Evolution of the Earth Part 7: Rocks and rock cycle

Most rock-forming minerals are silicates (silicon plus oxygen plus other elements, Fig. 1).

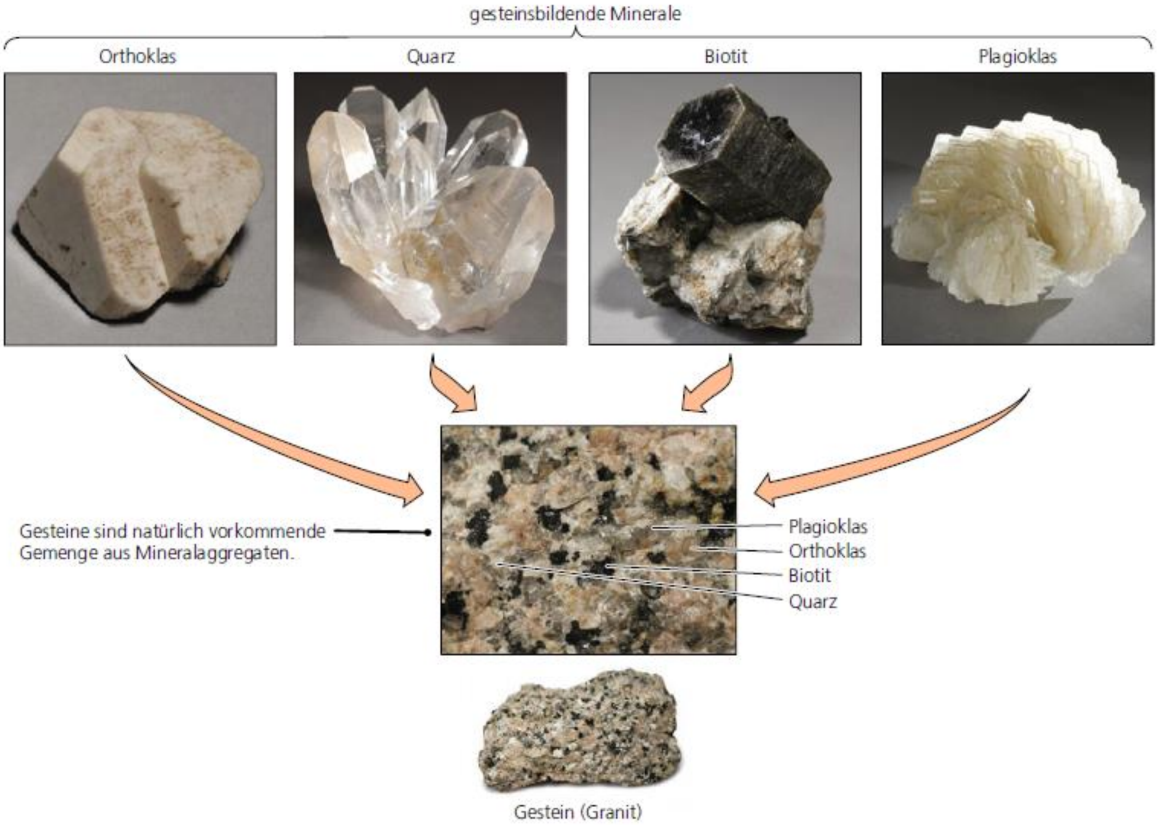

Fig. 1: Rocks are naturally occurring mixtures of mineral aggregates.

Rocks themselves can be divided into three classes: igneous rocks, sedimentary rocks, and metamorphic rocks (Fig. 2).

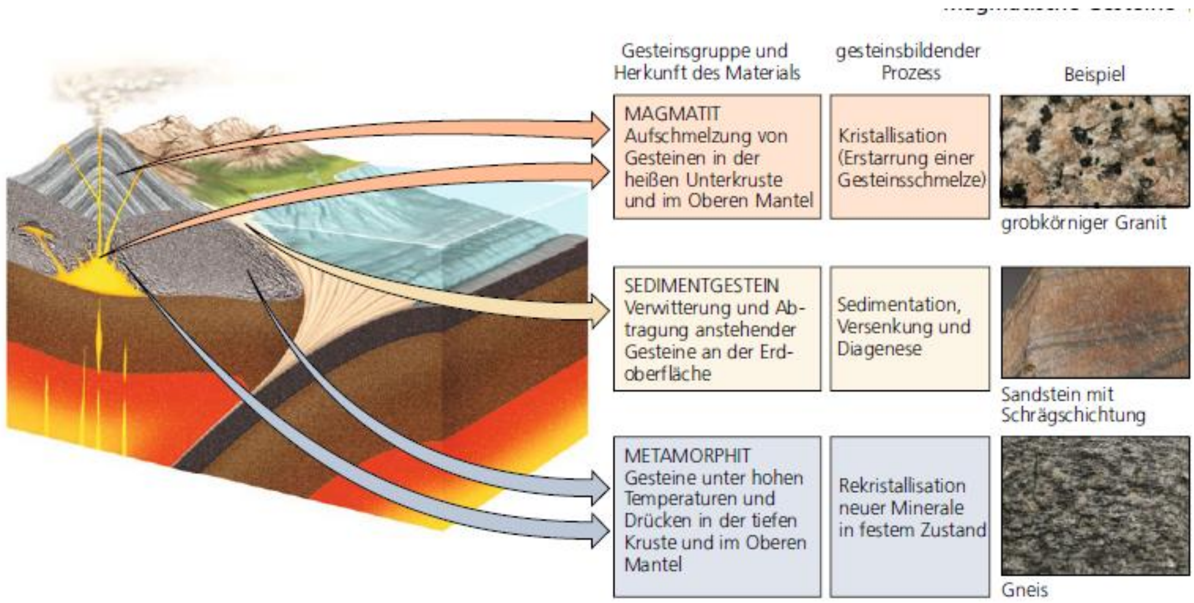

Fig. 2: Rock types

Igneous rocks

Igneous rocks are formed by magma (molten rock) from deep in the earth that rises up from deep plutons (magma chambers) and crystallizes as it cools. The size of the crystals in the rock depends upon how fast it cools and solidifies. If the molten rock is spewed out of a volcano, the magma cools quickly and the crystals have little time to form, so they are microcrystalline (“aphanitic”), too small to see with the naked eye. They are only visible in thin polished sections of rocks when viewed under a special microscope. If the crystals cool slowly over years to hundreds of years deep in an underground magma chamber, then they have time to grow larger. Sometimes they are still just barely visible to the naked eye, but still they are macrocrystalline (“phaneritic”) nonetheless. A few magmas cool extremely slowly over the course of decades or centuries or longer, producing pegmatites full of giant crystals.

Some igneous rocks have a composite texture with macrocrystalline crystals (phenocrysts) suspended in a rock that is mainly microcrystalline (called groundmass). This hybrid texture is called porphyritic and results from a magma that had a two-stage cooling history: the phenocrysts cooled slowly in a large magma chamber, then the semi-crystallized magma was blown out of a volcano where the rest of the lava cooled rapidly to form the groundmass surrounding the phenocrysts.

It is important to remember that crystal size is a result of time and type of cooling, so microcrystalline rocks are volcanic, macrocrystalline rocks cool slowly in plutons (plutonic rocks), and porphyritic rocks have both stages in their history. Magmatic rocks can be classified with the crystal size (Fig. 3).

Fig. 3: Classification of igneous rocks according to grain size.

The crystal size is one element of a classification of igneous rocks. The other axis is based on their chemical composition (Fig. 4).

Rocks derived from the Earth's mantle are relatively rich in magnesium, iron and calcium and are briefly referred to as "mafic" rocks. This composition of magnesium, iron and calcium produces minerals rich in these elements, such as olivine and pyroxenes and calcium plagioclase. If a mafic magma cools rapidly, it is the familiar black lava called basalt that erupts from Kilauea on Hawaii's Big Island and other mantle-derived volcanoes. If it cools slowly, the same magma that produces black basalt instead produces a macrocrystalline rock with visible pyroxene and calcium plagioclase known as gabbro.

Some magmas are so rich in magnesium and iron that they are called ultramafic. These contain almost nothing but olivine extracted directly from the mantle or lower crust. A macrocrystalline rock of pure olivine is called a peridotite. Currently, there are no ultramafic volcanic lavas anywhere on Earth, but they were common about 3 billion years ago and this olivine-rich lava is called komatiite.

At the other extreme of magma chemistry are melts rich in silicon, aluminum, potassium and sodium. This type of magma chemistry produces minerals such as quartz (pure silica), sodium feldspar (sodium, aluminum and silica), potassium feldspar and mica such as biotite and/or muscovite (rich in potassium, aluminum and silica). If the rock contains quartz and two-thirds of its total feldspar is potassium feldspar, then it is a true granite. True granites contain so much pink or red potassium feldspar that they tend to be pink or red as well. There are volcanic eruptions of magmas with the composition of granites. These are called rhyolite and are extremely fine-grained and generally pink or red because of the rusting of the iron they contain.

The rocks that most people call "granites" do not contain enough potassium feldspar to be true granites, as one geologist defines the term. Most geologists call these rocks granodiorite, not granite. For example, most of the deep rocks in the Sierra Nevada mountains in California are granodiorites or diorites. The volcanic equivalent of a granodiorite is called a dacite.

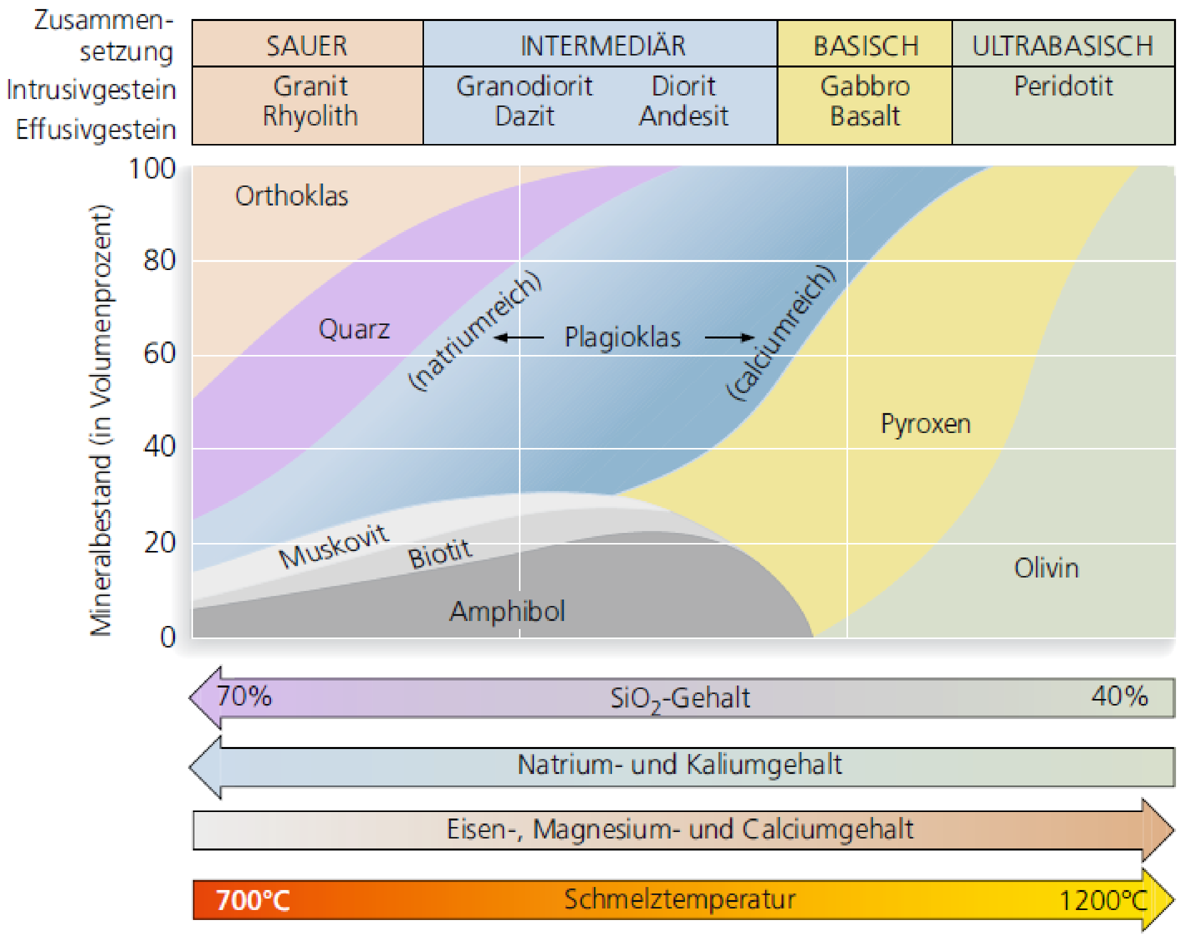

Fig. 4: Classification scheme of igneous rocks. The vertical axis shows the mineral composition of a given rock in volume percent. The horizontal axis shows the respective SiO_2 content of a given rock in mass percent. If a rock is known from chemical analysis to contain approximately 70% SiO_2, it can be inferred that it is composed of approximately 6% amphibole, 3% biotite, 5% muscovite, 14% plagioclase, 22% quartz, and 50% orthoclase. The rock would therefore be a granite.

Fractional crystallization (Fig. 5) is an important way in which an ultramafic magma rich in Mg, Fe, and Al can be transformed into a siliceous (felsic) magma rich in Si, Al, K, and Na. As the crystals rich in mafic components sink to the bottom of the magma chamber, they remove their Mg, Fe, and Ca, and the remaining magma becomes richer in more siliceous components, producing basaltic and andesitic magmas.

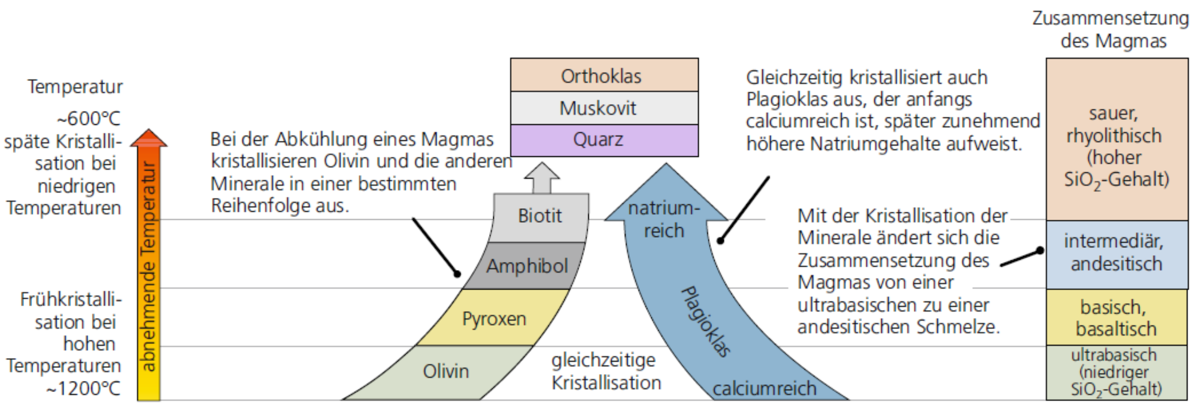

Fig. 5: Fractional crystallization

Another mechanism is called partial melting. Partial melting is the primary mechanism by which reheating of a cold igneous rock releases low-temperature minerals such as quartz and feldspar, producing granitic magmas. The first materials to detach from the original rock would be minerals that melt at the lowest temperatures, such as quartz, potassium feldspar, and sodium plagioclase. If this new low-temperature melt were then cooled, it would become a granodiorite or a granite.

Another important consideration is the cause of rock melting. This takes place at the subduction zones. Subduction zones are the areas where oceanic and continental plates meet, where one tectonic plate pushes over or under another plate. We will discuss the topic of plate tectonics at another chapter. It turns out that for rocks that are in subduction zones that dip deep into the mantle, there is a lot of water trapped in the seafloor basalts that once formed on a mid-ocean ridge. Water and other volatiles (gases) drastically lower the melting temperature of a rock.

Sedimentary Rocks

The rocks of the second main class are much more familiar to us because they form on the surface of the earth, not in deep magma chambers or dangerous volcanoes. They are called sedimentary rocks. They are of enormous importance because almost all of the economic products we extract from the earth come from unconsolidated sediments or sedimentary rocks. These include energy sources such as oil, gas, coal, and uranium; groundwater on which we depend; building materials such as sandstone or limestone, concrete made from crushed limestone plus sand and gravel, gypsum for drywall, silica sand for glass, etc. Many of our metallic mineral resources (especially uranium, iron and steel) are also included.

Sedimentary rocks are the source of almost all of our information about Earth history. It is the only source of fossils that demonstrate the history of life and help us determine geologic time. Finally, carbon-rich rocks like coal and limestone are the thermostats that make our planet livable. These crustal reservoirs fix carbon or release it into the atmosphere, so Earth is neither a hellish super greenhouse like Venus (where the atmosphere is hot enough to melt lead) nor a frozen ice ball like Mars.

All sedimentary rocks go through a certain basic process (Fig. 6). They always begin as weathered material of a pre-existing rock, which may be igneous, metamorphic, or sedimentary. Once this weathered material is transported by wind and/or water, it becomes loose sediment. Eventually, the sediment eventually comes to rest and is deposited. But it is still loose sediment until sometime later in its history the loose sand grains are cemented together or the silt particles are compressed and the loose sediment becomes sedimentary rock. Each step in this history can be traced in clues in the rock, and experienced sedimentary geologists act like detectives, gathering clues to the past from a sandstone or limestone that no one else notices.

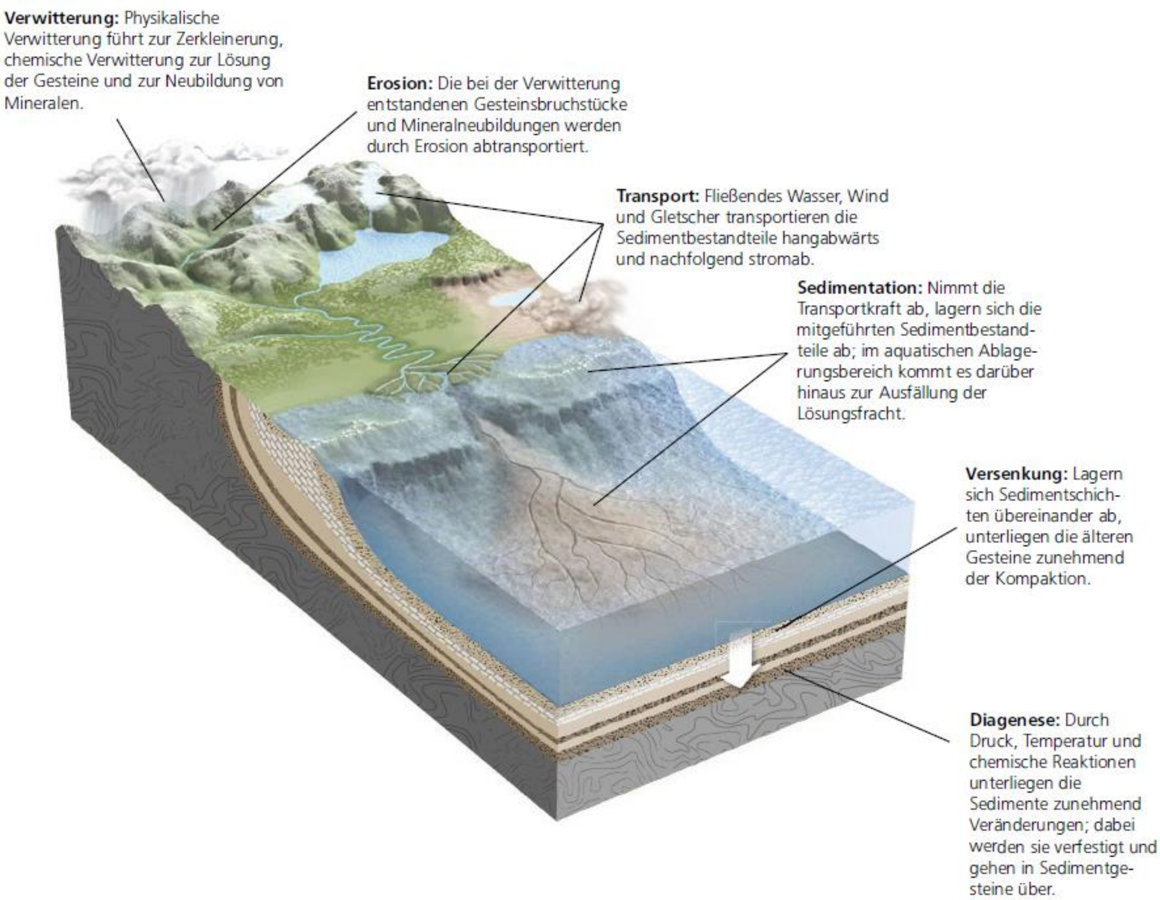

Fig. 6: Several of the processes of the rock cycle occurring at the Earth's surface contribute to the formation of sedimentary rocks.

There are two versions of this process. Most sedimentary rocks consist of broken particles of pre-existing rocks or minerals known as clasts. Therefore, clastic sedimentary rocks are made up of varying sizes of pieces of other rocks, from huge boulders to fine clay. Eventually, these loose gravel, sand, or silt grains must be lithified into sedimentary rock, through which sediments are compacted under pressure, release their pore water, and gradually become solid rock.

The second way is much simpler. Instead of fragments of rocks or minerals, the ions from the pre-existing rock weather out and are dissolved in water, where they stay until something causes them to precipitate from the water and crystallize into minerals like halite (forming rock salt), gypsum (hydrous calcium sulfate), calcite or aragonite (calcium carbonate), and many others. Thus, when they crystallize they are already lithified into solid rock. Since this is a purely chemical process, we call these chemical sedimentary rocks.

The most important property of rock fragments is their grain size, so the classification of clastic sediments is by size. It is also important because grain size is a good indicator of the type of deposition (wind, water, glacial ice) and grain size decreases downstream from the source, so it tells us about transport.

Like grain sizes, sediments are simply referred to as clay, silt, sand, or gravel (Fig. 7).

	Abgelagertes Sediment	Korngröße	Festgestein
grob			
	Blöcke		
		200 mm	
	Steine		Konglomerat, Brekzie
		63 mm	
	Kies		
		2 mm	
	Sand		Sandstein
		0,063 mm	
Schlamm	Silt (Schluff)		Siltstein
		0,002 mm	
Schlamm	Ton		Tonstein (zerbricht in unregelmäßigen Stücken)
fein			Schieferton (zerbricht entlang von Schichtflächen)

Fig. 7: Grain sizes of sediments

Loose rocks with a predominant proportion of coarse grain sizes (gravel, stones, blocks) are called crushed stone (for rounded particles) or rubble (for angular ones).

Loose rocks with a predominant proportion of coarse grain sizes larger than 2mm (gravel, stones, blocks) are called crushed stone (for rounded particles) or rubble (for angular ones).

These coarser particles, often together with the finer ones, can form conglomerates or breccias. Conglomerates consist of rounded rock debris, breccias of angular rock debris.

Particles that are between 1/16mm and 2 mm in size are called sands. Many sands are cemented to form the rock known as sandstone. Most sandstones are rich in quartz, the most stable mineral on the earth's surface, so quartz sandstone is the most common type. Rare sandstones, however, may be rich in feldspars, which are common in igneous rocks but rapidly break down into clay when weathered at the Earth's surface.

Sediment that is 1/16 mm and 1/256 mm is called silt; when it is compressed into rock, it is called siltstone.

If the sediment is finer than 1/256mm we have clay, which can be compressed into mudstone.

Siltstone and clay are usually subject to some burial and pressure. This pushes the clay minerals (phyllosilicates) down, pushing the water out from between them and causing it to form a slightly different rock called shale, which breaks into specific layers in a plane.

Chemical sedimentites are formed by the precipitation of solutes from supersaturated solutions (Fig. 8). Often the evaporites (carbonates such as limestone, sulfates, halides, and other salts) are formed in the process, which can comprise thick rock packages and form formations, such as the Zechstein in northern and southern Germany.

The most common method for this to occur is for organisms (plants or animals) to pull ions from seawater (such as calcium and carbonate) and precipitate their shells of calcium carbonate minerals such as calcite or aragonite. As these carbonate shells and coral skeletons accumulate from marine life, they build up carbonate sediments that can eventually crystallize into a rock known as limestone. Such limestones are almost always built from fossils even though recrystallization might make the fossils invisible. Most limestones that form today are confined to tropical or subtropical areas, with warm, shallow, clear water and no clastic sand or mud. Places like Florida, the Bahamas, parts of the Caribbean, the Persian Gulf, and the South Pacific are the main places where carbonate sediments are formed today. During the geologic past, vast shallow tropical seas flooded the continents for millions of years, accumulating enormous thicknesses of limestone in much of the world.

Another chemical found in water is silica. It can precipitate to form a rock known as chert, which consists of submicroscopic quartz crystals. Chert comes in many colors based on impurities. So if it is black, we call it flint; if it is red, it is jasper; white chert is novaculite. Chert in the form of flint or jasper was once important for arrow and spear points or to start fires.

Chert forms in two ways. In places where plankton, which use silica in their skeletons, are extremely abundant, it accumulates to form a silica-rich chert known as bedded chert or "ribbon chert." This type of chert is precipitated by organisms. The other types of chert form when silicate-rich groundwater percolates through other rocks (usually limestone) and replaces calcite with silica. These are called nodular chert.

Sediment	Sedimentgestein	chemische Zusammensetzung	Minerale
chemisch-biogen Carbonatsand und Carbonatschlamm (überwiegend bioklastisch)	Kalkstein	Calciumcarbonat ($CaCO_3$)	Calcit (Aragonit)
Kieselsediment	Hornstein	Siliciumdioxid (SiO_2)	Opal Chalcedon Quarz
Torf, organisches Material	Kohle	Kohlenstoff Kohlenstoffverbindungen (mit Sauerstoff und Wasserstoff)	(Kohle) (Erdöl) (Erdgas)
chemisch primär nicht abgelagert (durch Diagenese entstanden)	Dolomit	Calcium-Magnesiumcarbonat ($CaMg[CO_3]_2$)	Dolomit
Eisenoxid	Eisenerz	Eisensilicate; Eisenoxide; Eisencarbonat (Fe_2O_3; $FeCO_3$)	Hämatit Limonit Siderit
Evaporit	Evaporit	Natriumchlorid (NaCl); Calciumsulfat ($CaSO_4$)	Gips Anhydrit Halit Kalisalze
primär nicht abgelagert (durch Diagenese entstanden)	Phosphorit	Calciumphosphat ($Ca_5[PO_4]_3$)	Apatit

Abb. 8: chemische Sedimente

Metamorphic Rocks

The third main class of rocks are metamorphic rocks. We know the word "metamorphism" to describe many kinds of shape changes, such as the transformation of a caterpillar into a butterfly. Metamorphic rocks are transformed or changed from an original "parent rock" or protolith (usually an igneous or sedimentary rock) into a completely new and different type of rock with new minerals and new textures. Some metamorphic rocks are so completely transformed that they are unrecognizable, and we may never know what kind of protolith they started from.

Metamorphism occurs when the protolith is buried deep in the crust and subjected to extremely high temperatures and directed pressure. Thanks to the enormous flow of heat from the Earth's interior, the crustal rock beneath our feet gets hotter and hotter the deeper we go. In fact, the geothermal gradient is about 30 ° C per kilometer of depth, so the crustal rocks would be about 900 ° C (above the melting temperature of many minerals) at 30 km. Most people can't even imagine this, but when we descend an old abandoned mine shaft with no air conditioning, we can feel it getting hot as we descend. South African diamond and gold miners work at depths of nearly 3.9 km and require a continuous supply of cooled fresh air to survive shifts of only a few hours, as the temperature of the rock and air down there is 60°C. The deepest hole ever drilled reached only about 12 kilometers in the Kola region of Siberia, which is only 10 to 15% of the thickness of the Earth's crust.

Compared with other rock-altering processes, such as chemical weathering or diagenesis, rock metamorphism occurs under significantly elevated pressure and temperature conditions (Fig.9). This is often caused by mountain building or other processes more or less closely related to plate tectonics.

During metamorphism, new minerals and mineral aggregates are formed whose pressure- and temperature-dependent formation range corresponds to the environmental conditions. During pressure-driven metamorphism, there is often an alignment of the mineral grains in the rock, which reflects from which directions the greatest pressure occurred. This changes the rock structure (e.g. texture), distinguishing metamorphic rocks in terms of their microstructure from chemically similar plutonic rocks also formed in the Earth's crust.

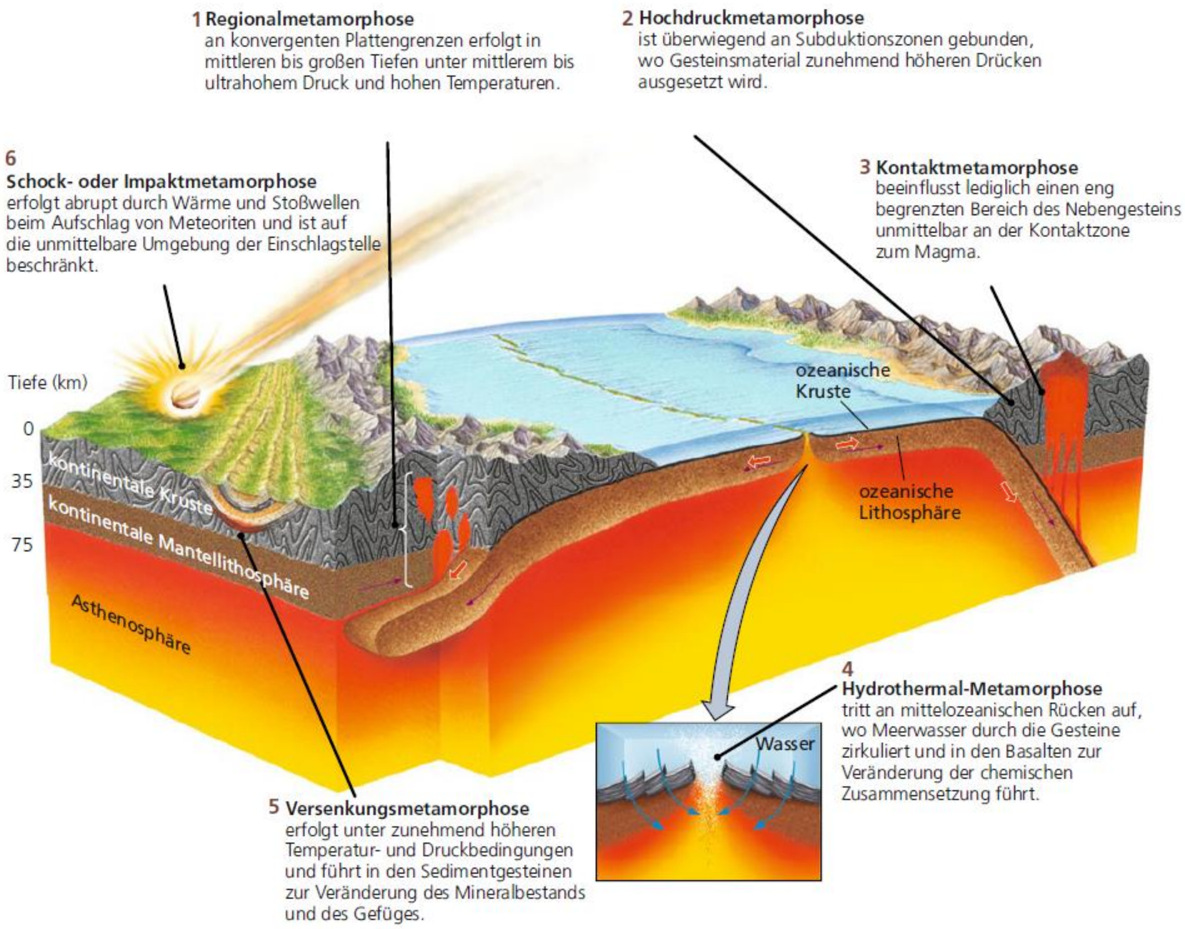

Fig. 9: Causes of rock metamorphism

In contrast to igneous rock and sedimentary rock, there is still no uniform nomenclature for metamorphic rock. If the unmetamorphic parent rock (protolith) of a metamorphic rock is recognizable, the name of the protolith is simply preceded by the prefix meta-, as in metabasalt. How does such a metamorphosis of the rock take place? Let's look at some examples for this:

Let us take, for example, shale (Fig. 10 A), a non-metamorphic clay rock belonging to the sedimentary rocks, as a protolith. These can have different chemical compositions: Silicon, aluminum, potassium, sodium, and other elements. The first metamorphic product is a stone known as slate, which is flat and highly foliated (Fig. 10 B). It is used, for example, for roofing tiles. With increasing temperature and directed pressure, the clay minerals in the foliated slate transform into tiny mica flakes such as muscovite or biotite (not yet visible to the naked eye) and the rock acquires a distinctive luster; this is called phyllite or sheen (Fig. 10 C).

Further pressure and temperature cause the new metamorphic minerals to grow large enough to be visible to the eye; this type of rock is called schist (Fig. 10 D). Eventually, at extremely high pressures and temperatures, some of the minerals begin to melt and segregate into bands of light minerals (typically quartz and plagioclase) and dark minerals (typically biotite and hornblende). This compositional banding is the diagnostic feature of a rock known as gneiss (Fig. 10 E). Any further increase in pressure and temperature and the gneiss melts completely and may become magma, which could cool to an igneous rock.

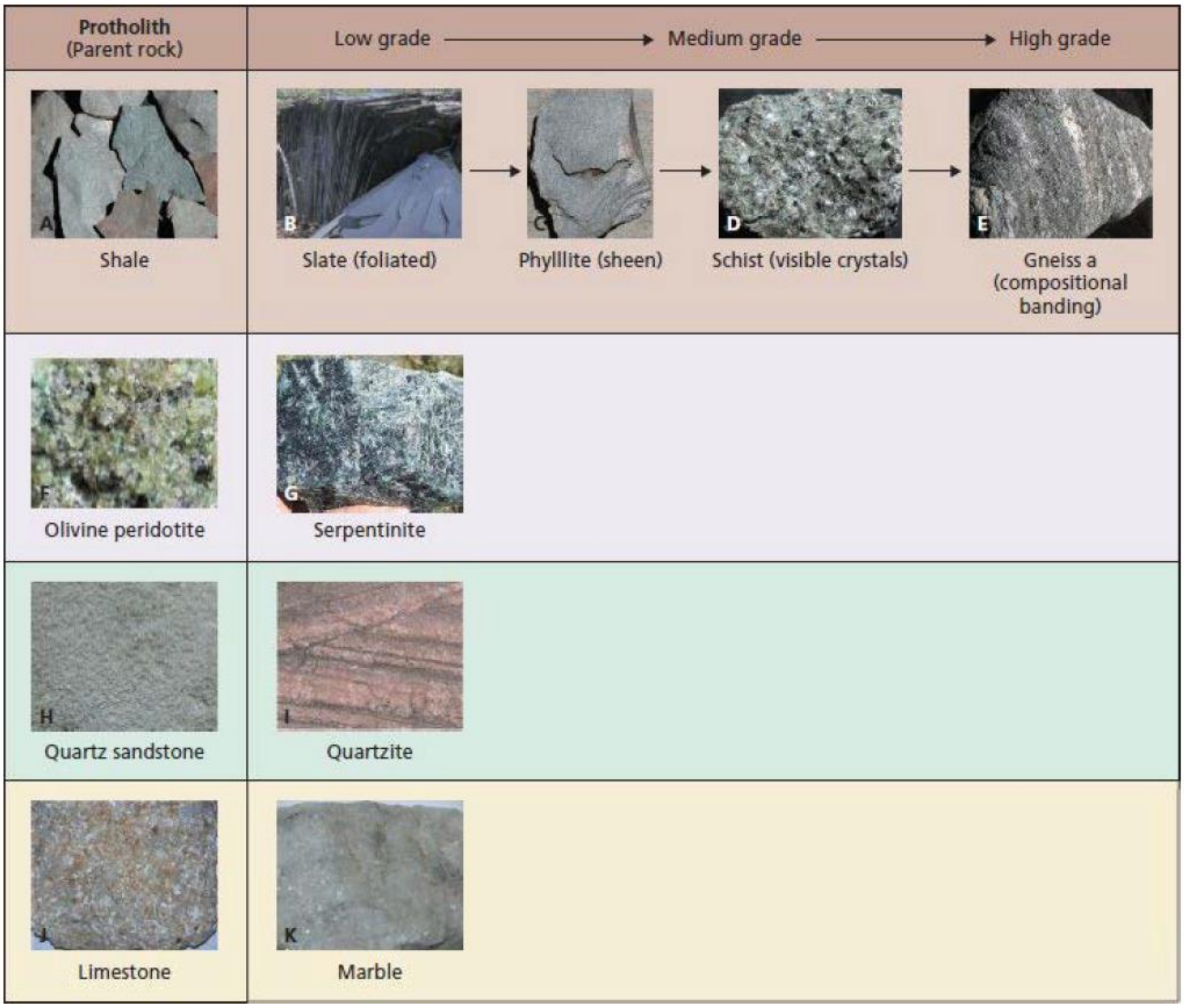

Fig. 10: Examples of rock metamorphism.

If we start with an olivine peridotite or a gabbro as a protholite (Fig. 10 F), we have a rock with only magnesium, iron and silica. Under high pressure and temperature, a new mineral called serpentine is formed. A rock made of the mineral serpentine is called serpentinite (Fig. 10 G). Serpentinite is common where ultramafic, olivine-rich layers of oceanic crust have been metamorphosed.

Quartz sandstone (Fig. 10 H) contains only one chemical, silica, and nothing but quartz can be made from this chemical, no matter how high the pressure and temperature. Thus, during metamorphism, quartz sandstone becomes another quartz-rich rock, quartzite (Fig. 10 I). The mineralogy will not change (it always forms quartz); but the original structure of packed together spherical quartz sand grains will disappear, and the grain boundaries will merge and interlock like pieces of a puzzle.

Let us consider another protolith: limestone (Fig. 10 J). Limestone has only one mineral available, calcite (calcium carbonate), so it can form only calcite regardless of pressure and temperature. Thus, a fossil-rich limestone protolith transforms into a marble under metamorphism (Fig. 10 K). A true marble is still composed entirely of calcite, but the minerals and fossil fragments have completely recrystallized so that no fossils are visible and only large, shiny calcite crystals remain.

Rock cylce

As we have seen, minerals and rocks can pass from one category to another quite easily. Let's take the example of the sedimentary rock known as shale. It can go from sedimentary rock to metamorphic rock as it is exposed to high directional pressures and temperatures. It then goes from shale to foliated slate, phyllite, schist, and gneiss. Finally, it gets hotter and hotter until it melts. Then it has become magma and can cool to an igneous rock. So we have a progression from sedimentary to metamorphic to igneous rocks. Magmatic rock at the Earth's surface weathers and can break down into loose sediment like sand, be recompressed and become sedimentary rock, which can further weather metamorphically and the cycle begins again. This is the rock cycle and it demonstrates the fact that one rock can transform into another (Fig. 11).

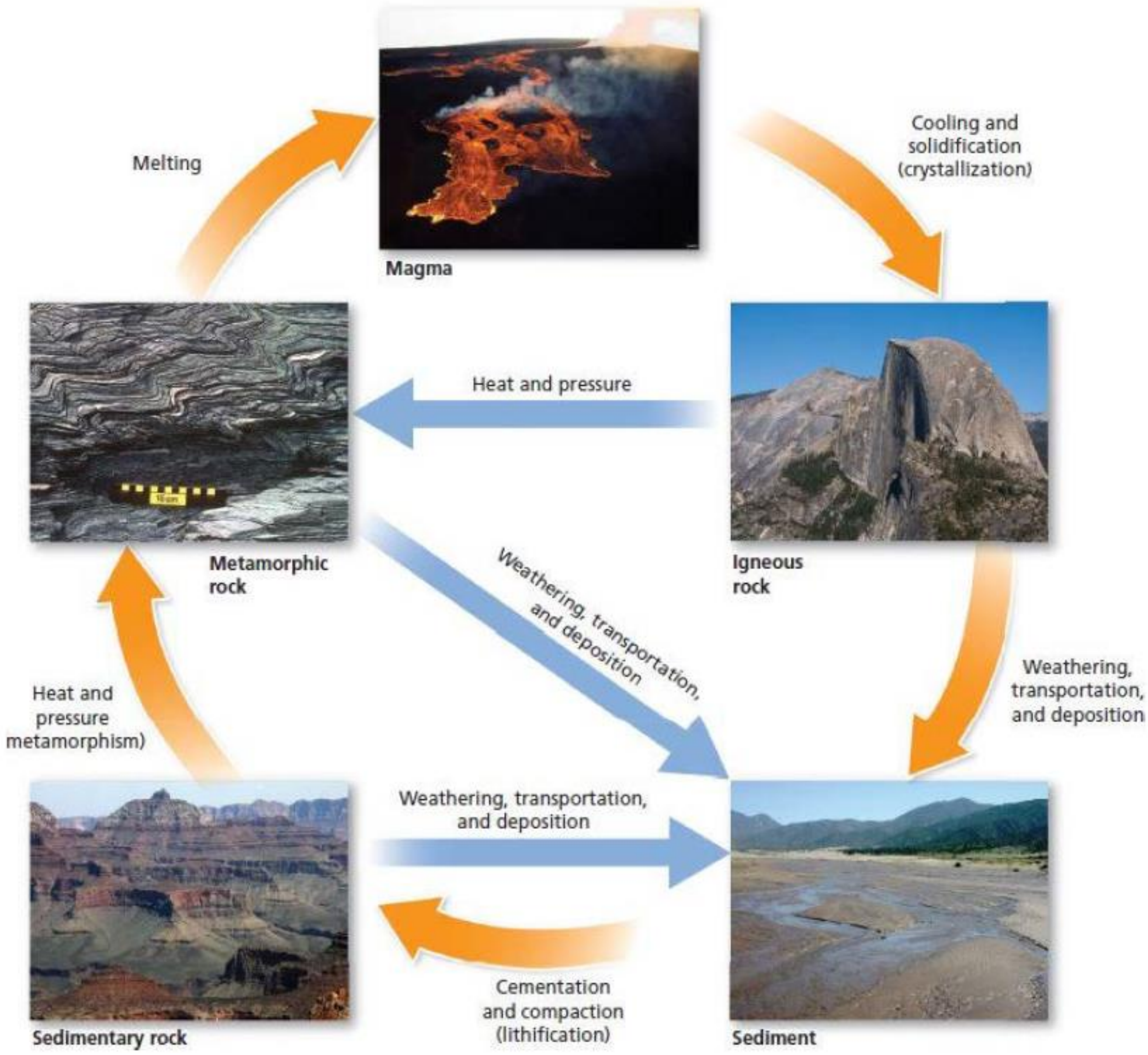

Fig. 11: Rock cycle

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