CHAPTER 8

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A fissure eruption on Krafla in northern Iceland in 1984. The fissure in the photograph is one kilometre long, although its total length is 8.5 kilometres. The lava is between 0.5 and 1 metre thick at the front of the flow, and about three metres thick further in. Permian fissure eruptions in the Oslo Rift may have been of this type, only many times greater. (Photo: A. Björnsson)

Volcanoes and faulting in an arid climate

The Oslo Rift and North Sea in the Carboniferous and Permian, 359–251 million years ago

310 million years ago, towards the end of the Carboniferous, marked the onset of the formation of what we call the Oslo Rift. The crust ruptured forming a rift from the Skagerrak (in the south) to Østerdalen (in the north), and extensive volcanic activity occurred where Oslo lies today. Throughout the Permian, major faults controlled crustal extension leading to the evolution of a rift valley. The Oslo Rift was characterised by volcanoes and an arid climate. Such conditions also prevailed in the North Sea during the Permian, and towards the end of this period, thick salt sequences were deposited in two vast evaporite basins.

Late Permian plate reconstruction.
Norway's location in yellow.
(Illustration: R. Blakey)

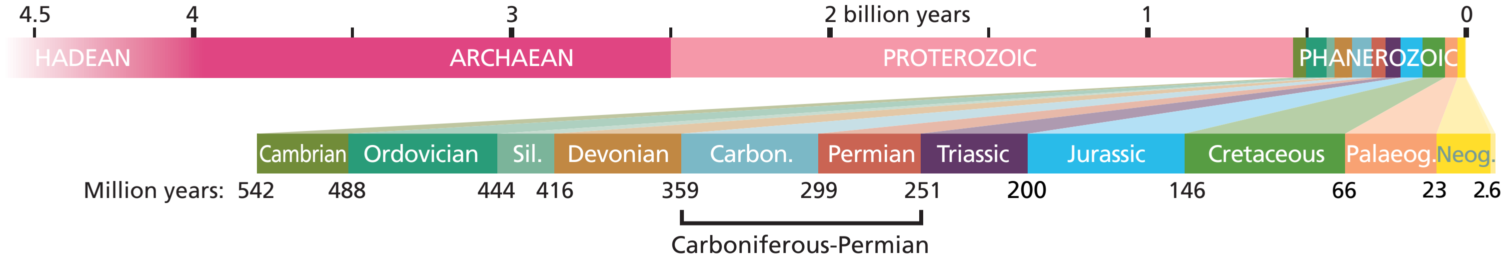
THE OSLO RIFT AND NORTH SEA IN THE CARBONIFEROUS AND PERMIAN

359–251 MILLION YEARS AGO

Towards the end of the Carboniferous, the great central European Variscan orogen (episode of mountain building) had reached its zenith. The southern lithospheric plate, Gondwana, had drifted northwards with several smaller plates and collided with the northern Laurussian plate. This major collision led to the formation of the great "supercontinent" Pangaea, and was one of the main causes of the formation of the Oslo Rift. The Variscan orogen formed part of an even greater mountain belt extending through Central Europe and further east towards what was then the Proto-Tethys Ocean. In the southern North Sea, on the mountain belt's northern flank, a great sedimentary basin was formed which gradually divided into two – a northern and a southern Permian basin.

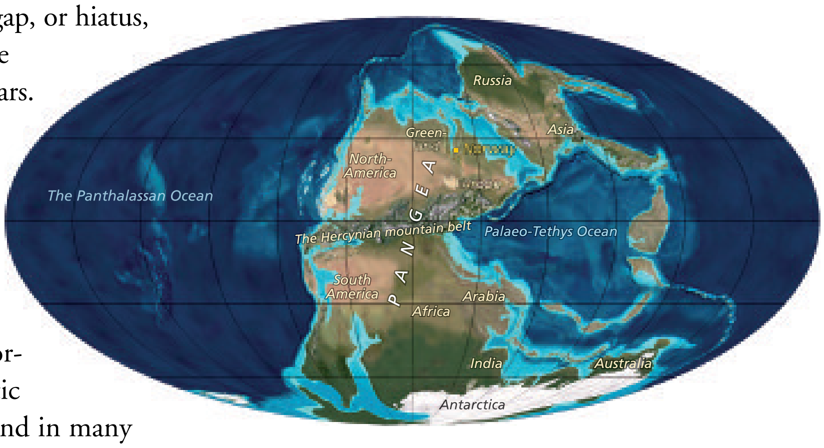
Introduction

Early Carboniferous (Mississippian) rocks are found neither on the Norwegian mainland nor in the Norwegian sector of the North Sea, and thus are not discussed in this chapter. Sedimentary deposits, lavas and plutonic rocks of Late Carboniferous (Pennsylvanian) and Permian age, however, form the important geological components of parts of the North Sea and the Oslo Region. The geological processes that produced these rocks left their mark in several places in southern Norway, mainly in the Oslo Region, but also in south-western Norway (Vestlandet). The diversity of geological processes and rocks displayed in the Oslo Region has earned the area international recognition as a "classical" geological province.



The discovery of silver in Kongsberg in 1623 was a crucial event in the development of geology as an academic science in Norway. These deposits were formed during the Permian as the result of magmatic activity in the Oslo Rift, and gave rise to the Kongsberg Silver Mines and the establishment of Kongsberg's Royal Norwegian Mining Academy (Bergseminaret), which in turn led to the foundation of H.M. King Frederik's University in Christiania in 1811, which later became the University of Oslo.

After the Caledonian mountain belt had evolved during the Silurian and Early Devonian, and the subsequent formation of Devonian intermontane basins, no dramatic geological events occurred across what is now mainland Norway prior to the end of the Carboniferous, about 310 million years ago, apart from the gradual erosion of the mountain belt itself. Of course, geological processes had occurred in this region, but no rocks or structures are preserved on mainland Norway from this period. The most likely interpretation of this is that Norway lay entirely above sea level, and that the most active processes were weathering and erosion of the Caledonian mountain belt. The period for which we lack geological information about mainland Norway ranges from the Mid-Devonian to the Late Carboniferous, between about 385 and 310 million years ago. If, during this time, deposition occurred or new rocks formed, they must have been removed *prior to* the Late Carboniferous, and are thus lost for ever. This time gap, or hiatus, was of even longer duration in the Oslo area, and lasted from the Late Silurian to the Late Carboniferous, a period of almost 100 million years. The Late Carboniferous marked the onset of formation of the Oslo Rift, a process that continued for almost 70 million years, characterised by volcanism and the intrusion of great volumes of molten rock. The Permo-Carboniferous also saw the evolution of sedimentary basins in the southern North Sea containing a wide diversity of sediments and volcanic rocks, a development that became of great economic importance to Europe. Carboniferous coal was important in driving the industrial revolution. The reservoirs of the gigantic Groningen gas field in the Netherlands are in Permian sandstones, and in many ways this discovery heralded the start of the North Sea oil and gas boom.

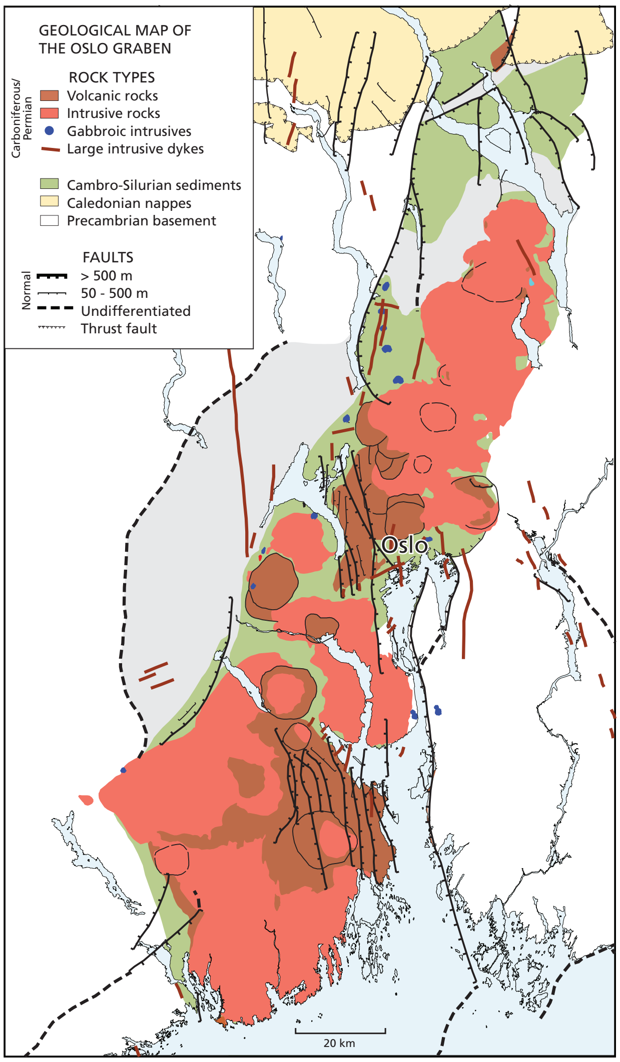


Reconstruction of the location of the continents about 280 million years ago. Brown indicates continental areas, light blue is continental shelves, and dark blue is oceanic crust. (Illustration: R. Blakey)

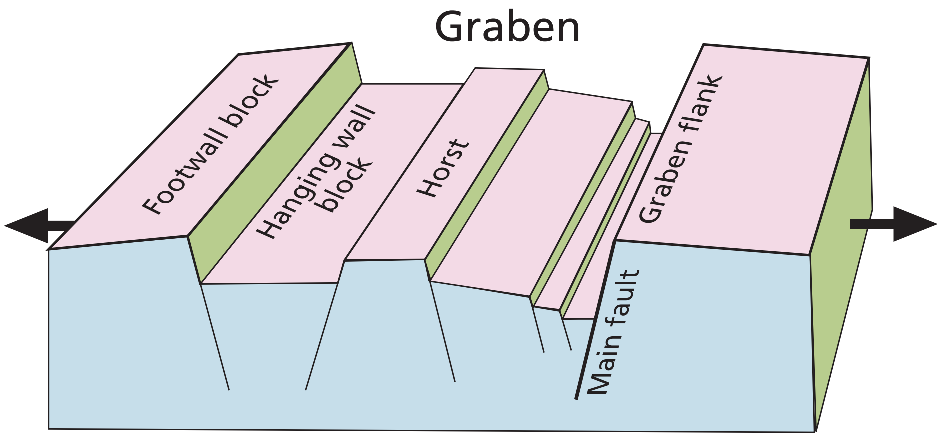
The Oslo Graben – a classic geological area

The rocks and geological structures preserved in the Oslo Rift serve to illustrate many of the processes that were active when the rift evolved. Several of the volcanic and other igneous rocks in the Oslo Graben are characteristic of rift structures. They were often given local and unusual names and early in the history of the science attracted the attention of geologists the world over. The igneous rocks and minerals of the Oslo Rift have been studied for almost 200 years.

Our geological description of the area will frequently refer to the following three terms; the *Oslo Region,* the *Oslo Rift*, and the *Oslo Graben*. The Oslo region comprises the Cambro-Silurian and Late Carboniferous to Permian rocks found in the elongated geological province from Langsundsfjord in the south to the northern end of Lake Mjøsa in the north. The Oslo Rift is the fault-bounded lithospheric fracture zone formed at the end of the Permo-Carboniferous, and encompasses the Oslo Region, together with rift structures in the Skagerrak and the sparagmite region of south-eastern Norway (Østlandet). Those parts of the crust that lie both within the rift and the Oslo Region later subsided and became the Oslo Graben. The Oslo Graben constitutes the classic part of the Oslo Rift, and is that part of the rift structure we observe on mainland Norway at the present day. Rift structures are



Map showing the generalised geology of the Oslo Region with principal rock types and structures. In the north, thrust nappes are shaded yellow. Cambro-Silurian sediments are shown in green, Permo-Carboniferous lavas in brown, and Permian intrusives in red. Faults are drawn in black with the line thickness giving an indication of magnitude.



Conceptual diagram of horst and graben structures, and some terms associated with rifts and grabens. Crustal extension often produces faults. Blocks are displaced up and down relative to each other along the fault planes..

described in general terms in Chapter 2, while the Cambro-Silurian history of the Oslo Region is described in Chapter 5.

The Oslo Region was already well-known for its distinctive geological features over 200 years ago. The German geologist Leopold von Buch was the first to put the Oslo Region on the world map. From 1806 to 1808 he travelled through Norway and as far north as Finnmark, describing the major geological features. A geological map of the Oslo area adorns the first page of von Buch's book describing his Norwegian expedition. One of the rocks he named and described is the rare rhomb porphyry, which he found both as a lava and an intrusive dyke rock.

Theodor Kjerulf began his pioneering geological mapping in the Oslo Region and described, among other things, the important erosional boundary, or *unconformity*, between the underlying folded Cambro-Silurian strata, and the flat-lying sedimentary rocks and lavas above it. Rocks from a period of over 100 million years are missing! W.C. Brøgger has, more than any other geologist, left his mark on the area with his studies of the Oslo Region's igneous rocks. He was the first to name and describe several minerals and rocks from the Oslo region. The fourth great investigative pioneer of the Oslo Region's Permian rocks was Victor Moritz Goldschmidt, who studied the alteration (contact metamorphism) of older sedimentary rocks resulting from the intrusion from depth of great volumes of molten rock.

Igneous rocks and rare minerals

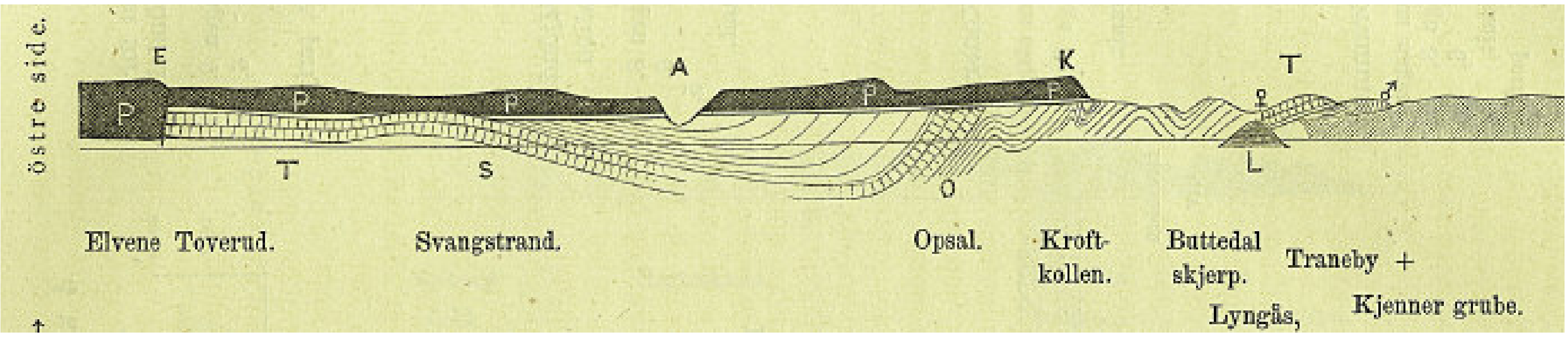
It was the intrusive and extrusive igneous rocks and rare minerals of the Oslo Region that first drew the attention of geologists. The area possesses many rare minerals and unusual rock types formed by the crystallisation of magma. Igneous rocks occur as lavas, shallow intrusive dykes and sills, and deep plutonic intrusions. Of these, it is the plutonic intrusions that are most easily visible at the present day. This is because between 1 and 3 kilometres of overlying rock has been removed from the Oslo Region since the Permian and Early Triassic, leaving the plutonic and extrusive rocks exposed. The terms *pluton* and *batholith* are often used in academic literature from the Oslo Region. *Pluton* is a term applied to all forms of deep intrusions, large and small, whereas the term *batholith* is reserved for the largest plutonic intrusions that, as a rule, extend over areas of many tens of square kilometres.

In the 1800s, the growth of Christiania (later named Oslo) demanded high quality building stone. Both granite from Drammen (the Drammen granite) and syenites from districts north of Oslo provided high quality building and monumental stone. Most of


From a portrait of Baron Leopold von Buch. (Reproduced with the permission of the US Geological Survey, Museum Property Program).


Reiſe durch Norwegen
und
Lappland.
von
Leopold von Buch
[illegible]
Erſter Theil
Berlin
bei G. C. Nauck
1810

Reproduction of the first page of Leopold von Buch's book, published in 1810.



In his book, published in 1879, Th. Kjerulf drew this north-south profile along Lierdalen in Lier. It shows the structural geology, the unconformity, and the geological framework of the Oslo Region as interpreted by Kjerulf in the mid-19th century. The syncline developed within sandstones of the Ringerike Group is seen clearly beneath the dark Permian lavas.

THE KONGSBERG SILVER

By Fred Steinar Nordrum

The Kongsberg Silver Mines were established in 1623 and, after the visit of King Christian IV in the spring of 1624, the mining town of Kongsberg was founded. The mines remained in production until their closure in 1958. Peak production was achieved in about 1770 when a total of 78 mines employed 4,000 workers. It is estimated that the mine employees put in about 300,000 man-hours altogether. All in all, about 1,350 tonnes of silver were produced, with peak annual production being achieved with the advent of modern operational methods in the 20th century, and the bests results in the operational year 1915-1916, when about 13 tonnes were produced.

Wire silver, Kongsberg. About 7 cm across. (Photo: P. Aas)

Silver crystals, Kongsberg. About 5 cm across. (Photo: O.T. Ljøstad)

The silver at Kongsberg occurs in narrow calcite veins of Permian age emplaced in fractures in metamorphic Precambrian rocks. It occurs only where the veins intersect so-called "fahlband" zones, which are impregnated with iron sulphide and exhibit an oxidised rust-like surface deposit.

The calcite veins, together with the silver, were precipitated from hydrothermal fluids generated during rifting and magmatism in the Oslo Region. The silver most probably formed at between 250 and 300 °C at between 3 and 4 kilometres' depth. Most silver occurs in its native mineral form, and as so-called "interstitial" silver, infilling the spaces between calcite and quartz crystals. Wire silver and silver crystals were found in larger pore spaces.

The Norwegian Mining Museum in Kongsberg is home to a celebrated collection of silver minerals. The silver normally contains about 1 % by weight mercury, and about 0.1 % antimony. In some veins, pure silver deposits also contained some gold. Calcite veins also contained smaller amounts of other silver minerals, most notably argentite, and a diversity of other minerals, often as beautiful crystals.

The Royal Norwegian Mining Academy was founded in Kongsberg in 1757 with the aim of educating Norwegian mining industry leaders, and became one of Europe's first higher educational institutions for mining technology. In 1786, the Academy achieved a significant boost in its resource base in the form of new buildings, a consolidated teaching staff, its own statutes, a curriculum, and a formal examination system. In 1811 it was decided that Norway's newest university should be founded in Kongsberg, but as early as in January 1812 the site was moved to Oslo (at that time named Christiania). After the foundation of University of Oslo, the Royal Norwegian Mining Academy was closed in 1814.

The Royal Norwegian Mining Academy, Kongsberg. (Photo: C. Berg)

Oslo's 19th century monumental buildings have exploited one or several of these Oslo Region rock types for their foundation walls and/or monumental stone. Today, granite, nordmarkite (the Grefsen syenite), and larvikite from the Oslo Region remain as important products for the building stone industry. Of these, larvikite is the most important, and is extensively quarried in Vestfold. Larvikite and rhomb porphyry are the most distinctive and best-known Oslo Rift rock types, both in terms of their economic importance and their rarity.

Lavas and volcanoes

Among the lavas of the Oslo Region we find *basalts, rhomb porphyry lavas, trachytes and rhyolites.* The contrasts in their mineralogical and chemical compositions can teach us much about the volcanic processes of the Oslo Rift.

W.C. BRØGGER, THE GODFATHER OF NORWEGIAN GEOLOGY

W.C. Brøgger with his rector's chain of office. A photograph from about 1910. (Photo: NHM, UiO)

Waldemar Christoffer Brøgger (1851-1940) was a brilliant research scientist, a highly capable organiser, and a persuasive politician. He was a commanding figure among Norwegian academic geologists from the end of the 1870s and virtually to his death.

His geological research work, beginning with palaeontological and stratigraphical studies of Cambro-Silurian rocks, is closely linked to the geology of the Oslo Region. During the 1880s he published, among other things, a detailed geological map of the islands around Oslo. However, his greatest scientific contribution involved his work with magmatic rocks and their associated minerals.

Brøgger became a student in Christiania in 1869 and a research associate in 1876. In 1881 he was appointed to the newly established professorship at Stockholm's Technical College and became a central figure in developing this institution. During his time in Stockholm he studied mineralogy, including the rare minerals of the Langesundsfjorden nepheline syenites (see separate fact box). His work with the Langesund minerals earned him international recognition among mineralogists, and in 1890 he published his research results. In the same year he was appointed professor in Christiania.

He spent the following decades researching the petrography and classification of magmatic rocks. The modern polarising microscope had just been invented, and this tool contributed to a major international expansion of petrography as an academic subject. He described several new rocks from the Oslo Region, and these became part of the international nomenclature. Both larvikite (see separate fact box), nordmarkite, and lardalite derive their names and descriptions from the Oslo Region. Together with J. Schetelig he published the first detailed geological maps of the Oslo Region, and his series of articles on the region's magmatic rocks made it, about a century ago, one of the best researched magmatic provinces in the world.

Brøgger was appointed as the University of Oslo's first rector in 1907, and he held this position until the University's centenary celebrations in 1911. Many of the University's most impressive building projects were planned or implemented during this period, including the University's assembly hall, the University Library in Drammensveien, and the Tøyen Museum. In 1917 Brøgger resigned his professorship in order to devote his attention entirely to research and to the magmatic rocks of the Oslo Region in particular.

Among our most celebrated national icons are the lions that take pride of place in front of the Norwegian parliament building (Storting). They were sculpted from syenite from Grorud in Oslo, and erected when the building was completed in 1866.
(Photo: B. T. Larsen)

LARVIKITE – A SUPERLATIVE ORNAMENTAL STONE

Larvikite is Norway's best known ornamental stone, and is a highly sought-after and expensive facing stone that can be found adorning building facades all over the world. It is known as the "pub-stone" in England, where it embellishes many a bar counter. As its name suggests, the rock is named after the town of Larvik in Vestfold, and any rock that possesses the fine, silver-blue sheen and the colourful, shimmering, so-called "schiller" effect, comes from the Larvik area. Larvikite occurs in both light and dark varieties, and the major quarries are located either at Klåstad or Tvedalen in Larvik municipality. The great larvikite complex in Vestfold is characterised by a concentric ring structure, with the oldest ring outermost, and the youngest situated at the core of the complex.

Larvikite is comprised almost entirely of the mineral feldspar. In terms of the formal international classification system for magmatic rocks (see Chapter 2), larvikite is defined as a monzonitic plutonic rock. However, unlike normal monzonite, which contains both plagioclase and orthoclase, larvikite possesses only a single, so-called "ternary", feldspar containing calcium (Ca), sodium (Na) and potassium (K). It also contains small amounts of clinopyroxene, amphibole, biotite, magnetite and apatite. The presence of the ternary feldspar, together with other petrological and geochemical characteristics, indicate that larvikite was formed primarily within the Earth's crust at depths of about 30 kilometres, very close to the boundary between the crust and the mantle. The large feldspar crystals formed at depths of several kilometres within the crust. Consequently, this feldspar is not stable at surface temperatures and pressures, and its crystalline structure undergoes microscopic alterations resulting from a chemical exsolution within its crystal structure. It is this phenomenon which, when viewed from certain angles and under special light conditions, produces the beautiful shimmering play of colours from the crystal surfaces.

Larvikite, commercially known as "Blue Pearl" and "Emerald Pearl", was in February 2008 named as the Norwegian national rock.

University of Oslo (UiO) Library at Blindern, an impressive building faced with larvikite. (Photo: B. T. Larsen)

Detail of a larvikite column showing the play of colours. (Photo: B. T. Larsen)

The magmatic mineral layering in larvikite from Ula is the result of the segregation and settling of crystals in the magma chamber. (Photo: B. T. Larsen)

THE MINERALS OF LANGESUNDSFJORDEN

By Alf Olav Larsen

Rare-mineral pegmatites

In terms of its mineralogy, the Langesundsfjorden district is not only restricted to the islands in the fjord itself, but also extends onto the mainland and eastwards into Vestfold. Here, we encounter innumerable coarse-grained pegmatite veins within the larvikite. The principal minerals within these pegmatites are feldspar, nepheline, aegerine, biotite and amphibole. In addition, we find several rare minerals rich in elements such as boron, fluorine, beryllium, sodium, zirconium, titanium, niobium and other rare alkaline earth metals. Similar deposits are found on the Kola Peninsula, in southern Greenland and in Canada.

Laavenite from Langesundsfjord. The crystal is 1 cm long. (Photo: P. Aas)

The early discoveries

Jens Esmark discovered the distinctive mineral deposits of south Vestfold at the close of the eighteenth century. However, it was his son, Hans Morten Thrane Esmark (1801-1882), who put the area firmly on the map. He was intensely interested in the natural sciences, and in mineralogy in particular, but studied to become a priest and was ordained in Brevik in 1826. In 1828, while hunting duck on the island of Løvøya in Langesundsfjorden, the young Esmark came upon a mineral that he could not identify. A sample was sent via his father to the renowned chemist J.J. Berzelius in Stockholm. Berzelius analysed the mineral and found that it contained an as yet unknown element which he named thorium, after the Norse god Thor. The mineral itself was a thorium silicate and was named thorite. Some years later Esmark discovered yet another as yet unknown mineral which, again, his father sent to Berzelius for identification. This was named aegerine after the Norse sea god Ægir. This discovery was made on the small island of Låven, in the outermost part of Langesundsfjorden. Esmark's discoveries soon drew many mineralogists to the area, and among the first of these were A. Erdmann, Th. Scheerer and P.C. Weibye. In the period between 1840 and 1854 they described the new minerals leucophanite, mosandrite, katapleiite, tritomite, astrophyllite, meliphanite and woehlerite. The first five of these were all discovered on the island of Låven, which was declared a nature reserve in 1970 on the basis of its mineral diversity.

Brøgger's great monograph

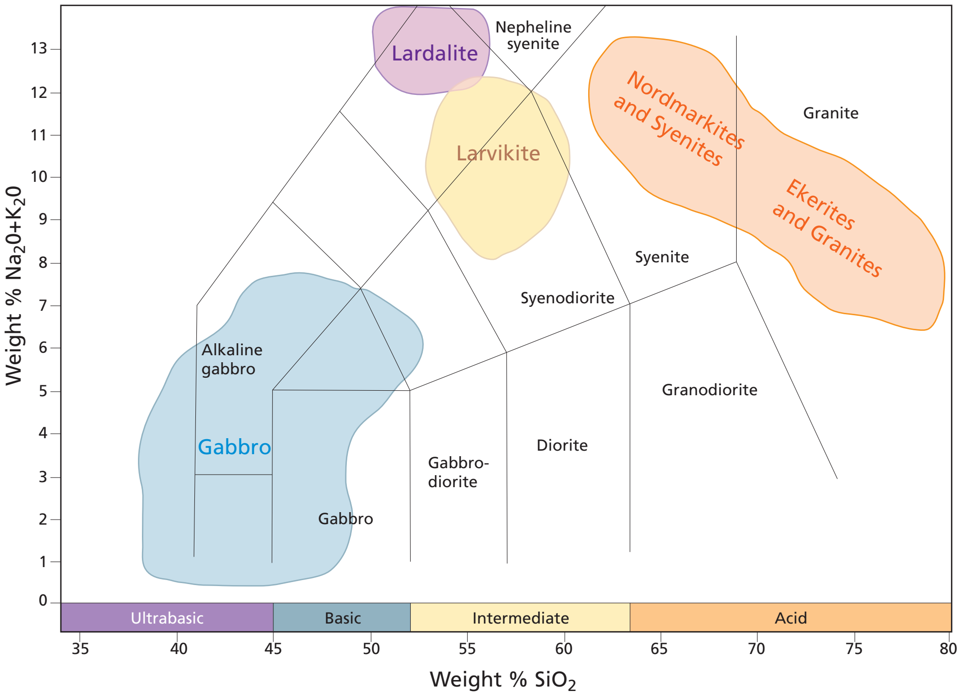
In 1890, W.C. Brøgger published his major, almost 950-page, monograph that was to give the Langesundsfjorden minerals international renown. He made detailed descriptions of all the 70 different minerals from the area that were known of at that time, including eight that were new to science; laavenite, cappelenite, melanocerite, nordenskioldine, rosenbuschite, eudidymite, hambergite and hiortdahlite. In addition, he gave the name larvikite to the area's characteristic rock type.

After Brøgger

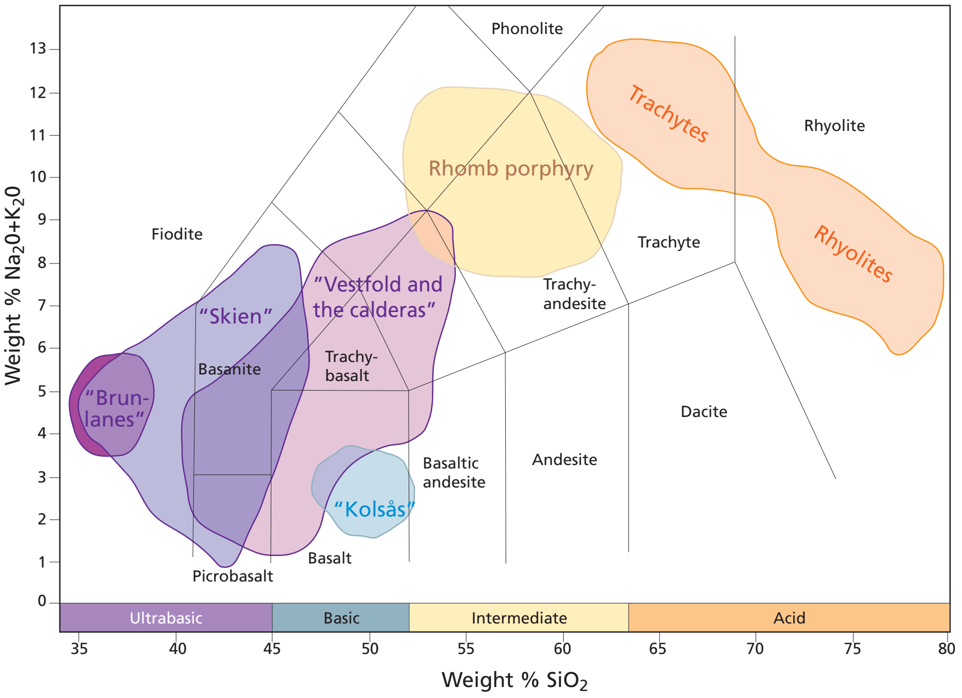
In recent decades more than 100 minerals new to the area have been discovered, almost all of them by amateur collectors. Four new minerals have also been described: gadolinite-(Ce), chiavennite, tvedalite and grenmarite. Langesundsfjorden is thus one of the most mineralogically diverse areas in the world.

Laucophane from Langesundsfjord. The green crystals are 6-7cm long. (Photo: P. Aas)

Katapleiite from Langesundsfjord. The flat crystals are 1-2 cm wide. (Photo: P. Aas)



A plot showing the composition of SiO$_2$ versus alkaline components (Na$_2$O + K$_2$O) for intrusive rocks (major and minor plutons) from the Oslo Rift. International rock classification names are shown in the background. The plot shows three groupings. On the left is a major concentration of gabbros. In the centre we find larvikite and lardalite, and on the upper right, with the highest SiO$_2$ and alkaline compositions, are the most acidic plutonic rocks: syenite, nordmarkite, ekerite and granite.



A diagram showing the classification of lavas as defined by the composition of alkaline components (Na$_2$O + K$_2$O) plotted against SiO$_2$. Terms in black are for internationally recognised lava types, while the coloured fields represent lavas we find in the Oslo Region. The four violet to blue coloured fields on the left represent distinct basalt lavas from the Oslo Region. From the left (violet), the Brunlanes (B1) nephelinites and melilitites, then (B1) basanites and alkaline basalts from Skien and Skrim. Then the alkaline basalts (B1, B2 and younger) from Vestfold, Jeløya, B2 from Krokskogen and its calderas and, on the right, B1 (blue) quartz tholeiites from Krokskogen (the "Kolsås basalt"). The brown field represents rhomb porphyry lavas, and the red field trachytes and rhyolites.

Field investigations and mapping of the basalt and rhomb porphyry lavas of the Oslo Graben reveal that they had relatively low viscosity and could thus flow over long distances, whereas the trachytes and rhyolites were more viscous, and only flowed over short distances. The composition of volatile components such as H_2O, CO_2, Cl, F, SO_2 etc., in acidic magmas can vary greatly. The more volatile components dissolved in the magma (in particular, water), the lower the viscosity. At the Earth's surface, molten rock containing large volumes of dissolved gas, such as the gas-rich rhyolites and trachytes, may erupt explosively and flow for long distances. Volcanic eruptions of this type involving large volumes of gas result in a rock containing compacted gas bubbles or welded pumice fragments. Compressed shards of pumice may be found welded together with what was originally hot volcanic ash, and these rocks are termed pyroclastic ash flow deposits or *ignimbrites*. We find trachytic and rhyolitic ignimbrites in Vestfold, and in most of the calderas. These must have reached the surface through volcanoes that erupted with exceptional explosive power, and some ignimbrite flows may have travelled over long distances. Some of the Oslo Graben's massive explosive caldera volcanoes have thus earned themselves the name "super volcanoes".

Contact metamorphism and hydrothermal activity

The intrusion of the great volumes of magma in the Oslo Region resulted in a massive increase in heat flow extending upwards and into the surrounding country rocks. Great volumes of *fluids*, composed of water and gases such as carbon dioxide, sulphur dioxide, fluorine, chlorine, and others, were separated from the magmas. Hot water and steam have a great capacity to dissolve minerals. It is a characteristic of many of the Oslo Region's igneous intrusions that minerals formed originally by primary crystallisation processes were later altered by hot fluids flowing through the rocks. Primary minerals such as quartz, feldspar, pyroxene, and olivine, among others, are often found chemically altered, oxidised or corroded. At some locations the rocks are "rotten to the core" as a result of *hydrothermal* alteration, and the primary minerals metamorphosed into new forms.

Sodium is a highly mobile element and this characteristic has led to the "albitisation" of Permian intrusions and basement rocks in and around the Oslo Region, with the result that the sodium feldspar albite is now the dominant mineral in these rocks. Several other sodium and potassium-bearing silicates, including zeolites and scapolite, were formed as secondary minerals in and around the Oslo Region, together with calcite and fluorite, which are commonly found along fault and fracture zones.

The hot water and gases also carried with them heavy metals such as silver, zinc, copper, lead, iron, molybdenum, bismuth and others. Hydrothermal activity resulted in the precipitation of minerals such as the pure native silver deposits at Kongsberg, galena and sphalerite such as those at Konnerud in Drammen and Grua in Hadeland, among others; iron oxides such as magnetite and haematite as in Bærum and Feiring, and molybdenite as in Drammen, at Tryvann near Oslo, and in Hurdal.

Most of these mineral deposits are associated with country rocks adjacent to the great batholiths, typically Cambro-Silurian limestones, and are termed "skarn" deposits. As ores they have been the targets of prospecting and mining operations, and many achieved economic importance from the 17th century and up to the beginning of the twentieth. Molybdenite became enriched at the very tops of granite plutons, and molybdenum mines were in operation in the Drammen area during the Second World War. There are vast molybdenum deposits in Hurdal at the apex of one of the youngest granites formed during stage 6 of the region's evolution, but these have yet to be exploited on a commercial basis.

The heat and fluids permeated the Oslo Region's country rocks near the roofs and flanks of the great intrusives region causing their alteration by *contact metamorphism*. As a young man, Victor Moritz Goldschmidt gained international recognition for his studies of contact metamorphism in the Oslo Region. Beautiful and often rare minerals often result from contact metamorphism. Limestones were altered to marbles, sandstones to glass-like quartzites, and clays and volcanic rocks to hornfels. The marble from Gjellebekk in Lier was used in the construction of the famous Marble Church in Copenhagen. The durability of hornfels has led to its extensive use as road aggregate.

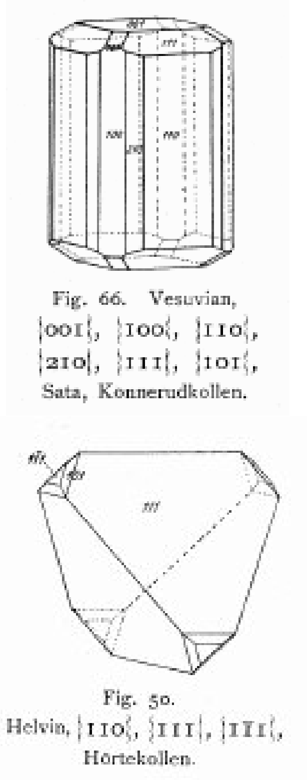
The geological structure of the Oslo Rift

There are several active and closely-studied continental rift structures in the world that provide excellent analogues to the Oslo Rift. The Kenya Rift in East Africa is remarkably similar, while other examples are provided by the Baikal Rift System in Siberia, the Rhine Graben in Germany, and the Rio Grande Rift System in the south-western United States. In about 1980, a generalised model for the evolution of continental rift structures was developed, using the Kenyan Rift Valley as its model.

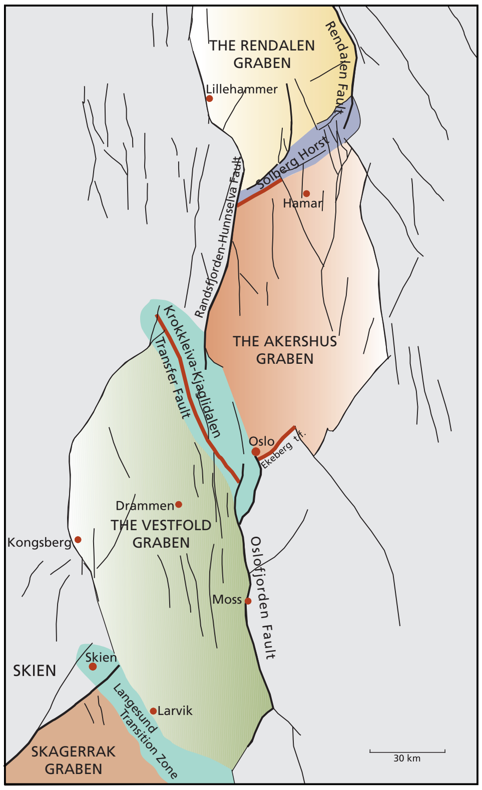
The Kenyan rift structure is composed of several graben segments. The width of each segment is approximately between 60-80 kilometres, and is thus similar to the lithosphere thickness. Normally, the graben segments are half-grabens; that is, grabens in which subsidence along one flank is much greater than on the other. Half-grabens are often more or less serially aligned within a rift structure, and where the controlling faults switch from one graben flank to the other, segments are commonly linked across a zone where so-called transfer faults are formed. Such zones are termed *transfer fault zones*.

We find transfer fault zones in the Oslo Rift. That part of the rift observed on mainland Norway at the

Minerals from the contact metamorphic zone in the Oslo Region. New minerals are formed by heat and hydrothermal fluids from the magmas. On the left are vesuvianite crystals from Landfalltjern, Drammen. The sample is about 3.3 cm across. (Photo J.H. Hurum)

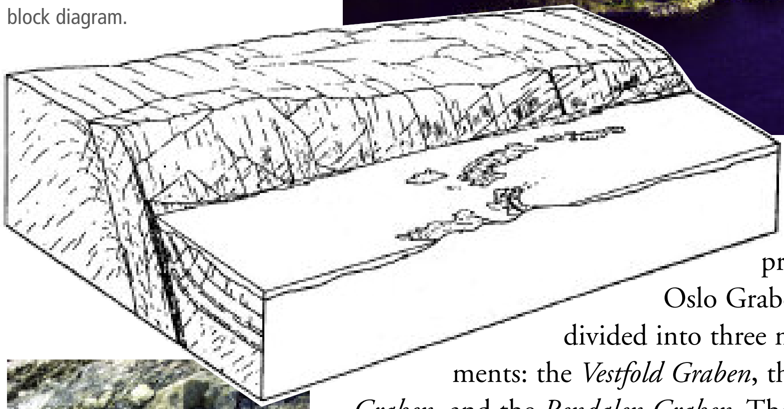


Diagrams from V. M. Goldschmidt's celebrated doctoral thesis.



General tectonic framework of the Oslo Rift showing four grabens, three transfer fault zones and associated transfer faults. The three grabens on the mainland exhibit different polarities (i.e., they dip alternately towards the east or west). The fourth, the Skagerrak Graben, lies entirely beneath the sea.

The northernmost extension of the Oslofjorden Fault is called the Nesodden Fault, and the fault escarpment is still clearly defined. The fault plane and breccia can be studied along the greater part of its length. (Photo: Fjellanger Widerøe)



The Nesodden Fault, after a sketch by Cloos from 1928. The small island of Struten is seen in both the photograph and the block diagram.

present day (the Oslo Graben), can be divided into three major segments: the *Vestfold Graben*, the *Akershus Graben*, and the *Rendalen Graben*. The Vestfold and Rendalen Grabens have their major fault on the eastern flank, whereas the Akershus Graben has its on the western flank. The transfer fault zone between the southern Vestfold and Akershus Graben segments is called the Krokkleiva-Kjaglidalen Fault Zone, which transects Krokskogen from Sandvika to Sundvollen. The transfer fault zone between the Akershus and Rendalen Graben segments to the north is made up of two parallel faults that transect Neshalvøya in Ringsaker, where basement rocks have been uplifted as part of the Solberg Horst.

Volcanic rocks are common in both southernmost graben segments. Giant plutons (batholiths) are also found in the Vestfold and Akershus Grabens with the northernmost batholith being found at Totenåsen, located to the west of the southern part of Lake Mjøsa. The rift structure continues to the north-east, although the Rendalen Graben lacks plutonic intrusives and possesses only a few examples of lavas, such as those at Brumunddal. The Rendalen Graben is superseded at Engerdalen and Femunden by several other graben segments, some of which have their controlling faults on their western flanks, others on the eastern. However, the best-known examples of Oslo Graben bounding faults are the Oslofjorden Fault and its northern extension, the Nesodden Fault, together with the Bunnefjorden

From the Nesodden Fault. Crush breccias are found along most of the length of the fault, but can vary greatly both in appearance and in the degree of crushing. (Photo: B. T. Larsen)

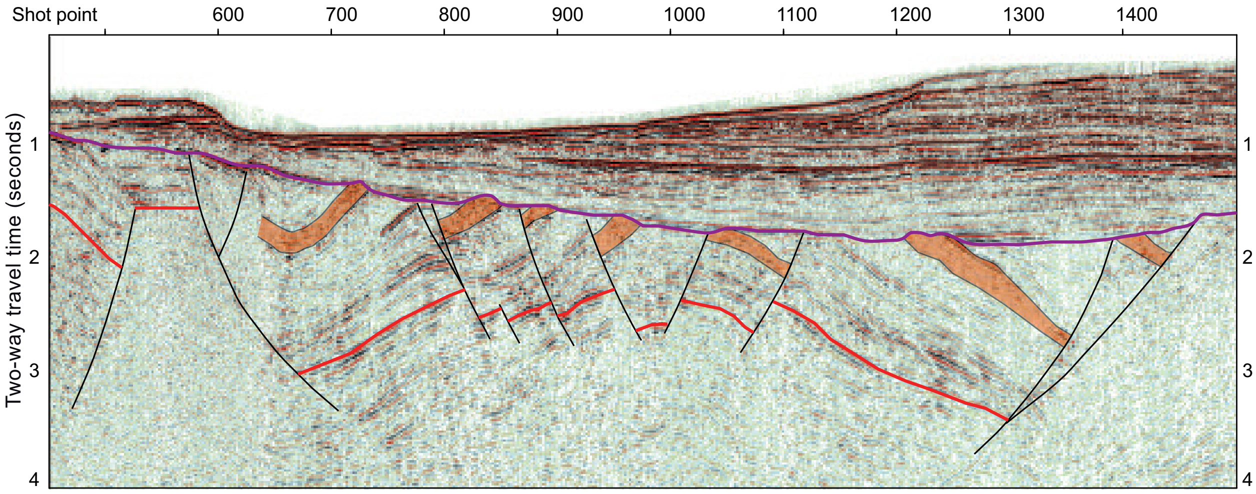
View looking towards the south-east of the Krokskogen lava plateau and Krokkleiva near Sundvollen in Hole. The great pass is developed along the Krokkleiva-Kjaglidalen Transfer Fault, which is one of the major transfer faults in the Oslo Rift. The steep basalt and rhomb porphyry lava escarpment is seen on both sides of the fault. (Photo: B. T. Larsen)

Erik Pauelsen's dramatic depiction of Krokkleiva from 1789. Until 1855, Krokkleiva formed part of the main highway between Kristiania and Bergen, and was one of the most difficult sections along the eastern part of the route. Geologically, the pass is part of the great Krokkleiva-Kjaglidalen Transfer Fault. The fault, which exhibits a predominantly right-lateral displacement, can be traced from Hole (Sundvollen) to Bærum (Sandvika) where it finally meets the great Nesodden Fault. (Reproduced with the permission of the State Museum of Art, Copenhagen)

and the Ekeberg Faults. The western flanking block of the Nesodden Fault has subsided about 1000 metres in relation to its eastern flank, and in the outer Oslofjord district, the throw on the Oslofjorden Fault is about 3000 metres. The vertical throw along the northern part of the Rendalen Fault is calculated to be about 1300 metres, and along Randsfjorden, the Akershus Graben is thought to have subsided by about 1000 metres. The Oslo Rift extends subsea from the outer part of Oslofjord towards the southwest as part of a large, composite, graben segment termed the *Skagerrak Graben.*

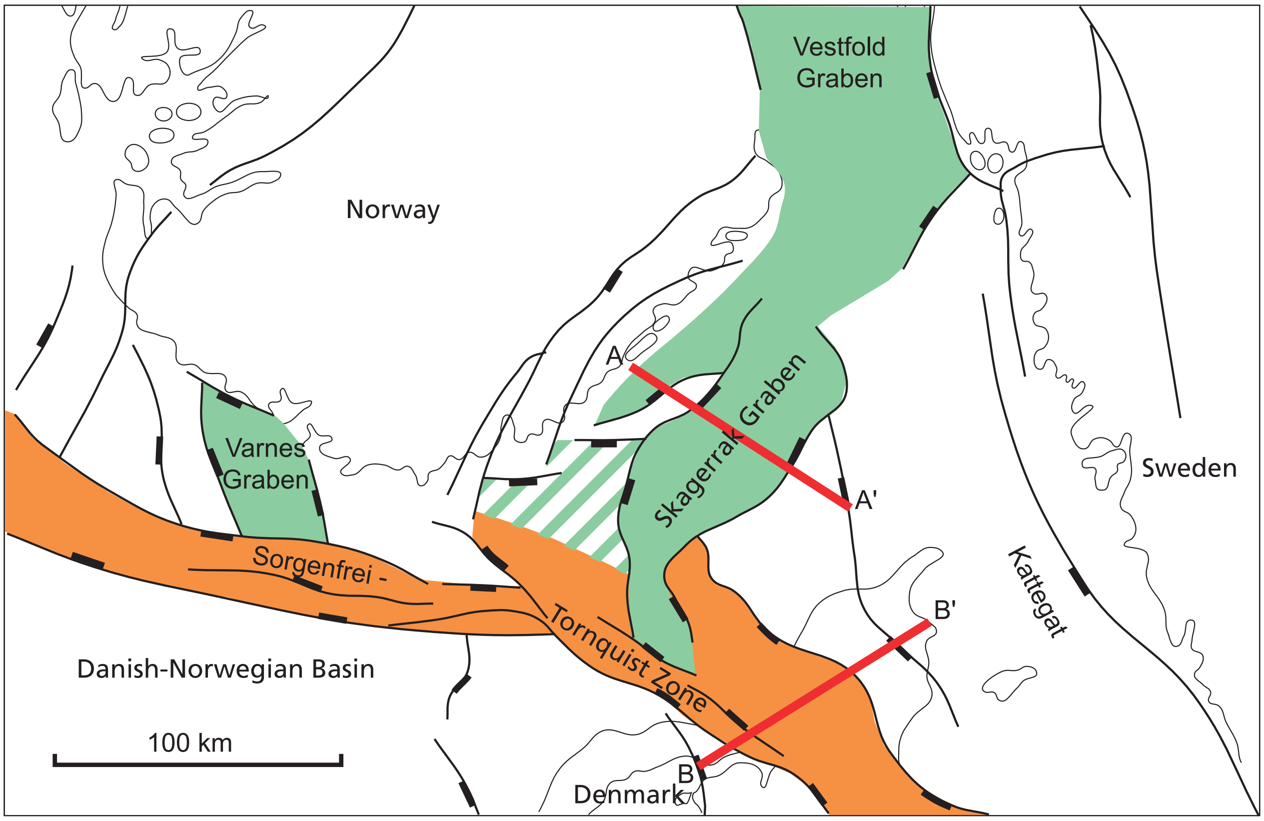
The Skagerrak Graben

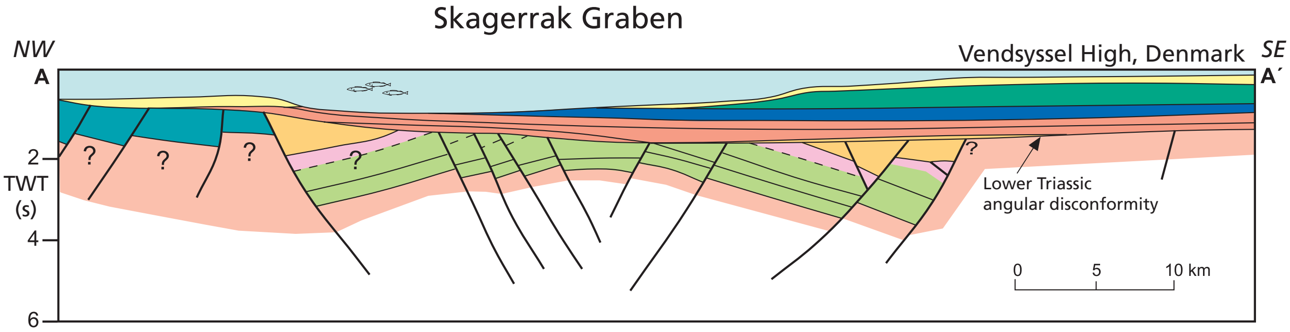
The Skagerrak Graben forms that part of the Oslo Rift lying south of the Vestfold Graben. It can be traced from the outer part of Oslofjord in the north, to a point about 150 kilometres further south where it intersects the Sorgenfrei-Tornquist Zone. In the early 1970s, the southern extension of the Oslo Rift in the Skagerrak was mapped using gravimetric and geomagnetic data. By the end of the 1980s, seismic data had confirmed the presence of a graben structure, and found the Skagerrak Graben to be composed of several half-graben segments bounded by major faults. The graben lies beneath a thin sequence of Mesozoic and Cenozoic sedimentary rocks.



Seismic profile across the Skagerrak Graben. A dramatic unconformity separates Palaeozoic from Mesozoic sequences. The strata shaded orange are interpreted as Permian lavas. These are more resistant than the surrounding rocks and thus protrude above the unconformity surface. The lavas are believed to be equivalent to the rhomb porphyry and basalt lavas that we find on land in the Oslo Rift.

Map showing the Skagerrak Graben. The structure exhibits a more south-westerly trend and is structurally more complex than the Oslo Graben to the north. The transition zone in outer Oslofjord is the least known segment of the Oslo Rift. The major structural units are coloured. Graben structures are shaded green; the hatched area represents a possible extension. The Sorgenfrei-Tornquist Zone is shaded orange. The Varnes Graben south of Lista is assumed primarily to be of Permo-Carboniferous age. The two profiles below are indicated with two red lines.

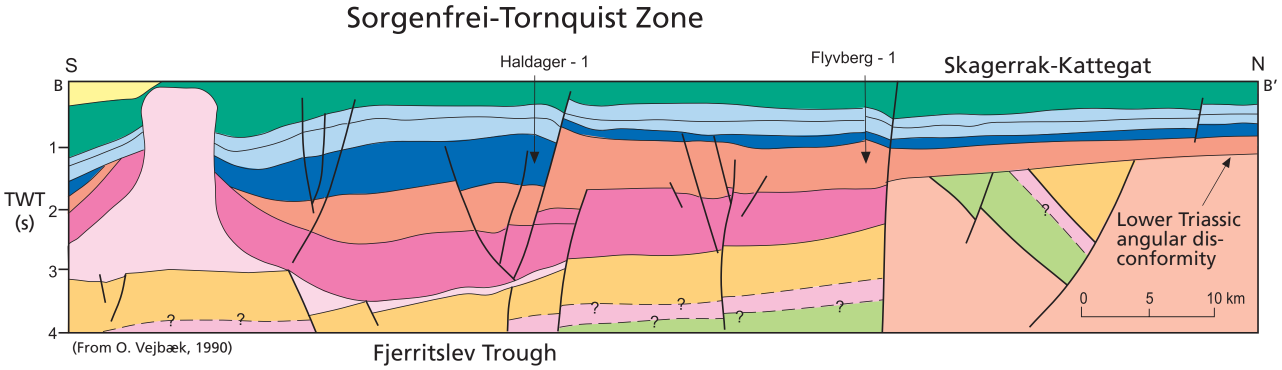




A geological profile across the Skagerrak Graben with an interpretation of the main stratigraphic units. TWT – Two-way travel time.

🟨 Quaternary
🟩 Lower Cretaceous
🟦 Middle to Lower Jurassic
🟧 Middle to Upper Triassic
🟪 Lower Triassic
🟦 Palaeozoicum
🟨 Permian

⬜ Upper Permian, Zechstein
🟨 Lower & Middle Permian, Rotliegendes
🟪 Upper Carboniferous, Permian volcanics and sediments
🟩 Lower Palaeozoicum
🟧 Precambrian Basement



A geological profile across the Sorgenfrei-Tornquist Zone with an interpretation of the main stratigraphic units. TWT – Two-way travel time.

Geophysical data, combined with information from a few boreholes, have revealed important correlations between the Skagerrak and Oslo Grabens, including dipping strata that are apparently similar to the Cambrian, Ordovician and Silurian sedimentary sequences observed on the mainland. In addition, there is a thin sequence of Permo-Carboniferous lavas and sills in the Skagerrak Graben. These are overlain, at the very top of the sequence, by continental Permian sediments including, among others, volcanoclastic conglomerates and sandstones.

The intrusion of rhomb porphyry and diabase dykes, and the formation of faults of Late Carboniferous and Early Permian age along the Skagerrak coast in Norway and in Bohuslän, Sweden, are linked to the evolution of the Skagerrak Graben. A Permian diabase dyke at Tvedestrand has been found to contain oil, and this unusual occurrence lends support to the possibility that oil and gas-bearing sedimentary rocks will be found in the Skagerrak itself. Gravity data from the Skagerrak indicate that dense gabbros are located at depths of between 25 to 30 kilometres in the crust beneath the Skagerrak Graben.

Oslo Rift rocks from outside the Oslo Graben

Igneous activity also occurred beyond the boundaries of the Oslo Region itself, as is demonstrated by the presence of dykes permeating country rocks in some cases significant distances beyond the rift. These dykes are of three major types; diabase, rhomb porphyry, and syenite. The diabase intrusions are usually quite narrow, being about one metre across and up to a few hundred metres in length. However, some are over ten metres across and several tens of kilometres in length, such as the example at Tonsåsen in Valdres. Most dykes exhibit a north-south orientation, and many thousands are found both within and beyond the boundaries of the Oslo Region, often in broad dyke swarms, as for example in Bærum.

There are fewer rhomb porphyry dykes and these are generally broader and extend for greater distances than the diabase intrusions. The longest recorded example belongs to a dyke system that can be traced from Modum to Etnedalen in Valdres. It is normally about 40 metres across, but at Modum it is as much as 80 metres in width. The dyke system is almost 120 kilometres in length and strikes parallel to the Oslo Graben's dominant north-south orientation.

This broad rhomb porphyry dyke in Ringerike is a good example of a possible magma supply fissure for the great rhomb porphyry fissure eruptions. However, we do not know precisely which rhomb porphyry lava erupted from this dyke. Rhomb porphyry dykes vary between 10 and 80 metres across, and can be traced over distances of more than 100 kilometres. (Photo: B. T. Larsen)

Very long rhomb porphyry dykes are found both east of Oslo, along the Skagerrak coast, in the Ringerike/Hadeland area, and in Bohuslän in Sweden. These are generally between 10 and 30 metres across and several tens of kilometres in length. Many major rhomb porphyry dykes are found within the Oslo Graben itself and, ever since the pioneering work of W.C. Brøgger, are thought to have acted as supply fissures for the rhomb porphyry lavas, although this still remains uncertain.

Syenite dykes are less frequent, and they are generally relatively broad and short in length. Those found both within and beyond the boundaries of the Oslo Region are frequently fractured, especially along their flanks, where the magma was cooled most rapidly after intrusion. These fracture systems can act as groundwater reservoirs, and many dykes thus act as important sources of fresh water, especially at locations where they cut through impermeable shales.

The Variscan Orogen and heat from the depths

At the close of the Carboniferous period, two major geological structures were formed across what is now Central Europe and Denmark; the Variscan mountain belt and the major fault lineament termed the *Sorgenfrei-Tornquist Zone*. The formation of these structures was of great significance for the evolution of the Oslo Rift located further to the north.

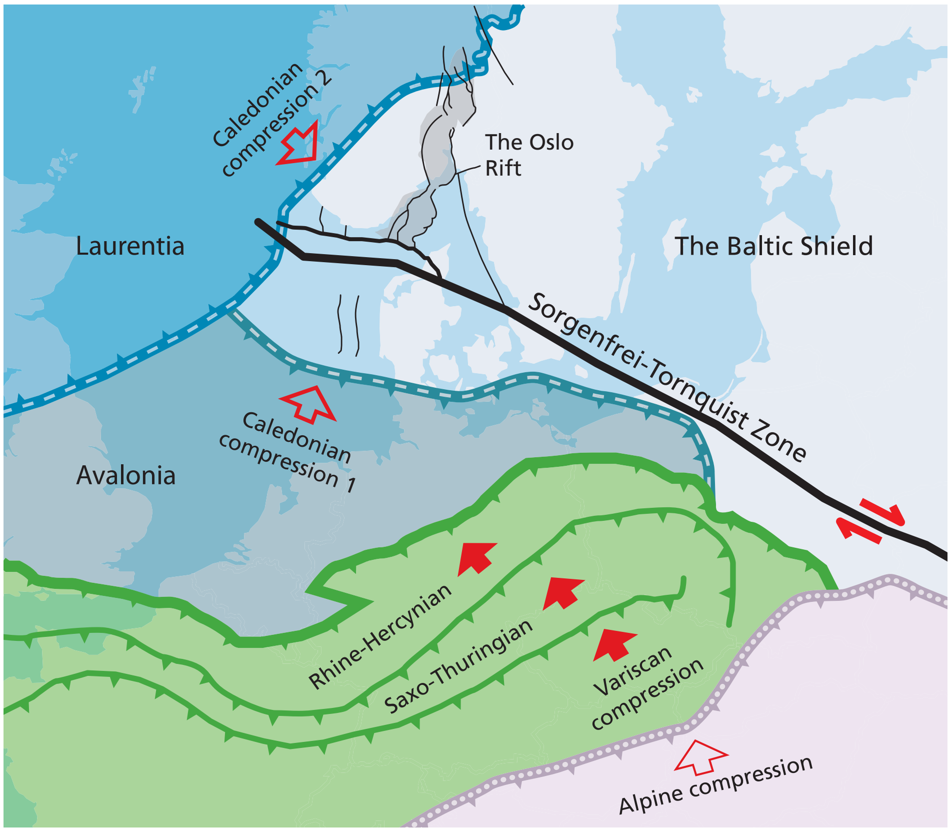
When the Gondwana plate and other micro-continents collided with "our" Laurussian plate during the Carboniferous, the resulting Variscan mountain belt became the most prominent geological structure in Europe. Today, we know that the collision began first in the west and progressed gradually eastwards, thus gradually closing the *Proto-Tethys Ocean* from west to east. The mountain belt extended from southern Ireland in the west, and continued through northern France, Belgium and Germany to Poland in the east. A major foreland basin developed on the northern flank of the Variscan mountain belt. At first, this basin was partly marine in character but during the Permo-Carboniferous it gradually became dominated by continental deposits, including thick coal sequences. The evolution of this area is described in detail later in this chapter.

In the Oslo Region we find preserved a thin, 5 to 90-metre thick, sequence of Late Carboniferous sedimentary rocks, but coal sequences are absent. In fact, these deposits indicate somewhat more barren environments than further south. Desert conditions most probably prevailed in south-eastern Norway at this time, and we find conditions similar to those typical of present day central Africa.

A major strike-slip fault

The tectonic stresses that built up in association with plate collision in the south resulted in major crustal dislocations in the area north of the mountain belt. The northernmost of the resulting fracture systems follows the *Sorgenfrei-Tornquist Zone,* which exhibits a northwest-southeast trend. The Sorgenfrei-Tornquist Zone extends approximately from the Sleipner gas field in the North Sea, through the Skagerrak and into Denmark, and thence via Skåne (Scania) in southern Sweden and into Poland. It then continues in a south-easterly direction into the present remnants of what was the Proto-Tethys Ocean. This major tectonic feature constitutes the geological boundary between Fennoscandia and the rest of Europe. The crust on the north-eastern flank of the Sorgenfrei-Tornquist Zone was displaced towards the southeast relative to the province in the southwest. Today, in northern Germany and Denmark, these strike-slip faults are overlain by

The Variscan tectonic plate configuration as it appeared towards the end of the Variscan orogeny in Europe, close to the transition between the Carboniferous and Permian. We see the Sorgenfrei-Tornquist Zone, the two great sedimentary basins situated north of the mountain belt, the Oslo Rift and the Skagerrak and Oslo Grabens to the north. The ancient Baltic Shield is shown in white, while the two plates (Laurentia and Avalonia) that collided during the Caledonian Orogeny are shaded blue. The various segments of the European Variscan Orogen are shaded green. The later collision zone formed during the Alpine Orogeny is shaded pink. (From: J.E. Lie)



younger sediments, and on land the Sorgenfrei-Tornquist Zone may only be studied in Skåne. Extensive crustal subsidence along the Sorgenfrei-Tornquist Zone produced a major seaway connecting the oceans of the Proto-Tethys to those of northern Europe.

The lithosphere underwent extension both north and south of the Sorgenfrei-Tornquist Zone, and shear displacements resulted in the formation of rift structures and grabens that today lie buried beneath younger sedimentary sequences in Denmark, northern Germany and the North Sea. The Oslo Rift forms the largest, and the most northern, of these grabens or rift structures.

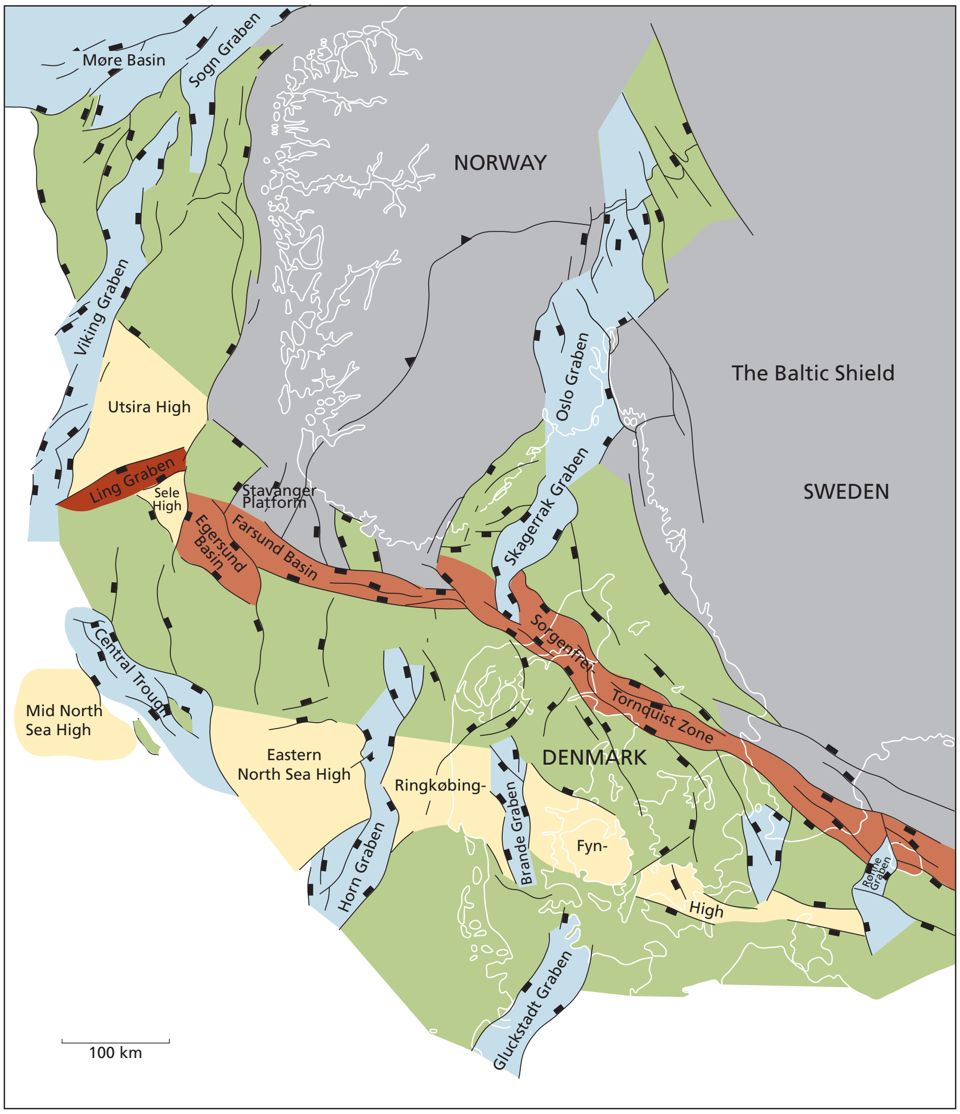
Heating of the crust beneath the Oslo Graben

The long axis of the Oslo Rift runs mainly north-south, reflecting the east-west oriented extensional forces that produced the rift. Volcanic activity began early in the rift's evolution, although the major faults only became active somewhat later. Volcanic activity was more pronounced in the south than in the north, where the rift dies out. We deduce from this that volcanism started in the south, although little is known of the detailed sequence of events.

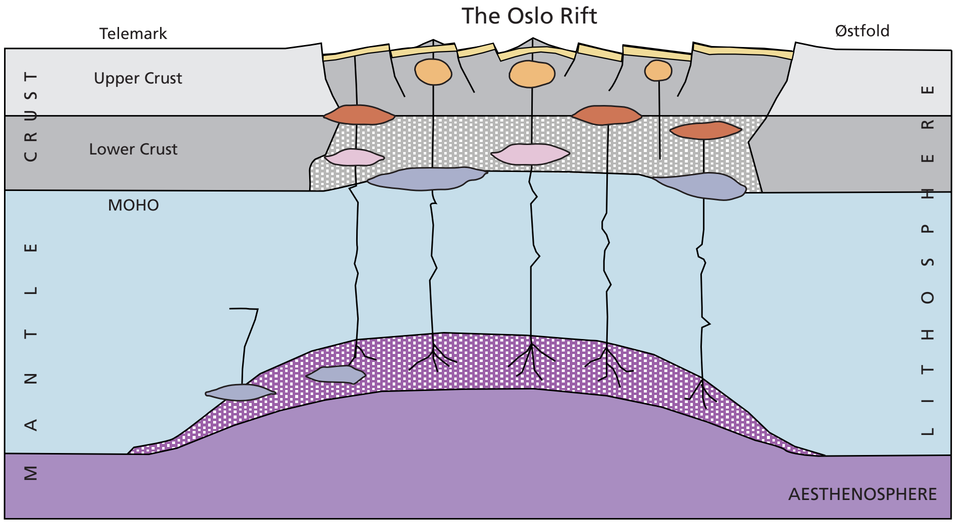
There were probably two major causes of the formation of the Oslo Rift. We have already described the tectonic stresses that were transmitted northwards via the Sorgenfrei-Tornquist Zone by the collision that produced the Variscan mountain belt. The other major factor was increased heat flow in the region arising from abnormally high crustal temperatures at depth that had already mechanically weakened the lithosphere.

The increase in heat flow beneath the Oslo Rift began as early as the Late Carboniferous, when melting began at about 30 kilometres depth in the uppermost mantle and lower crust. At the end of the Carboniferous, magma was located beneath the southern part of the Oslo Graben, where the increased temperatures had also weakened the lithosphere.

Movements along the Sorgenfrei-Tornquist Zone resulted in east-west directed extension and this phenomenon progressed further north, further weakening the lithosphere and promoting further melting. Initially, the magma intruded as sills at depth, followed later by the surface eruption of basalt lavas, and the formation of the first basalt volcanoes.



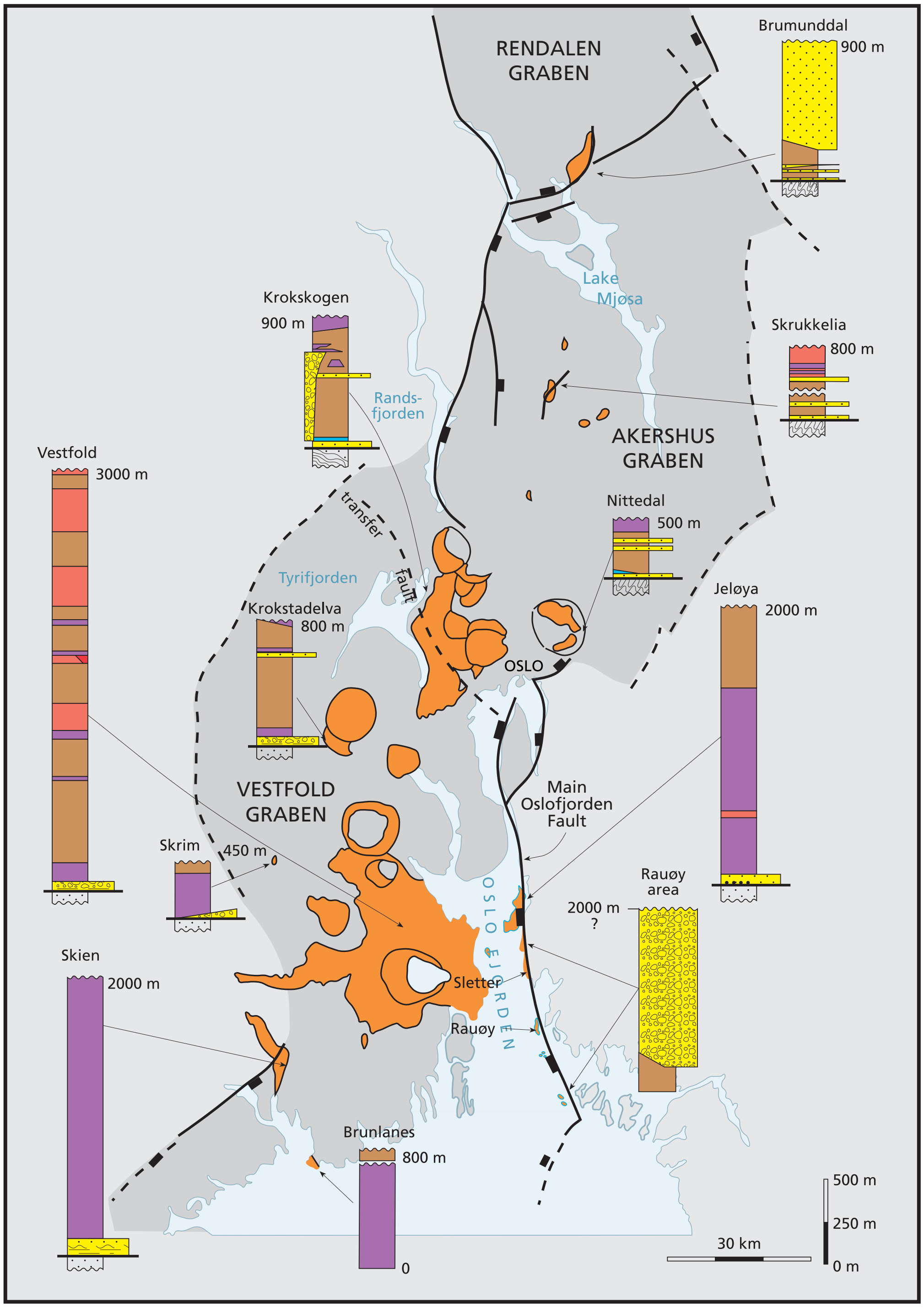
Map showing the structural elements of the North Sea, the Skagerrak and southern Norway. Many of these were active extensional features during the Late Carboniferous and Permian. The Oslo Rift is the largest extensional structure. The Sorgenfrei-Tornquist Zone transects the entire area. Rift and graben structures are shaded blue. The westernmost areas were active or reactivated during the Mesozoic. The Sorgenfrei-Tornquist Zone is shaded orange. Highs, most notably the Mid-North Sea High and the Ringkøping-Fyn High, which were active during Carboniferous-Permian, are shaded yellow. The Baltic Shield is shaded grey and the platforms, terraces and other areas influenced by faulting are shaded green.



An east-west profile through the Oslo Rift illustrating crustal and lithospheric thinning. In addition, temperatures were much higher beneath the rift, resulting in parts of the mantle becoming molten. (From: E-R. Neumann)

Geological evolution of the Oslo Rift

The evolution of the Oslo Rift can be divided into a series of six stages that developed over a period of 70 million years, including such phenomena as deep crustal magmatic processes, volcanism, faulting, sedimentation, and the thermal metamorphism of the Oslo Region's older rocks.



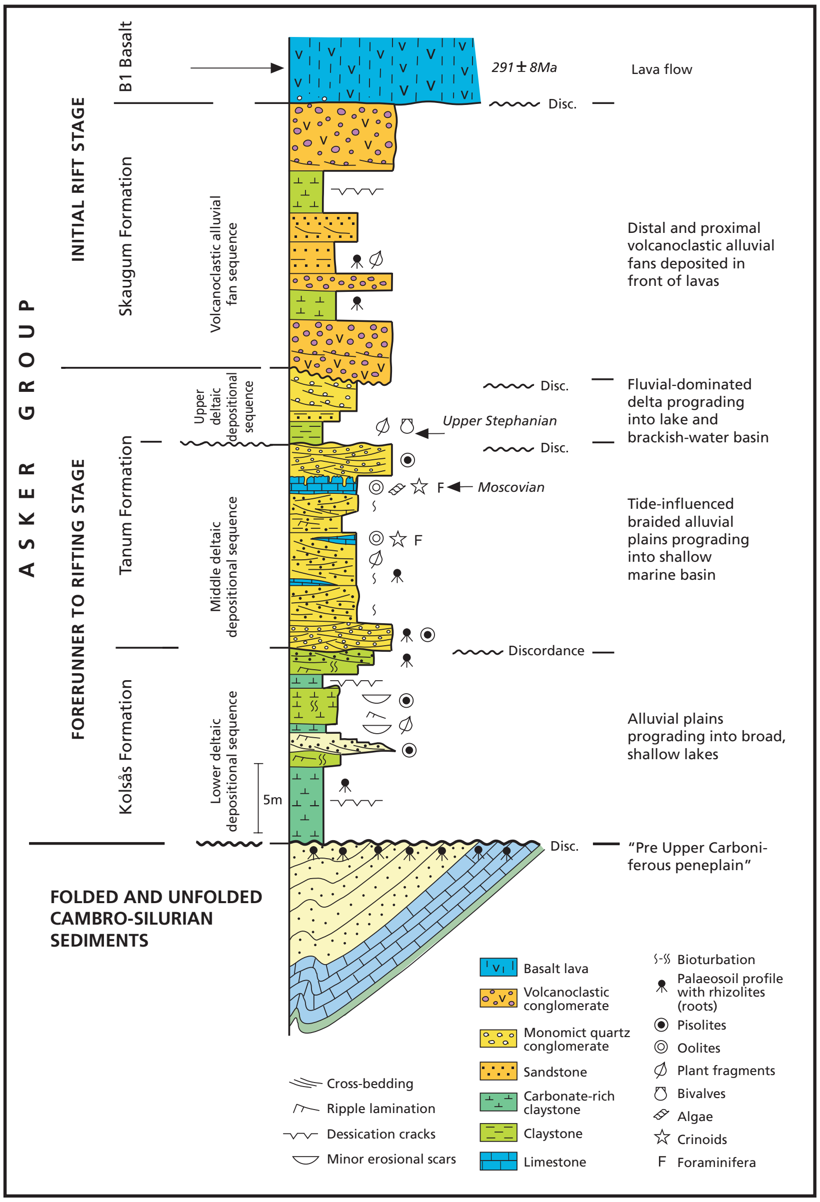
Distribution of Carboniferous and Permian lavas and sediments currently preserved in the Oslo region. The stratigraphic columns refer to the various provinces, and illustrate thickness variations between the sediments (yellow), and the three major volcanic rock types; basalt (violet), rhomb porphyry (brown), and trachyte/rhyolite (red).

The earliest igneous rocks within the Oslo Rift were formed about 310 million years ago, and the latest about 241 million years ago. During this period, lasting almost 70 million years from the Late Carboniferous, through the entire Permian and extending into the Early Triassic, both magmatic and tectonic processes were active within the Oslo Graben. The geological evolution of the rift may be divided into six stages. Not all the stages are necessarily contemporaneous within the rift, nor are they all represented in all provinces. For example, rocks from the first two stages are absent in the northern Oslo Graben. The six-fold division is best observed in the central tracts of the Oslo Graben, centred around Oslo, Bærum, Ringerike and the districts further south.

Most age determinations of the rocks have been conducted using the Rb-Sr (rubidium-strontium) method. More recent ages determined using the U-Pb (uranium-lead) method have revealed that some of the earlier datings had given ages that were too young. On the other hand, ages determined using the Ar-Ar (argon-argon) method are also relatively young for some rocks. Future age determinations using different methods will almost certainly help to modify our current interpretation of the timing of events that make up the evolution of the Oslo Graben.

The forerunner to rifting – stage 1

We see the first signs that something new was to happen in the Oslo area during the Late Carboniferous when, prior to the start of active volcanism and faulting, a vast, shallow, sedimentary basin



Stratigraphic subdivision of the Asker Group. We define three formations based on observations in the central Oslo Region, in particular from Asker, Bærum, Lier, Hole and Ringerike. The Asker Group is not found north of Nittedal, and the Skaugum Formation overlying the Tanum Formation is local to Asker and parts of the Bærum and Lier districts.

EVOLUTIONARY STAGES OF THE OSLO RIFT

Stage 1. *Late Carboniferous, 310-296 million years ago.* **The forerunner to rifting**.
A shallow sedimentary basin forms in front of the remains of the Caledonian mountain belt.

Stage 2. *Transition from Carboniferous to Permian, 300-292 million years ago.* **The initial rift stage.**
Volcanism begins with the eruption of the first basalts.

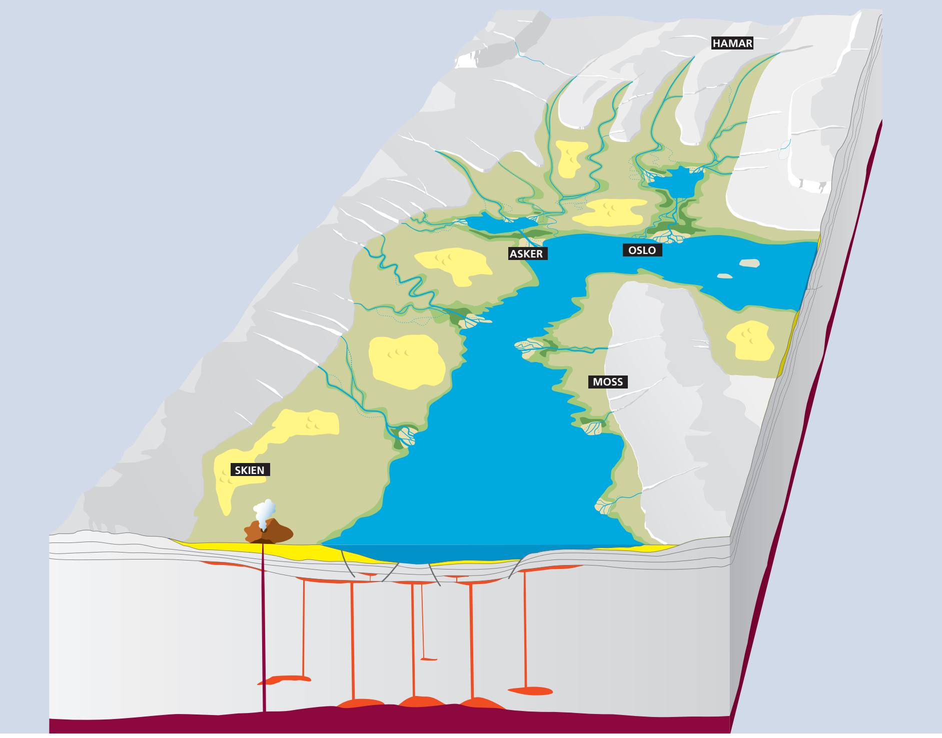
Stage 3. *Early Permian, 292-275 million years ago.* **The climax of rift formation.**
The area is characterised by rhomb porphyry lavas, major faults and fissure volcanoes, and the rift itself is formed. The first larvikite batholiths are formed during batholith phase 1.

Stage 4. *Early to Mid-Permian, 280-265 million years ago.* **Massive central volcanoes and calderas.**
Development from basaltic central volcanoes to explosive volcanism and caldera formation. Early during this stage the two great granite batholiths (the Drammen and Finnemarka granites) were formed during batholith phase 2.

Stage 5. *Mid- to Late Permian, 270-250 million years ago.* **The age of the great batholiths.**
The formation of deep-seated granites and ekerites, syenites and nordmarkites during batholith phase 3.

Stage 6. *Early Triassic, 250-241 million years ago.* **The concluding stage, the final batholith phase.**
Deep intrusion of the youngest small granites during batholith phase 4.

The Tanum Formation conglomerate is characteristic of large tracts of the Oslo Region from Oslo, Ringerike and areas further south. Conglomerates were deposited in braided river systems and vary in grain size from coarse conglomerates to sandstones. This photograph is from the Gaupeskard road in Ringerike, and illustrates the coarsest conglomerates found. The true size of the photograph is about 40 centimetres across, and the largest cobbles are about six centimetres in diameter. Most of the clasts are well-rounded and composed mostly of hydrothermally-derived quartz. We also find clasts of gneiss, quartzite, limestone and granite. The thin red haematite film gives the conglomerate the reddish colour characteristic of the Ringerike area. (Photo: B. T. Larsen)

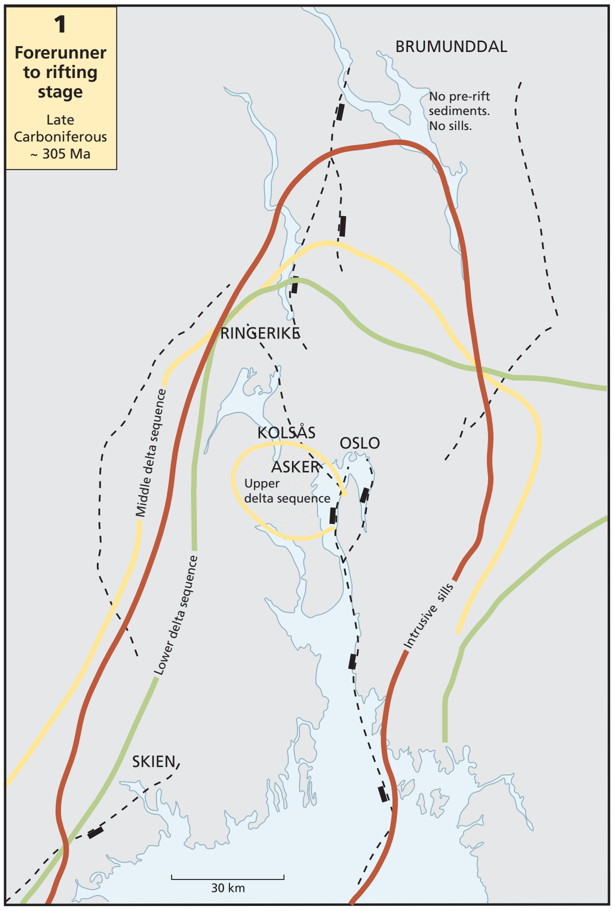


Block diagram showing the shallow basin in which Asker Group sediments were deposited during the Late Carboniferous. Sediments thin towards the north and northeast, but become thicker towards the south-west. Most sediments were deposited in river systems and transported from the north, northeast and north-west. The sea encroached into the basin gradually from the south and east.

developed in the Oslo area. The remains of this basin are preserved from Skien in the south to Nittedal in the north, in the form of its sedimentary sequence, termed the Asker Group, which is up to 90 metres thick in the south-west of the province.

The earliest sedimentary rocks of the Asker Group comprise up to 30-metre thick red claystones with thin interbeds of sandstones and some calcareous units. Occasional evaporite (anhydrite and gypsum) beds are also found. This earliest unit is called the Kolsås Formation, which was deposited in a flood plain environment containing lakes subject to periodic dehydration where evaporites were precipitated. Thin, carbonate-rich, beds are found interbedded with the red mudstones, and these contain small carbonate nodules, or pisoliths, and calcified fossil plant roots (rhizolites). This indicates that the carbonate-rich horizons represent the remains of fossil soil profiles (palaeosols) and carbonate crusts (calcretes). Calcretes develop in hot and arid areas, indicating that such conditions must have prevailed during the deposition of the Kolsås Formation. Only very few fossils have been discovered in this formation, and these are mainly restricted to the lithified and silicified tree trunks of species known from the Upper Devonian to the Permian.

There is a sedimentary hiatus between the Kolsås Formation and the overlying *Tanum Formation.* This is an erosional boundary cutting down into the Kolsås Formation, and above which we find a sequence of strata bearing sandstones and conglomerates. In the Oslo area the Tanum Formation is up to 20 metres thick, whereas the equivalent unit in the Skien area is up to 60 metres thick. The Tanum Formation comprises alternating sandstones, conglomerates, green and red shales and limestones.



The key geological features of Stage 1 – the forerunner to rifting. This stage contains three depositional units, and only in Asker southwest of Oslo do we find the youngest and most local of these units. The oldest unit is represented by the Kolsås Formation, whereas the two youngest both constitute parts of the Tanum Formation. In addition to sedimentation, active magmatism occurred with the intrusion of sills at about 1 km depth.

Sedimentary rocks from the Asker Group in a cutting along Dronningveien in Hole. Red claystones of the Kolsås Formation and pale sandstones of the Tanum Formation are faulted against each other. The Kolsås Formation strata have been dragged downwards. The overlying basalts are not faulted. (Photo: B. T. Larsen)

At some locations, the top of the limestone units has been dissolved by fresh water (karstified), and downcut by river erosion, forming a highly uneven surface that has subsequently been infilled by conglomerates. A thin and local limestone bed containing marine fossils of Late Carboniferous (Moscovian) age is called the *Knabberud Limestone Member* after the farm of that name located northeast of Kolsås. It is somewhat surprising to note that this marine limestone and its fossils share a greater affiliation with units of the same age from the Barents Sea and Eastern Europe than the carbonates of the western part of Central Northern Europe. This must mean that the Fennoscandian lowlands were at this time flooded periodically by marine environments encroaching probably from the east and/or south.

At Semsvik in Asker, among other places, we find a thin sequence of green to dark grey claystones and sandstones deposited in a river delta that advanced into a fresh or brackish water environment. Within the claystones, the remains of plants, together with fossil bivalves, fish and, most probably, the skin of an amphibian or reptile have been found. The flora and depositional environments of these strata are very similar to the Westphalian/Stephanian stage coal-bearing deposits encountered in England, Belgium and Germany.

The sedimentary rocks of the Tanum Formation were deposited on alluvial plains characterised by gravel-rich braided rivers and shallow lakes, aeolian sand dunes, deltas, estuaries and marine carbonate-sand beaches. These are combined with deposits resulting from unstable sediment slides. During periods of erosion or only limited deposition, soil profiles with calcretes were formed. This diversity of depositional environments may be explained by a combination of irregular topography resulting from the initial crustal movements, climatic variations,

The Knabberud Limestone Member within the Tanum Formation. This cross-bedded and horizontally-laminated calcareous sandstone containing marine fossils is most likely a beach deposit resulting from periodic encroachment of the sea across more continental deposits. (Photo: B. T. Larsen)

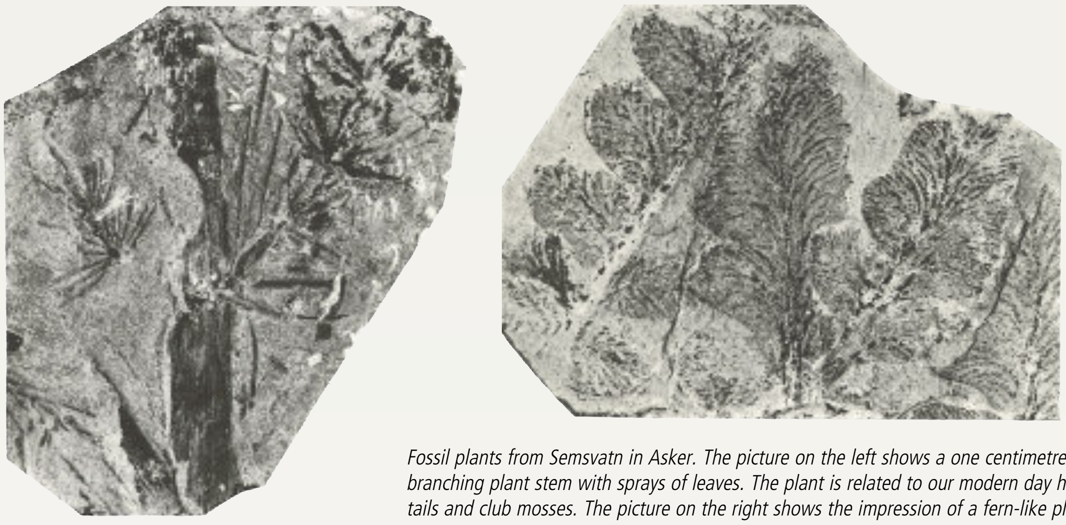
FOSSILS IN THE ASKER GROUP SEDIMENTS AND THE AGE OF THE OSLO GRABEN

The age of the sedimentary rocks of the Asker Group has always been somewhat uncertain. Brøgger knew these sediments well and believed that they were of Devonian age. In 1931 Professor Olaf Holtedahl led his students on a field trip to Semsvann in Asker, where they discovered plant fossils and freshwater bivalves within greyish-green claystones located immediately beneath the earliest basalt, and about halfway up the sequence above the folded Cambro-Silurian rocks. These indicated an Early Permian or latest Late Carboniferous age. At once, the Oslo Graben became much younger than previously thought. Later, plant fossils were discovered between the basalt lavas at Holmestrand, and subsequently at Kolsås and in the Skien area. From this time, the majority of the Oslo Graben strata were believed to be of Permian age.

Fish scales from the uppermost part of the Tanum Formation at Skaugum in Asker.
(Photo: NHM, UiO)

Thin section of a fusilinid viewed through a microscope. From the Tanum Formation on Jeløya near Moss.
The fossil is 0.5 mm across.
(Photo: S. Olaussen)

In 1980, marine fossils were found both at Kolsås and on Jeløya, indicating that the Asker Group sediments are most likely of Late Carboniferous age. Recent re-evaluations of the plant fossils and bivalves from Semsvann have confirmed a Late Carboniferous age, indicating that they were deposited at about the same time as the thick coal sequences of Central Europe.



Fossil plants from Semsvatn in Asker. The picture on the left shows a one centimetre-long branching plant stem with sprays of leaves. The plant is related to our modern day horsetails and club mosses. The picture on the right shows the impression of a fern-like plant at approximately natural size. (From: O. Arboe Høeg).

In the 1980s, a comprehensive radiometric dating project was initiated to date the rocks of the Oslo Region, incorporating the vast majority of the larger rock outcrops and the most important lavas and structures, mainly using the Rb-Sr method. These datings have confirmed that the Oslo Graben is primarily a Permian structure, but that its age ranges over a period of as much as 70 million years, from 310 million years ago during the latest Carboniferous, to the very earliest Triassic some 241 million years ago. These datings constitute the basis for our current geological model of the Oslo Rift and the successive stages of its evolution. However, even though we have a serviceable model for the rift, there are many key issues related to its evolution that remain unresolved. Further and more precise age information is required.

Maenite sills from Kistefoss in Jevnaker. Maenites are acidic syenitic intrusions from the first stage of the evolution of the Oslo Rift, and are its earliest intrusions. They were intruded horizontally as sills, and lie parallel to the sedimentary bedding. In the Oslo Region, they are most commonly found within Cambrian or Ordovician shales, most notably the Alum Shale. The thickness of an individual sill can vary from one centimetre to 15 metres, and they most often occur as suites within a stratified network. The thickness of the sills in the photograph is between 30 centimetres and 1.2 metres. Basic (camptonitic) sills were intruded at the same time. (Photo: B. T. Larsen)

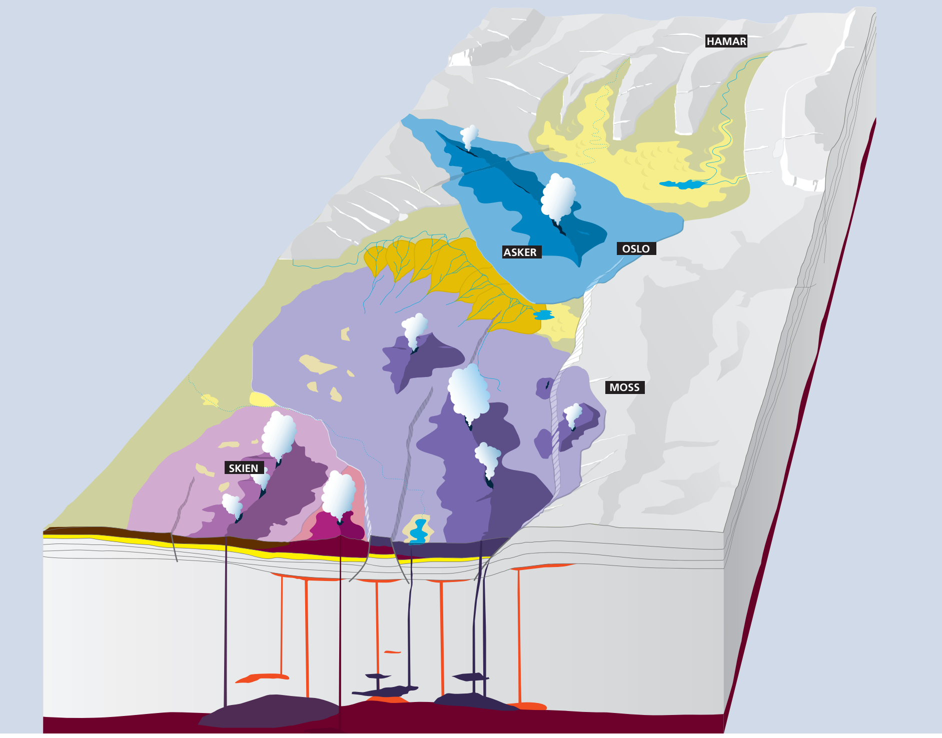
and relative sea level changes. In low-lying areas, such as along the downthrown flanks of major faults, there evolved shallow lakes or marine embayments which eventually filled with sediments. Thick soil profiles were developed outside the river flood plains, and in elevated regions where sediment supply was limited. The Tanum Formation was deposited at the end of the Carboniferous during a period of major climatic and sea level variations, and at the same time as a major glaciation was taking place in the southern hemisphere.

In some localities, the uppermost part of the Tanum Formation contains a few lava fragments and thin layers of tuff indicating that small-scale volcanic activity had already begun in the southern part of the Oslo Rift. However, the vast majority of these early magmas solidified within the crust at about one kilometre depth as near horizontal acidic and basic intrusions (sills). These are found almost everywhere within the Oslo Region, most notably within the Cambrian and Lower Ordovician Alum Shales. Maenaite is a rock named after lake Mæna near Brandbu in Hadeland, and is an example of a rock type from one such sill. The sills are between 300 and 310 million years old and are the earliest known intrusive rocks in the Oslo Rift, having been formed at the same time as the deposition of the Asker Group.

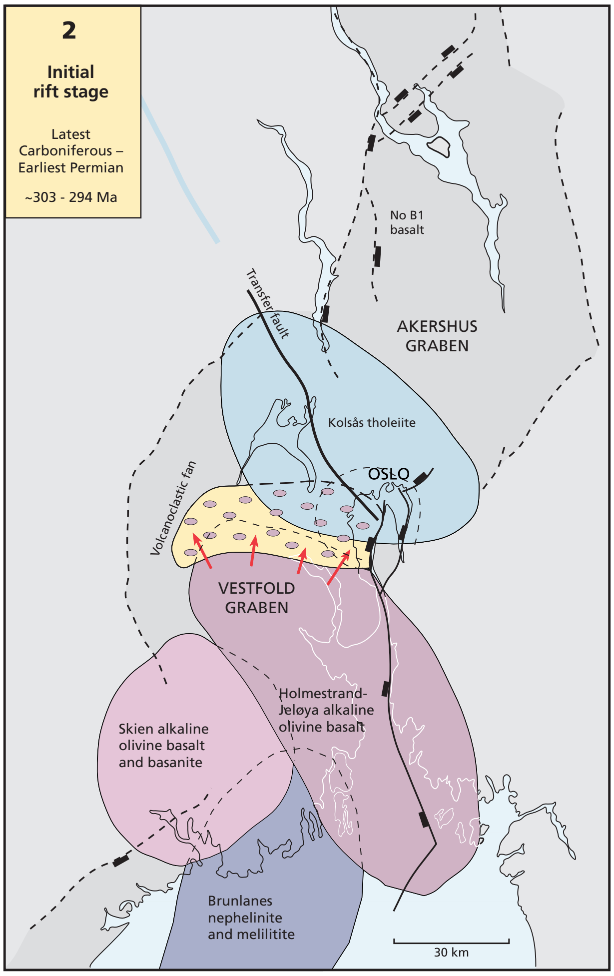
The initial rift stage – stage 2

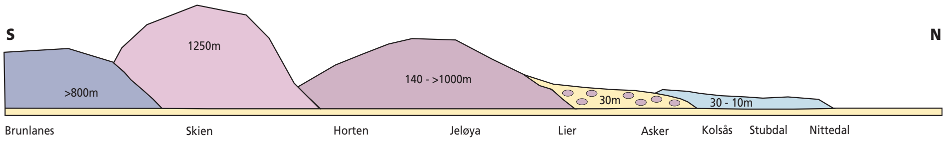
In most areas, stage 2 of the evolution of the Oslo Rift is characterised by the first basalt lavas. Basalt eruptions started somewhat earlier in the south than in the north, and the earliest basalts are absent both within, and north of, the Hadeland area. Basalt flows can be grouped into four provinces based on their thickness, the total number of flows, and their chemical and mineralogical compositions. These are

Block diagram showing the key features of Stage 2 – the initial rift stage. Basaltic volcanism was active from Vestfold in the south to Oslo in the north. No basaltic volcanoes from this stage are found north of Nittedal and Ringerike, and only minor faults were active, of which the embryonic Oslofjorden Fault was probably the largest.



The key geological features of Stage 2 – the initial rift phase. The extent of the four basalt provinces is clearly illustrated. Their age distributions and thicknesses are displayed along the north-south trending profile. In general terms, the oldest basalts occur in the south, and the youngest in the north. Both the total number of basalt flows and their thicknesses decrease towards the north. The profile runs N-S through the basalts.





Pahoehoe lava from the Horten area. Both aa and pahoehoe lavas are found among the "B1" basalts in Vestfold. Pahoehoe and aa are names taken from Hawaii, translated as "ropy" and "blocky" lava, respectively. (Photo: B. T. Larsen)

the Brunlanes, Skien-Porsgrunn, Holmestrand-Jeløya and Krokskogen-Kolsås-Nittedalen provinces. Variations may be due to the fact that the basalts were sourced from different regions of the upper mantle. They may also represent different degrees of mantle melting, and all may have had their composition modified by mixing with parts of the crust on their way up to the surface.

The Brunlanes basalts are the southernmost and most probably the earliest basalts in the entire Oslo Region. The sequence is about 800 metres thick, and is made up of several thin basalt flows, each of which varies from less than one metre to five metres in thickness. The Brunlanes basalts are the most silica-undersaturated of the Oslo Region's basalts, and lavas of this type have been given specific names such as nephelinites and melilitites. Nephelinite and melilitite lavas are characterised by the minerals nepheline and melilite, respectively.

In Skien today we find an approximately 1,250-metre thick suite comprising several hundred basalt lava flows stacked one on top of the other. The Skien basalts form a distinct, south-westerly early basalt province, and are now tilted and dip quite steeply to the east. Many of the basalts in the Skien area, most notably the earliest, are also relatively silica-undersaturated, and are termed basanites. A small province at Skrim with early basalts also belongs to this province.

Further north we find the somewhat more extensive Holmestrand-Jeløya basalts province, which extends all the way to Drammen. This province comprises a large number of alkaline olivine basalt flows that together form a suite about 150 metres in thickness at Holmestrand, somewhat thicker at Horten, and up to 1,200 metres thick on Jeløya near Moss. A particular feature of the Jeløya basalts is that they may contain pure native (metallic) copper. Alkaline olivine basalts are slightly silica-undersaturated and contain olivine, clinopyroxene and plagioclase phenocrysts.

Flood plains, lakes, and one basalt lava. In the fourth basalt province (Krokskogen-Kolsås-Nittedal), the onset of stage 2 was marked somewhat differently than in the other provinces. In Asker we find volcanoclastic sedimentary rocks within the *Skaugum Formation,* which for the most part comprises sandstones, conglomerates/breccias and red shales with associated calcretes. In general, the sand grains and rock fragments within the conglomerates consist of material derived from eroded basalt lavas from the

The boundary between two alkaline olivine basalt lava flows on Gullholmen on Jeløya. The lowermost flow displays pahoehoe structures on its upper surface. Thin (up to one metre thick) beds of red sandstone are commonly found between the lavas. These thin, oxidised and well-sorted sandstones commonly represent the remains of aeolian sand dunes that swept across the tops of the lava flows under arid climatic conditions. The sandstone in the photograph has also been reworked and re-deposited in running water. (Photo: A. Groth)

The eroded boundary between the Asker Group conglomerates (Tanum Formation), and the overlying earliest Kolsås basalt (B1) at Krokskogen. The basalt is younger than those in Vestfold to the south, and exhibits a distinct mineralogy. From Gaupeskardveien in Ringerike. (Photo: B. T. Larsen)

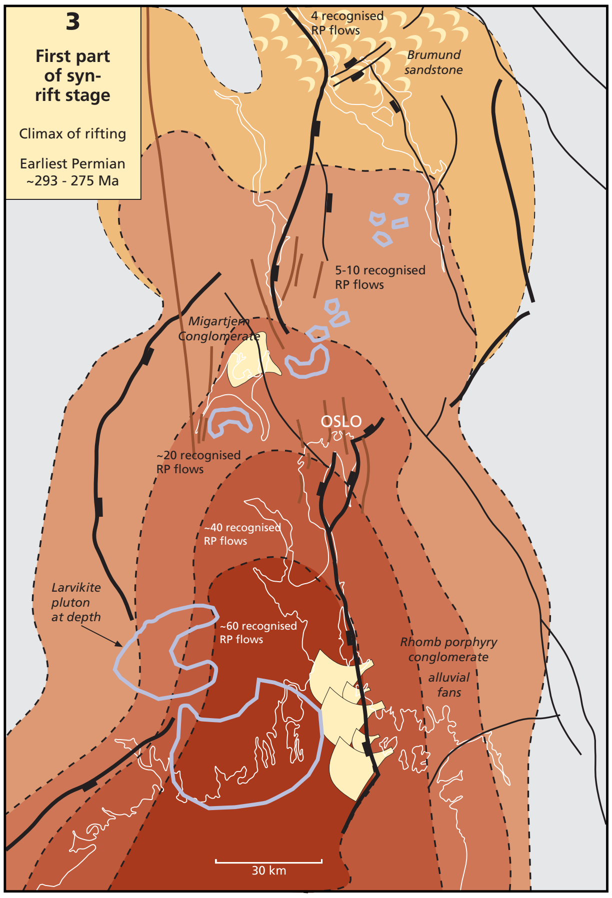
Holmestrand-Jeløya province to the south. These volcanoclastic sediments have thus been deposited after, or at the same time as, the basalts. Further west, near Sylling in Lier, this sedimentary sequence is split into two subunits, separated by a thin basalt lava. The Skaugum Formation contains cobbles and alkaline olivine basalt lava fragments. Flow-direction indicators in these volcanoclastic sediments indicate that they were formed by erosion of the Holmestrand-Jeløya basalts to the south, and later transported in northerly and north-easterly directions prior to deposition.

The Skaugum Formation also contains bivalves and plant fossils similar to those found in the Tanum Formation. Coarse-grained sediments were deposited from rivers that flowed from south to north and which built out broad flood plains into shallow lakes, often in the form of gravel fans at the front of the lava flows. Layers of volcanic ash (bentonites) were deposited during gas-rich eruptions. In some places, calcareous tuffs were precipitated where hot carbonate-saturated groundwater flowed to the surface, and these are now preserved as the porous limestone, travertine.

At Krokskogen, Kolsås and in Nittedal, sedimentary rocks of the Asker Group are overlain by a single basalt lava flow. It is between 10 and 30 metres thick and contains no phenocrysts. We know that this basalt is younger than those found further south, because the underlying Skaugum Formation contains fragments of the southern basalts. Its distinct mineralogy makes it the only basalt of its kind in the entire Oslo Rift, and it must thus have come from a separate source within the mantle. It is also likely that crustal material has been incorporated into the lava. The younger basalt is silica-oversaturated, and we call this type of basalt a tholeiite. It erupted from volcanoes located in the transition zone between the Vestfold and Akershus Grabens. Its structural location may have been significant in influencing the lava composition, and this is supported by the presence of major diabase dykes of similar composition found along the same zone.

The climax of rift formation – stage 3

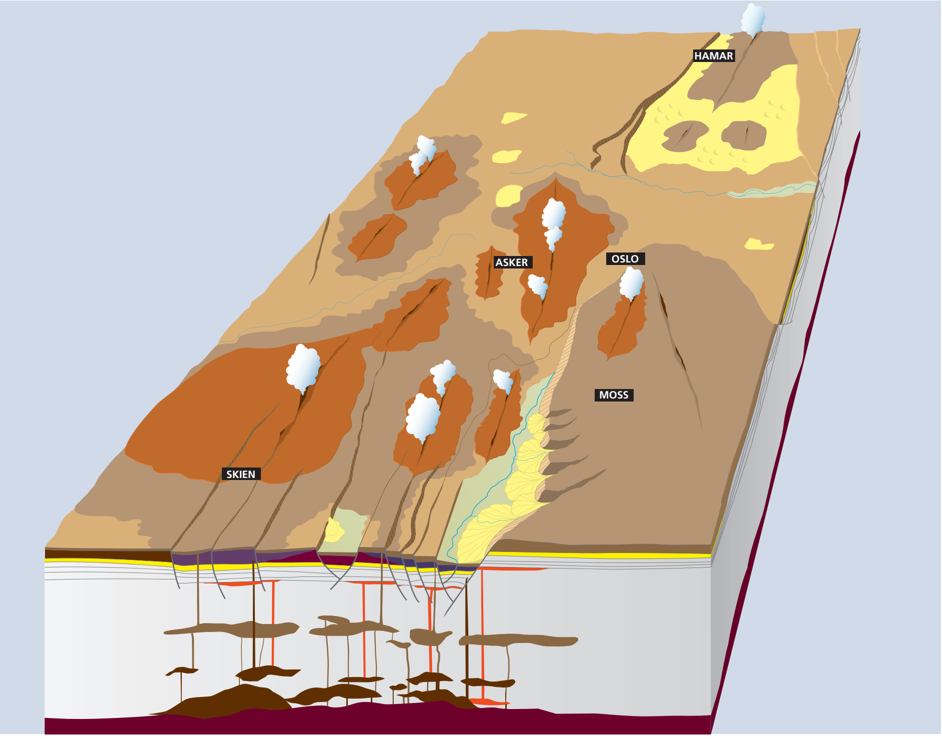
Stage 3 is the climactic stage of the evolution of the Oslo Rift, characterised by large-scale volcanism and intense fracturing and faulting. At the same time as some basalt volcanoes continued to be active, *rhomb porphyry lavas* erupted and flowed across vast areas. The volume of lava erupting at the surface was up to 10 times greater than during the previous stage. The first rhomb porphyry lava flow (RP1) is over 100 metres thick at Krokskogen west of Oslo, and even



The key geological features of Stage 3 – the climax of rift formation. Rhomb porphyry lava flows extended some distance beyond the strict confines of the rift. Erosion was active during the extended periods between each eruption. In the latter part of this stage, alluvial fans were deposited both along the Oslofjorden Fault and on the Krokskogen lava plateau. Basalt volcanism was also active, but was subordinate to rhomb porphyry eruptions. Larvikite batholiths were emplaced at depth.

thicker on Jeløya. This lava may originally have covered an area greater than 10,000 km^2, equivalent to a volume of about 1,000 km^3. By way of comparison, one of the largest basaltic lava flows in the Tertiary Columbia River basalt plateau in the western USA extends over an area of 40,000 km^2, comprising a volume of 1,400 km^3. This climactic stage involving rhomb porphyry volcanism continued from about 292 to 275 million years ago.

The rhomb porphyry lavas were most probably erupted from elongate fissure volcanoes. The fissures followed the primary fracture orientations of the Oslo Rift and extended down to huge magma chambers at the boundary between the crust and mantle. Rhomb porphyry lavas differ from basalts in their composition containing, among other things, greater amounts of silicon, sodium and potassium, but less iron and magnesium. This demonstrates that new types of magma were being formed beneath the Oslo Rift.



A block diagram illustrating Stage 3 – the climax of rift formation, and the major evolutionary stage of the Oslo Rift. The area was dominated by rhomb porphyry eruptions from great north-south trending fissures that gradually evolved into major faults, leading to the formation of the rift itself. Volcanism was most intense in Vestfold in the south, and less so further north, although traces of rhomb porphyry volcanism are found much further north in Brumunddal, in the southernmost part of the Rendalen Graben.

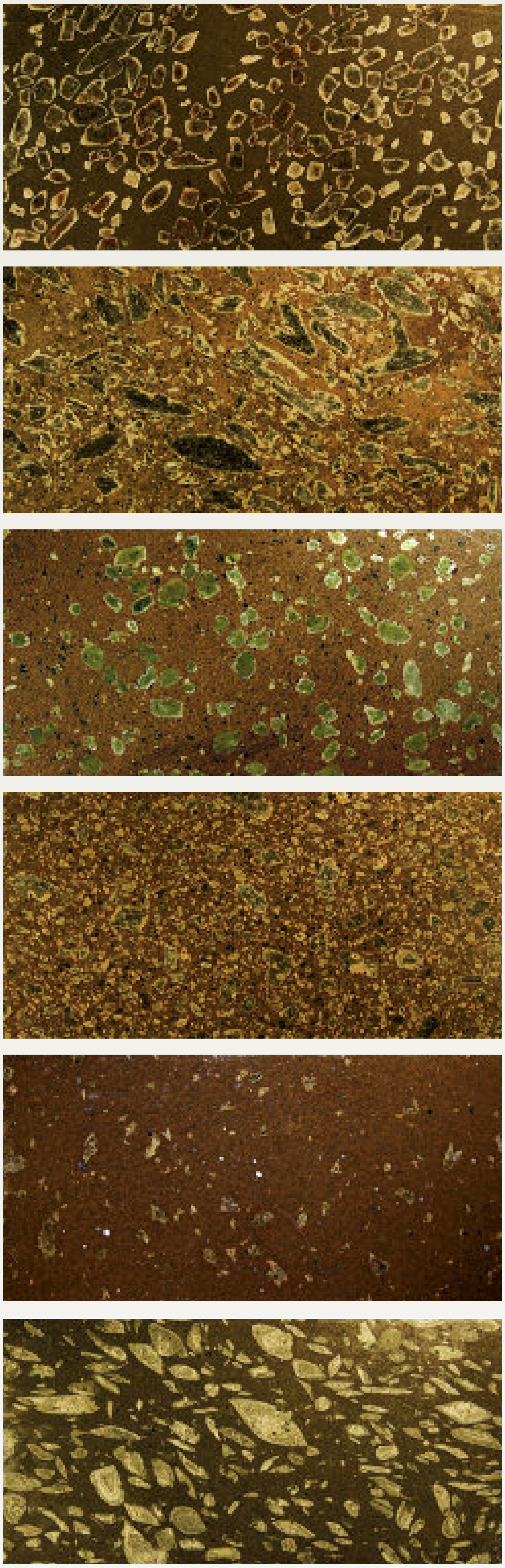
Pillow-like structures from the base of the earliest rhomb porphyry lava flow (RP1) at Krokskogen, which are probably the result of lava flowing across a wet surface. This phenomenon is seen almost exclusively at the base of RP1, west of Krokskogen. Thin sandstone beds occur within the strata between the "pillows". (Photo: B. T. Larsen)

RHOMB PORPHYRY – A RARE LAVA AND A VOLCANOLOGICAL MYSTERY

Rhomb porphyry (RP), with its large feldspar crystals set in a reddish-brown matrix, is one of the most characteristic rocks of the Oslo Region. It erupted as lavas from great fissures in the crust, and the rhomb porphyry in the Oslo Region today is thus encountered either as extrusive lavas or major dykes. The RP lavas of the Oslo Region vary in thickness from four to 130 metres. Thin beds of red aeolian sandstone or alluvial conglomerates are commonly found between the lava flows. The largest RP dyke system is more than 130 kilometres in length, and the largest dyke up to 80 metres across. Rhomb porphyry is a rare rock type, and true examples are found in only two places in the world outside the Oslo Rift; the East African Rift Valley and the Antarctic. All three locations occur in continental rift settings.

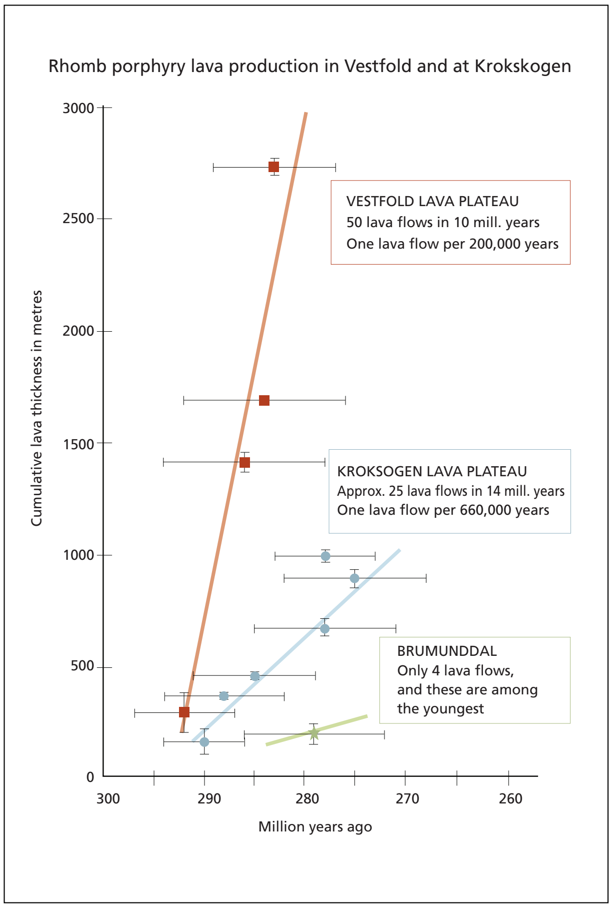
In terms of volcanology, the RP lavas remain a mystery. How can lavas of this composition, with such high silica and phenocryst contents, flow across such large areas? All field observations indicate that the RP lavas erupted as normal, relatively quiet, non-explosive lavas, very similar to basalts. Their viscosity must thus have been lower than we would normally suppose from their composition, possibly as a result of the lava's high temperature (between 1000 and 1100 °C), or the presence of dispersed water and a high content of dissolved fluorine (F). Recent studies have revealed that the RP lavas in the Oslo Rift currently contain between 0.2 and 0.45 % fluorine, making it likely that they had a low viscosity, only slightly higher than that of normal basalts. This discovery has done much to resolve the almost century-old mystery of the volcanology of the RP lavas.

The earliest RP lava flow in the Oslo region (RP1) has a remarkably similar appearance across the entire Oslo Region from Nittedal and Ringerike in the north to Tønsberg and Jeløya in the south. It is uncertain whether this unit represents one and the same lava flow or flow unit, but it currently extends across an area of about 10,000 km^2, and is more than 100 metres thick. This is equivalent to a volume of about 1,000 km^3. Volumes of this magnitude are not unknown for single lava flows from other major lava provinces. In total, there are more than 20 distinct RP lavas at Krokskogen, and more than 50 in Vestfold. Recent studies indicate that each lava flow has its own distinctive "fingerprint" in terms of its trace elements. In the future this characteristic, together with the general appearance and stratigraphic position of each lava flow, will help us to identify individual units over extensive areas.



Rhomb porphyry lavas from the classic suite of the lava stratigraphy at Krokskogen.
These six examples demonstrate the contrasting features of the lavas. W.C. Brøgger and J. Schetelig exploited these differences while mapping these unique lavas and their stratigraphy.
They are arranged in correct stratigraphical order from bottom to top with the earliest at the base. The lowermost is termed RP1, the Kolsås lava type. The first four are from the Krokskogen plateau and of these, the two youngest are from the Øyangen caldera. Each of these examples measures 10 × 20 centimetres, and are reproduced at one third of their natural size. (Photo: B. T. Larsen)

It is likely that two thirds of the Oslo Rift province was covered by rhomb porphyry lavas, and that several of the lava flows reached significant distances beyond the boundaries of the rift structure itself. In general, the earliest rhomb porphyry lavas exhibit consistent thickness over large areas, indicating that the terrain was relatively flat at the beginning of stage 3. Major differences in elevation occurred only along the Oslofjorden and other major faults.



A plot of thickness versus age for the various rhomb porphyry lavas from the Vestfold lava plateau and Krokskogen. Age determinations from the earliest rhomb porphyry lava (RP1) from both areas reveal a common origin, marking the onset of the rhomb porphyry lava eruptions about 292 million years ago. In Vestfold, the rate of eruption was about three times greater than at Krokskogen. The only age from Brumunddal, in the far north, indicates later activity, some 10 million years after the RP1 eruption in the south. Only four rhomb porphyry lavas are found in Brumunddal, indicating a very low eruption rate in the north.

Rhomb porphyry lavas are preserved in two large provinces, and in a number of smaller districts. Across the *Vestfold Lava Plateau,* which extends across the greater part of the northern and central parts of Vestfold, over 50 separate rhomb porphyry lava flows have been identified, and these combine to form a suite of lavas over two kilometres thick. Some individual flows are over 100 metres thick, whereas others may be only a few metres in thickness.

The *Krokskogen Lava Plateau* extends across parts of Lier, Asker, Bærum, Hole and Ringerike. A total of 22 flows combine to form a lava suite about 800 metres thick. Several of the earliest rhomb porphyry flows, including RP1 and RP2, are found in both the Vestfold and Krokskogen plateau provinces, while later flows higher up the series are more local in their distribution, both in Vestfold and at Krokskogen.

The northernmost rhomb porphyry lavas are found in Brumunddal near Lake Mjøsa. Here, the lavas overlie in part a thin unit of sedimentary rocks, but no underlying basalts are present. Only four lava flows occur here, and all appear to be of local origin. Rhomb porphyry lavas are also found covering smaller sites in Hurdal (Skrukkelia), Gran, Nittedal, Drammen, Eiker, Modum, Jeløya, Skrim, Brunlanes and in Skien.

The grand total of more than 50 rhomb porphyry flows were erupted in the Vestfold province over a

Red sandstones interbedded with rhomb porphyry lavas. Most of these sandstones are aeolian deposits resulting from sand blown across dry lava and trapped in depressions in the irregular lava surface. Some sediments were deposited in water and later reworked by seasonal river systems. Conglomerates are also found. This example is from the southern side of Bastøy in the central part of Oslofjorden. (Photo: B. T. Larsen) period of about 10 million years, equivalent to a rate of about one flow every 200,000 years. The 22 flows of the Krokskogen lava plateau were erupted over a period of about 14 million years, at an average rate of one flow every 600,000 years. In Brumunddal, the rhomb porphyry lava eruptions, both in terms of volume and the total number of lava flows, probably represent only 10 per cent of the activity at Krokskogen. This clearly reflects the progressive reduction in volcanic activity the further north we move within the Oslo Region.

Even though the rhomb porphyry lava series predominate in terms of thickness, volume and total number of flows during this stage of rift evolution, other types of lava are also found. Among these, the most notable are basalts, which often occur between the rhomb porphyry flows. Examples are found both in Vestfold and at Krokskogen. In Vestfold we also find trachytic lavas and ignimbrites in between the rhomb porphyry lavas in the uppermost levels of the lava suite. This indicates that explosive "acid" volcanism was occurring at the same time as eruption of the later rhomb porphyry lavas.

In several areas, we find beds of thin red aeolian dune sandstones in between some of the lava flows. Other sandstones and conglomerates were deposited as alluvial gravel and sand fans. These sedimentary rocks occur between the rhomb porphyry lavas at Krokskogen, in Brumunddal, on Jeløya, and in Vestfold.

Remains of a sandy desert in Brumunddal. More than 1 km of lavas and sedimentary rocks are preserved in Brumunddal. It is currently proposed by the authors that this rock unit be termed the *Brumunddal Group*. The lower unit of the group is termed the *Bjørgeberg Formation* and consists of four rhomb-porphyry lava flows interspersed with thin, red-stained sandstones and conglomerates. The overlying unit, the *Brumund Formation* is made up of approximately 800 metres of

These red and orange aeolian sandstones are coarse to medium-grained and well-sorted, and commonly exhibit finely-laminated cross-bedding inherited from their origin as aeolian dunes. The Brumund Formation sandstone exhibits up to 20 % porosity and is an important groundwater reservoir for the small community at Brumunddal. (Photograph on the right). (Photo: B. T. Larsen)

Bjørgeberget in Brumunddal represents the northernmost outcrop of Permian lavas and sediments in the Oslo Rift. The fault follows the Brumunda river valley. The escarpment in the west (on the left) is composed of lavas and sediments. The photograph is taken from Neshalvøya, looking towards the north. (Photo: B. T. Larsen)

This fault near Nærsnes chapel in Røyken trends in a north-south direction. It is a normal fault along which the eastern block was displaced downward in relation to the western flank. The well-developed fault plane hades at about 50 ° towards the east, and is antithetic to the great west-hading Nesodden Fault to the east. (Photo: B. T. Larsen)

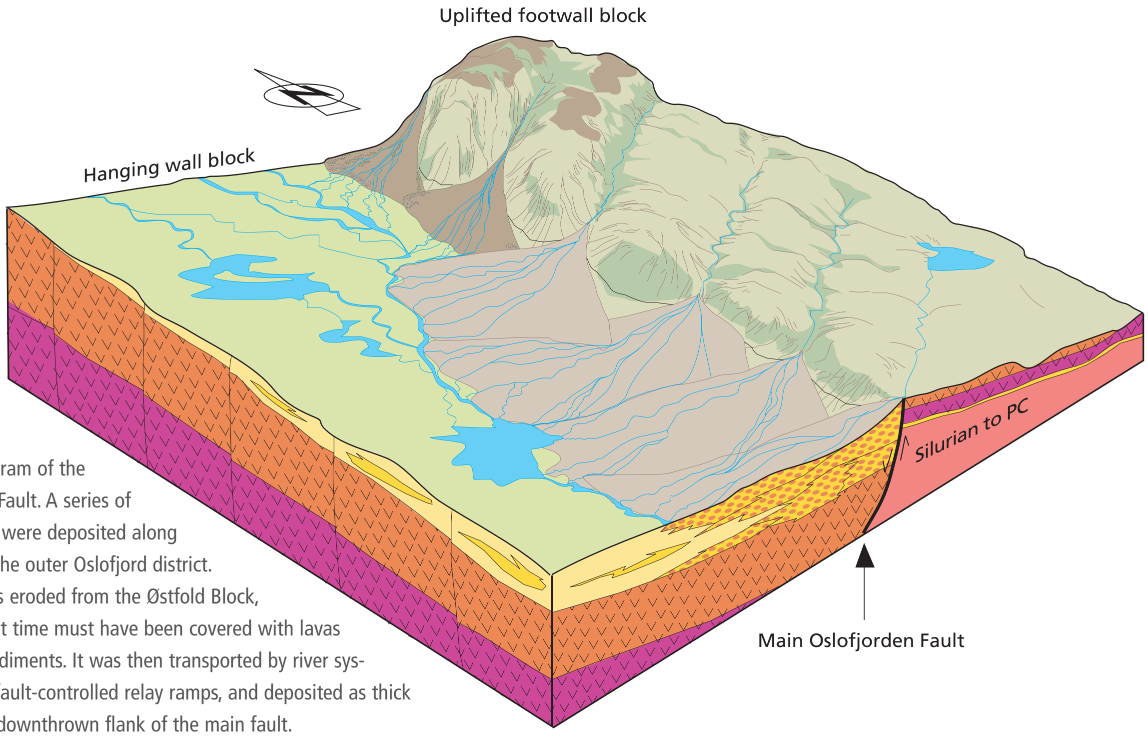
thick, red and yellow-coloured sandstones containing well-sorted and rounded sand grains. Thin red claystones and limestones are occasionally encountered in association with the sandstone. The sandstone was originally deposited as aeolian dunes that were periodically reworked and the sand then re-deposited by seasonal rivers that appeared sporadically in wadis after heavy rainstorms. Fossil soil profiles, calcareous tuffs, freshwater limestones, and traces of evaporite minerals are also found in the Brumund Formation sandstones. These rocks demonstrate that the Brumunddal area was part of a larger desert covering the northern Oslo Rift, and which may also have extended over vast areas of southern Norway and Northern Europe.

Early in the 1960s, the international oil industry was drawn to the Brumund Formation sandstone due to its high porosity and similarity to the reservoirs in the enormous Groningen gas field in the Netherlands, discovered in 1959. Studies of the Brumund Formation can thus be said to have made a small contribution to Norwegian oil and gas exploration, and this has now been recognised in the form of a large sandstone block currently on display outside the Norwegian Petroleum Museum in Stavanger.

Faulting, erosion, and a rift valley. Some of the major faults within the central and southern parts of the Oslo Rift were already active during the early parts of stage 3. However, it was only later during this climactic stage that a more intensive phase of structural evolution, involving horst and graben formation, began.

The Oslofjorden Fault, situated along the coast of Østfold and extending southwards from Jeløya, is one of the most prominent structural features of the Oslo Rift. Along this fault, and extending for a distance of 40 kilometres from Moss in the north to Hvaler in the south, we find a series of small islands composed of *rhomb porphyry conglomerates*. These conglomerates were formed when great masses of coarse sediment, including blocks up to six metres in dimension, together with boulders and gravel, were dumped on the western flank of the fault escarpment by rivers in full spate. The material making up the conglomerate is dominated by clasts of rhomb porphyry lava, together with a diversity of basalts and other blocks and rock fragments from sedimentary rocks of the Asker Group. Clasts of Late Silurian sandstone are rare, and basement fragments

Coarse rhomb porphyry conglomerates derived from alluvial fan deposits along the Oslofjorden Fault. These distinctive sediments occur only on a few small islands in Østfold. The blocks may be up to six metres in diameter and are dominated by a variety of rhomb porphyry lava types. Finer-grained sandstone beds are also found. The conglomerates are mostly quite poorly sorted, but it is usually possible to detect some weak lamination. The blocks may be rounded or highly angular. The photograph was taken at Mellom-Sletter near Larkollen. (Photo: B. T. Larsen)



A block diagram of the Oslofjorden Fault. A series of alluvial fans were deposited along the fault in the outer Oslofjord district. Material was eroded from the Østfold Block, which at that time must have been covered with lavas and older sediments. It was then transported by river systems along fault-controlled relay ramps, and deposited as thick fans on the downthrown flank of the main fault.

are entirely absent. The lithic clasts within the conglomerate are derived from a sequence that overlies the basement in Østfold, but it appears that the rivers did not manage to erode down into the basement itself. The rhomb porphyry conglomerates found on the islands in Oslofjord bear spectacular witness to the powerful geological forces active along the Oslo Rift's major faults during the Permian.

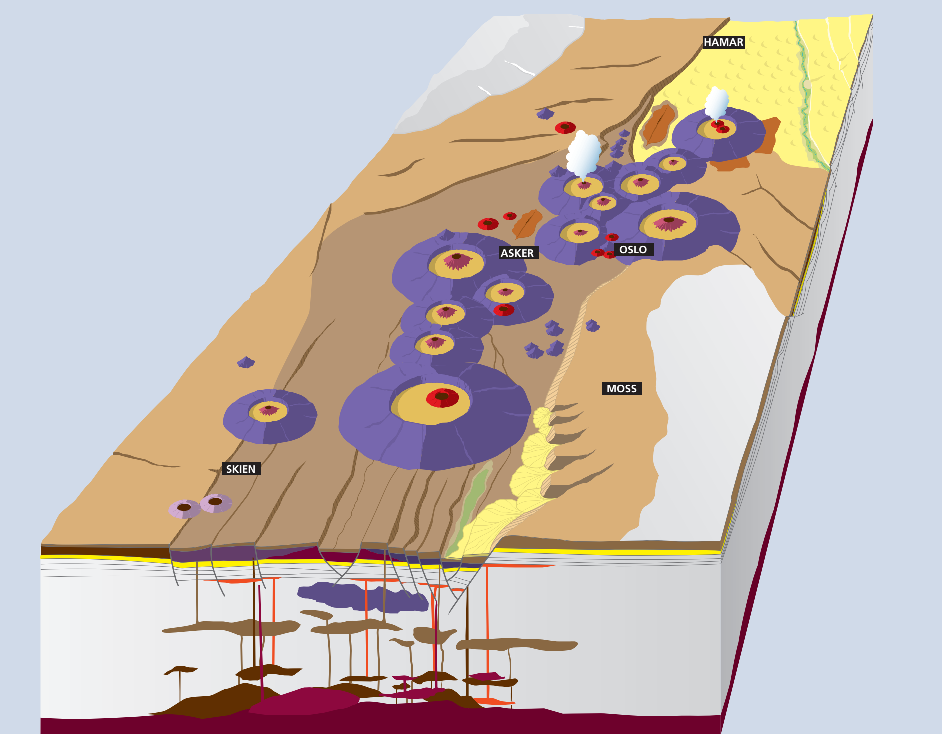
Rhomb porphyry conglomerates are also found at Krokskogen. At Gyrihaugen, a conglomerate has completely filled a 400-metre deep gorge cut into the rhomb porphyry plateau by Permian rivers. At Krokskogen, the conglomerate contains clasts of all the rhomb porphyry lavas from RP1 to RP9. It is overlain by two basalt lavas that are in turn overlain by lava RP11. The sequence at Krokskogen demonstrates that intense erosion was taking place at the same time as volcanism was active elsewhere in the region, as is also the case in active volcanic provinces around the world today.

A particularly important result of active faulting during this climactic stage was the formation of a topographic depression, or *rift valley*, similar in structure to the present-day East African Rift Valley. The Oslo Rift incorporated all of the graben segments within the rift structure, and was bounded along its flanks by high fault escarpments. The rift valley itself was characterised by lava flows and minor lakes that frequently dried out.

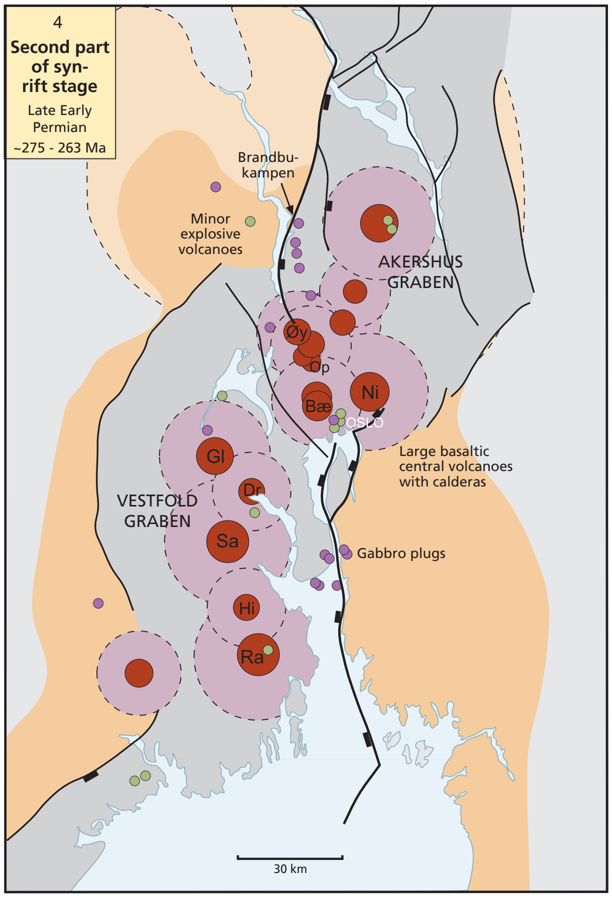
Larvikites – the initial batholith phase. During the latter part of stage 3, the first great deep intrusive igneous bodies were emplaced. These comprised the *larvikites* that crystallised at depth from great volumes of monzonitic magma at the same time as the rhomb porphyry lavas were erupting at the surface, most probably from the same magma source. Today we find larvikites in southern Vestfold, at Skrim, in Nordmarka, and in Hurdal. The Vestfold larvikite, and in particular the pale blue Tvedalen and darker Klåstad varieties, is Norway's best known industrial stone. It is quarried on a commercial basis, and is one of the world's most popular facing and ornamental stones.

Massive central volcanoes and calderas – stage 4

Great changes accompanied the transition to the fourth evolutionary stage of the Oslo Rift, mainly involving the formation, under arid climatic conditions, of a volcanic rift valley. There probably occurred a gradual decrease in lava production within the Oslo Graben, and the new volcanoes were of a



Block diagram illustrating Stage 4 – characterised by central volcanoes and caldera formation. The central volcanoes were characterised by basaltic volcanism, but rhomb porphyry eruptions continued elsewhere. Gradually, several of the central volcanoes across the Oslo Graben "matured", eventually exploding as "super volcanoes" and resulting in caldera subsidence. Today, we find large and small-scale traces of these volcanoes from Ramnes in Vestfold in the south to Hurdal in the north.



The key geological features of Stage 4 – characterised by central volcanoes and caldera formation. The great central volcanoes were concentrated firstly along the north-south trending axis of the Vestfold Graben and secondly, as a close-knit group centred near the transition between the Vestfold and Akershus Grabens.

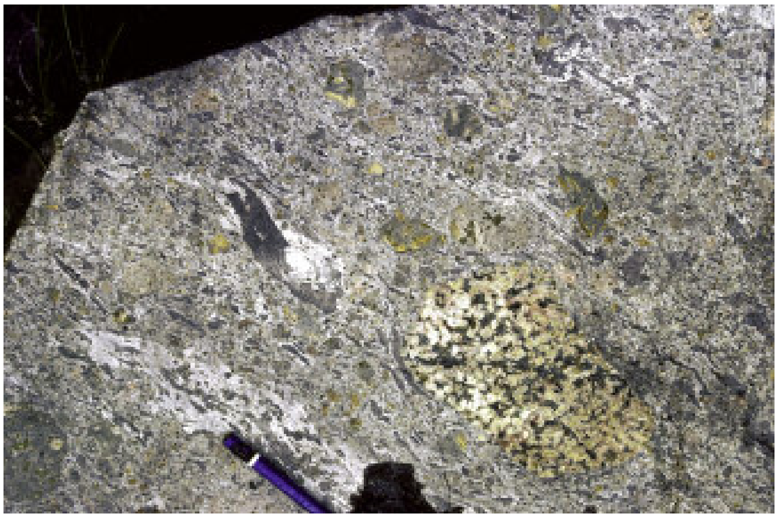
different character from those seen previously, most probably resembling the great cone-shaped volcanoes characteristic of active volcanic provinces at the present day. The cone-like shape is the result of the accumulation of basalt resulting from successive cyclic eruptions and outpourings of lava from a central crater over a period of a few million years. In contrast to the earlier *monogenetic fissure volcanoes,* where the rhomb porphyry lavas erupted from elongate fissures, the new generation of basalt volcanoes evolved around a central crater. These volcanoes are characterised by frequent and multiple minor eruptions from the same crater, and are called *polygenetic central volcanoes.*

In the Vestfold Graben, the central volcanoes were aligned along the north-trending central axis of the rift depression. The southernmost and largest was located in Ramnes, where the original central volcano was probably about 35 kilometres in diameter prior to its collapse into a caldera. Further north we find volcanoes at Hillestad, Sande, Drammen, and Glitrevann. The volcanoes may originally have risen 1,000 metres or more above the rift floor.

At Bærum and Nittedal there were two large central volcanoes located in the southern part of the Akershus Graben. There was also a group of several large central volcanoes to the north at Krokskogen, including one at Oppkuven, and others at Heggelia, Svarten, and at Øyangen-Ringkollen, which was the northernmost. Even further to the northeast, there were most probably central volcanoes north of Stryken in Nordmarka and in Hurdal. The locations of several of these volcanoes are somewhat uncertain since they were almost entirely engulfed by great intrusive bodies that were emplaced at a later stage.

Exploding volcanoes and subsiding calderas. The great central volcanoes were constructed above basalt magma chambers lying at depths of between 4 and 10 kilometres. Gradually, as the magma chamber's supply of new basalt melts from greater depths dwindled, heavy minerals such as olivine, pyroxene and others began to sink downwards through the molten rock. The remaining magma thus became less dense and richer in silicon (Si), aluminium (Al), and the alkalis (Na and K), especially near the top of the magma chamber. This process is termed fractional crystallisation and is described in Chapter 2. The acidic magmas remaining at the top of the chamber contained large volumes of dissolved gas and steam.

When these gas-rich melts ascended, gas was released causing the pressure within the magma chamber to increase. The chamber became unstable, and its roof started to collapse along faults and fractures. This led to the release of even more gas and, if the faults extended through the roof of the magma chamber, gas was released to the surface producing explosive volcanic eruptions. The pressure then dropped dramatically within the magma chamber beneath the volcano and caused the total collapse of its roof. A great *ring fault* was formed around the volcano, and finally, the entire structure collapsed inwards into the magma chamber along the fault. This process resulted in a great cauldron- or saucepan-shaped depres-



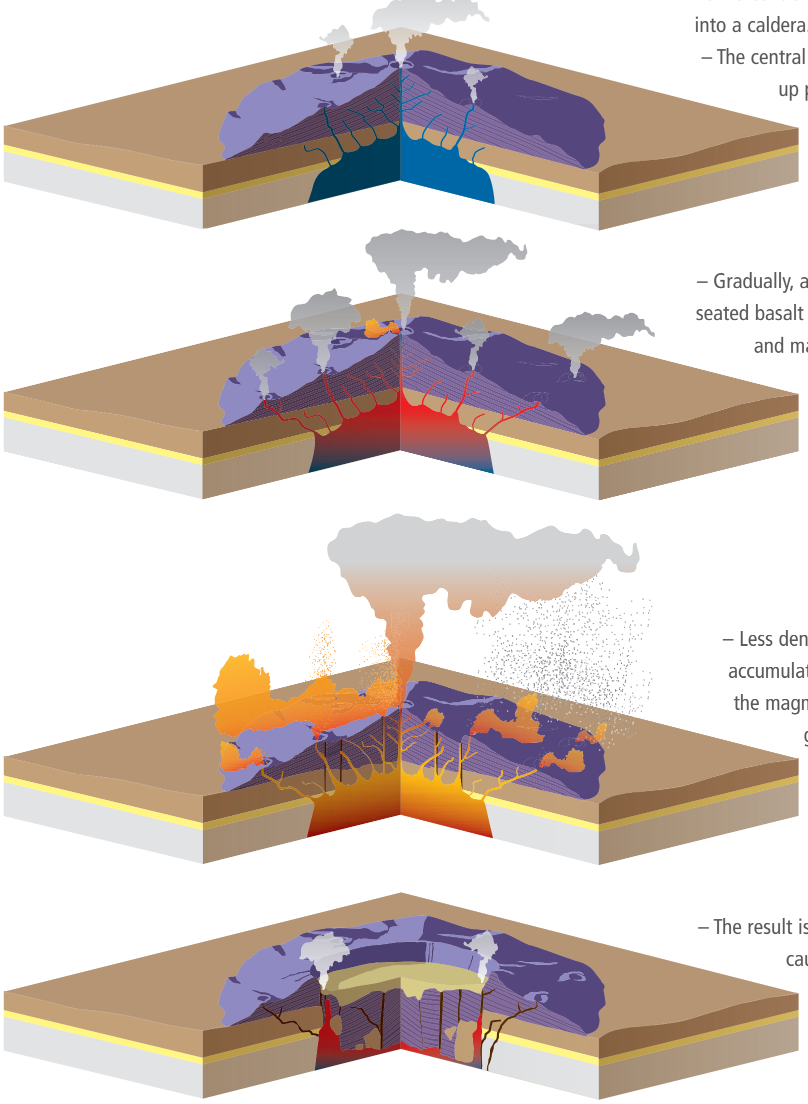
An ignimbrite from Oppkuven in Krokskogen, containing large clasts (lithic fragments) that have been torn from the country rock during the explosion. A well-defined layering or striping within the rock represents compressed pumice fragments (dark grey) that were formed during the explosive eruptions of the "Oppkuven volcano" that occurred during formation of the Oppkuven caldera. The presence of fragments of this size within the ignimbrite indicates that we are quite close to the site of the eruption. The pencil is about 8 cm long. (Photo: B. T. Larsen)

Other material from the final, explosive, eruptions of the super volcano were thrown through the air and deposited as tuffs. Here, we see well-developed lamination and sorting, indicating that we are some distance from the eruption site. This locality is at the Øyangen caldera's southern margin, north of Damtjern in Krokskogen, although the tuff itself is probably derived from another caldera further to the south. The hammer is 43 cm long. (Photo: B. T. Larsen) sion called a *caldera.* Caldera formation by these means is a natural phase in the evolution of large polygenetic central volcanoes. The Askja volcano in northern Iceland, and Teide on Tenerife in the Canary Islands, are examples of caldera volcanoes.

All the great central volcanoes in the Oslo Rift eventually evolved into calderas, even though today the cauldron-shaped landforms have disappeared and erosion has cut deep into the once circular and sunken structures. However, it is by identifying ring-shaped caldera structures that we can now trace the remains of the Oslo Graben's great central volcanoes, such as those at Ramnes, Glitrevann, Bærum, Nittedal, and Øyangen.

Immediately after caldera collapse, the remaining magma forced its way up along the ring fault and formed *ring dykes*, while new supplies of magma were emplaced as intrusions in the caldera cores. The best-preserved calderas are at Glitrevann north of Drammen, and the Bærum caldera in Bærumsmarka. Here we find basalts from the central volcano, ignimbrites and breccias from the caldera formation process, and central intrusions emplaced after caldera collapse.

At Krokskogen in Ringerike four calderas are found intimately nested together in a caldera group, the Øyangen caldera being the northernmost and also the youngest. Here we find a central syenite intrusion and a broad syenitic ring dyke formed after the caldera collapsed. The ring dyke and central pluton have been dated to 268 million years old, with a



A schematic diagram showing how a central volcano evolves into a caldera.

– The central structure builds up progressively to form a basaltic central volcano.

– Gradually, access to deep-seated basalt magma is cut off, and magma in the chamber begins to fractionate.

– Less dense, gas-rich melts accumulate at the top of the magma chamber, and gases force their way through and explode.

– The result is a deep, massive cauldron or caldera.

The Brandbukampen hill at Hadeland is regarded as the archetypical volcanic plug. In common with other minor gabbro plugs in the Oslo Rift, it was probably situated beneath a small basaltic cone. However, all the major volcanoes of the Oslo Rift eventually evolved into calderas. View from the south. (Photo: B. T. Larsen)

Ramvikholmen outside Tofte in Oslofjord is another example of the Oslo Rift's small gabbro plugs. On Ramvikholmen, a twin plug, the steeply-dipping layering is clearly displayed. This layering is the result of convection within the magma chamber and the fractional crystallisation of minerals such as olivine, clinopyroxene, plagioclase and other minerals characteristic of an alkaline olivine basaltic magma. Brøgger believed that these plugs were the magma supply conduits for the great B1 basalts in Vestfold, although we now know that they are too young, and that they belong to Stage 4. (Photo: B. T. Larsen) window of uncertainty of only 3 million years. This event marked the end of stage 4.

Gabbro necks and minor volcanoes. Minor intrusions or gabbro necks were also formed during stage 4. Such necks are often found in pairs (or triplets), with individual examples varying from between 100 or 200 metres, to about two kilometres in diameter. Such necks are found from Skrim in the southwest to Hurdal in the north. A group of four gabbro plugs occurs centrally in the Oslofjord district. We also find a twinned neck at Ullernåsen and Husebyåsen in Oslo. At Hadeland a line of five gabbro necks are found with Brandbukampen as the northernmost.

The minerals of the gabbro necks commonly exhibit a steeply-dipping rhythmic layering that most probably developed as a result of convection within the magma chamber. The best known example is found in Oslofjorden at Ramvikholmen, south of Tofte in Hurum. Earlier, it was thought that these necks were magma supply conduits for the great basaltic volcanoes formed during stage 2, but radiometric dating has revealed that they are in fact younger, and belong to stage 4. It is now believed that the gabbro necks formed the magma chambers supplying lava to relatively minor basaltic central volcanoes situated between the great central volcanoes that later developed into calderas.

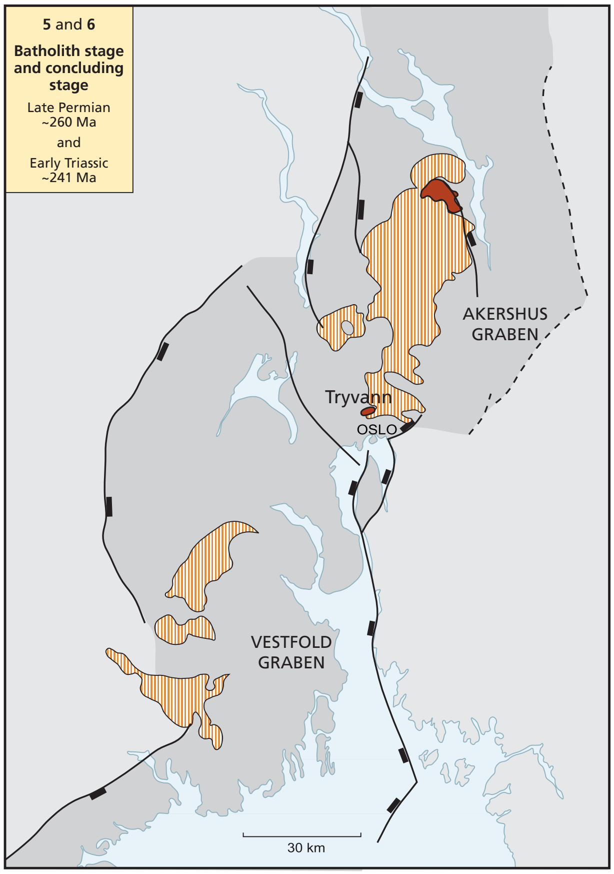
Granites – the second batholith phase. Age determinations of two large granite bodies located in the centre of the Oslo Rift have shown that granite batholiths crystallised at depth early in stage 4, thus revealing the second batholith phase in the Oslo Rift's evolutionary history. The Drammen granite, which forms the country rock throughout the Drammen area and also across parts of the Hurum peninsula, is a red, coarsely-crystalline granite of normal composition, containing quartz, plagioclase, potassium feldspar and dark mica (biotite). The Finnemarka granite found north of Drammen is of similar age and composition, also containing biotite. Smaller granites of this age are found at Bjørgeseter in Grua, and in Hurdal. The Drammen granite is used extensively as a building and monumental stone, and is today an important product of the quarries at Røyken, and is thus known as the "Røyken granite".

Explosion breccias. At several locations within the Oslo Rift, we find suites of explosion breccias in the form of small, circular plugs. These vary from 100 metres to one kilometre in diameter and cut through older rocks, fragments of which are commonly found as clasts within the breccias. The age of these breccias remains unknown, but since explosive volcanism was active in the calderas at this time, they fit best into stage 4. The largest of the breccia plugs is the Holmen-Dagali breccia in Oslo. Breccias of this type are also found in both northern and southern provinces of the Oslo Graben, the example at Langesund being the furthest south, and that in Hurdal the most northerly.

The age of the great batholiths – the third batholith phase, stage 5

No surface rocks of either sedimentary or extrusive volcanic origin are preserved in the Oslo Graben from the two concluding stages of the Oslo Rift's evolution and today we only find rocks that were formed deep in the crust. Stage 5 is of Mid to Late Permian age and is dated to between about 263 and 250 million years ago.

During stage 5 the magma supply to the Oslo Graben was renewed, and new batholiths crystallised both in the southernmost Vestfold Graben, and throughout the Akershus Graben extending to Skreifjella near Lake Mjøsa in the north. Up until stage 5, deep-seated magmas beneath the Oslo Rift had changed character, becoming progressively enriched in silicon, potassium and sodium. Due to chemical processes within the magma, the plutonic rocks of the third batholith



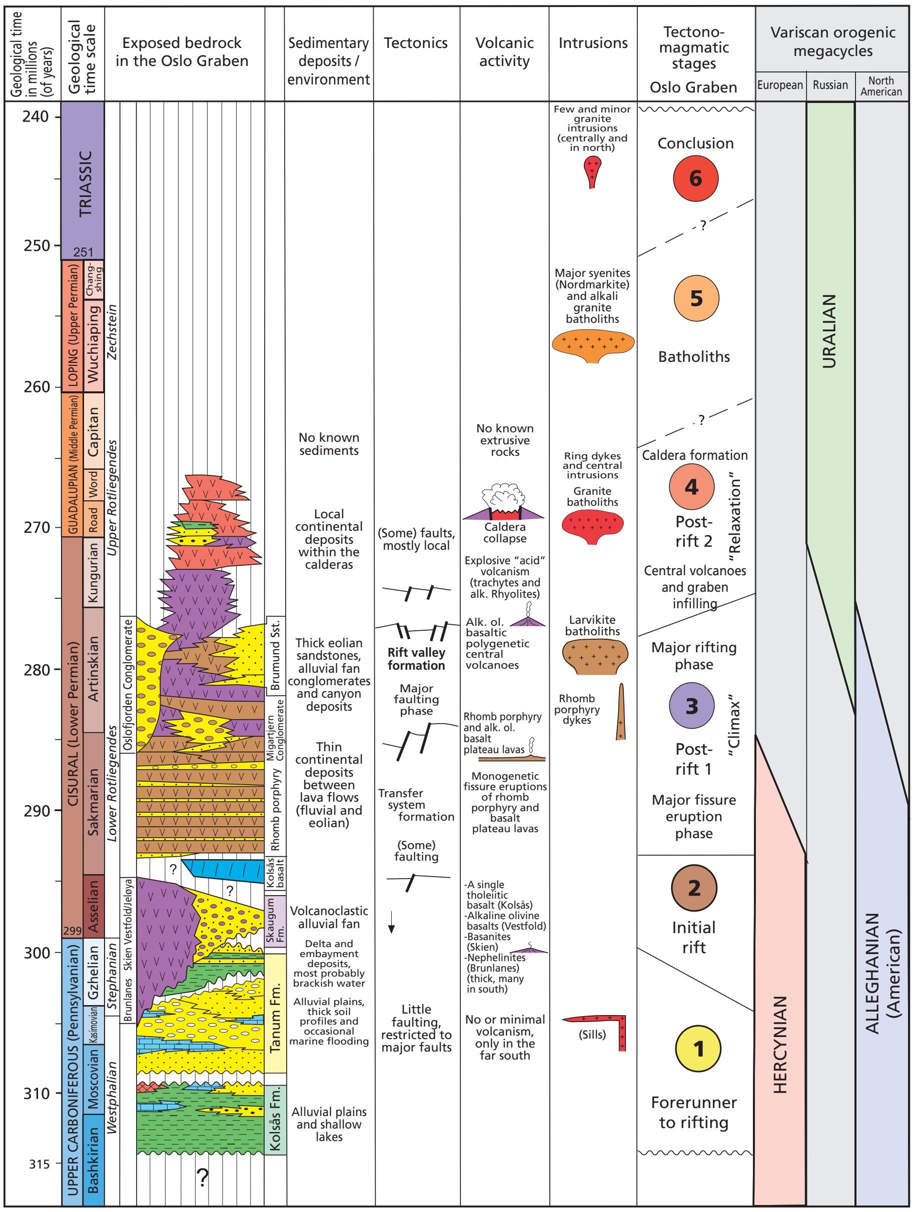
The key geological features of Stages 5 and 6 – the final batholith phases. During Stage 5 (the third batholith phase) the primary intrusives are nordmarkite, syenite, and ekerite. During Stage 6, representing the concluding phase in the Oslo Rift's evolution, only a few granites are formed. This stage also represents the fourth and final batholith phase, and the granites are of Early Triassic age.

phase are thus of syenitic, nordmarkitic or ekeritic composition. Ekerite is an alkaline granite containing alkali-pyroxene and/or alkali-hornblende, and derives its name from Lake Eikeren. Nordmarkite is a syenitic rock named after the Nordmarka forest north of Oslo. It contains very little quartz, but possesses a red alkali feldspar that gives the rock its characteristic colour, together with an alkali-pyroxene and/or alkali-hornblende as its dark ferromagnesian mineral. The Grefsen syenite is similar, and contains biotite as its dark mineral. All these plutonic rocks have been used in foundation walls and as monumental stone, and the Grefsen syenite continues to be quarried today.

The concluding stage; the final minor granites – fourth batholith phase, stage 6

During the final stage in the Oslo Graben's magmatic evolution it is possible that some tectonic activity persisted, but we have no convincing evidence for this and thus believe that the "life" of the Oslo Graben ended at the same time as the formation of the youngest igneous rocks. The formation of these final granite intrusions constitutes "the fourth batholith phase".

The only confirmed representatives of this concluding stage are some relatively minor intrusions with normal granitic compositions. The largest of these granite provinces is in Hurdal where several individual intrusions are found. Their ages have been determined as between about 249 to 241 million years old, equivalent to the latest Permian and Early Triassic periods. The smallest, and best-known of these young granites, is a minor intrusion found in the Holmenkollen-Tryvann area in Oslo. The Tryvann granite has been dated to about 241 million years old and of Early Triassic age, and is consequently the Oslo Graben's youngest intrusion. Dykes associated with these latest granites probably exist, and it is possible that among these we will one day discover the Oslo Region's latest magmatic event.



This somewhat complex figure summarises all the evolutionary stages of the Oslo Rift (excluding the Skagerrak Graben) during the approximately 70 million years of its active geological history. We can see the characteristic features of the six stages including sedimentation, tectonics and faulting, the characteristic lava types, their petrological compositions and associated volcano types, together with intrusions in the form of batholiths, dykes and sills.

The Carboniferous and Permian in the North Sea – volcanoes, coal, salt and gas

From the Early Carboniferous, thick sequences of continental sand, clay, mud and coal beds were deposited in the Variscan Foreland Basin, often interbedded with marine strata. During the Late Carboniferous and Early Permian, and similarly to the Oslo Rift, both faulting and volcanism were active in northern Germany and the southern North Sea, where the Permian was dominated by very arid conditions. During the Late Permian, the prevailing shallow seas dried up, and salt was deposited in both the northern and southern Permian basins. Carboniferous coal sequences acted as source rocks for North Sea gas, and salt played an important role in the formation of hydrocarbon traps.

Mainland Norway, together with extensive areas of the Norwegian sector of the North Sea were probably dry land during much of the Carboniferous. Early Carboniferous deposits are very rare in the Norwegian sector of the North Sea, although the Ling Graben, located west of Stavanger, may represent a rare example of an Early Carboniferous graben in this area.

During the Carboniferous, oceanic crust, volcanic island arcs, older sedimentary and crystalline rocks, together with more recent marine sediments, were folded and overthrusted as part of the Variscan orogen. Early in the Carboniferous, the climate in this part of Europe was arid and characterised by deserts. While the compressive Variscan mountain belt was being formed, a foreland basin evolved across the area we now identify as the southern part of the North Sea, northern Germany, Denmark, and the greater part of the British Isles. Large volumes of sand and mud were deposited on extensive coastal plains in deltas, coastlines, swamps, rivers, lakes and shallow marine embayments.

Massive Late Carboniferous coal deposits

In the Late Carboniferous, after the climate had changed and become tropical and humid, the vast coastal and delta plains of Central Europe provided habitats for a diverse and productive flora, including tall trees related to our smaller horsetails, club mosses and ferns. The swamp forests were inhabited by many species of reptiles and amphibians, and insects ruled the air. Gradually, as the vegetation died, thick layers of peat and plant remains accumulated on the forest floor, and when these were later buried and compacted by younger sediments, they were gradually transformed into coal beds. Today, these deposits occur as thick sequences of coal seams, most notably in Poland, Germany, Belgium and Great Britain. As an energy source, this coal exerted a major influence during the development of the industrial revolution.

A pronounced feature of the coal-bearing units of the Carboniferous sequences is the repeated and rhythmic succession of delta and coastal plain sands and mudstones, with the coal seams uppermost, and succeeded by open shallow sea limestones. This *cyclicity* resulted from sea level variations in direct response to the glacial and interglacial cycles that developed on the Gondwanaland continent in the southern hemisphere. During glacial periods, great volumes of water were locked up in continental ice sheets and glaciers, the sea level fell, and the coastal plains were able to advance into the basin. When the continental ice masses melted, the sea level rose again and the sea encroached back onto the land, forming a shallow sea where carbonate mud was deposited.

The Late Carboniferous coals are between 318 and 305 million years old. No coal has been found as far

This is how the coal forests of northern Germany and the North Sea must have appeared at the end of the Carboniferous. The tall tree on the right is a *Lepidodendron*, which grew up to 40 metres in height. Leaning somewhat on the right-hand side of the picture is an example of *Calamites,* and a little to left of centre, a *Sigillaria*. By present day standards, these were fully-grown trees. The ground vegetation comprises *Sphenophyllum*. These are all related to modern horsetails and club mosses, and some are found as fossils in the Oslo region. (Illustration: R.W. Williams).

north as the Norwegian sector of the North Sea, where at this time alluvial sands were deposited under hot, semi-arid climatic conditions. A few exploration wells from the southernmost part of the Norwegian shelf have encountered sandstones of the same age as the Asker Group in the Oslo Region.

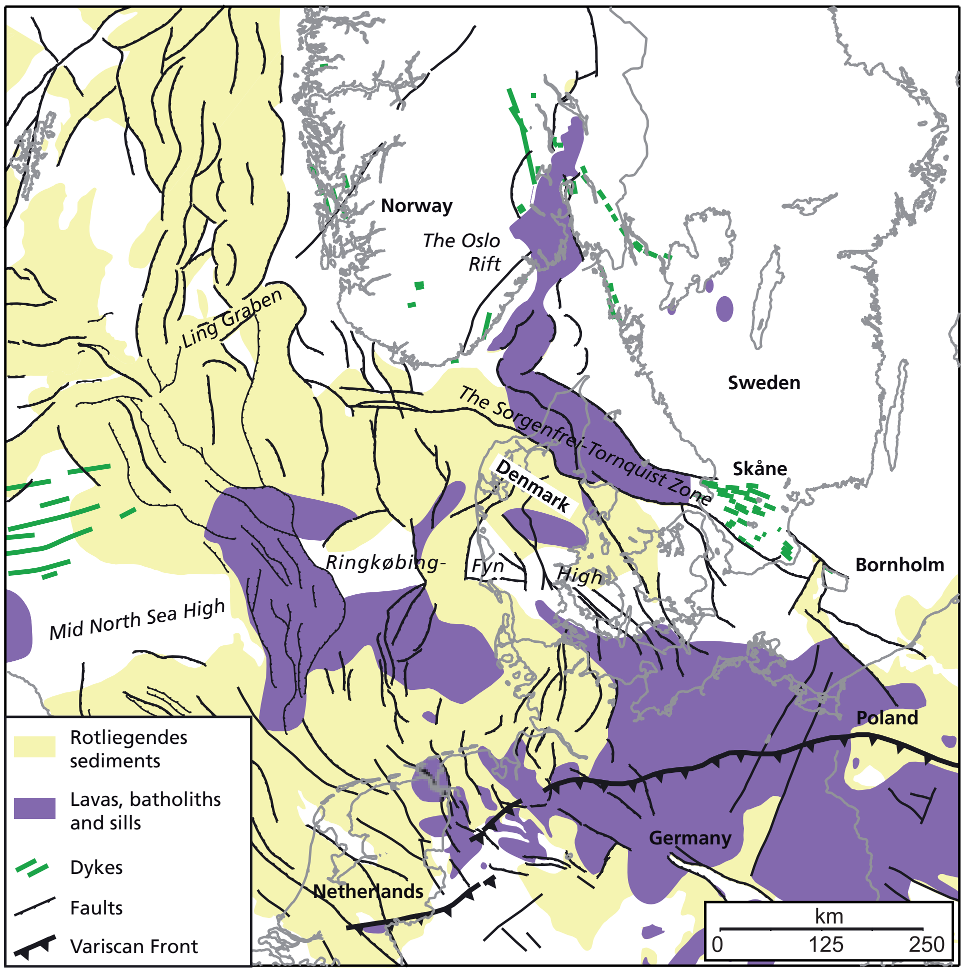
At the close of the Carboniferous, the northern European Variscan foreland was dominated entirely by continental environments. Extensional movements gave rise to volcanism that continued into the Early Permian. The climate continued to be hot and arid, and these conditions persisted throughout the Permian and the greater part of the Triassic. The change in climate was linked to the northward drift of the Pangaean plate, and this caused the area that we now know as central northern Europe to pass from the strictly equatorial climatic zone into subequatorial belts north of the equator. Northern Europe was also in the rain shadow of the Variscan mountain belt.

The final phases of Variscan folding and thrusting also affected the foreland basin, and these processes combined with faulting linked to crustal disturbances that had the same origin as those that were active during the formation of the Oslo Rift. Parts of the Carboniferous sequence were uplifted and eroded, resulting in the formation of a marked erosional boundary, the Saalian unconformity. This unconformity is encountered across much of the North Sea area, where it forms a distinct boundary between the oldest units of the Carboniferous sequence and overlying Permian and younger sequences.

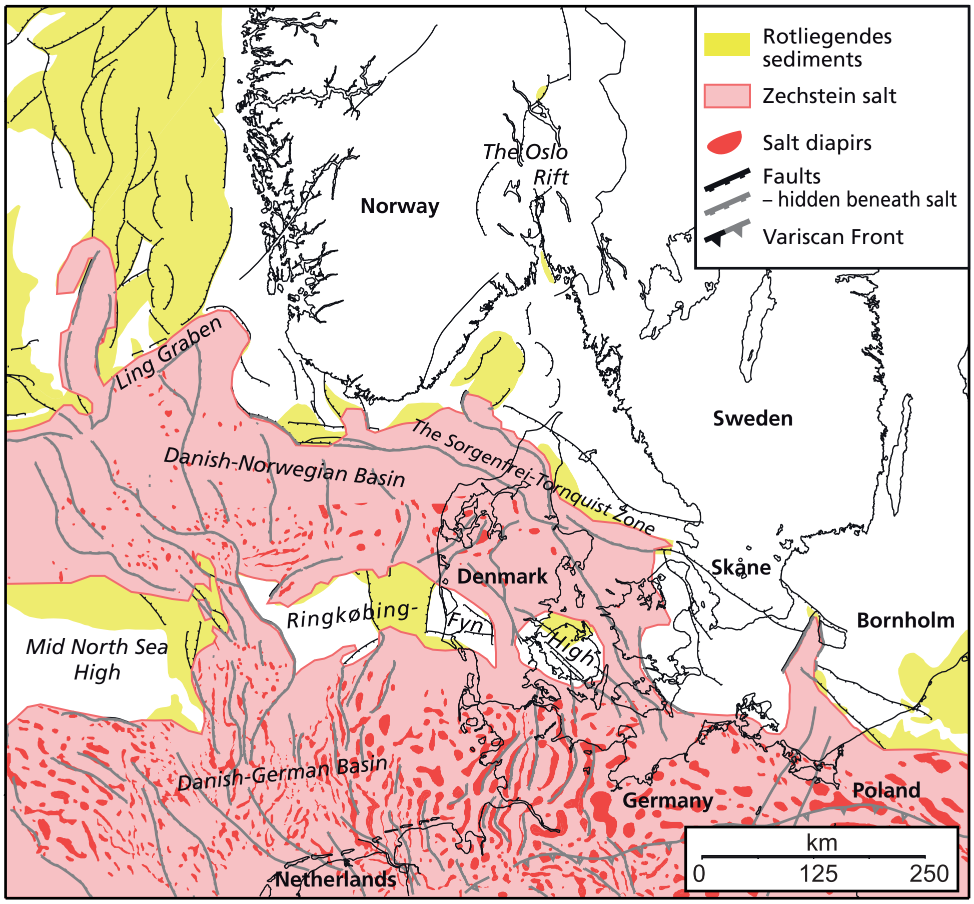
The arid Permian

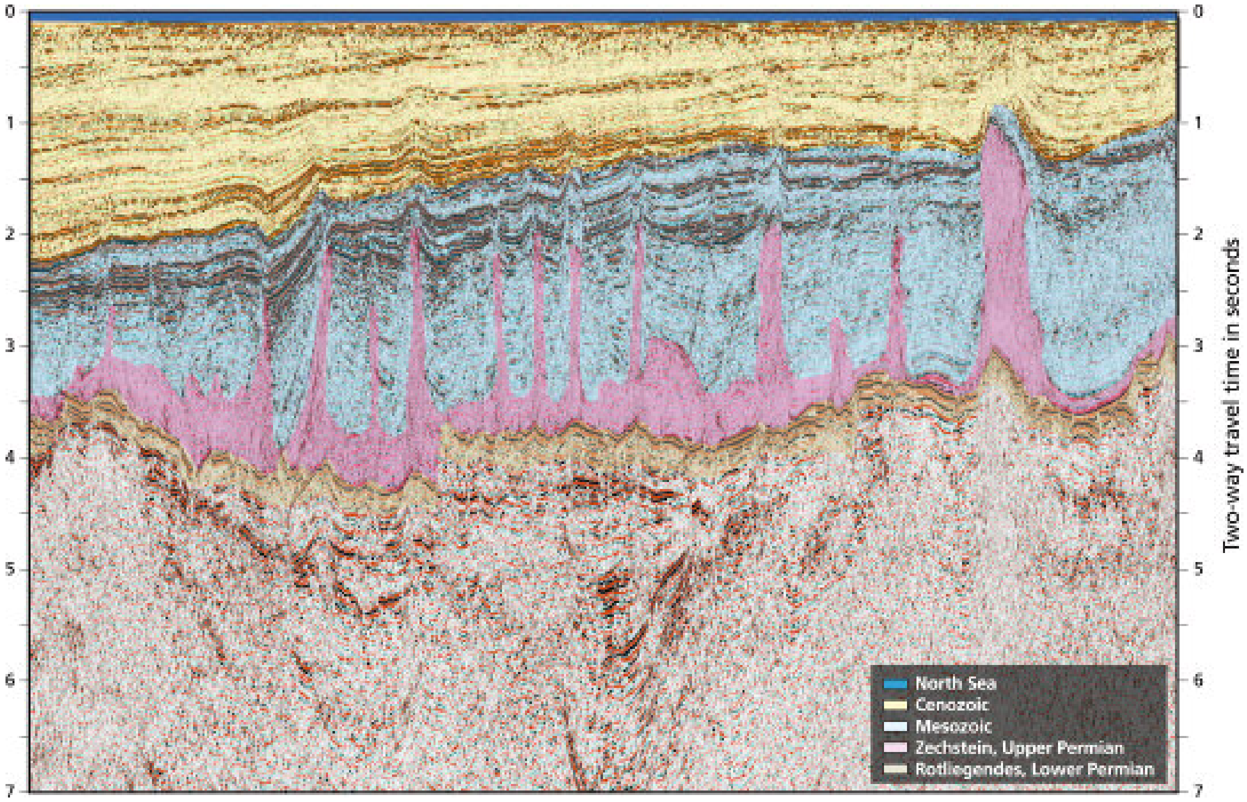
We use two key terms when describing the Permian period in northern Europe and the North Sea, namely *Rotliegendes* and *Zechstein*. The first of these terms, *Rotliegendes,* describes Early to Mid-Permian deposits. The name is derived from the rocks' red colouration, resulting from the partial oxidation of iron within the rock when it comes into contact with air. Rotliegendes sediments were deposited in continental desert environments as sand dunes and deposits from seasonal rivers that flowed rapidly along wadis for short periods, and then dried up. There were also small seasonal lakes or waterholes (salt pans, also known as sabkhas) that also dried up for long periods. The second term, *Zechstein,* is used to describe Late Permian deposits. The name is derived from the German term "eine Zeche", for a mine. The Zechstein sediments of northern Europe were deposited towards the end of the Permian period in shallow seas that developed as the land masses slowly subsided below sea level. Clays, limestones, and extensive salt and gypsum deposits (evaporites) were formed in these seas under the hot and arid climatic conditions of the Late Permian. Gradually, the restricted North Sea basins became isolated from the

Map showing the distribution of sedimentary basins and structures in the North Sea during the Early Permian (Rotliegendes). These basins contain magmatic and sedimentary rocks of Late Carboniferous and Permian age, equivalent to those in the Oslo Rift. The locations of major intrusive dykes are also shown.



Map showing the distribution of the two great Upper Permian Zechstein salt basins in the North Sea; the Danish-Norwegian and the Danish-German basins. Salt was deposited after most of the Permian faults had become inactive. It is mobile and less dense than the overlying rocks and at several locations has flowed upwards to form salt diapirs (see profile next page).





An east-west seismic profile across the central parts of the Danish-Norwegian Basin. Beneath the Late Permian salt layers (Zechstein – in pink), we can trace a Lower Permian rift topography comprising continental sedimentary and magmatic rocks (Rotliegendes – in greyish-green), not unlike those found in the Oslo Rift. Salt diapirs (pink) have forced their way up through the overlying Mesozoic rocks (blue). The entire sequence is overlain by Cenozoic rocks (yellow). The seismic line is 235 km long (From TGS Nopec).

larger oceans, and the sea water evaporated leaving only salt.

Red sandstones and volcanism

Volcanoes were active in the North Sea at this time, especially during the early *"Rotliegendes"* period during the Early Permian, and basalts have been encountered in several exploration wells in the central North Sea. These basalts are about 300 million years old, and are thus the same age as the earliest lavas found in the Oslo Region. Major volcanic eruptions occurred across northern Europe, and we find a great diversity of lava suites, several kilometres in thickness, buried beneath northern Germany. We also find lavas, dykes and other intrusives in the Danish-Norwegian Basin along the Sorgenfrei-Tornquist Zone (both in Skåne and on Bornholm), and in Scotland. The most extensive volcanic province currently lies beneath thick sedimentary sequences in eastern Germany. Here, the sequences of lavas and sediments are known as the "Lower Rotliegendes". These rocks are the same age as the lavas and sediments in the Oslo Rift, confirming that events in the Rift itself were neither random nor local, but that the evolution of large tracts of northern Europe was at this time under the influence of a massive heat source buried deep in the crust or mantle.

In the North Sea, the majority of lavas and sediments belonging to the *"Lower Rotliegendes"* have been faulted and tilted by later tectonic events. We have already seen examples of this in the Skagerrak Graben and the North Sea. As in the Skagerrak, we see indications of what we call a "palaeorelief", formed by erosion of the resistant lavas. This Early Permian erosion can be seen over large areas of northern Europe, and no sediments were deposited in these areas at this time. We call this period of erosion or "non-deposition" the "*Saalian unconformity*". The faulting of the "Lower Rotliegendes" was caused by the same tectonic forces that induced faulting in the Oslo Rift.

Faulting also resulted in the formation of two large continental basins. These have been named the *Danish-German* or *Southern Permian Basin,* and the *Danish-Norwegian or Northern Permian Basin.* These were separated by an extensive, east-west trending ridge called the "Mid North Sea High", which extends eastwards beneath Denmark where it is called the "Ringkøbing-Fyn High". The southernmost part of the Norwegian sector of the North Sea lies within the Danish-Norwegian Basin. At the same time as faulting was active, "Upper Rotliegendes" sediments were being deposited in both of the great basins. These include great volumes of aeolian red and yellow dune sands of similar character to, and most probably the same age as, the Brumund Formation sandstone. In addition, we find both salt pan deposits derived from dried-up lakes, and seasonal alluvial (wadi) deposits similar to those found in Brumunddal. Towards the middle of the Permian, and very much as in the Oslo Region, a hot desert climate prevailed across the North Sea area, and there was little life. This explains the lack of fossils, and our difficulties in obtaining accurate ages for these sequences.

Saline seas – Late Permian

In the Late Permian, the North Sea area continued to subside, and the sea transgressed (flooded) the two great basins again. Slowly but surely, two shallow marine basins evolved, and these now form the so-called *Zechstein Basins*. Initially, a thin transgressive shale unit, the *Kupferschiefer,* was deposited in the central parts of these basins. In Germany, this shale was exploited as a source of copper and other metals as early as the 13th century. Limestones were deposited along the basin margins. The climate remained hot and arid and enormous volumes of water evaporated. Gradually, the remaining water became oversaturated with salt that began to precipitate on the sea floor. Seven distinct cycles of evaporation and salt deposition are recognised during the following millions of years, resulting in the accumulation of salt and gypsum sequences, known collectively as *evaporites.* Zechstein is the term used to describe both the evaporite rocks in the North Sea and northern Europe, and the time period during which they were formed.

When, after the Permian, younger sediments were deposited above the Zechstein salt sequences, the pressure of these overlying sediments eventually became sufficient to cause the salt to flow plastically and force its way up to shallower levels, resulting in the formation of *salt pillows* and *salt diapirs*. These salt structures are clearly visible on seismic data.

Carboniferous and Permian gas and oil reservoirs in the North Sea area

Southern North Sea Carboniferous coals are the source rocks for several large gas fields, including the giant Groningen Field in the Netherlands, and it was this gas discovery that provided the major impetus for gas and oil exploration in the North Sea. Gas formed after the Permian when the coals were buried several kilometres deep at temperatures of about 150 °C. Rotliegendes sandstones are now important oil and gas reservoirs at several localities in the southern North Sea.

One of the important properties of salt is that it is impermeable to fluids. This allows salt sequences to act as "*seals*", and thus combine with reservoir rocks to form oil and gas traps both beneath, and against, the salt sequences. The salt movements producing the pillows and diapirs have thus contributed to the formation of several oil and gas traps in the southern North Sea.

The transition to the Triassic

Towards the end of the Permian, when magmatic and, perhaps also, tectonic events had finally ceased in the Oslo area, these processes moved westward where they continued into the Triassic period. New rift structures were formed in the North Sea, the Norwegian Sea, and in East Greenland.

The climate during the transition from the Permian to the Triassic continued to be extremely arid and probably also hot. "Oslo" had in the meantime simply drifted to a location about 20 degrees north of the equator, and now lay within an intensely arid climatic zone together with the larger part of what is now North-West Europe.

However, the most dramatic event of the transition from the Permian to the Triassic periods was the massive and catastrophic global mass extinction. This event is the most all-embracing mass extinction that we know of, more catastrophic even than the demise of the dinosaurs that occurred much later at the transition between the Cretaceous and the Tertiary.

A Permian (Rotliegendes) sandstone from the east coast of Scotland. The large-scale cross-bedding (beds lying at an angle) is indicative of sand dunes deposited in a desert environment, not unlike that in the Sahara at the present day. Large parts of Northern Europe were covered with desert sands during the Early and Mid-Permian. This sandstone forms an excellent hydrocarbon reservoir in Germany and the southern part of the North Sea, most notably in the gigantic Groningen gas field in the Netherlands, among others. (Photo: From the Millennium Atlas, 2003)