in Chapter 4.

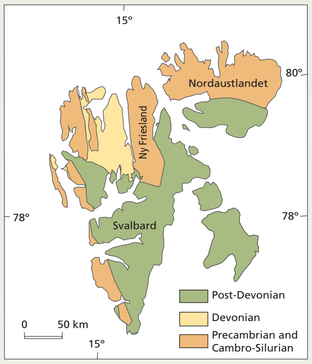
The uppermost part of the Raipas Group consists of more than 2000 m of sandstone (the Skoadduvarri sandstone), which can be correlated with the Caravarri Formation in the Kautokeino Greenstone Belt. Ripple marks that may have formed on tidal flats are preserved in fine-grained sandstone beds with thin shale horizons. Younger beds become increasingly coarse-grained and conglomeratic, and in several places the sandstone contains large cross-beds formed in rivers and deltas. These deposits gradually filled the rift basin.

ABOVE: Kvenvika greenstone with pillow structures.
BELOW: Storviknes dolomite with stromatolite structures.
(Photos: S. Bergh)



The rocks of the Raipas Group tell an exciting geological story. Fluid basalt lava (brown) poured out of joint systems in a marine rift basin (a) and was followed by explosive volcanic eruptions (b) which gave rise to tuffs (light green). At the same time, the rift zone sank in fits and starts, resulting in the formation of a thick volcanic sequence (Kvenvik Greenstone), c). The basin was subsequently filled, initially by carbonate sediments (Storviknes dolomite) and finally by thick continental sandstones (Skoadduvarri sandstone).

PRECAMBRIAN ROCKS IN SVALBARD



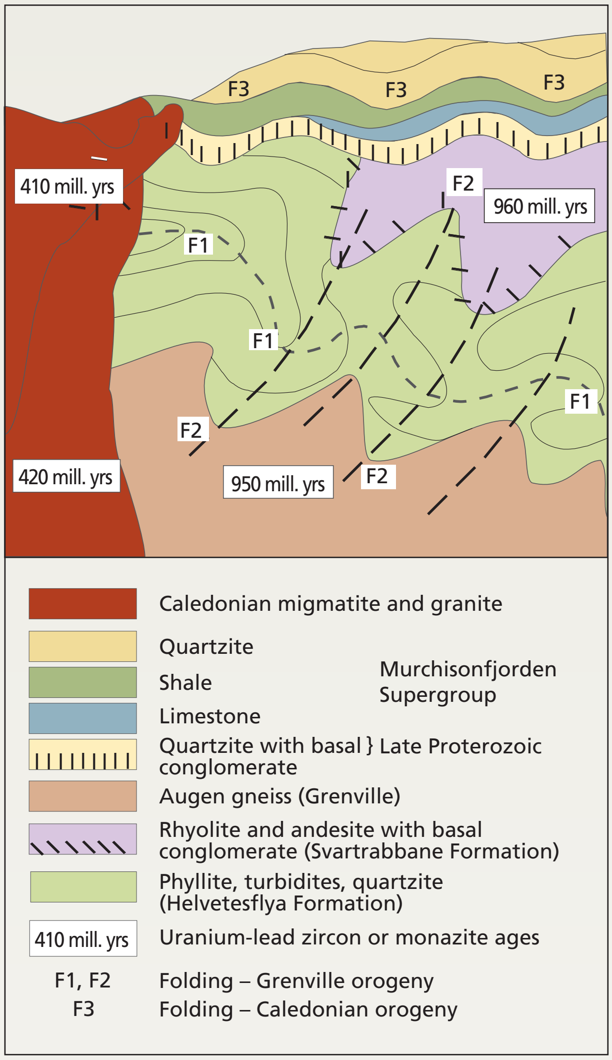
Precambrian rocks are found along the western part of the Svalbard archipelago and in the northeast, in Ny-Friesland and the island of Nordaustlandet. These rocks have been known under the collective name of Hecla Hoek ever since the well-known polar scientist, Adolf Erik Nordenskiöld (1832-1901), mapped them in the 19th century. Over the years, the term came to include all the pre-Devonian rocks. At the same time, it became clear that they have evolved over a long period of Precambrian time, as well as during the Caledonian.

On Nordaustlandet, the basement underlies undeformed Palaeozoic and younger strata. The oldest rocks here comprise a 2-3 km-thick, Middle Proterozoic succession of deformed and weakly metamorphosed sedimentary rocks, mainly phyllites, turbidites and quartzitic sandstone (the Helvetesflya Formation). Following a folding episode (F1) and subsequent erosion, conglomerates were deposited with a distinct angular unconformity on the older deposits. These were overlain by up to 1000 m of volcanic rocks (rhyolite and andesite),the Svartrabbane Formation, and intruded by younger quartz porphyries. An age determination of 960 million years shows that the volcanic activity took place just before the Grenville orogeny, which corresponds to the Sveconorwegian orogeny in Norway. During this event, the rocks were folded once more (F2) and intruded by granites whose age is about 950 million years.

Uplift and erosion followed more or less immediately, and the Grenvillian mountain chain was eroded and worn down. The erosion surface cuts across different units of the folded succession and is overlain by a Late Proterozoic succession starting with a basal conglomerate, which is succeeded by shales, siltstones and quartzite and thereafter by predominantly carbonate strata (the Murchisonfjorden Supergroup). This deposition continued into Palaeozoic time, before all the rocks were metamorphosed, intruded by granites and folded (F3) during the Caledonian orogeny.

When we move westwards to Ny-Friesland, we no longer see evidence of the impact of the Grenville orogeny. The Atomfjella Complex in this area includes the oldest rocks so far dated in Svalbard. This complex was probably formed in the Caledonian and consists of alternating sheets of granitic gneiss and sedimentary rocks. Most of the gneisses have ages of around 1750 million years, but one granite has given a greater age, Late Archaean. Dolerite dykes in the complex have been dated to approximately 1300 million years.

Migmatites, schists and marbles of probable Middle Proterozoic age are found in north-western Svalbard. They are intruded by granitic plutons dated to around 960 million years. The rocks here are strongly overprinted by Caledonian deformation. The Precambrian rocks along the southwest coast are part of the Tertiary fold and thrust belt in Svalbard. Some areas here have rocks affected by the Grenville orogeny and overlain by Late Proterozoic sediments. Even though there are differences in the details, the general geological evolution has many aspects in common with those on Nordaustlandet.



The figure shows a schematic section illustrating the geological evolution in Nordaustlandet. Two unconformities separate three important stratigraphical units, the Helvetesflya Formation, the Svartrabbane Formation and the Murchisonfjorden Supergroup. An unconformable surface is an expression of a fundamental time interval – a milestone in the geological evolution of an area. It marks the end of a cycle of mountain chain formation and folding (F1 and F2 in the figure) followed by breakdown and erosion. The basal conglomerates record the onset of a new period of deposition of strata on an erosion surface. The youngest folds (F3) are Caledonian. The age of igneous rocks (granites and volcanic rocks) helps to time the various events.

Troms and Nordland

Precambrian basement rocks in Troms and Nordland are most prominent on the outer coastal islands. The hard rocks generally crop out on mountains with dramatic, jagged peaks. In several areas, Precambrian massifs fall precipitously into fjords and the open sea, as in the Lofoten Wall. The mountains have been chiselled out by Quaternary glaciers, while the basement in other parts of the mainland was worn down several hundred million years earlier.

The Precambrian rocks along the coast of northern Norway from the islands of Værøy and Røst in the southwest, through Lofoten and Vesterålen to the island of Vanna in western Troms in the northeast, were formed in the Archaean and Early Proterozoic and were reshaped during a number of later geological events. These rocks are probably a westerly extension of basement complexes found over large parts of northern Sweden and northern Finland. On the mainland, the basement rocks are concealed beneath a thick pile of Caledonian nappes that were thrust onto the Fennoscandian Shield during the Devonian. The basement was deep in the roots of the Caledonian mountain chain (see Chapter 7). It is difficult to find traces of this event in western Troms. In Lofoten, the thrusting only led to limited, localised metamorphic impact. In this respect, the bedrock along the coast of northern Norway differs from that in the Western Gneiss Region on the west coast of southern and central Norway, and also the small basement windows along the coast of Nordland.

Following the Caledonian orogeny, the crust underwent extension concentrated along normal faults that separate the Precambrian rocks from young sedimentary deposits on the shelf. In many places on land, the Caledonian nappes are bounded in the west by steep, normal faults along which the Precambrian rocks on the coast have been uplifted 2-3 km relative to the Caledonian rocks on the mainland further in. This is particularly obvious in the Tromsø district, where several of the fjords (e.g. Straumsfjorden) and straits (e.g. Sandnessundet and Langsundet) follow such faults because the rocks there are highly crushed making them less resistant to erosion, including that exerted by the Quaternary glaciers.

Archaean rocks in western Troms

The basement complex in western Troms refers to the area of Precambrian rocks stretching from Senja in the south to Vanna in the north. These rocks have a very long history.

The oldest dated rocks consist of tonalite and tonalitic gneiss occurring on islands north of Tromsø. These white to greyish-white rocks, composed mainly of plagioclase feldspar and quartz, are 2880 million years old and are therefore among the very oldest rocks in Norway. They belong to the Archaean TTG group mentioned previously from several places in eastern Finnmark, and were formed when magma forced its way up through the crust to solidify at a depth of some 10-15 km. The rocks intruded by the 2880 million-year-old tonalite must be at least as old, but no precise age determinations are available yet.

A greenstone belt composed of igneous rocks alternating with sedimentary rocks derived from eroded volcanic rocks occurs in the northern part of the basement complex in an approximately 10 km-wide zone stretching east to west across the island of

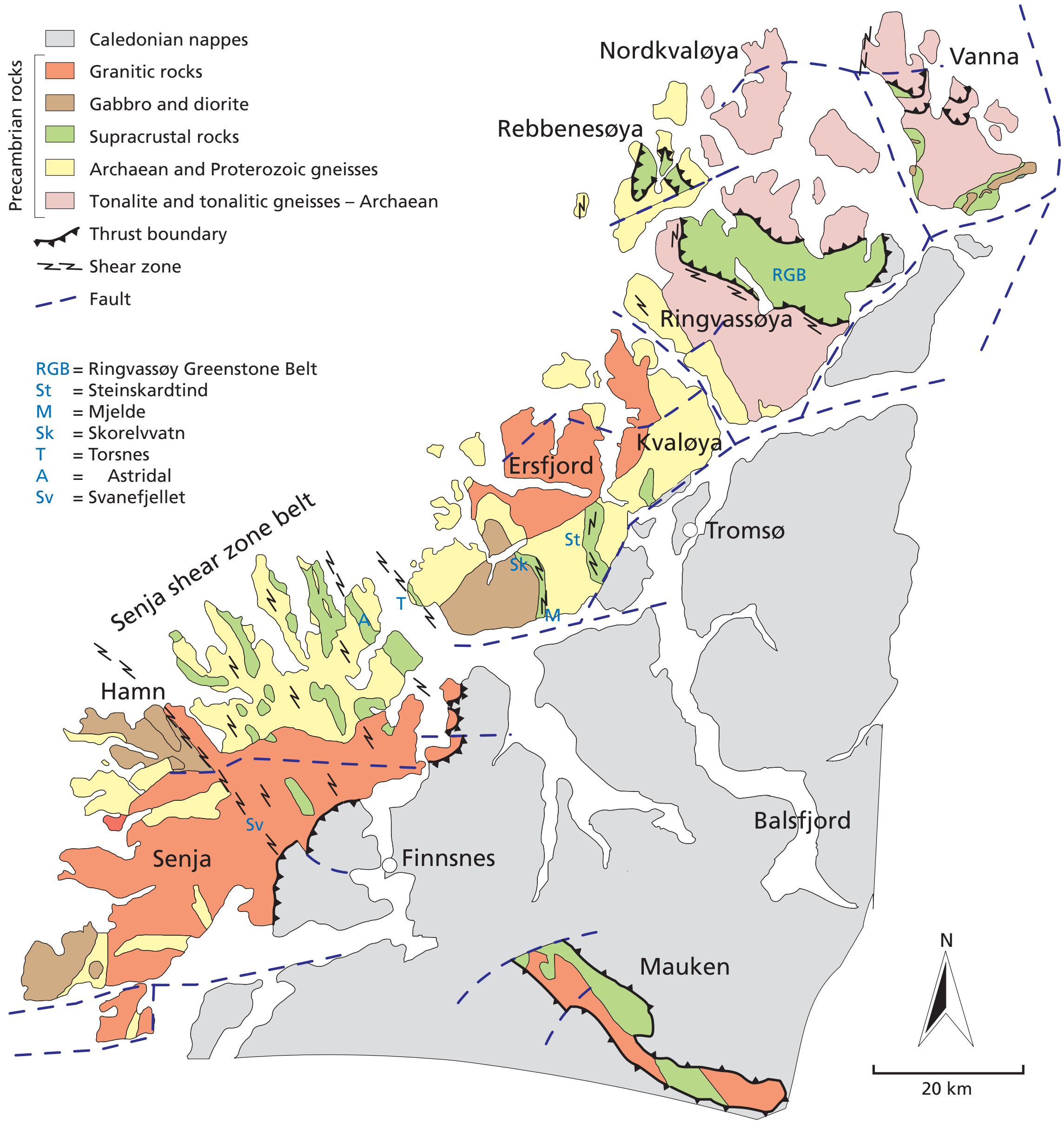
The mountains north of Ersfjorden on Kvaløya, Troms, from Skamtinden in the west to Blåmannen and Orvasstinden in the east (right), consist of 1800 million-year-old granite. (Photo: K. Kullerud)

Ringvassøya and continuing north-westwards over Rebbenesøya. The belt consists mainly of mafic rocks, comparatively rich in iron and magnesium and poor in silica. These rocks were probably thrust-emplaced within the underlying and overlying tonalitic rocks. Gold is found on Ringvassøya, as it is on Finnmarksvidda and in many other Precambrian greenstone belts around the world. Several international mining companies have prospected for gold here in the past 30-40 years, but all have concluded that there is too little to permit profitable extraction.

The crust splits

Stable continental crust had been established in western Troms by the end of the Archaean. This crust underwent extension and fracturing approximately 2400 million years ago. At the same time, mafic magma invaded the fractures and crystallised as fine-grained, dark, hypabyssal rocks. This magma originated from partially melted mantle rocks. In the northern part of the basement area, these dykes form decorative, black bands traversing the host rocks. On fine summer days, the dykes on Ringvassøya are easily visible from high on Tromsøya.

Similar dyke rocks of about the same age (2400-2200 million years) are found elsewhere in the Fennoscandian Shield and also on several other Archaean continents, such as in Canada, Australia, India and South Africa. This implies that a *supercontinent* existed as early as the Late Archaean and that it fractured along major rift zones (such as the



Geological map depicting the main features of the bedrock from Senja in the southwest to Vanna in the northeast. The Precambrian rocks along the coast underlie the Caledonian nappes that were thrust from the northwest. At Mauken, there is a tectonic window where Precambrian rocks show through the nappes.

Polmak-Pasvik-Pechenga Rift), after which the various segments began to drift apart.

The next episode in the Precambrian history of western Troms can be found on the island of Vanna, in the far north of the basement complex. Small areas of little metamorphosed, mostly calcareous, sandstone and siltstone are found there, and these rocks lie on an eroded surface composed of the ancient tonalitic gneisses and the 2400 million-year-old dyke rocks. The sandstones originated as deltaic or coastal sand deposited in a river or a shallow sea. Since the sedimentary rocks were intruded by diorite that has a cooling age of 2220 million years, the Archaean rocks must have been raised to the surface and eroded before the sediments were deposited between 2400 and 2220 million years ago. These were then overlain by further sediments and transformed into sandstone and siltstone before the dioritic magma intruded and solidified.

Large granite intrusions are emplaced

Vast volumes of granitic magma rose up from depth and solidified some 10-15 km below the surface about 1800-1770 million years ago. The impressive row of peaks along the north side of Ersfjorden on the island of Kvaløya, from Skamtinden in the west to Blåmannen in the east, is composed of the

Ersfjord Granite, which is about 1792 million years old. Several other large bodies of granite were also formed at this time.

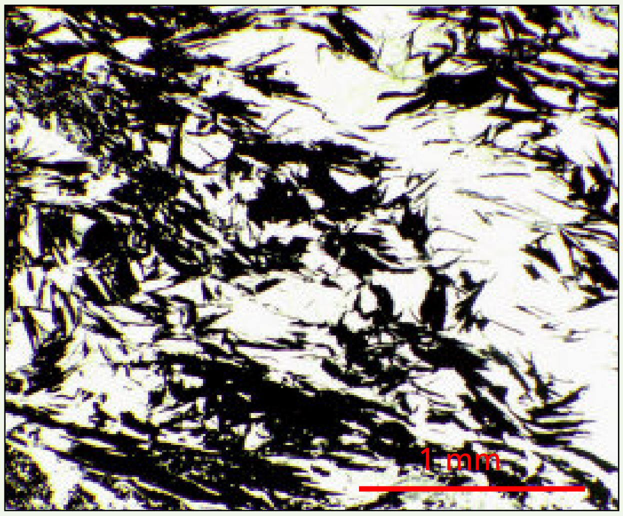
At approximately the same time as the granites were emplaced, magma rich in iron and magnesium was intruded, and it solidified to form dark, coarse-grained gabbro in the area around Hamn on the outer coast of Senja. Large gabbro bodies may be locally enriched in metals, and nickel in the form of *pentlandite* (an iron-nickel sulphide mineral) has been found in the gabbro at Hamn. A mine worked this nickel deposit at Hamn for a few years at the end of the 19th century.

Magmatic activity, deformation and metamorphism continued in western Troms until approximately 1750 million years ago. Evidence of plastic deformation is shown by steeply inclined, northwest-south-east trending shear zones that generally follow belts of schists and other metasedimentary rocks. Good examples of these are found in the Mjelde-Skorelvvatnet zone on Kvaløya and in a 30 km-wide belt on north-eastern Senja that contains several shear zones. The origin of this Senja Shear Belt is probably related to that of several extensive deformation zones that can be traced for hundreds of kilometres south-eastwards through the Precambrian basement in northern Sweden.

Sandstone at Jøvik, Vanna. The sandstone, which is between 2400 and 2220 million years old, has cross-bedding which shows that it was deposited as sand in a large, deep river, a delta or along a shore beside a sea or a large lake. (Photo: K. Kullerud)

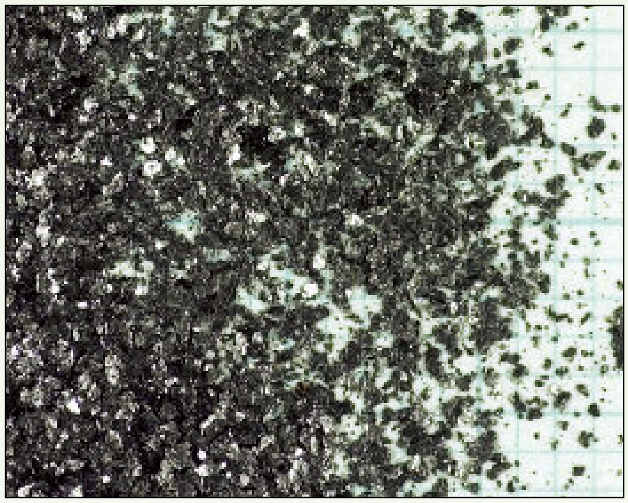
GRAPHITE AT SKALAND, SENJA *By Håvard Gautneb*

Graphite is a fairly common mineral in many metasedimentary rocks, but only a few Norwegian deposits have had any economic importance. The principal one is on the island of Senja in Troms, where the Skaland Graphite Mine has worked 10-12 fairly large bodies of graphite ore.



Photomicrograph of a thin section of the graphite ore from Senja; everything black is graphite.

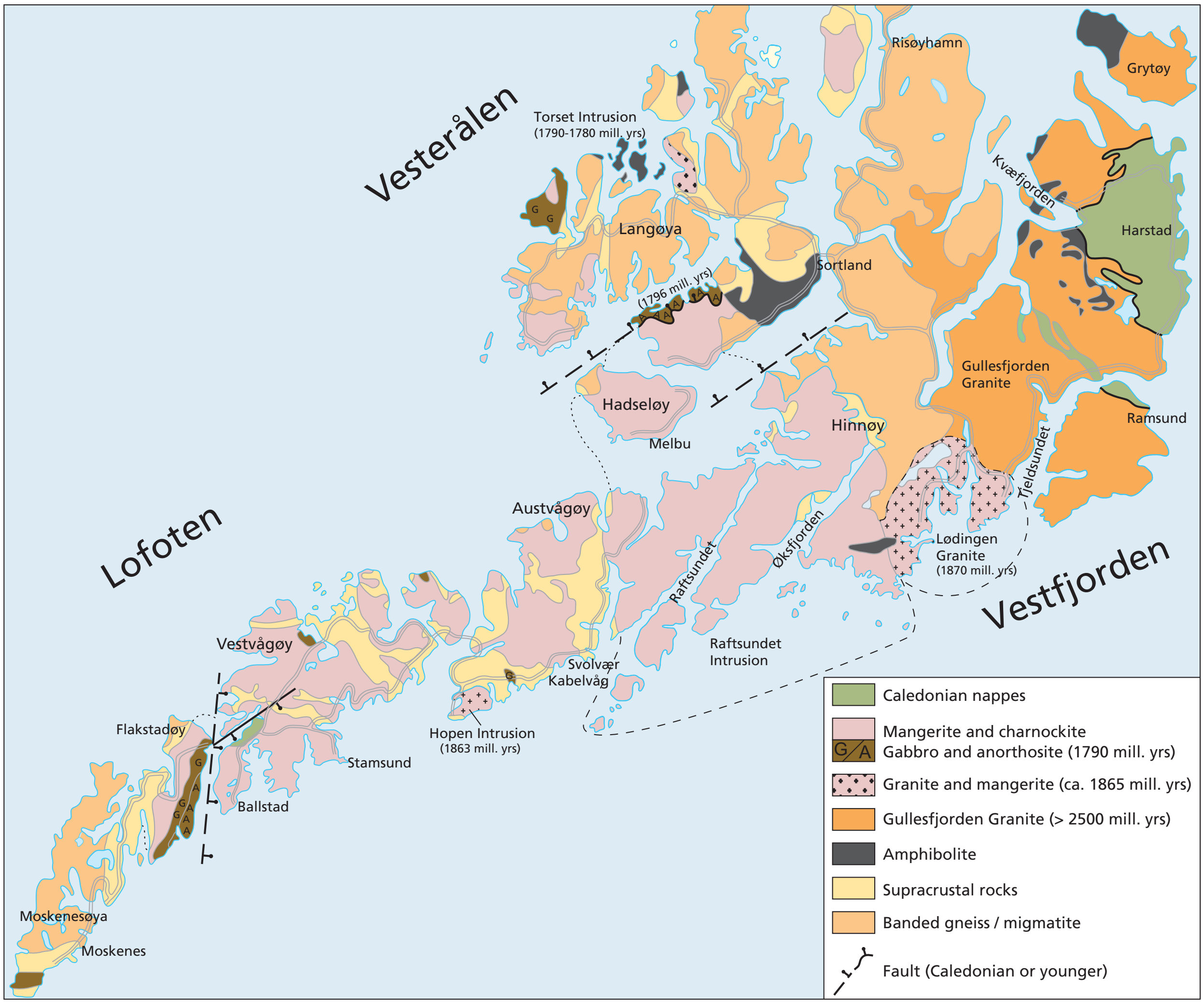
Graphite is one of the industrial minerals which we come into contact with early in life, as it is the most important constituent in pencils. Finely crushed graphite is mixed with clay in varying proportions to give the differing hardness of the "lead". As graphite has very high heat resistance and is chemically stable, one of its principal areas of use is in steelworks and smelting plants. Other important uses are in brake linings for cars, batteries and lubricants.



The finished product, Silvershine, from Skaland Graphite Mine. (Both photos: H. Gautneb)

Graphite deposits of the type found in Norway are formed during high-grade metamorphism of rocks that were originally rich in organic constituents. Organic material is converted into graphite at pressures above 6.3 kbar and temperatures in excess of 400 °C. The partial pressures of CO_2, CO, CH_4 and H_2O are important parameters during the formation of graphite. Graphite deposits have frequently undergone several phases of metamorphism and deformation, and all traces of the original sedimentary rock have been wiped out. The result is often graphitic schist which may contain 5-40 % carbon. A typical concentration for Norwegian graphite ore is about 20 % carbon. The occurrence of graphite ore is extremely structurally controlled, and the greatest thicknesses are found in fold hinges, where the ore generally lies along the fold axis.

Skaland graphite must have been utilised for the first time in the 1870s. Boys being confirmed at Skaland Church were renowned for having unusually highly polished shoes, having used local stones that were particularly suitable for the purpose. The first graphite mine opened in 1917. Prices were very good then, thanks to the First World War, but the mine went bankrupt already in 1920. Mining started again in 1927, and graphite flotation began in 1932. Lengthy modernisation of the plant started after the Second World War and a new flotation plant was ready in 1953. The mine then experienced many good years. The graphite from Skaland was particularly suitable for manufacturing batteries and Eveready was one of the owners. Around 1980, Skaland was responsible for 75 % of the European production and 5 % of the world production of graphite. The flotation plant burnt down in 1985 and all mining ceased. Graphitwerk Kropfmuhl, a German graphite manufacturer, took over and built a new flotation plant. This company went bankrupt after a few years and the facilities were sold to a Norwegian company, Elkem, which worked the deposit for some years before a new bankruptcy occurred. Another company was formed, partly owned by Berg Borough Council. The international graphite market has been under serious pressure from large producers in China for the last 10 years. In 2004, the Skaland Graphite Mine was taken over by a local firm of contractors, Leonard Nilsen & Sønner, which is still running it. The original ore bodies in the village of Skaland are now (2006) almost worked out, and the company has recently been undertaking extensive prospecting, including drilling, to start a new mine at Trælen, a few kilometres from the present one.



Geological map of Lofoten and Vesterålen.

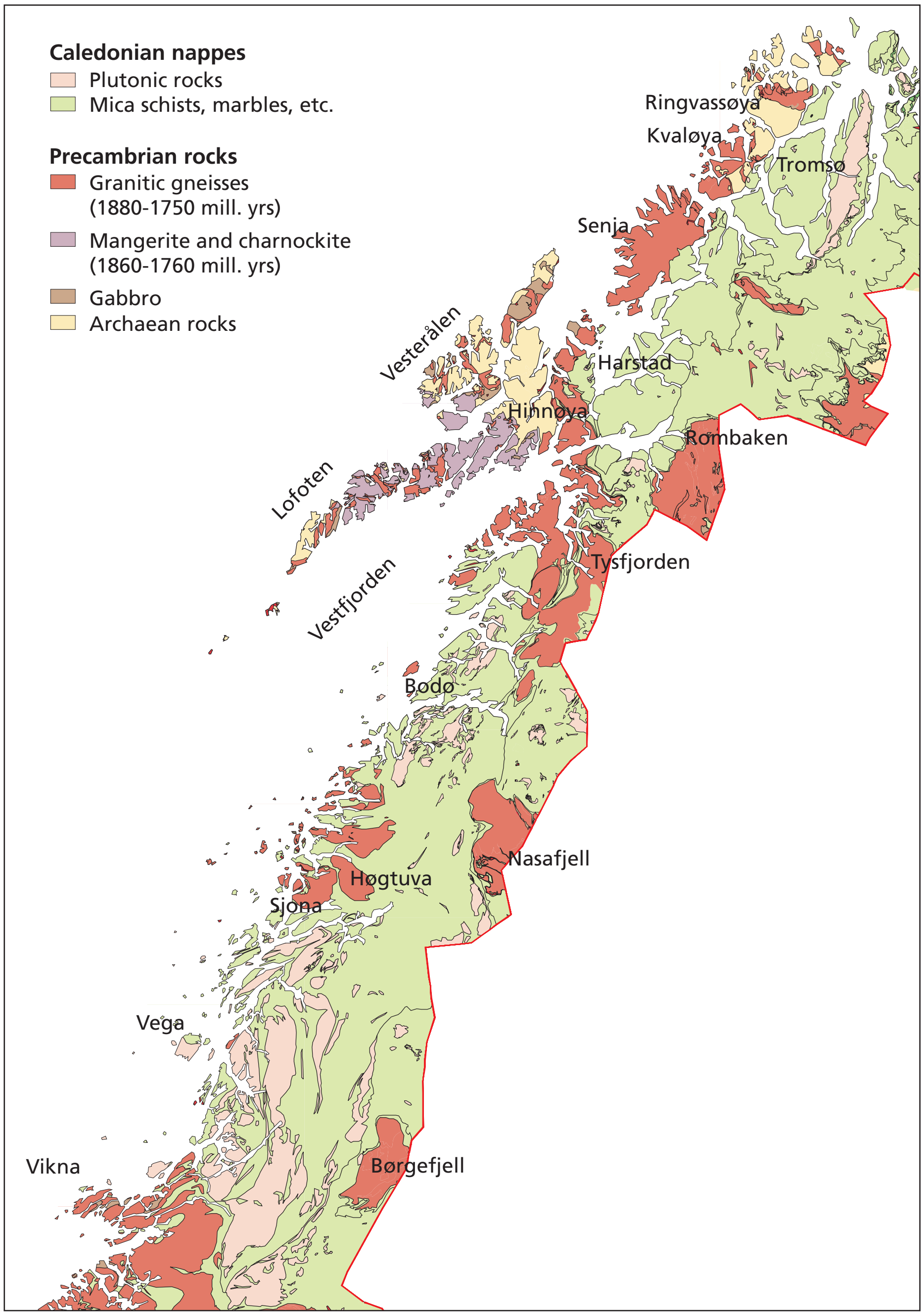
Lofoten and Vesterålen – a fragment of the lower crust

The basement in the 160 km-long Lofoten Wall reaches far above sea level because, in the period following the Caledonian orogeny, it was uplifted along a series of faults mostly trending northeast-southwest. Seismic studies in Vestfjorden and on the shelf off Lofoten and Vesterålen show that the basement immediately off the coast is covered by a thick pile of younger sediments (see Chapter 14).

The landforms in Lofoten are controlled by faults related to later crustal extension. Narrow fjords and straits between the islands are oriented northeast-southwest to north-south and follow fault zones where the bedrock is crushed. In many places, the bedrock is deeply eroded, suggesting that Lofoten has been exposed to chemical weathering for a long period and the high peaks probably reached above the ice as *nunataks* throughout the last Ice Age.

The rocks in Lofoten and Vesterålen are approximately as old as those in western Troms. Archaean rocks are found on the islands of Langøya and Hinnøya. Those on Langøya are highly metamorphosed migmatitic rocks of sedimentary and volcanic origin, whereas tonalitic gneiss and small greenstone belts comprise most of the bedrock on Hinnøya. Small areas of Archaean rocks also occur on the south-western point of Austvågøya. A younger succession of Early Proterozoic metasedimentary rocks has an uncertain age of around 2100 million years. These rocks are scattered throughout Lofoten and mainly consist of quartzo-feldspathic gneisses and minor banded-iron formations (BIF), graphitic schists and marble.

The Archaean and Early Proterozoic rocks are transected by younger plutonic rocks that make up more than 50 % of the bedrock in Lofoten. The oldest of these is the Lødingen Granite, which is approximately 1870 million years old. Otherwise, age determinations from several parts of Lofoten show that the plutonic rocks solidified during a short period from 1800 to 1790 million years ago. Unlike the plutonic



Geological map showing the distribution of Precambrian rocks and Caledonian nappes in Nordland and western Troms. Archaean rocks occur furthest north. The basement windows in Nordland are mainly composed of Early Proterozoic granitic gneisses. Similar rocks also occur in Nord-Trøndelag.

rocks of the same age in western Troms, those in Lofoten show evidence of having crystallised deep in the crust. The minerals in these rocks are typical of granulites. Orthopyroxene (such as hypersthene mentioned above) is a characteristic dark mineral, and the feldspars are generally dark brownish-yellow. Charnockite and mangerite are the most common rock types and they form large bodies of plutonic rocks, such as beside Raftsundet and at Hopen. Charnockite is a granite carrying orthopyroxene as its typical dark mineral, whereas mangerite is orthopyroxene-bearing monzonite (see Chapter 2). Smaller bodies of gabbro and anorthosite are scattered on the islands. Small granites and pegmatites were formed until about 1770 million years ago. Together, all these plutonic rocks form a single group, the anorthosite-mangerite-charnockite-granite suite, which is characteristic of crust formed in Proterozoic time. These rocks stem from magma originating in the mantle, mixed with varying quantities of melt derived from Archaean rocks in the lower crust.

Basement windows in Nordland

Many of the well-known mountainous areas in Nordland consist of Precambrian rocks which form tectonic windows in the Caledonian nappe pile. The bedrock in these windows was uplifted and locally deformed during crustal extension after the Caledonian orogeny. Granitic gneisses with zones of mica schist and metamorphosed sandstone are the most important rocks in basement windows like Børgefjell, Sjona, Høgtuva, Nasafjell and Tysfjord. The plutonic rocks are 1800 million years old and, together with similar rocks in Lofoten and Vesterålen, they comprise part of the Trans-Scandinavian Igneous Belt stretching westwards from Sweden beneath the Caledonian nappes. The granites in Tysfjord, notably forming the majestic peak of Stetind, are well known for their occurrences of coarse pegmatites in which individual minerals may be several metres across. At Drag in Tysfjord, quartz from such pegmatites is processed into ultra-pure quartz to be used in optical devices, microchips in computers, and other products.

The Rombak window, straddling the Swedish border, displays the transition between the Archaean and the Proterozoic basement in the Fennoscandian Shield. Tonalitic gneisses of uncertain age are overlain by 1900 million-year-old sedimentary and volcanic rocks with a chemical composition showing that they were deposited in basins adjacent to volcanic island arcs. These arcs probably developed above subduction zones located along the south-western margin of the Fennoscandian Shield. The geological evolution within the Rombak window is thus a parallel to the Svecofennian tracts in northern Sweden and Finland.

In summary, approximately 1800 million years ago, various types of plutonic rock formed over large parts of the Fennoscandian Shield, apart from in the cores of the larger Archaean domains. This was probably a result of important changes in the plate movements along the margin of the old crustal blocks at the very end of the Svecofennian orogeny.

Trænstaven is a well-known landmark on the Norwegian coast. The bedrock on the island of Træna is a westerly continuation of the basement window at Sjona. Prominent peaks of gneisses that are resistant to weathering extend up from the strandflat, which is very well developed in Nordland. (Photo: edelpix, P. Eide)

The basement in south Norway

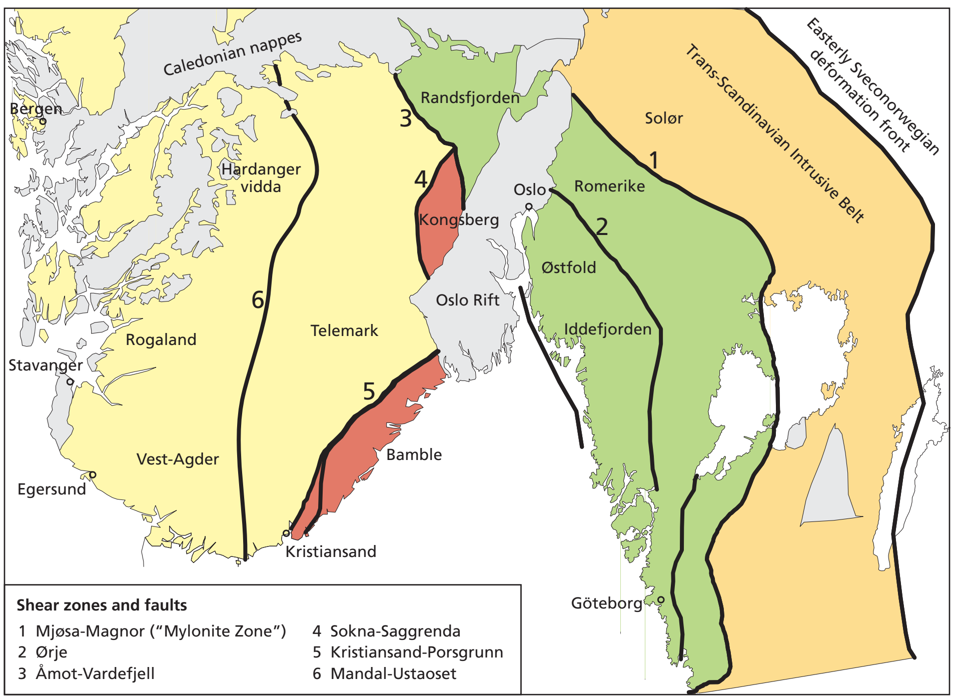
The Precambrian rocks in the basement of southern Norway constitute the youngest part of the Fennoscandian Shield and took several hundred million years to evolve, ending 900 million years ago. Ancient, worn-down mountain chains offer glimpses of this history and insight into how the interplay between the internal and external forces shaped the country.

The basement is mostly composed of crustal blocks. Geologists have referred to these blocks by a variety of terms over the years, including *sectors* and *terranes*. The amount of lateral and vertical movement that has taken place along the various shear zones that separate the blocks is not known. It is also uncertain how the various blocks have been situated in relation to one another 1600-1700 million years ago and subsequently.

Whereas the oldest rocks in northern Norway were formed in Archaean time, more than 2500 million years ago, most of the basement in southern Norway was formed substantially later, around 1750 to 900 million years ago. Furthest east, the rocks belong to the Trans-Scandinavian Intrusive Belt, which consists of plutonic and extrusive rocks that are more than 1650 million years old. An important period of crustal accretion coincided with the formation of the *Gothian mountain chain* 1750 to 1500 million years ago.

However, large parts of the basement in southern Norway formed later, 1500 to 1040 million years ago, after the Gothian orogeny. They are metamorphosed rocks which mostly originated as sedimentary and volcanic deposits. The Precambrian evolution of southern Norway culminated with the formation of the *Sveconorwegian mountain chain* 1130-900 million years ago, when the majority of the rocks in southern Norway were folded and in part strongly deformed and metamorphosed. A few granite batholiths that were emplaced in the crust some 925-930 million years ago escaped this deformation.

The legacy of these events is readily visible in the present landscape, where the structure, composition and joint patterns of the bedrock are decisive for both landforms and soils, and hence vegetation and settlement patterns. In the coming pages, we will look more closely at the geological history concealed in the bedrock of some selected basement areas in southern Norway.



A mosaic of crustal blocks

Basement areas in southern Norway and south-western Sweden are composed of several crustal blocks, each of which is characterised by rocks bearing features that distinguish it from the rocks in adjacent areas. These blocks are separated by *shear zones*, which are steeply inclined, linear belts where the rocks have been exposed to severe plastic deformation. The shear zones vary from a few tens of metres up to several kilometres in width, and most are oriented approximately north-south to northwest-southeast. The severe deformation along the shear zones was probably caused by transform (lateral) fault movements between the blocks late in the Sveconorwegian orogeny. Substantial movement took place along a few zones on a still earlier occasion, and some experienced movements when the Oslo Rift was formed in the Permian.

Basement composed of Precambrian banded gneiss (in the foreground) beneath flat-lying Cambro-Silurian deposits (dark, in the background). The photograph is taken at Rognstranda in Bamble, Telemark. This locality is situated in an area in the counties of Vestfold and Telemark which was designated as a European geopark in autumn 2006, the first in the Nordic countries. The geoparks are approved by UNESCO and their intention is to display the most important geological environments on the Earth.
(Photo: S. Dahlgren)

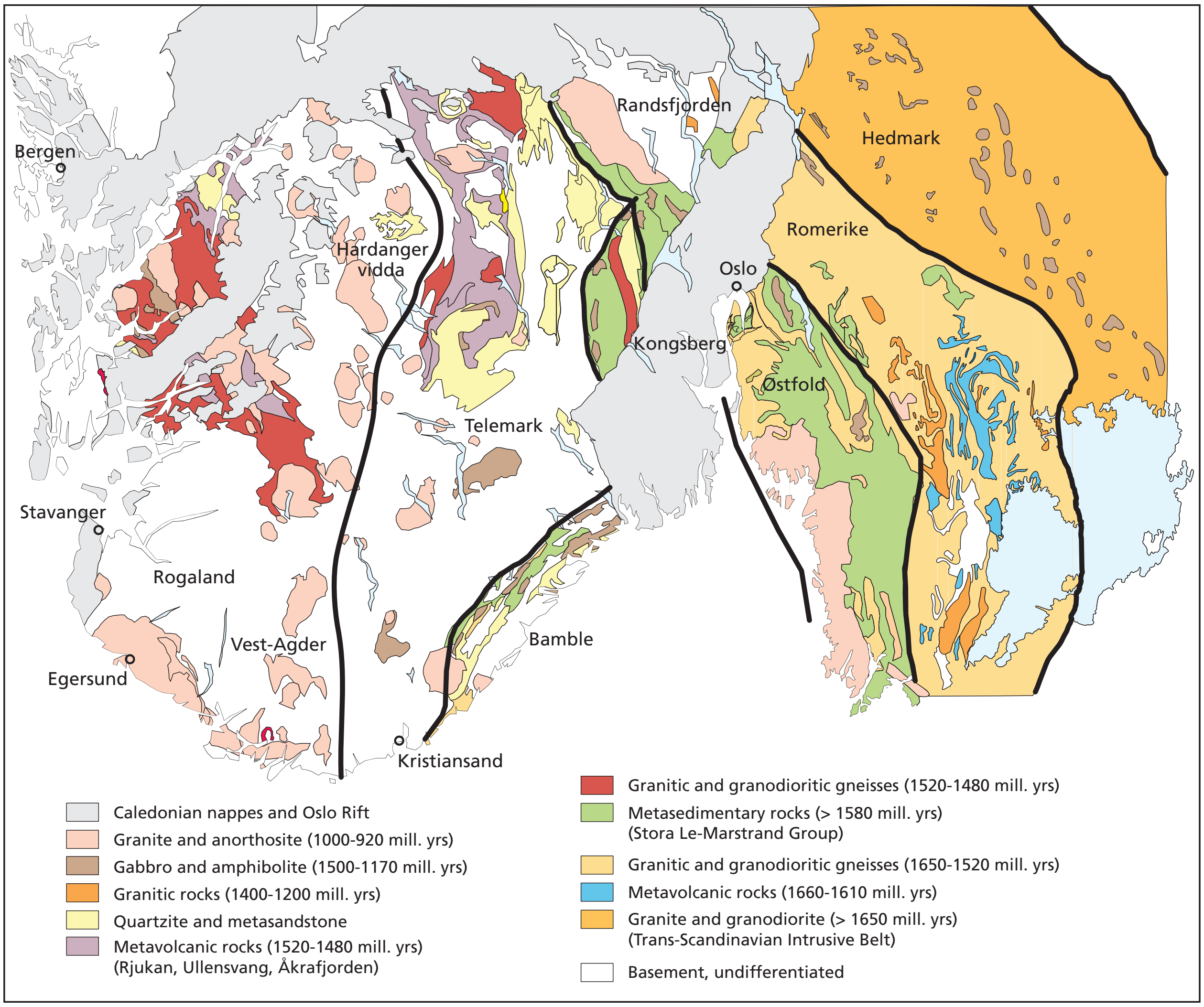
Hedmark – basement along the Swedish border

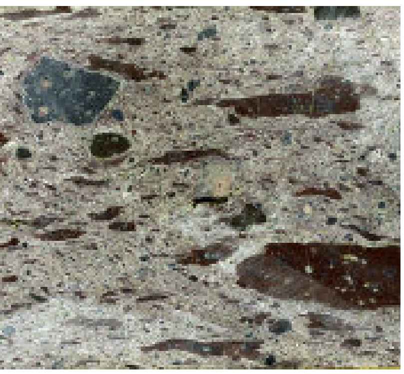
East of Lake Mjøsa, a broad zone of granites and volcanic rocks (the Trans-Scandinavian Intrusive Belt) abuts against older Svecofennian rocks in Sweden. The barely 1700 million-year-old Trysil Granite belongs to this belt. It is often referred to as the "tricoloured granite" because parts of it contain minerals with three colours, red K-feldspar, greenish plagioclase and bluish quartz. The Odal Granite that crops out over large areas north of Storsjøen (a lake 70 km northeast of Oslo) is similar, and the same type of granite is found in basement windows in the Caledonian mountain chain furthest north in south-east Norway. Rhyolitic and more basic lavas are common in Trysil and mark the westernmost extension of a vast area of lavas in Dalarna in Sweden. These lavas are often developed as porphyries, and are intermingled with rocks formed following tremendous eruptions of red-hot pumice fragments and ash, like those which buried Herculaneum and Pompeii.

Lava and ash from large volcanoes were dispersed along the margin of the Fennoscandian Shield still further west in Hedmark. These volcanics were the precursors of fine-grained, reddish-pink gneisses that occur in Solør and further west towards Mjøsa. Gold has been found in quartz veins in these areas, and the first goldmine in Norway opened at Eidsvoll in 1758.

Many narrow zones of greenstone, metarhyolite, schist and quartzite (the Kongsvinger Group) occur in a belt stretching south-eastwards from Mjøsa in the direction of Kongsvinger. The Kongsvinger Group also occurs elsewhere in eastern Hedmark. Some of its quartzites here contain the bluish mineral, lazulite, a hydrous magnesium-aluminium phosphate. The age of the volcanics is uncertain, but they are older than many large and small bodies of gabbro, which are a characteristic feature of the bedrock in southern Hedmark. These plutonic rocks are hard and resist erosion, and therefore form ridges and rounded hills with better soil and vegetation than occur on the granitic gneisses surrounding them. The gabbros are 1570–1470 million years old and date from the late phase of the Gothian orogeny.

A simplified geological map of south-western Scandinavia. The map focuses on the oldest rocks in the basement. Several parts of southern Norway (not differentiated on the map) have rocks which are at least as old.





Ignimbrite from Flendalen in Trysil, scanned on a polished stone. This volcanic rock was formed by the welding together of dark pumice fragments and ash.
(Photo: J.P. Nystuen)

The Trysil sandstone – an exotic element in the basement

In eastern Trysil in Hedmark, and extending into Dalarna in Sweden, the bedrock consists of dark, reddish-violet sandstone with scattered conglomeratic horizons. This is the Trysil sandstone, known in Sweden as the Dala sandstone. This very little metamorphosed unit occupies a 50-60 km-broad, trough-shaped fold and is clearly demarcated from underlying, older, partially deformed porphyries. In several places, the base of the formation is variegated, fluvial conglomerate containing pebbles of porphyry and agate. The Trysil-Dala sandstone was deposited on vast alluvial plains and in scattered, shallow lakes. The sandstone is famous for its very well-preserved ripple marks. A layer of basalt shows that the sedimentation was periodically interrupted by volcanism, and the sandstone sequence is cut by broad dykes and sills of dolerite. The formation is probably 1500-1300 million years old. During that period, the rocks underlying the Trysil sandstone were exposed at the surface, weathered and eroded. The large, trough-shaped syncline was produced by weak Sveconorwegian deformation of the sandstone formation and the underlying porphyries. The folding is strongest in the west, in Norway, and becomes weaker eastwards into Sweden.

Mylonite zones in the basement

The Mjøsa-Magnor mylonite zone stretches from Kongsvinger to Mjøsa, where it vanishes beneath the Caledonian nappes. It is more than 10 km broad east of Mjøsa, and the degree of mylonitisation and foliation of the granitic gneisses varies both along and across the zone, which continues south-eastwards into Sweden. It arose through sinistral movement between the gneisses in Solør and Ringerike, which probably culminated in Sveconorwegian time. The Ørje mylonite zone probably had a similar history. The rocks along the several-kilometre-wide zone are partially transformed into mylonites and phyllonites.

GNEISS-FORMING PROCESSES DEEP IN THE CRUST

By Ane Engvik

Most of the Precambrian rocks in Norway were metamorphosed at a great depth in the crust. Dark rocks like gabbro and basalt are metamorphosed to amphibolite and eclogite under high-grade metamorphic conditions, while light-coloured rocks (granitic and sedimentary rocks) form gneisses. Gneiss is the most common rock in the Norwegian basement. Orthogneisses are formed from magmatic rocks and paragneisses from sedimentary rocks. In addition, gneisses are given names based on characteristic minerals occurring in the rock, hornblende gneiss, for instance.

When gneiss is heated to more than 600 °C, the light minerals, quartz and feldspar, begin to melt and migmatite forms. Migmatite is a banded or streaky rock where the melted material has solidified as light-coloured granitic layers while the host rock is preserved as dark layers. If the melting is unusually intense, the light material may migrate from its original location and solidify as pegmatite in wide, very coarse-grained dykes.

The minerals occurring together in a rock are determined by temperature and pressure, and this tells us how deep the rock has been in the crust. Granulite is a rock found in most basement areas in Norway. It mostly consists of the minerals pyroxene, plagioclase and garnet, and forms at temperatures in excess of 800 °C. Eclogite, which consists of red garnet and the green pyroxene omphacite, forms at a great depth when the crust is depressed during an orogeny. In Norway, eclogites are found in the Western Gneiss Region and in the nappes along the Caledonian mountain chain. The Norwegian eclogites were formed during the Caledonian orogeny at a depth of more than 60 km. Some eclogites contain small inclusions of coesite, a mineral strongly suggesting that the crust was pressed down to more than 100 km.

On the surface, rocks may be found side by side even though they formed at very different depths in the crust, or are completely different in age. Shear zones may cause differential movements that may juxtapose rocks formed at different depths in the crust. In such movement zones, the grain size in the rock is reduced, and finely laminated or schistose rock called mylonite is formed.

The photographs show three rocks that occur together in the Western Gneiss Region. The uppermost photograph shows a granulite with alternating dark and light bands formed during the Sveconorwegian orogeny. The dark layers in the middle photograph were transformed into eclogite and mixed with light-coloured quartzite at a depth of 60 km in the root of the Caledonian mountain chain. The lowermost photograph illustrates the banded gneiss that formed during the subsequent uplift, folding, flattening and metamorphism of the eclogite and quartzite. (all photos: A. Engvik)

ABOVE: Mylonite from the Mjøsa-Magnor mylonite zone east of Lake Mjøsa. (Photo: G. Viola)

BELOW: Metasedimentary rock composed of light-coloured layers of metasandstone alternating with darker layers of mica schist. The vertical beds were originally horizontal and were deposited in a marine basin near the Fennoscandian Shield 1600–1500 million years ago. Photograph taken at Veme, west of Hønefoss. (Photo: Ø. Nordgulen)

Remains of a Gothian subduction mountain chain in southern Norway

The landscape in the basement areas in southern Hedmark, Østfold, Akershus, south-eastern Buskerud and the Bamble district in Telemark is dominated by forested, rounded hills. Rivers and lakes follow rectilinear depressions and valleys where faults and zones of weakness have made the bedrock more prone to weathering and erosion.

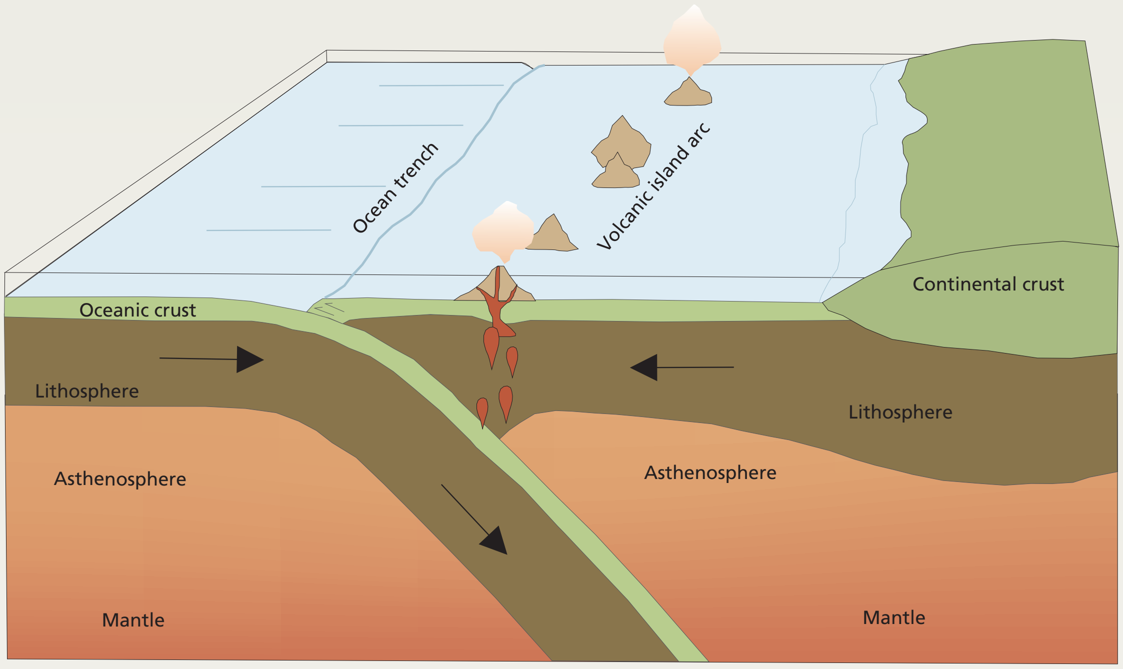
The rocks in these areas were formed and deformed when the Gothian mountain chain arose. Granitic gneisses whose ages range between 1660 and 1500 million years occur widely, but metamorphosed volcanic and sedimentary rocks are also common. The bedrock in the area was metamorphosed and deformed during the Sveconorwegian orogeny about 1000 million years ago. This transformation took place at such high temperatures that partial melting with formation of migmatites occurred in many places.

The oldest rocks are found in the Romerike district, east of the Ørje mylonite zone, and north-westwards to the area around Randsfjorden on the west side of the Oslo Rift. Common rocks are grey, biotite-rich gneisses and mica schists, and smaller amounts of amphibolite and hornblende gneiss. These are mostly metamorphosed supracrustal rocks which, in many places, are intruded by plutonic rocks of tonalitic to granitic composition. Porphyritic granite that occurs over a large area of Vestre Toten has been dated to 1610 million years.

Younger plutonic rocks with ages of around 1555-1500 million years occur west of the Ørje mylonite zone in the area flanking Oslofjord, in Bamble and in the Kongsberg district. They show great variations in composition from dark gabbro to light-grey and reddish, porphyritic and equigranular granitic gneisses. Many plutonic rocks have properties that favour their use as crushed rock and building raw materials, and dioritic rocks near Feiring and gneisses at Vinterbro are used for these purposes today. The supracrustal rocks in these areas also have various features in common, which suggests that the crustal blocks in south-eastern Norway were connected late in the Gothian orogeny.

The Gothian mountain chain probably arose when oceanic crust sank beneath the south-western margin of the Fennoscandian Shield, perhaps over a period of more than 200 million years. Island arcs with high mountains and rows of volcanoes formed in the convergence zone between the lithospheric plates, while lava and ash were extruded in ocean basins. In periods when erosion took place, thick successions of immature, sandy and silty sediments were deposited, probably with the addition of sediments derived from the erosion of older rocks on the Fennoscandian continent in the east. The best-known deposits of this type are the Stora Le-Marstrand Group, represented by metasandstones and mica schists, which crop out over large areas in Østfold and southern Buskerud. The granitic gneisses were originally rocks that solidified in deep parts of the volcanic island arcs.

CRUSTAL FACTORIES ALONG SUBDUCTION ZONES



The geological conditions in southeast Norway in an early phase of the development of the Gothian mountain chain can be compared with the situation along the Pacific Ocean margin today. The island arc was located on ocean floor crust where thick volcanic and sedimentary strata were deposited. The subduction zone and the volcanic activity gradually moved to the edge of the continental crust and the rocks in the island arc accreted onto growing continental crust. A situation developed that can be compared with that on the west coast of South and North America today, where new crust is being formed from magma that solidifies as plutonic rocks in the continental crust or reaches the surface to form volcanic rocks.

When an ancient ocean floor plate descends into the mantle beneath a continent, the oceanic crust with the sediments resting upon it will be heated and will undergo an increasing degree of metamorphic alteration. As the pressure and temperature gradually rise, basalts in the ocean floor crust will be transformed into amphibolite and eclogite. This may lead to local melting at depth, either in the descending ocean floor crust or because hot fluids driven out of the crust force their way up into the overlying mantle. This will reduce the melting point and may initiate partial melting in the mantle.

Melted rock from various sources will move upwards. On their way towards the surface, these magmas will also transfer heat that may contribute to melting in the deeper parts of the overlying continental crust. This is how magmas with variable composition can be formed from different sources. These magmas can be mixed and undergo fractionated crystallisation, i.e. the minerals are first crystallised and then removed from the melt, causing gradual changes in its composition. The magmas will either solidify later as plutonic rocks deep in the crust, or they will follow feeding pipes up to volcanoes and flow out on the surface as lava or form violent ash eruptions.

Igneous rocks formed in this type of plate tectonic setting have a distinctive composition that distinguishes them from rocks formed in other settings, such as rift zones. This is a property which the rocks will always retain, and it can be used as a kind of geochemical fingerprint revealing something about their origin, even after they have been deformed and metamorphosed.

This situation exists today in several areas around the Pacific Ocean, where the heavy ocean floor crust of the Pacific Plate with its overlying veneer of sediments is sinking beneath lighter continental lithosphere. Magmas are being formed along the subduction zone and these are rising and solidifying as plutonic rocks, or breaking out on the surface as volcanoes. Rows of volcanoes line the west coast of South America (the Andes Mountains) and the north-western parts of North America, as well as Japan. Andesite is the most common volcanic rock in these areas, and has a composition close to the average for continental crust. Subduction zones are geologic factories that recycle the Earth's oceanic crust and upper mantle, producing arc magmas and resulting in the formation of continental crust. The residue left after the melting in the subduction zone is returned to the depth of the mantle, completing a cycle that is an important part of the geochemical evolution of the Earth. Chapter 2 includes a summary of plate tectonic development.

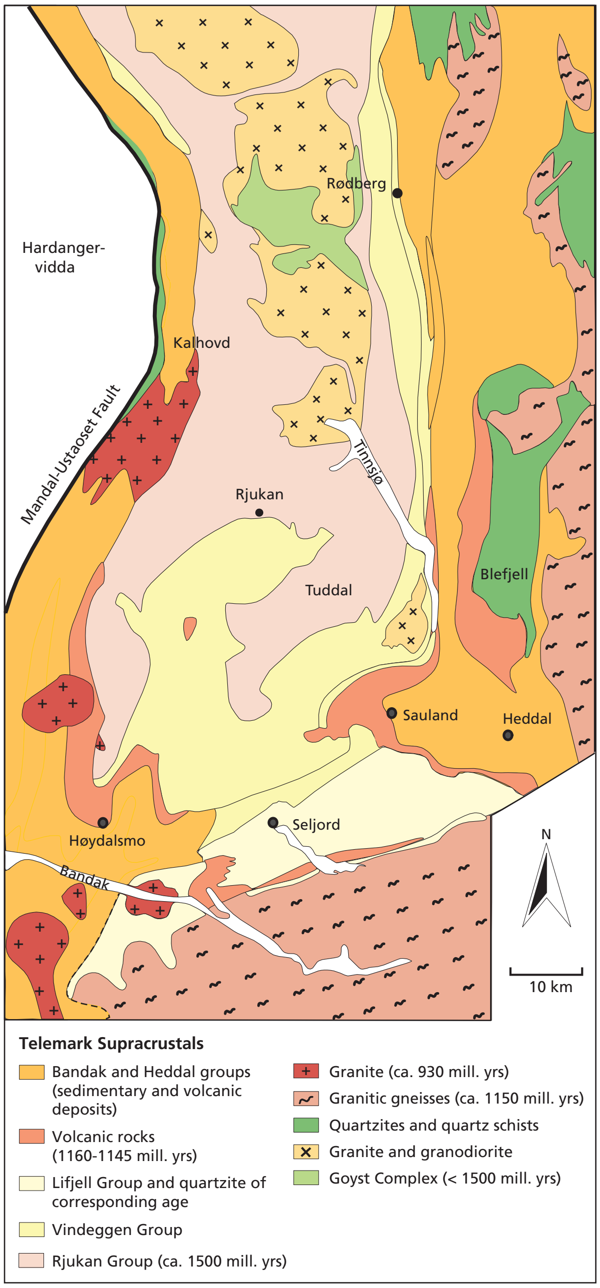
The bedrock in the Bamble-Kongsberg block is known for its many mineral deposits. The iron ores in the Arendal Region were worked from around 1600, and periodically played an important role in the national economy until most of the ironworks ceased production towards the end of the 19th century. The iron oxide, magnetite, occurs in skarn deposits formed in a reaction zone along the boundaries of marbles in the gneisses.

Together with the silver mines in Kongsberg, the Cobalt Mine (Blaafarveværket) in Modum (1776-1898) is one of the best-known enterprises in Norwegian mining history. The cobalt-bearing ore, which occurs in 1500 million-year-old supracrustal rocks, formed the basis for the manufacture of the popular colour, cobalt blue. This pigment was used to make the blue porcelain for which the company was renowned.

The basement in the western part of southeast Norway and in southwest Norway

The bedrock in the basement of southern Norway west of the Bamble-Kongsberg block mostly consists of strongly metamorphosed gneisses. Knowledge of the oldest geological history in many of these basement terranes is still limited. Some of the granitic gneisses may be associated with the evolution of the Gothian mountain chain described above. Metamorphosed plutonic rocks that are 1650 million years old are found on Hardangervidda. They are accompanied by quartzites and other metamorphosed sedimentary rocks. Similar quartzites are also found in the valley of Hallingdal; they are formed from material eroded from Proterozoic and Archaean rocks. The most likely source area is the Fennoscandian Shield in the east. Remnants of ancient crust are also found in various gneisses and granites in southern Norway. Detailed geochemical studies suggest that they originated from older Palaeoproterozoic source rocks that may still exist at great depth in the more than 30 km-thick continental crust in southern Norway.

Clear evidence exists of several episodes of post-Gothian magmatic activity and crustal extension in southern Norway. One of these episodes occurred roughly at the end of the Gothian orogeny about 1500 million years ago. Igneous rocks that occur over large areas of inner Hordaland, Rogaland and Telemark (see below) were formed at this time. Weakly metamorphosed volcanic and sedimentary rocks were deposited on the ancient gneissic basement in various periods from about 1500 to 1100 million years ago. These rocks are particularly well preserved in Telemark, where they were studied already in the early 19th century. The succession therefore became known as the *Telemark supracrustals*; the term “supracrustal” means rocks that have their origin in deposits on the surface of the Earth, as sediments or volcanics (both lava and ash deposits). Similar supracrustal rocks are also known on several parts of Hardangervidda and in inner Rogaland and Hordaland. We will first look in more detail at the Telemark area.



Geological map of parts of Telemark and Numedal. The stratified supracrustal rocks have been folded one or more times, which explains why the boundaries between the various rock types are arcuate on the map. The youngest granites cut the boundaries between the older strata.

Rhyolite from the Rjukan Group north of Heddersvatn. The original layering is distinct. (Photo: S. Dahlgren)

Telemark – evidence of ancient landscapes

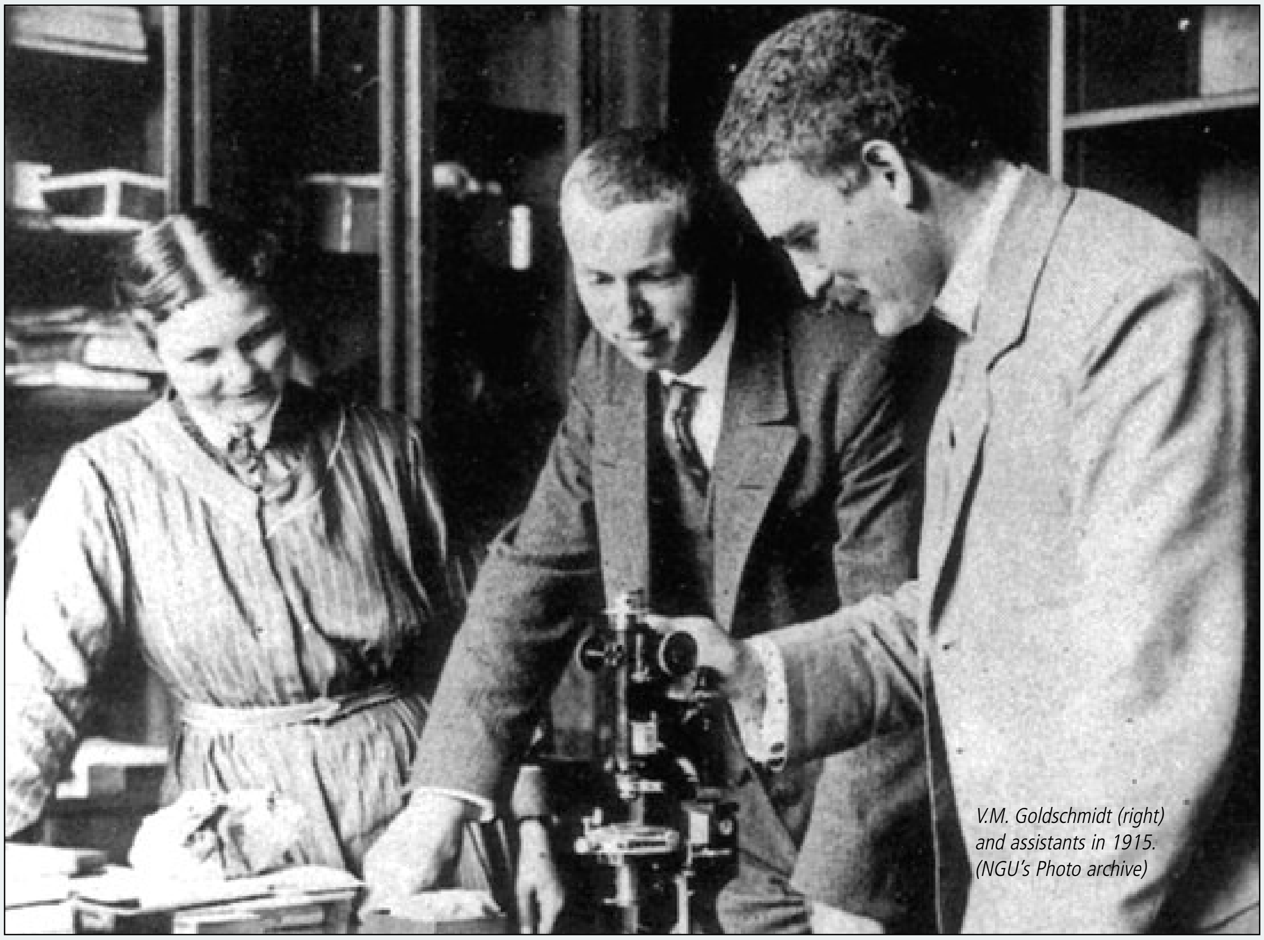
The Telemark supracrustals are divided into four main units: the Rjukan Group (oldest), the Vindeggen Group, the Heddal Group and the Bandak Group (youngest). Together, these can be traced in an approximately 100 km-wide belt stretching from central Telemark northwards until they disappear beneath the Caledonian nappes. A major fault, the Mandal-Ustaoset Fault, demarcates the area of sedimentation from Hardangervidda in the west.

The oldest part of the Rjukan Group consists of a thick succession of rhyolitic lava and *pyroclastics*, which are debris derived from explosive volcanic eruptions and include fragments of lava and of the older rocks adjacent to the volcanoes. This is the Tuddal Formation. Basaltic lava becomes more common higher in the succession, and alternates with conglomerate and sandstone to form the Vemork Formation. The basalts may possibly be younger than the rhyolites and instead belong to the oldest part of the Vindeggen Group. In several places, the basaltic rocks have given rise to till that is rich in nutrients and produces good soil for forestry and agriculture.

Whereas the basalts derive from melting in the mantle, the magma that gave rise to the silica-rich rhyolites originated in the lower part of the continental crust. The chemical composition of the rhyolites may indicate that the volcanic rocks in the Rjukan Group were deposited in a rift valley, or a system of rift valleys. The volcanic activity lasted 10-15 million years about 1500 million years ago, and conditions may have resembled those along the Great Rift Valley in East Africa today. Faulting created deep rift valleys where volcanoes spewed out lava and ash which, along with gravel, sand and mud on alluvial plains and in lakes and shallow-marine bays, gradually filled the grabens. High ground flanking the rift consisted of older gneisses uplifted by the faulting.

VICTOR MORITZ GOLDSCHMIDT (1888-1947)

By Inge Bryhni



V.M. Goldschmidt (right) and assistants in 1915. (NGU's Photo archive)

As chairman of the Norwegian Committee for Raw Materials from 1917, Goldschmidt was involved in the exploitation of geological resources such as dunite from Sunnmøre as a raw material for refractory materials and moulding sand that did not cause silicosis. He also considered ilmenite from southernmost Norway as a raw material for the pigment, titanium white, production of aluminium from anorthosite in inner Sogn, and the use of Norwegian minerals that are rich in potassium and phosphorus to manufacture fertilisers. Many of these proposals which Goldschmidt and his colleagues at the Raw Materials Laboratory put forward eventually led to economic utilisation.

However, what made Goldschmidt the internationally best-known Norwegian geologist was his outstanding contributions to the development of geology as a science. He began with petrology, where he explained contact metamorphism in the Oslo Region and plutonic rocks in the Caledonian mountain chain. He then flung himself into crystallography and revived it by employing X-rays to determine structures, and finally made a name for himself as the "father of geochemistry". Outside Norway, his memory is honoured by the awarding of the prestigious Goldschmidt Medal and the holding of annual Goldschmidt Conferences around the world.

When he was only 23 years old, Goldschmidt received his doctorate for a 482-page book on the alteration of older rocks through contact with the hot magmas that had intruded the Oslo Region. He later became engrossed in the regional metamorphism and magmatic rocks of the mountain chain. He classified the latter in a number of "tribes", a form of grouping which subsequently received more thorough explanation in plate tectonic contexts. He began to use X-ray techniques on geological material, and 20 of his works from this period dealt with studies of the crystal structure and crystal chemistry of minerals, and mineralogy in general. His contribution to geochemistry gave him particularly high international status.

He began using spectrographic techniques to perform chemical analyses of minerals and rocks at an early date, and worked out laws for their natural occurrence. His major works were the nine-volume *Geochemische Verteilungsgesetze der Elemente* and *Geochemistry*, the latter being published after his premature death. In his geochemical contributions, he estimated the relative frequency of the elements and their occurrence in the universe, showing that the size of the atoms determines in which minerals they occur, and that physical properties like hardness and lustre are determined by the distance between the atoms and their charges.

Towering to a height of 1883 m a.s.l., Gaustatoppen is the highest mountain in southeast Norway. The bare upper slopes of the mountain consist of hard quartzite that is poor in nutrients and is metamorphosed ripple-marked sandstone, originally deposited in basins close to sea level. (Photo: S. Dahlgren)

Quartzite with ripple marks formed on a sandy shore more than 1200-1300 million years ago. Vindsjåen, Telemark.
(Photo: S. Dahlgren)

A number of large bodies of granite and gabbro are found along the central part of the belt of Rjukan Group rocks. The Tinn Granite at the northern end of the long, narrow lake, Tinnsjøen, is approximately 1476 million years old, somewhat younger than the volcanic rocks in the Tuddal Formation. Several other granites, near Gol for example, are of about the same age and show that, shortly after the volcanic eruptions, huge volumes of magma intruded the volcanic deposits, solidifying at depth to form large plutons.

Similar volcanic rocks to those in the Rjukan Group are found further west, in Hardanger and Sunnhordland, for example. Metamorphosed rhyolite (the Jåstad Formation) in the Ullensvang Group has been dated to 1489 million years, and volcanic rocks in Skånevik and Suldal have given about the same ages (1491-1496 million years). In addition to this volcanic activity, a number of plutonic rocks simultaneously intruded the crust in south-western Norway.

A quiet episode

The dramatic period of volcanism was succeeded by a quiet episode when the rift landscape was eroded. Gradually, southern Norway became covered by shallow sea and the volcanic strata were overlain by quartz-rich sand deposited on fluvial plains and in shallow-marine basins. These sand deposits now form thick beds of quartzite in the Vindeggen Group. Like all other quartzites, these are hard rocks, poor in nutrients and producing poor soils like those in the upland areas around the peaks of Gaustatoppen, Blefjell and Norefjell. The contrast to the areas of basalt in Telemark is striking.

The Vindeggen Group is younger than the approximately 1500 million-year-old Rjukan Group volcanics, but was buried, folded and metamorphosed together with them, and then uplifted and eroded before being covered by about 1150 million-year-old lava flows. This *unconformity* shows that a substantial interval ensued from the deformation and metamorphism of the older deposits until new crustal extension, fracturing, volcanism and renewed sedimentation occurred in Telemark.

New periods of crustal extension and volcanism

Before this final event in Telemark, sediments and volcanics were deposited near Sæsvatn and Valldal, on the south-western part of Hardangervidda. The succession in Valldal consists of quartzites, volcanic rocks and metamorphosed sandstones and shales that were deposited on 1480 million-year-old basement gneisses. An age determination performed on zircon from metamorphosed rhyolitic lava gave a cooling age of 1260 million years. At Sæsvatn, supracrustal rocks are preserved in a down-folded synform in the basement. The oldest part of the succession belongs to the Breive Group (1265-1275 million years old), which consists of metamorphosed rhyolite and amphibolite. The Skyvatn Group rests unconformably on the Breive Group, showing that a period of tectonic activity separated their deposition. The Skyvatn Group consists of alternating layers of metamorphosed basalt and sandstone. Dating of zircons from sandstone uppermost in the succession shows that it must have been deposited less than 1210 million years ago. This is the only area in southern Norway where supracrustal rocks from this period are known to be preserved.

In Telemark, a new phase of crustal extension, development of rift valleys, volcanism and sediment accumulation began 1155-1145 million years ago. Bedrock from this period mainly occurs in two areas, Bandak in the west and Heddal in the east. The Bandak Group and the Heddal Group consist of alternating volcanic (rhyolite and basalt) and sedimentary (quartzite, sandstone, conglomerate and breccia) rocks. The quartzite and sandstone on the mountains of Lifjell and Blefjell were probably deposited in shallow-marine areas over a comparatively short period. Approximately simultaneously, 1147 million years ago, magma solidified at depth to form the Hesjåbutind gabbro in the quartzites near Gaustatoppen. Many gabbro sills, varying in thickness from one metre to almost a kilometre, are found in the Rjukan and Vindeggen groups.

Sandstones higher up in the Heddal and Bandak groups are younger than 1120 million years. The very youngest deposits are sandstones at Kalhovd. These were deposited less than 1065 million years ago. At Kalhovd, basement gneiss is overlain by conglomerate containing large, angular clasts derived from its substrate.

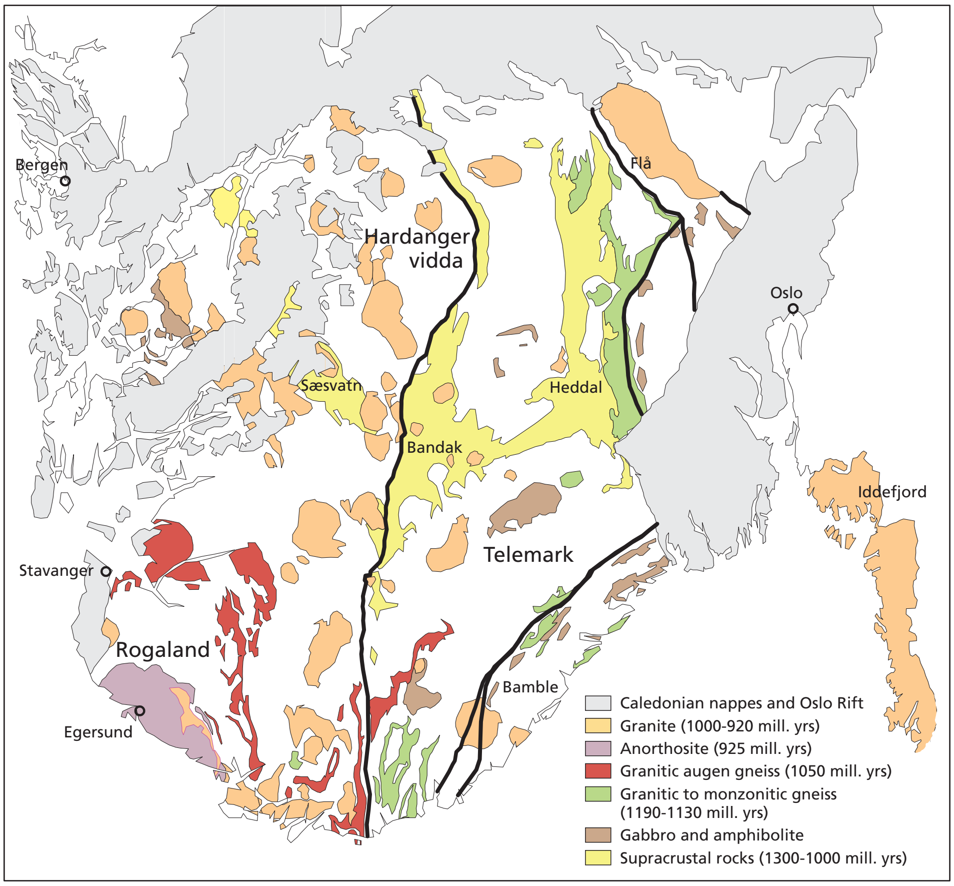
The Sveconorwegian mountain chain

The Sveconorwegian mountain chain has been referred to on several occasions in this chapter, and will be summarised in more detail here. This orogenic belt is at least 500 km wide and developed from 1130 to 970 million years ago, when plates collided west of the Fennoscandian Shield, as it had been formed following the Gothian orogeny. The crustal blocks in southern Norway were displaced laterally during these movements and adhered to blocks of predominantly Gothian origin along the western margin of the Fennoscandian Shield. The Sveconorwegian mountain chain was probably part of a larger, continuous system of orogenic belts that extended through parts of Greenland into North America, where it is called the *Grenville orogenic belt.*

High-pressure and high-temperature metamorphism began first in the Bamble-Kongsberg district 1130-1100 million years ago, suggesting the presence of an early collision zone in this area. The rocks in the Bamble area were then thrust north-westwards over the inner Telemark rocks along the Porsgrunn-Kristiansand shear zone. This event was approximately coeval with the formation of the Heddal and Bandak groups. The rocks in inner Telemark must therefore have been close to the surface at the same time as those in the Bamble area were being metamorphosed far down in the crust.

In the later part of the evolution of the orogenic belt, the rocks over large areas were metamorphosed and deformed, most strongly in the west and south and apparently with decreasing intensity towards the east or northeast. In south-western parts of the basement (the counties of Rogaland and Vest-Agder), high-grade metamorphism took place 1030-970 million years ago, that is 100 million years later than in the Bamble-Kongsberg district. Eclogites are found in western Sweden that formed at a great crustal depth through continental collision about 970 million years ago when the orogeny reached its peak and the crust in south-western Scandinavia was probably much thicker than it is today. Afterwards, the crust was gradually uplifted and cooled, and slowly returned to its normal thickness.

Erosion boundary (unconformity) between coarse conglomerate (Kalhovd Formation) with large, angular clasts (uppermost) and banded gneiss with several generations of granite and pegmatite veins (below). This shows that the gneiss was uplifted to the surface and was overlain by the conglomerate more than 1000 million years ago. Strengen, Kalhovd, Telemark. (Photo: S. Sigmond)



Simplified map of southern Norway focusing on the Sveconorwegian mountain chain. The most important types of plutonic rocks are grouped according to their age. The blank areas on land indicate bedrock older than 1300 million years; e.g. older than the Sveconorwegian orogeny. Black lines indicate major faults.

The plutonic rocks – the interior of the orogenic belt

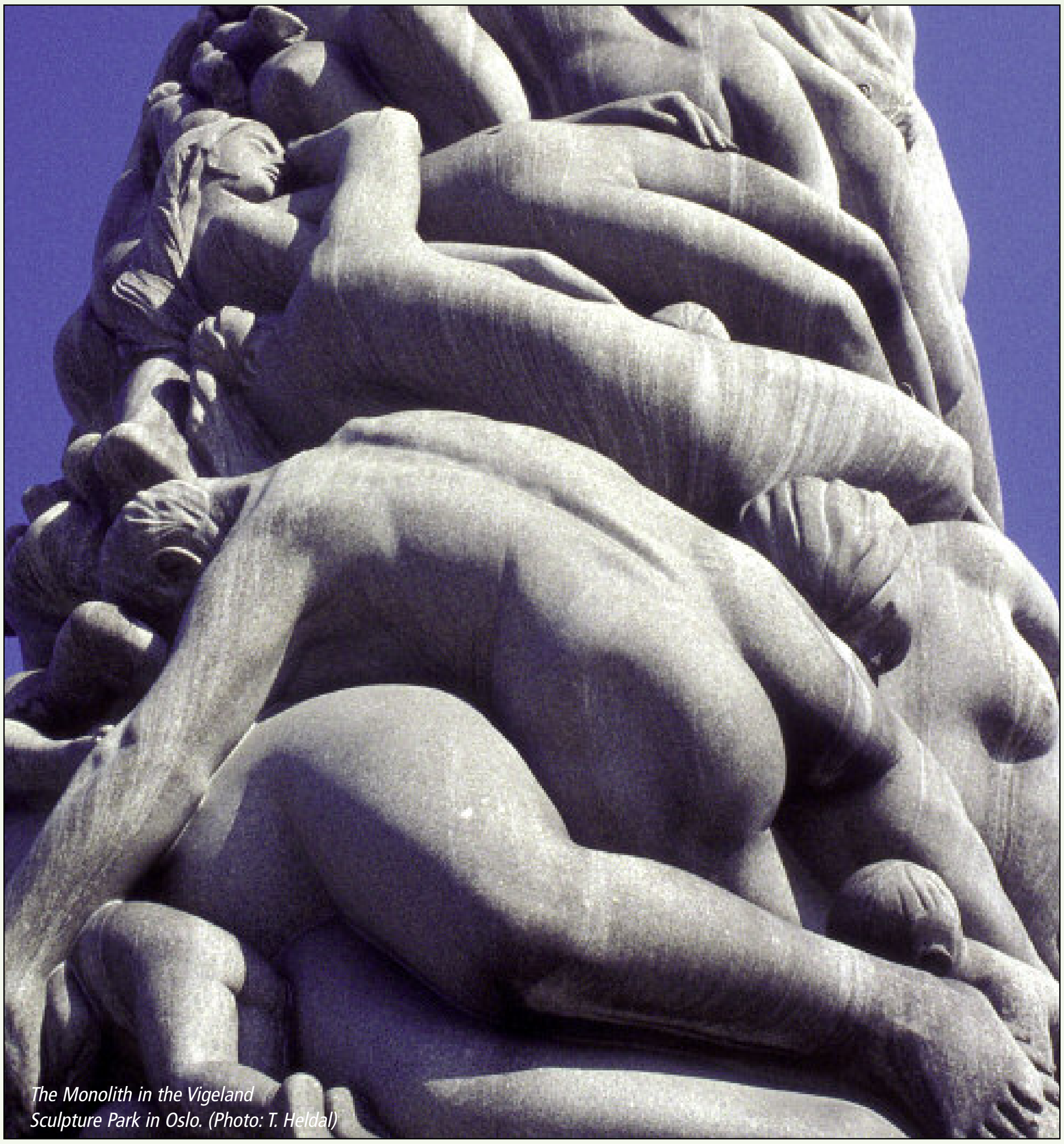
All large orogenic belts have several types of plutonic rock formed from magma rising from the mantle or lower crust. Large and small bodies of plutonic rocks constitute an important part of the bedrock in the Sveconorwegian domain. Several groups can be distinguished on the basis of the age of the rocks, their composition and their geographical location.

Some of the oldest plutonic rocks are almost 1200 million years old and crystallised in an early stage of the evolution of the orogenic belt. The most important ones are, nevertheless, a large number of granites with ages ranging from about 990 to 925 million years, which were emplaced at the end of, or immediately after, the development of the orogenic belt. Some of the largest granite batholiths cover areas of several hundred square kilometres and are concentrated in a belt from the southernmost coast of Norway to Hardangervidda. They also reappear further northwest, in Sognefjord and Sunnfjord, where they form the youngest Precambrian rocks in the Western Gneiss Region. The Grimstad Granite and the Vrådal Granite are well-known representatives of this generation of deep intrusives.

Many kinds of mineral deposits occur in the plutonic rocks. There are many granitic pegmatites near Evje and Iveland in Setesdal, and these coarse-grained rocks contain many rare and beautiful minerals which attract visitors from all over the world. The scandium-bearing mineral, thortveitite, was described for the first time from this area. The molybdenum mines at Knaben in Kvinesdal are also associated with the basement plutons. This ore consists of molybdenite, which occurs as laminae and small, scaly aggregates in the rock. The mining had its golden age in the early 20th century and production ceased in 1973.

The youngest plutonic rocks are not visibly affected by Sveconorwegian metamorphism. This applies especially to the Flå Granite, which occupies most of the mountainous area between Hallingdal and Valdres, and the Iddefjord Granite, which crops out from southern Østfold more than 100 km southwards along the west coast of Sweden. These rocks have remained virtually unchanged since they crystallised some 925 million years ago. They are beautiful to look at, have few joints and good mechanical properties, which is why the Iddefjord Granite has been quarried for many different building purposes. The sculptures in the Vigeland Sculpture Park in Oslo are hewn from this rock, and paving stones of Iddefjord Granite used to be very common.

IDDEFJORD GRANITE *By Tom Heldal*



The Monolith in the Vigeland Sculpture Park in Oslo. (Photo: T. Heldal)

One of the most valued Precambrian rocks in Norway is the Iddefjord Granite, which has been quarried on a large scale, particularly around Iddefjord, ever since the mid-19th century. It was Swedish quarrymen who brought the idea and knowledge across the border from Bohuslän, and around the turn of the century some 5000 men were employed in quarrying paving and building stone. The grey granite is not one of our most exciting types of natural rock, but it has extremely good technical properties. It is easy to cleave in several directions, very large blocks can be quarried and it is extremely durable. These properties led Gustav Vigeland to choose it to fashion his sculptures in Frogner Park in Oslo. For a long time, his Monolith was the largest single piece of rock extracted from Norwegian bedrock, until the Norwegian Embassy in Berlin had an entire wall installed from a single block of granite, that too from Iddefjord. This block is 14 m high, and one side has a natural, ice-polished surface.

In addition to paving Norwegian roads and facing many of the most beautiful buildings in Norway, Iddefjord granite has been widely used over large parts of the world. If you walk around the streets of Buenos Aires or Havana, there is a reasonable chance you will be treading on paving stones (cobbles) from Iddefjord. Important harbours in England, the Netherlands, South Africa, Argentina, Gibraltar, Bermuda and Singapore are built of granite blocks from Iddefjord, as too are numerous prestigious buildings in many countries, including the Ritz Hotel in London.

FROM STONE AXES TO KITCHEN BENCHES: 9000 YEARS OF QUARRYING

By Tom Heldal

Specialised exploitation of resources in the bedrock has taken place as long as people have lived along the Norwegian coast. As long ago as the Early Stone Age, hard, resistant rocks were highly prized as raw materials for arrowheads, axes and knives. This led to what we may call the first Norwegian quarrying industry. One of the most prominent remains from this period is the greenstone quarry on the islet of Hespriholmen, off Bømlo in western Norway. Archaeological studies have shown that this began to be worked nearly 9000 years ago.

In the Bronze Age, people began to realise the value of soft soapstone which can easily be shaped and is also heat-resistant. Soapstone was used for some tools, moulds and fishing sinkers. The fashioning of soapstone cooking pots and vessels began in the Early Iron Age. This marked the beginning of a quarrying industry that would continue for almost 2000 years. A large cooking pot quarry high in the mountains near Kvikne, in central Norway, shows that soapstone cooking pots were mass-produced well before the birth of Christ. This industry reached its peak in the Viking period and the Middle Ages, and we can still see traces of it in several hundred quarries scattered throughout the country.

A number of other useful rock types were utilised in the same period. Soft chlorite-talc schist was worked in 26 quarries in a small area at Ølve in Hardanger, west Norway, to obtain griddles for baking. Querns made from characteristic garnet-mica schist from Hyllestad in Sogn, west Norway, have been found in southern Sweden and large parts of Denmark. These quarries in the Hyllestad district, which were worked from about AD 600 until the beginning of the 20th century, are estimated to extend over an area of nearly 30 km^2. The manufacturing of whetstones also flourished in the Iron Age, and whetstones from Eidsborg in Telemark, southeast Norway, were a particularly important trading item.

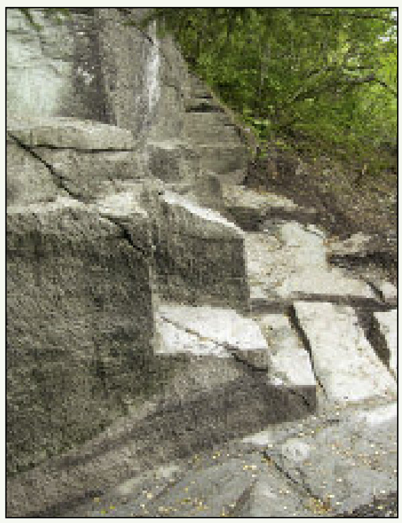
Stone quarried for building purposes did not begin to be used to any marked extent before Christianity reached Norway. When stone churches were to be built, there was a need for coastal sources of easily worked rock, and soapstone once more became a natural material to use, in addition to marble and limestone. Early in the 12th century, large, efficient quarries supplied building stone to the larger towns to build numerous churches, monasteries and convents. Good examples are the old soapstone and chlorite schist quarries in and near Trondheim, which supplied stone to Nidaros Cathedral.

After a long period of inactivity, the building of the Royal Palace in the 1820s started a new boom for Norwegian quarrying. As the 19th century advanced, more and more quarrying took place near Oslofjord, first the Grefsen syenite, then the Iddefjord and Drammen granites, and, about 1880, larvikite. Stone was used extensively for roads, bridges, foundation walls and monumental buildings. Towards the end of the century, many granite and gneiss deposits also began to be worked elsewhere in the country, the flagstone and slate industry became thoroughly industrialised, and marble quarrying started near Fauske in Nordland. Natural stone production in Norway reached a peak at the beginning of the 20th century. Several thousand people in Halden and Fredrikstad alone were employed in granite quarrying.

From around 1930, new construction techniques, together with the predominance of functionalism in architecture, led to a lengthy decline in the Norwegian quarrying industry. It was only when natural materials again became popular in the 1980s that the production of natural stone in Norway recovered once more. The industry now has an annual turnover of around one billion Norwegian kroner, with export of larvikite blocks accounting for most of this, but the production of flagstone and slate in Otta, Oppdal, Alta and Nord-Trøndelag, soapstone in Otta and Troms, and many small quarries throughout the country have now transformed this into a more thriving industry than it has been for a long time. Substantially more Norwegian stone is sold in other countries than in Norway, at the same time as foreign stone is being increasingly used in Norwegian buildings, such as the Opera House in Oslo.

Querns were hewn directly from the rock face in Hyllestad, west Norway.

Undressed blocks remain in one of the medieval quarries worked when Nidaros Cathedral was being built. A medieval soapstone quarry at Bakkaunet in Trondheim, now covered with grass and concrete.

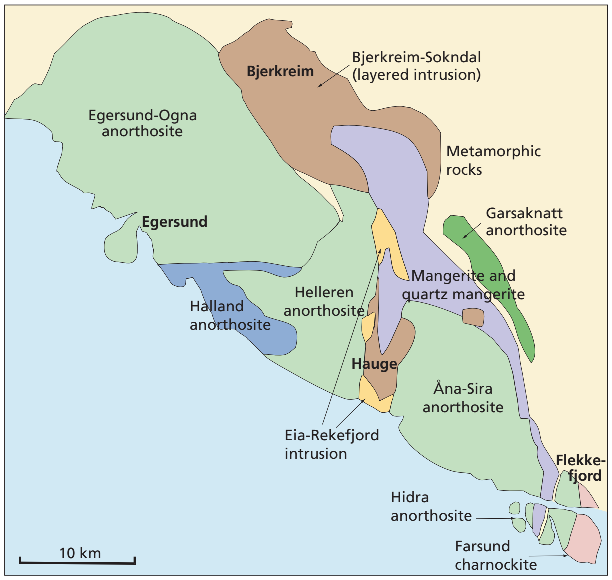


The soft greenschist from a medieval quarry at Øye in Melhus was one of the most important building stones used in Nidaros Cathedral. (All photos: T. Heldal)

Anorthosite landscape in Rogaland. (Photo: G. Meyer)

The anorthosites in Rogaland

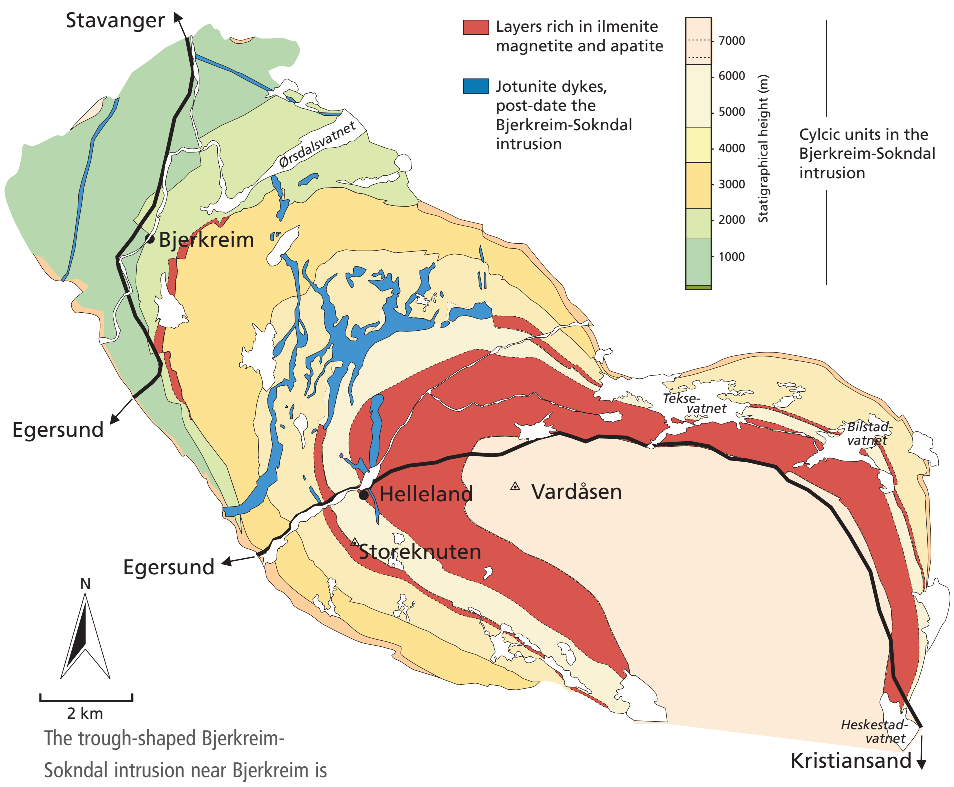
The landscape in south-western Rogaland is characterised by narrow, fertile valleys flanked by steep, rounded knolls and hills with very little vegetation. In 1897, a well-known Norwegian geologist, Carl Fredrik Kolderup, described the landscape thus: "*It is these Labrador rocks which, with their bare domes on which not a scrap of vegetation can be found, in all their frightfulness seem so impressive for a passer-by and leave him with an impression of desolation and barrenness that is difficult to forget.*"



The Rogaland Anorthosite Province consists of two large and several smaller anorthosite bodies. The western part of the Egersund-Ogna anorthosite consists entirely of anorthosite, but some light-coloured norite bodies occur further southeast. The Åna-Sira anorthosite consists mostly of light-coloured norite and anorthosite. In addition, there are small intrusions, mostly comprised of jotunite, mangerite and charnockite.

An area of more than 1700 km^2 from Jæren to Farsund is composed of several large bodies of plutonic rocks known collectively as the *Rogaland Anorthosite Province* (previously known as the Egersund region). Geophysical measurements have shown that the same rocks continue over an equally large area in the North Sea. The bodies consist of several different igneous rocks, mostly anorthosite and norite, but also jotunite, mangerite and granite. Norite and jotunite are special kinds of gabbro, while mangerite is a monzonite, as mentioned earlier in this chapter. The magmas formed by melting of the mantle and the deepest parts of the crust at the very end of Sveconorwegian time and cooled at a depth of many kilometres between 932 and 920 million years ago, at the same time as the Flå and Iddefjord granites in southeast Norway.

Storeknuten, south of Helleland in Rogaland. Note the sharp, oblique boundary between rock containing apatite at the lower left, and rock lacking apatite that stands up as a naked knoll. (Photo: L.-P. Nilsson)



The trough-shaped Bjerkreim-Sokndal intrusion near Bjerkreim is composed of six units which correspond to repeated injections of new magma from depth. Together, these units make up a several thousand-metre-thick succession in which economically valuable minerals like apatite and ilmenite are concentrated in specific layers. Younger jotunite dykes cut the layering in the intrusion. (Drawn by G. Meyer)

The country rocks to the anorthosites consist of banded gneisses, granites and subordinate amounts of quartzite and mica schist. These rocks were deformed and metamorphosed in Sveconorwegian time. The heat emanating from the large masses of crystallising magma spread into the country rocks and resulted in contact metamorphism in a zone stretching scores of kilometres around the intrusions.

Micaceous gneisses, which were originally clay-rich sediments, were partially melted, and here and there a very rare violet mineral, osumilite, occurs, showing that a great deal of heat must have emanated from the anorthosites. The Bjerkreim-Sokndal intrusion is the youngest of these plutons. It is squeezed between the large anorthosites and the country rock in the northeast of the province. There are also several younger, small bodies and dykes of jotunite and mangerite.

The *Bjerkreim-Sokndal intrusion* crystallised from magma that intruded from depth to slowly fill a large chamber in the crust at a depth of about 20 km. The melt gradually cooled, and during repeated alternations of periods of fractionated crystallisation (see Chapter 2) and episodes when new magma entered the chamber, kilometre-thick cyclic units of rock types composed of characteristic minerals built up. The trough shape seen on the map is a result of pressure exerted on the intrusion by the country rocks while the magma was solidifying and cooling.

In periods when no new magma was being supplied, layers of valuable minerals like ilmenite, magnetite and apatite gradually formed. Apatite contains the valuable plant nutrient, phosphorus, and the apatite-rich zones therefore stand out clearly in the landscape due to their lush vegetation compared with areas where the bedrock is poor in nutrients.

FROM ILMENITE TO TITANIUM WHITE *By Odd Nilsen*

Many of the important metals we use are extracted from plutonic rocks. One of these is titanium – the ninth commonest element in the crust. Titanium is found naturally in the minerals rutile (TiO_2), ilmenite ($FeTiO_3$) and titanite ($CaTiSiO_5$). These minerals are first and foremost utilised in the form of titanium dioxide (TiO_2) obtained from rutile or ilmenite. Titanium dioxide gives the best whiteness of all pigments and is employed as a very well-covering, environmentally friendly, chemically durable fill in paint, paper, plastics and rubber. More than 90 % of the world's consumption of titanium is in the form of titanium pigment ("titanium white").

Rogaland has numerous ilmenite and magnetite deposits that are associated with various bodies of norite in the anorthosites. Many of these deposits were first mined as early as the 18th century. Production from Koldal and Blåfjell took place at the end of the 18th century and modern mining started on Storgangen in 1918. Storgangen is an approximately 4 km long, sickle-shaped dyke of ilmenite-rich norite whose width varies from a few metres to about 50 m in its central part.

The rebuilding of Europe after the last war brought a major boom in ilmenite production, and from the beginning of the 1950s it was clear that Storgangen could no longer meet the rising demand for ilmenite concentrate. A great deal of prospecting in the 1950s, including aeromagnetic surveys, was rewarded with the discovery of the Tellnes deposit, which held more than 300 million tonnes of ore containing an average of 18 % TiO_2. The Tellnes ore is linked to a young norite dyke that is more than 2.7 km long and about 400 m broad in its central part. Mining of the ore began in 1960, and large quantities are extracted annually from an opencast mine. Titania A/S is now one of the largest suppliers of ilmenite in the world.

Opencast mine at Tellnes, Sokndal, Rogaland, where Titania AS works ilmenite ore. (Photo: L.-P. Nilsson)

The Jotunheimen and its surroundings – basement derived from far to the west

In many places, basement rocks are predominant elements in the nappes of the Caledonian mountain chain. The Jotunheimen Mountains is the most prominent area containing basement rocks with such an origin. When Baltica and Laurentia collided in the Devonian Period, some 400 million years ago, kilometre-thick sheets of plutonic rocks were torn from the crust and thrust eastwards, perhaps several hundred kilometres from their original location far west in the marginal zone of Baltica (Chapter 7). The rocks in the Jotun Nappe Complex have been thrust across younger, both thrust-transported and autochthonous, Late Precambrian-Ordovician sandstones and shales which overlie autochthonous basement. Fragments of the Jotun Nappes that have survived complete erosion remain as upstanding monadnocks on Hardangervidda, forming well-known landmarks like Hallingskarvet and Hårteigen. Similar thrust sheets are also found further southwest in Sauda and Ryfylke.

Rock detached from deep in the crust

The Jotun Nappe Complex can be divided into an upper and a lower thrust sheet. The lower sheet largely consists of syenites and monzonites that are 1600-1700 million years old, along with younger gabbros whose age is about 1250 million years. These rocks were metamorphosed in the crust at a depth of some 15 km and are characterised by, among other things, the hydrous mineral, amphibole. This grade of metamorphism is called the amphibolite facies.

The rocks in the upper sheet of the Jotun Nappe Complex were metamorphosed in the granulite facies, which means that hydrous, dark minerals like amphibole are no longer present, but instead there is "dry" mafic orthopyroxene, hypersthene. These rocks derive from a depth corresponding to the lower part of the continental crust (20-25 km or deeper). When the Caledonian continents collided, such rocks must therefore have been detached from a great depth in the crust and thrust onto the lower sheet of the Jotun Nappe Complex.

Anorthosite and small amounts of gabbro occur in the upper sheet of the Jotun Nappe Complex. These rocks crop out over large areas in the beautiful landscape around Nærøyfjord in inner Sogn which, together with the Geirangerfjord area, was inscribed on the UNESCO World Heritage List in 2005.

The most important rock types in the north-eastern part of the upper sheet are charnockite, mangerite and jotunite, all of which have hypersthene as the dark mineral. With one exception, a rock dated to approximately 1250 million years, all the bedrock in this part of the Jotun Nappe Complex dates from 1630 to 1660 million years, that is, coeval with the formation of the Gothian mountain chain. Significantly younger dykes and small intrusions of light-coloured granite also occur in inner Sogn. These are of Silurian age and therefore constitute a Caledonian component among the other rocks of the nappe complex.

Already early in the 1900s, small portions of the Caledonian nappes along the coast of west Norway were compared with the Jotun Nappe Complex. The Lindås Nappe in Nordhordland is part of what has been called the Bergen Arcs and consists of rocks of the same type as the Jotun Nappe Complex. The Dalsfjord Nappe in Sunnfjord is another example. Dating work has confirmed that the history of the Lindås-Dalsfjord Nappe can, on the whole, be compared with that found in the Jotun Nappes. It has therefore been assumed that the Jotun Nappe Complex once extended over large parts of southern Norway (Chapter 7).

Basement rocks occur in a number of other Caledonian nappe complexes in southern Norway. Those in the Valdres Nappe Complex and the lower nappe of the Jotun Nappe Complex are of the same type. Further east in northern Gudbrandsdalen and northern Østerdalen, and onwards towards Härjedalen in Sweden, granite, augen gneiss, gabbro, anorthosite and amphibolite occur as basement sheets and slices in a number of metasandstone-dominated nappes. Their primary age is around early Gothian time (1600-1700 million years).

Long before the basement became incorporated in the Caledonian mountain chain, the rocks in these nappe complexes had been deformed and partially metamorphosed during a late stage in the Sveconorwegian orogeny some 950-930 million years ago. In some places, new igneous rocks also intruded the older gneisses. This took place at about the same time as the anorthosites in Rogaland were formed, and large granite plutons crystallised in the basement in southern Norway. The many features they have in common with the autochthonous basement in southern Norway show that the Precambrian rocks in the Caledonian nappe pile are slices detached from deeper parts of a continental crust. This crust was originally formed far west in the Fennoscandian Shield during the Gothian orogeny.

The Sogn area and the Jotunheimen Mountains have hard plutonic rocks which Quaternary glaciers moulded into a beautiful massif with mountain tops, jagged peaks, knife-edge ridges, cirques, deep valleys and lakes. The landscape is illustrated in J.C. Dahl's famous painting, "Fra Stalheim", depicting Nærøydalen in Sogn. The painting shows the view from the summit of Stalheimskleivi above two farms, Brekke and Sivle, looking towards Sivlesnipa (1240 m a.s.l.) and the characteristic summit of Jordalsnuten (937 m a.s.l.) in the background to the right. The white mountains in the background consist of anorthosite, which belongs to the upper unit of the Jotun Nappe Complex. The painting dates from 1842. National Museum of Art, Architecture and Design, Oslo. (Photo: J. Lathion)

The Western Gneiss Region

During the Caledonian plate collision just over 400 million years ago, the Precambrian rocks along the western margin of the Fennoscandian Shield were conveyed down to a great depth, heated, metamorphosed and deformed. Even though Caledonian metamorphism was very intense in places, at least two Precambrian crustal-accretion events can still be recognised in the rocks, the same Gothian and Sveconorwegian orogenies as those which affected the basement south of the central area of nappes.

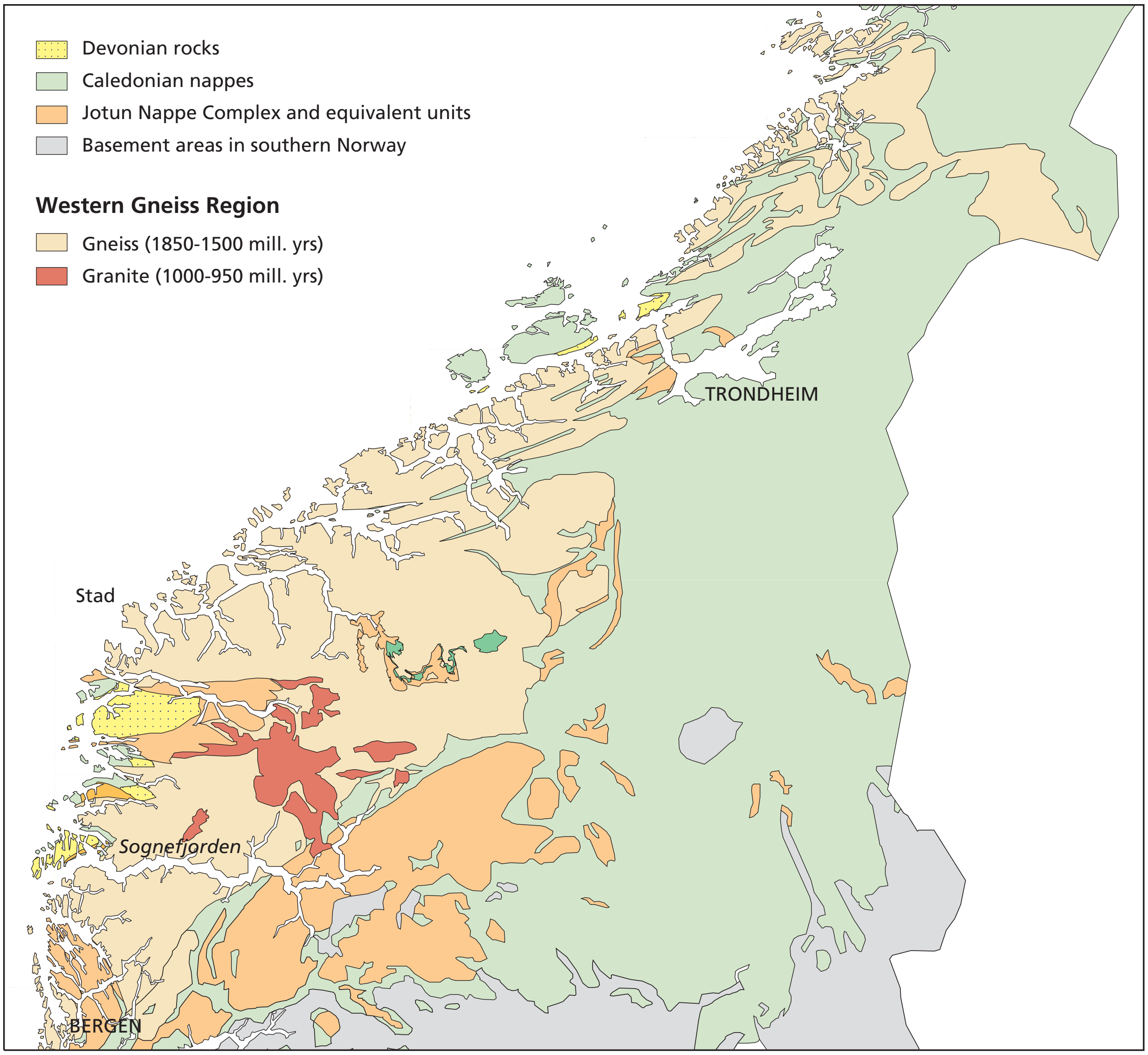
Precambrian rocks, generally referred to as the *Western Gneiss Region*, cover an area of more than 25,000 km^2 west of the Caledonian nappes from Sogn to Nord-Trøndelag. The landscape here varies between high mountains with remains of palaeic land surfaces dissected by peaks, knife-edge ridges, more rounded ridges, precipitous cliffs, valleys and long, deep fjords.

The geological structures in the Western Gneiss Region mostly result from the collision between Laurentia and Baltica when the Caledonian mountain chain was formed. The Precambrian rocks along the western fringe of Baltica were forced down to a great depth in the crust and metamorphosed. Some may have been as deep as 120 km or more, so deep that elements from the upper mantle and the lowermost crust have been incorporated into the rock associations in the gneiss region. The greater part of the Western Gneiss Region consists of granitic gneisses and migmatites formed between 1700 and 1500 million years ago. The bedrock in the southern part of the region was strongly affected by the Sveconorwegian orogeny 1250-900 million years ago. In large parts of the region, it is still difficult to distinguish between originally Precambrian rocks and structures and those of Caledonian origin.

Autochthonous basement or nappes?

Several circumstances suggest that the entire Western Gneiss Region is a nappe complex that was thrust in relation to the Fennoscandian Shield east of the Caledonian mountain chain. In the Grong-Olden district in Nord-Trøndelag, rocks in the northern part of the gneiss region are thrust over gneisses that can be traced into the basement in Sweden. Seismic profiles in Trøndelag show that the basement in tectonic windows in the Caledonian orogenic belt overlie a reflector that corresponds to the top of the basement in Sweden. In outer Trøndelag and Nordmøre, Caledonian nappe rocks are folded deep down into the orthogneisses along zones from the central nappe area in central Trøndelag. Mylonitic rocks displaying strong Caledonian shear deformation show that the boundaries with the gneisses are thrusts. In the Trollheimen Mountains, good examples can be seen of internal thrust boundaries where sheets of gneiss overlain by Neoproterozoic sandstones and conglomerates are piled on top of one another.

The southern part of the Western Gneiss Region is divided into two major complexes, the Jostedal Complex in the east and the Fjordane Complex in the west. The former consists largely of Precambrian migmatites, orthogneisses and granites, whereas the latter resembles deformed versions of Caledonian nappes. Further to the north are large areas and narrow zones of coarsely crystalline marble, calc-silicate rocks and banded amphibolites, kyanite-garnet-mica gneisses, garnet-plagioclase rocks and thinner beds of quartzite and conglomerate. The calc-silicate rocks are assumed to be metamorphosed calcareous sedimentary rocks, while the paragneisses accompanying them are metamorphosed silty sandstones and shales. Even though some of these supracrustal rocks may have been deposited directly on a surface of Precambrian igneous rocks, represented by the adjacent migmatitic orthogneisses, the majority of these



Map showing the general distribution of rocks in the Western Gneiss Region. The Jotun Nappe Complex and other Caledonian nappes overlie the gneisses.
(Map drawn by Arne Solli)

distinctive zones of lithologies are clearly Caledonian nappes.

Granites, gneisses and migmatites in the Western Gneiss Region

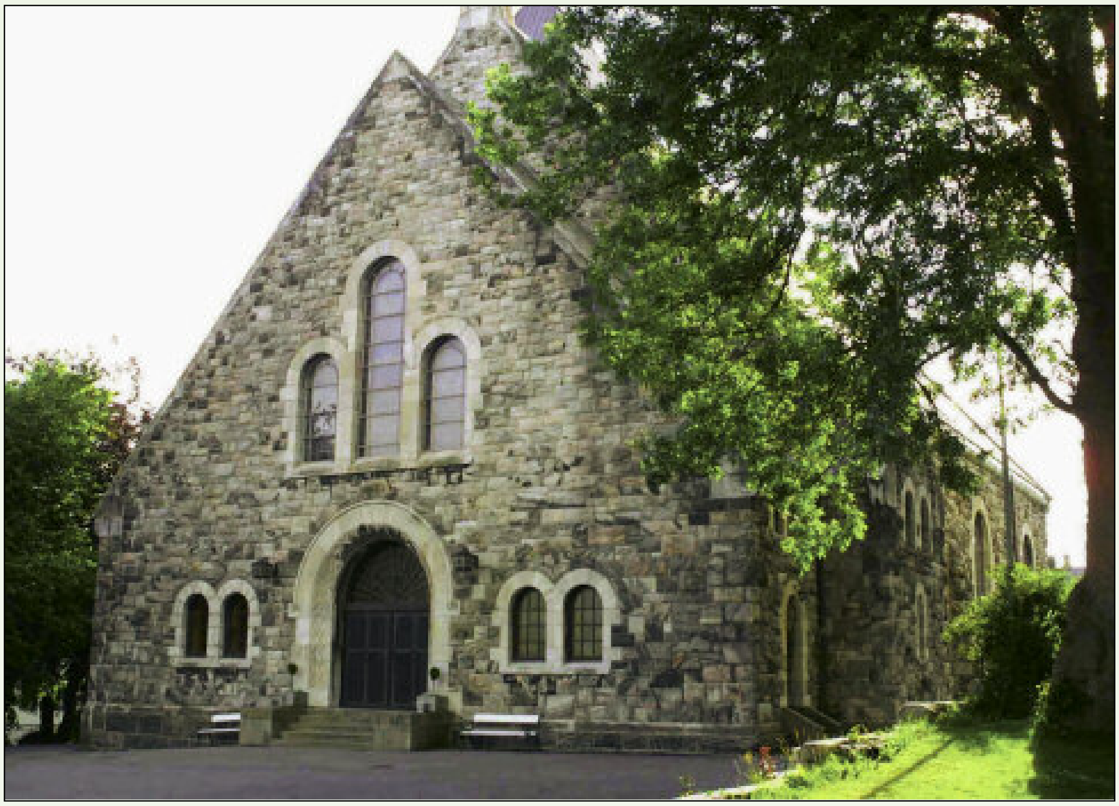
The most important rock types in the Western Gneiss Region are various kinds of granitic gneisses and migmatites which often have lenses and layers of micaceous gneisses and amphibolite.

The oldest rocks known are the Geitfjell Granite near Grong and a tonalitic gneiss east of Vikna in Nord-Trøndelag, which are 1830-1840 million years old. The northern part of the Western Gneiss Region is therefore a continuation of the older portion of the Trans-Scandinavian Igneous Belt in Sweden. Corresponding bedrock is also found in the outer part of the Western Gneiss Region between Molde and the mouth of Trondheimsfjord. Gabbroid gneiss, granitic gneiss, migmatitic gneiss and granite were formed from 1686 to 1653 million years ago.

Plutonic rocks in the southern part of the Western Gneiss Region, which are 1650-1630 million years old, show that new crust was created at that time. This agrees with the evolution in the basement in southeast Norway, where this period was important for the accretion of new crust west of the Trans-Scandinavian Intrusive Belt during the Gothian.

Large and small gabbro bodies are scattered within the Western Gneiss Region, particularly in the area from Nordfjord northwards to Trondheimsfjorden. In a few places, they have a clear dyke form, but subsequent deformation has usually divided them into lenticular inclusions in the granitic gneisses and migmatites. Gabbros at Haram in Sunnmøre show magmatic layering formed in a magma chamber. Their age is between 1650 and 1200 million years.

MARBLE HAS MANY USES *By Inge Bryhni*



Ålesund Church is built of variegated marble with some amphibolite, which often occurs with the marble. Here, the builders have returned to the building practices used in the 12th-century stone churches in the northern part of west Norway. (Photo: I. Bryhni)

White, yellow or red marble generally occurs along with micaceous gneiss and dark amphibolite in "stripes" of metamorphosed supracrustals in the Western Gneiss Region. When there was a demand for beautiful stone for building churches in the 12th century, it was not long before marble occurrences were found in the northern part of western Norway. Stone churches were built wholly or partly of marble in Åheim, Herøy, Ulstein, Giske, the Borgund trading centre, on Veøy and in Tingvoll. Marble was particularly employed for finer details like corners, portals, and window and door posts. The marble was probably transported to the building sites by sea. In Sunnmøre, it may have come from the Larsnes-Breivik area, Ørsta or the Humla-Blindheim-Magerøy area, and in Nordmøre perhaps from Visnes, Nås near Eide or the north side of Surnadalsfjord.

Isotope studies have recently shown that the marble for one of the churches in the former Borgund trading centre in Ålesund may have come from Humla, just across the fjord, the closest major occurrence. Stonemasons hired from other countries shaped the stone into ashlars, which were installed using lime mortar that was perhaps also produced locally. The art of using marble was probably forgotten later, but when Ålesund was to be rebuilt after the town fire in 1904, a thriving stone industry started once more at Eide in Nordmøre. It supplied marble and other kinds of stone for the beautiful buildings in the fire-torn town. One of these was Ålesund Church which, like the 12th-century churches, was built of marble.

No lime kilns were operating when Hans Strøm completed his account of the geography of Sunnmøre in 1766, but marble was slaked in many lime kilns there in the 19th century. More recently, the smelting and cellulose industries, and agriculture, have obtained lime from here, and Hustadmarmor AS, a factory in Elnesvågen, Fræna, has for many years been crushing marble from local quarries and others elsewhere in Norway to manufacture highly refined powder that is cleaned and washed in water to produce slurry. The firm is now the largest manufacturer of such "liquid marble" in the world. The marble slurry is used as fill, white pigment and coating substances in paper, paint and plastics, to lime lakes and rivers, and for agriculture. 99 % of the production is exported and the annual turnover is about 1.8 billion kroner. This book is probably printed on paper containing a great deal of Hustad marble.

WHERE THE BEDROCK ESCAPED CALEDONIAN DEFORMATION *By Inge Bryhni*

Intrusion breccia with angular blocks of the Precambrian bedrock carried up from depth in a dark plutonic rock nicely presented on a wave-washed shore at Farstad. (Photo: I. Bryhni)

Out towards the open Hustadvika, in a district in the northern part of west Norway where Caledonian metamorphism on the margin of Baltica is generally strong, is an area containing plutonic rocks that have almost entirely escaped the Caledonian orogeny. This Hustad Complex has been dated to 1654 million years and consists of reddish granite surrounded by monzodiorite and some pyroxenite. Inclusions of the bedrock which the magma originally intruded occur particularly frequently in the pyroxenite. Here, samples of the basement deep below the present surface have been brought up and laid before us as an intrusion breccia. These samples, or more correctly xenoliths, consist of dark rock types that seem to have been formed by early differentiation from the magma itself (cumulates) and light-coloured dioritic rocks, and in addition granulitic, garnetiferous gneiss which is quite unlike any of the country rocks now known in this area.

A gabbro (or dolerite) dyke, at least 50 m thick and more than 4 km long, cuts the plutonic rocks in the Hustad Complex and has been dated to 1251 million years. The dyke form has been preserved in the country rock that is approximately 400 million years older. This suggests that the numerous lensoid gabbro inclusions in the Western Gneiss Region may once have been transecting dykes that were squeezed out and pinched off to form lenses while the surrounding plutonic rocks were being transformed into gneisses.

A similar process can be recognised along the boundaries of granitic rocks belonging to the Hustad Complex, and in shear zones within them. Here, the massive plutonic rocks have been deformed into gneisses resembling those we see everywhere in the Western Gneiss Region. The undeformed plutonic rocks in the Hustad Complex therefore give us a chance to study the original character of the gneisses.

The jagged peaks between Molladalen and Hjørundfjorden consist of charnockitic rocks, which have produced the dramatic, characteristic erosion forms. (Photo: I. Bryhni)

Charnockites – bedrock in magnificent peaks

The row of peaks flanking the valley of Molladalen, and mountains elsewhere in the area west of Hjørundfjord in Sunnmøre, have been carved out of massive, relatively dark, charnockitic rock with fresh orthopyroxene in the parts least modified by Caledonian events. In several places, the charnockitic granites have a rapakivi texture, with large crystals of dark alkali feldspar rimmed by light-coloured plagioclase. Similar rocks occur near Molde and at Flatraket and Måløy in Nordfjord. Rapakivi granite near Molde has given an age of 1508 million years and syenite at Flatraket one of 1520 million years. These ages show that these intrusions were emplaced in older gneisses after the formation of Gothian rocks in the Western Gneiss Region, at the same time as the large rapakivi granites further southeast in the Fennoscandian Shield.

Several isolated bodies of only slightly metamorphosed, massive anorthosite occur furthest north in Nordfjord and in the southern part of Sunnmøre. Their white colour tends to make them stand out clearly on mountainsides. The most conspicuous one is a particularly coarse-grained variety at Fiskå in Sunnmøre, which has crystals of dark or white plagioclase up to half a metre across, along with some orthopyroxene and ilmenite. Large anorthosites are also known from the Caledonian nappes south of Nordfjord. Metamorphosed anorthosite occurs together with dark, quartz-biotite-epidote gneisses formed by the mylonitisation and metamorphism of syenites and mangerites.

Young granites in the Western Gneiss Region

The southern part of the Western Gneiss Region was strongly affected by both migmatisation and magmatism during the Sveconorwegian orogeny. Granulitic rocks on the islands of Hisarøya in outer Sogn and Bårdsholmen in Sunnfjord imply that Sveconorwegian granulites once cropped out widely in the south-western part of the Western Gneiss Region. Quartzites interfolded with gneisses in Sogn may have the same origin as the more than 1500 million-year-old quartzites on the northern part of Hardangervidda and in Hallingdal. Granite intrusions, dated to 1000-920 million years, occur at Hafslo and Gaupne in Sogn and continue northwards and westwards beneath the Jostedalsbreen ice cap to Nordfjord. The granites are least affected by

View from Litjegrønova (south of Lunde in Jølster) towards the mountains along Nordfjord, west of the Jostedalsbreen ice cap. In the foreground is deformed granite (now augen gneiss) with layers of aplite and a small pegmatite dyke. (Photo: I. Bryhni)

Caledonian metamorphism beneath and southeast of the glacier, and become increasingly deformed towards the west and northwest, where they were transformed into augen gneiss in places.

This distribution of rocks with a Sveconorwegian age or imprint in the southern part of the Western Gneiss Region suggests that the basement in this area is a continuation of the corresponding basement province in south Norway, east and southeast of the central axis of the Caledonian orogenic belt.

Ancient (Archaean?) rocks from the mantle

Hundreds of large and small occurrences of peridotite, dunite and pyroxenite are dispersed over a large area in the western part of the Western Gneiss Region. Owing to their high content of magnesium and iron minerals, these olivine-rich ultramafic rocks are easy to spot in the terrain due to their yellowish-brown weathering colour, or a more reddish-brown surface where they are altered to serpentinite. Place names containing “Raud” (Red) (Raudbergvik, Raudeberg, Raudhammaren, Raudegrot, etc.) reveal the presence of many bodies of ultramafic rock. They generally occur in rows in belts associated with anorthositic rocks, and along shear zones or faults. How and when these hundreds of small and large occurrences of ultramafics in the Western Gneiss Region were emplaced is still controversial. It may have occurred in the Silurian, perhaps after they had been detached from the deeper parts of the crustal plates when Fennoscandia was dragged deep into the mantle during the Caledonian collision phase.

The peridotites and pyroxenites are colourful and very beautiful rocks. The composition of the minerals in garnet peridotite and garnet pyroxenite suggest that they formed under very high pressure in the upper mantle. The rocks give scientists an outstanding opportunity to study rock brought up from the mantle, since they carry information about processes taking place at exceptional depths during and after the Caledonian continental collision.

Shortly after the Second World War, the Norwegian Government commenced dunite quarrying near Åheim in Vanylven, Sunnmøre, and large quantities of dunite are now obtained from deposits in Nordfjord and Sunnmøre. The rock is crushed to sand grade to make moulds for cast-iron production,

VISITORS FROM REALLY GREAT DEPTHS (THE MANTLE) *By Inge Bryhni*

At least 14 of the hundreds of dunite occurrences in the Western Gneiss Region contain remnants of garnet pyroxenite and garnet peridotite, and have therefore to some extent escaped the effects of the Caledonian orogeny even though they were carried down to a depth of more than 120 km. These rocks have proved to have the same radiometric age as the surrounding gneisses, 1686-1653 million years. Model ages calculated from isotope analyses of rhenium and osmium suggest that they stem from a source that is as much as 2700-3100 million years old, and that at any rate some may be fragments of Archaean mantle. Some interesting miscibility textures have also been found which suggest that a mineral (majoritic garnet), which is formed at extreme pressures, once existed in the rock. This high-pressure mineral was formed at a temperature of 1300-1500 °C at a depth of 180-250 km or more, but became unstable and changed into new minerals when the dunite rose closer to the surface.

If all this is correct, the dunites in the Western Gneiss Region carry evidence of processes that began at greater depths and earlier in Earth history than anything we have found traces of in other rocks in southern Norway.

Garnet pyroxenite with orthopyroxene (grey), clinopyroxene (green) and garnet (violet) from Nordøyane, Sunnmøre. The rock contains mineral grains that are partitioned from the high-pressure mineral, majoritic garnet. (Photo: I. Bryhni)

for sandblasting instead of quartz sand which used to give workers the terrible lung disease, silicosis, to manufacture heat-preserving and heat-resistant forsterite, and for several other purposes, such as capping bottom sediment contaminated by industrial heavy metal pollutants.

From crustal accretion to crustal breakdown

In this chapter, we have seen how the basement of the Fennoscandian Shield grew through a series of events involving rifting, intrusion of melts and mountain chain formation over a long period of time, from nearly 3000 million years ago to approximately 900 million years ago. Even though extensive erosion and breakdown of older crustal rocks took place in some periods, the Fennoscandian Shield gradually enlarged and ultimately amalgamated with a number of other shields to form the vast continent, Rodinia, during the Sveconorwegian plate collisions. This gigantic continent began to break up about 850 million years ago, and Fennoscandia was replaced by Baltica as a new continent and plate. The old Fennoscandian rocks were exposed to extensive erosion. This is the topic of the next chapter.

Trollveggen illustrates how active geological processes break down the Precambrian bedrock in the Western Gneiss Region. (Photo: edelpix, P. Eide)