8. Metamorphic rocks

In chapter 7, we talked about the transformation of soft sediments into hard sedimentary rocks by compaction and cementation. These processes occur once the sediments are buried under new sedimentary layers. Thick accumulation of sediments and sedimentary rocks is made possible by a process called ***subsidence*** (see chapter 7). As depth increases, temperature and pressure increase too. At a certain depth, temperature and pressure are so high that it may affect the mineralogy, texture or chemical composition of rocks. Rocks undergo a process called ***metamorphism***. Most metamorphic rocks are produced in the middle and lower crust at a depth of 10 to 30 km. Plate tectonics leads to metamorphism where shallow rocks are forced down to great depths during the process of mountain building at convergent plate boundaries (i.e. ***orogeny***). But metamorphism can also occur at or near Earth's surface where rocks are in contact with hot magma (i.e. contact metamorphism, see section 8.4). The ***metamorphic grade*** of a rock refers to the pressure and temperature to which the rock has been subjected. Metamorphic rocks formed at relatively low pressure and low temperature have been subjected to a ***low-grade metamorphism***. Those produced at high pressure and high temperature result from a ***high-grade metamorphism***.

It is important to understand that rocks remain ***solid*** during the process of metamorphism. If rocks melt, the resulting magma will produce an igneous rock which is another domain of the rock cycle.

Rock metamorphism is driven by three factors that are described below: (1) temperature, (2) pressure, and (3) heated fluids (hydrothermal fluids).

8.1. Temperature

The average ***geothermal gradient*** of the Earth's crust is 30°C/km. A rock buried 15 km below the surface is subjected to a temperature of 450°C. At such temperature, a rock re-crystallizes. Preexisting minerals grow larger and new ones may even form. Different minerals are stable at different temperatures. For example, chlorite is a sheet-like silicate commonly forming during low-grade metamorphism. Garnet, another silicate mineral, is characteristic of a higher-grade of metamorphism. The temperature at which one mineral assemblage changes into another has been determined experimentally. Therefore, by studying the mineral composition of a metamorphic rock, geologists can determine the temperature at which the rock has formed. Metamorphic mineral assemblages are natural ***geothermometers***.
The depth at which metamorphism occurs depends on the geothermal gradient. The geothermal gradient can be more or less steep according to the geological setting. An old, stable continental crust has a geothermal gradient that is lower than average. On the other hand, regions where the crust is stretched and thinned (e.g. Basin and Range in US, East African Rift) are characterized by a geothermal gradient higher than average.

8.2. Pressure

Due to the weight of overlying rocks, pressure increases with depth in Earth's crust at a rate of 300-400 bar/km. The pressure at 15 km is thus approximately 5000 bar. For comparison, the atmospheric pressure at sea level on Earth is 1 bar. In the ocean, the pressure in the deepest trenches about 10,000 m below the surface is approximately 1000 bar. The pressure resulting from the weight of overlying rocks is called ***confining pressure***. Crustal rocks are squeezed in all directions by this confining pressure which increases with depth. There exists another kind of pressure: the ***directed pressure*** caused by tectonic forces. For example, there are tremendous compressional forces affecting crustal rocks at convergent boundaries. The shape and orientation of minerals formed during metamorphism are greatly influenced by tectonic forces. Elongated and platy crystals tend to orientate perpendicularly to the direction of compression. The parallel alignment of platy crystals in a metamorphic rock produces a distinct texture called ***foliation*** (see section 8.5). Crystal orientation in a metamorphic rock is therefore useful to reconstruct the tectonic history of a region. Moreover, like for temperature, different minerals are stable at different pressures. Geologists can use the mineral assemblages they recognize in metamorphic rocks to determine the pressure at which they formed. Metamorphic mineral assemblages are natural ***geobarometers***.

8.3. Hydrothermal fluids

Another factor that can lead to modifications of the mineralogical and chemical composition of a rock is the presence of heated fluids (hydrothermal fluids) in the crust. Even in dry rocks, water can be present in the crystal structure of some minerals (e.g. clay minerals). Increasing pressure eventually squeezes out water molecules. Heated water can react with surrounding rocks and dissolve components like CO_2, SiO_2, Na, K, S, Cu, and Zn, changing the initial composition of the rocks. New minerals can also precipitate from a hydrothermal fluid as it penetrates different regions of the crust. The transformation of rocks' mineralogical and chemical composition in contact with hydrothermal fluids is called ***metasomatism***.

An example of such transformation is related to the formation of ***black smokers***, already mentioned in chapter 4. Seawater penetrating the oceanic crust near mid-ocean ridges is heated and reacts with the surrounding basalt. The heated water leaches elements such as sulfur and various metals from the rock. Meanwhile, the mineralogical composition of the basalt changes and new minerals form (e.g. chlorite). Due to the presence of these new minerals, the color of the rock changes too and becomes green (hence the name given to this type of rock: ***greenstone***). When the heated water returns to the ocean floor and cools suddenly in contact with the cold deep ocean water, metallic sulfides precipitate and form large chimneys from which seeps a blackish mixture of hot water and mineral particles (hence the name black smoker).

8.4. Types of metamorphism

Regional metamorphism: metamorphism which affects large regions of the crust at convergent boundaries where rocks are subjected to high temperature and high pressure. Rocks that are carried to huge depths in subduction zones can undergo high to ultra-high pressure metamorphism. Metamorphic rocks formed under very high pressure are called ***eclogites***. They are rarely brought back to the surface and therefore rarely seen at outcrops. They contain minerals indicative of extremely high pressures, such as ***coesite*** (a high-pressure polymorph of quartz) or microdiamonds which form under 40,000 bar at a depth of 120 km!

Contact metamorphism: metamorphism which affects rocks in contact of a magmatic intrusion within the crust or in contact with lava at the surface. In this case rocks are subjected to high temperature but not necessarily to high pressure.

Seafloor metamorphism: metamorphism which affects rocks of the oceanic crust near mid-ocean ridges in contact with hydrothermal fluids (metasomatism, see explanations in section 8.3. of this chapter)

Burial metamorphism: metamorphism which affects sedimentary rocks as they are buried under an increasingly thick pile of sediments. This metamorphism typically starts at depths ranging between 6 to 10 km where rocks undergo a pressure of about 3000 bar and temperatures are comprised between 100 and 200°C.

Shock metamorphism: metamorphism which is caused by a meteorite impact. The kinetic energy of a meteorite is released in the form of heat and shock waves. Temperature can be high enough to melt rocks at the impact site. The rock is pulverized and small molten pieces cool in the air and form small glassy bead-like objects called ***tektites***. The presence of tektites in sedimentary rock layers is used as one of the criteria to recognize a meteorite impact in the rock record. The shock wave can modify the mineralogy of the rocks at the impact site. For examples, the crystal structure of quartz can be modified to produce coesite. The presence of high-pressure minerals like coesite or microdiamonds can also be used as supporting evidence for a meteorite impact in the rock record.

8.5. Metamorphic textures

Metamorphism guides the size, shape, and orientation of crystals and has a profound influence on the texture of rocks. A common texture observed in metamorphic rocks is ***foliation***, already mentioned in section 8.2 of this chapter. Foliation results from the preferential orientation of platy crystals which tend to align in the direction perpendicular to compressional forces. Minerals forming platy crystals and common in metamorphic rocks are ***micas***. The foliation plane is a plane along which the rock splits more easily (***metamorphic cleavage***). For example, ***slate*** is a low-grade foliated metamorphic rock composed of small platy crystals whose preferential orientation enables the rock to be split easily into flat sheets. Due to this property, slates are commonly used to make floor and roof tiles.

Based on their texture, two main families of metamorphic rocks can be distinguished: foliated metamorphic rocks and non-foliated (granoblastic) metamorphic rocks.

8.5.1. Foliated metamorphic rocks

Foliation is produced when metamorphic rocks are subjected to directed pressure. As the grade of regional metamorphism increases, foliation becomes more pronounced and the size of crystals increases. Foliated metamorphic rocks include the following common rock types, classified here from a lower (top of the list) to a higher (bottom of the list) grade of metamorphism (see slides for illustrations):

- ***slate***
- ***phyllite***
- ***schist***
- ***gneiss***
- ***migmatite***

Foliation becomes more conspicuous as the grade of metamorphism increases from slate to phyllite to schist. In gneiss, minerals are segregated into distinct lighter and darker bands. In migmatites, banding becomes more diffuse as temperature increases and the rock approaches its melting temperature.

8.5.2. Granoblastic (non-foliated) metamorphic rocks

Granoblastic rocks are metamorphic rocks which have not been subjected to directed pressure and consequently do not display any foliation. One example of such rock type is ***greenstone***. Greenstones form in the context of seafloor metamorphism as explained in section 8.3. Another example is ***marble***. Marbles form by recrystallization of sedimentary rocks composed primarily of $CaCO_3$ (limestones) subjected to high pressure and high temperature. ***Quartzite***, another granoblastic metamorphic rock, is the name given to a sandstone rich in quartz grains that has undergone high pressure and high temperature. Note that in metamorphosed sedimentary rocks such as marble and quartzite, fossils are destroyed during the process of recrystallization.

8.5.3. Porphyroblastic texture

The term porphyroblastic is used to describe a rock composed of large crystals (***porphyroblasts***) “floating” in a much finer-grained matrix. The interpretation of this texture is that the large crystals have formed over a broad range of pressure and temperature. The small crystals in the matrix on the other hand are not stable over such a broad range of pressure and temperature. They have had to recrystallize repeatedly as pressure and temperature increased which did not give them enough time to grow large.

8.6. Metamorphic rocks: a tool to study the history of crustal rocks

8.6.1. Index minerals

As explained in section 8.1 and 8.2, mineral assemblages in metamorphic rocks can be used as a kind of geothermobarometer. Of particular interest are so-called ***index minerals*** which are stable in a relatively limited range of pressure and temperature. Mapping the distribution of index minerals in a region where metamorphic rocks are exposed to the surface enables to delineate zones of the crust which have experienced different grades of metamorphism. The lines delimiting these zones are called ***isograds***.

Ancient mountain chains are often characterized by extensive belts of different metamorphic grades (with different index minerals) parallel to their axis with isograds following the main deformation features of the rocks (folds and faults). Therefore, mapping metamorphic zones is useful to recognize ancient convergent plate boundaries. In addition, the mineralogy of metamorphic rocks gives access to the conditions of pressure and temperature existing when they formed. The next step is to identify the precise geological setting to which these metamorphic rocks are related.

8.6.2. Metamorphic facies

The mineralogy of metamorphic rocks does not only depend on pressure and temperature but also on the composition of the parent rocks. As an example, let's consider a shale (mainly clay minerals and quartz) and a basalt (mainly feldspars and pyroxene). Let's raise the pressure and temperature so that both rocks experience the same intermediate-grade metamorphism. The mineralogy of the metamorphosed shale and that of the metamorphosed basalt will overlap (presence of garnet in both rocks) but will not be the same. Both metamorphic rocks however belong to the same ***metamorphic facies*** (in this case the facies called ***amphibolite***) because they are characteristic of a specific domain of pressure and temperature typically found deep under mountain chains. Another example is the metamorphic facies called ***greenschist*** which includes a variety of rock compositions characterized by a high abundance of green minerals such as chlorite and which typically forms by low-grade metamorphism under mountain chains. Rocks belonging to the ***blueschist*** facies on the other hand are characterized by the presence of the blue mineral glaucophane and indicative of conditions of moderate temperature and high pressure typically experienced by rocks of the oceanic crust caught in a subduction zone. There are of course other metamorphic facies characteristic of other tectonic settings which are not mentioned here.

By subjecting rocks of various compositions to various conditions of pressure and temperature in the lab, geologists can match the compositions of metamorphic rocks from a surveyed area to specific domains of pressure and temperature (hence metamorphic facies) which provides valuable information about the geological setting in which these rocks formed (e.g. subduction zone, mountain belt, contact metamorphism).

8.6.3. The pressure-temperature paths of metamorphic rocks

The history of pressure and temperature of a given metamorphic rock is called its pressure-temperature path or ***P-T path***. The P-T path consists of two segments: a prograde and a retrograde segment. The ***prograde segment*** reflects the increase in pressure and temperature since the rock began to experience metamorphism. The ***retrograde segment*** reflects the decrease in pressure and temperature when the rock is brought back to the surface through the process of ***exhumation*** (see section below). Rocks from different tectonic settings have different P-T paths (see slides for illustration). It is therefore very useful to know the P-T path of a metamorphic rock.

In order to reconstruct the P-T path of a metamorphic rock, geologists target large ***porphyroblasts*** (see section 8.5.3). One example is ***garnet*** which grows over a broad range of temperature and pressure. The key point here is that the chemical composition of garnet evolves as pressure and temperature increase. Experiments conducted in the lab have shown exactly how the composition changes with pressure and temperature. Hence, by analyzing changes in the abundance of specific elements along the transect connecting the center of a porphyroblast of garnet (oldest age) to the rim of the same crystal (youngest age), it is possible to reconstruct the evolution of pressure and temperature during the crystal's growth.

8.7. Exhumation process

Metamorphic rocks can sometimes be brought back to the surface (luckily for geologists who can then study these rocks). This process is called ***exhumation***.

One hypothesis suggests that exhumation results from the combined effect of ***tectonic uplift*** and ***erosion***. At convergent boundaries, rocks at the core of mountain chains are uplifted by tectonic forces. Meanwhile the surface of the mountain chain is affected by erosion which removes rocks from the top. The result is that deep-seated rocks become progressively closer to the surface as they are pushed upward by tectonic forces and the rocks above are removed by erosion. Since erosion is controlled by climate, this theory implies that ***climate*** and ***tectonic uplift*** control the rate of exhumation.