CHAPTER 6

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A huge mountain chain formed along the length of Norway some 400–500 million years ago, transforming the Cambrian Norwegian continental margin into mountainous terrain comparable to the present-day Himalayas. No geological event has made greater impact on Norwegian bedrock than this slow but steady collision between Laurentia and Baltica. Greenstone belts with sulphide ores were formed, half of Norway was transformed into gneiss and schist, distinctive metamorphic rocks like eclogite were formed at depth, and enormous massifs of the crust were detached and moved hundreds of kilometres from northwest to southeast.

Creation of a mountain chain

The building up of the Caledonides: about 500–405 million years

Photo: Piotr Zycki (CAMC, Polen), Lhotse, Nepal

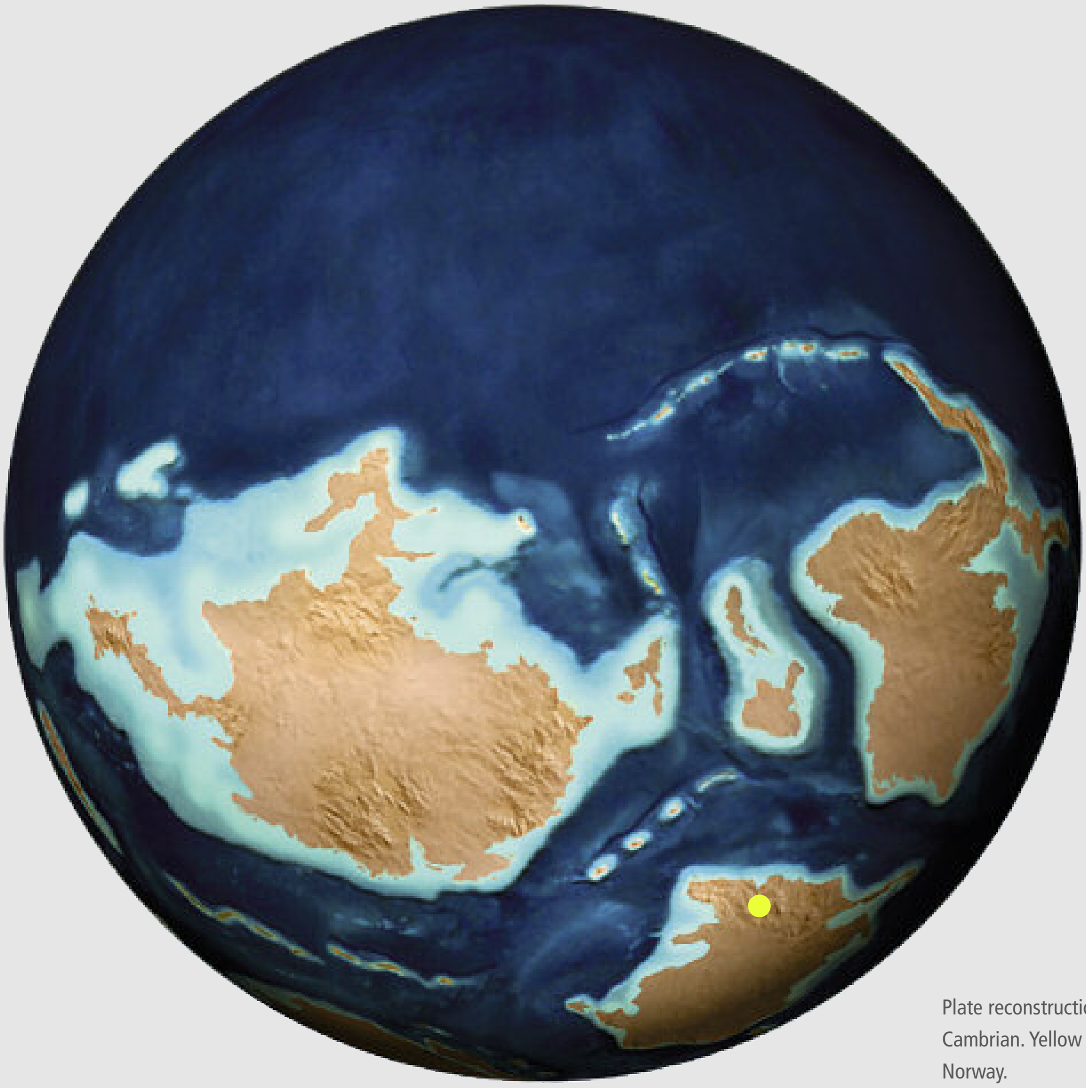


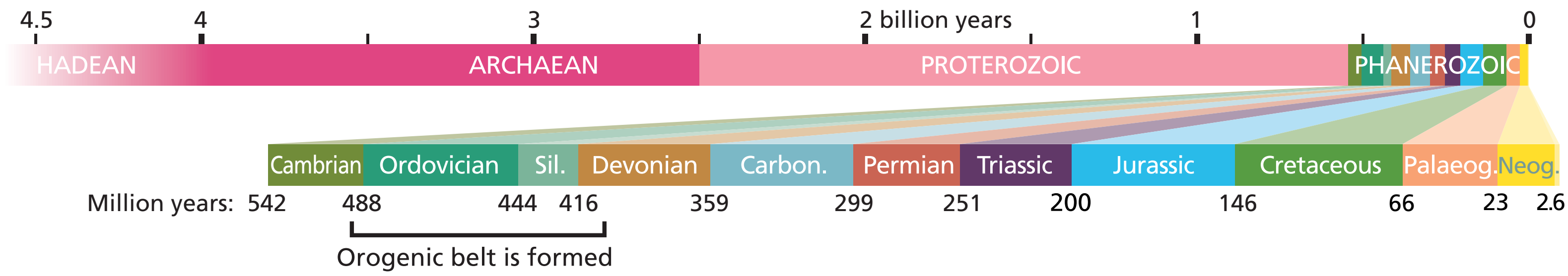
Plate reconstruction for the Late Cambrian. Yellow marks the position of Norway.
(Illustration R. Blakey)

The Caledonian mountain chain
500–405 million years

In the Cambrian, an ocean opened between Baltica and Laurentia, but less than 100 million years later, this Proto-Atlantic Ocean closed when Scandinavia collided with the Laurentian continent. The result was an impressive mountain chain – the Caledonian mountain chain.

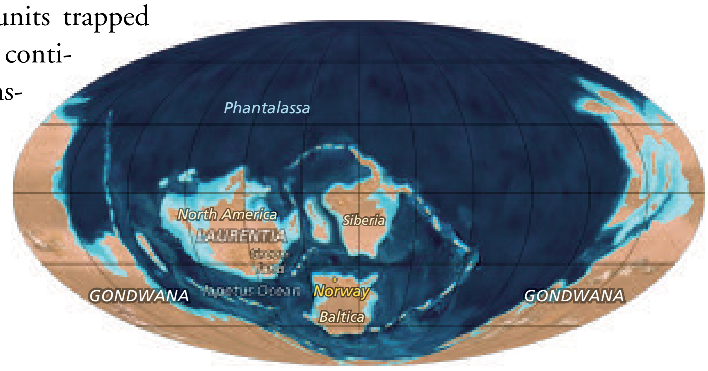
Introduction

A mountain chain is more than rows of peaks. It is a belt where the Earth's crust is exposed to enormous forces that knead and rework it from top to bottom.



The Caledonian mountain chain stretches from western Europe in the south via Ireland, Scotland and Scandinavia to Svalbard in the north, but it is best developed and preserved in Norway. It has its counterpart on the east coast of Greenland and is linked with the Appalachian mountain chain on the east coast of North America. Its name stems from Scotland (Caledonia), where early British geologists performed important investigations and made valuable discoveries. Only the worn-down remnants of the belt are left today. The present-day mountainous landforms have arisen through considerably younger geological processes. What is left now is a section through a more than 400 million-year-old orogenic belt that was originally located deep down in what resembled the present-day Himalayan mountain chain.

The Caledonian orogenic belt was formed when the North American continent (Laurentia), headed by Greenland, drifted towards "Norway" and the rest of the Baltica continent (northern Europe and Russia). The two continents ultimately collided, wreaking havoc on the geological units trapped between them, especially in the oceanic area between the continents and on the continental margins on either side. Huge sheets of rock were torn loose and transported onto the continents as large and small nappes. The fragmentation and intermixing of the original rock units was so intense during the formation of the Caledonian mountain chain that we are left with a complex jigsaw puzzle where some pieces are missing. Reconstructing the evolution of the mountain chain is no simple matter, and theories and models have shifted over time.



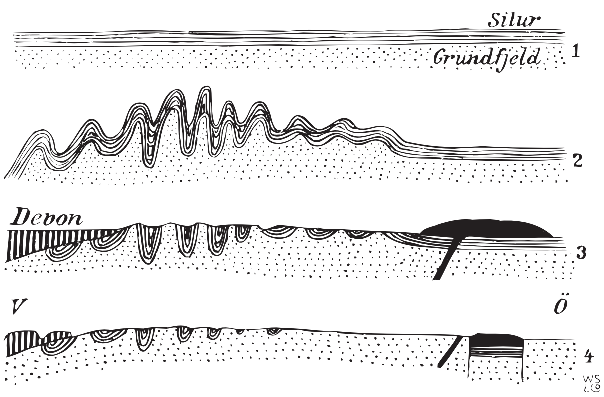
Reconstruction of the position of the continents approximately 500 million years ago, in the Late Precambrian. Brown denotes continents, light blue continental shelves and dark blue oceanic crust. (Reproduced by permission of R. Blakey, Northern Arizona University)

Iapetus – an ancient (Proto-)Atlantic Ocean

The remains of an ancient ocean that was destroyed when Greenland and Norway collided during the evolution of the orogenic belt are found in the Caledonian mountain chain that once stretched so majestically along Norway. The gradual closure of this ocean, which is called Iapetus, marked the start of the formation of the Caledonian mountain chain.

There is now consensus that the Caledonian orogenic belt consists of many thrust sheets, some of which were detached from the Precambrian basement and the Late Precambrian to Ordovician deposits on Baltica, while others derive from the Iapetus Ocean and perhaps even further northwest. All these nappes are now piled up on one another. Together, the detached units form a *tectonostratigraphy* where the uppermost nappe units are, in general, transported furthest and the lowermost ones shortest. At the base is more or less autochthonous basement with its overlying sediments (autochthonous and parautochthonous). Detached slices of the Baltica basement and the overlying sediments are referred to as the Lower Allochthon or lower series of nappes. More long-transported continental nappes, probably deriving from the destroyed, deeper margin of Baltica, form the next level in the nappe pile (the Middle Allochthon). Above this are remnants from the Iapetus Ocean and perhaps even bedrock that originally belonged on the Laurentian side of that ocean (the Upper and Uppermost Allochthons).

These bedrock units have experienced the formation of the orogenic belt in rather different ways. The evolution in the Iapetus Ocean was in fact quite different from that within the Baltic Shield. The history which the various nappes can recount must therefore be deciphered if we are to understand the formation of the entire belt. We will start by considering everything from the aspect of the Iapetus Ocean before shifting our viewing point to more continental settings.



This is how Hans Reusch, one of the pioneers in Norwegian geology, imagined that the Caledonian mountain chain was formed. The crust was pressed together by folding, but the enormous sheets of rock, or nappes, which we now know were detached, are missing.

It all started in the ocean

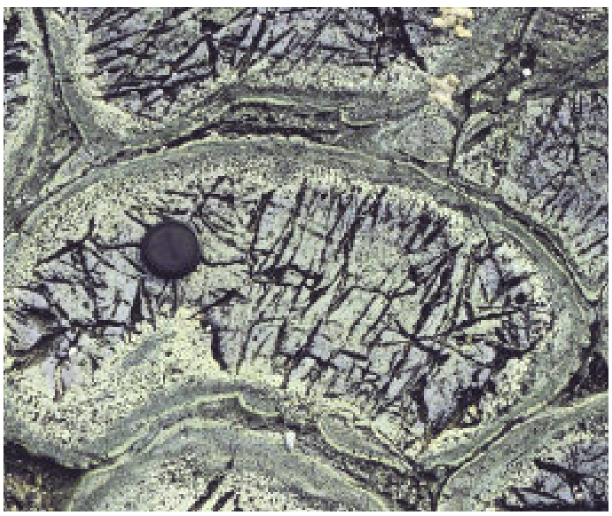
For a time from the end of the Precambrian through the Cambrian Period, Baltica and Laurentia, or "Norway" and "Greenland", moved apart, and an intervening ocean, the Iapetus Ocean, formed. Then the plate movement was reversed sometime around the transition from the Cambrian to the Ordovician. Greenland and Norway drifted towards each other again, resulting in what geologists call plate convergence. Little is known about the reason for this change in plate movement; the organisation of all the crustal plates and their movements is a big game with many variables. However, it is clear that the plate convergence ultimately resulted in a gigantic continental collision. It all started in the ocean several tens of millions of years before the continents actually collided.

The oldest dated components of the Caledonian island-arc and ophiolite complexes represent parts of immature island-arc systems and ocean floor remnants. Uranium-lead dates suggest that the former were developing as early as around 500 million years ago. Island arcs, or strings of volcanic islands, are exclusively created above subduction zones, zones where one plate is pulled beneath another. The island-arc formation consequently shows that Baltica and Laurentia moved towards each other as early as the transition from the Cambrian to the Ordovician.

The ophiolites along the Norwegian coast

Remains of ophiolitic rocks are found all along the coast from Karmøy to Lyngen and are interpreted as ancient oceanic crust from the Iapetus Ocean between Baltica and Laurentia which was emplaced on the basement during the formation of the orogenic belt. Ophiolites consist mainly of gabbro, greenstone and ultramafic rocks and are cut by somewhat younger igneous rocks of various compositions. Apart from the Solund-Stavfjord ophiolite in west Norway, all the Norwegian ophiolites seem to have formed in the course of some 30 million years, around the Cambrian-Ordovician boundary.

The term ophiolite was introduced with respect to Norwegian rocks in the mid-1970s when Cambro-Silurian greenstones on the island of Karmøy were described as part of an ophiolite complex. A period of widespread investigations followed, and soon ophiolite complexes were being recognised and named from Karmøy in the south to Lyngen in the north. The Norwegian ophiolite complexes are deformed and fragmented by faulting, and all the components of an ophiolite complex are only found complete in a few places. On the other hand, they are unusually well exposed on islands, islets and ice-polished rocks along fjords and in the mountains. The upper parts can be studied on Karmøy, in Solund and in the Trondheim region. The deeper, gabbroic parts can be seen on Gullfjellet near Bergen and along mountainsides and beside glaciers in the Lyngen Alps in Troms. On the island of Leka in Nord-Trøndelag, the secrets of the mantle are exposed for all to see. Together, the ophiolite complexes along the Norwegian coast are a natural laboratory where the formation of oceanic crust can be studied in detail.



Pillow lava from Leka, Nord-Trøndelag. Pillow structures are formed when basaltic lava erupts into water. Note the fine-grained rim around the pillows and the gas vesicles further in. (Photo: R. B. Pedersen)

A field trip to Karmøy

The most complete ophiolite complex is found on Karmøy, near Haugesund. On the northern part of this island in west Norway, the farmland is intersected by long ridges composed of a hard, light-coloured, banded rock displaying beautiful folds. This is chert, and consists almost exclusively of silica (SiO_2). It was probably formed from the shells of innumerable siliceous algae that lived in the sea and sank when they died, to be deposited on the sea bed. Such sediments are deposited in deep-ocean settings with little influx of sediment from the continents, and a single centimetre may take several thousands of years to deposit. The hard chert beds on Karmøy are interbedded with softer phyllite, which represents clay deposited in the deep ocean nearly 500 million years ago.

Several types of greenstone are encountered further south on Karmøy. They stratigraphically underlie the metamorphosed deep-ocean sediments in the north of the island. Greenstone is metamorphosed basalt and its colour derives from such green minerals as chlorite, epidote and amphibole. On Karmøy, as in all other ophiolite complexes, the greenstone displays oval, pillow-like structures which form when lava is extruded under water where it cools abruptly. From a submersible at a depth of several thousand metres on the Mid-Atlantic Ridge, the sea floor can be seen to be composed almost solely of pillow lava.

The deeper layers of the oceanic crust can be studied between Kopervik and Skudeneshavn on Karmøy. The pillow lava is replaced by more massive greenstone and dolerite, which closer examination reveals are made up of dykes formed when basic magma intruded fissures. The dykes are usually 0.5 to 1 m wide, and on good coastal exposures it can be seen that they lead up to and pass into pillow lava. The dykes are therefore feeders to the lava flows on the surface.

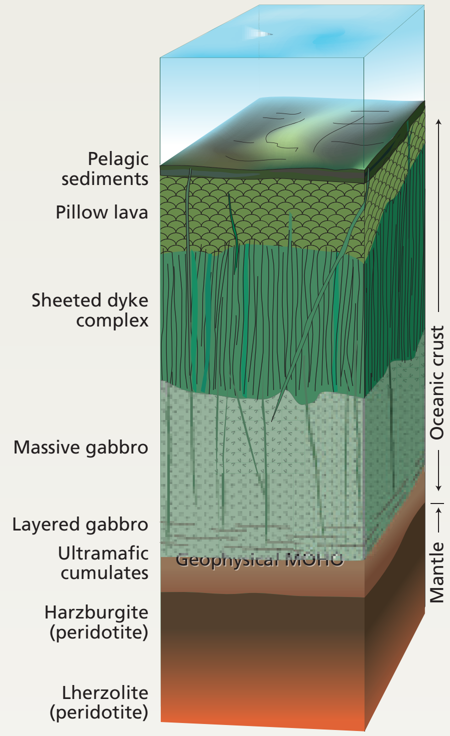
Further south on Karmøy, gabbro replaces the greenstone. Gabbro consists of plagioclase, pyroxene and olivine, and alternations in the amounts of light and dark minerals give rise to layering, which is clearly seen along the east coast

Reconstructions of plate movements when Iapetus was closing.

OFIOLITTER

Ophiolite is an old term describing a bedrock association consisting of peridotite, serpentinite, gabbro, dolerite and greenstone. The name derives from the Greek word for snake or serpent, Ophis, and alludes to the glossy sheen on serpentinites, which occur abundantly in the lowermost (mantle) portion of a complete ophiolite sequence, together with peridotite (pyroxene-olivine rock). This segment is overlain by several kilometres of gabbroic rock followed by a kilometre-thick doleritic unit (sheeted dyke complex), which passes into several hundred metres of basaltic pillow lava, usually altered to greenstone. The Troodos Mountains in Cyprus provide the type example of an ophiolite complex, and successively deeper parts of this layered structure are encountered en route to the highest peaks.

The formation of ophiolite complexes was a mystery for a long time. They always occur in association with orogenic belts, and are always bounded by faults or shear zones. The gabbroic plutonic rocks have never been observed to intrude other country rocks, as is seen in the Oslo region or the basement.



The mystery of ophiolite complexes was only solved when geologists began to understand the geology of the deep oceans towards the end of the 1960s. Cruises to mid-ocean ridges provided marine geologists with samples of basalt, dolerite, gabbro and peridotite, the same rock types that are found in ophiolite complexes. At the same time, seismic investigations showed that the oceanic crust is layered and that its structure must be largely like that known from ophiolites. Ophiolite complexes were therefore quickly accepted as fragments of oceanic crust that had been thrust onto land.

of the island. This marks the deep part of the oceanic crust and the rock is assumed to have crystallised in a large reservoir filled with magma whose temperature was more than 1000 °C. Seismic investigations have shown that such magma chambers are found along mid-ocean ridges, and the tops of the magma reservoirs along the Pacific Ridge are located about 3 km below the sea floor.

Deepest on Leka

Some 700 km north of Karmøy is the island of Leka in Nord-Trøndelag, where the very deepest parts of the oceanic crust can be studied. The first thing that strikes us when we reach the northwest side of Leka is the strange colours. The drab grey and greenish rocks seen on the mainland have gone. Here, the bedrock is coloured in shades of yellow and rusty red. It is the weathering skin that displays these warm colours, and they are caused by iron oxidation; this unusually iron-rich rock has simply rusted.

Beneath the weathered surface, the rocks are extremely dark, ultramafic in geological terms. They consist of olivine and pyroxene, and have names like dunite and peridotite. Such rocks are rare on the Earth's surface, but peridotite is in fact the commonest rock **inside** the Earth. The whole of the mantle, the mass of rock beneath the crust, consists of peridotite, and it is the mantle that is actually exposed here on Leka!

A walk from Skråa in the west to Skei in the east is one of the most tremendous experiences Norwegian geology has to offer. In the west, the rocks are layered. Ridges of dunite, weathering bright yellow and a hundred metres broad, alternate with reddish and green layers of peridotite. Chromite layers can be followed here for several kilometres, and thin sulphide-rich horizons contain noble metals like platinum and palladium. If we can drag our eyes away from these unusual rock formations we will see old, stony beaches about 90 m above the present shoreline, and if we look still higher we may see a soaring white-tailed eagle.

The mantle exposed

To the east, the rocks suddenly change character. The regular layering is replaced by irregular banding and structures resembling those found in migmatites and granitic gneisses. Indeed, we have entered a gneiss complex – ultramafic gneiss. Over a space of just 50 m, we have walked from layered rocks representing the lowest parts of the oceanic crust to banded peridotites from the upper mantle. We have crossed a former Moho, the seismic boundary between the crust and the mantle (see Chapter 2), one of very few places in the world where this is possible.

Geochemical "fingerprints"

The discovery that ophiolites really are old oceanic crust that has been thrust onto land brought new insight into how orogenic belts are formed, but the ophiolites held more secrets. Chemical analyses were required to disclose them.

In common with several other fields of geoscience, geochemistry developed rapidly in the 1970s. New techniques made geochemical analyses simpler and more rapid, and more and more trace elements could be analysed with greater precision. The analyses showed that basalt samples from mid-ocean ridges had a different content of trace elements from basalt lava formed along subduction zones and continental rifts. Each plate tectonic setting proved to have its own special geochemical fingerprint.

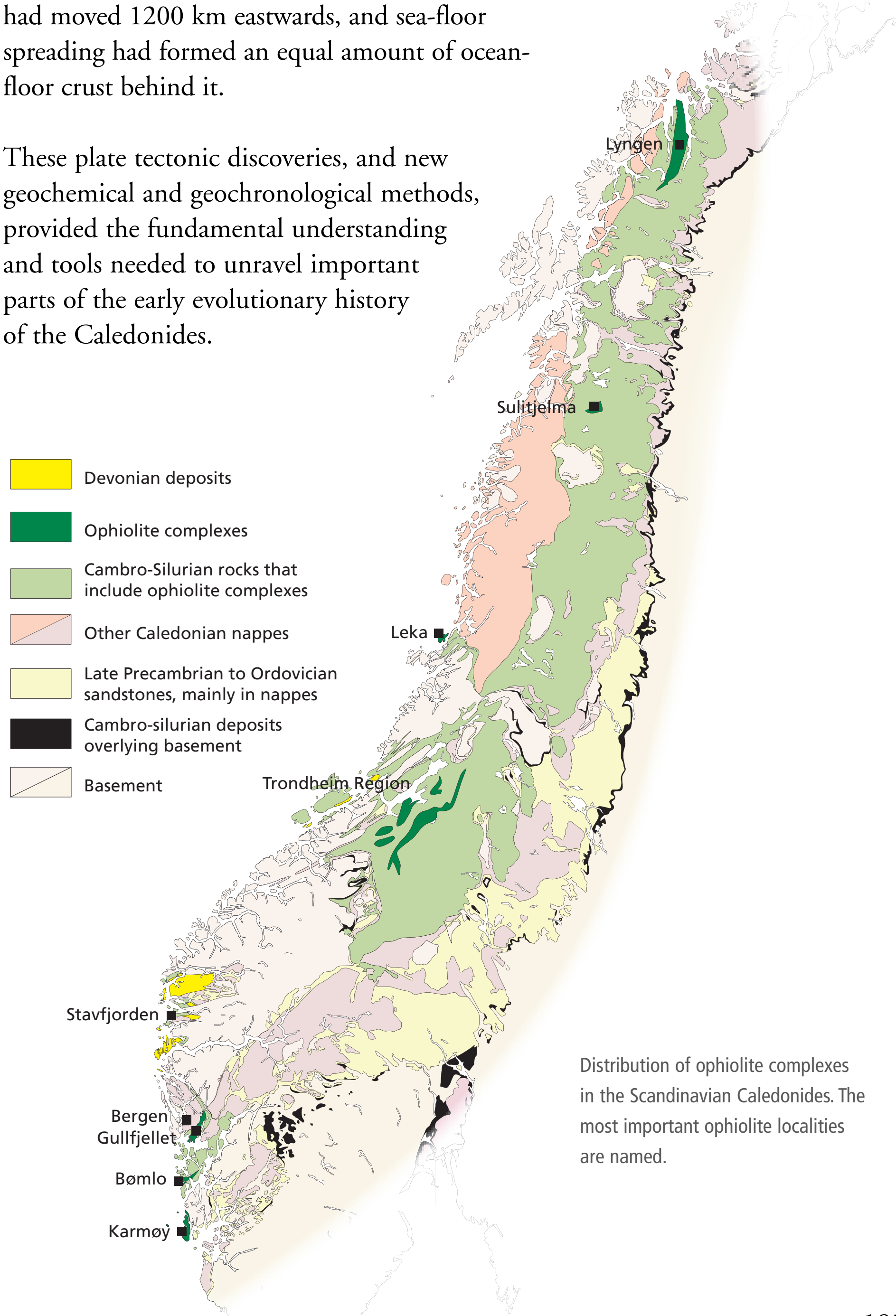
If greenstones from ophiolite complexes were analysed, the geochemical fingerprint might reveal the plate tectonic setting in which these old volcanic rocks formed. The answer was taken to be a foregone conclusion; ophiolites represented ancient oceanic crust, and therefore had to originate on former mid-ocean ridges. However, the analyses told a different story. The greenstones had a trace element signature that indicated subduction zones and volcanic island arcs. Could this be correct? Or had the metamorphism from basalt to greenstone changed the trace element signature?

The answer was yet again found in the deep sea, this time in the western Pacific Ocean, and was unexpected; both the apparently contradictory observations were correct. An active spreading ridge was discovered in the area just west of the Mariana Trench, where the Pacific Ocean Plate is being pulled down in a gigantic subduction zone. Ocean floor crust of normal thickness and constitution was being formed along this spreading ridge, but the basalt lava that pours out along the ridge has the geochemical fingerprint of island-arc magma.

However can sea-floor spreading take place in association with a convergent plate boundary? The explanation is that the subduction zone in this area is moving steadily eastwards. In such circumstances, tension and sea-floor spreading occur near the subduction zone. In the course of 40 million years, the Mariana island arc had moved 1200 km eastwards, and sea-floor spreading had formed an equal amount of ocean-floor crust behind it.

These plate tectonic discoveries, and new geochemical and geochronological methods, provided the fundamental understanding and tools needed to unravel important parts of the early evolutionary history of the Caledonides.

Peridotite on Leka. This is what the very lowest part of the iron-rich oceanic crust looks like after it has been on land for more than 100 million years – thoroughly rusty and weathered. (Photo: R. B. Pedersen)



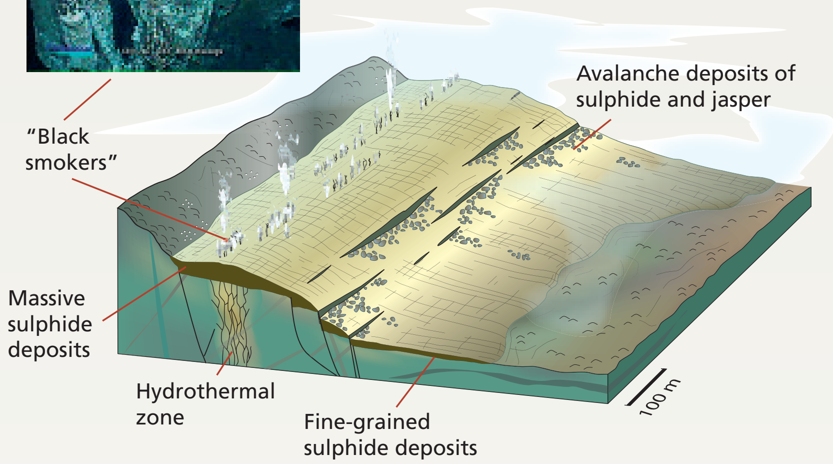
Distribution of ophiolite complexes in the Scandinavian Caledonides. The most important ophiolite localities are named.

SULFIDMALM

The copper facing the Statue of Liberty in New York is said to be made of ore from Visnes Copper Mine on Karmøy. If so, it is a final interesting chapter in the history of Norwegian sulphide ore. Many Norwegian sulphide ore deposits have been discovered and worked down the years, particularly at places like Sulitjelma, Røros, Folldal, Skorovatn, Ølve-Varaldsøy, Stord and Karmøy. The deposits are closely linked to the greenstone belt in the Upper Allochthon of the Caledonian mountain chain which, in turn, was thrust-emplaced from the ancient Iapetus Ocean. Many of the sulphide ore deposits therefore originated on a former volcanic ocean floor some 490–470 million years ago.

On the Mid-Atlantic Ridge north of Jan Mayen, is a fairyland forest of 5-10 m tall "chimneys" from which water at a temperature of 250-300 °C is pouring.

Block diagram below from T. Grenne.



Studies of the present-day deep ocean show that similar sulphide deposits are being formed around submarine hot springs. Hot springs were discovered in the deep ocean in 1978, when scientists in the submersible, "Alvin", saw black "smoke" issuing from chimney-like features. These submarine hot springs were therefore called "black smokers". The "smoke" that rises from the sea floor is formed of tiny sulphide particles that are precipitated when hot water from the volcanic substrate pours into cold seawater. The hot water is mainly seawater that has seeped 1-2 km down into the sea floor, where it is heated to more than 400 °C before rising to the surface again. The heat energy derives from red-hot magma 2-3 km beneath the surface.

Seawater contains an abundance of sulphate ions (SO_4^{2-}). When it seeps into the bedrock and is heated in contact with minerals, the sulphate ions are reduced to sulphur ions (S^{2-}). At a water depth of several thousand metres, the pressure is so high that water cannot boil, even though it is heated to more than 400 °C. Instead, it acquires the ability to leach iron, copper, zinc and other elements from the rocks with which it comes into contact. When the hot water pours from vents in the seabed and is cooled, positively charged Fe, Cu and Zn ions bind to negatively charged S ions and form iron sulphide (FeS), copper sulphide (Cu_4S) and zinc sulphide (Zn_2S). Precipitation of these minerals around the hot springs may lead to the growth of "chimneys" that can be several scores of metres tall. Gold and silver can also be concentrated in this manner.

JASPER

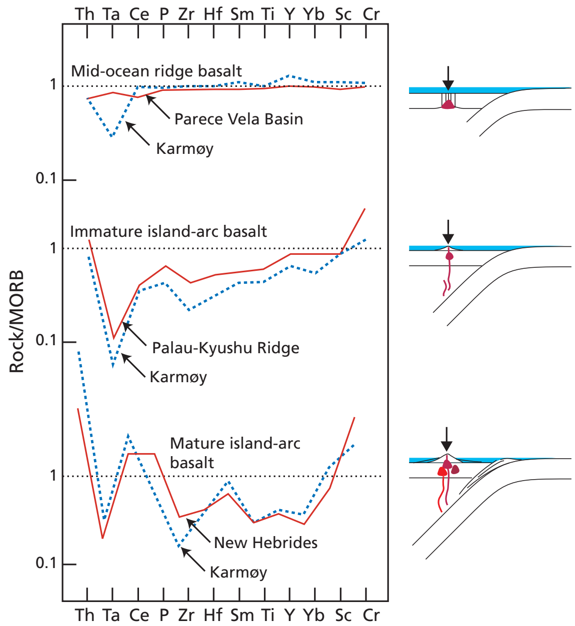
The photograph shows polished jasper from near Trondheim. This mineral, which mainly consists of silica (SiO_2), is associated with sulphide ore deposits in many places. Its characteristic deep-red colour is produced by numerous minute haematite grains. Jasper is probably formed by precipitation of silica and iron hydroxide from hydrothermal solutions around hot springs in the deep ocean. Probable traces of iron-precipitating bacteria that lived in the deep ocean nearly 500 million years ago are seen in specimens of jasper from the orogenic belt.

The first island arcs are formed

Ophiolite complexes are difficult to date. The microfossils found in deep-ocean sediments overlying the ophiolites are often unidentifiable, and the metamorphism of the volcanic rocks makes most radiometric age determination methods unsuitable. However, as the uranium-lead dating method was greatly improved in the 1980s, enabling small quantities of the mineral zircon to be dated, it was possible to determine the age of ophiolites. Age determinations of gabbros in Norwegian ophiolites showed that most of them formed 495-485 million years ago, that is in the course of 10 million years at the transition between the Cambrian and the Ordovician. Ophiolite complexes in Scotland and Ireland, and further south in the Appalachian part of the orogenic belt along the east coast of North America, gave similar ages. Geochemical analyses revealed that the ophiolites had a geochemical fingerprint that fits the imprint of immature island arcs in the western Pacific Ocean. This showed that subduction zones were formed in the Iapetus Ocean around the transition between the Cambrian and the Ordovician. The ophiolites were thus the first sign that the Iapetus Ocean had begun to close.

What caused the shift in the plate movement is still an enigma. From the time the ophiolites formed in immature island arcs some 490 million years ago, the geological consequences of large-scale subduction can be traced right up to when Laurentia and Baltica collided. That was when the eclogites in west

Gold is also found in ophiolite complexes in Norway. The largest find has been made on Bømlo, where 137 kg of pure gold were extracted in 1882-1898. Gold can still be found at the site. (Photo: H. Fossen)



Comparison between the content of rare elements in basalts from Norwegian ophiolites and known, modern examples shows that there has been an evolution from mid-ocean ridge basalt (MORB) to an increasingly more mature island-arc situation in Early Ordovician time. The broken line shows ideal ocean floor basalt, and the differences increase with increasing degree of maturity.

Island-arc rocks (quartz diorite with granite dykes) in the Sunnhordland batholith. (Photo: H. Fossen).

Norway formed, nearly 100 million years after the closure started.

The island arcs grow and mature

In addition to ophiolite complexes, which represent actual oceanic crust, remains of volcanic islands are also preserved. The Geitung Volcanics on the island of Bømlo in Hordaland, west Norway, are probably the remnants of one such island. This sequence consists of basalts and basaltic andesites which were probably extruded in a shallow sea. They have been dated to 496 million years and show that volcanic islands formed coevally with oceanic crust, just as in modern island-arc settings in the western Pacific.

A younger, kilometre-thick volcanic sequence composed of andesites and rhyolites is found on Bømlo and neighbouring Stord. Stone Age people prized these hard rocks and used them for a variety of tools. Archaeologists have found quarries near Bømlo, and tools that probably derive from there are known from many habitation sites along the entire coast of western Norway. The glass-like rhyolites can be studied beside the road leading to the top of Kattnakken, and volcanic banding and textures there show that parts of the sequence originated as ignimbrite flows which form in explosive volcanic eruptions. The rhyolites on Bømlo and Stord have a geochemical fingerprint resembling lava from the Indonesian island arc. This arc includes Krakatoa, which exploded in 1883 spewing ash 50 km up into the stratosphere and reducing the average temperature on the Earth by 1.2 °C the year following the eruption. The people of Bømlo and Stord live on the remains of such an explosive volcano, but since the rhyolites on Kattnakken have been dated to 476 million years, they can rest assured that the volcano will never come to life again.

Some 20 million years passed between the formation of the andesites at Geitung and the rhyolites on Kattnakken. During this period, the arc evolved from an immature island arc dominated by submarine volcanism to a mature one with large volcanic islands and explosive volcanism. This trend is also found elsewhere in the orogenic belt, such as the Skorovass area in Trøndelag.

Island arc – continent collision

The ophiolites and island-arc sequences are intruded by various light-coloured granites, which are conspicuous in the field. They occur as minor dykes and as batholiths scores of kilometres across. The oldest intrusions consist of a granitoid rock called trondhjemite, but the magma changed composition somewhat about 475 million years ago. Granites that are rich in potassium feldspar and aluminium-rich minerals like tourmaline and sillimanite began to intrude the ophiolite complexes on Karmøy and in Helgeland (southern Nordland). Such granites form by melting of sedimentary rocks and are therefore called *S-type granites*. They are well exposed along

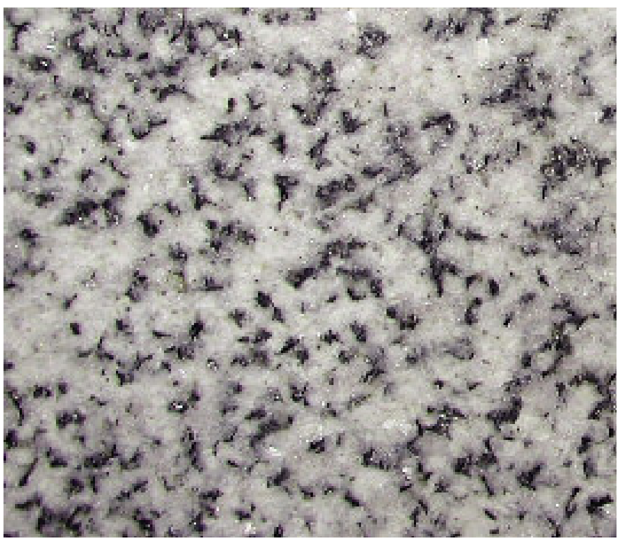
The Cambro-Silurian rocks of oceanic derivation (Upper Allochthon) range from acid granites that are resistant to weathering to phyllites and other "rotten rocks". This gives great contrasts in soil and vegetation, as here at Huglo in Sunnhordland where acidic rhyolite forms naked ridges between lush areas of calcareous phyllite. (Photo: H. Sunde) the west coast of Karmøy, where they are sometimes so rich in inclusions that the rock was once described as sedimentary conglomerate. Close examination shows that most of these inclusions consist of sedimentary lithologies. They represent unabsorbed relics of the deposits that otherwise melted into the granites at depth. Inclusions of arkose, quartzite, marble and calc-silicate rocks reveal that the granites partly formed by melting of sediments from the continental margin, and the island arc was therefore probably colliding with a continental margin when intruded by S-type granites.

A modern example of such an island arc – continent collision is seen along the northern coast of Australia. Australia is moving northwards towards Asia at a rate of 5 cm a year and is colliding with the Indonesian island arc. Seismic profiles show that the Australian continental margin is being pushed beneath the island arc. Afterwards, Australia will probably continue its northward journey, with the island arc and oceanic crust thrust onto its continental margin.

Americans or Europeans?

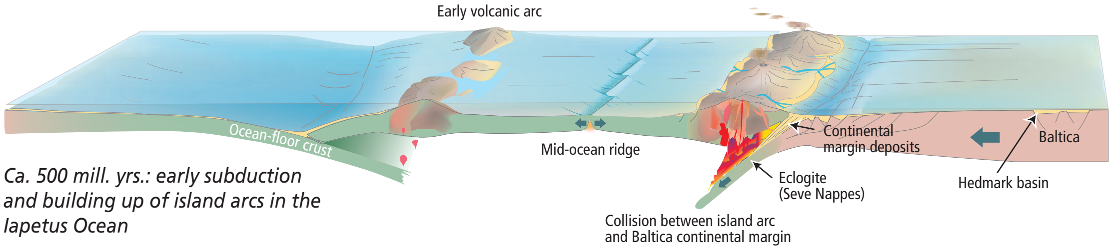
Did the Norwegian, Caledonian island arc collide with Laurentia or Baltica? Fossils provide an indication. Most fossils in Ordovician strata in North America and on Baltica differ, and are relatively easy to distinguish from one another. This implies that a large ocean, the Iapetus Ocean, separated the two continents at this time, preventing extensive contact between the faunas on either side. However, North American types of fossils are found in a few parts of the Caledonian orogenic belt in Norway, in sedimentary rocks deposited on some ophiolite complexes. Early Ordovician brachiopods, trilobites and conodonts have been found in the Lower Hovin Group in the Trondheim region and these fossils more closely resemble the fauna that lived along sub-tropical parts of the Laurentian continental shelf than that known from the Baltic Shield area. This volcano-sedimentary sequence was deposited on the Løkken ophiolite, and probably identifies one of the volcanic islands in the long island arc. Similar fossils are found in island-arc deposits on the island of Smøla, further west. The North American affinity of these fossils in the western part of the Trondheim region suggests that the related volcanic island arc evolved closer to Laurentia than Baltica.

Modern dating techniques have yielded new knowledge that supports this. Zircon is a robust heavy mineral that survives erosion and transport, and is therefore common in sandstones. If a large number of zircons from a sandstone are dated, the age of the source rock is obtained, thus enabling the source, or provenance, of the sediments to be traced. Zircons in Ordovician sedimentary rocks deposited along the Baltica margin in south Norway are mainly from the last period of the Precambrian, the Proterozoic, and probably derive from the basement in south Norway. On the other hand, the main source in Ordovician deposits along the Laurentian margin was old gneisses from the first part of the Precambrian (the Archaean) (> 2500 million years). Consequently, the sandstones deposited on the two margins have a different age signature. How about the sedimentary xenoliths found in the S-type granites on Karmøy? They give a Laurentian age signature. Both sediments and fossils therefore indicate that some of the ophiolites which rest firmly on Norwegian basement may have been in America!

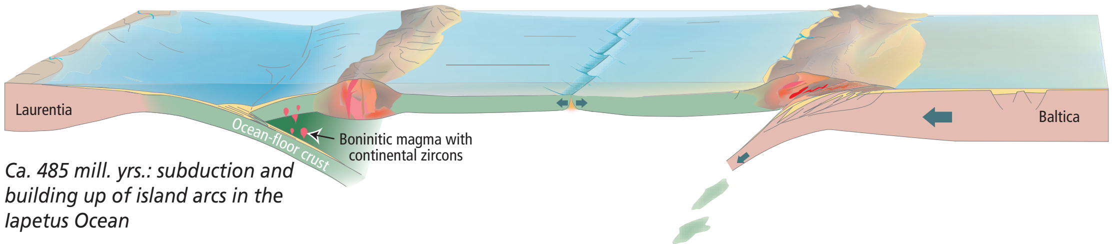


Granite is one of the commonest rocks in Norway. It largely consists of white to reddish feldspar, quartz and a little mica. Many of the granites in the orogenic belt were formed in island-arc complexes or batholiths prior to the main collision between Norway and Greenland. Trondhjemite (lowermost) was formed first and more ordinary granites (uppermost) later. (Photo: H. Fossen)

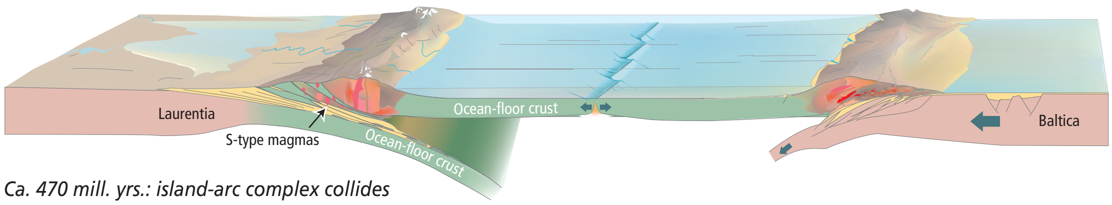
Possible evolution of the Caledonian orogenic belt from just after the plates began to converge in the Late Cambrian until the ocean closed and the actual mountain chain really began to rise around the transition from Silurian to Devonian.



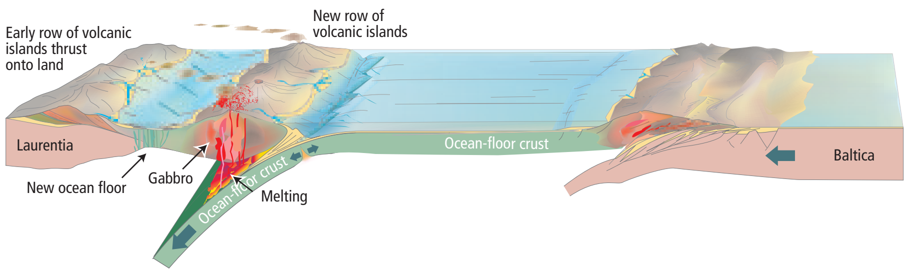
Ca. 500 mill. yrs.: early subduction and building up of island arcs in the Iapetus Ocean



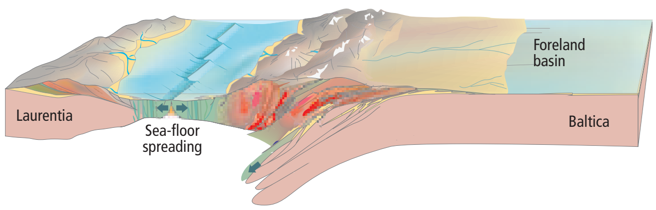
Ca. 485 mill. yrs.: subduction and building up of island arcs in the Iapetus Ocean



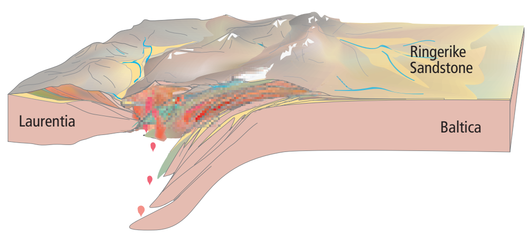
Ca. 470 mill. yrs.: island-arc complex collides with the Laurentian continental margin



Ca. 440 mill. yrs.: new island-arc system develops above a westward-dipping subduction zone near the Laurentian margin. New oceanic crust forms between Laurentia and the row of islands



Ca. 430 mill. yrs.: island arc collides with the Baltica continental margin



Ca. 420-410 mill. yrs.: complete closure of the ocean; ultimate pile up of nappes with rocks of Laurentian origin at the top

The granites and associated plutonic rocks in Nordland are remnants of island arcs in the Iapetus Ocean. Heilhornet, near the border with Nord-Trøndelag. (Photo: H. Fossen)

What went on along the Norwegian coast?

So far, little is known of events along the Baltic margin early in the Ordovician. Was it a passive margin, or an active one experiencing subduction and collision between island arcs and the continental margin? Current knowledge points several ways. Eclogites in some nappes at least suggest that rock was carried down to a great depth some 500 million years ago, and perhaps also 50 million years later. The eclogites are found in amphibolites that may have originated as basaltic dykes linked to rifting prior to the opening of the Iapetus Ocean, but they may also have formed off the Baltic margin. At any rate, a subduction zone seems to have existed along, or west of, this continental margin 500 million and perhaps also 450 million years ago.

The big granites arrive

The really big granites formed 450-430 million years ago. They mark an important, new event in the history of the Caledonides and show that the closing of the Iapetus Ocean entered a new phase at this time. The Bindal Batholith on the coast of Helgeland, the Smøla-Hitra Batholith in central Norway and the Sunnhordland Batholith in west Norway are the largest Caledonian granitic complexes that are preserved. The Sunnhordland Batholith consists of a number of *plutons* (separate bodies of intrusive igneous rock) which, together, cover some 1600 km^2. The Bindal Batholith is equally large and is composed of more than 50 individual plutons. The Smøla-Hitra Batholith consists of more than 20 major plutons and covers an area of 3000-4000 km^2. Corresponding rocks are also found in a large area between the Svartisen glacier and Saltfjord, not far north of the Bindal Batholith. The batholiths consist mainly of granite and granodiorite, but more basic intrusions like gabbro and diorite are also present. These are *I-type granites*, that is granites formed from igneous rocks. Such granites usually form above subduction zones where basaltic magma rises from the mantle, intrudes the continental crust, melts the country rocks and mixes with these melts.

Silurian quartzite conglomerate uppermost in the sedimentary sequence deposited unconformably on the Gullfjellet ophiolite in the Bergen Arcs. (Photo: H. Fossen)

The magmas in the Sunnhordland Batholith intruded ophiolites and associated sedimentary and volcanic strata, referred to collectively as oceanic terrane. On the Helgeland coast, the magmas intruded both an oceanic and a continental terrane. The latter consists of migmatitic gneisses, calc-silicate rocks and marble from the end of the Precambrian and the beginning of the Palaeozoic. This demonstrates the large scale of the plate movements that brought the oceanic terrane into contact with continental rocks before the granites intruded 450 million years ago, and it confirms the history told by the older S-type granites.

The large granite batholiths probably formed along a continental margin. The western margin of South America is a modern parallel, at any rate for the first part of the history. There, the Nazca Plate, one of the Pacific Ocean plates, is sinking beneath the continental margins, leading to andesitic volcanism and intrusion of granites at depth.

Approximately 50 million years passed from the formation of the ophiolite complexes in the ocean to the intrusion of the granite batholiths. During this period, intra-oceanic island arcs formed and developed before colliding with a continental margin, where a new subduction zone created the enormous granite intrusions.

The sediments take the floor

Yet another dramatic change took place in the latter part of the Ordovician. The ophiolite complexes, island-arc sequences and granites were pressed together, uplifted and deeply eroded, thus exposing deeper parts of the crust. Goldschmidt found a fossilised weathering profile in granite on Karmøy in 1921, and a similar one is known on Leka, but there in gabbroic rock. The sea then rose and deposited sediments on the eroded and weathered rock surfaces. Lithified and variably metamorphosed remains of these sediments are now found on Karmøy and Stord, in the Bergen and Trondheim districts, on Leka and in Lyngen. They consist of conglomerate, sandstone, shale, siltstone, marble and limestone. Some of these sequences were probably deposited on alluvial plains, others in the shore zone and a shallow-marine environment.

Fossilised corals and brachiopods can be found in the limestones, and a trained eye may spot graptolites in the shales. The fossils are dated to Late Ordovician to Early Silurian, which means that these successions were deposited 445 to 435 million years ago. Signs of older Ordovician animal life are found in such deposits in the Trondheim region, and they seem to be as old as 470 million years. Kjerulf and Brøgger described these fossils as early as the 1870s. The fauna along the shores of the Norwegian ophiolite complexes at that time was cosmopolitan, lacking clear distinction between Baltica and North America. That is yet another sign that the Iapetus Ocean was changing and had shrunk considerably since the Cambrian.

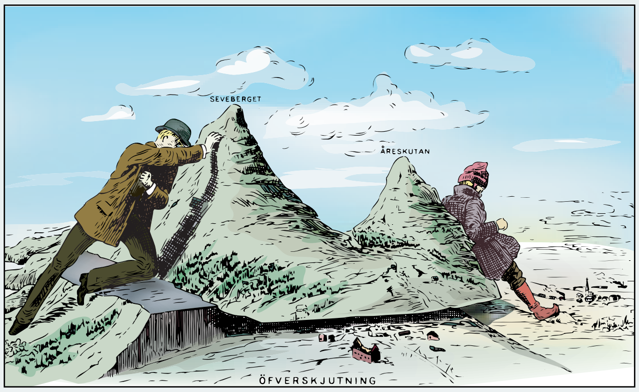
What was causing the land uplift and the degradation of the ophiolites and island arcs? Several clues exist. Clasts in the conglomerates in the lower parts of the successions are composed of granite, gabbro, greenstone and greenschist which derive from the underlying ophiolite and granite complexes. Higher up, there are also well-rounded quartzite clasts. These contain zircons that must stem from a continent, and they have an age signature which resembles that of the Cambrian quartzites on Hardangervidda. Land uplift, erosion and deposition of the Silurian successions may therefore be caused by the oceanic terrane, which now consisted of ophiolite, island-arc and granite complexes, having come into contact with the Baltica margin. Radiometric age determinations from high-pressure rocks in west Norway (the Lindås and Dalsfjord nappes) and the central parts of the mountain chain (the Seve Nappes), which are probably slices detached from this margin, give ages of around 450 million years, and may suggest that the Baltica margin was pressed down to depth, heated and then cooled at this time.

Iapetus is on its last legs

Yet the Iapetus Ocean had still not closed. Proof of this is found in the Solund-Stavfjord area in outer Sognefjord in west Norway. The Solund-Stavfjord ophiolite proved to be a fragment of 443 million-year-old crust, 50 million years younger than the other ophiolite complexes in the mountain belt. At the same time as sediments were being deposited on the Early Ordovician ophiolite complexes, which were already deformed and eroded, the Solund-Stavfjord ophiolite was forming by sea-floor spreading. This complex is otherwise like the older ophiolites and consists of pillow lava, a dyke complex of dolerite, and gabbro. The pillow lava is well exposed on the islands in Solund, and the dyke complex, the actual hallmark of crust formed by sea-floor spreading, can be studied on Tviberget, off the island of Atløy.

"THE ROCK PROBLEM"

When geology was in its infancy, it was thought that rocks largely moved vertically in the Earth's crust. No-one envisaged that major lateral movements were feasible. The strange tripartite division of the bedrock found in the Caledonian mountain chain, with basement lowermost, then phyllite and mica schists, and finally new basement-like rocks at the top, was therefore problematical. Various theories were proposed, many of them based on the geology of Hardangervidda.



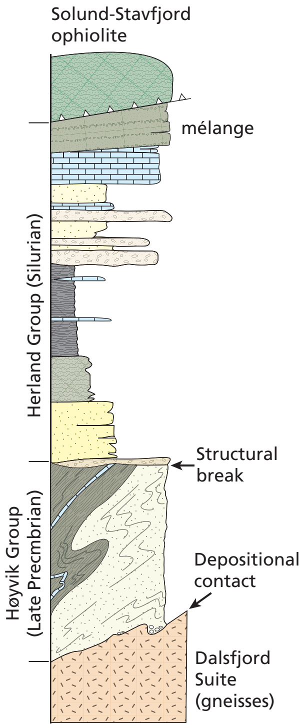
Baltazar Mathias Keilhau, the first to graduate in geology at the forerunner of the University of Oslo (Det Kongelige Frederiks Universitet), was a Neptunian and believed that all the three units were originally sedimentary rocks that had undergone a mystic transmutation or metamorphosis. His student, Theodor Kjerulf, rejected this reasoning around 1850 and assumed that the basement rocks both above and below the phyllite were molten granite that had intruded the phyllite during the Precambrian. A few years later, fossils were discovered in the phyllite at Holberget on Hardangervidda, and Kjerulf's assumption that all the beds were basement was doomed. Waldemar C. Brøgger claimed in 1877 that the uppermost layer was intruded above the phyllite and was therefore youngest.

A Swede had to come on the scene to bring the debate a step further. In his famous work, "Om fjällproblemet" (On the rock problem), in 1888, Alfred Elis Törnebohm published his revolutionary theory that enormous sheets of rock had been pushed more than 100 km south-eastwards across the Swedish-Norwegian basement. The uppermost basement-like layer with its sharp boundary with the phyllitic layer was thus explained in a completely different and revolutionary way. Törnebohm, himself, thought that such enormous lateral overthrusting of basement sheets was rather extreme, but could think of no other explanation. We now know that this was a conservative estimate. When Knut Olai Bjørlykke and Hans Reusch, the newly appointed head of the Geological Survey of Norway, studied Hardangervidda in 1900, they found support for Törnebohm's theory. However, since Bjørlykke was fully aware that Brøgger was sticking to his opinion, he chose to write "Overskyvningshypotesen maatte oppgives…" (The overthrusting hypothesis had to be abandoned) in the concluding remarks of his doctoral thesis, knowing full well that Brøgger would be the opponent when he defended it. Reusch, however, hedged by taking a middle-of-the-road position – a little thrusting, but not as much as Törnebohm would like.

The controversy regarding the Swedish overthrusting hypothesis swung back and forth after that, until Anders Kvale's internationally renowned work on the Bergsdalen Nappes east of Bergen helped to remove the final remnants of doubt regarding the validity of the theory.

This complex stands out from the older ophiolites in one way. Sandstones, not deep-marine sediments, cover the pillow lava. The sea-floor spreading must have taken place close to a continent. The geology in the Sulitjelma district in Nordland suggests the same. The Sulitjelma gabbro intruded a sedimentary sequence at the same time as the Solund-Stavfjord ophiolite formed. The Sulitjelma district also has a marine volcanic sequence and a substantial sulphide ore deposit that was worked until the 1980s. The geology and geochemistry show that the Sulitjelma complex formed by sea-floor spreading in the vicinity of a continental margin, possibly when a marginal basin began to open.

On Bremangerlandet, greenschists associated with the Solund-Stavfjord ophiolite pass into an unusual rock type called *mélange,* which means mixture. The mélange on Bremangerlandet is a chaotic mixture of boulders of chert, greenstone, dacite and quartz keratophyre in a matrix of black shale. Both submarine avalanches and crustal movements are capable of mixing rocks together in such a mélange. Mélange is often found near deep-sea trenches and subduction zones. The mixture of volcanic boulders of island-arc type and boulders composed of deep-sea sediments shows that the mélange on Bremangerlandet formed close to a volcanic island arc. It is intruded by gabbroic and granitic magmas



The simplified stratigraphy on the island of Atløy in Sogn og Fjordane. The Høyvik Group corresponds to the sparagmitic rocks further east, and the Särv rocks in Sweden. It was folded and tilted before the deposition of the Silurian Herland Group which, in turn, was overridden by the Solund-Stavfjord ophiolite when the Iapetus Ocean closed late in the Silurian.

that solidified in the deeper parts of a volcano. Age determinations of these igneous rocks show that the island-arc volcanism took place at the same time as the Solund-Stavfjord ophiolite was forming by sea-floor spreading.

This therefore provides the missing pieces of the jigsaw puzzle needed to outline the plate tectonic setting. Mélange with island-arc volcanics, subduction-related island-arc plutons and oceanic crust overlain by clastic sediments imply an island arc and associated continental margin basin. Many modern examples of this are found in Southeast Asia.

The ocean closes

The Solund-Stavfjord ophiolite represents the last evidence of the Iapetus Ocean known in the orogenic belt. The oceanic crust was thrust onto land not long after the ophiolite was formed by a spreading ridge. The rocks which tell that part of the story are found on Atløy, an island about 30 km west of Førde. On the south side of Atløy, crustal movements have folded thick beds of conglomerate so that they are now steeply inclined before bending out towards the sea in the west like a train. Coastal fishermen lost themselves in a dream and called this white hillside Brurestakken (the Bridal Skirt). The conglomerates in Brurestakken alternate with sandstones and shales containing graptolites and brachiopods. These are Early Silurian fossils and show that the Herland Group, as this sedimentary succession is called, was deposited approximately at the same time as the Solund-Stavfjord ophiolite was being formed by sea-floor spreading and as corresponding sedimentary successions were being deposited on the “old” ophiolite complexes. However, the Herland Group differs from these in being deposited directly on continental crust and probably representing continental margin deposits.

The conglomerates at the base of the Herland Group largely consist of quartzite clasts derived from the underlying rocks (the Høyvik Group). The lithologies in the upper parts of the sequence are significantly greener, and the clasts consist of greenstone, greenschist, jasper and occasionally gabbro and serpentinite. The Solund-Stavfjord ophiolite, which is situated just west of Atløy and is in fault contact with the Herland Group, is probably the source of these clasts. In just a few million years, the oceanic crust was brought to the surface so that erosive forces began to take effect. At this time the Iapetus Ocean must have been closing.

Repercussions of the orogenic belt formation on the continent

The sea level on the Baltica continent had risen throughout the Cambrian Period. The lower part of the Cambro-Silurian succession was deposited on a basement surface that was almost as flat as a pancake and is known as the sub-Cambrian peneplain.

Clastic sediments in the marginal zone of the mountain chain in central and southern Norway are partly characterised by material eroded from basic igneous rocks, and special minerals like chromite, which typify oceanic crust and immature island-arc systems, are unusually abundant. This erosion started already in the Early Ordovician, but reached its peak towards the end of the Ordovician. It has been claimed that the chromite grains may derive from island-arc systems that were thrust over the Baltoscandian basement from the west in Ordovician time. Recent dates of the Caledonian ophiolite and island-arc fragments, however, show that the island-arc systems here were still being built up at that time. This was taking place west of the Baltica margin, unreasonably far from the marginal zone to be likely for transport of chromite grains. The chromite grains can, however, be explained by an island-arc system that collided with the margin of Baltica before the ocean closed. Perhaps there is a link here with the Ordovician eclogites in the Seve Nappes. Further work on the nappe pile is required to clarify what was really taking place along the continental margin before the final closure of the Iapetus Ocean.

However, several interesting discoveries have been made in the marginal zone of the orogenic belt. The Bruflat sandstone is the first formation in the well-preserved Cambro-Silurian succession in the Oslo region that shows rapid infilling of clastic material. It marks a significant shift in sedimentation, and shows that a land area had risen from the Late Ordovician – Early Silurian sea. This land probably formed when the Iapetus Ocean closed, collision took place and the Caledonian nappes approached the Oslo region in the Silurian, some 430 million years ago. Further west on the Baltoscandian continent, a transition took place from sandstone, shale and limestone to turbiditic deposits as early as the Middle Ordovician. The remains of these deposits are now seen in the lowermost nappes along the entire mountain chain. The turbidites may have formed ahead of advancing nappes that were being eroded while moving south-eastwards, which may suggest that nappes formed along the Baltoscandian margin prior to the main Caledonian collision.

THE USE OF STONE GOES BACK A LONG WAY

It started in the Stone Age, naturally. Flint was scarce, and other rocks like greenstone, dolerite, rhyolite, quartzite and siltstone were quarried for weapons and tools. The oldest of these quarries (dating from about 8000 BC) has been found on Hespriholmen, an islet southwest of Bømlo in Hordaland, west Norway.

Prior to the Middle Ages (AD 1050), stone was little used in Norway for building purposes, except to construct hill forts and for simple masonry. When churches and monasteries were to be erected in stone, deposits of soft soapstone, which Norwegians had long used for cooking pots, net sinkers, loom weights and so on, became an attractive building stone. Limestone and marble also began to be burnt to make lime mortar. Later, particularly in the 18th century, blocks of marble and limestone were extracted in the counties of Hordaland, Akershus and Vestfold, mostly to build palaces in Denmark. The huge marble deposits at Fauske in Nordland began to be worked in the 1880s.

Quarrying of harder kinds of rock, like granite, syenite and gneiss, was not particularly feasible before the beginning of the 19th century, which was when the first quarry in the Grorud syenite of the Oslo region opened. The large areas of granite in Østfold, and the popular bluish larvikite near Larvik in Vestfold, began to be quarried towards the end of the century. The demand for cobbles and building stone also led to hard stone being quarried elsewhere in the country in this period. The large roofing slate quarries also had their heyday from the second half of the 19th century up to about 1950.

As the Second World War approached, steel, concrete and brick began to take over as building materials, but a new "stone age" dawned towards the end of the 20th century. Natural stone achieved a renaissance for outdoor spaces, facing of buildings and stone walls. Much of this stone is imported from distant parts, but some of the good, old, Norwegian rocks are holding their own. The best-known ones are probably larvikite and perhaps Fauske marble, along with the flagstones and slates from Otta, Oppdal and Alta. Crushed rock must not be forgotten either. Crushing plants to produce aggregates provide most of the income in the modern quarrying industry. The peridotite quarry at Åheim in west Norway, nepheline syenite on Stjernøya in Altafjorden, and limestone used for cement are other examples which show that money can be made from crushed rock.

Anorthosite quarry at Sirevåg, Rogaland (Photo: T. Heldal)

The continents collide – Baltica takes a dive

It was the continental margin that first experienced the full effect of a continent-continent collision. The marginal deposits were pressed together and transported south-eastwards over the old basement surface.

The Caledonian nappes were piled up in a wedge-shaped stack of nappes in front of the Laurentian "bulldozer".

Greatly simplified, this process can be compared with what happens when a bulldozer clears snow. The bulldozer is the Laurentian continent that crashes in across the continental margin of Baltica, and the snow that is piled up ahead of it is the Caledonian nappes. Just as the snow pile in front of the bulldozer grows, so does the volume of sediments and rock sheets being carried in across Norway, and the ground beneath the snow is the solid Baltica basement.

The basement is carried down into the depths of the Earth

The basement was now pressed deeper and deeper as more and more masses of rock were continuously transported over Baltica as nappes. The wedge-shaped nappe pile was always thickest near the collision zone in the west and decreased in thickness towards the foreland in the east. Correspondingly, the Baltica basement was deepest in the west. The depression of the basement must have continued as long as the building up of the nappe wedge went on, so that the basement was at its deepest level when the forces driving the collision ultimately ceased.

There is abundant confirmation that both the temperature and the pressure in the basement increased from east to west. In the eastern parts of the orogenic belt (the foreland), from Finnmark in the north to the Oslo region in the south, the basement is only insignificantly affected by the orogenesis. Here, too, there are well-preserved remains of the sedimentary succession that was deposited on the basement before it was overridden by the nappes. These are mostly clay-rich (*pelitic*) and sandy (*psammitic*) deposits that are only slightly affected by increased pressure and temperature. At Tyrifjord, west of Oslo, data exist from deformed Palaeozoic deposits which show that the temperature did not exceed 110-200 °C (except around the Permian intrusions); consequently, the strata were never buried deeper than around 4-7 km. However, north-westwards from the Oslo region, the temperature in the Lower Palaeozoic deposits must have reached about 350 °C in Valdres.

Along the entire chain, the metamorphosed pelitic deposits change in character from phyllite to mica schist westwards, implying a continuous rise in temperature in that direction. Here, however, it becomes more and more difficult to find deposits that still remain in place on the basement on which they were once deposited. The basement, too, is thoroughly kneaded and metamorphosed, and new minerals that grew in the actual basement during the Caledonian orogeny in the west can therefore also be studied. Studies of the composition of metamorphic minerals like mica, amphibole, garnet, kyanite and so on have provided a basis for assuming that both the temperature and the pressure increased towards the west coast of Norway. The basement in the northern part of west Norway seems to have been

ECLOGITE

Eclogite, the county stone of Sogn & Fjordane, is a comparatively uncommon rock characteristically composed of two minerals, reddish-brown to pink garnet and omphacite (green pyroxene). Such rock is only formed at great depths, roughly 50 km or more. It used to be thought that Norwegian eclogites had to be Precambrian in age. However, isotopic dates performed in the 1970s and 1980s gave Early Palaeozoic ages (450-400 million years) and indicated that the rocks formed during the Caledonian orogeny. Along with the plate tectonic model, which had become commonly accepted long before, these ages brought a new understanding of what had taken place in the Caledonian backland during the collision. They showed that western Norway had been dragged down into the depths beneath a thick pile of nappes that was building up as the mountain chain formed.

Eclogite is quarried as natural, ornamental and precious stone. This dense, heavy rock is also used as ballast and cover rock, and as an aggregate to manufacture concrete. Eclogite also contains the mineral rutile (TiO_2), and extraction of titanium dioxide from eclogite in Naustdal and at Holsnøy near Bergen has been evaluated.

Eclogite from Nordfjord

hottest and deepest, since it is here minerals and rocks are found that can only be formed at extreme depths.

Eclogite, coesite and diamond

The formation of the rock, eclogite, is one of the best-known results of the high pressures and temperatures to which the basement was exposed. It was chiefly lenses of basic rocks that were transformed into eclogite. A great deal of eclogite is found in the gneiss belt between Bergen and Roan (Sør-Trøndelag), in the basement in Lofoten, in the Middle Allochthon in the Bergen Arcs and Sweden (the Seve Nappes), and in the Uppermost Allochthon in Troms. The eclogites in the nappe pile have probably been down to a great depth in the hinterland of the orogenic belt, before being carried onto the Baltica basement towards the end of the collision stage.

The discovery of micro-diamonds in gneisses at Fjørtoft, near Ålesund in the northern part of west Norway, is perhaps most exciting. True enough, the diamonds are too small to be seen with the naked eye, but their presence is important because many geologists believe that diamonds can only crystallise at a depth of more than 100 km. These diamonds are therefore believed to have formed when the margin of the Baltica continent was at its deepest during its collision with Laurentia.

Coesite, a less well-known mineral than diamond, indicates that the pressure was at least as high. *Pseudomorphs* of coesite are found in many places in the northern part of west Norway. These pseudomorphs are composed of quartz which replaced the coesite crystals while still preserving the characteristic crystal shape of coesite. Coesite is otherwise found in connection with meteorite impacts, since its formation requires extremely high pressure, but preferably not a very high temperature. This may imply that the collision took place quite rapidly. Rates of movement up to some 10 cm a year are likely. The rocks were at any rate rapidly carried down to a great depth. It takes time to heat up rock, and high-pressure minerals such as diamond and coesite were formed before the temperature reached what is normal for these depths.

When did the collision take place?

It is not easy to determine just when a continent-continent collision takes place. Since the transition between continental and oceanic crust may be diffuse and irregular, the continents come into contact with each other at different times in different sites along the collision zone. The stratigraphic and radiometric dating methods are, moreover, uncertain and the interpretation of the dating results is seldom entirely unambiguous. Furthermore, a collision between continents is a slow, complex process that develops over a long period of geological time.

Radiometric dates from the Western Gneiss Region show a wide scatter, and even though they have been used to support initial continent-continent collision around 425 million years ago, the uncertainty is great. Moreover, the youngest fossiliferous beds that are involved in the collision are of Early Silurian age (ca. 430-425 million years). This indicates that the collision is younger than 430 million years, but since sand and clay are deposited continuously during orogenesis, this is not a reliable criterion either. It is more trustworthy to use dates on the youngest components of the island-arc systems. Their geochemical evolution shows that their formation was complete before the actual collision took place; hence, the youngest granitic island-arc components give a maximum age for the closure of the Iapetus Ocean. Radiometric age determinations suggest that these granites are about 430 million years old. Until more precise dates are available, it can therefore be estimated that the violent collision between the two continents was in progress around 425 million years ago. This event is generally referred to as the *Scandian Phase.*

How did the basement tackle the collision?

The collision of the continents led to the Baltica basement colliding with Laurentia, or with one or more microcontinents that may have existed between them. Furthest from the collision zone, in the foreland area, the basement is not visibly deformed. Beneath the nappes, the Caledonian deformation may reach a few metres or tens of metres down. In addition, weak folding of the sub-Cambrian peneplain beneath the nappes can be discerned. The amplitude of these folds may reach several kilometres. However, the effect is extremely mild relative to what takes place above the peneplain. This is called a classical *thin-skinned deformation style.*

Deep-seismic data from the 1980s indicate that the basement may not be as unaffected as many earlier

The basement along Sognefjorden has been kneaded like dough during the Caledonian orogeny. (Photo: H. Fossen)

workers believed. Many of the well-known basement windows, like the Alta-Kvænangen window, the Rombak window, the Børgefjell window, the Tømmerås window, the Grong-Olden culmination and the Western Gneiss Region, are probably to a certain extent affected by Caledonian and post-Caledonian deformation. Deep-seismic profiles show seismic reflections that probably identify shear zones (both Caledonian thrust zones and Devonian extensional shear zones) beneath several of the Caledonian windows.

As the central zone of the orogenic belt is approached, the basement has suffered really severely. Precambrian structures are flattened, and foliation or banding has been produced that is more or less parallel with the Caledonian foliation in the overlying nappes. It becomes difficult to decide whether the basement should be considered autochthonous, locally transported (par-autochthonous) or substantially thrust (allochthonous). This especially applies where it is exposed in windows that are isolated from the autochthonous basement in the marginal zone of the mountain chain. The collision zone itself can be expected to contain detached sheets of basement and everything from autochthonous basement to long-transported basement nappes.

The stacking of nappes

During the period when the Laurentian and Baltica continents were approaching each other and ultimately colliding, rock units were detached and transported, some for a long distance, towards the foreland in an impressive wedge-shaped pile of nappes. A general division into Lower, Middle, Upper and Uppermost Allochthons (nappe series) is much used, even though it may be problematical in some places to classify bedrock units using this division.

Lower Allochthon – detached, but local

The Lower Allochthon comprises rock units that are completely detached from their original location, but have not been transported as far as the overlying nappe units. The rocks in these nappes are remains of sedimentary deposits on the Baltic Shield or the Baltica margin from the time prior to the collision. They show evidence of having been deformed and metamorphosed under conditions of relatively low pressure and temperature. The lowermost sparagmite nappes in the foreland area in southern Norway and the Gaissa Nappe in Finnmark are examples of this. The term also covers basement sheets at the base of the nappe wedge that have been detached, but not transported very far.

Middle Allochthon – continental margin travellers

Continental nappes overlie the Lower Allochthon units, and these also belong to the Baltica margin, or to microcontinents or basement islands that may have existed in the ocean separating Laurentia and Baltica. These nappes consist of basement units with or without Late Proterozoic to Cambro-Silurian deposits, but having a higher grade of metamorphism than the Lower Allochthon. The Jotun and Kvitvola nappe complexes in south Norway, the Särv Nappe in central Norway and parts of the Kalak Nappe Complex in Finnmark are good examples.

Flattening of the basement during the collision.
TOP: Migmatitic gneiss with Precambrian structures.
BOTTOM: Flattened version of the same rock. (Photo: H. Fossen)

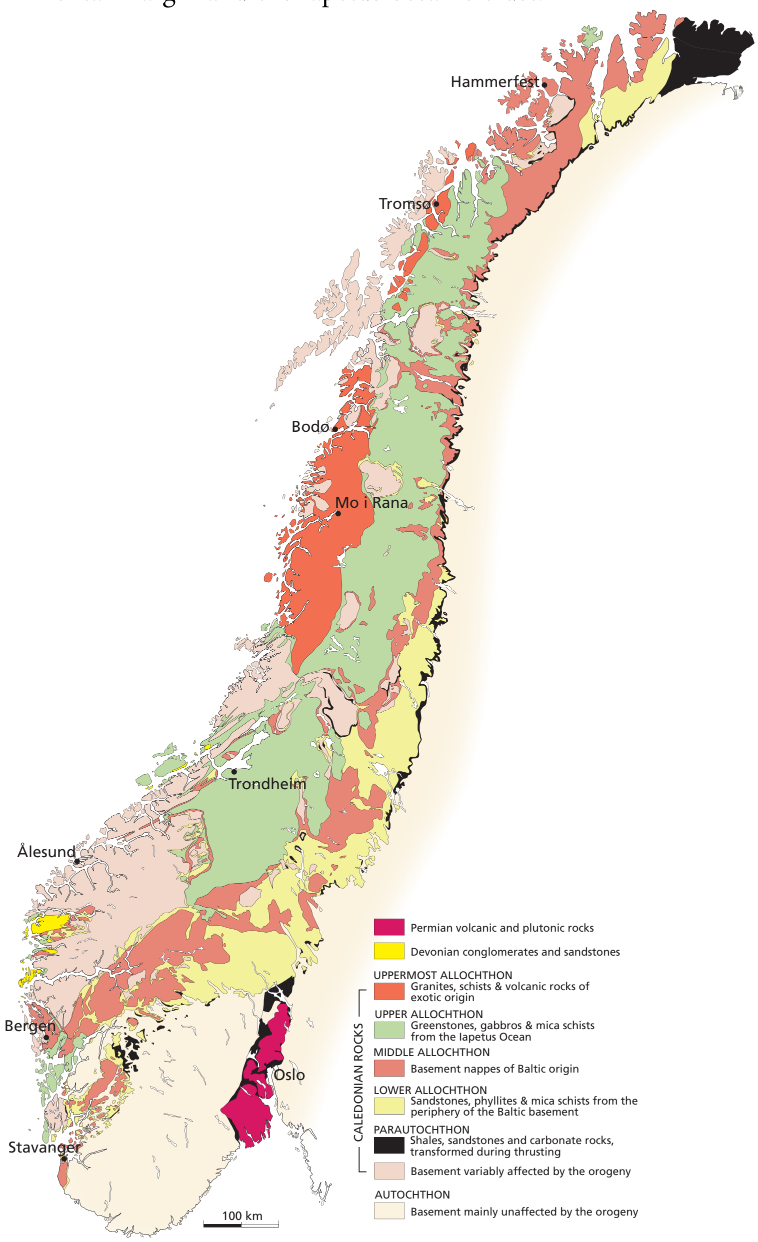
MYLONITE

Mylonite is a term that was seriously introduced into Norwegian geology in the 1970s. This was when geologists became aware of the intense deformation to which many Caledonian nappes had been exposed. Rock that is being progressively strained in the middle or lower crust passes from an undeformed state to protomylonite, mylonite and finally ultramylonite. If a granitic rock is being deformed, minerals like quartz and mica will recrystallise, whereas feldspar will tend to be crushed, provided the temperature is not too high (not above about 550 °C). The general grain size will be reduced while large grains of feldspar known as augens remain (augen gneiss). If the deformation is sufficiently intense, most of the feldspar augens also disappear and the rock becomes fine-grained (ultra)mylonite. It is important to recognise mylonites in orogenic belts because they indicate important movement zones. Through much of the 20th century, many such fine-grained rocks were wrongly interpreted. Mylonitised granites in particularl were interpreted as meta-arkose, "leptite" or rhyolite. This resemblance was realised in the 1970s and 1980s, and the mylonite zones began to be mapped correctly, as zones of intense shearing. The mylonites were immediately interpreted as Caledonian thrust zones. Now we know that some of them are later extensional shear zones (see Chapter 7).

Mylonitic augen gneiss (Photo: H. Fossen)

Upper Allochthon – ocean floor on land

Many of the nappes that are classified as belonging in the Upper Allochthon are quite different from the underlying ones. The rocks found here show great variations in composition, style of deformation and degree of metamorphism, and include gabbros, greenstones, granitoids, polymict conglomerates, marbles, mylonites, mica schists, gneisses and ultramafic rocks. Some of the typical metasedimentary rocks are of Ordovician to Lower Silurian age. The oceanic crust and island-arc systems from the Iapetus Ocean have ended up here, piled up on the continental nappes, just as would be expected following a proper continental collision. All the ophiolites belong in this Upper Allochthon or in the Uppermost Allochthon. The classical Seve-Köli Nappes, which have a more varied composition, are also situated here. The rocks of the Seve Nappes probably represent the transition between the continental margin and the Iapetus oceanic crust.



MAP ON RIGHT
The tectonostratigraphy of the Norwegian Caledonides.

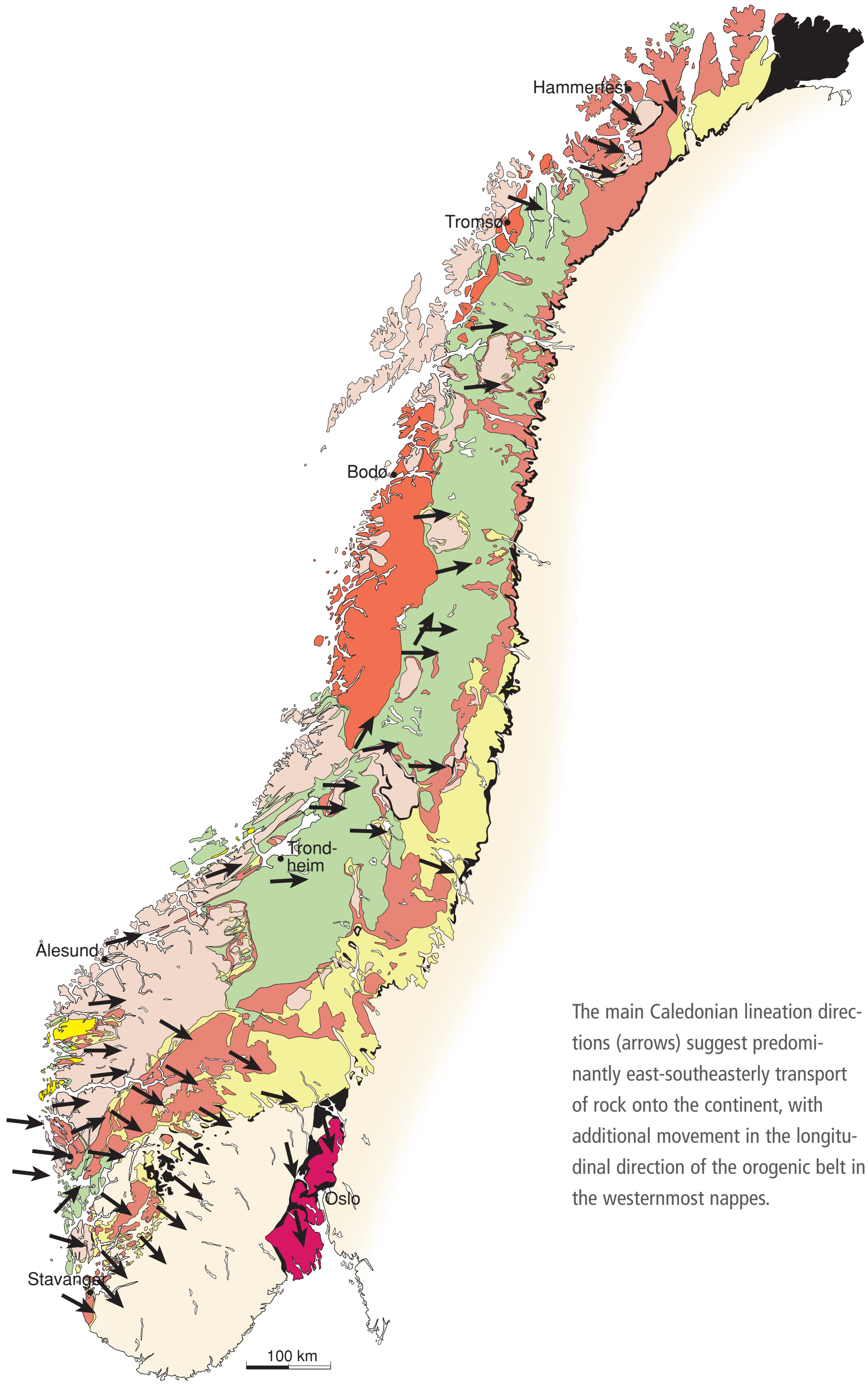
Visitors from America?

Nordland and Troms also have nappe units located above the oceanic units of the Upper Allochthon. These rocks seem to derive from a continental margin related either to the eastern margin of Laurentia or to a micro-continent between Laurentia and Baltica. The Helgeland, Rödingsfjället and Tromsø nappe complexes are the names given to the Uppermost Allochthon in the Scandinavian Caledonides.

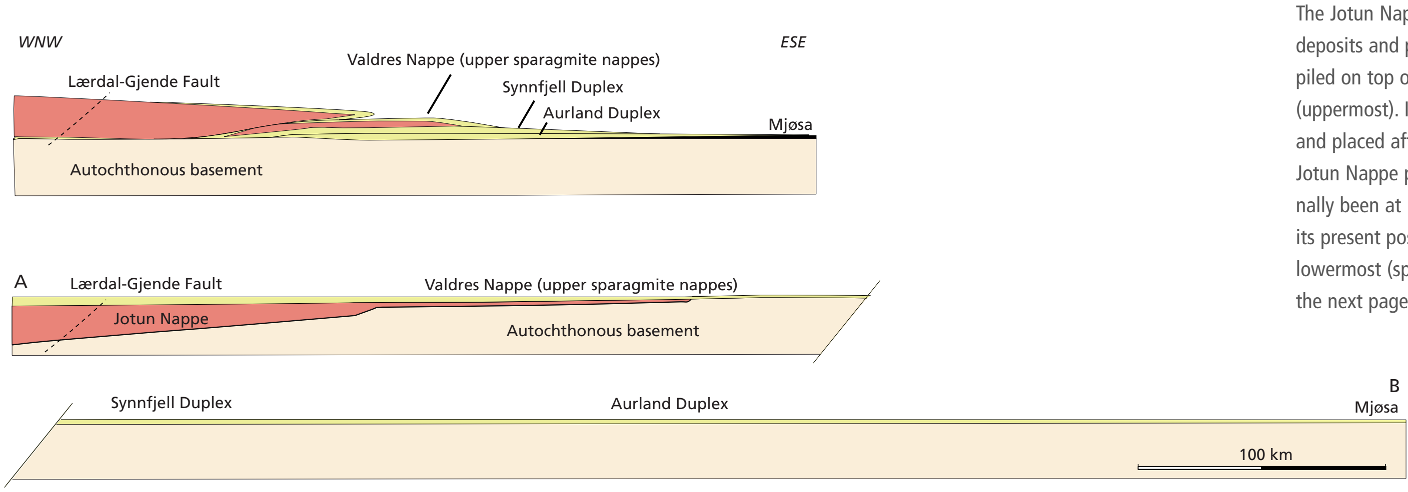
Lineations and transport directions

The general geological setting clearly shows that the Caledonian nappes were transported from the coastal or oceanic areas onto the continent during the collision between Baltica and Laurentia, but the precise direction of the movement is perhaps not so easy to determine. However, *stretching lineations*, linear structures found in deformed, locally mylonitic rocks, can be used as a clue. Such lineations are rod-shaped minerals and drawn-out augen and conglomerate clasts, and they reflect the stretching direction of the rocks. Applied with a little care, it can be assumed that this direction also reflects the transport direction.

On the whole, the lineation pattern shows that the nappes were transported in an easterly to south-easterly direction. In the southernmost areas of nappes, a shift is found from easterly transport via southeast to a south-southeasterly direction in the Oslo graben. Such patterns probably express variations in the transport direction perpendicular to the mountain chain. Lineations that trend almost parallel to the coast are also found at several places in the Uppermost Allochthon. They may indicate that movement also took place parallel to the collision zone in central parts of the orogenic belt, which agrees with an oblique collision between the Laurentian and Baltica continents.



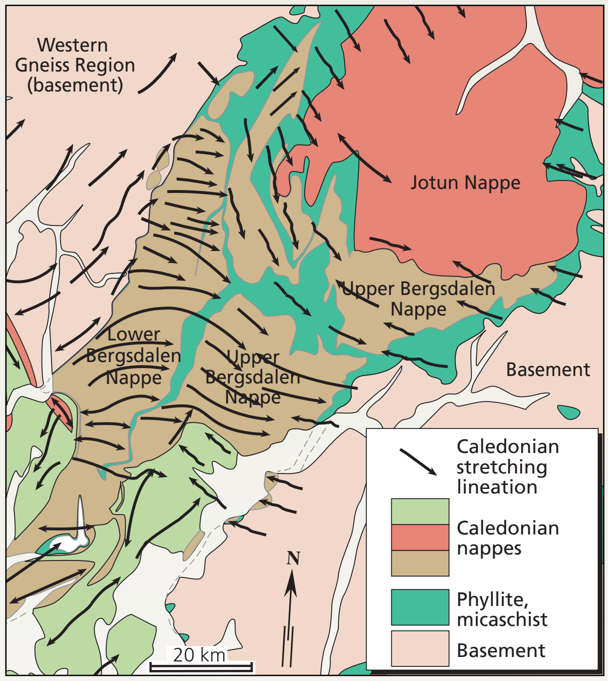
The main Caledonian lineation directions (arrows) suggest predominantly east-southeasterly transport of rock onto the continent, with additional movement in the longitudinal direction of the orogenic belt in the westernmost nappes.

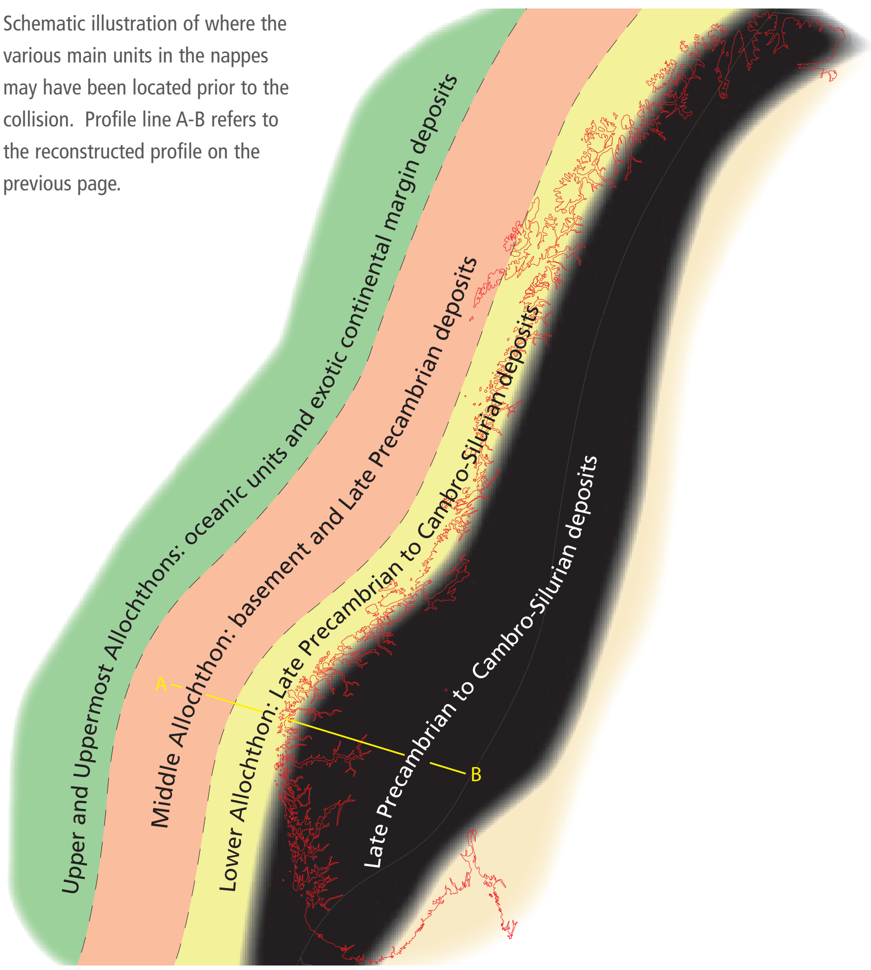


The Jotun Nappe, sparagmitic deposits and phyllitic rocks now lie piled on top of one another (uppermost). If they are drawn out and placed after one another, the Jotun Nappe proves to have originally been at least 300 km west of its present position, as the lowermost (split) profile shows. See the next page for location.

LINEATION DIRECTIONS AND NAPPE TRANSPORT

The Bergsdalen Nappes is the name Anders Kvale gave to a nappe complex squeezed between the Jotun Nappe and the basement and mica schists of the décollement zone east of Bergen. They consist of Precambrian rocks with intrusive rocks and supracrustals that resemble the Telemark Group. During the Second World War, Anders Kvale studied the lineation pattern in these nappe rocks. Whereas many people at the time assumed that lineations in nappes generally formed perpendicularly to the movement direction, Kvale argued that the movement had taken place in the lineation direction. He won considerable recognition for his work and helped to enhance our understanding of the substantial movements that have taken place in both the Caledonian and other orogenic belts.





Schematic illustration of where the various main units in the nappes may have been located prior to the collision. Profile line A-B refers to the reconstructed profile on the previous page.

How far have the nappes been moved?

To answer this question, an attempt must be made to reconstruct the mountain chain. The eastern and lowermost units in the nappe pile, the Late Precambrian to Silurian shallow-water deposits, are fragmented and packed together in *imbrication zones* or *duplexes*. The Gaissa Nappe in Finnmark, and the Moelv, Aurdal and Synnfjell duplexes in the Osen-Roa Nappe Complex in south Norway, are good examples. Each fragment must be moved back into place to find the original westward extension of these strata. Above these compressed Late Precambrian to Silurian strata are sparagmite nappes that were originally located further west or northwest on the former continental margin, beyond the present-day coastline. The next element in the nappe pile is the detached basement in the Middle Allochthon. This was probably transported further, around 300 km. The Upper and Uppermost Allochthons in part had an even more westerly derivation. Information is lacking here since the oceanic crust, which probably lay between these ophiolitic and island-arc units, has been removed by subduction. However, it seems clear that a reasonable estimate is 300-400 km or more in the majority of cases.

Stretched out conglomerate clasts are examples of lineations that may help us to calculate both the transport direction and the deformation intensity. Rundemanen Formation near Bergen. (Photo: H. Fossen).

How long did the thrusting of the nappes last in Scandinavia?

Just when the Caledonian orogeny, the collision between Laurentia and Baltica, ended has been a disputed topic for a great many years. When did the converging plate movements cease and when did Greenland stop crashing against the Norwegian coast? These events may not necessarily have taken place simultaneously along the entire collision zone. The last signs of Caledonian thrusting in the foreland are found in the Oslo region, where the Ringerike sandstone is gently folded as a consequence of the final nappe movements. This sandstone is of Ludlow and Lower Pridoli age, around 423-418 million years, and was at a varying depth during the folding; some was newly deposited sand and some was buried to a depth of several kilometres. The final nappe movements in the foreland near Oslo must therefore be younger than about 415 million years. This calculation agrees with recent information from the nappe pile in the west, where sedimentary deposits of Lower Silurian age are found. The Skarfjell Formation in the Bergen Arcs is a good example. Here, basic dykes intruded the Silurian succession before the entire area was exposed to strong Caledonian deformation. Recent isotope dating of the deformed dykes suggests that the deformation took place approximately 415 million years ago.

Some dates are available from the area between west Norway and the Oslo region which suggest that nappe movement there lasted somewhat longer. Since isotope dates of around 405 million years have been obtained from thrust-related mylonites beneath the Jotun Nappe, the stacking of the nappes there seems to have continued into the Early Devonian. Moreover, some mylonites in the same area show evidence of having formed (or been rejuvenated) during the later, post-Caledonian backward sliding of the nappes (see Chapter 7). The ages for these mylonites group around 400 million years and suggest that collision had ceased and collapse and extension were in full swing at this time. The major nappe thrusting on the mainland thus seems to have taken place in Silurian and Devonian times and was complete between 400 and 405 million years ago. This should mean that the Caledonian orogeny lasted 100 million years, from the first subduction zone becoming established in the Iapetus Ocean until the stacking of the nappes was complete – a respectable duration of activity for an orogeny.

Finnmark – a compressed platform

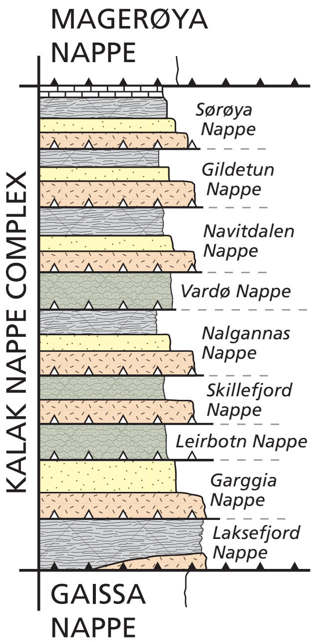
When you travel westwards over Finnmarksvidda, it is difficult to avoid noticing the marked shift from the drift-covered and partially deciduous-wooded plateau to the hilly terrain in the west. In many places, the shift is a marked escarpment, and the hills, or gáissi as they are called locally, are built of hard rocks with quite a different history to recount than the ancient basement on the plateau.

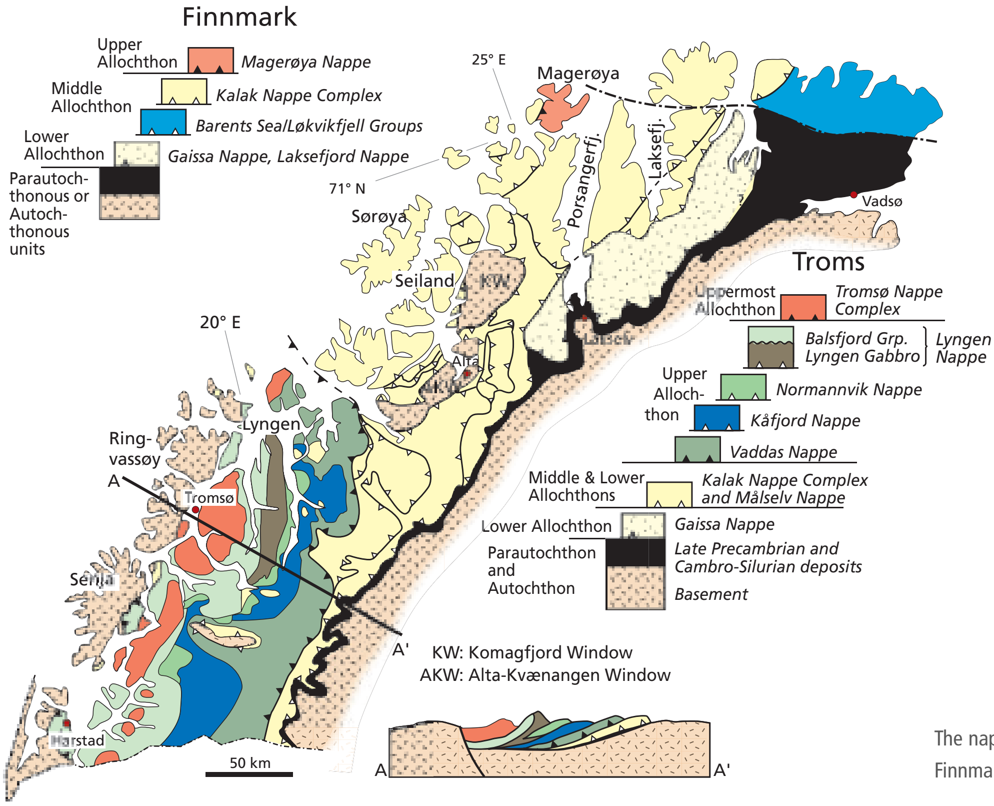
Sandstone, siltstone and shale, the lithified products of sand and clay deposited on the Finnmarksvidda basement in the Late Proterozoic and the Cambrian, crop out in the escarpment. We could follow these relatively thin Cambrian deposits southwards all the way to the Oslo region, but this would mostly necessitate travelling through Sweden. On the Norwegian side of the border, the Cambrian beds, which form the uppermost part of the Dividalen Group here in the north, are best represented in Troms and Finnmark.

Quartzites that are obviously folded and compressed overlie the Cambrian deposits uppermost in the escarpment. We have now climbed up into the lowermost of the Caledonian nappes, the Gaissa Nappe. These quartzites are a little older than the Cambrian beds beneath, and were deposited somewhere further west before being thrust over the shales and sandstones during the Caledonian orogeny. The escarpment is thus the Caledonian thrust front as it presents itself today.

Our journey continues north-eastwards, following the sub-Cambrian beds. They rapidly increase in thickness until they eventually form a succession of Late Precambrian to Cambrian sandstones, siltstones and shales that is more than 4 km thick and comprises the Vadsø, Tanafjorden, Vestertana and Digermulen Groups. This is on the southern part of the Varanger Peninsula. However, we can walk over this thick succession and return to the Gaissa Nappe near Laksefjorden. How does this fit in? The explanation must be that the thrust beneath the Gaissa Nappe, and the boundary of the Caledonian orogenic belt, dies out eastwards.

The sandstones in the Gaissa Nappe here at Austertana in east Finnmark are distinctly folded. One of the world's largest quartzite quarries (operated by Elkem Tana) dominates the landscape to the right. (Photo: S. Bergh)





Tectonostratigraphic map of the allochthons in Troms and Finnmark. All the nappes in the Kalak Nappe Complex have slices of Precambrian rocks (orange) overlain by feldspathic quartzite (yellow) and mica schist.

The nappe pile in Finnmark and Troms.

The northern part of the Varanger Peninsula is also worth a visit. The sandstones, siltstones and shales there are probably related to those in the south, but they are separated by a major fault, the Trollfjorden-Komagelva Fault Zone, which was active both before and during the Caledonian orogeny. Before the Cambrian, during the Timanian orogeny (see Chapter 4), the crustal block to the northeast of the fault was translated several hundred kilometres south-eastwards at the same time as the succession was folded. The successions on both sides of the fault zone were again disturbed during the Caledonian orogenic movements. The strata to the north were once more translated south-eastwards, at least 50 km. The Caledonian folding of the succession in Finnmark can be compared to what may take place when a heavy chest of drawers is dragged across a carpet. The carpet ahead of it is crumpled if it is not held taut. The “chest of drawers” in Finnmark is the Kalak Nappe Complex.

The Kalak Nappe Complex

The Kalak Nappe Complex is a pile of rock sheets resembling a pack of cards. It has been transported scores of kilometres and is considered to be either the Middle Allochthon or the lower part of the Upper Allochthon. The sheets have one thing in common; they consist of older (Precambrian) basement overlain by younger (Late Precambrian to Cambro-Silurian) metasediments. The basement is granite and gneiss from the westerly continuation of the Finnmarksvidda basement, while the overlying metasediments are mica schist, metasandstone, quartzite, amphibolite and marble. The succession on Sørøya, an island in west Finnmark, became classical many years ago because the strata are recognisable in several nappes in west Finnmark, thus enabling reconstruction of the nappes from before their disruption and thrusting during the orogeny. The Sørøya-Seiland Nappe also stands out from the underlying units in the Kalak Nappe Complex by containing a large accumulation of plutonic rocks called the Seiland Igneous Province.

Kalak Nappe rocks. The light-coloured quartzitic rock derives from the pre-collision Norwegian continental margin. The dark lenses (boudins) and bands are metamorphosed dolerite dykes which were partially dismembered during the Caledonian orogeny. Porsanger, Finnmark. (Photo: S. Bergh)

A PRELUDE TO THE OROGENY

There are many indications that Laurentia and Baltica began to converge about 500 million years ago, and that collisions between island arcs and continents, and ultimately between Laurentia (Greenland) and Baltica (Scandinavia), took place over the succeeding 90 million years. Data from east Finnmark and Russia show that a plate collision also took place along the Timanian marginal zone on the north-eastern margin of Baltica about 600-560 million years ago. This was the Timanian orogenic belt which, on the Russian side, comprises island arcs and subduction zones, and involved thrusting and folding. The collision along the eastern part of the Varanger Peninsula has a crustal shortening direction that differs clearly from that indicated by the Caledonian folds and thrusts. Whereas Caledonian deformation structures suggest a northwest-southeast direction of crustal shortening, the folds furthest east on the Varanger Peninsula display northeast-southwest crustal shortening which must have taken place before the Caledonian orogeny in Finnmark, and studies in the Kalak Nappe Complex also show that the nappe rocks carry traces of a Late Proterozoic orogeny, which may mark the north-westward extension of the Timanian orogenic belt (see Chapter 4).

The lowermost parts of the Kalak Nappe Complex also contain metamorphosed feldspathic sandstones (meta-arkoses), whose precursors were deposited in rhythmic pulses that resulted in alternating sandstones and thin shales. Since the forces acting during the Caledonian orogeny gave these rocks a marked schistosity in many places, they split readily along parallel planes, making the rock very suitable as flagstone and roofing slate, marketed as Alta Slate.

Other parts of the Kalak Nappe Complex are also highly deformed. Several generations of folds and thrust faults (with mylonitisation) are recognised, and the metamorphic grade was also higher here than in the lowermost and easternmost nappes. Special interest has been attached to the succession on Sørøya. When the Caledonian nappe rocks in Finnmark were mapped in the 1970s and 1980s, the succession on Sørøya was considered to be older than the main thrusting of the nappes in the orogenic belt further south in Norway. There was said to be a separate orogenic phase in Finnmark, even called the *Finnmarkian orogeny*. Before long, "proof" of this Finnmarkian phase was also being reported from other parts of Norway. The reasoning behind the establishment of the so-called Finnmarkian deformation phase in Finnmark was that the intrusion of dolerite dykes dated to 490-540 million years seemed to be coeval with the folding and thrusting in the area. Recent studies of the intrusive relationships and new radiometric dates have, however, shown that the dykes intruded before the metasediments were deformed. Moreover, what were considered to be Finnmarkian structures in the Sørøya succession on the Porsanger Peninsula are cut by granites that are older than 700 million years. Consequently, the main basis for a Finnmarkian phase, as it was originally defined, no longer exists. It is true that 500 million-year-old eclogites in the Seve Nappes suggest that there was an orogenic event at that time, but using the term "Finnmarkian" for that phase further south in the orogenic belt results at best in geographical confusion.

The Alta flagstone is metamorphosed Late Precambrian sediment that was foliated during the Caledonian orogeny. It has been quarried for use both indoors and outdoors for around 100 years. (Photo: T. Heldal)

Zircons from the island of Seiland are not just beautiful and sought after by mineral collectors, they are ideal for age determinations using the uranium-lead method. They are just over 550 million years old, that is, from the very latest Precambrian. (Photo: H. Fossen)

The Magerøya Nappe

The uppermost Caledonian nappe in Finnmark is named the Magerøya Nappe, and this is the only tectonic unit in Finnmark that is allocated to the Upper Allochthon. The rocks are for the most part less strongly metamorphosed than those in the Kalak Nappe Complex and consist of characteristic calcareous metasiltstones, sandstones and conglomerates. Interesting finds of Ordovician-Silurian fossils have been made in these rocks, which permits them to be compared with similar rocks in the Upper Allochthon further south in northern Norway.

The Seiland Igneous Province – deep parts of an ancient rift valley?

Stjernøya is world famous for its “superfeldspar”, mined for the ceramics industry. However, this product from the mine on Stjernøya is not actually feldspar, but mainly a related mineral called nepheline (a feldspathoid). Nepheline is one of the principal minerals constituting nepheline syenite, one of several igneous rocks found on the islands of Seiland, Stjernøya and Sørøya, and in the Øksfjord area on the mainland, and which belong to the Seiland Igneous Province. These plutonic rocks intruded a succession dominated by metasandstones and schists which together make up the Sørøya-Seiland Nappe in the uppermost part of the Kalak Nappe Complex. The Seiland rocks are generally linked to the Neoproterozoic deposits found in the underlying nappes that are associated with Baltica. If the Seiland Igneous Province, with its enveloping metasediments, is part of Baltica, the Sørøya-Seiland Nappe must represent the westernmost margin of Baltica, since a nappe of exotic rocks (the Upper Allochthon) is found immediately above the Sørøya-Seiland Nappe.

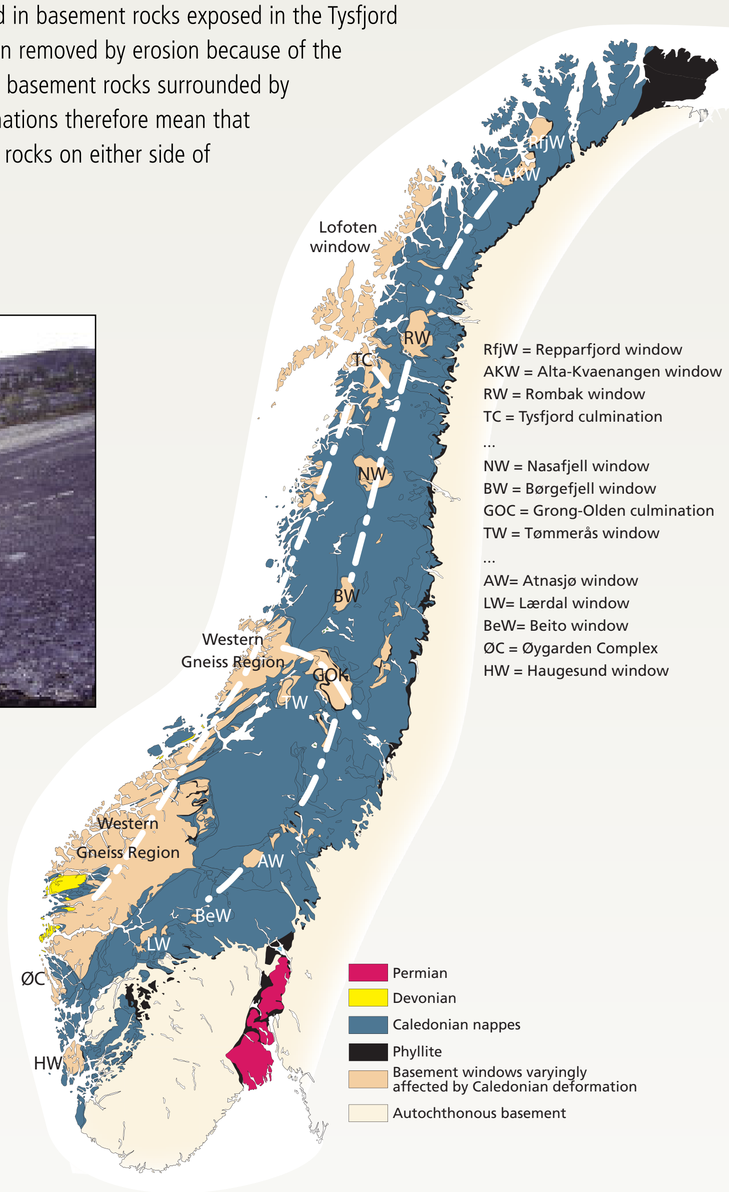
Since the Seiland Igneous Province includes nepheline syenites and carbonatites, the implication is that it represents the deeper part of a Late Proterozoic continental rift valley, because such rocks are closely associated with continental rifts, as in the East African Rift Valley for instance. Recent age determinations, which show that key plutonic rocks in the Province are 550-580 million years old, also support this interpretation. An alternative interpretation is that the intrusion of magma took place in connection with a separate orogenic event in Finnmark, called the *Porsanger Peninsula Event.* A final conclusion regarding the origin of the Seiland Igneous Province must await more data.

WINDOWS REVEALING THE SUBSTRATE OF THE OROGENIC BELT

The orogenic belt ends rather abruptly eastwards along a border that is mostly situated in Sweden, except where it crosses Finnmark. The nappes take over west of this border, but the basement is not entirely forsaken even if we travel westwards into the Caledonian nappes, because a number of culminations or domes follow the north-easterly trend of the orogenic belt. These allow us to glimpse the basement through tectonic windows. The Caledonian basement windows are situated along two almost parallel zones, an easterly culmination represented by the basement windows fairly close to the Swedish border (the Rombak and Tømmerås windows, etc.), and a westerly one represented by the more high-grade metamorphic rocks along the coast from Bergen to Troms (e.g. Lofoten and the Western Gneiss Region).

The major areas of granite with little vegetation cover seen when travelling from Saltfjellet or Bjørnfjell towards Narvik, belong to the easterly row of culminations. In addition to these culminations, which follow the Swedish border, there are two important culminations transverse to the mountain chain, one in the Lofoten-Tysfjord area and the other in the Grong-Olden area. The fantastic granite slabs that characterise the Tysfjord-Hamarøy area, including Stetind, are formed in basement rocks exposed in the Tysfjord culmination. The overlying nappes have been removed by erosion because of the up-doming, resulting in domes or islands of basement rocks surrounded by Caledonian schists and gneisses. The culminations therefore mean that in many places it is difficult to correlate the rocks on either side of the domes.

Granite slab in Tysfjord. (Photo: E. Rykkelid)



The impressive Šávču Canyon, with the River Alta in the bottom. The river has eroded down through the lower nappes (the Lower Allochthon) into the Dividal Group, the Late Proterozoic to Cambrian deposits over which the Finnmark nappes slid during the orogeny. (Photo: Norsk Bildebyrå)

Corals and ocean floor in Troms and northern Nordland

The lowermost nappes, so well represented in Finnmark, are sparingly present in Troms and northern Nordland, which, instead, are dominated by exotic terranes belonging to the Upper and Uppermost Allochthons. These nappes have been transported much further than most of the Finnmark nappes.

The nappes belonging to the Lower and Middle Allochthons, which are so widespread and thick in Finnmark, also occur in Troms (the Målselv Nappe and the Kalak Nappe Complex), but become much thinner here. They are partly composed of feldspathic metasandstones and schists corresponding to those found in the sparagmite nappes further south, and originated in a depositional basin located on continental crust that stretched north-westwards from where they are now situated. They are overlain by the Upper Allochthon, including the Vaddas and Kåfjord nappes (mica schists, marble, quartzite and amphibolite), the Nordmannvika Nappe (garnet-kyanite gneisses, mylonites and sagvandite) and the Lyngen Nappe or Lyngsfjellan Nappe (gabbro and metasediments). Some geologists choose to place the latter in the Uppermost Allochthon, but in Troms this is generally restricted to the Tromsø Nappe Complex.

Neither the age nor the origin of the rocks in the exotic nappes in Troms is known, but there are some clues, not least because some characteristic fossiliferous marble units can be traced from islands northwest of Lyngen in the north to beyond Ofoten in the south. Furthermore, a few new age determinations are available on important units. A characteristic feature of several of the exotic terranes is the great variation in rock types. Large areas of limestone or marble and dolomite are found in several of the nappes, and these are quarried in some places.

The Balsfjord conglomerate in Troms, flattened and folded.
(Photo: S. Bergh)

The exotic terranes occur in different thrust sheets and the grade of metamorphism and the degree of deformation often vary greatly from one thrust sheet to another. The same applies to the quantity and types of plutonic rocks found in the various thrust sheets. A few of these plutonic rocks have been dated recently using the uranium-lead method, and this has provided more specific information about the evolutionary history of a few of the exotic terranes. Since age determination of plutonic rocks only gives a *minimum age* for the deposition of the beds they have intruded, there is still great uncertainty regarding when the successions in the exotic nappes were deposited.

Fossils

Fossils have been discovered in the exotic nappes in two parts of the Troms-Ofoten region. Corals, and crinoid and brachiopod fragments have been found in metamorphosed limestone in the mountains southeast of Kåfjord (in the Vaddas Nappe) in northeast Troms, and a similar fauna occurs in graphitic marbles and dolomite in the Lyngen Nappe beside Balsfjord and further southwest near

The Lyngen Alps consist mainly of gabbro from the ancient Iapetus Ocean between Norway and Greenland. The layering formed when the gabbro magma crystallised, and is an alternation of layers rich in plagioclase and pyroxene and amphibole, respectively. (Photo: S. Bergh)

Sagelvvatnet. Diagnostic fossils found close to Sagelvvatnet are chain corals, including *Catenipora maxima* and *Catenipora distans.* None of the fossils is particularly well preserved, and it requires the observant eyes of an alert field geologist to recognise them as traces of Cambro-Silurian animals. However, the fossils are adequately preserved for palaeontologists to be able to estimate their age as around 450 million years, that is, Late Ordovician or Early Silurian. Even though the fossiliferous limestones prove to have approximately the same age, they occur in two completely separate nappes.

The fossiliferous rocks near Sagelvvatnet have provided important information helping us to understand the development and origin of the exotic terranes in this part of the orogenic belt. They form part of the Balsfjord Group, a pile of sedimentary rocks that is up to 10 km thick and was deposited in a basin above an eroded remnant of old ocean-floor crust (an ophiolite fragment), now represented by the Lyngen Gabbro. The Balsfjord Group, which consists of low-grade metamorphic sandstones, phyllites, greenstones, micaschists, limestone, dolomite and several horizons of characteristic conglomerates, lies discordantly above and west of the Lyngen Gabbro. The clasts in the conglomerates include greenstone, which derives from the underlying Lyngen Gabbro, and marble and quartzite, perhaps from underlying nappes and other unknown island-arc settings.

The largest ophiolite fragment in the Caledonides

The Lyngen Gabbro takes up the greater part of the Lyngen Peninsula and is the largest known ophiolite fragment in the Scandinavian Caledonides, but it

On the summit of Tromsdalstind is eclogite which originated at a depth of 80 km. (Photo: S. Bergh)

displays in no way a complete section through typical ocean-floor crust as known from spreading ridges and more complete ophiolite complexes. On the other hand, it contains remnants of at least two ocean-floor fragments divided along the length of the peninsula by a major, perhaps transform, lateral fault. This fault is recognised by extensive shearing and by being the locus of lensoid bodies of ultra-mafic rocks (serpentinite and pyroxenite), as well as numerous mafic and felsic intrusives. The chemical composition of the eastern part of the Lyngen Gabbro is "boninitic", which shows that it was formed near a subduction zone, whereas the western part of the gabbro contains fragments of layered gabbros, dyke complexes and overlying pillow lava of the type found close to modern spreading ridges.

The fact that both the Lyngen Gabbro and the discordant, overlying, carbonate-rich sedimentary rocks in the Balsfjord Group can be traced more or less continuously from islands northwest of Lyngen in the north to beyond Ofotfjorden in the south is important for the regional correlation of the units in the Upper Allochthon. Some of the carbonate-rich rocks that predominate over large parts of Troms and northern Nordland may be of Upper Ordovician age. This is supported by age determinations which show that the ophiolite fragments forming the substrate for the carbonate-rich rocks in Balsfjord and Ofoten are approximately 480 million years old. However, there are also older (Late Proterozoic) carbonate-rich rocks in the region, and these can be distinguished by carbon and strontium isotope analyses.

Long development

The observations mentioned above demonstrate another very important aspect regarding the exotic terranes in the Upper Allochthon in Troms and northern Nordland; they have undergone a long geological development. The presence of fossiliferous carbonate-rich rocks in the deeper parts of the old ocean floor implies substantial tectonic activity after the ocean floor formed approximately 480 million years ago, but before the sediments were deposited about 450 million years ago. This tectonic activity must have included uplift of the ocean floor, erosion and then subsidence and basin formation.

The Uppermost Allochthon in Troms probably represents an exotic fragment which may derive from the portion of the Laurentian Shield that collided with Baltica. The Tromsø Nappe Complex crops out in the outer part of the Malangen Peninsula and in areas west of a line from Ullsfjord to southern Senja. It is usually divided into three main portions, mylonitic gneisses lowermost, overlain by a peculiar amphibolitic gneiss (the Skattøra Gneiss) and, uppermost, carbonate-rich metasedimentary rocks with a number of eclogites and ultramafic rocks. The eclogites show that the rocks in the Uppermost Allochthon were formed at extremely high pressures and a great depth in the crust before being carried landward onto the Baltic Shield region.

From a depth of 80 km to the summit of Tromsdalstind

The 1238 m peak of Tromsdalstind, with its permanent snow fields, towers high over the city of Tromsø. In addition to being a well-known landmark and popular hiking and skiing destination, it is a geological treat because red and green mottled eclogite occupies the upper slopes of the summit, along with amphibolites and marbles in the uppermost part of the Tromsø Nappe Complex.

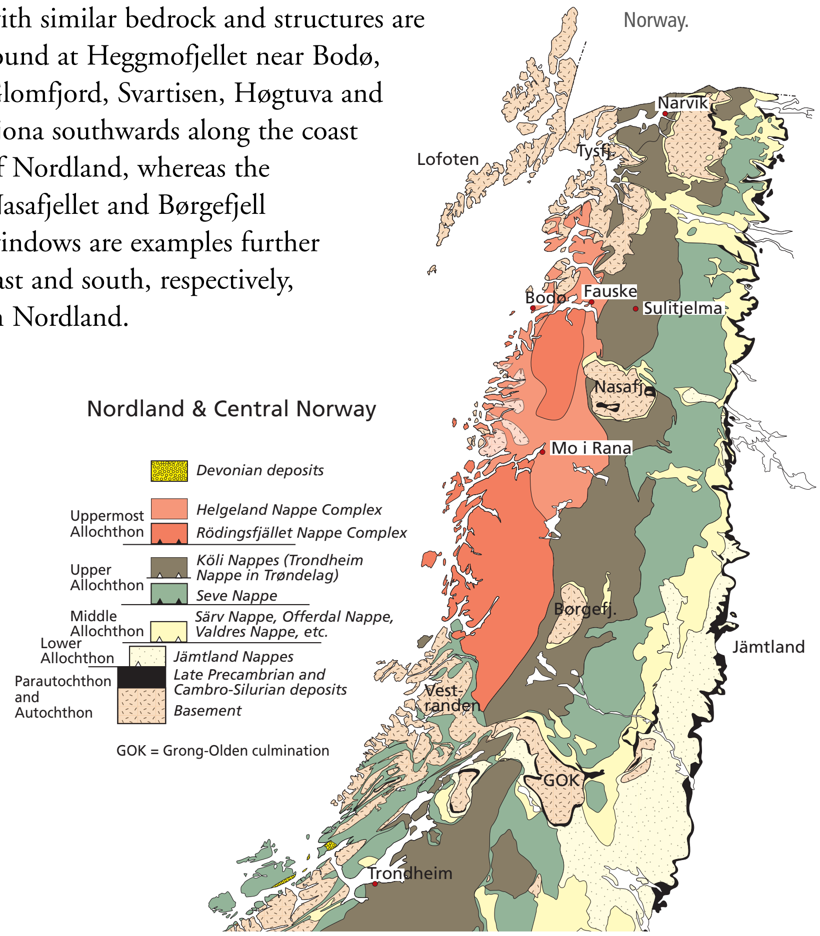
The eclogites in the Tromsø Nappe Complex occur as large and small lenses in coarse-grained marbles, or as more continuous layers alternating with various kinds of gneiss. The lens-shaped bodies of eclogite are thought to represent metamorphosed dolerite dykes that intruded the limestone beds before they were forced down to a great depth in the crust during an early phase in the evolution of the Caledonian orogenic belt. The chemical composition of garnets and pyroxenes in the eclogites suggests that they crystallised at temperatures of 725 °C and a pressure of 28 kbar, corresponding to a depth in the crust of some 70-80 km.

Age determinations suggest that the eclogites reached their maximum depth around 450 million years ago. They are therefore older than those found in the basement in the Western Gneiss Region (see Chapter 3) and pre-date the main collision between Laurentia and Baltica. Comparison between the age of formation of the eclogites and the depositional age (also about 450 million years) of the underlying fossiliferous rocks clearly shows that these two units must have had a very different derivation. It has therefore been speculated that the eclogite-bearing rocks around the summit of Tromsdalstind represent remnants of the collision or underthrusting zone associated with the eastern margin of the Laurentia Plate. During the subsequent main collision and the closure of the Iapetus Ocean, they must then have been transported eastwards over the only slightly metamorphosed fossiliferous rocks on which they now rest. The eclogites must, in any case, have been exhumed from a depth of some 80 km to near the surface in a space of 30 million years; geologists are still trying to work out just how and where this took place.

On the northern part of the island of Tromsøya, there are more indications that the rocks in the area really have been down at a great depth. The Skattøra Gneiss that is widely exposed here consists of dark, amphibolitic rock cut by light-coloured, plagioclase-rich hypabyssal rocks – anorthosite dykes formed by the melting of the amphibolite. Detailed field and laboratory studies of these rocks have shown geologists at the University of Tromsø that the temperature must have been as high as 900 °C to be able to melt this rock, and that this process must have taken place approximately at the same time as the eclogites were formed.

The granite slabs in Tysfjord

When you drive along the E6 highway between Narvik and Fauske you cannot avoid noticing the fantastic, naked, granite slabs that dominate the landscape and the geology in the Tysfjord-Hamarøy district. These granites are some 1800 million years old, and in the north they form part of the Lofoten-Tysfjord culmination. In many ways, they resemble the somewhat older mangeritic plutonic rocks further west in Lofoten and Vesterålen. These basement granites were incorporated in tight overfolds together with overlying nappes at a late stage in the evolution of the Caledonian orogenic belt. Other Precambrian granitic gneiss windows with similar bedrock and structures are found at Heggmofjellet near Bodø, Glomfjord, Svartisen, Høgtuva and Sjona southwards along the coast of Nordland, whereas the Nasafjellet and Børgefjell windows are examples further east and south, respectively, in Nordland.



Tectonostratigraphical map of the allochthons in Nordland and central Norway.

FAUSKE MARBLE

The major marble deposits in the Fauske Nappe derive from limestone and limestone conglomerate deposited furthest out on a shallow carbonate shelf off a coast more than 500 million years ago. The water was warm at that time, and Norway was probably located much further south than it is now. The carbonates were subsequently compacted, and then folded and metamorphosed during the emplacement of the Caledonian nappes.

Fauske marble has been chosen as the county stone for Nordland, partly because Nordland is the marble county above all others. The rock has had, and still has, great economic value, particularly the "Norwegian Rose" variety, which is one of the products at the prosperous Løvgavlen quarry in Fauske. The best-known varieties of marble consist of an alternation of red and pink calcareous marble and white dolomitic marble, called colour-banded marble, in addition to colour-banded conglomeratic marble. The marble can be readily split, and the natural surface that appears following the splitting has a very special play of colours. This has made Fauske marble unique in the world. The marble is extracted as blocks for export, and is sawn into plates that are polished to be used to face buildings and make floors and walls. Several well-known buildings in Norway and other countries have been decorated with Fauske marble, including Nidaros Cathedral in Trondheim, Oslo City Hall, Oslo Court House and Oslo Airport at Gardermoen. The UN Building in New York and the Emperor's Palace in Tokyo are also decorated with Norwegian Rose. A pure white variety of Fauske marble is also most important as raw material for lime burning, and for the cellulose and cement industries.

SEVE-KÖLI

The Seve-Köli Nappes is an old term in the Scandinavian Caledonides. The Swedish geologist, A.E. Törnebohm, introduced these two names in the 19th century. "Seve" was the name he gave to the quartzites and other non-fossiliferous schists and gneisses that overlie the Cambro-Silurian succession in the foreland area in Jämtland. He called the volcanic and metasedimentary strata above the Seve rocks, the Köli Group. These names are now used for nappes belonging to the Upper Allochthon in the orogenic belt on both sides of the border. The Seve Nappe contains large amounts of quartzite, quartz schist and amphibolite, and also some gneisses and migmatites. It is thought to represent a detached and far-transported distal portion of the Baltoscandian continental margin. The nappe must have been subducted deep enough to have undergone amphibolite to granulite facies metamorphism. Eclogites are also found in the Seve Nappe, and these seem to be older than those found in the basement, since they have given ages approaching 500 million years. They show that a subduction zone was active in the Iapetus Ocean as long ago as 500 million years and perhaps also around 450 million years ago.

Granitic rocks in the Rombak window. (Photo: S. Bergh)

A characteristic aspect of the granites in the windows is that they define elongate to circular domes, which explains why they were earlier thought to be Caledonian igneous rocks that had intruded the crust as diapirs in connection with the Caledonian orogeny. We now know that they are Precambrian and underwent large-scale folding together with the overlying nappe rocks, and were in part thrust together with these over the continental margin.

The granite slabs form metre-thick sheets or layers that are virtually peeling off the granite. This characteristic feature of granites is called exfoliation. Exfoliation takes place because of the build-up of stresses in an expanding body of rock. Such stresses may be caused by cooling or release of pressure linked with erosion following the peak of the Caledonian orogeny. Granites can also preserve stresses from the time they crystallised or were at a great depth. When a granite body reaches the surface, these stresses are released and it peels apart like an onion.

To the top of the nappe pile in Nordland

The highest nappes in the orogenic belt, the Upper and Uppermost Allochthons, are found between Tysfjord and Grong. The lower nappes are only seen in Sweden, to the east, or further south or north in Norway. The nappes in Nordland are divided into three principal units: (1) the Köli Nappes (Upper Allochthon), including the Gasak Nappe and the Fauske Nappe, (2) the Rödingsfjället Nappe Complex (the lowest part of the Uppermost Allochthon), and (3) the Helgeland Nappe Complex (the topmost part of the Uppermost Allochthon). These are all exotic or alien in respect of Baltica, and they differ from one another as regards both the age and the nature of the rocks. Moreover, it is difficult to decide from where they really derive, but enough is known to say something about the plate tectonic setting in which they formed.

The *Köli Nappes*, which extend into Norway from Sweden in the eastern part of Nordland, and also southwards from eastern Troms, are dominated by metamorphosed basic volcanic and sedimentary rocks. These rocks locally contain major copper deposits, for example at Sulitjelma. They also contain occasional fossils similar to those in the probably equivalent Vaddas Nappe. Copper deposits are also found at a corresponding level in the nappes in the Grong area in Nord-Trøndelag. The overlying Gasak Nappe contains great thicknesses of mica

Caledonian nappes in Nordland.
(Photo: H. Fossen)

schist and amphibolite. The *Fauske Nappe* occupies a belt between the Gasak Nappe and the Rödingsfjället Nappe Complex in central Nordland, and is dominated by thick calcareous and dolomitic marbles, mica schists and locally thick conglomerates, correlatable with the Balsford Group in Troms. The world famous Fauske Marble is also found here.

The *Rödingsfjället Nappe Complex* overlies the Fauske, Gasak and Köli nappes in a belt running from Røssvatnet in the south to Fauske in the north, and is at the base of the Uppermost Allochthon. This nappe complex is assumed to lie directly on the basement substrate in the west. In the Rana district, the succession is divided into the Beiarn Nappe and as many as seven smaller thrust sheets beneath. The Beiarn Nappe largely consists of granitic gneisses, whereas the underlying units are best known for their impressive calcareous and dolomitic marbles. Mica schists are also present, and locally contain major deposits of sedimentary iron ores, such as in the Rana district.

The *Helgeland Nappe Complex* is situated at the very top of the nappe pile in south-western Nordland and neighbouring Nord-Trøndelag. The boundary to the Rödingsfjället Nappe Complex is quite easy to follow on the east side of Korgfjellet down to Ranafjorden, but the boundary with the basement rocks in the west is more uncertain, because the rocks are rather similar. The main rock types in the Helgeland Nappe Complex are micaceous gneisses and mica schists, which are more highly metamorphosed than in the underlying units, and also large granitic intrusions (batholiths). Unlike the granites in the Precambrian windows, these are of Caledonian age. The high proportion of plutonic rocks is a characteristic feature of the Helgeland Nappe Complex; granites and granodiorites predominate, but monzonite, trondhjemite, tonalite, diorite and gabbro are also found. The impressive Seven Sisters ridge near Sandnessjøen is sculpted out of the granitic rocks in the Helgeland Nappe Complex.

Whereas the boundaries between the major nappe units in Nordland are everywhere defined as thrusts formed during the Caledonian translation, as the next chapter describes, they are also affected by later, extensional tectonics.

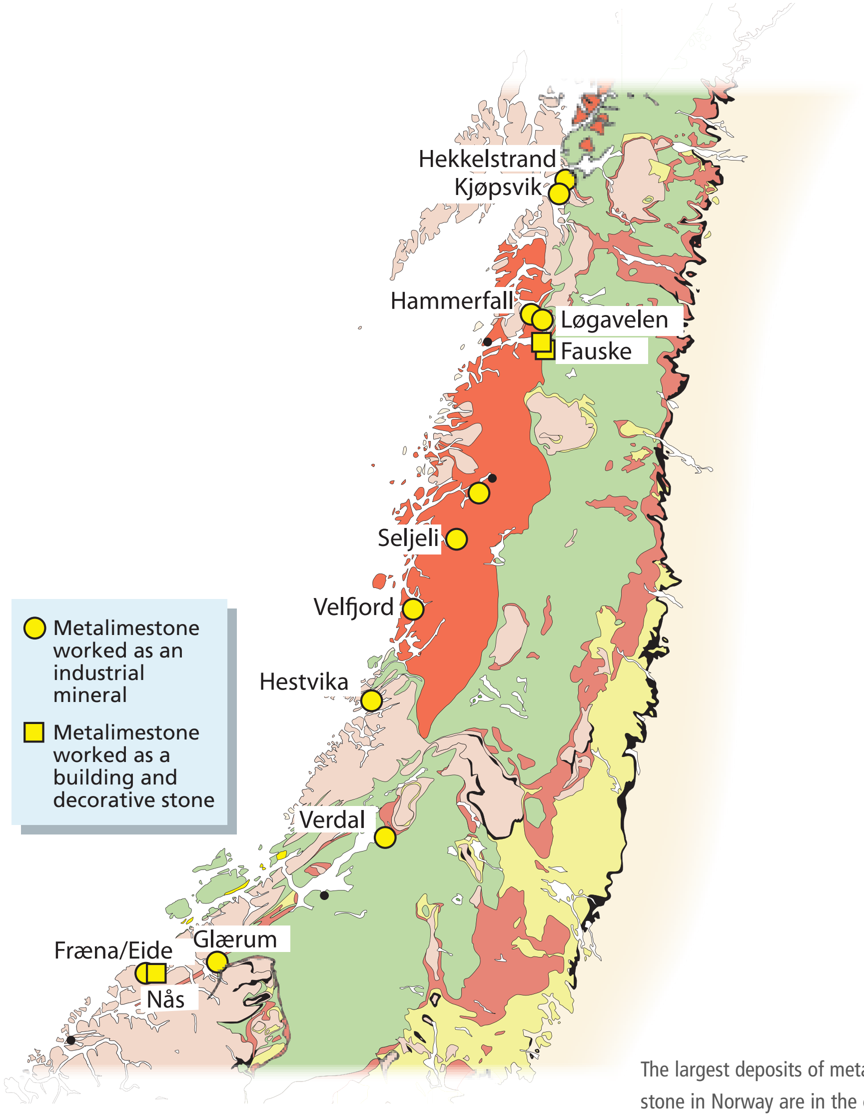
The Sulitjelma copper mines

The largest ore deposits at Sulitjelma lie in the thrust zone between the Köli Nappe and the Gasak Nappe, over an approximately 7 km long stretch in a pillow-shaped amphibolite (metamorphosed gabbro) and in adjacent dark schists (the Furulund Schist). This part of the Köli Nappe is thought to be overfolded, so that it is now inverted with the gabbro uppermost (originally lowermost) followed by a complex of gabbro intrusions, greenstones with pillow lavas and, lowermost, various dark schists. This arrangement greatly resembles present-day oceanic crust. If the Sulitjelma Gabbro was a fragment of ancient oceanic crust, an ophiolite, the occurrence of the large ore deposits is easier to explain because we now know that metallic ores and sulphide solutions are often precipitated on the ocean floor on and close to a mid-ocean ridge, that is, where the seawater is heated by magma welling to the surface.

The ores in the Sulitjelma district consist of chalcopyrite, sphalerite, iron pyrites and pyrrhotite in varying amounts and proportions. The first ore was discovered in 1858, and trial mining started just a few years later, but full-scale working did not begin before 1891, operated by a Swedish company, Sulitelma A/B. Just after the turn of the century, the mining had expanded so much that Sulitelma A/B was the second largest industrial firm in Norway and employed more workers than any other mine in the country. At the most, in 1913, the company had nearly 1750 employees, and Sulitjelma had then become the largest producer of iron pyrites and copper in Norway. In 1933, Sulitelma A/B became the Norwegian-owned A/S Sulitjelma Gruber. After the rights had been exercised for 50 years, the concession to mine in the district reverted to the Norwegian government, but poor copper prices made it difficult to find a new company to operate the mines, and they closed in 1991 after being worked for 100 years.

The iron ores at Mo and Storforshei

The large iron ore deposits in the Mo i Rana district lie in the lower part of the Rödingsfjället Nappe Complex. Only one mine, Rana Gruber, is currently working and it has been extracting ore from deposits in the Dunderland valley since 1965. The deposits consist of rich impregnations of haematite and magnetite (up to 33 % iron) in mica schists and marbles, and magnetite-rich metavolcanic rocks with a high phosphorous content. The Rana district is also rich in deposits of massive iron pyrites, zinc and lead, and the largest deposits of these ores were worked by Mofjellet Gruber, just south of Mo i Rana, for many years until 1987.



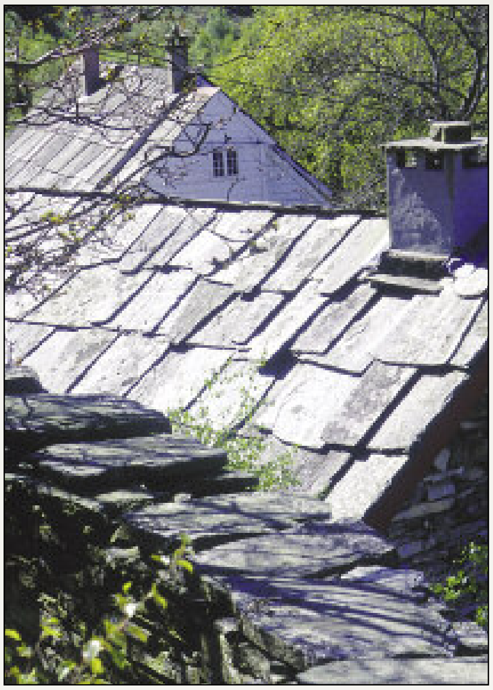
The largest deposits of metalimestone in Norway are in the central part of the Caledonides. The map shows localities where quarrying is taking place for building stone or industrial use.

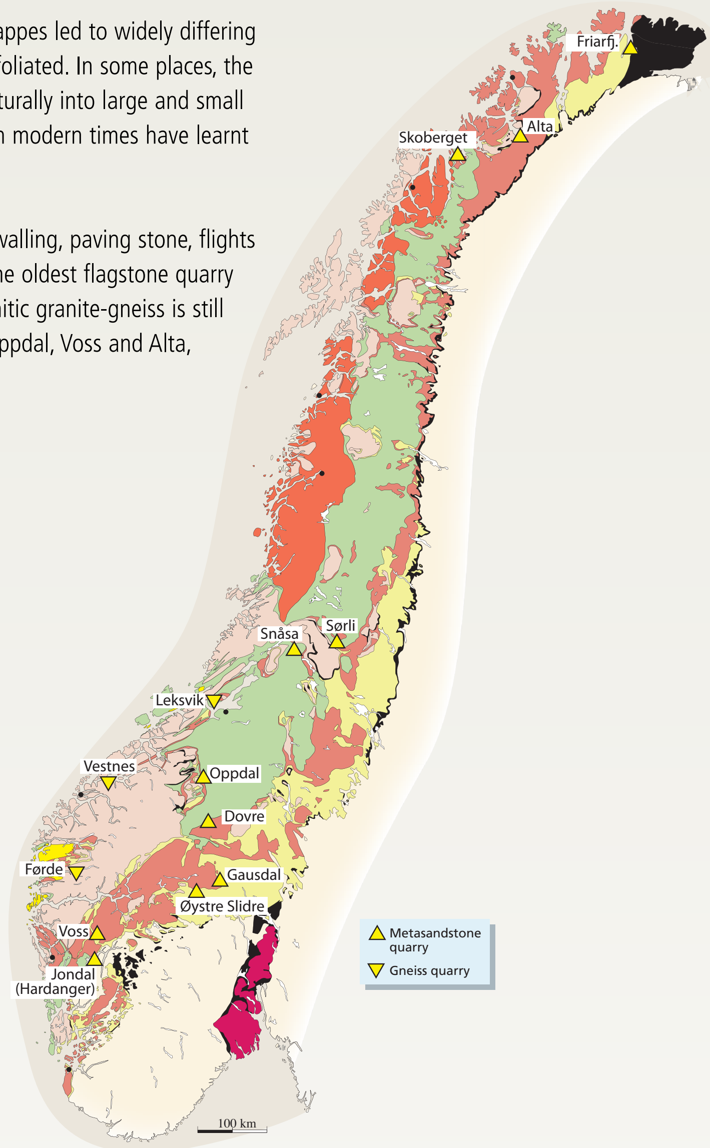
Chalcopyrite and iron pyrites from Sulitjelma, Nordland. (Photo: H. Fossen)

FLAGSTONE – A USEFUL RESULT OF THE OROGENY

The strong movements during the thrusting of the nappes led to widely differing types of rock, like sandstone and granite, becoming foliated. In some places, the foliation is so intense that the bedrock breaks up naturally into large and small flagstones, which people in the old days as well as in modern times have learnt to make good use of.

These foliated rocks are used as roofing slate, stonewalling, paving stone, flights of steps and flooring in many parts of the country. The oldest flagstone quarry was probably in Hardanger, and this flattened, mylonitic granite-gneiss is still being worked. However, at many other places, like Oppdal, Voss and Alta, the raw material is foliated metasandstone.





Rana Gruber is now the only operating iron ore mine in Norway and has an annual capacity of some 1.4 million tons of iron ore concentrate composed of magnetite and haematite. The haematite is used to manufacture steel, the magnetite for powder metallurgy and cleansing of water and coal, and in a finely pulverised state for pigments. Rana Gruber became a separate company in 1955, but did not begin full-scale operations before 1965. The raw ore is now worked in an opencast mine at Storforshei and transported by 110-ton dumper trucks to a nearby crushing plant, from where it is taken by train some 40 km to the separation plant at Gullsmedvika, near Mo i Rana.

The iron ore deposits in the Rödingsfjället Nappe Complex are believed to have been formed by precipitation of iron-bearing solutions in the sediments as these were deposited. Since they largely occur in quartz-rich mica schists and marbles, and are not linked to ophiolite complexes, their formation must have taken place in relatively shallow water, such as near a continental margin bordering the Iapetus Ocean.

Large parts of the bedrock in Nordland and Troms were severely deformed and strongly metamorphosed deep in the crust during the Caledonian orogeny. The photograph shows micaceous gneiss with granitic layers formed by partial melting at depth. These layers were subsequently disrupted and the rock was strongly metamorphosed, foliated and folded. From the Uppermost Allochthon on Kjerringøy, Nordland. (Photo: Samfoto)

The orogenic belt in the south

The Caledonian nappes in Nordland are completely disrupted near Grong, where the basement forms an east-west culmination. In the west, it crops out in the northern extension of the Western Gneiss Region, here referred to as Vestranden, and in the east the basement outcrops are known as the Grong-Olden Culmination. The basement is also uplifted in the Tømmerås window, south of Lake Snåsa.

A major structural breach also occurs in the same area. This is the southwest-northeast trending Møre-Trøndelag Fault Complex, which follows the coast of Nord-Møre, crosses the entrance to Trondheimsfjorden, dissects the length of the Fosen Peninsula and continues to Snåsa. The bedrock along the fault zone is vertical, unlike its more flat-lying attitude within the adjacent nappes. A great deal remains to be learnt about the role of this zone during the orogeny but, among other things, its size suggests that it was an important zone of deformation with a substantial component of lateral movement.

The greatest exposed breadth of the orogenic belt (about 400 km) occurs south of the Møre-Trøndelag Fault Complex. Here, almost unaffected bedrock in the marginal zone in the east is replaced westwards by increasingly altered rocks, with the deepest buried ones in the west. We will first look at the southernmost part of the belt, in the Oslo region.

Foreland structures in the Oslo Region

The foreland deposits, the deposits in the marginal areas of the orogenic belt, are preserved thanks to the subsidence of the Oslo Region during the Permian Period. There is a complete succession here from Cambrian shales and siltstones deposited on the basement to strata deposited around the transition from Silurian to Devonian time.

In the Oslo Region, a 5-150 m thick succession of Late Proterozoic to Ordovician (Llanvirn) age covers the basement. The weak Cambrian Alum Shale was an efficient lubricant zone when the sparagmite nappes were thrust south-eastwards. A décollement or sole thrust was established in the Alum Shale as far as the Oslo-Asker area, and folds and faults

Thrust fault and folds in Ordovician strata near Fornebu, Oslo, formed when the Caledonian nappes were transported from the northwest. (Photo: B. T. Larsen)

The phyllites in the sole thrust between the nappe pile and the basement here in Voss testify to the intense deformation which they underwent. (Photo: H. Fossen)

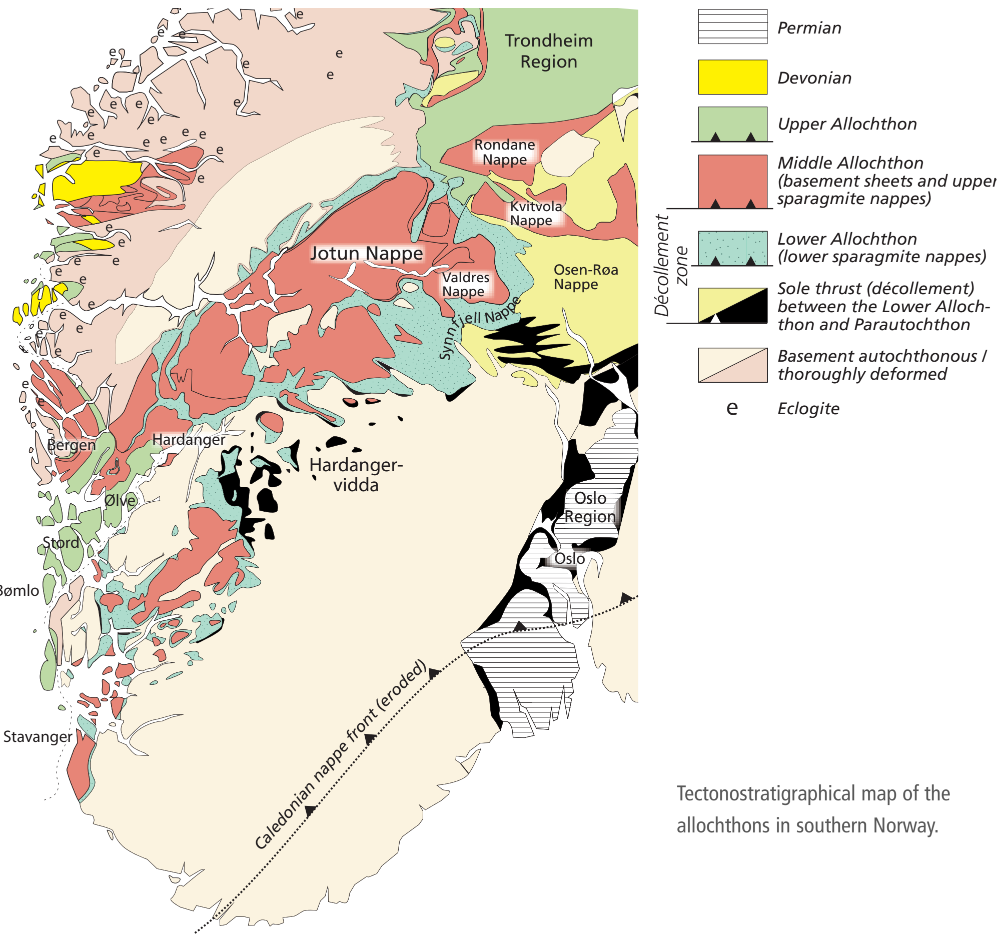
developed in the overlying, transposed deposits. Classical compression structures were developed where bedrock units were piled up and repeated between more or less horizontal floor and roof thrusts. Corresponding structures are found in Scotland on the Laurentian side of the orogenic belt, and in the marginal zone of other belts.

The sole thrust

The sole thrust or décollement at the base of the nappes is found throughout southern Norway because of the great difference in rigidity between the solid basement, the relatively robust nappes and the substantially weaker and easily deformable, intervening Cambro-Silurian pelitic deposits. These micaceous and, in part, phyllitic rocks acted as a lubricant for the nappes when they moved over the basement.

When the nappes slid over the hydrous deposits, the water was trapped between the basement and the nappes, resulting in overpressure in the deposits; the fluid in the pores was compressed without being able to escape. Overpressure neutralises the weight of the overlying bedrock pile and is a prerequisite for the ability of large nappes to be transported. As a great deal of the thrust movement was concentrated along the Cambro-Silurian schists, most of the original sedimentary structures and fossils in the décollement zone were destroyed.

Primary structures, and locally also fossils, are nevertheless found in the décollement zone as far west as



Tectonostratigraphical map of the allochthons in southern Norway.

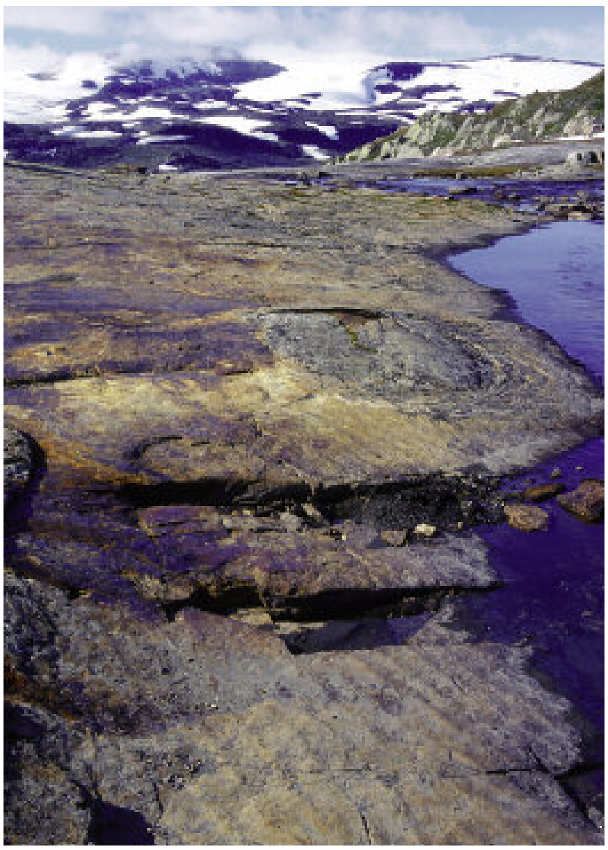
Hårteigen and Finse on Hardangervidda. The fossils are preserved just above the basement. Likewise, the depositional contact of the conglomerate and quartzite on the sub-Cambrian peneplain is more or less well preserved in many places as far west as the western part of Hardangervidda and inner Hardangerfjord.

The lower sparagmite nappes

The large volumes of quartzite-dominated sedimentary rocks in the Valdres-Mjøsa-Rondane district have been a controversial topic for many years. Was the Valdres sparagmite, which rests on Cambrian and Ordovician sedimentary rocks, Ordovician-Silurian or Late Precambrian? Were the sparagmite successions deposited where we now find them or have they been transported as Caledonian nappes?

The Late Precambrian sparagmite beds are now believed to be piled on top of one another in nappes, the lowermost of which (the Osen-Røa Nappe Complex and the overlying Synnfjell Nappe) are allocated to the Lower Allochthon, whereas the higher nappes (the Valdres, Kvitvola and Rondane nappes) belong to the Middle Allochthon. Remnants of the basement on which the feldspathic sandstones were originally deposited occur in both horizons, having been detached from more marginal parts of the pre-Caledonian Baltic Shield. It is still uncertain just how far the individual nappes were transported.

Basement slices in the Lower Allochthon sparagmite nappes are seen near lake Femunden and east of the valley of Rendalen. The major portion of the nappes consists of feldspathic sandstones, quartzites, conglomerates, limestones and schists of Late Proterozoic and Cambro-Silurian age. The Late Precambrian portion of the stratigraphy is difficult to correlate across the area, and separate basins probably existed until the rise in sea level in the Cambrian. The most easily correlated horizons are the Moelv tillite, which is interpreted as an ancient glacial deposit dating from around 650 million years ago, the Cambrian quartzite (the Ringsaker quartzite) and the overlying, fossiliferous beds. Knowledge of this stratigraphy has facilitated the mapping of the internal structure of these lower sparagmite nappes.



Ripple marks preserved in the arkose overlying the sub-Cambrian peneplain, or basement surface, near Finse. The Caledonian nappes at the Hardangerjøkulen ice cap are seen in the background. (Photo: H. Fossen)

The sparagmite nappes display classical tectonic structures resembling those found in the deposits in the Oslo region. Duplex structures are prominent, the best-known one being the Aurdal duplex in the Osen-Røa Nappe in which numerous stratigraphic units are piled on one another, thus halving the original length of the succession. Corresponding examples are found elsewhere near lake Mjøsa and in Østerdalen, and also in the Synnfjell Nappe. These structures show that the succession has not only been transported over the autochthonous units and at the same time been overrun by overlying units, but also that the beds forming the sparagmite nappes have been significantly foreshortened.

More long-transported sparagmite nappes

The lower sparagmite nappes are overlain by nappes of similar bedrock that have come from still further west. Both the Valdres Nappe and the Kvitvola Nappe are stratigraphically, lithologically and structurally closely related to the underlying sparagmite nappes. Basement rocks that occur in these nappes consist partly of anorthosite and related rock types that are not found in the basement, but which are characteristic for the Jotun Nappe. The nappes are largely composed of Late Proterozoic to Ordovician deposits with a stratigraphic thickness of several kilometres. The primary depositional contact between these metamorphosed deposits and basement rocks in the nappes is locally preserved.

Lithologies corresponding to the Moelv tillite and other sequences found in the lower sparagmite nappes are recognised among these sedimentary rocks. Conglomerates occur in several places, the best known probably being the Bygdin conglomerate which immediately underlies the thick Jotun Nappe in the vicinity of Bygdin. The quartz clasts in this conglomerate show how strong the deformation beneath the Jotun Nappe was, and how the sparagmites in some places experienced strong stretching in a northwest-southeast direction, whereas they were highly flattened elsewhere. The same deformation has also produced large and small folds and also penetrative schistosity and cleavage which cause the rocks to split easily into flagstone in many places. These uppermost sparagmite nappes are thought to have been transported around 300 km south-eastwards.

Hardangervidda, Jotunheimen and the Jotun Nappe

The triplex division of the tectonostratigraphy that is so characteristic for this part of the Caledonides is found on both Hardangervidda and in Jotunheimen. Lowermost is the basement with the sub-Cambrian peneplain, uppermost are the remains of basement rocks in the Jotun Nappe, and sandwiched between is a relatively thin, but usually continuous layer of phyllite. The phyllite is the metamorphosed remains of clay and mud that were deposited over the entire Baltic Shield in the Cambrian. Autochthonous beds rest directly on the basement in several places.

The Jotun Nappe mainly consists of crystalline Proterozoic rocks, with some incursions of quartzite. The most characteristic rocks are mangerites and anorthosites belonging to the Bergen-Jotun kindred, which was the name geologists like V.M. Goldschmidt and Carl Fredrik and Niels Henrik Kolderup used for this characteristic suite of metamorphosed intrusive rocks. Such rocks are not found in the basement, either in this area or in the Western Gneiss Region, which implies that the nappe was transported from somewhere west of the present coastline. Like corresponding rocks in the Bergen Arcs, the crystalline rocks of the Jotun Nappe underwent high-grade metamorphism (granulite and amphibolite facies) during the Sveconorwegian orogeny. Sveconorwegian granites transect parts of the nappe and show that its interior was protected from Caledonian deformation, most of which took place along the base which is intensely deformed in a sole that is up to several hundred metres thick.

Balancing of the underlying sediments and recon-structions of the situation prior to the orogeny show that the nappe was transported more than 300 km. In the southeast, this impressive nappe was thrust over the sparagmite nappes, and it also pushed the sparagmites ahead of it during the thrusting. However, sparagmite deposits with a depositional contact on the crystalline rocks have survived in an

The Jotun Nappe includes anorthosite, which is typically white as here in Nærøydalen, on the boundary between Hordaland and Sogn & Fjordane. (Photo: I. Bryhni)

inverted position in a few places. Some nappe fragments with the same tectonostratigraphic position as the Jotun Nappe are also found locally on Hardangervidda, and in the Røldal and Ryfylke uplands (the Hardangervidda-Ryfylke Nappe Complex). These nappes are, however, more complex than the Jotun Nappe and consist of gneissose or schistose volcanic, sedimentary and intrusive rocks of assumed Precambrian age.

The secrets of the Bergen Arcs

The Bergen Arcs, like the natives of Bergen, have rather special characteristics. The arcuate shape is easily visible on both satellite images and topographical maps, and a number of nappes have been carried far down into the basement. The largest and most intact tectonic unit has been renamed the Lindås Nappe (formerly called the anorthosite complex). It contains anorthositic and charnockitic rocks of the Bergen-Jotun kindred, resembling those in the Jotun Nappe further east. It is therefore tempting to correlate these units, and the Lindås Nappe is consequently considered to belong to the Middle Allochthon. An important type of rock in the Lindås Nappe is eclogite, which occurs in the western anorthosite zone. Age determinations show that this high-pressure rock formed during the Caledonian orogeny, which implies that the Lindås Nappe was initially on its way down to

QUARTZ

Quartz coated with anatase crystals is one of the geological trademarks of Hardangervidda. This unusual intergrowth occurs relatively frequently on Hardangervidda and is sought after by mineral collectors. However, it is illegal to take specimens from the national park and state-owned common land.

a great depth in a subduction zone, but was then detached and eventually incorporated in the tectonostratigraphic succession.

The Blåmanen Nappe is found along with the Lindås Nappe and is interpreted as a basement nappe with a younger sedimentary cover sequence. The metasedimentary rocks (the Rundemanen Formation) have a locally preserved depositional contact with the basement gneisses and have been correlated with the sparagmitic rocks in the foreland area.

The Major and Minor Bergen Arcs delimit these nappes in the east and west, respectively. Both these arcs contain ophiolites and associated supracrustal rocks that typify the Upper Allochthon. The problem, however, is that the Lindås and Blåmanen Nappes rest on this Upper Allochthon, which suggests that the tectonostratigraphy may be inverted in this area.

The arcuate structure itself also poses a problem for geologists. Several models have been proposed for its formation. One model proposes that it was formed during a late phase of folding under north-south contraction. Another is that it originated as a consequence of spatial problems during the post-Caledonian extensional movements along the curved Bergen Arc Shear Zone (see Chapter 7). Neither of these explanations seems fully satisfactory and it is conceivable that the structure is a result of several processes.

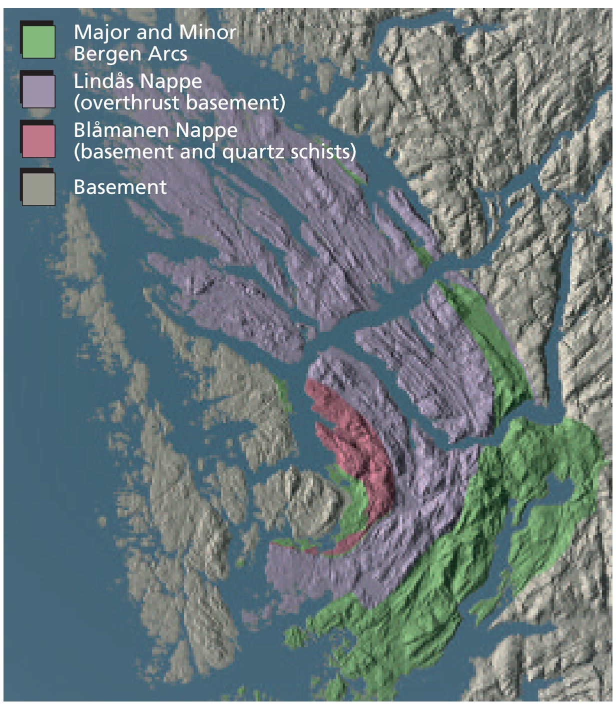
The Särv Nappes: the Swedish counterpart to the sparagmite nappes

The Middle Allochthon in Jämtland (Sweden) is divided into two. The lowermost part consists of sparagmite-like lithologies and their Proterozoic basement substrate, while the uppermost part also consists of sparagmites, including tillites, but is transected by dolerite dykes. These dykes have a geochemical composition which suggests that most are of mid-ocean ridge type, but some have a more alkaline character. Most geologists believe that these dykes were intruded during the rifting of the continent prior to the formation of the Iapetus Ocean. The Särv Nappes become more attenuated westwards, but survive in the marginal zone around the Norwegian basement windows like the Tømmerås window (the Leksdal Nappe), the Grong-Olden Culmination and further southwest in the Oppdal-Trollheimen area (the Risberg Nappe and the Sætra Nappe). Metasandstones with dolerite dykes that can be correlated with the Särv Nappes are also found further west, such as on the west side of Orkangerfjord and along the Surnadal syncline.

The green Trondheim region

The Trondheim Nappe Complex is the name given to the green, overthrust rocks in the Trondheim region, which can be compared with the Köli Nappes. These lithologies were comparatively thoroughly investigated in the latter half of the 19th century by such geologists as Keilhau, Kjerulf and Törnebohm who showed that they rested in a depression or open trough that stretches northeast-southwest along the central part of Trøndelag. Metamorphosed Cambrian or older sediments, greenstones and gneisses belonging to the Gula Nappe occupy the centre. These rocks may have been detached from the continental margin before

A bird's-eye view of the Bergen Arcs. The arcs stand out as both topographical and lithological features.



the collision, or belong to a microcontinent in the Iapetus Ocean. On either side of the Gula Nappe are two series of volcanic rocks, each several kilometres thick (the Støren and Fundsjø Groups), and these are overlain by sedimentary and volcanic rocks that are probably of Ordovician or Silurian age. The Støren Group forms the bulk of the Støren Nappe, which is interpreted as a detached fragment of oceanic crust, and consists of several kilometres of pillow lava and hypabyssal rocks, along with thin layers of chert and phyllite. Gabbro and dyke complexes are also found in the Støren Nappe. Ophiolite fragments occur on Vassfjellet, in Bymarka (Trondheim), at Løkken and on Resfjellet, and have given ages of around 485-480 million years. The ophiolitic nature of the Støren Nappe implies the presence of an important tectonic contact (thrust zone) with the underlying Gula Nappe.

A series of low-grade metasedimentary and other rocks rests on the deformed ophiolites of the Støren Group. They were formed after the ophiolite was deformed, metamorphosed, uplifted and deeply eroded. Theodor Vogt called this unconformity the “Trondheim disturbance”, and it is now known as the Trondheim phase of the Caledonian orogeny. The Lower Hovin Group lithologies include shallow-marine sandstones and andesites, limestones, dark schists, turbidites, and even thick greenstones, dyke complexes and gabbro. The limestones contain fossils of Arenig and Llanvirn age, but the fauna is largely of North American type. These strata are overlain by conglomerates and greywackes forming the Upper Hovin Group, and finally the Horg Group metasediments.

The small Røros Nappe Complex belongs in the Upper Allochthon (part of the Köli Nappes). It contains ore deposits which made Røros a well-known mining community in Europe several centuries ago.

ANORTHOSITE – A USEFUL ROCK

Anorthosite from Gudvangen. (Photo: I. Bryhni)

Large quantities of anorthosite are quarried in the Gudvangen-Mjølfjell area of west Norway. Anorthosite, which mainly consists of plagioclase feldspar, has many potential uses. In addition to its more ordinary use as gravel on garden paths and aggregate for roads (to obtain a light-coloured surface), anorthosite is used as an abrasive in washing powder and toothpaste, to cleanse sewage and drinking water, and to manufacture refractory bricks for furnaces. It can also be used to make mineral wool, in the ceramics and porcelain industries and as covering on factory floors. Anorthosite is also unusually rich in aluminium, containing more than 30 % Al_2O_3. As Professor Goldschmidt wrote as early as 1917, the amount and quality of the anorthosite in Sogn should offer possibilities for producing aluminium in the future.

The Western Gneiss Region

A special feature of the Caledonides of southern Norway is that a large area of basement is exposed from the Bergen Arcs in the south to the Helgeland Nappe Complex in the north. It is bounded in the east by the Caledonian nappes. The area is known as the Western Gneiss Region and has suffered much more Caledonian deformation and metamorphism than the basement further east.

The degree of Caledonian impact in this region has been discussed for a long time, but most geologists now regard this area as part of the Baltica basement that became involved in the Caledonian orogeny. On the whole, the western part is more affected by the orogeny than the eastern. In the east, in the Oppdal district for instance, basal quartzite or conglomerate displaying a depositional contact with the basement is locally preserved; in the west, the basement-cover contact is tectonic. In structural terms, the Western Gneiss Region is a large, elongate dome mainly generated by post-Caledonian extension.

Sognefjord offers an unusually good profile through the entire Western Gneiss Region. Studies of this profile reveal the presence of a mylonitised and folded zone beneath the nappe rocks in the east, but the Caledonian structures soon disappear at depth in the gneiss region, and Proterozoic structures seem to dominate completely in quite a large, central area. The Caledonian deformation once again becomes more prominent towards the west until it completely overshadows the earlier structures. Many bodies of eclogite which give Silurian and Devonian isotopic ages are also found here.

Eclogites also occur in the more central parts of the Western Gneiss Region, and mineral compositions show that both pressure and temperature increase north-westwards. Furthest in the north, at Roan, granulites are the oldest component in the Caledonian evolution of these gneisses.

GEOLOGY OF THE TRONDHEIM REGION *By David Roberts*

The area traditionally known as the *Trondheim Region* has been recognised since the late 19th century for the pioneering work of Törnebohm (1896) who maintained that thrusting had played a major role in the structural development of the Scandinavian Caledonides. This part of Norway is dominated by metamorphosed volcanic and sedimentary assemblages in three nappes of Köli affinity which together constitute the *Trondheim Nappe Complex* (TNC). These are the Støren, Meråker and Gula nappes. The TNC rests upon thin, lensoid representatives of subjacent nappes or thrust sheets equivalent to the Seve, Särv and Offerdal nappes of Sweden. At lower tectonostratigraphic levels, diverse Palaeoproterozoic to Mesoproterozoic orthogneisses and felsic volcanites characterise the thrust sheets of the Grong-Olden district, Tømmerås window, antiformal structures in the border area to the east and, not least, the vast, strongly Caledonised basement domain of the Western Gneiss Region. Devonian molasse deposits, derived from rapid erosion of the high Caledonian mountains, are also represented in the region in coastal areas, on islands and in a small outlier at Røragen east of Røros.

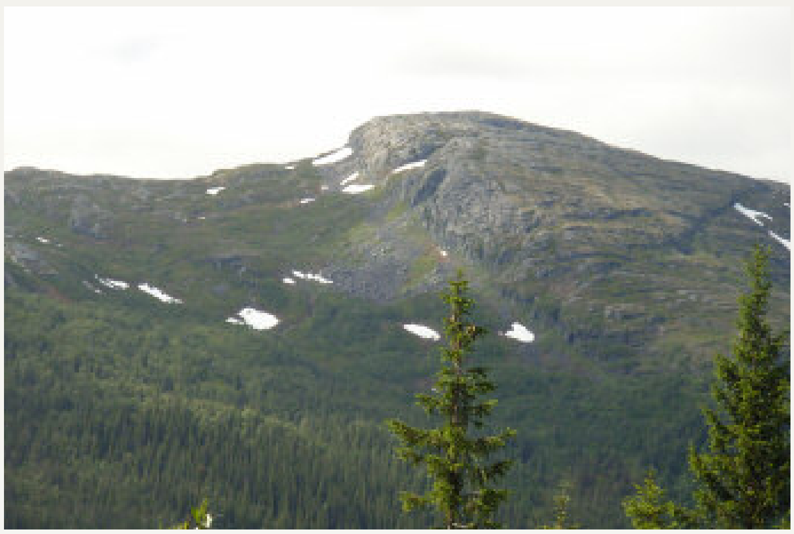
An offshoot of the Olaberget trondhjemite pluton cutting through deformed mafic and felsic volcanites of the Hersjø Formation, Meråker Nappe. From the quarry at Olaberget, 7 km north-northeast of Vingelen, Hedmark county. The trondhjemite is of Early Silurian age, dated isotopically to 431 Ma. (Photo: D. Roberts)

The *Gula Nappe* occupies a NE-SW-trending axial zone within the TNC and also occurs as thin tectonic slices in the west and northwest. Metasedimentary rocks, locally with staurolite, kyanite and sillimanite (in places migmatised), and mafic to ultramafic volcanic units are the principal components of what is now termed the Gula Complex of inferred Mesoproterozoic to earliest Ordovician age. The Gula Complex is intruded by large, composite, trondhjemite-diorite-gabbro plutons and trondhjemite dykes of Early Silurian age.

Over most of the region, the Gula Nappe is tectonically overlain by the Støren Nappe in the west and by the Meråker Nappe in the east. The *Støren Nappe* is a composite unit with a fragmented ophiolite of Cambrian to Tremadoc age at the base, succeeded above a marked unconformity by a Mid-Arenig to Caradocian, low-grade, volcanosedimentary succession containing a profuse and diverse faunal assemblage of mainly North American affinity. The *Meråker Nappe* consists of a bimodal but largely mafic, amphibolite-facies volcanic complex at the base, overlain unconformably by a thick, low-grade succession of mainly turbiditic sediments of Ordovician to Early Silurian age.

The Støren and Meråker nappes have long been considered to be broadly temporally equivalent, and share a similar tectonic and thermal evolution. The Støren ophiolite was obducted upon the Gula Complex in Late Tremadoc-Early Arenig time (constrained by isotopic dating and the ages of the oldest fossils in overlying sediments), coevally with a deformation and metamorphism of the Gula rocks. The entire TNC was ultimately deformed, metamorphosed and thrust upon the Seve and lower nappes in Mid-Silurian times (430-425 Ma) during the Scandian orogeny. Evidence for a close relationship between the Støren and Meråker nappe successions can, in fact, be found in the extreme northeast of the Trondheim Region where the two nappes clearly merge into one common allochthon above an antiform comprising rocks of the Gula Complex. Notwithstanding this relationship, the Støren and Meråker units are physically separated over most of the region and continue to be described as separate nappe assemblages.

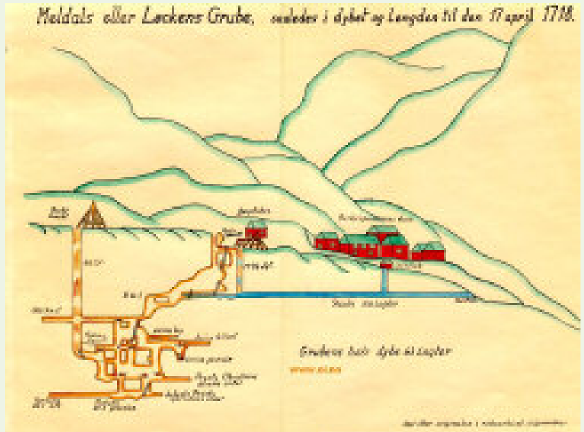
Later stages of the Scandian orogeny are characterised by a widespread extensional and left-lateral shear regime, Devonian sedimentation, and the formation of the Møre-Trøndelag Fault Complex. Subsequent sedimentary cover in the region has been almost entirely removed, although a Jurassic basin is preserved in Beitstadfjorden.



The eastern thrust contact of the Meråker Nappe, Trondheim Nappe Complex, just below Steinfjellet (909 m a.s.l.) about 1 km west of the Swedish border, close to Storlien; looking southwest. A thin slice of Seve Nappe rocks below the cliff, mostly covered by scree, overlies rhyolites and quartzites of the Lower Allochthon. (Photo: D. Roberts).

SULPHIDE ORES *By Tor Grenne*

The Trondheim Region is host to most of the previously economic sulphide ores of the VMS ("Volcanogenic Massive Sulphides") type in Norway. The vast majority are either volcanic-hosted ores in Early Ordovician ophiolites or island-arc sequences, or sediment-hosted ores in Late Ordovician clastic sequences subject to gabbro intrusion.



A map of the Løkken mine produced in 1718 looking towards the north. Only the shallow part of the deposit, dominated by copper-rich sulphide stockwork ore, was mined. Subsequent extraction of the main, massive pyritic ore body continued along the westward extension to a depth of more than 1,000 m below the surface. (Illustration: Orkla Industrimuseum)

The most notable example of volcanic-hosted ores, and perhaps also the largest in the world, occurs in the Løkken ophiolite, located south-west of Trondheim. Here, the setting and characteristics are similar to sulphide deposits currently being formed on the deep ocean floor. The deposit originally contained 25–30 million tonnes of massive pyritic ore with 2.3 % copper and 1.8 % zinc in a 4 km-long ore body that was up to 60 m thick and 400 m across. Its morphology is the result of deposition from ascending hydrothermal solutions along fault escarpments and parallel fissure-related conduits on the sea floor. Deposits formed in association with island arcs, such as those found in the Folldal district, generally contain more zinc and less copper.

Sediment-hosted ores are particularly abundant near Røros. Here, the host rocks are metagreywacke and phyllite that were intruded by syn-sedimentary gabbroic sills. The ores comprise massive and disseminated pyrrhotite or pyrite with varying proportions of copper and zinc, and form plate or ruler shaped ore bodies emplaced concordant with the sedimentary bedding. They are commonly less than one metre thick and contain less than 3 million tonnes of ore. In common with the volcanic-hosted ores, they were deposited from ascending hydrothermal fluids that had been heated by magma at depth, although sulphide precipitation occurred largely by pore-filling and replacement along favourable bands within the unconsolidated sediments, and only locally on the sea floor.

Massive pyritic ore in contact with jasper bed, Løkken. The deposition of both the ore and jasper was related to hydrothermal venting at the sea floor. (Photo: T. Grenne)

Historically, mining has been a very important industry for Norway. Copper and silver ores were worked locally from medieval times. However, the significance of these ores increased rapidly during the 16th century when the Danish-Norwegian King Christian III summoned Saxonian mine representatives to provide assistance at the Sundsberg copper mines in Telemark. In addition, Saxonian mining regulations were employed as a model for the first Norwegian mining legislation. Exploration for new ores was promoted by King Christian IV in particular. During his reign (from 1588 to 1648), he was in great need of capital to fund his various military campaigns. Following the discovery of silver at Kongsberg in 1623, increased exploration efforts, combined with the application of Saxonian mining expertise, resulted in many successful discoveries of sulphide deposits, most notably in the Trondheim Region. Copper mines were opened at Kvikne (Kvikne Kobberverk) in 1633, and for the next two decades these became Norway's largest producers of copper. In 1644, they were succeeded by copper mines at Røros (Rørøs Kobberverk), which soon became the country's leading mining company and for a long time made a significant contribution to Danish-Norwegian export revenues. The Løkken Verk mines were put into production in 1654.

For about 200 years the sulphide ores were mined exclusively for copper. From the mid-19th century there developed a growing demand for sulphuric acid for use in the chemical industry. This, combined with falling copper prices, led many companies mining pyritic deposits to trade in bulk ore from which copper was only a by-product. This activity laid the foundation for the growth of the Løkken Verk mines in the early 20th century, and these became the most important mines in Norway for many decades. They also paved the way for the growth of Orkla, now one of Norway's largest corporations. The relatively high contents of zinc found in many VMS ores were of little interest until the latter half of the 20th century, when sulphur prices fell and technology was developed for the production of mineral concentrates of sphalerite (Zn,Fe)S and chalcopyrite ($CuFeS_2$).

The Caledonides in Svalbard

The geology of Svalbard is regarded as a window down into the Barents Sea succession. The opening of the Atlantic Ocean, with subsequent uplift and erosion in the Palaeocene, Neogene and Quaternary (Tertiary and Quaternary), means that not just the uppermost part of the crust, with its relatively flat-lying sedimentary deposits, is exposed in Svalbard, but a portion of the underlying, strongly deformed and metamorphosed bedrock is also seen in northern and western parts of the archipelago.

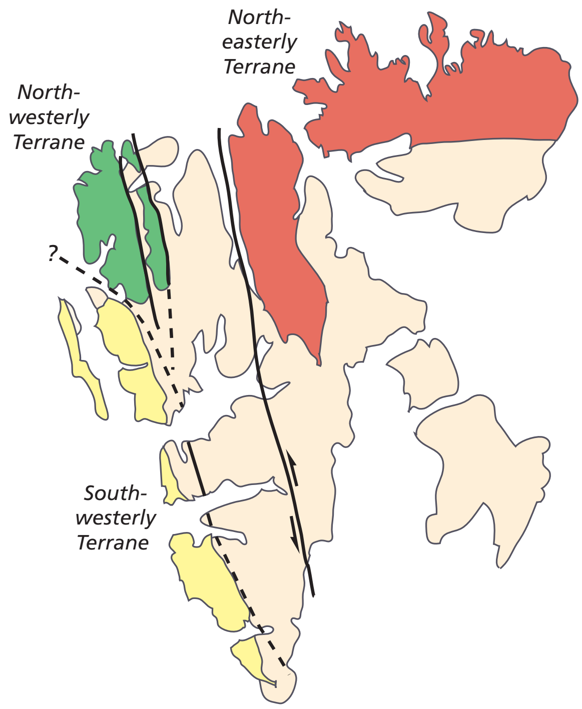
Bedrock map of Svalbard

In earlier descriptions, the pre-Devonian rocks in Svalbard were often grouped together under the term *Hecla Hoek*. Their deformation and metamorphism was linked with the evolution of the Caledonian orogenic belt. The occurrence of Precambrian fossils and well-preserved deposits testifying to periods of global glaciation in the upper part of the Hecla Hoek Complex meant that it was early concluded that the entire complex represented deposits from the end of the Precambrian and the beginning of the Palaeozoic Era. Various models have been applied to try to link the Caledonian rocks in Svalbard to the Caledonides on either side of the Atlantic. Currently available data suggest that they are mostly affiliated to the Greenland Caledonides, but details are still obscure. Recent uranium-lead age determinations show that a substantial portion of the pre-Devonian deposits found in Svalbard have undergone a long, complex geological evolution that includes both Precambrian and Caledonian magmatism and orogenic folding.

The oldest and most altered rocks are primarily found along the western and northern coasts of Svalbard. They are exposed here because of local uplift during transpressional south-eastwards movement of the Barents Sea area relative to Greenland. Corresponding rocks are known in central Spitsbergen, beneath 2-4 km of almost flat-lying sedimentary rocks, mostly of Mesozoic and Tertiary age. The Precambrian and Early Palaeozoic rocks were forced up in the deformation zone between Greenland and the Barents Sea to produce a mini mountain chain. The occurrence of pre-Devonian rocks along the north coast of Spitsbergen and on Nordaustlandet results from general crustal uplift, possibly linked to polar up-doming before the North Polar Basin was formed.

Three building blocks

Great differences in rock types, structural development and thermal history, combined with the occurrence of several north-south oriented, regionally developed fault zones with long, complex deformation histories led the British geologist, Brian Harland, to propose at the end of the 1960s that all the pre-Devonian rocks in Svalbard belong to three blocks or crustal fragments that were united in post-Silurian time. Based on their distribution in Svalbard, these blocks have been termed the *north-easterly*, *north-westerly* and *south-westerly* terranes. All these three terranes or blocks are in varying degrees affected by the Caledonian orogeny. However, the relatively consistent nappe construction seen on the Norwegian mainland is not found; indeed there is little to suggest that these terranes have anything directly to do with the Scandinavian Caledonides. On the contrary, the fossil content and chemical composition of the rocks, the age of metamorphism and the cooling age of granite intrusions indicate that Svalbard has much more in common with the Caledonian orogenic belt in Greenland. Hence, it appears that Norway has sovereignty over a piece of the orogenic belt that geologically belongs to the North American (Laurentian) side of the collision zone.



The three terranes of Caledonian-deformed rocks in Svalbard. The division is based on differences and similarities in both rock type and structural development.
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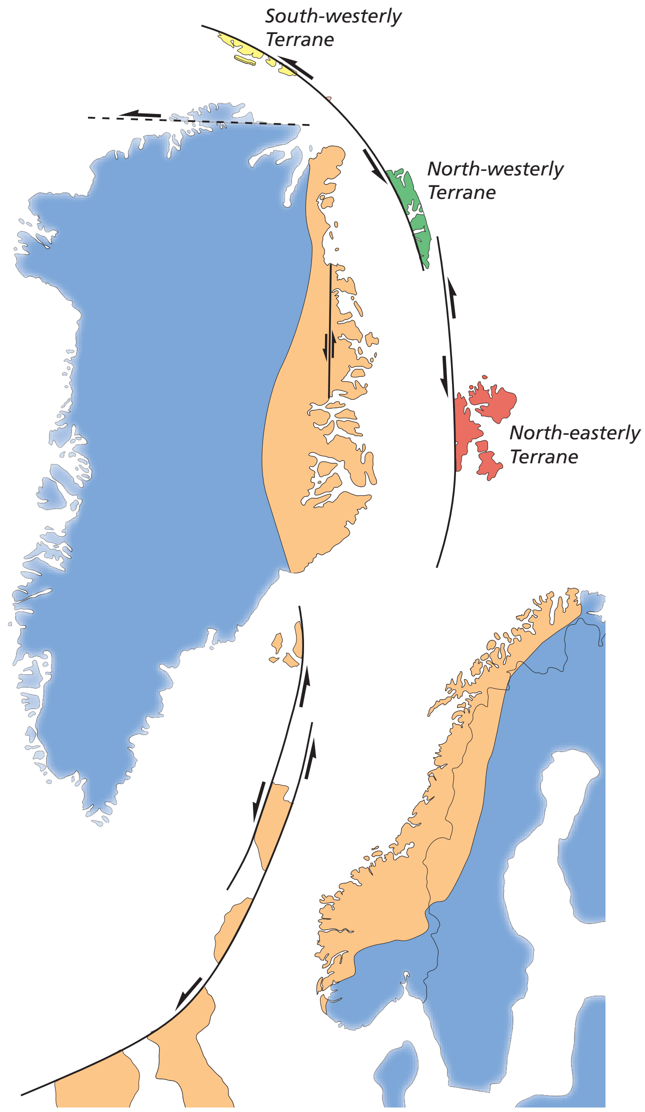
BELOW: Marble, mica schist and amphibolite, recumbently folded during the Caledonian orogeny; Sigurdfjellet, northern Spitsbergen. Red Devonian sandstones in the background are separated from the basement by a major fault (the Breiboge Fault).
(Photo: Norwegian Polar Institute)

MAP ON RIGHT: The terrane model for Svalbard proposed by Brian Harland, where enormous lateral movements explain geological differences across substantial lineaments. This map shows the three terranes schematically replaced in their positions at the beginning of the Silurian, as Harland envisaged.



The north-easterly terrane – a piece of East Greenland

Even though Nordaustlandet is virtually covered by large glaciers, valuable information can be gleaned from rocks exposed along the coast. For instance, recent age determinations show that lavas poured into a depositional basin there about 1200-950 million years ago, giving an alternation of sedimentary (1150-1000 million-year-old) and volcanic (some 960 million-year-old) rocks. Shortly afterwards (about 950 million years ago), these strata were intruded by various igneous rocks. Folding, uplift and erosion followed before the well-preserved Hecla Hoek rocks with their world-famous, approximately 630 million-year-old, glacial deposits, rapidly succeeded by limestones, formed. This apparently rapid change in climate indicated by these and corresponding deposits elsewhere on the planet has led some scientists to propose that the Earth was completely glaciated for a short period (the "Snowball Earth" theory) and that it is not fortuitous that this event coincides with the advent of an oxygen-rich atmosphere and a boom in life revealed by the remains of large fossils. The thick beds of non-metamorphosed marine limestones have also provided information on the composition of the seawater at about the time when the first macro-fossils appeared in sedimentary deposits.

Beds of marine limestone lying directly on glacial deposits not only indicate a rapid shift in climate, but also provide evidence on the origin of the north-easterly terrane. The same applies to characteristic fossils (trilobites) found in metamorphosed shales in Ny-Friesland. Corresponding rocks and fossils are, in fact, found along the coast of northeast Greenland and on the North American continent. Hence, a great deal suggests that eastern Svalbard was detached from northeast Greenland during the collision between Laurentia and Baltica some 430 million years ago. This is supported by another feature they have in common, approximately 420 million-year-old undeformed granites that may be associated with island arcs. The highest peak in Svalbard, the nunatak of Newtontoppen (1717 m) in Ny-Friesland, is built of such granite.

The north-westerly terrane – a visitor from the deep crust

The north-westerly terrane is characterised by rift-related, Late Precambrian, dolerite dykes that cut the Precambrian substrate, which is dominated by gneisses and migmatites. There are also a large number of Caledonian granites. Northeast of Raudfjorden, mylonites, mafic and ultramafic rocks occur in narrow shear zones formed deep in the crust. There are indications that the dolerite dykes have been eclogitised in similar shear zones before being brought to the surface where, together with the gneisses, they formed the substrate for the Devonian deposits in northern Svalbard.

The south-westerly terrane – remains of an old plate boundary

The south-westerly terrane is more complex. Its most interesting feature is that the northern part, in addition to Late Precambrian sedimentary rocks, consists of a 2-5 km wide and at least 50 km long zone of eclogites, serpentinites and blueschists, as well as metamorphosed marine carbonate rocks (flysch). Such rocks are typical for subduction zones. Motalafjellet, south of St. Jonsfjorden, is the best-known locality for such rocks, but similar rocks and shear zones are also found in Wedel Jarlsberg Land and the Hornsund and Sørkapp areas. They occur in nappes separated by major thrust faults and shear zones. Radiometric age determinations of igneous rocks in the shear zones imply a mid-Ordovician (Early Caledonian) age for the subduction, but the carbonate rocks were deformed in the mid-Silurian (Late Caledonian).

How can we explain a subduction zone with remnants of oceanic rocks between two such similar fragments of continents, both carrying glacial deposits and limestones with fossils typical of North America?

One possible explanation is that a continent split along a rift that evolved into a marine basin which subsequently closed by subduction. Another is that the continent was divided into blocks that moved laterally relative to one another near the assumed subduction zone. The latter alternative forms the basis of Harland's terrane model, which envisages a lateral translation of around 1000 km. A third possibility is that the rocks in Svalbard represent the continuation of the northeast Greenland Caledonides, which now strike straight out to sea, and that this part was ruptured by transform faults during the Devonian. As mentioned in the introduction, the reconstruction and understanding of what took place during the Caledonian orogeny is a jigsaw puzzle with missing pieces. More pieces will definitely turn up, but only time will show whether they will give an overall, acceptable model.

Irrespective of the model, it is clear that the evolution of the orogenic belt took a different course in Svalbard than on the Norwegian mainland, but here, too, the orogenic processes died out some time in the Devonian. This terminated a very important period in the geological history of Norway and Svalbard.

Folded and disrupted layers in a marble-gneiss unit at Liefdefjorden, Svalbard. The severe deformation is Caledonian and the strata belong to the Proterozoic Generalfjella Formation. (Photo: NPI, W. Dallmann)