METAMORPHIC ROCKS

Smith and Pun, Chapter 6

WHERE DO METAMORPHIC ROCKS OCCUR?

Metamorphic rocks are:

1. **Widely exposed in actively forming mountain ranges**
2. **Always found in eroded ancient mountain belts in the interior of continents**

Metamorphic rocks are the oldest rocks on Earth.

WHAT IS METAMORPHISM?

Metamorphism describes the mineralogical, chemical, and textural changes to preexisting rocks that occur without substantial melting.

Metamorphism occurs in Earth's crust and mantle at conditions differing from those under which the rock originally formed.

Conditions of metamorphism range from those lithifying sediment into sedimentary rocks to conditions of temperature and pressure just before rock melts to make magma (see Figure 6.2 on page 136).

WHAT IS METAMORPHISM? (2)

Metamorphic petrologists describe the intensity of temperature and pressure during metamorphism as ranging from:

- **Low grade**
- **Medium grade**
- **High grade**

The original composition of the rock is essential in determining the reactions that actually occur during metamorphism. However, significant changes in rock composition may occur if large amounts of chemical active fluids are involved in the metamorphism.

THE ROLE OF TEMPERATURE IN METAMORPHISM

Temperature increases with depth below Earth's surface. Some metamorphic reactions occur when minerals that formed at low temperature are subsequently transformed to different minerals as the temperature increases (see Figure 6.3 on page 138).

Where sedimentary rocks accumulate in sinking basins, the earliest deposited sediment experiences progressively higher temperatures as more sediment accumulates on top. The sedimentary rocks are eventually buried sufficiently deep for there to be enough heat to initiate metamorphism.

THE ROLE OF TEMPERATURE IN METAMORPHISM (2)

Rocks can also be buried as a result of tectonic action (see Figure 6.4 on page 139).

Tectonic burial occurs when one block of crust is forced over the top of another block. The block on the bottom is heated to the higher temperature associated with greater depth beneath the Earth's surface.

THE ROLE OF TEMPERATURE IN METAMORPHISM (3)

Intrusion of magma into rocks can also increase the temperature (see Figure 6.5 on page 140).

When magma intrudes into rocks, it raises the temperature in the surrounding rock. The transfer of heat from magma may result in metamorphism of the surrounding rocks.

THE ROLE OF TEMPERATURE IN METAMORPHISM (4)

High-temperature metamorphism causes the break down of minerals that contain water or gas molecules, and results in the release of these components. These reactions are called:

1. **<u>Dehydration</u> <u>reactions</u> – loss of water**

$$KAl_3Si_3O_{10}(OH)_2 + SiO_2 \rightarrow Al_2SiO_5 + KAlSi_3O_8 + H_2O$$

muscovite + quartz → sillimanite + potassium fsp + water

THE ROLE OF TEMPERATURE IN METAMORPHISM (5)

Dehydration reactions may increase the rate of metamorphic reactions that require the presence of water.

The presence of water can also decrease the melting temperature of silicate minerals and enhance the formation of magma.

Dehydration reactions during metamorphism of subducted oceanic crust lead to magma generation at convergent plate boundaries.

THE ROLE OF TEMPERATURE IN METAMORPHISM (6)

2. **Degassing reactions – loss of gas**

$$CaCO_3 \rightarrow CaO + CO_{2(g)}$$

Calcite → Lime + Carbon dioxide

The most common degassing reactions release carbon dioxide from carbonate minerals.

THE ROLE OF PRESSURE IN METAMORPHISM

Pressure, like temperature, also affects mineral stability and influences crystal size and orientation.

Pressure is related to the concept of stress.

Both stress and pressure are defined as the magnitude of a force divided by the area of the surface on which the force is applied (see Figure 6.7a, b, and c on page 142).

<u>Strain</u> is the deformation of rock as a result of an applied stress. Normal stress causes change in volume and commonly the shape of material. Shear stress always causes changes in shape but not in volume.

THE ROLE OF PRESSURE IN METAMORPHISM (2)

Mineral stability is related not only to temperature, but also to applied stress.

Atoms rearrange into denser, more closely packed crystal structures at high pressure, such as the conversion of graphite to diamond.

Laboratory experiments show that this metamorphic reaction occurs when pressure exceeds 25 kilobars, or 25,000 times the pressure exerted on Earth's surface by the atmosphere.

THE ROLE OF PRESSURE IN METAMORPHISM (3)

Rock texture may change during metamorphism without changing chemical composition or minerals.

One example of recrystallization occurs when quartz sandstone undergoes metamorphism (see Figure 6.9 on page 143).

Once metamorphosed, the individual, round quartz grains within the sedimentary rock have a texture of straight-sided crystals that form three-sided junctions.

THE ROLE OF PRESSURE IN METAMORPHISM (4)

Strain during metamorphism results in changes in the texture of a rock.

Crystals are rearranged into planes, called <u>foliation</u>, depending on the type and orientation of the stress. Foliation planes are recognized by:

- **Preferred orientation of minerals (see Figure 6.10 on page 144)**
- **Alternating bands of different minerals (see Figure 6.11 on page 144)**
- **Flattening and stretching of minerals (see Figure 6.12 on page 145)**

THE ROLE OF PRESSURE IN METAMORPHISM (5)

Foliation forms by mechanical rotation of preexisting minerals or dissolution and new mineral growth along preferred orientations.

1. **Mechanical rotation or growth of crystals parallel to the direction of least stress typically forms foliation in rocks with platy minerals, such as clay and mica (see Figure 6.10).**

2. **Minerals may also dissolve and recrystallize, or their atoms rearrange into new minerals that form parallel to the direction of smallest normal stress (see Figure 6.12).**

THE ROLE OF PRESSURE IN METAMORPHISM (6)

3. **In some cases, the minerals segregate into compositional layers that are oriented according to the stress orientation (see Figure 6.11).**

All types of foliation are planes in the rock that are perpendicular to the greatest normal stress or parallel to shear stress.

THE ROLE OF FLUID IN METAMORPHISM

Fluids participate in metamorphism in two ways:

1. **Fluid reacts with minerals to form new minerals that contain constituents of the fluid molecules. These reactions typically create minerals containing constituents of water or carbon dioxide molecules.**
2. **Fluids generally alter the composition of metamorphic rocks compared to the parent rock by adding and removing dissolved ions. Fluid facilitates the occurrence of metamorphic reactions and increase the rate at which they occur.**

THE ROLE OF FLUID IN METAMORPHISM (2)

Metamorphic reactions that produce different minerals by the addition of water or carbon dioxide occur at higher temperature and pressure than chemical weathering.

The metamorphism of olivine in mafic and ultramafic igneous rocks is a common metamorphic reaction that involves both water and carbon dioxide.

$$2Mg_2SiO_4 + 2H_2O + CO_{2(g)} \rightarrow Mg_3Si_2O_5(OH)_4 + MgCO_3$$

Mg-olivine + water + carbon dioxide → serpentine + magnesite

THE ROLE OF FLUID IN METAMORPHISM (3)

Chemical reactions between solids do not occur, or take place very slowly, in the absence of water (see Figure 6.13 on page 146).

The results of laboratory experiments have demonstrated repeatedly that metamorphic reactions occur more quickly in the presence of water, and often at lower temperature, than by placing the dry ingredients together.

This is true even if the new minerals do not contain water. In fact, even dehydration reactions occur more readily when the minerals are immersed in water.

THE ROLE OF FLUID IN METAMORPHISM (4)

Fluids may either be part of the original parent rock or be introduced into the metamorphic environment.

1. **All rocks that form at or near the surface contain water in pore spaces or fractures, or along boundaries between mineral grains. When these rocks are subjected to low-grade metamorphic conditions, the fluids are already present to participate in reactions.**

   The presence of these fluids facilitates metamorphic reactions at these less extreme temperature and pressure conditions.

THE ROLE OF FLUID IN METAMORPHISM (5)

2. **Igneous intrusions are another important source of migrating fluids. These fluids, rich in dissolved ions, move into the surrounding rock as it is metamorphosed in response to heating from the intrusion.**

   This fluid not only delivers water, but also heat and ions from the magma.

3. **The presence of abundant fluid always produces a metamorphic rock with a very different bulk composition than the parent rock.**

THE ROLE OF FLUID IN METAMORPHISM (6)

In summary,

- **Fluids present in the original rock or introduced from magma or high-temperature dehydration and degassing reactions, create metamorphic minerals containing constituents from water and gas molecules.**
- **Metamorphic reactions occur faster and at lower temperatures in the presence of water than under dry conditions.**
- **Movement of fluid during metamorphism adds some ions and carries others away in solution so that the resulting metamorphic rock has a different composition than the parent rock.**

WHY METAMORPHIC ROCKS EXIST AT THE SURFACE

Most metamorphic rocks form a few to many kilometers (km) beneath the surface of the Earth, and are exposed to view only when the overlying rock and/or sediments are removed.

The primary reason that metamorphic rocks are most commonly associated with ancient or active mountain belts is that mountain building processes involve the uplifting of rock (see Figure 6.14 on page 148).

WHY METAMORPHIC ROCKS EXIST AT THE SURFACE (2)

Once exposed at the surface, minerals in metamorphic rocks are not transformed back to the original mineral because:

- **Heat is generally required for reactions to occur, but the temperature decreases as rocks are uplifted to the surface. Therefore, there is not enough heat available to drive the reactions.**

- **The loss of fluid during metamorphic dehydration also inhibits metamorphic minerals from transforming back to their original minerals. The reactions are not reversible if fluids have moved away from the rock and are no longer available to participate in reactions.**

WHY METAMORPHIC ROCKS EXIST AT THE SURFACE (3)

- **Reaction rates also tend to be very slow, and if the rocks rise rapidly toward the surface, there is not enough time for the reactions to be reversed.**

In summary, once metamorphic rocks have formed, the minerals present are not converted back to the original minerals in the parent rock. There is not sufficient temperature, pressure, fluid, or time to facilitate the necessary reverse reactions.

DETERMINING THE STABILITY OF METAMORPHIC MINERALS

Many minerals are stable over limited ranges in temperature and pressure. Changes in one or both of these variables cause a mineral to react and form a new mineral or minerals (see Figures 6.15 through 6.18 on pages 149-150).

The results of numerous laboratory studies performed with different minerals and under controlled conditions of temperature and pressure document the conditions where metamorphic minerals (and other minerals) are stable.

DETERMINING THE CONDITIONS OF METAMORPHISM

Some minerals, referred to as <u>index</u> <u>minerals</u>, are used to estimate the temperature and pressure conditions of metamorphism (see Figure 6.19 on page 151).

Index mineral reveal metamorphic grade, either low, medium, or high.

Only minerals with limited ranges of stability are useful as key index minerals. For example, minerals such as quartz and feldspar, are stable over a large range of temperature and pressure conditions and do not indicate the grade of metamorphism.

CLASSIFYING METAMORPHIC ROCKS

The variation in mineral content and texture of metamorphic rocks reveal the temperature and pressure of metamorphism and the composition of parent rocks and reactive fluids.

Composition and texture, therefore, are used as criteria for classifying metamorphic rocks (see Figure 6.20 on pageS 153-154). The primary textural attributes in metamorphic rocks are the presence or absence of foliation and mineral grain size.

CLASSIFYING METAMORPHIC ROCKS (2)

Rocks with Foliation

Slate is the first formed metamorphic rock and exhibits well-developed rock cleavage planes produced from the parallel orientation of very fine, microscopic mica grains.

Rock cleavage foliation is the preferential splitting of rock along planes of parallel microscopic micas; it is different than mineral cleavage.

Slate is used as a roofing material and also for making pool table tops.

CLASSIFYING METAMORPHIC ROCKS (3)

Rocks with Foliation

Phyllite forms under conditions of increasing metamorphic grade. Mica grains in phyllite are coarser than those in slate and generate a sheen from the reflection of light from the parallel mica cleavage surfaces.

Schist forms at still higher temperature and pressure. This rock has larger mica grains that are strongly parallel, easily seen with the naked eye, and relect light.

CLASSIFYING METAMORPHIC ROCKS (4)

Rocks with Foliation

Gneiss forms under conditions of high grade metamorphism and is identified by its characteristic foliation of parallel compositional layers of light-colored (quartz, feldspar) and dark-colored (biotite, amphibole, pyroxene, garnet) minerals. At the highest metamorphic temperatures gneisses lack mica or amphibole because these water-bearing minerals are broke down by dehydration reactions.

CLASSIFYING METAMORPHIC ROCKS (5)

Rocks with Foliation

Migmatite forms if the high-grade temperature, pressure, and fluid conditions are appropriate for melting to begin (see Figure 6.22 on page 156).

Migmatite resembles gneiss except that the light-colored bands have the igneous crystallizations texture of granite, and the dark layers show metamorphic crystal growth and recrystallization.

CLASSIFYING METAMORPHIC ROCKS (6)

Rocks without Foliation

If the metamorphic rock is nonfoliated or only weakly foliated, then the mineral content is more important for classification purposes (see Figure 6.20 on page 154).

Marble is the rock composed primarily of metamorphically recrystallized calcite.

Quartzite consists of metamorphically recrystallized quartz.

These nonfoliated rocks are distinct from limestone and sandstone because they have metamorphic recrystallization textures, such as large grain sizes meeting along straight edges, or both.

CLASSIFYING METAMORPHIC ROCKS (7)

Rocks without Foliation

Amphibolite is a metamorphic rock composed primarily of amphibole minerals with plagioclase feldspar.

Serpentinite is a metamorphic rock composed almost entirely of serpentine.

CLASSIFYING METAMORPHIC ROCKS (8)

Rocks without Foliation

Organic compounds also undergo metamorphic reactions. Coal contains few minerals, but as the temperature increases, H- and N-rich organic compounds are broken down and escape from the coal as gas. This results in conversion of the organic matter to 90 percent or more pure C. Pyrite (FeS_2), commonly found in coal also breaks down, and the sulfur is released as gaseous compounds.

Metamorphosed coal, called anthracite, is the highest quality coal because it provides the most heat upon combustion and contains low quantities of the sulfur compounds that pollute the atmosphere.

CLASSIFYING METAMORPHIC ROCKS (9)

Rocks without Foliation

Hornfels is the name applied to any very hard, nonfoliated metamorphic rock composed mostly, or entirely of, microscopically small crystals, regardless of composition.

The newly formed metamorphic minerals in hornfels are those whose origin is related more to changes in temperature than changes in pressure.

The insignificance of pressure in the formation of hornfels is also suggested by the lack of foliation.

CLASSIFYING METAMORPHIC ROCKS (10)

Rocks without Foliation

Other nonfoliated or weakly foliated metamorphic rocks containing many minerals include greenstone and eclogite formed by metamorphism of mafic igneous rocks.

Greenstone is a metamorphic rock that contains abundant green minerals. The Fe-Mg mica, chlorite, is generally the primary constituent, although green amphibole, feldspar and quartz are typically present as well.

Eclogite is a very high grade metamorphic rock that lacks water bearing minerals. It is dominated by garnet and pyroxene, sometimes with minor quartz. Eclogite is denser than peridotite.

WHAT WAS THE ROCK BEFORE METAMORPHISM?

Metamorphosed Sedimentary Rocks

Quartz sandstone and limestone typically metamorphose to nonfoliated rocks composed of a single mineral, because a single, nonplaty mineral dominates the rock (see Figure 6.23 on page 157).

Arkose or lithic sandstone containing significant nonquartz grains may form micas at the expense of feldspar and other minerals during low-grade metamorphism in the presence of water. The resulting rocks may be weakly foliated mica-rich quartzite or even schist if the amount of quartz in the sandstone is minimal.

WHAT WAS THE ROCK BEFORE METAMORPHISM? (2)

Metamorphosed Igneous Rocks

Low- to medium-grade metamorphism of mafic and intermediate igneous rocks in the presence of water generates dark-colored metamorphic rocks with abundant Fe- and Mg-bearing mica, like chlorite or biotite (see Figure 6.23).

If foliated these rocks are chlorite or biotite schists, and if not foliated, they are greenstones.

WHAT WAS THE ROCK BEFORE METAMORPHISM? (3)

Metamorphosed Igneous Rocks

At higher metamorphic grade, hornblende becomes increasingly stable and forms amphibolites.

At the highest grade of metamorphism, the rock is gneiss or eclogite.

WHAT WAS THE ROCK BEFORE METAMORPHISM? (4)

Metamorphosed Igneous Rocks

Felsic igneous rocks metamorphose to schist is water is available to convert feldspar to muscovite. Otherwise, substantial textural or mineralogical changes may not occur, until high-grade conditions cause segregation of minerals into bands to form gneiss.

Gneiss formed from metamorphism of igneous rock may be difficult to distinguish from a highly metamorphosed shale. Igneous gneisses, however, are less likely to contain the very Al-rich minerals such as muscovite, staurolite, corundum, kyanite, and sillimanite formed by metamorphism of clay.

WHERE DOES METAMORPHISM OCCUR?

Field studies of the distribution of metamorphic rocks and their associations with igneous and sedimentary rocks indicate that there are three general types of metamorphic settings (see Table 6.1 on page 158). These are:

- **Contact**
- **Hydrothermal**
- **Regional**

WHERE DOES METAMORPHISM OCCUR? (2)

Contact Metamorphism

Contact metamorphism occurs near the contacts of igneous intrusions, or less extensively, beneath erupted lava flows (see Figure 6.24 on page 159).

Heat results in metamorphism, which is limited to the region adjacent to the magma or lava. The amount of heat introduced by the magma or lava and the extent of fluid movement determines the volume of rock metamorphosed.

Heat is the dominant factor in contact metamorphism, so the resulting rocks are generally nonfoliated. Hornfels is the most common contact metamorphic rock.

WHERE DOES METAMORPHISM OCCUR? (3)

Contact Metamorphism

Metamorphic grade is highest close to the contact with the igneous rock and decreases with distance from the intrusion.

In the field, the observation of decreasing grade of metamorphism away from the intrusion indicated that heat from the intruding body caused the metamorphism. This is the most diagnostic field criterion for recognizing contact metamorphism.

WHERE DOES METAMORPHISM OCCUR? (4)

Hydrothermal Metamorphism

Hydrothermal metamorphism involves the migration and reaction of hot, ion-rich fluids. As a result, this metamorphism involves chemical change in the rock because of hot water circulating through pore spaces and cracks.

Hydrothermal metamorphism is commonly associated with contact metamorphism on a local scale, but also occurs on a large scale at volcanically active mid-ocean ridges.

WHERE DOES METAMORPHISM OCCUR? (5)

Hydrothermal Metamorphism

At mid-ocean ridges, hydrothermal metamorphism occurs where hot magma rises to create ocean floor and circulating seawater is available for metamorphic reactions (see Figure 6.25 on page 161).

These sites are often associated with genesis of ores, where metal-rich sulfide minerals precipitate from hot, circulating hydrothermal fluids within and above fissures in the sea floor (see Figure 6.26 and 6.27 on page 161 and 162).

WHERE DOES METAMORPHISM OCCUR? (6)

Regional Metamorphism

Regional metamorphism refers to metamorphism over large areas and to volumes of rocks not related to specific igneous intrusions or sources of hydrothermal fluid.

This metamorphism typically relates to the formation of mountain belts along subduction zones.

Regional metamorphism involves progressively increasing temperature- and pressure-driven mineralogical and textural changes to rock. Large volumes of continental crust are involved, and in some cases, oceanic crust and mantle.

WHERE DOES METAMORPHISM OCCUR? (7)

Regional Metamorphism

Regional metamorphism occurs under the influence of tectonic stresses as well as the pressure exerted by overlying rock (see Figure 6.28 on page 162).

These stresses include near-horizontal normal and shear stresses associated with the horizontal convergence of plates at subduction zones.

As a result, regional metamorphic rocks are nearly always foliated; the foliation may be vertical or at some intermediate angle depending on the orientation of stresses.