CHAPTER 2

JOHAN PETTER NYSTUEN

Solar radiation and heat flowing from the interior of the Earth supply energy to the external and internal geological processes, respectively, on the Earth. (Computer graphics: M.C. Bjørndal, Photo: T. Andersen of a volcanic eruption on Iceland)

The changing face of the Earth

Geological processes

The Earth is continually changing. Heat flow from its interior and from the Sun, along with gravity, is the driving force behind geological processes. Old continents and oceans disappear, while new ones arise and are altered; mountain chains are raised and broken down. Molten rock pours up from the interior of the Earth, solidifying deep in the crust or forcing its way to the surface as volcanoes. Crustal blocks move and create earthquakes. Unconsolidated material fills sedimentary basins as layers of sediment. Life forms shift with the changes in the face of the Earth. Mankind lives and functions within the framework of the physical and chemical processes that control the evolution of the Earth.

A landscape tells geological history. At Nesna in Nordland, basement granites and gneisses form the naked mountain, Brenslafjellet, in the background north of the fjord, Sjona, and the peaks further north. Cambro-Silurian schists and marbles are downfolded into the basement in the lush areas on either side of Litlesjona in the foreground, and on the green slopes and valleys north of the fjord. The long, shallow inlet in the foreground is an estuary. Streams enter it carrying sediments which tidal currents and waves rework and deposit on tidal flats, in tidal channels, tidal deltas and sand dunes. (Photo: Fjellanger Widerøe Foto AS)

Introduction

The Earth has been changing continuously since its formation 4.6 billion years ago. The internal geological processes that build up its crust and the external geological processes that break the crust down alter its appearance. Life on the Earth has been shaped in the struggle between the internal and external geological forces.

"The ancient peaks against the sky always look alike«, Ivar Aasen wrote in his poem «The ancient peaks«. The mountains change little during a single person's lifetime. Nevertheless, just minute changes in the course of a human generation bring about great changes over a long period. The world will look completely different in a few million years. The face of the Earth is changing continuously.

The changes on the Earth are driven by geological processes, some slow and unobtrusive, others rapid and violent. Streams and rivers carry sand and mud to the coast every day. Waves lap against the beach, shifting one grain of sand today, another tomorrow, year after year. Earthquakes, volcanic eruptions, rock and earth slides, flood waves and floods occur in a matter of minutes, hours or a few days, and often lead to natural disasters. Over many millions of years, the Earth changes through the interaction of many geological processes, unobtrusive and violent. By studying processes today, we can learn what has happened earlier: «The present is the key to the past« has been an established principle for geological research.

The Earth came into existence some 4.6 billion years ago. Dust and gas were concentrated and formed the Sun and the planets. The heat radiating from the Sun is the Earth's external motor, and along with Earth's gravity, it drives processes like weathering, erosion, transport and deposition. The internal motor is the heat flowing from the interior of the Earth causing the movement of huge crustal plates, the upwelling of molten rock and the formation of mountain chains.

The internal and external geological forces meet at the Earth's surface and form the physical frame around all life on Earth as it has been ever since the first organisms evolved more than 3.5 billion years ago. Mountains and valleys, plains, rivers, lakes, shallow and deep seas, hot and ice-cold tracts, arid and wet – all natural environments are inhabited by living organisms. When geological processes change the physical environment, life forms adapt. The geological history of Norway is also a history of how life forms have evolved and adapted to changes in the face of the Earth.

Internal geological processes build up the Earth's crust

The Earth is an active planet. The heat flow from its interior drives the internal geological processes that give rise to plate tectonics, volcanism, earthquakes, land uplift and mountain chains.

The Earth has an internal construction composed of a *core* of iron and nickel surrounded by the *mantle*. An approximately 30–100 km thick *crust* forms the outermost shell. Ten to fifteen per cent of the total heat flow from the Earth's interior comes from the core and the rest from the mantle and the crust through nuclear decay of radioactive elements. There may also be some residual heat left from when the Earth was a red-hot ball, and some heat is released by mineral reactions in the core and the mantle. This geothermal heat causes the temperature to rise on average 30 °C per km from the surface downwards. It rises still more rapidly in some areas, such as many active volcanic regions. Geothermal heat is an enormous power resource that has so far been little harnessed.

Even though the heat flow from the interior of the Earth is only one five-thousandth of that received from the Sun, it drives many processes on the Earth's surface and in the atmosphere. It causes parts of the mantle and crust to melt and well up to the surface as lava. Water vapour, carbon dioxide and other gases from the Earth's interior contribute to the greenhouse effect in the atmosphere. The greenhouse effect results from gas and water vapour in the atmosphere reducing the amount of solar radiation that can be reflected back to space. Without the greenhouse effect, it would have been too cold for advanced life on Earth. The internal source of heat propels the break-up of continents, the formation of new oceans and mountain chains, as well as volcanism. The internal geological processes lead to the formation of new crust.

The contours of the coastlines on both sides of the Atlantic Ocean and the geological structures in Africa, South America, Europe and North America suggest that these continents once formed a single supercontinent. Figure adapted from Marshak 2005.

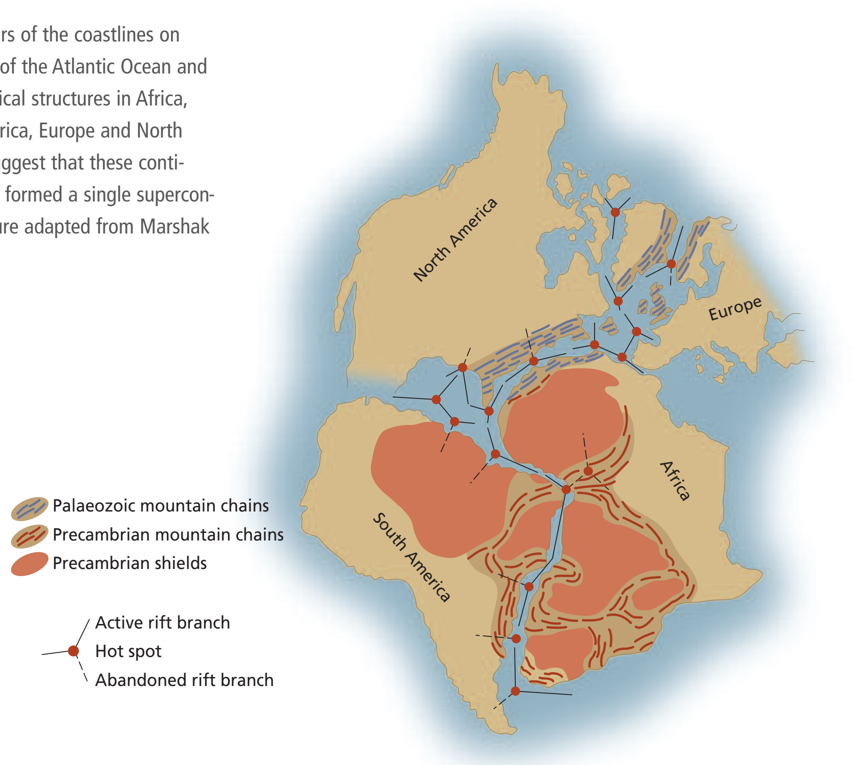


Plate tectonics – we drift around on plates of rock

The crust, along with the outermost, solid part of the mantle, forms plates that float on the underlying, softer part of the mantle. These movements are called plate tectonics. Tectonics is the collective name for all kinds of movement in the crust and mantle. The plate tectonic theory, one of the most revolutionary scientific theories concerned with the planet Earth, has its precursor in the continental drift hypothesis.

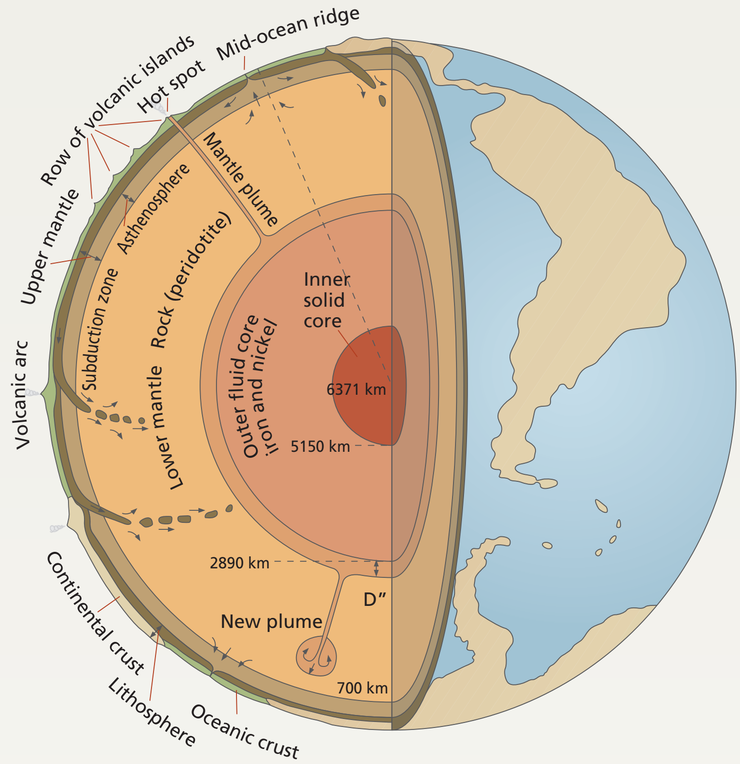
When the German meteorologist, Alfred Wegener, followed by the British geologist, Arthur Holmes, claimed in the first part of last century that the continents must once have drifted apart from one another and from an original supercontinent, no one believed them. Wegener and Holmes pointed to the astoundingly good correspondence between the coastal contours of the continents, the great

THE INTERNAL STRUCTURE OF THE EARTH *By Valerie Maupin*

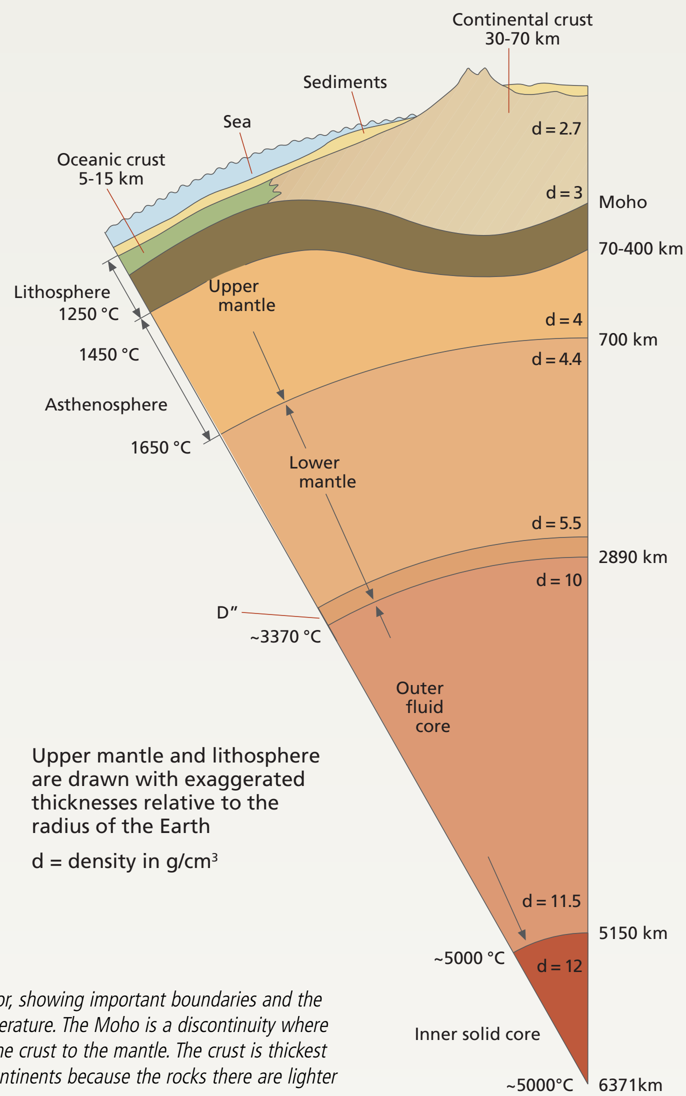
In contrast to the upper part of the crust, our knowledge of the deeper parts of the Earth is comparatively new. Only about 100 years ago did scientists begin to appreciate that the Earth was built up of three main elements: crust, mantle and core. It was the propagation of the earthquake waves, that is, how they are reflected and refracted when they encounter the various layers, which enabled geophysicists to map the inaccessible parts of the Earth's interior.

The first records of earthquake waves were made around 1880, but several years passed before there were sufficient records to understand the systematics in the different waves and visualise the structure behind them. The boundary between the crust and the mantle was first discovered and published in 1910 by the Croatian seismologist, Andrija Mohorovičič. He studied seismic waves from a powerful earthquake southeast of Zagreb on 8 October 1909. This boundary, which was subsequently found to pass right round the Earth, was named after him and is now usually referred to as the *Moho*. The existence of an Earth core had been suggested as early as 1897, based on an analysis of the distribution of density in the Earth. A realistic figure for the radius of the core was given in 1913 by a German seismologist, Beno Gutenberg, on the basis of how the arrival times for the seismic waves at an observatory vary with the distance from the site of an earthquake. That the core consists of two parts, an outer, mobile part and an inner, solid part, was demonstrated by a Danish female seismologist, Inge Lehmann, in 1936.

We now know that the silicates in the mantle pass through several phase transitions and this results in great increases in the velocity of the waves at depths of 440 and 670 km. Tomographic techniques which employ several millions of seismic registrations (corresponding to computer tomography, CT, in medicine) give us a picture of how the internal structure of the Earth varies. For example, differences in temperature influence the speed of the waves, and the results of the tomographic techniques may therefore be used to study the flow patterns in the mantle, and hence the forces that lie behind plate tectonics. It has also been shown that, in several places, lithosphere which vanishes down subduction zones probably sinks right down to the core-mantle boundary.



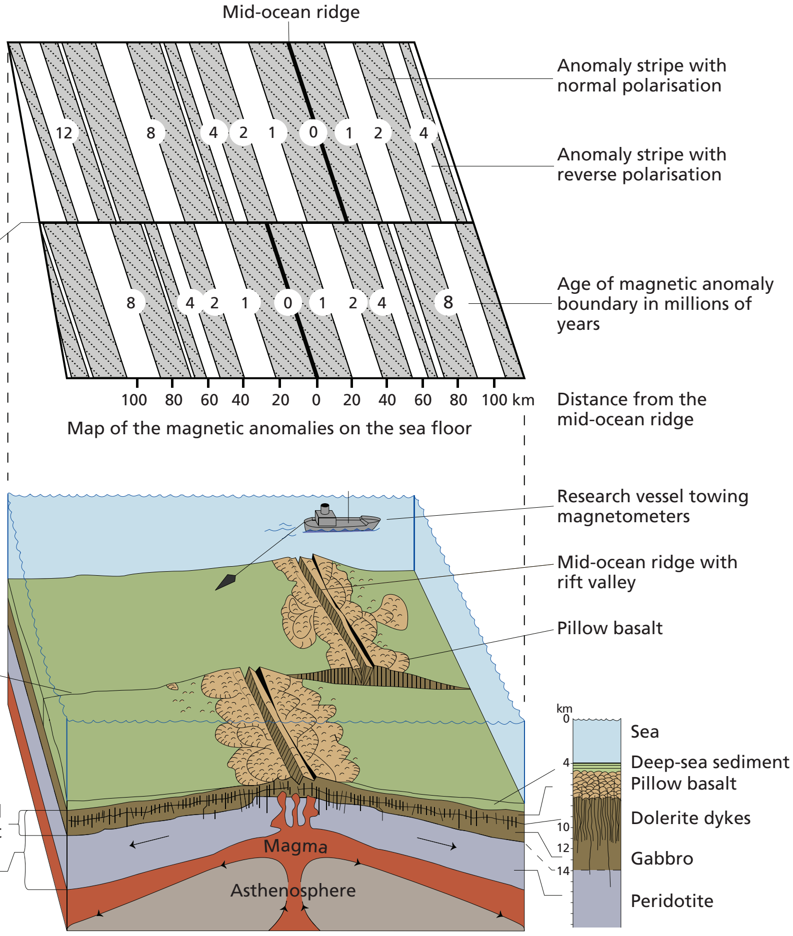
The Earth's interior, its shell-shaped structure and its main elements. Mantle plumes are upwellings of molten rock from hot domains in the mantle which end in volcanoes on the Earth's surface. Cold plates of lithosphere which sink beneath lighter plates may go all the way down to the base of the mantle before they disintegrate.



A section through the Earth's interior, showing important boundaries and the distribution of density (d) and temperature. The Moho is a discontinuity where the density increases rapidly from the crust to the mantle. The crust is thickest beneath mountain chains on the continents because the rocks there are lighter than beneath the oceans.

Peeping into the centre of the Earth. The Mid-Atlantic Ridge with its longitudinal fissures and canyons crosses Iceland from south to north. At Thingvellir in southern Iceland, the site of the former Icelandic Althing, the Earth's crust is still spreading along deep canyons that cut the terrain. Lake Thingvalla, in the background, contains active volcanoes. (Photo: J.P. Nystuen)

The magnetic anomaly stripes reflect the orientation of the Earth's magnetic field when the rocks solidify along the mid-ocean ridges. Grey stripes show normal orientation and white stripes reverse orientation.



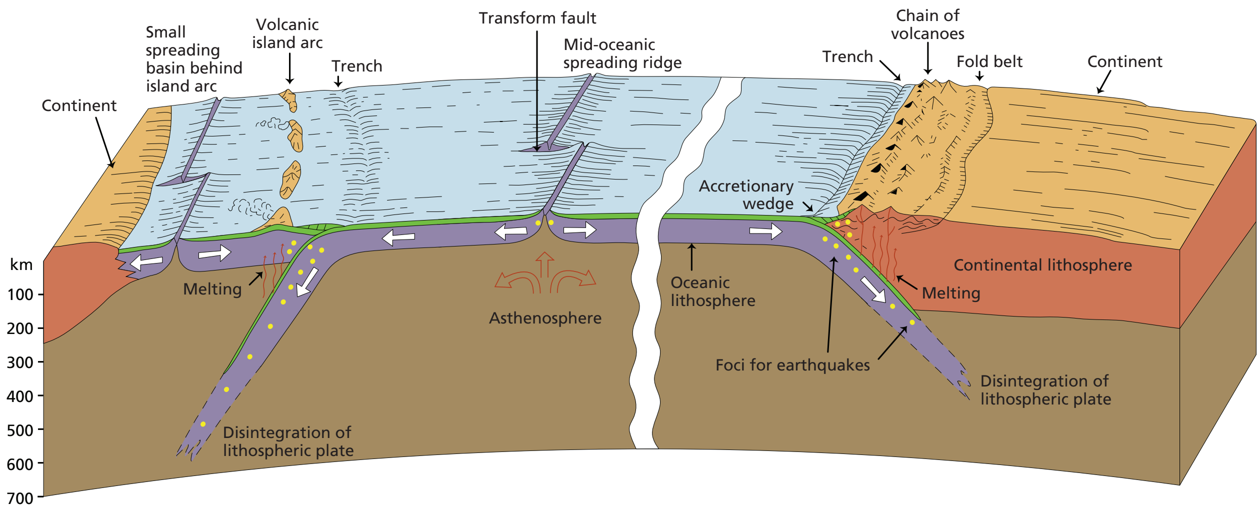
similarity in the geological make-up of continents that are now separated by oceans, and that animals and plants on separated continents have common evolutionary histories up to a certain point in time – the point when the supercontinent split and plant and animal life began to evolve differently on the new, isolated continents. The continental drift hypothesis was refuted because no one could explain how the continents could split apart and drift from one another like floats on a sea.

The relief of the ocean floors was mapped in the 1950s and 1960s. The mid-ocean ridges with their deep, longitudinal rifts and transverse fracture zones, as well as deep-sea trenches and submarine volcanoes, were discovered. The discovery of the submarine ridge along the middle of the Atlantic Ocean was ground-breaking. It caused another stir when scientists showed that the volcanic islands of Iceland and Jan Mayen stood on the Mid-Atlantic Ridge. How could this have come about?

Later in the 1960s, it became clear that the rocks in the oceanic crust are *magnetised*. The magnetic pattern displays a series of stripes almost parallel with the mid-ocean ridges. Geophysicists discovered that these *magnetic anomaly stripes* demonstrate that the oceanic crust is oldest furthest from the mid-ocean ridges and youngest on the ridges themselves. New crust is being formed today along the mid-ocean ridges, as on Iceland and Jan Mayen, where molten rock (*magma*) is welling up from depth and solidifying to lava rock.

Magma seeps up along the rift valleys in the mid-ocean ridges and solidifies in large openings, fissures, crevices and on the ocean floor itself. The crust grows outwards from the sides of the mid-ocean ridges so that the oceanic crust is gradually sliding outwards on both sides of the ridges. This process is called *sea-floor spreading* and the mid-ocean ridges are *spreading ridges.*

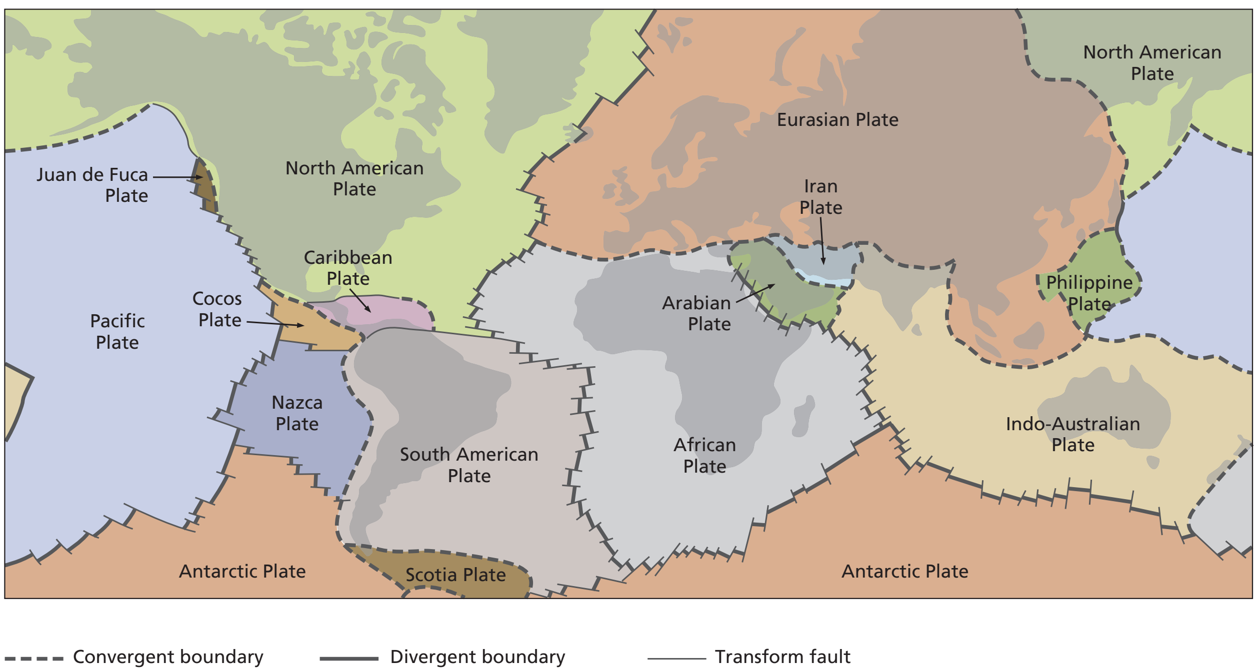
This new understanding of how the crust beneath the oceans is formed led to the plate tectonic theory in the mid-1960s. The crust and the outermost part of the mantle consist of concentric slices of solid rock, *lithospheric plates*, which ride on a soft, plastic layer of mantle, the asthenosphere. «Lithos» is Greek and means rock, so the lithosphere is simply a stony



The main features of plate tectonics. New oceanic crust is formed along mid-ocean ridges, while old, heavy crust sinks beneath lighter crust in subduction zones where mountain chains form. Ocean-floor sediments are subducted together with the oceanic plate or are scraped off in accretionary wedges. Crustal stresses trigger earthquakes along the plate boundaries.

shell outermost on the planet Earth. The continents form the upper, light part of the lithosphere and move as the rock plates gradually drift. A distinction is drawn between *ocean-floor crust* and *continental crust*. The difference is that the crust in the continents predominantly consists of light rocks like granite, gneiss, sandstone, limestone and shale, whereas the oceanic crust consists of heavy rocks like gabbro, dolerite and basalt.

Today, the planet Earth has eight large and a number of smaller lithospheric plates. In Norway, we live on the *Eurasian Plate* which embraces the whole of Europe and Asia, except India and the eastern part of Siberia. Our plate borders onto the *North American Plate* along the Mid-Atlantic Ridge. These two plates are in contact across the centre of Iceland. There are three main types of plate boundaries, divergent boundaries, convergent boundaries and transform boundaries. These boundaries are important features in a plate tectonic development that starts with the break-up of one continent and ends with the formation of a new one. This is the *plate tectonic cycle.*



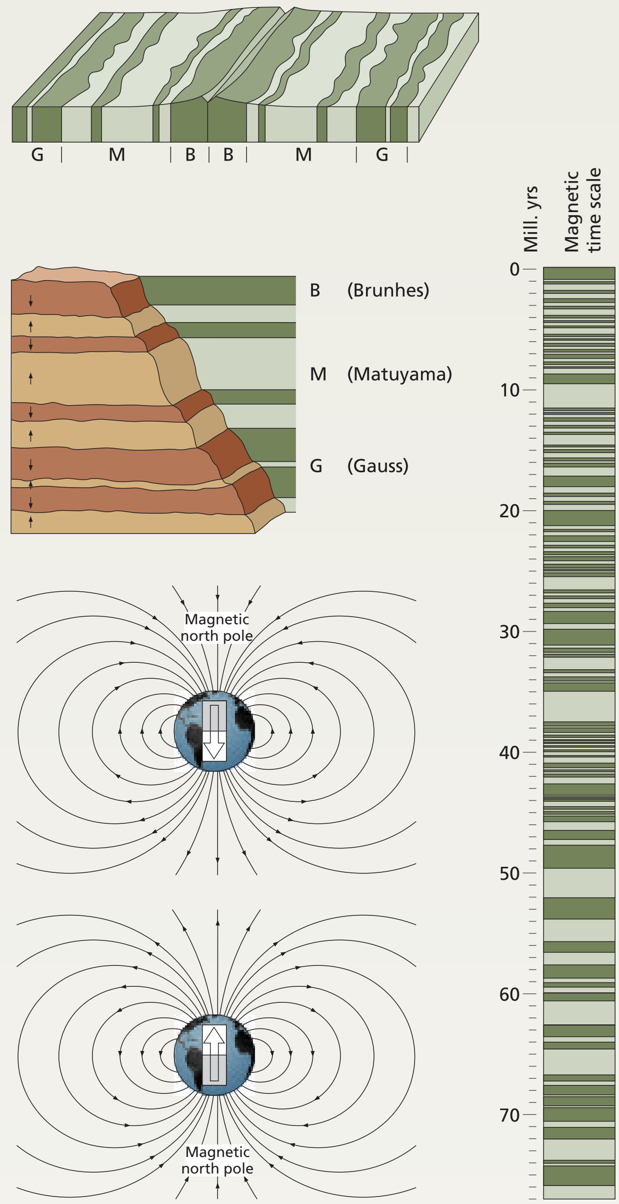
Present-day lithospheric plates. The plates drift apart along divergent boundaries where new ocean-floor crust forms, and meet each other along convergent boundaries where mountains form. Transform faults are transverse fractures along divergent boundaries where the mid-ocean ridges are apparently fragmented and pushed aside.

GEOMAGNETISM

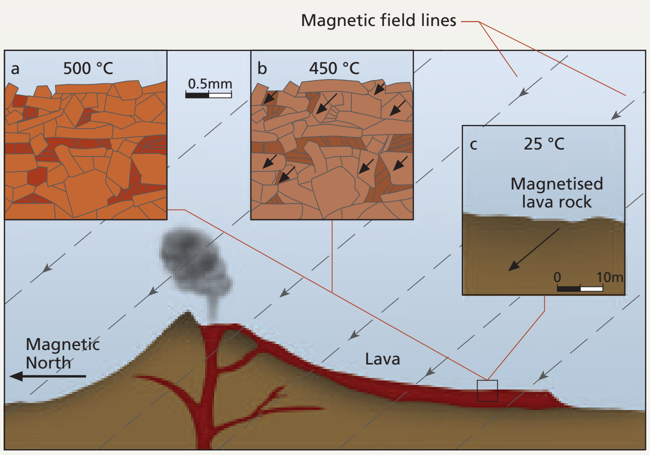
The Earth's magnetic field originates in the fluid mass of iron and nickel constituting the outer core of the Earth. The Earth can be likened to a bar magnet surrounded by a magnetic field, where magnetic field lines pass from the core at the geomagnetic south pole and re-enter at the geomagnetic north pole, with the *magnetic dipole* pointing towards the south. The magnetic poles are situated close to the geographical poles, but are continuously moving slightly and have also switched places many times in the course of Earth history. The present orientation of the magnetic field is called *normal polarisation,* whereas its opposite orientation in the past is called *reverse polarisation.*

The magnetic field lines are measured with respect to their direction relative to the geographical north and south poles, their declination and the angle at which they meet the Earth's surface, their inclination. The inclination is high at high latitudes and low at low latitudes. Minerals in basalt lava, for example, will obtain an internal «print« of the magnetic field lines in accordance with the polarity and orientation which the Earth's magnetic field had when the lava cooled. Sedimentary rocks can also be given a print of the Earth's magnetic field at the time they formed.

The polarity and orientation of past geomagnetism, *palaeomagnetism*, can be measured from the magnetic print preserved in the rocks. Since the magnetic poles have always been located close to the geographical poles, the palaeomagnetic print in a rock of known age can be used to find out where on the Earth the rock formed in the period in question. In other words, the «fossil» magnetic field in the rocks can be used to reconstruct where the Earth's lithospheric plates were located at any one time, and how they have drifted relative to one another through Earth history. The *magnetic time scale,* constructed on the basis of shifting normal and reverse polarity in rocks of known age, is also employed to determine the age of the ocean-floor crust with the help of the magnetic anomaly stripes of normal and reverse polarity, the basis for magnetostratigraphy.



The Earth as a magnet. In our time, when polarisation is normal, the magnetic dipole points south, whereas it points north in periods with reverse polarisation (lowermost left). Basalts of known age have preserved the print of the magnetic dipoles from the named times with normal and reverse polarity (middle left). A magnetic time scale (right) is used to determine the age of corresponding magnetic anomalies in ocean-floor crust (uppermost left).
Figure adapted from S. Marshak.



Magnetisation of lava. When the temperature in a lava rock drops below about 450°C, the dipoles in all magnetised minerals become oriented parallel with the Earth's magnetic dipole. An internal print is preserved of the polarity, direction and angle of the magnetic lines at the place where the lava was formed relative to the Earth's surface. Figure adapted from P.J. Wylie.

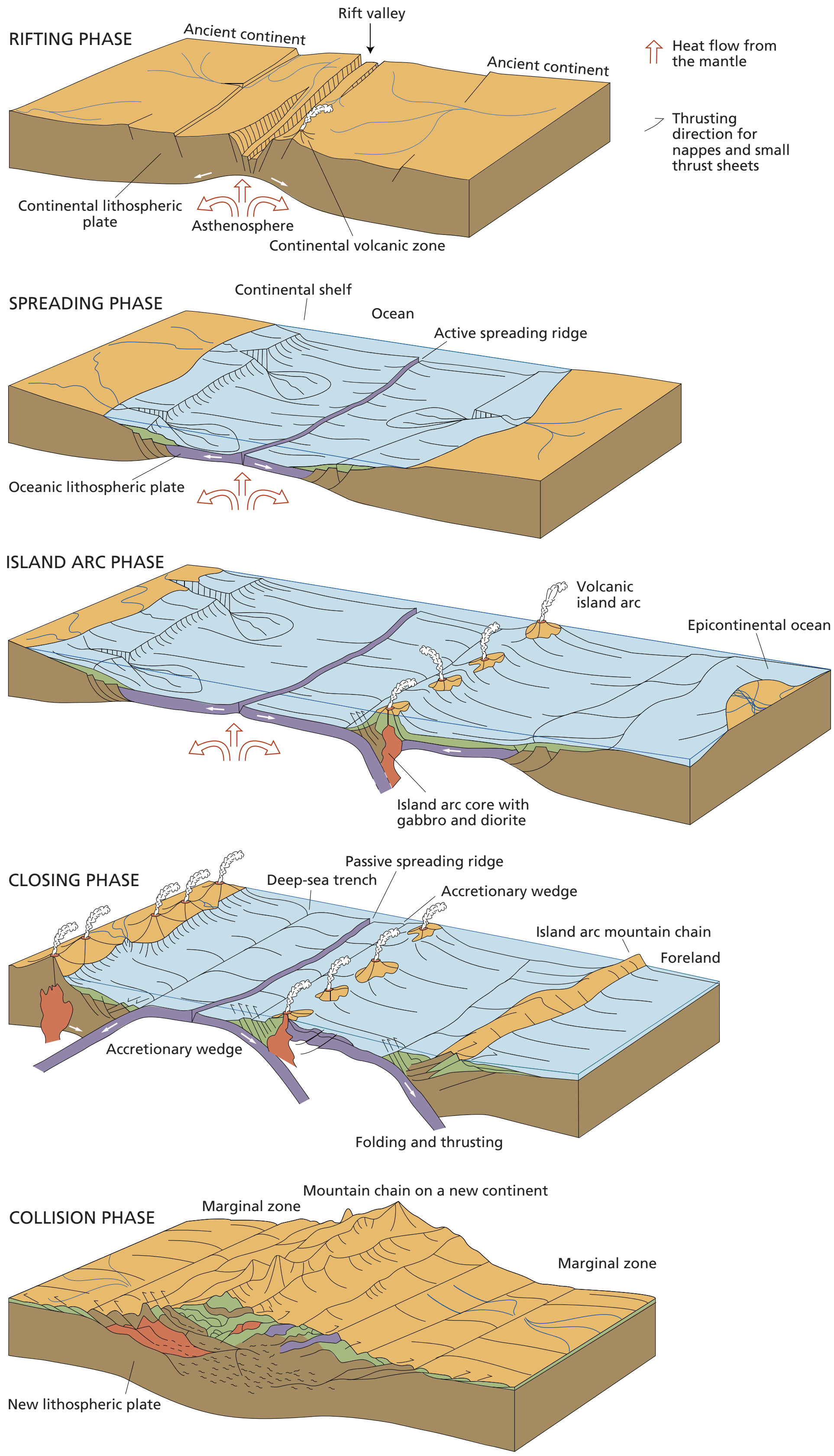
The oceans open and close

The plate tectonic cycle is a grand-scale geological process. It begins with the splitting of a large continent into two or more continents separated by new areas of sea, and ends with continents and volcanic island arcs being welded together into a new, large continent, while the oceanic areas close. It is called the «Wilson cycle« after the Canadian geophysicist, John Tuzo Wilson, who, in the mid-1960s, demonstrated that many hundred million years ago an ocean, later called the Iapetus Ocean, had opened and closed where the North Atlantic is now situated. The evidence for the Iapetus Ocean is now found as old oceanic rocks in mountain chains on both sides of the Atlantic Ocean. The Atlantic Ocean will also disappear sometime in the future, and Europe and North America, along with Greenland, will once more be welded together in a new mountain chain. A plate tectonic cycle may take many hundred million years. Let us now look at what broadly takes place.

When a lithospheric plate with a continent riding upon it stretches and cracks, a rift or *rift valley* is formed, like the East African Great Rift Valley today. Magma rises from a great depth and leads to volcanism. In time, the valley may fill with sediments and/or volcanic rocks. As the crust continues to stretch, the plates on either side of the rift are pulled apart, and new crust forms because magma from the mantle solidifies in the gap between the two detached plates.

When the rift valley opens as far as the sea, it is flooded and transformed into a long arm of sea. Continued crustal extension and sea-floor spreading give rise to a new ocean. The boundary between the plates is a *divergent boundary*, also called a constructive boundary. The Red Sea is a young arm of the sea that opened when Africa and the Arabian Peninsula began drifting apart 4–5 million years ago.

Ocean-floor crust is gradually cooled, becomes heavier and sinks as it moves further away from the spreading ridge. That explains why the oceans become deeper the further away from the spreading ridges the ocean floor is located. The mid-ocean ridges rise because the rocks there are hotter and lighter than the cooled, older, ocean floor rocks. In a few places, a spreading ridge reaches above sea level, as in Iceland. The North Atlantic is widening today at a rate of some 2 cm a year.



The plate tectonic cycle from the break-up of an old continent to the formation of a new one.

At Bitihorn in the outer part of the Jotunheimen Mountains in Valdres, south-central Norway, Precambrian gabbro was thrust over younger Precambrian sandstones that form the bedrock in the ridge in the foreground. The thrusting took place when two plates collided during the Caledonian orogeny at the end of the Silurian about 415 million years ago. (Photo: I. Bryhni)

In periods when sea-floor spreading takes place very rapidly, the mid-ocean ridges displace so much water that the sea floods the continental margins. This took place, for example, at the beginning of the Cambrian, 542 million years ago, and at the end of the Cretaceous, 66 million years ago, when the present oceans opened completely. These are the two periods in Earth history when the sea has stood highest relative to the land.

Lithospheric plates collide along *convergent boundaries*, also called destructive boundaries, and mountain chains gradually come into existence there. In collision zones where a heavy (dense) oceanic plate meets a lighter continental or oceanic plate, the denser plate sinks beneath the lighter one. This zone where plates sink is called a *subduction zone* and the process is called *subduction.* On the surface, such downgoing zones are characterised by the presence of long ocean trenches where the ocean floor bends down. When the oceanic plate sinks into the mantle, it takes with it ocean-floor sediments containing large amounts of salt water. As the plate descends, its temperature rises and the water is driven off and rises into the mantle of the overriding plate, lowering the melting temperature of the rock it encounters. This can therefore more easily melt when heated. The melt formed within and above a subduction zone rises and may cause volcanism, as in the Andes of South America, the Aleutian Islands in Alaska, the Kamchatka Peninsula in Siberia, Japan, the Philippines and New Zealand. This is the 'Ring of Fire' encircling the Pacific Ocean.

In the collision zones, piles of sedimentary rocks are also peeled off the basaltic layer on which they have been deposited, pushed, folded and squeezed together. Such *compression zones* consist of highly deformed rocks and are situated, for instance, in parts of Japan, the Philippines and Indonesia, where mountain chains are being formed at present. In young mountain chains, rocks containing fossils of marine organisms can often be found at heights of several thousand metres. Mount Everest, 8850 m high, consists of fossiliferous limestone from the Tethys Ocean that was pressed up when India collided with Asia 30–40 million years ago.

Slices of heavy oceanic rocks may also be pressed up during the formation of a mountain chain. Remains of such ancient oceanic crust are found as *ophiolite sequences* in the Caledonian mountain chain in Norway. Sheets of ancient continental crust comprised of granite, gabbro and gneiss may also be torn loose and thrust up where mountain chains are formed. Examples of such nappes are found in the Jotunheimen Mountains in south central Norway and elsewhere in the approximately 400 million-year-old Caledonian mountain chain which stretches the length of Norway. High tension arises along convergent boundaries, leading to violent earthquakes, such as occur around the Pacific Ocean in Central and South America, Japan and the Philippines. The powerful earthquake that led to the tremendous flood wave (*tsunami*) and subsequent disastrous inundations in southern Asia on 26 December 2004 was triggered because the Indian Plate is colliding with the Eurasian Plate. In some millions of years, a mountain chain will tower where there are now idyllic beaches in Thailand.

Transform boundaries are plate boundaries where lithospheric plates slide sideways relative to each other. They are also called conservative plate boundaries because the plates are neither constructed nor destroyed, but, rather, they are preserved. The famous San Andreas Fault in California is a transform boundary located where the Pacific Plate in the west is gliding north-westwards relative to the North American Plate in the east. A great deal of friction arises along transform boundaries, and some of the most powerful earthquakes in the world occur in such zones. Deep rift valleys are commonly associated with transform boundaries. Lake Baikal in Siberia, reaching a depth of 1637 m, is the deepest lake in the world and is situated in a transform rift through the eastern part of the Eurasian Plate.

Magma also reaches the surface within lithospheric plates, not just along their boundaries. In particular, high heat flow takes place through pipe- or mushroom-shaped structures, *plumes*, in the mantle. Such loci are also called *hot spots*. An enormous flow of heat is currently building up beneath the North American continent, in the Yellowstone National Park in Wyoming, where it is feared that a gigantic volcanic eruption will take place in the near future. Tremendous amounts of magma may pour to the surface from mantle plumes and solidify to give piles of plateau basalts many thousands of metres thick. Vast areas of *plateau basalt* are found in Ethiopia, India, eastern Siberia and north-western USA.

Mantle plumes are believed to be stationary features over which the lithospheric plates move. A row of submarine volcanic seamounts and volcanic islands forms when a plate drifts over such a plume beneath an ocean; Norway's Bouvet Island in the South Atlantic was originally such a submarine volcano that built up to above sea level. The volcanic Hawaii Islands and their submarine continuation in the Pacific Ocean are located where the Pacific Plate drifted over a hot spot, and this process is still taking place on Hawaii. A mantle plume has existed in the northeast Atlantic for the last 55–60 million years and gave rise to a land of plateau basalt stretching from Scotland to East Greenland. This has mostly sunk into the sea, but basaltic lava from the plume crops out on the Faeroe Islands, Iceland and the east coast of Greenland. The hot bulge in the mantle now lies beneath Iceland and explains why Iceland does not sink into the sea.

New bedrock from molten rock

The temperature in the Earth's mantle and crust may become so high that rock begins to melt. This *molten* rock is called *magma*. Geologists therefore refer to all rocks formed by the solidification and crystallisation of magma as *magmatic* rocks or *igneous* rocks.

Magma is hot when it reaches the surface, generally between 800 and 1250 °C. It contains minerals that have crystallised early, along with water vapour (H_2O) and a number of gases. Volcanism often releases huge volumes of the greenhouse gases water vapour, carbon dioxide (CO_2) and methane (CH_4). Other poisonous gases that reach the surface during volcanic eruptions have sometimes killed people, animals and plants.

Magma is lighter than the cooler bedrock encompassing it and therefore rises through the crust, forcing its way into other rocks and perhaps breaking out on the surface as *lava* or volcanic ash. The process that takes place when molten rock forces its way into existing bedrock is called *intrusion*. An *eruption* takes place when magma is extruded on the surface; this is called a volcanic eruption, and a volcano is formed. These two processes give rise to *intrusive* and *extrusive* rocks, respectively.

Magma that solidifies in the crust becomes *plutonic* rock. When it cools in fissures and joints, it is called *hypabyssal* rock, and when it solidifies on or just beneath the surface it is designated *volcanic* or *extrusive* rock. Igneous rocks may have many different forms and vary in volume from several thousand cubic kilometres in certain plutonic rocks to just a few cubic metres or less in narrow hypabyssal rocks. Volcanoes have many different forms, too, from small explosion craters to long fissure volcanoes or large stratovolcanoes with a single main crater in the middle, like Mount Etna on Sicily.

Minerals crystallise when the magma cools. A mineral is a solid substance with an orderly crystal structure consisting of atoms of specific elements. The mineral quartz, for instance, has the chemical formula, SiO_2, that is to say that one molecule of quartz consists of one atom of silicon (Si) and two atoms of oxygen (O). A *rock* is a solid accumulation of one or more different types of minerals. Rocks

MINERALS

Minerals are the fundamental components of almost all rocks. A mineral is a homogeneous, naturally- occurring, solid, inorganic substance with a definite chemical composition expressible by a formula and having an orderly crystal structure where the atoms occupy specific positions. Several thousand minerals have been described. They are distinguished by colour, streak, lustre, hardness, specific gravity, external crystal form and internal crystal structure, cleavage and other special properties. A well-developed crystal is a mineral that is demarcated by plane, natural crystal faces. Crystals may be cubic, six-sided, pyramidal and many other shapes.

Minerals are formed in many different geological environments. They may supply information on temperature, pressure, fluids and gas in the environment in which they formed, and on the age of the rock of which they form a part. Minerals are important industrial raw materials, many are valuable gemstones, and they are popular collectors' items. Minerals belong to the landowner and cannot be collected without permission. Some mineral localities are protected by law.

MINERALS MAY BE DIVIDED INTO EIGHT MAIN CLASSES

I. *Pure elements*	V. *Carbonates*
II. *Sulphides*	VI. *Sulphates*
III. *Oxides*	VII. *Phosphates*
IV. *Halides*	VIII. *Silicates*

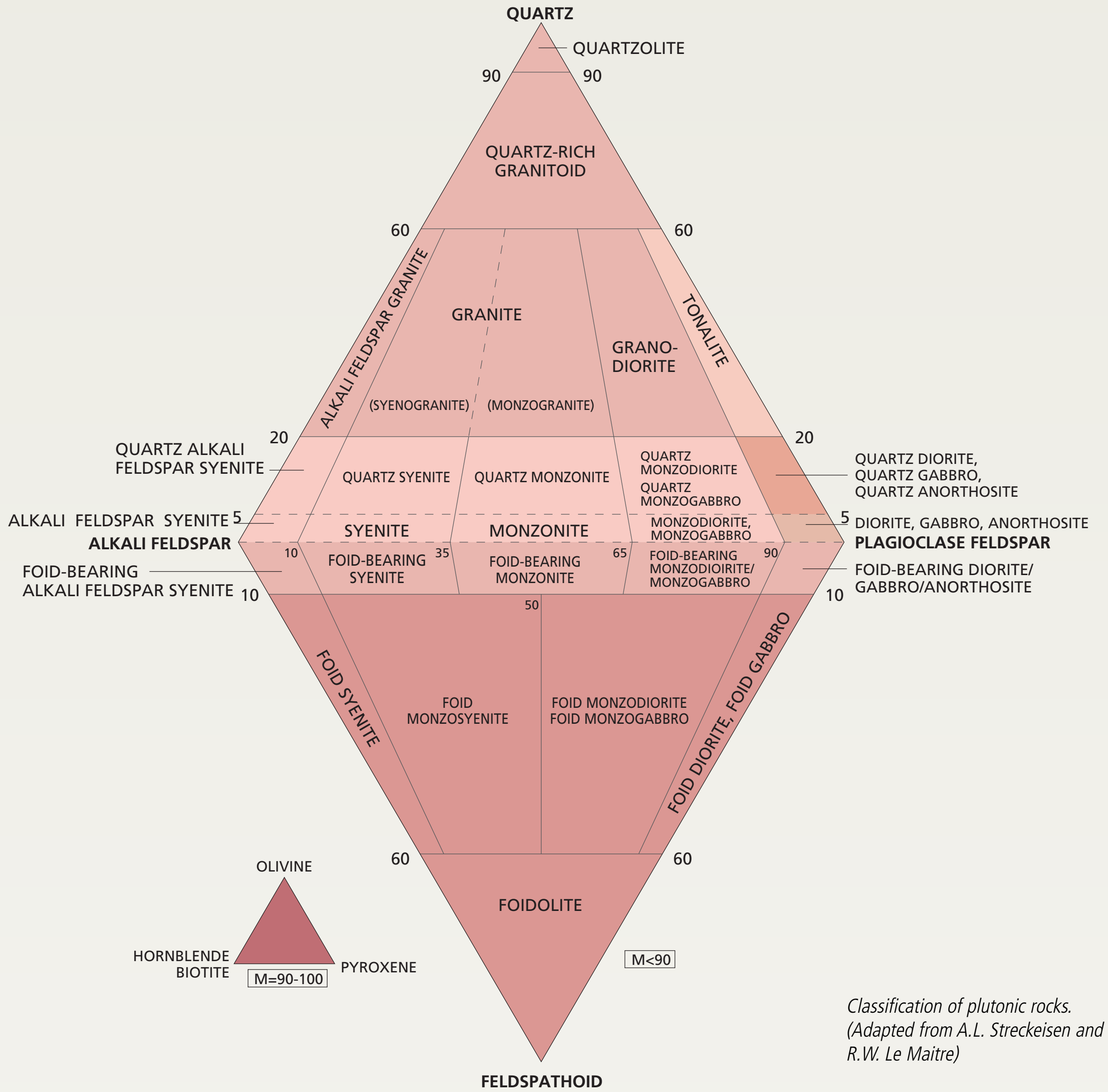
Two quarz crystals (rock crystal) coated with anatase crystals. Hardangervidda. (Natural History Museum Collection, photo: P. Aas)

formed by solidification usually have a crystalline texture where the minerals interlock, as in granite. Sedimentary rocks, like sandstones, have a depositional texture where the mineral grains are compressed and cemented together. Metamorphic rocks, like gneiss, have a texture resembling that of igneous rocks. The most common light-coloured minerals formed by crystallisation from magma are quartz, feldspar and nepheline. They are characterised by their content of silicon (Si), aluminium (Al), sodium (Na), potassium (K) and/or calcium (Ca) and the lack of heavy metal atoms. The commonest dark minerals rich in iron (Fe) and magnesium (Mg) are biotite (black mica), pyroxene, amphibole and olivine.

When magma with the chemical composition of basalt cools in a chamber in the crust, the dark, iron- and magnesium-bearing minerals crystallise first, generally in the order olivine, pyroxene, amphibole and biotite. The light-coloured minerals crystallise later, except for feldspars in the sodium-calcium series, the *plagioclase* feldspars, which crystallise simultaneously with pyroxene, olivine and amphibole, and form gabbro and basalt. As the dark minerals crystallise from the magma, the residual melt becomes relatively richer in silica, aluminium, potassium and sodium. Feldspars rich in potassium and to some degree sodium (*alkali feldspars* or *K-feldspars*), along with quartz, therefore crystallise during the last phase in the cooling of the magma, together with biotite. The plutonic rocks, granite and syenite, and their corresponding extrusive rocks, are typical of the late phase in the crystallisation of magma. This process is called *fractional crystallisation* and may explain how so many different igneous rocks can be formed. A number of other processes may also take place in magma, and give rise to a great diversity of magmatic rocks. Magma may, for example, mix with other magma, be divided into several types of magma each of which crystallises in its own way, change composition by melting and absorbing small portions of its enclosing (country) rock, or be chemically changed through the removal of water vapour and gases or the addition of various components.

Igneous rocks have been given a variety of names depending on their mode of formation as plutonic, hypabyssal or extrusive rocks, as well as their mineral or chemical composition. Rocks with a high content of silica (Si) are generally called *acid* rocks, and those with little silica *basic* rocks. These old terms date

CLASSIFICATION OF IGNEOUS ROCKS

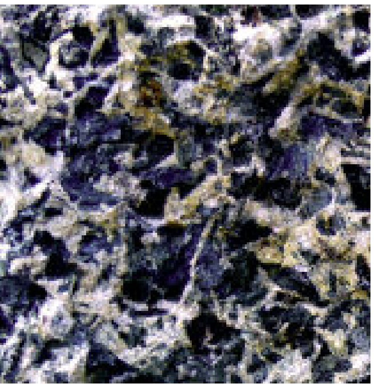


Classification of plutonic rocks. (Adapted from A.L. Streckeisen and R.W. Le Maitre)

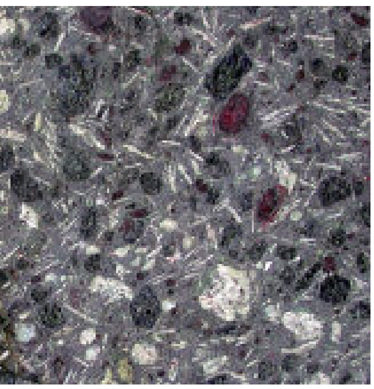
Igneous rocks are mainly classified according to their content of five main groups of minerals: (Q) quartz, (A) alkali feldspar (sodium-potassium feldspar, or K-feldspar), (P) plagioclase feldspar (sodium-calcium feldspar), (F) feldspathoids and (D) dark (mafic) minerals. The feldspathoids, or simply «foids«, are silicate minerals containing sodium, potassium or calcium, but having less silica than feldspars. The most common feldspathoid is nepheline ($NaAlSiO_4$). The minerals in groups Q, A, P and F are the light-coloured minerals, while the dark minerals include olivine, pyroxene, amphibole, mica and ore minerals. The dark minerals have a great deal of iron (Fe), magnesium (Mg), manganese (Mn), titanium (Ti) and other heavy metals.

The currently most widely used classification system was devised by the Swiss geologist, Albert Streckeisen, in 1973. It distinguishes between *plutonic rocks* and *volcanic rocks*, and *light* (felsic), *dark* (mafic) and *extremely dark* (ultramafic) rocks. The division of the rocks is based on their mineral composition, expressed as the volumetric percentage of the five mineral groups mentioned above. The chemical composition is also used for fine-grained volcanic rocks. Rocks that have more than 90 % of dark minerals (D) are separated into a major group of extremely dark rocks. These have a number of special names that will not be taken up here, but are discussed in Chapter 3. Rocks whose total content of dark minerals (D) amounts to less than 90 % are classified in a *double triangular diagram*. The corners of one triangle are Q (quartz), A (alkali feldspar) and P (plagioclase feldspar), while the other triangle has F (foids), A and P at its corners. Because the mineral groups A and P enter into both triangles, the triangles are placed back-to-back on their common A-P side to form a double triangle. The percentage-wise distribution of the three main groups of minerals is plotted in the triangles. A plot in the middle of the Q-A-P triangle means that the rock contains just as much (33.33 %) of the minerals from each of the groups, a plot centrally between corners A and Q means that the rock consists chiefly of quartz and alkali feldspar, and just as much of each, and so on. The classification diagram for plutonic rocks is shown here; a corresponding diagram exists for volcanic rocks.

Precambrian granite from Grimstad. The granite consists of red alkali feldspar, pale-pink plagioclase feldspar, grey and blue quartz, and black mica and iron oxide. The largest grains measure about 1 cm. Photo: I. Bryhni)



Precambrian gabbro (doleite) from the Western Gneiss Region. The gabbro consists of light-coloured plagioclase and black pyroxene. The largest grains measure about 1 cm. The gabbro contains valuable plant nutrients which support numerous flowering plants. Photo: I. Bryhni)



Permian basalt from Horten. The porphyritic basalt has large phenocrysts of light-coloured plagioclase, black pyroxene and reddish-brown oxidised olivine. The largest crystals are about 1 cm long. (Photo: B.T. Larsen)

from the time when chemists stated the silica content of the rocks as silicic acid (H_4SiO_4). Acid rocks generally contain fewer plant nutrients than basic rocks.

Granite and *granodiorite* are the commonest plutonic rocks in continental crust. Granite has a great deal of silica, aluminium, potassium and sodium and is considered an acid rock; its corresponding extrusive rock is *rhyolite*. Granites and rhyolites are poor in nutrients. Granodiorite has more plagioclase feldspar than granite, but is otherwise very like granite and is often referred to as granite. *Diorite* and *quartz diorite* are common plutonic rocks in volcanic mountain chains. *Andesite*, named after the Andes Mountains, is the lava rock that corresponds to diorite. *Monzonite* and *syenite* are common plutonic rocks in the Permian of the Oslo region; their corresponding lava rocks are *latite* and *trachyte*, respectively.

Gabbro is a dark, heavy, plutonic rock containing comparatively little silica, but a great deal of calcium, magnesium and iron, and is termed a basic rock. Gabbro is divided into several varieties partly depending on the type of pyroxene it contains. *Anorthosite* is related to gabbro, but is composed almost solely of calcium- and aluminium-rich plagioclase feldspar. It is an important future source of aluminium. *Dolerite (diabase)* and *basalt* have a similar composition to gabbro, but are hypabyssal and extrusive rocks, respectively. Gabbro, dolerite and basalt typically occur in oceanic crust. Basalt is the most widespread extrusive rock in the world. Gabbro and its corresponding hypabyssal and extrusive rocks are generally rich in nutrients, partly because they often contain the important plant nutrient, phosphorous, in the mineral apatite.

Peridotite is typical of the mantle and contains a great deal of iron and magnesium in the minerals olivine and pyroxene. Peridotites containing more than 90 % olivine are called dunite. *Serpentinite* is formed from olivine-rich peridotite under the influence of hydrous fluids, and consists of serpentine group minerals. Dunite and serpentinite lack many important plant nutrients and often occur as conspicuous, almost naked, reddish-brown knolls. The boundary between the crust and the mantle (the Moho) coincides with the boundary between peridotite in the mantle and gabbro in the lower part of the crust.

Igneous rocks vary in grain size and texture, depending on how they solidified. Coarsely crystalline, even-grained, massive plutonic rocks solidified during slow, gradual cooling. Such rocks are used as cobbles, facing stones, monuments and for many other building purposes. Pegmatite is an especially coarsely crystalline, dyke-like mass of minerals like those in granite or similar plutonic rocks. Pegmatite dykes may contain rare minerals, occasionally gemstones like emerald, tourmaline and topaz. Granite-pegmatites may also contain uranium- or thorium-bearing minerals and may give off the radioactive gas, radon.

Lava that wells rapidly up to the surface cools quickly and crystallises as a dense mass of small grains. Basalt is one such rock. It is resistant and durable, and suitable as crushed stone chippings and as aggregate in asphalt. *Porphyries* are hypabyssal or lava rocks having individual mineral grains that are significantly larger than the minerals in the fine-grained groundmass. These large crystals, phenocrysts, may be quartz, feldspar, olivine, pyroxene or amphibole. Phenocrysts in porphyries, like those in the well-known rhomb porphyries in the Oslo region, have probably crystallised slowly while the magma was still at a considerable depth. When lava cools unusually rapidly, it may solidify as *volcanic glass*, obsidian. Pumice is volcanic glass with so many air-filled vesicles that it may float on water.

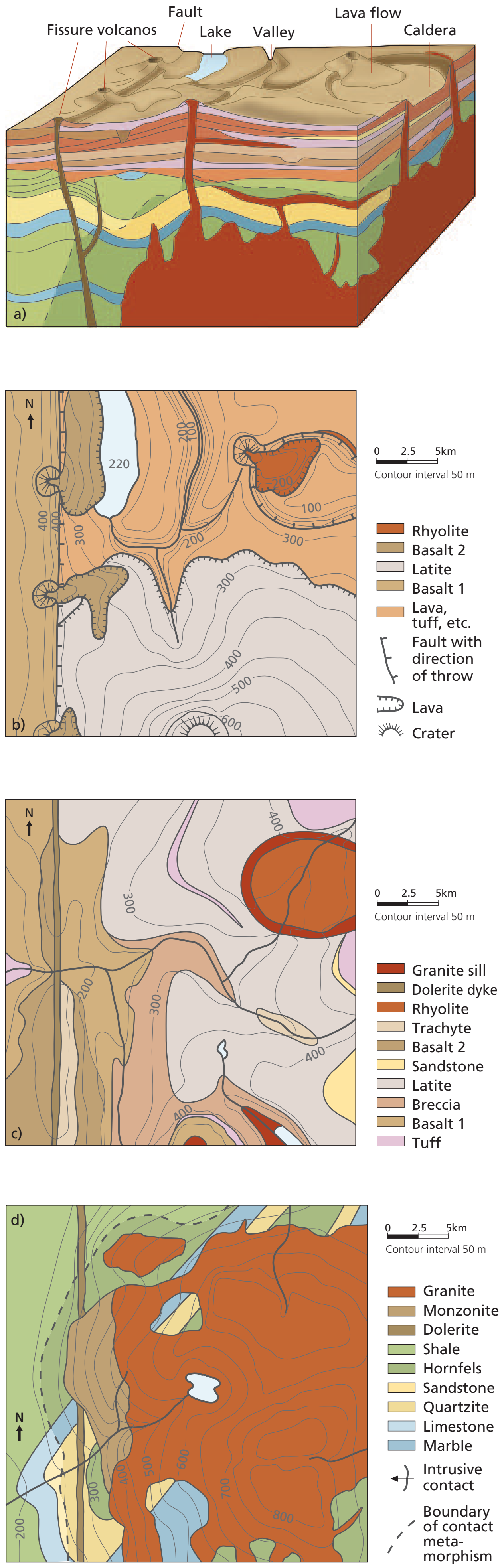
Magma may contain dissolved constituents like gold, copper, lead, zinc, molybdenum, cobalt, chrome, titanium, iron, tin and other metals. When it forces its way up through the crust, the country rocks are metamorphosed, partly due to the heat, partly through the influence of water, water vapour and gases which emanate from the molten rock. Metals precipitated from gases and water vapour form *pneumatolytic* metasomatic contact ore deposits while water that cools may give rise to *hydrothermal* ore deposits in joints and fissures in the country rocks. The lead and zinc deposits in the Oslo region and the silver ore at Kongsberg were formed in these ways, respectively, during the Permian. Gold is often linked with hydrothermal quartz veins. Water and gas that pour up through fractures along the mid-ocean ridges are particularly rich in metals. Many sulphide ore deposits that have been valuable for the Norwegian mining industry for almost four hundred years were formed in this manner in ancient ocean-floor crust.

The crust is deformed

Tectonics covers, as mentioned earlier, all kinds of movements in the crust. These movements are caused by stresses that build up over time. We can distinguish two main types of stress, *extensional stress*, extension, and *compressional stress*, compression. If we stretch a rubber band, it gets longer. If we let it go, it regains its original shape. This is called elastic deformation. If we continue to pull the rubber band, the strain (stress) will ultimately be greater than the elastic limit of the material, and the rubber band snaps. Some materials can absorb a permanent plastic deformation after their elastic limit has been exceeded and before they reach their fracture limit. The Earth's crust behaves in a similar manner. It tolerates a certain degree of elastic and plastic deformation before it gives way. When it does give way, a *fracture* arises and a *joint* is formed. If two crustal blocks on either side of the fracture are displaced relative to each other, the fracture surface is a *fault*. Faults in the Earth's crust may lead to crustal blocks rising as *horsts*, or sinking as *grabens*. Horst and graben are German words that mean ridge and ditch, respectively. Displacements may also take place laterally. Most faults are steeply inclined, but almost horizontal ones may also occur. Areas where the crust is undergoing great extension are often characterised by long ridges separated by correspondingly long depressions. During the Permian, the landscape of the Oslo region was made up of crustal blocks that had become displaced along faults, and the same was the case in the present North Sea area towards the end of the Jurassic.

Brittle deformation occurs when cold crust is exposed to extensional stress. The rock in such fracture zones is torn apart and *fault breccia* composed of angular fragments is formed. Fault zones are generally full of fissures and loose, and can be readily excavated by rivers and glaciers to form valleys and fjords. Fault and crush zones may cause problems when tunnels are constructed for roads and railways.

Cataclasite and *mylonite* are rocks formed by particularly severe crushing and reduction in grain size under brittle and plastic conditions, respectively. They are found in zones where severe *shearing* has taken place, that is, movement between two bodies in opposite directions along a surface. The energy generated in the shearing leads to deformation (compare with the heat generated when we rapidly rub the palms of our hands together). Cataclasites and mylonites may be hard rocks that resist erosion well. When extremely high stresses are triggered in the crust, as in the very strongest earthquakes, the deformation may generate such a high temperature that



PLUTONIC, HYPABYSSAL AND VOLCANIC IGNEOUS ROCKS

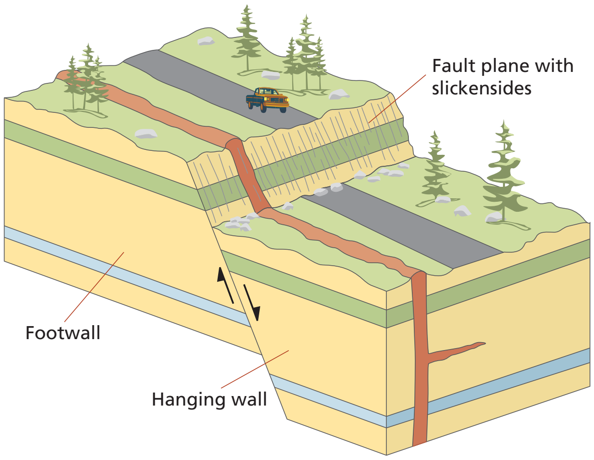
a) shows volcanic surface forms

b) geological map of the same landscape

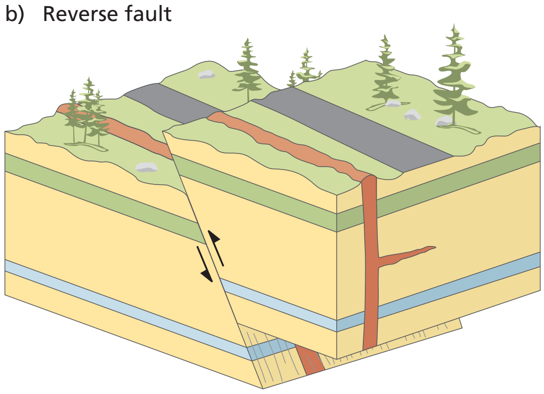
c) geological map after erosion has brought a deeper section in the lava succession up to the surface, and

d) geological map of a land surface that represents an erosion level that reaches right down to the plutonic rocks; the topography in the volcanic landscape shows the volcanic forms, while the terrain following deeper erosion shows the varying ease with which the different rocks erode.

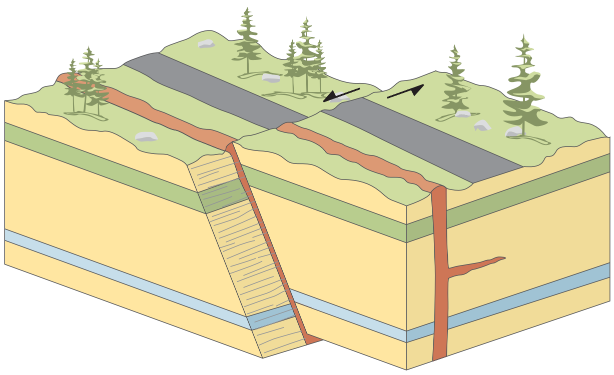
a) Normal fault



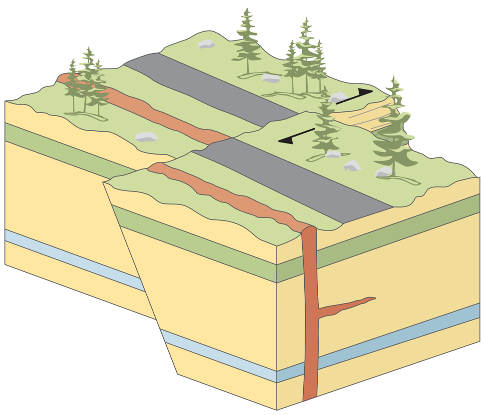
b) Reverse fault



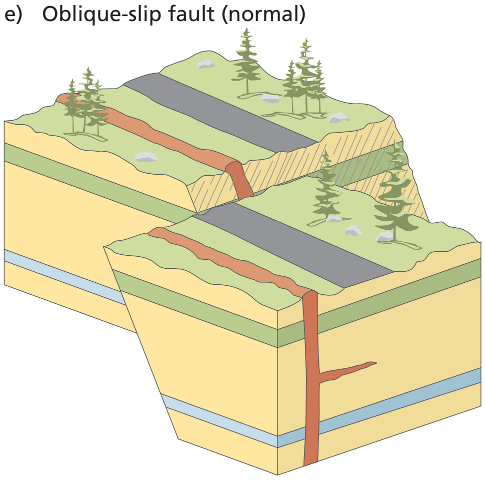
c) Strike-slip (wrench) fault (sinistral)



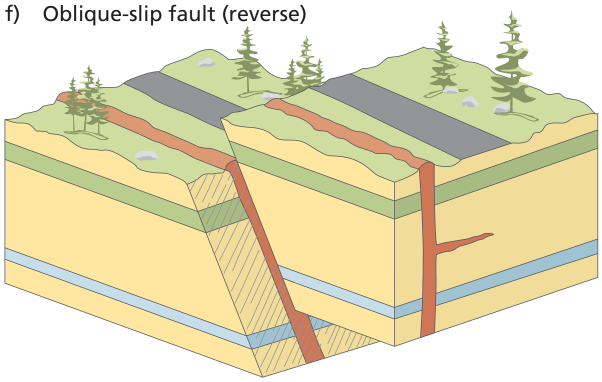
d) Strike-slip (wrench) fault (dextral)



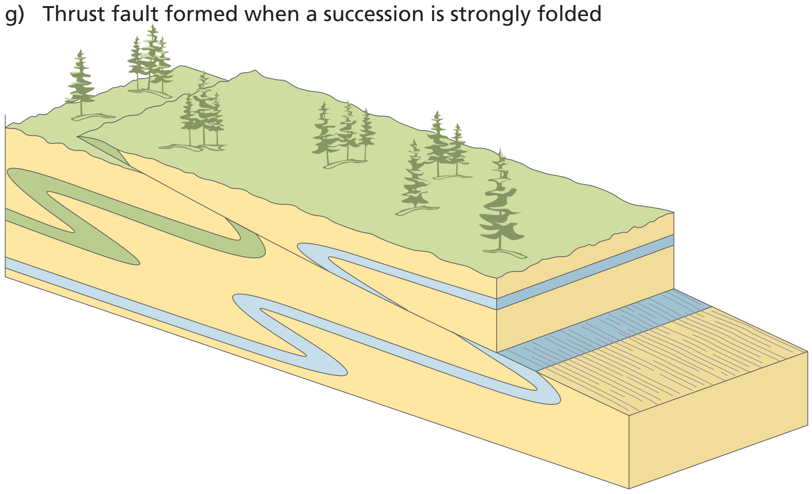
e) Oblique-slip fault (normal)



f) Oblique-slip fault (reverse)



g) Thrust fault formed when a succession is strongly folded



Faults are fractures in the Earth's crust along which displacement has occurred. The relative movement between the crustal blocks forms the basis for distinguishing different kinds of faults, as shown in a) to g).

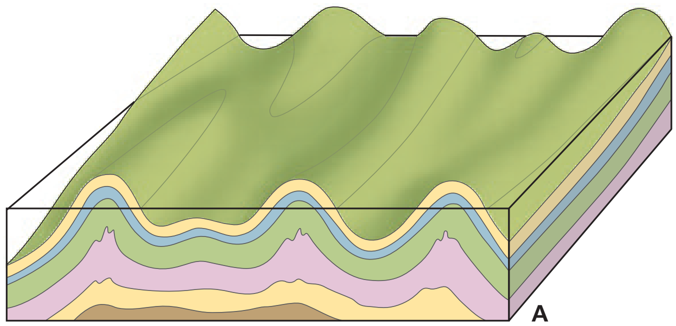
the rocks along the fracture zone melt. The glass-like, extremely fine-grained rock (pseudotachylite) that forms when cooling subsequently occurs therefore represents a kind of «fossil earthquake«.

If crustal stresses affect rocks that are many kilometres below the surface, where temperature and pressure are high and they are under the influence of chemically active water and gas, the rocks may be deformed by *ductile* or *plastic deformation*. Rock deformed in this manner, marble and gneiss for instance, may show structural evidence that it behaved almost like a lump of clay we kneed between our hands, plastic and easily shaped.

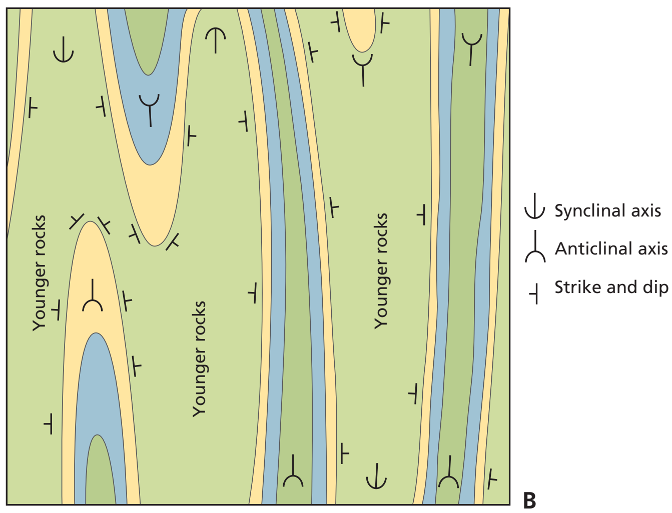
When the crust is exposed to compression, stratified rocks behave like a cloth that is pushed together on a table top. They fold. Upfolded strata form *anticlines* and downfolded strata form *synclines*. If the elastic limit of the rocks is exceeded, fractures or plastic deformation may occur, depending on the physical state of the crust during the deformation. When faulting takes place in compression zones, it is usual for the crustal block located above an oblique fault to be thrust upwards. This can be compared with what takes place when sea ice is pressed together. The ice breaks up into floes that are pressed up and ride over one another. There are many examples of the thrusting together of sheets of rock in the Caledonian mountain chain in Norway and the Tertiary fold and thrust belt in Svalbard.

The largest deformation structures in the Earth's crust are *mountain chains*. As we have seen above, mountain chains form in collision zones between lithospheric plates. Their central zone contains rocks that may have been forced many kilometres down into the crust, strongly metamorphosed and folded. In some mountain chains, magma has solidified as plutonic rocks. Outwards from the central zone, the rocks have been thrust and folded into *nappes* and *thrust sheets*, perhaps travelling hundreds of kilometres, as in large parts of the Caledonian mountain chain in Norway. The folds become smaller and fewer the further from the central zone of the chain one moves, and the rocks may ultimately be completely unaffected by this deformation. Such rocks are *autochthonous*, that is, they are located where they formed.

When a mountain chain forms, large volumes of light rocks containing water are pressed down into the crust. When this compression ceases, the chain is rapidly uplifted and exposed to severe erosion. The explanation for this is that, over time, all mass in the crust and the lithosphere will endeavour to achieve equilibrium as regards weight, *isostasy*. Bedrock comprised of lightweight rocks, as in a young mountain chain, may therefore reach great heights, whereas heavy rocks, like those in the oceanic crust, sink and form depressions.



A

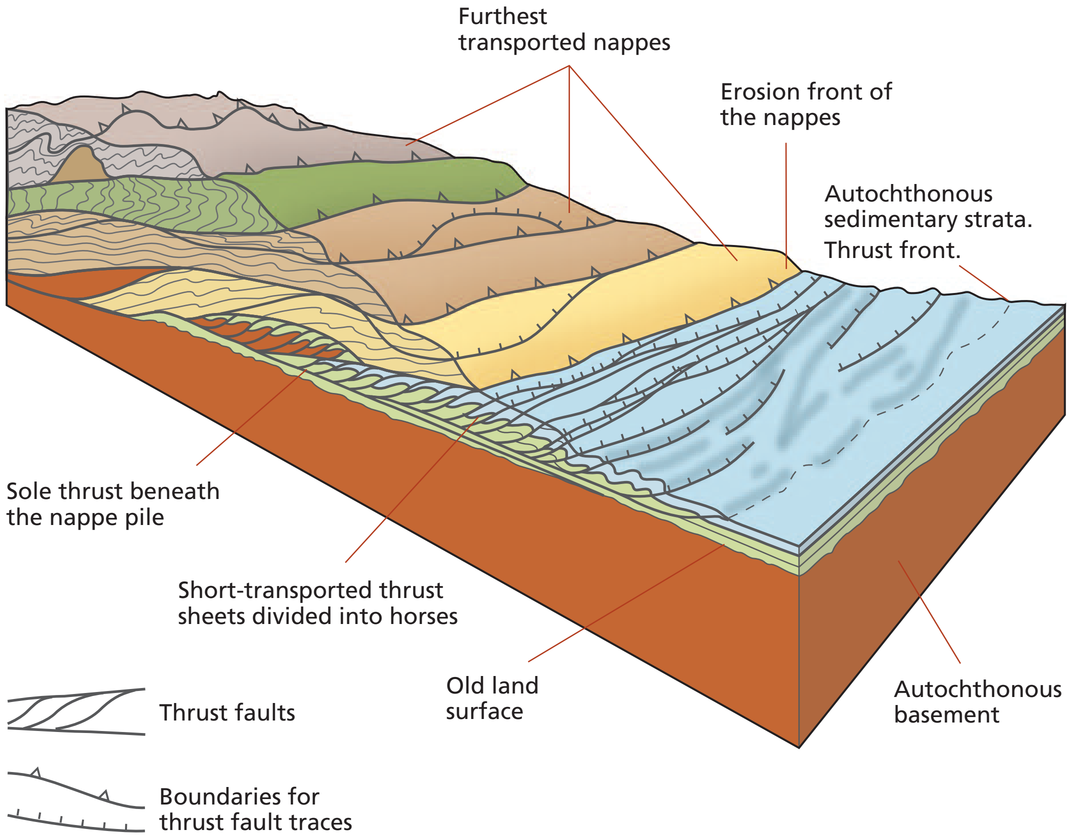


B

A. Anticlines are folds that bend the beds upwards; synclines bend them downwards.

B. A folded succession shows a characteristic pattern on the geological map. The orientation of the beds is indicated by symbols for strike and dip and the direction of the fold axes.

Nappes and thrust sheets in a mountain chain. Beyond the mountain chain, a sedimentary succession remains undisturbed on its original basement. Towards the mountain chain, the strata are folded and thrust together in thrust sheets and nappes. The further into the chain you come, the further the nappe rocks have been thrust.



An uplifted, old mountain chain, like the Caledonian mountain chain running through Norway, will be so worn down by erosion that what we see today is a deep section in the original chain. The block diagram above shows a typical section from the lowermost part of a mountain chain, where nappes and thrust sheets are piled on top of one another and above a plinth of sedimentary rocks deposited on a flat basement substrate. The flat-lying and folded strata located beyond the nappes in the right of the diagram can represent the Cambro-Silurian strata preserved in the Oslo region from Langesundsfjord in the south to Lake Mjøsa in the north. The closer to the central portion of the mountain chain, the more intense the folding, and the succession is eventually fragmented along a number of thrust faults into small thrust sheets and horses that have been displaced a few hundred metres to a few kilometres. The thrust faults meet in a major dislocation, a sole thrust, at the base of the folded and thrust succession.

The outermost and lowermost nappes forming the uplands in the northern part of the county of Hedmark, southeast Norway, westwards to Valdres and Hemsedal and eastwards to Elverum and Trysil, consist of hard sandstones. These sandstone nappes are coloured yellow in the figure. The steep south- to southeast-facing flanks of the hills form the erosion front of the mountain chain. Hard rocks form ridges and hills, while softer rocks, like shales, siltstones and limestones, form depressions and valleys. The nappes situated higher in the nappe pile have been transported a long way, perhaps several hundred kilometres. The rocks comprising such nappes may be sedimentary and volcanic in origin, and derive from the oceanic area that was compressed when two crustal plates collided. Portions of the original basement may also be thrust up as nappes, as in the Jotunheimen Mountains. The far-transported rocks are generally severely deformed and in part significantly metamorphosed. If we study the rocks in the various nappes, we will be able to determine their age, how they originated and in which geological environments. We will also be able to find out the physical conditions under which they were metamorphosed and deformed when the mountain chain was formed.

A similar nappe architecture as shown here with examples from southeast Norway is found throughout the Caledonian mountain chain northwards to Finnmark, and in most mountain chains around the world. A mountain chain is a dynamic meeting place between the internal and the external geological processes. When the external geological processes have chance to dominate over a long span of geological time, even the highest geological mountain chain will disappear. This is the topic of the next section.

Climbing Besseggen, a well-known ridge in the Jotunheimen Mountains in south-central Norway. Gjende is the lake on the left and Bessvatnet that on the right. Gjende was excavated by a glacier following a fault zone in easily eroded bedrock. The gabbro on Besseggen is traversed by bands of hard crush rock called mylonite, which have fortified the ridge, preventing it from being completely worn down by the glacial erosion that otherwise marks the landforms in the Jotunheimen Mountains.

The small picture shows the appearance of the mylonite at close quarters. The layer with thin, dark and light bands is a result of locally intense shearing and recrystallisation under plastic conditions to produce a very fine-grained, extremely deformed rock.

The fault zone along Gjende divides the bedrock in the Jotunheimen Mountains into two provinces, a southern one with mostly «fresh« magmatic plutonic rocks like gabbro and granite, and a northern one with older, metamorphosed plutonic rocks called pyroxene granulite or pyroxene gneiss. It continues in a straight line south-westwards past Tyin and can also be traced all the way to Aurlandsfjorden and Nærøyfjorden in the county of Sogn & Fjordane, forming a link between two magnificently scenic areas and also being an important element in the geology of Norway. (Both photos: J.P. Nystuen)

External geological processes break down the Earth's crust

Heat radiating from the Sun is the Earth's external motor and causes the evaporation of seawater, which is condensed to precipitation, leading to atmospheric and oceanic circulation, and weathering of the Earth's crust. Radiant heat from the Sun, along with gravity, results in erosion, transport and deposition of superficial deposits.

The radiant heat reaching the Earth from the Sun produces an air temperature at the surface that alternates around the freezing point of water. It varies in cycles of around twenty thousand, forty thousand and one hundred thousand years. These cycles may explain changes in climate on the Earth. Climate change will be considered in more detail in Chapters 15–17.

Water, whose chemical composition is H_2O, two atoms of hydrogen and one atom of oxygen, is the most important substance for life on our planet, besides oxygen (O_2) and carbon (C). Water is also an important factor in many geological processes. The Sun's heat drives the circulation of air masses and the evaporation of water. Water vapour condenses to rain and snow. Snow may be transformed into glaciers. Together with the Earth's gravity, *gravitational force*, it is air circulation and circulation of water in the atmosphere, on the Earth's surface and below the surface that drive processes like weathering, erosion and transport of unconsolidated materials with the help of air, running water and glaciers. The gravitational forces of the Moon and the Sun help to produce ocean currents. The *external geological processes* wear down and smooth out the Earth's crust.

Weathering – disintegration of the Earth's crust

Weathering is the breaking down and disintegration of bedrock and sediments by mechanical, chemical and biological processes. *Mechanical weathering* is the breaking down of the bedrock. Frost wedging takes place when water in rock crevices freezes to ice. The ice occupies more space than the water and, hence, splits the rock apart. Plant roots winding their way into crevices may have the same effect. Tension arises in rocks heated by the Sun in daytime and cooled at night. This may disintegrate the rock, particularly if moisture is present. Mechanical weathering breaks the bedrock down into particles of all sizes, boulders, cobbles, gravel, sand and silt. Silt is the grain size between sand and clay.

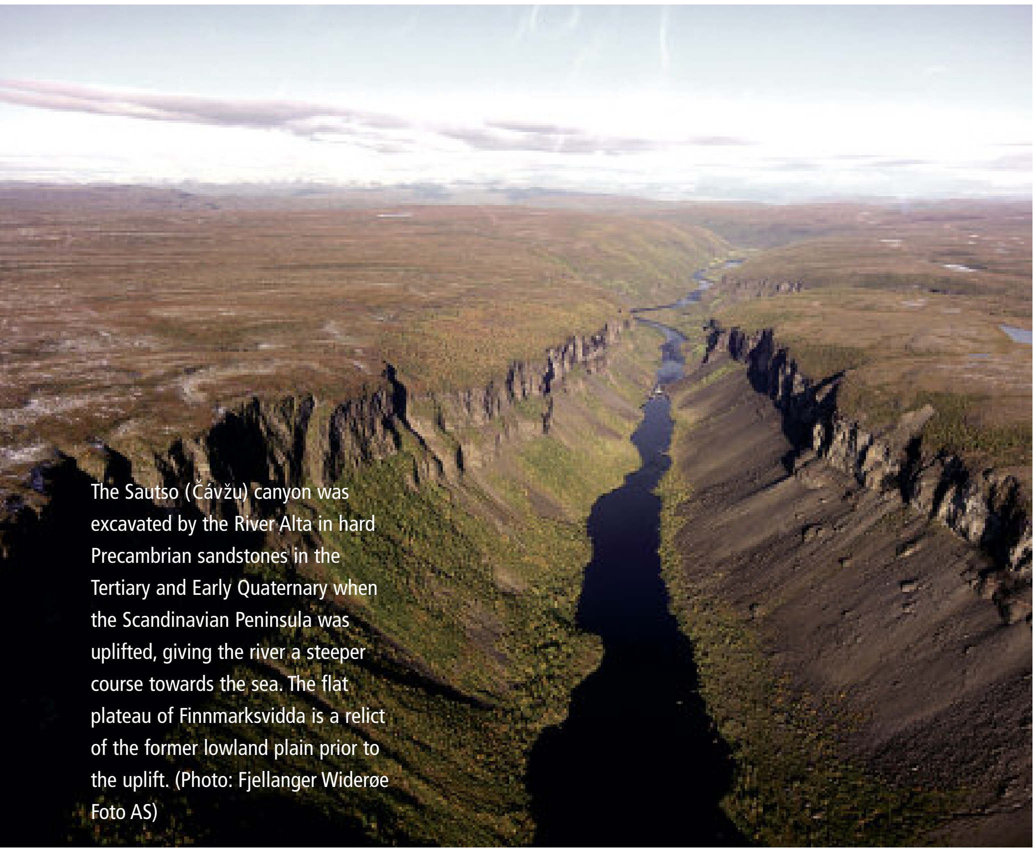
Bedrock is also broken down by *chemical weathering*, including biochemical processes. Most minerals are formed in a temperature interval of approximately 400–1000 °C in the crust and are not stable at the Earth's surface temperature and under the effects of air and water. Olivine, pyroxene, amphibole, biotite, calcic feldspar and other minerals formed at high temperatures weather rapidly by oxidation and the influence of acid water. Acid water contains so much of the positively charged ion, H_3O^+, that its pH is lower than 7. It forms when carbon dioxide (CO_2) in the air dissolves in water. It also forms from organic acids produced by the conversion of dead plant remains in the soil, and from sulphurous and nitric gases discharged into the atmosphere and water in the form of acid precipitation. Rivers carry the dissolved components of this weathering to the sea, and in the long course of geological time these make the sea salt.

Of the commonest minerals, quartz is most resistant to weathering. This explains why sand and sandstone are rich in quartz grains. Limestone and marble are particularly strongly affected by acid water and dissolve readily. Limestone caves, like those in Nordland, are formed by chemical solution of limestone. Chemical weathering causes corrosion of statues, gravestones and wall facings of limestone or marble. When we lime the soil, the lime is dissolved

and neutralises the acid soil water. Clay minerals are formed by chemical weathering of feldspars, micas, pyroxenes, amphiboles and other silicate minerals. They are extremely minute and can only be seen individually with the electron microscope. The use of clay to make pottery is one of the most important inventions in world history. Houses in many parts of the world have been, and still are, built with dried clay, and clay is an important industrial raw material, in part for the ceramics industry. The clay mineral, kaolinite, is used among other things in book paper, often together with calcite, as in the paper in this book.

Soil is the ultimate end product of chemical weathering. Various kinds of soil are produced due to differences in bedrock, precipitation, temperature, drainage and vegetation cover. Chemical weathering liberates nutrients in the bedrock and the soil so that plants on land and in water may take up nutrition. The *topsoil* is the uppermost part of a soil layer and contains organic material, earthworms, beetles and micro-organisms which break down the remains of dead plants and animals. The properties of the topsoil are fundamental for plant growth and agriculture. Chemical weathering is one of the most important geological processes for all life on Earth.

Acidic water flowing over marble has produced deep flutes because the carbonate minerals in the rock have dissolved. Fræna, Møre og Romsdal. (Photo: I. Bryhni)



The Sautso (Čávžu) canyon was excavated by the River Alta in hard Precambrian sandstones in the Tertiary and Early Quaternary when the Scandinavian Peninsula was uplifted, giving the river a steeper course towards the sea. The flat plateau of Finnmarksvidda is a relict of the former lowland plain prior to the uplift. (Photo: Fjellanger Widerøe Foto AS)

Hardangervidda, the plateau spread out around Hårteigen, approximately corresponds to the sub-Cambrian peneplain formed near sea level more than 542 million years ago, but rejuvenated by later erosion. (Photo: Fjellanger Widerøe Foto AS)

Weathering is also an important process in the cycling of nutrients between the Earth's crust, water and air.

Erosion and landforms

Erosion is the process that removes the weathered material using agents like gravity, glaciers, running water and moving air. Weathering and erosion create many magnificent landforms. Jagged cliffs and narrow ridges in the mountains are formed by frost action. Blocks and smaller rocks work loose, fall down and build up scree at the foot of a mountainside.

Chemical weathering is prominent in tropical regions and in temperate latitudes with plenty of precipitation and fairly stable, moderate temperatures. The landforms in such areas are generally characterised by rounded ridges and haycock-like hills. Such landforms were common in Norway prior to the Quaternary glaciations, and are still preserved on many parts of the upland plateaus in Norway.

Running water in streams and rivers excavates V-shaped gorges and ravines in steep terrain. In areas undergoing continuous uplift, rivers may excavate hundreds of metres straight down into the bedrock, as in the Grand Canyon, gouged out by the Colorado River in western North America. The Norwegian equivalent of the Grand Canyon is Sautso (Čávžu), the gorge eroded by the River Alta in west Finnmark when the Scandinavian Peninsula was uplifted during the Tertiary.

The landforms in present-day Norway were largely shaped by glaciers during the Quaternary ice ages. Glaciers excavate valleys and fjords, giving their floors and sides a rounded, U-shaped cross section. Unlike rivers, glaciers can erode below sea level owing to their weight, as was the case in the deep fjord troughs and the Norwegian Channel in the North Sea. Glaciers in the mountains chisel out sharp ridges, peaks, pinnacles, crests and cirques. They also leave behind small erosion forms like smoothly polished rocks with ice striae, friction cracks, chatter marks and other abrasive marks. Furrows and plough marks made by drifting icebergs that have scraped soft sediments can be observed on the continental shelf.

The waves in the sea cause coastal erosion where they pound the land with full force, particularly during storms and hurricanes. The Atlantic Ocean has battered the Norwegian coast for millions of years, creating steep cliffs at Stad and the North Cape. The *strandflat* along the west coast of Norway forms a low brim of land on the mainland and on headlands, islands and skerries shaped by coastal erosion over millions of years.

Through the long ages of geological time, weathering and erosion can wear down lofty mountain

The Lyngen Alps in northern Troms were moulded by glacial erosion. A U-shaped valley was carved out by a valley glacier that amalgamated with the main glacier flowing south to north along Storfjorden and Lyngenfjorden, from left to right in the photograph. The glacial river from the mountains has excavated a V-shaped valley within the older U-shaped valley since the last Ice Age. Glacial mud (rock flour) is pouring into Storfjorden, building up a delta by the hamlet of Storeng. (Photo: Fjellanger Widerøe Foto AS) chains to form plains drained by gently flowing rivers. Such a landform, created over several tens to hundreds of millions of years, is called a *peneplain*. We find remnants of ancient landforms, *palaeic surfaces*, in many parts of Norway, including Hardangervidda, Stadlandet, inner southeast Norway, Finnmarksvidda and Svalbard.

Sediment transport

Gravity causes glaciers to move and water to flow. Glaciers transport debris ranging in size from huge blocks of rock down to tiny clay particles in their sole, within the ice, on their surface and along their sides. This material is left behind as *moraine* when the ice melts. Ground moraine (basal til) is material that melts from the glacier sole and covers the bedrock like a carpet. This is the most common kind of soil in Norway and largely reflect the properties of the bedrock from which it is formed. Schist and phyllite give good soils rich in fine-grained material, while granite and gneiss produce blocky and stony soils that are poor in nutrients. Terminal (or end) and lateral moraines form long ridges. Morainic material dumped by melting ice often forms irregular, undulating topography. Large blocks of glacier ice that become buried in glacial drift give rise to kettle holes, which are small, round tarns.

Glaciers that reach the sea calve to form icebergs that drift out along fjords and in the sea. Boulders, rocks and gravel fall from melting icebergs and are left scattered in the clay carpeting the floor of Arctic seas and derived from the deposition of mud and rock flour carried to the sea by glaciers and meltwater. Moraine ridges and deltas form ice-marginal deposits left by glaciers that enter the sea. The Ra ridges in Østfold and Vestfold, southeast Norway, are examples of such deposits.

Rivers transport large quantities of material. Glacial rivers, or meltwater rivers, deposit boulders, gravel and sand along the margins and snout of a glacier, or in tunnels beneath the glacier. The former are called *kames* or *kame terraces*, and the latter *eskers*. Moraine deposits and sediments associated with glaciers and their melting are described in more detail in Chapters 15 and 16.

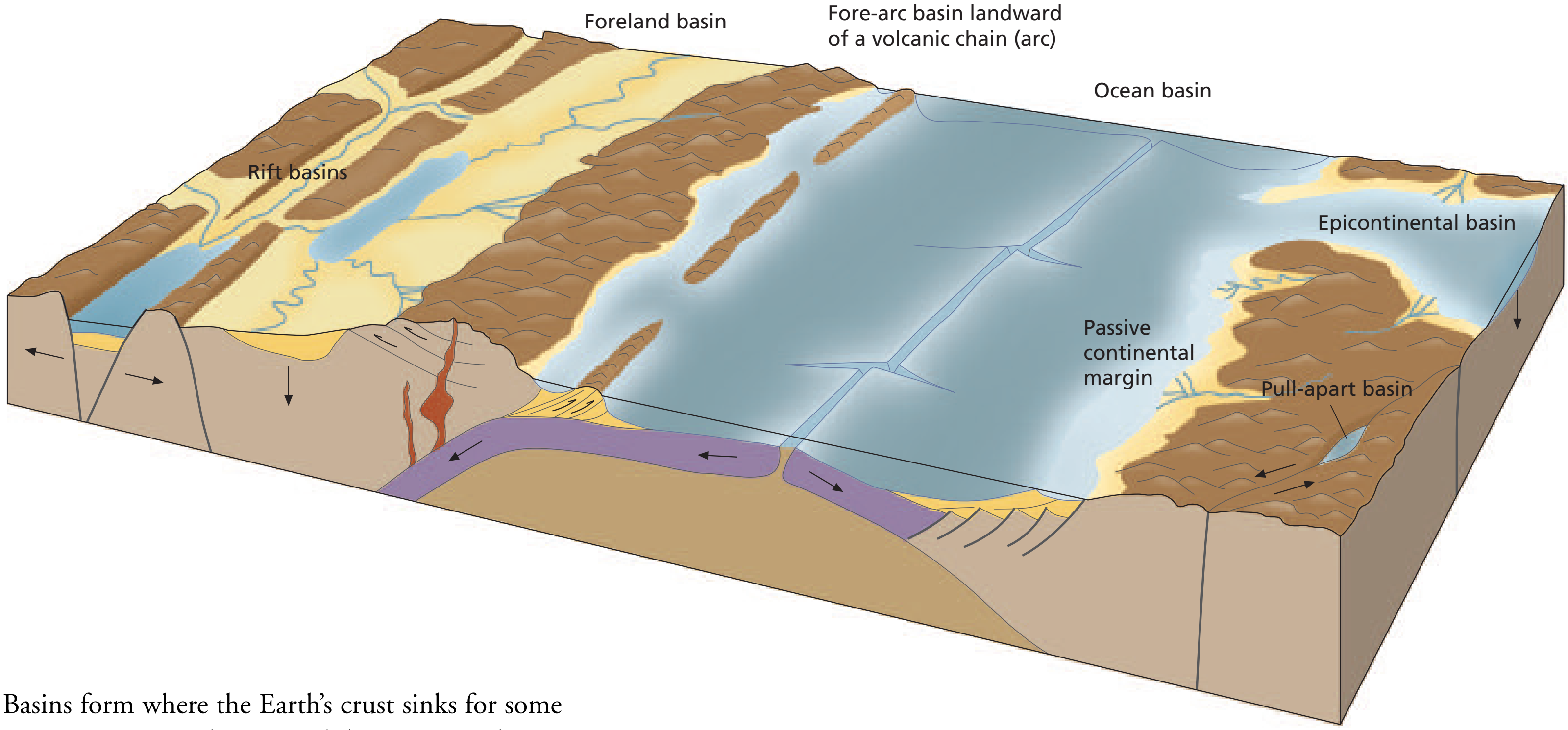
Streams and rivers transport sediment. When a fairly fast-flowing river reaches more gently sloping terrain, its speed will drop below a certain level that is critical for transport, and banks of gravel and sand will be deposited. They divide the river into a number of small channels that form a braided pattern. A montane river dumps its load when the water suddenly loses its ability to transport material when the river reaches a plain, or enters a large, gently sloping valley. The load is spread out in a fan composed of rocks, pebbles and sand. Many towns and villages in Norway are located on such *sandbars* or *sandbanks* and risk devastation if the river suddenly shifts its course during a severe flood. Accumulations of gravel and sand deposited by glacial rivers or ordinary rivers form important resources of industrial raw materials and are also valuable groundwater aquifers.

Rivers can transport sand, silt and clay up to hundreds of kilometres. The material may be deposited on vast river plains and in lakes before the rivers reach the sea. Rivers flowing slowly and lazily over gently sloping terrain often have winding, meandering courses. If channels are excavated to straighten out such courses, the current flow will increase and the river may begin to erode in unforeseen places. The sediment load that rivers carry down to the coast is deposited on coastal plains, in deltas and in shallow areas along the coast. Plant remains may accumulate in swamps on the coastal plains and be converted into peat and coal if they are buried. The Early Jurassic coal found on the Halten Bank and the Tertiary coal deposits on Spitsbergen have such an origin. Vast fluvial plains have dominated many parts of Norway in past geological eras.

Wind is an important mechanism for transporting fine sediment in windy places that receive little precipitation, such as along certain stretches of coast and in many deserts. The wind carries fine sand and silt, called loess. Norway has periodically had deserts, and fossil sand dunes of Permian and Triassic age are preserved in the Oslo region and the North Sea.

Sediments are deposited in sedimentary basins

Stones, gravel, sand, silt and clay are *deposited* in depressions, or *sedimentary basins*, where the *sediments* may be stored for shorter or longer periods of time. The surface of the sea is the *base level* for *fluvial* (river) erosion, that is, the lowest level to which rivers can excavate. The sea level relative to the continents has risen and fallen innumerable times in Earth history. When it is high, sediments may be deposited in the inundated area. If it falls again, and the area is left dry, rivers may excavate courses and valleys in these sediments. This is precisely what happened in the Norwegian lowlands shortly after the last Ice Age, as we shall see in Chapter 16.



The main types of sedimentary basins, as they are formed in a plate tectonic context.

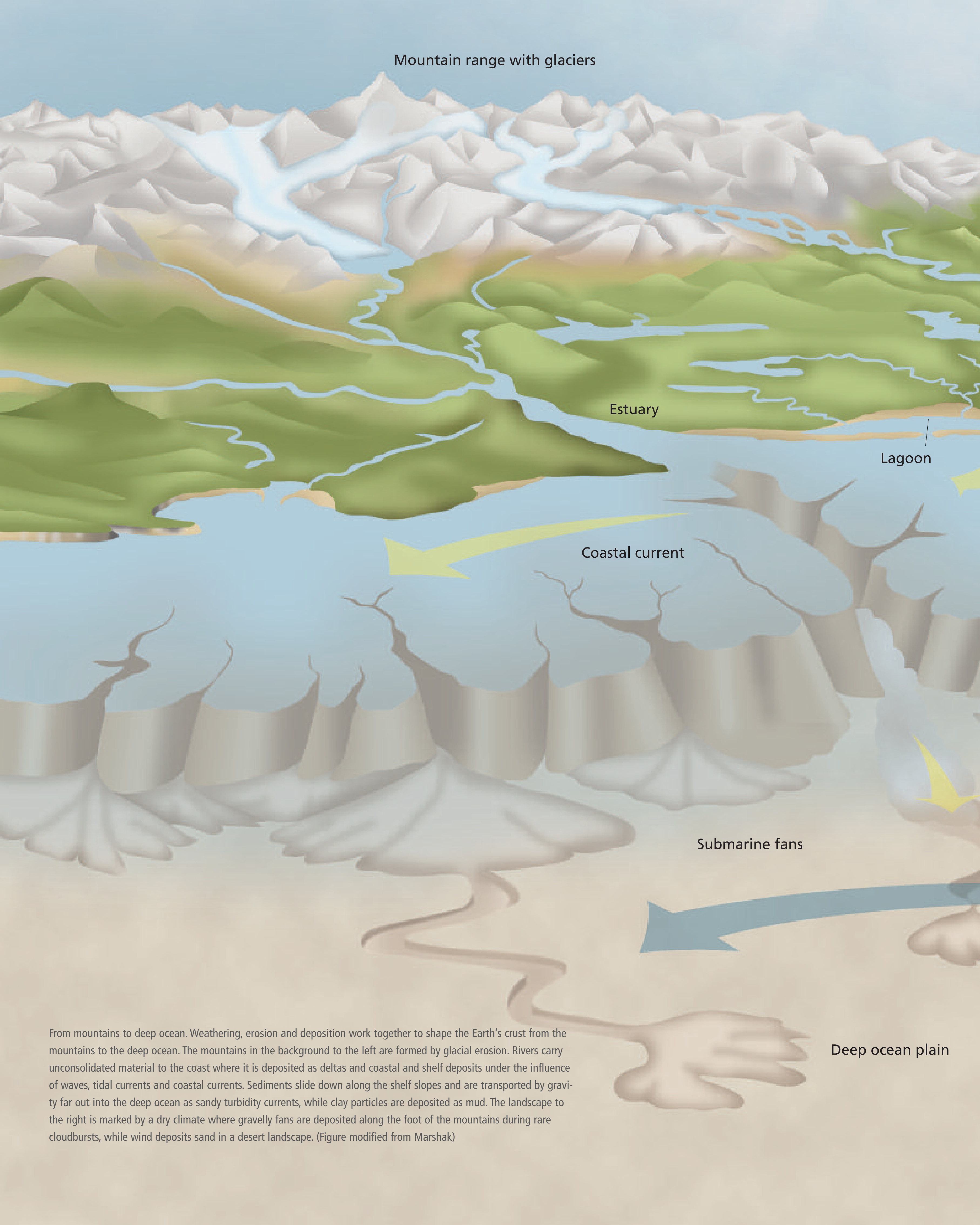
Basins form where the Earth's crust sinks for some reason, or erosion has created depressions. The basins may be filled by the sea or lakes, or be entirely located on land. A depression that is delimited by faults is a *graben*, which we have mentioned earlier. Large *rift basins*, such as the East African Rift Valley, often comprise a series of graben depressions. Many graben depressions have existed in Norway during its geological history.

Where the Earth's crust is depressed in front of a mountain chain that is being thrust across a continent, an elongate sedimentary basin arises along the foot of the chain. Such depressions are called *foreland basins*. The Po Plain in northern Italy and the Ganges Plain in India are foreland basins to the Alps and the Himalayas, respectively, both of which are young mountain chains. A corresponding foreland basin lay to the east of the Caledonian mountain belt of Scandinavia at the end of the Silurian and in the Early Devonian. The sediments in this basin have subsequently been removed by erosion, except in the Oslo region and the Baltic States.

Sediment is carried to the coast and deposited on coastal plains and shallow parts of the shelf. Whereas pebbles and sand are mostly deposited close to land, in deltas and on sandy beaches for instance, finer-grained fractions like silt and clay may be carried from the land by coastal and ocean currents. Currents in the sea arise as a result of storms, wind, the rotation of the Earth and contrasts in temperature and salinity, and consequently in the water density, in different parts of the sea. Tidal currents are important along coasts which experience a large difference between high and low tide.

Sediments deposited along continental margins build up shallow areas on the shelf. Pebbles, sand, silt and clay particles may end up far out in deep-sea areas because sediments slide out along the front of deltas and slopes on the continental shelves. Mudflows and suspension currents carry pebbles, sand and mud down the slopes to deposit the material along the foot of the slope or still farther out in the deep ocean. Such suspension currents are called *turbidity currents*, and graded sequences of pebbly conglomerate, sandstone, siltstone and shale formed in this way are called *turbidites* («turbid» means cloudy). The submarine Storegga Slide down the shelf slope off Møre and Trøndelag, central Norway, about 8100 years ago swept 2400–3200 km^3 of sediment out into deep water 810 km westwards across the floor of the Norwegian Sea, up to 410 km as mudflows and a further 400 km as turbidity currents. Submarine slides and sediment flows may represent hazards for installations like oil-production platforms, submarine telephone cables, and oil and gas pipelines.

The very finest clay particles are deposited as extremely fine mud (ooze), often together with particles formed in the open sea. *Pelagic ooze* is mainly composed of minute carbonate or siliceous (SiO_2) shells secreted by floating, unicellular algae. Volcanic ash also helps to form pelagic ooze.



From mountains to deep ocean. Weathering, erosion and deposition work together to shape the Earth's crust from the mountains to the deep ocean. The mountains in the background to the left are formed by glacial erosion. Rivers carry unconsolidated material to the coast where it is deposited as deltas and coastal and shelf deposits under the influence of waves, tidal currents and coastal currents. Sediments slide down along the shelf slopes and are transported by gravity far out into the deep ocean as sandy turbidity currents, while clay particles are deposited as mud. The landscape to the right is marked by a dry climate where gravelly fans are deposited along the foot of the mountains during rare cloudbursts, while wind deposits sand in a desert landscape. (Figure modified from Marshak)


Desert
Lake
Salt lakes
Gravel fans
Sand dunes
Coastal plain
Alluvial plain
Tidal flat
Tidal current
Calcareous reef
Continental shelf
Delta
Submarine canyon
Landslide scars
Turbidity current
Deep ocean current
Submarine mudflow
Deep ocean channel
Deep ocean fan

This sandstone originated as sand in a shallow Early Cretaceous sea on Spitsbergen. The geologist is filling in a log recording observations on the thickness, grain size and sedimentary structures. The compass is used to measure the orientation and directions in the sandstone beds and the geology hammer to collect samples. (Photo: E. Tallaksen)

Whereas sediment particles like quartz and clay are transported from land to the sedimentation area, *marl* and *limestone* are formed by organisms taking up calcium carbonate ($CaCO_3$) from the sea water to form a protective limy shell around their soft parts. During Earth history, innumerable kinds of invertebrate marine animals, algae and bacteria have helped to produce carbonate in the sea. In the cool waters off Norway today, molluscs, gastropods (snails), deep-water corals, barnacles and certain calcareous algae are the commonest carbonate-secreting organisms. In warmer regions, corals and algae construct reefs that can cover large areas in the form of carbonate banks, platforms, atolls and islands. Unicellular, floating, planktonic calcareous algae flourished during the Cretaceous. The chalk in the North Sea was formed as lime mud mainly derived from the minute shells of coccolith algae. Biological carbonate production in the sea is a very important regulating factor for the greenhouse gas, carbon dioxide (CO_2), in the atmosphere. While volcanism and fossil fuel combustion furnish the atmosphere with carbon dioxide, it is extracted from the atmosphere when carbonate forms in the sea and becomes limestone.

In warm, dry regions of the world, sea water trapped in marine basins that are cut off from the sea will evaporate and precipitate *salt* minerals. When the sea water in such basins has been continuously renewed, salt deposits, *evaporites*, many hundreds of metres thick, have been formed in Germany, in the North Sea, on the shelf off central Norway and in the Barents Sea during the Permian and to some extent the Early Triassic.

Groundwater

Groundwater is the portion of precipitation that does not evaporate, flow away on the surface, or become absorbed by living organisms, and which therefore soaks into the ground. Beneath the *water table*, all pore spaces in the soil, and pores and crevices in the bedrock, are filled with water. Groundwater is an important source of drinking water, and several large municipal waterworks in Norway utilise it. Wells dug in the ground or drilled in bedrock also tap it for private water supplies. Groundwater also flows out on the surface as springs and seeps. Glaciofluvial and fluvial deposits are particularly important groundwater aquifers in Norway. Groundwater comprises about 1 % of all the water on the planet and is an important part of the water cycle linking the sea, the atmosphere, rivers and lakes, glaciers, living organisms and the bedrock.

From sediment to sedimentary rock

Sediment packages up to several thousand metres thick may be deposited and preserved in sedimentary basins. Water fills the pores between the grains in a deposit. The *porosity* of a sediment or rock is the ratio of its total pore space to its total volume. The porosity in recently deposited sand is 40–45 %. *Permeability* is the ability of liquid or gas, *fluids*, to flow through a sediment or rock. Porosity and permeability generally decrease when sediment is buried beneath new sediment. This takes place first by physical *compaction*. When the temperature rises as the depth of burial increases, the pore volume is further reduced because calcite, quartz and clay minerals crystallise diagenetically in the pores. This cement binds the deposit together, pebbles become conglomerate, sand becomes sandstone, clay becomes claystone or shale, and lime mud becomes limestone. In most basins, sandstones that have been buried to a depth of 5000–6000 m, corresponding to a rise in temperature of about 170–200 °C, will be impermeable, without any pore spaces remaining.

All processes that lead to a deposit becoming a sedimentary rock are lumped under the term *diagenesis*. Cementation is controlled by the original mineral composition, grain size, temperature, pressure and fluids. Sand is cemented more rapidly in basins with high heat flow than in «cold» basins. In connection with oil and gas exploration, it is therefore most important to understand the diagenetic history of a basin.

CLASSIFICATION OF SEDIMENTS AND SEDIMENTARY ROCKS

Deposits, *sediments*, which may consist of boulders, cobbles, pebbles, sand, silt, clay and mud, or mixtures of these components, can become lithified *sedimentary rocks*. Limestone formed as a coral reef becomes lithified after it is formed. The same applies to deposits formed by mineral precipitation.

SEDIMENTS AND SEDIMENTARY ROCKS ARE GENERALLY DIVIDED INTO THE FOLLOWING MAIN GROUPS

1. Clastic sediments, comprised of particles formed by weathering and erosion of older rocks, and which have been physically moved and deposited (pebble and conglomerate, till and tillite, sand and sandstone, clay and claystone, and so on).

2. Carbonate sediments (carbonate mud, marl, calcareous reefs, limestone and dolostone).

3. Evaporites, carbonaceous sediments, siliceous, iron and phosphate deposits, and residual deposits. Evaporites are precipitated as minerals such as halite and gypsum from aqueous solutions that evaporate. Carbonaceous sediments are formed from plant and animal remains (peat, coal and gyttja). Siliceous, iron and phosphate deposits are precipitated by inorganic and/or organic processes in special aqueous environments in the sea or lakes. Residual deposits are formed *in situ* by weathering of underlying bedrock or sediment (weathered soil, palaeosol (fossilised weathered soil), laterite and so on).

4. Volcanic sediments and volcanic sedimentary rocks (tephra and tephra rocks, such as volcanic breccia, ash, tuff and so on).

The deposits in group 1 may be classified according to the size of the fragments and the content of sand, clay, silt and carbonate. Sandstones may also be classified according to mineral content. Quartz sandstone, also called quartzite, for example, is sandstone consisting of more than 95 % quartz. Arkose is sandstone with more than 25 % feldspar. The other sediments and sedimentary rocks from groups 2, 3 and 4 have still more diversified classifications and terminology.

ROCK NAME	DESIGNATION OF CLASTIC MATERIAL			GRAIN SIZE Millimetre	GRAIN SIZE Phi (Φ)
CONGLOMERATE, SEDIMENTARY BRECCIA	BOULDER			256	-8
	COBBLE			64	-6
	GRAVEL	COARSE GRAVEL		16	-4
		MEDIUM GRAVEL		4	-2
		FINE GRAVEL		2.00	-1.0
SANDSTONE	SAND	COARSE SAND	Coarse-grained coarse sand	1.00	0.0
			Fine-grained coarse sand	0.50	1.0
		MEDIUM SAND	Medium sand	0.25	2.0
		FINE SAND	Coarse-grained fine sand	0.125	3.0
			Fine-grained fine sand	0.0625	4.0
MUDSTONE	SILT	COARSE SILT	Coarse silt	0.031	5.0
		MEDIUM SILT	Medium silt	0.016	6.0
		FINE SILT	Coarse-grained fine silt	0.0078	7.0
			Fine-grained fine silt	0.0039	8.0
	CLAY				

Classification of sediments and sedimentary rocks according to grain size. (Figure from S. Gjelle and E. Sigmond)

Oil and gas

Organic material from terrestrial plants, as well as from algae and zooplankton living in water, may be preserved in the mud on the floor of marine basins and large lacustrine basins to form the basis for oil and gas. Small planktonic algae are the most important source of oil and gas. The algae sink to the basin floor when they die. If there is little circulation of oxygen in the basin, the decaying process may use up the oxygen in the bottom water. The organic matter is preserved and buried together with deposited mud. Shales rich in organic material, like the black alum shale in the Cambrian strata of the Oslo region and Jurassic shales on the continental shelf, are formed in this way. Such shales are potential *source rocks* for oil and gas.

With rising temperature, the organic material in shale is converted into a wax-like substance called *kerogen*. In the temperature interval of 80–150 °C, kerogen converts to oil, together with a little gas. This is the «oil window« in the maturing process. Oil and gas (*petroleum*) consist of a number of chemical compounds of the atoms, carbon (C) and hydrogen (H). These molecules are called *hydrocarbons*. Oil consists of large, complex hydrocarbon molecules, whereas gas has a simpler composition. The simplest gas is methane, natural gas (CH_4). Methane forms by biological processes in bogs, swamps, waste dumps and at shallow depths in sedimentary basins. It is also formed when coal is heated, and is the dreaded mine gas. Methane is the only hydrocarbon that can exist at temperatures of around 220–230 °C, byt breaks down at higher temperatures, leaving only pure carbon (C) from the original oil.

Oil and gas are lighter than the water in the pores and gradually flow out of the source rock up through strata and fissures that have high permeability. If they are trapped in a pocket in porous rock, sandstone or limestone, an *oil trap* or a *gas trap* results. Such traps are generally domes, anticlines, or dipping strata overlain by impermeable ("tight") mudstone, a *cap rock*. The oil- or gas-bearing rock is a *reservoir rock*. The oil and gas found on the Norwegian continental shelf have been discovered in such structures or similar locations. Porosity and permeability are fundamental factors in the recovery of oil from a reservoir. Chapters 12–14 take up the topic of oil and gas on the Norwegian continental shelf.

Rocks are metamorphosed

Igneous and sedimentary rocks exposed to heat, pressure, stress, shear movements and fluids in the Earth's crust may be transformed into *metamorphic rocks*. *Metamorphism* is the collective term for all the processes that transform rocks. Most metamorphic processes take place in connection with orogenesis (the deformation of the Earth's crust to form a mountain chain) and rises in temperature around hot, melted rock in the crust. The elements in the original minerals take part in chemical reactions and form new minerals. The original minerals may also be recrystallised as, for example, when small calcite grains in limestone form large, new calcite crystals in marble. Metamorphism generally takes place under the influence of water, water vapour and other gases. Metamorphism is an important process in the cycling of material between the mantle, the crust, the surface and back again (the *rock cycle*).

Rocks like *phyllite, mica schist, greenstone, marble, quartzite* and *gneiss*, formed by *regional metamorphism*, are among the commonest rocks in mainland Norway. Phyllite is slightly metamorphosed siltstone or shale, whereas mica schist was metamorphosed under still deeper burial and higher temperature. Mica schist often has garnet and staurolite crystals, for instance in the mica schists once used as millstones. Greenstone and greenschist are metamorphosed basaltic rocks and their colour derives from the green minerals, chlorite and epidote. Marble is metamorphosed limestone, and quartzite is a very hard rock metamorphosed from quartz-rich sandstone.

Gneiss is the most common rock type in mainland Norway. It forms many kilometres down in the crust, and numerous varieties with various forms of banding occur. It is formed both from originally igneous and sedimentary rocks, and its composition usually resembles that of granite. Augen gneiss is characterised by having large crystals, «eyes«, of feldspar. Gneiss is often found along with *amphibolite*, a dark rock that may be metamorphosed from basalt or dolerite. Soapstone contains talc and is unusually soft; it is formed by metamorphism from dunite or serpentinite, and was formerly used to make pots and bowls. *Eclogite* is an attractive rock with red garnet and green pyroxene, and is occasionally found along with gneiss. Most eclogites are probably recrystallised from basalt or dolerite at a depth of 50–60 km in the central zone of a fold belt (mountain chain). Eclogites seem to have been exposed at the surface only a few million years after

they were at their greatest depth in the Earth's crust. This is because fold belts are uplifted rapidly after compression ceases and this intensifies the erosion. Rapid uplift may also lead to parts of the mountain chain collapsing, causing large slices of rock to peel off, slide sideways and expose deeper levels containing eclogites and gneiss.

All these metamorphosed rocks are typical for ancient, worn-down fold belts. They occur in the Precambrian basement and the Caledonian mountain chain in Norway.

Hornfels is a hard rock formed by contact metamorphism in the zone surrounding a rising magma that solidifies and releases heat, water vapour and gas into the country rocks. Shales and volcanic rocks in the marginal zone around the Permian plutonic rocks in the Oslo region have been transformed into hornfels. Marble may also be formed during contact metamorphism when heat recrystallises minute calcite grains in limestone, causing them to grow into large crystals.

Rocks found in zones where thrusting and sliding have taken place generally have a marked *schistosity*, enabling the rock to split along parallel fracture planes. Such rocks have long been used as roofing slates, paving stones and for dry-stone walls.

Many metamorphic rocks contain valuable minerals and ores, including the Norwegian sulphide deposits mentioned previously and the iron ore deposits in the Precambrian basement.

Pale rose-coloured gneiss and black amphibolite, both transected by granitic veins, were formed deep in the crust in a fold belt about 1000 million years ago. The Precambrian basement near Drøbak, east of Oslofjord. (Photo: J.P. Nystuen)

External geological forces from space

Since they were formed some 4.6 billion years ago, the Earth and the other planets have been bombarded by large and small celestial bodies, asteroids. The Moon and Mars are clearly pock-marked by *impact craters*. Most of the bodies that bombard the Earth are small meteorites that burn up in the atmosphere as «shooting stars«, but some of these iron and stony meteorites reach the Earth's surface and can be recovered.

Weathering, erosion and burial beneath layers of sediment have removed all traces of most of the impact craters on the Earth's surface, or made them difficult to identify. A lump of stone measuring several hundred metres in diameter striking the Earth at high speed imparts a great deal of energy to the surface. This energy is released in a fraction of a second and brings catastrophic destruction. The bedrock is smashed into fragments as tiny as fine dust, which is sent whirling into the atmosphere. There may be so much dust that sunlight and the temperature at the surface are so dramatically reduced as to be life-threatening. An asteroid that falls in the sea generates enormous flood waves. Asteroids carry the heavy metal, *iridium*, which is found in a few thin layers of silt thought to have been deposited in the sea immediately after an impact. Some people speculate, too, that life may have been brought to the Earth from outside via asteroids from other stellar systems.

The extinction of the dinosaurs around the Cretaceous–Tertiary boundary some 66 million years ago may have been a consequence of a 10-km-wide bolide which fell at Yucatán in Mexico, forming the gigantic Chicxulub Crater. Two major impacts have been recognised in Norway. One, dating from the end of the Precambrian, is the Gardnos Crater in Hallingdal. The other is the Mjølnir Crater in the Barents Sea, approximately at the Jurassic–Cretaceous boundary about 145 million years ago.

PHOTO TO THE LEFT: An artist's impression of a night-time impact of a huge asteroid in a built-up area. We see the lights of a city, fires starting and columns of smoke. Ring-shaped shockwaves spread out from the point of impact, and enormous volumes of impact melt, dust and pieces of rock torn from the bedrock are slung high into the sky along with debris from the city and the shattered asteroid. The sunlight will soon be obliterated, and the disaster will be succeeded by a prolonged "nuclear winter" with icy conditions, a polluted atmosphere and wholesale death.

The situation is not inconceivable. Impacts of cosmic material are widespread in space, and we can see countless numbers of craters on the Moon and the terrestrial planets. The largest and most frequent impacts admittedly took place in the earliest history of the solar system, some 3.8 to 4.6 billion years ago, but they have occurred many times since and may well happen in the future.

It has been calculated that our planet may have had as many as three million impact craters with a diameter ranging from 1 km to more than 1000 km. That only about 160 of them have so far been definitely proved is because traces left on the surface of the Earth – in contrast to the situation on the Moon and the terrestrial planets – are continuously being erased by the indefatigable internal and external geological processes. (Graphic: D.A. Hardy's AstroArt)

How do we find out how Norway originated?

The geological exploration of Norway has been taking place for more than two hundred years. The natural sciences and scientific research techniques have progressed by leaps and bounds in this period. Our knowledge of the country's geological history is nevertheless founded on just a few absolutely fundamental geological methods.

Our knowledge of Norway's nearly three billion year-long history is based on our understanding of geological processes and the sequence of geological events that have shaped the country. Advances in physics, chemistry and biology over the past century have had great significance for our insight into geological processes as a complex interplay of many factors. In geological research, it is important to learn the *timing* of the various geological events, and age determination techniques are vitally important.

Geological mapping

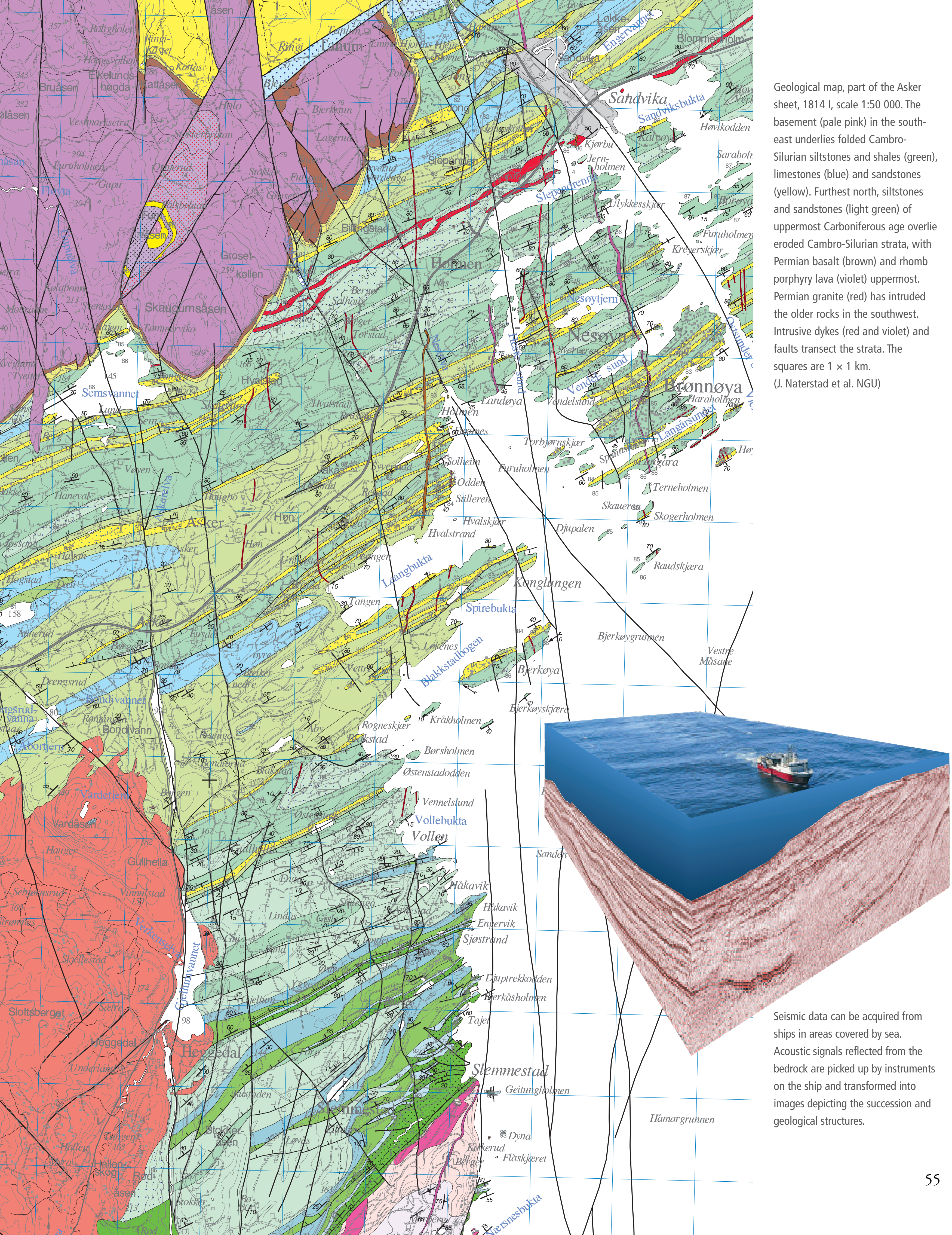
Mapping is a particularly important way of documenting the results of scientific investigations. The maps may depict the rocks forming the crust, superficial deposits, groundwater, ores, oil deposits, magnetism, distribution of heat, or other properties. The first modern geological maps were made in Great Britain and France at the beginning of the 19th century. In Norway, geological mapping became an important task for society when the *Geological Survey of Norway* was set up in 1858. Whereas the most important tools of the geologist when mapping on land used to be a topographical map, a geological hammer and a compass, modern mapping of bedrock and superficial deposits often requires far greater resources. Recording heat flow, radiation, variations in gravity and a number of other properties demands modern electronic measuring equipment, often based on planes and satellites.

Mapping the bedrock on the continental shelf is no less resource demanding. Here, *seismic mapping* is extremely important. Seismic mapping takes place from ships that transmit acoustic signals into the succession beneath the sea floor and record reflected signals. Modern seismic data can give an approximately three-dimensional image of how the bedrock is built up.

Geological maps and successions

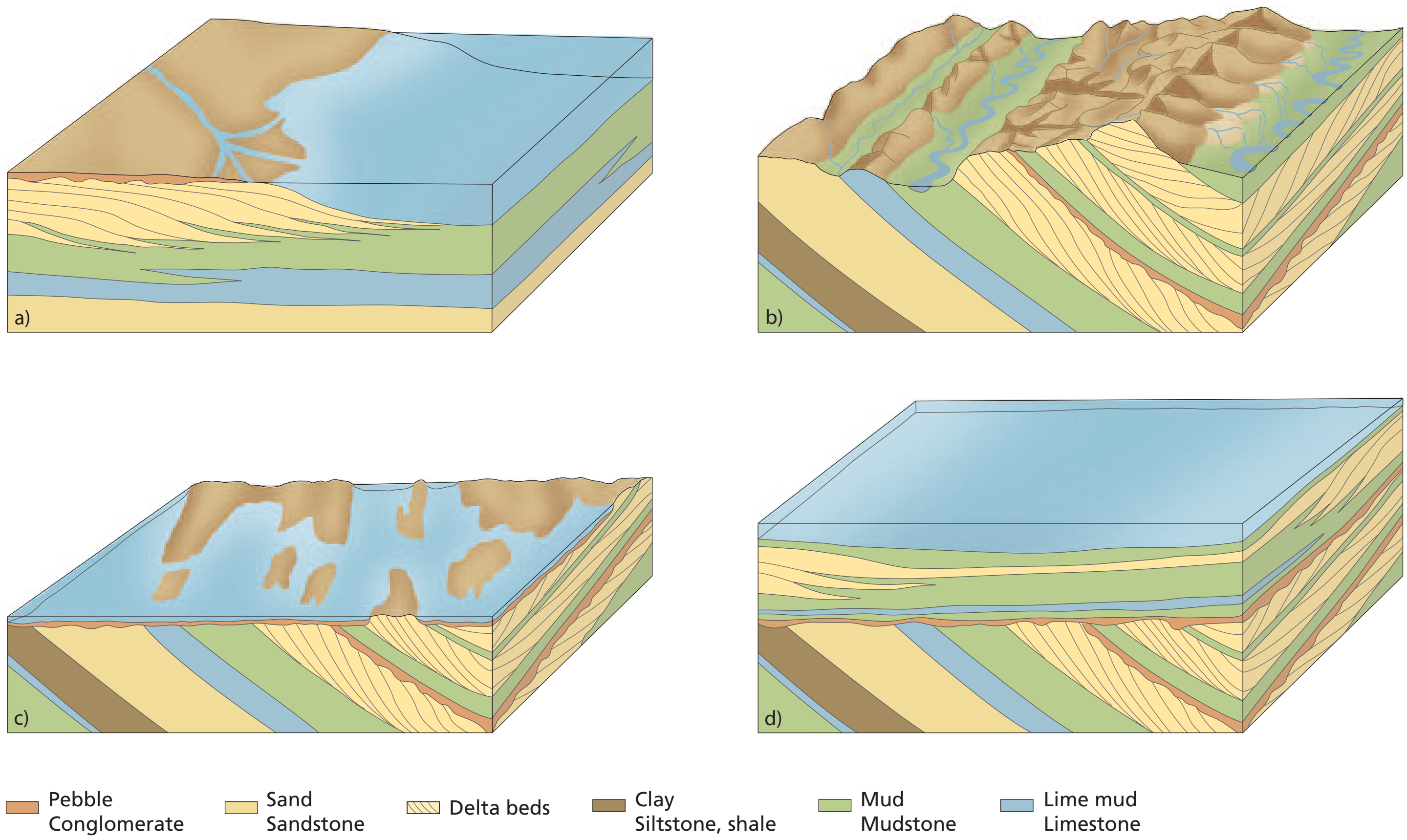
A high-quality geological map not only shows the distribution of rocks and superficial deposits, it also provides information on the age and order of formation of the rocks, superficial deposits, folds, faults, moraine ridges and many other structures and landforms. We learn the order of the geological events by determining relative and absolute ages.

Relative age means that we have determined the order in which rocks and superficial deposits were formed and the order of various geological events like folding, intrusion of magma, faulting and erosion. A simple example will illustrate this. In a certain area, gneiss with the composition of quartz diorite dominates the bedrock. It has amphibolite inclusions and is intruded by red granite dykes and veins. A fault transects both the gneiss and the granite. Using these observations, we can reconstruct a simple geological history. The oldest rock in the area was gabbro. This was invaded by quartz dioritic magma leaving inclusions of gabbro. The quartz diorite and the gabbro were metamorphosed to gneiss and amphibolite, respectively, deep in a fold belt. The rise in temperature during the orogenesis caused parts of the gneiss to melt. This melt intruded other parts of the gneiss and solidified as granite veins and dykes. The fault arose when new earth movements affected the area. This example teaches



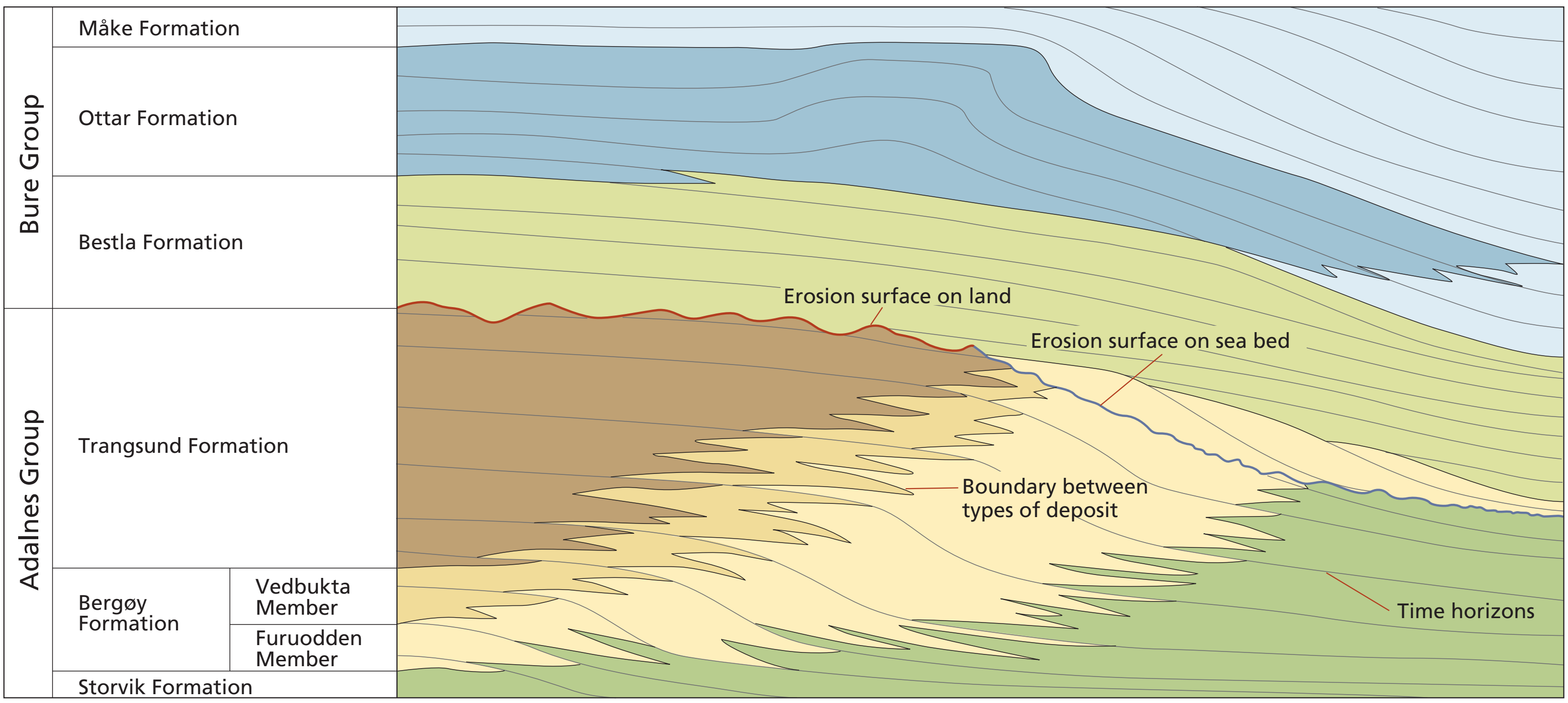
Geological map, part of the Asker sheet, 1814 I, scale 1:50 000. The basement (pale pink) in the south-east underlies folded Cambro-Silurian siltstones and shales (green), limestones (blue) and sandstones (yellow). Furthest north, siltstones and sandstones (light green) of uppermost Carboniferous age overlie eroded Cambro-Silurian strata, with Permian basalt (brown) and rhomb porphyry lava (violet) uppermost. Permian granite (red) has intruded the older rocks in the southwest. Intrusive dykes (red and violet) and faults transect the strata. The squares are 1 × 1 km. (J. Naterstad et al. NGU)

Seismic data can be acquired from ships in areas covered by sea. Acoustic signals reflected from the bedrock are picked up by instruments on the ship and transformed into images depicting the succession and geological structures.



RELATIVE AGE IN A SUCCESSION

a) A succession is deposited, in part as delta sand and silty clay in the sea, b) the succession is folded and eroded; valleys and ridges reflect the varying hardness of the beds, c) the mountains are worn down to a peneplain over which the sea has flooded, and d) a new succession is deposited.

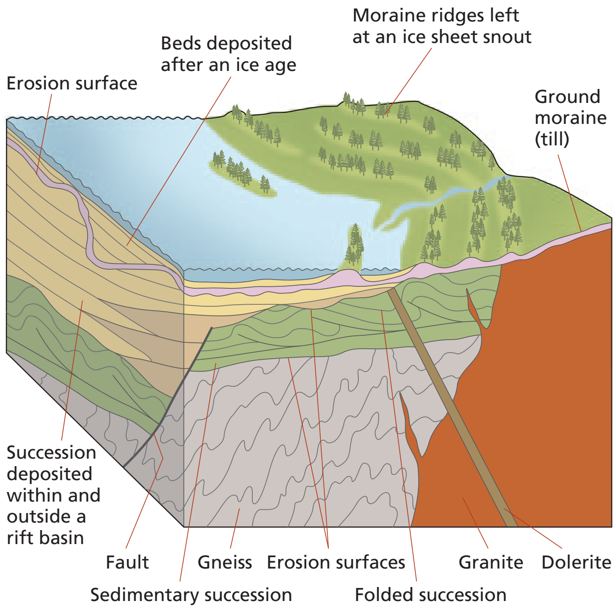


STRATIGRAPHICAL DIVISION

Lithostratigraphical successions like groups, formations and members are given proper names. Time horizons (synchronous surfaces) are lines of the same age that cut through the lithostratigraphical units. Chronostratigraphical units are beds deposited between two time horizons; they may contain several lithostratigraphical units. It is important to map time horizons and erosion surfaces in a succession, as on the continental shelf.

an important principle: *a rock or structure which cuts another rock or structure is younger than the object that is cut.*

Relative age in a succession is decided by the *principle of superposition*, which states that of any two strata the one that was originally the lower is the older; earth movements may, however, have caused older rocks to overlie younger ones. *Stratigraphy* is the study of the order, age and evolutionary history of successions. *Stratum* is Latin for layer. There are many ways of dividing a succession. Geological maps have a key that gives information about the succession mapped, rock types, order and ages. The division of the rock types may follow different principles.



RELATIVE AGE IN PART OF THE EARTH'S CRUST Order of age is shown by boundary relations between rocks, deposits, structures and landforms. Younger layers are deposited above older ones, folds are formed after the beds are deposited, younger intrusive rocks cut through older rocks, erosion surfaces cut down into underlying beds, and so on. Find the order of the geological development!

In *lithostratigraphy*, the succession is divided on the basis of rock type (*lithology*). A *formation* may, for example, consist of sandstone beds that overlie siltstones and shales and underlie a limestone. Formations may be divided into *members*, and more than one formation in a succession can be combined in a *group*. Groups, formations and members outcropping on land are generally given names from the place where the rock unit was first described. The successions on the continental shelf are named after coastal areas, marine areas, fish, marine mammals, seabirds, fishing gear and other objects or phenomena associated with the sea, history or mythology.

Successions that contain *fossils* are divided according to the relative age of the fossils. This kind of division is called *biostratigraphy*. The successions were divided and named on the global scale in the 18th and 19th centuries on the basis of their fossil content. Some designations were based on place names (Cambrian, Devonian, Permian), others on ancient peoples (Ordovician and Silurian), or distinctive physical characteristics of the succession (Carboniferous, Triassic). Today, all detailed successions throughout the world are named after *type areas* where the composition of the strata, fossils and absolute ages have been thoroughly investigated and published.

In *chronostratigraphy*, the successions are divided according to time (Greek «khronos») and age. A chronostratigraphical unit embraces all rocks, irrespective of rock type, deposited within a specific period. An example is the *Cretaceous* succession, named after Crete. The Cretaceous succession was deposited in the period from 145.5 ± 4 to 65.5 ± 0.3 million years ago. Cretaceous strata are characterised by typical fossils for this period. The very uppermost Cretaceous strata, the Maastrichtian, are from the period 70.6 ± 0.6 to 65.5 ± 0.3 million years ago. They are named after the town of Maastricht in the Netherlands.

On many geological maps, the age of a rock is stated both as a named period and as a certain span of years. A *geochronological unit* is merely a *division of time*. Geochronological units have the same name as the chronostratigraphical successions on whose basis they are defined. Cretaceous and Maastrichtian, referred to above as successions, are also divisions of time (*periods*).

Absolute ages of minerals, deposits, fossils and former land surfaces are their age in number of years from the present. Several analysis techniques are used to determine absolute ages. *Radiological age determination* is the commonest method. Radioactive elements in minerals decay over time and undergo transformation into new elements or isotopes. It is possible to calculate when a mineral was formed by analysing the quantity of the elements and isotopes that belong together in a disintegration process. The breakdown of uranium is important for old rocks, and the C14 method is used for young strata containing organic material; ^{14}C is a radioactive isotope of the carbon atom. These methods are dealt with in more detail in Chapters 3 and 15. Absolute age determinations are important for understanding the succession and the relationship between geological processes.

BALTAZAR MATHIAS KEILHAU (1797–1858) – FOUNDER OF GEOLOGY IN NORWAY *By Inge Bryhni*

As lecturer and, later, Professor of Geosciences in the University of Oslo, Keilhau had taken upon himself an «Obligation to undertake scientific journeys in the less studied parts of our fatherland«. The aim was to obtain an impression of the geological conditions in the country as a whole, and he carried out his studies over extensive areas from Spitsbergen and Finnmark in the north to far south in the country. His principal work, *Gaea Norvegica*, was published in three parts from 1838 to 1850 and described the bedrock, with accompanying geological maps, of the Oslo region (1838), North Norway (1844) and South Norway (1850). He also undertook valuable studies of the uplift of Norway after the Ice Age. These pioneering works on Norwegian geology earned him international recognition, and their wealth of precise observations provided a valuable basis for later generations of geologists to build upon.

Painting of Keilhau by Christiane Schreiber, presented to the University in 1857. (Photo: NHM, University of Oslo).

Werner's Neptunistic ideas strongly influenced Keilhau, and his «transmutation theory«, stating that massive granites in the Oslo region might be formed from sedimentary deposits, got hold of the wrong end of the stick. He must, nevertheless, be viewed as one of the great pioneers; indeed W.C. Brøgger went as far as to describe him as the founder of Norwegian geology.

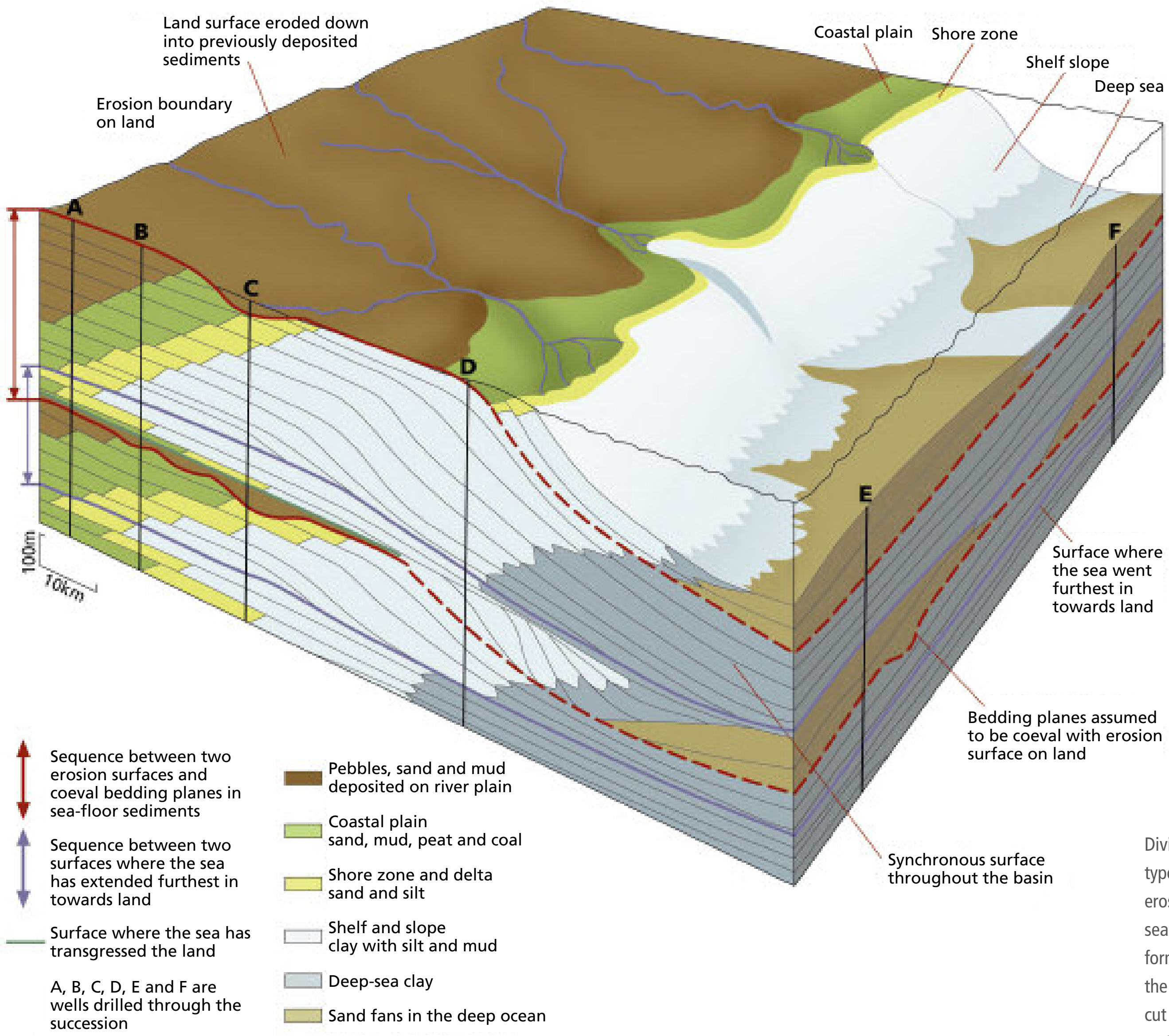
The discoverers of the Jotunheimen. Up to 1820, the area we now call the Jotunheimen Mountains was little known outside the circle of local farmers and huntsmen. Botanists had admittedly collected plants there, but it was the joint trips undertaken by Keilhau and his friend Christian Boeck, along with a newspaper article by Keilhau, that opened people's eyes to what they called the «Jotunfjeldene»; the «so far unknown piece of southern Norway«. The first volume of *Magazin for Naturvidenskaberne* in 1823 opened with an account of the journey, and Keilhau's watercolours and drawings of views were seen by many people. Posterity has honoured these two men, along with botanists like Christen Smith and painters like Johannes Flintoe, as «the discoverers of the Jotunheimen«.

THEODOR KJERULF (1825–1888) *By Inge Bryhni*

n 1854, Theodor Kjerulf won a university prize for a work in which he demonstrated that the granitic rocks in the Oslo region had been formed by crystallisation from magma that had forced its way into the sediments, and the flint-like rock in the boundary zone was sediment metamorphosed by heat. This understanding seems obvious today, but Theodor Kjerulf had to refute earlier erroneous opinions. In a general account of the geology of southern Norway (1857), he and Tellef Dahll described the Cambro-Silurian successions, and he was the first to apply the glaciation theory to explain the unconsolidated sediments, moraines, erratics and ice striae in south-eastern Norway. It was due to him that the glaciation theory was accepted in Norway. He showed, for instance, that the various moraine ridges in the Oslofjord district could be grouped as stillstands or stages during the deglaciation, that the sea had once stood as high as 220 m above the present level, and that the wide expanses of clay in the lowlands had been deposited by glacial rivers flowing into what was then shallow sea.

Kjerulf's portrait on a stamp in the series of Norwegian geologists in 1974. (Photo: I. Bryhni)

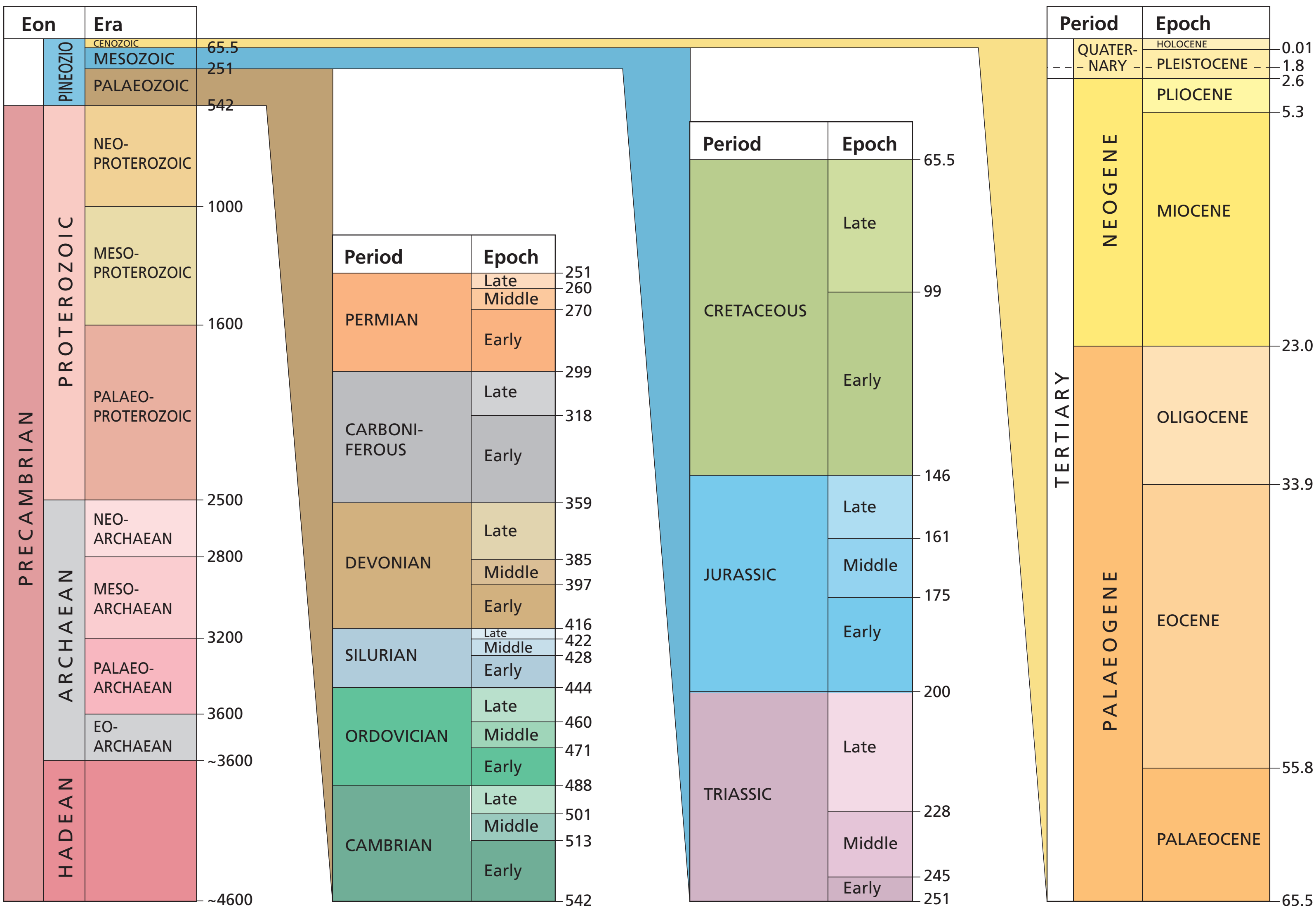
The start of the Geological Survey of Norway. Along with Tellef Dahll, Theodor Kjerulf took the initiative to have an institution established to undertake systematic investigation of the geology of Norway, and this led to the *Geological Survey of Norway* being set up in 1858. Theodor Kjerulf was the natural choice for the person to build up the organisation, and together with Dahll he was able to publish valuable general accounts of the geology of Norway, accompanied by bedrock maps. In 1877, he published a map of the geology of Norway on a scale of 1:1 000 000, and in 1879 a general account entitled *Udsigt over det sydlige Norges geologi* (Overview of the geology of southern Norway), where he gathered all the observations which he and his co-workers had made. The work was translated into German and remained the main source of knowledge on Norwegian geology for a long time. On a more local scale, he was responsible for publishing soil maps with accompanying descriptions, and bedrock maps on a scale of 1:100 000 for large parts of the country.



Division of successions into two types of sequences, between two erosion surfaces formed by a fall in sea level and between two surfaces formed when the sea transgressed the land. Surfaces with the same age cut through the boundaries of the various sedimentary strata. It is important to correlate – establish a mutual connection between – the successions in the wells that have been drilled through the succession.

Stratigraphy as an aid in petroleum exploration and recovery

When petroleum exploration is taking place, it is particularly important to have an intimate knowledge of the succession that may contain oil and gas. Seismic mapping is by far the most important means of following beds over distances. Drill holes provide valuable information about the succession, especially whether it contains hydrocarbons. A hole drilled to find oil or gas is called a *well*, like a hole drilled to seek groundwater. The stratigraphy and physical properties of the succession in the well are thoroughly described. Biostratigraphy is a particularly useful aid when we are investigating the succession on the continental shelf. The fossils recorded in the various wells show which beds belong together and, hence, the appearance of the succession in three dimensions. Both biostratigraphy and seismic mapping are employed in *sequence stratigraphy*. A *sequence* is a succession deposited under a single set of controlling physical conditions, such as variations in sea level, tectonic movements and sediment supply. An understanding of how the sequence is formed may provide a basis for predicting where a basin may contain source rocks for oil, and where reservoir rocks may occur. In an oil or gas field that is in production, detailed seismic imaging of the reservoir, biostratigraphy and sequence stratigraphy are valuable techniques for constructing a correct *reservoir model*, which is a three-dimensional view of how the reservoir rocks are dispersed and how oil, gas and water are expected to flow in the reservoir.



The geological time scale on the Earth. The figures give ages in millions of years before the present, the length of the individual periods are proportional with the extent in time. The column furthest left shows the highest-ranking chronostratigraphical units (systems) on the Earth, column two, the Palaeozoic), column three, the Mesozoic, and the column furthest right, the Cenozoic. Adapted from Gradstein et al. (2004).
There has recently been some discussion on the status of Tertiary and Quaternary. Here, we use the 2008 version of ICS's *International stratigraphic chart* drafted by Gabi Ogg where the base of the Quaternary has been extended from 1.8 to 2.6 million years.

Knowledge provides insight

The presentation of the geological history of Norway in the succeeding chapters of this book is a synthesis of research performed by many geologists over nearly two hundred years. Our understanding of geological processes has changed in pace with advances in physics, chemistry and biology. Nowadays, we measure many properties on the surface of the Earth, in the sea and the atmosphere, and inside the Earth. Computers analyse enormous volumes of data. Mathematical models are designed to quantify various factors in complicated systems in Nature, to map natural resources and to monitor how physical conditions on the Earth change.

Finally, an example of current interest that shows why it is vital to have an insight into what has happened earlier to understand what is taking place today, and what may take place tomorrow. The development of climate in the past, the *palaeoclimate*, is a research discipline that is crucial in connection with the current debate on global climate change (see Chapter 17). *Permafrost* is a geological phenomenon now being studied in an international research project in which Norway is participating. Permafrost occurs where the ice, or frost, in the ground does not melt in summer. Approximately one-fifth of the Earth's land surface has permafrost

today at high latitudes and in the mountains. The permafrost layer may be up to several hundred metres thick in Arctic regions. Its thickness depends upon the air temperature at ground level and the heat flow from the interior of the Earth. Temperature measurements in deep boreholes drilled in the permafrost layer provide information on changes in the average annual temperature over the past few hundred years and whether changes in temperature are taking place nowadays. Mapping the distribution of permafrost since the last Ice Age has shown that significant variations in climate have occurred. The lower limit of permafrost in the mountains has risen in recent times due to an increase in the air temperature. If the permafrost thaws completely, it will release vast volumes of the greenhouse gas, methane, which may lead to a further rise in temperature. This example shows that we must be able to see back in time in order to see ahead. We can rephrase the old geological principle with which we began this chapter, that «the present is the key to the past« by adding that *the past is the key to the present – and to the future.*

Permafrost is widespread in Svalbard right down to sea level. The ring-shaped accumulations of stones on Vardeborgsletta on the south side of outer Isfjord on Spitsbergen are formed by stones being pressed up from the permafrost in the ground beneath, and sorted (patterned ground). The stones were originally shore pebbles, and are clean and light coloured because they have been buried in the ground. (Photo: O. Salvigsen)