Geochemistry of Metamorphic Rocks

Metamorphic rocks are derived from other rocks of igneous, sedimentary or metamorphic origin. The chemical composition of this primary material (= protolith) determines the chemical and mineralogical composition of metamorphic rocks to a large degree. The structure of metamorphic rocks is often inherited from the precursor material. In low-grade metasedimentary rocks, for example, the sedimentary bedding and typical structures of sedimentary rocks such as cross-bedding and graded bedding may be preserved. Ophitic structure, characteristic of basaltic lava, may be found in mafic metamorphic rocks. Very coarse-grained structures of igneous origin can occasionally be found even in high-grade metamorphic rocks. Most metamorphic rocks, however, exhibit structures that are of distinct metamorphic origin. The structures typically result from a combination of deformation and recrystallization. Deformation normally accompanies large-scale tectonic processes causing metamorphism.Large-scale tectono-thermal processes move rocks along unique paths in pressure-temperature-time (P-T -t) space. Rocks may undergo continuous recrystallization and new minerals may replace old ones in a complex succession. Earlier-formed minerals and groups of minerals often experience metastable survival because of unfavorable reaction kinetics. This happens particularly if an aqueous fluid phase is absent. Metamorphism may proceed episodically. The study of metamorphic rocks aims at the correct identification of the group of minerals that may have coexisted in chemical equilibrium at one stage during the evolutionary history of the metamorphic rock. This group of minerals is the mineral assemblage. The total succession of mineral assemblages preserved in a metastable state in the structure of a metamorphic rock is designated mineral paragenesis. Discussion and analysis of phase relationships in metamorphic rocks is greatly facilitated by the use of composition phase diagrams. mineral assemblages.

Primary Material of Metamorphic Rocks

All metamorphic rock-forming processes make rocks from other rocks. The precursor rock or protolith determines many attributes of the new metamorphic rock. Metamorphism results from the addition (or removal) of heat and material to discrete volumes of the crust or mantle by tectonic or igneous processes. Metamorphism, therefore, may affect all possible types of rock present in the earth's crust or mantle. Protoliths of metamorphic rocks comprise rocks of all possible chemical compositions and include the entire range of sedimentary, igneous and metamorphic rocks. Metamorphic processes tend to change the original composition of the protolith. Addition of heat to rocks typically results in the release of volatiles (H20, COz, etc.) that are stored in hydrates (e. g., clay, micas, amphiboles), carbonates and other minerals containing volatile components. Therefore, many metamorphic rocks are typically depleted in volatiles relative to their protoliths. Metamorphism that releases only volatiles from the protolith is, somewhat illogically, termed isochemical. On a volatile-free basis, the chemical composition of protolith and product rock is identical in isochemicalmetamorphism. In truly isochemical metamorphism, protolith and productrocks are of identical composition including the volatile content. Isochemical metamorphism in such a strict sense is extremely rare. Many, if not most, metamorphic processes also change the cationic composition of the protolith. This type of metamorphism is termed allochemical metamorphism or metasomatism. The aqueous fluid released by dehydration reactions during metamorphism may contain dissolved cations. These are then carried away with the fluid and lost by the rock system. It has been found, for example, that many granulite facies gneisses are systematically depleted in alkalis (Na and K) relative to their amphibolite facies precursor rocks. This can be explained by loss of alkalis during dehydration. Silica saturation is a general feature of almost all metamorphic fluids. Pervasive or channeled regional-scale flow of silica-saturated dehydration fluids may strongly alter silica-deficient rocks (ultramafic rocks, dolomite marbles) that come into contact with this fluid. Unique metamorphic rock compositions may result from metasomatism on a local or regional scale. Efficient diffusion and infiltration metasomatism requires the presence of a fluid phase. Metasomatism is fluid-rock interaction at elevated temperature and pressure. Fluid-rock interaction is also important in sedimentary and other near-surface environments. Interaction of rocks with externally derived fluids is referred to as allochemical metamorphism. The volatile composition of the fluid may not be in equilibrium with the rock's mineralogy and, consequently, the rock may be altered. Some examples: flushing of rocks with pure H20 under high P-T conditions may initiate partial melting; it may form mica and amphibole in pyroxene-bearing rocks; it may induce wollastonite or periclase formation inmarbles.

Metamorphic Rock Classification

Crystal Size	Mineralogy	Protolith	Metamorphism	Rock Name
Foliated Metamorphic Rocks				
very fine	clay minerals	shale	low grade regional	slate
fine	clay minerals, biotite, muscovite	shale	low grade regional	phyllite
medium to coarse	biotite, muscovite, quartz, garnet, plagioclase	shale, basalt	medium grade regional	schist
medium to coarse	amphibole, plagioclase, biotite	basalt	medium grade regional	amphibolite *(Note: may be unfoliated)*
medium to coarse	plagioclase, orthoclase, quartz, biotite, amphibole, pyroxene	basalt, granite, shale	high grade regional	gneiss
Unfoliated Metamorphic Rocks				
Crystal Size	**Mineralogy**	**Protolith**	**Metamorphism**	**Rock Name**
fine to coarse	quartz	sandstone	regional or contact	quartzite
fine to coarse	calcite	limestone	regional or contact	marble
fine	pyroxene, amphibole, plagioclase	shale	contact	hornfels

Metamorphic rocks arise from the transformation of existing rock types, in a process called metamorphism, which means "change in form". The original rock (protolith) is subjected to heat (temperatures greater than 150 to 200 °C) and pressure (100 megapascals (1,000 bar) or more), causing profound physical or chemical change. The protolith may be a sedimentary, igneous, or existing metamorphic rock.

Metamorphic rocks make up a large part of the Earth's crust and form 12% of the Earth's land surface. They are classified by texture and by chemical and mineral assemblage (metamorphic facies). They may be formed simply by being deep beneath the Earth's surface, subjected to high temperatures and the great pressure of the rock layers above it. They can form from tectonic processes such as continental collisions, which cause horizontal pressure, friction and distortion. They are also formed when rock is heated by the intrusion of hot molten rock called magma from the Earth's interior. The study of metamorphic rocks (now exposed at the Earth's surface following erosion and uplift) provides information about the temperatures and pressures that occur at great depths within the Earth's crust. Some examples of metamorphic rocks are gneiss, slate, marble, schist, and quartzite.

Metamorphic minerals

Metamorphic minerals are those that form only at the high temperatures and pressures associated with the process of metamorphism. These minerals, known as index minerals, include sillimanite, kyanite, staurolite, andalusite, and some garnet.

Other minerals, such as olivines, pyroxenes, amphiboles, micas, feldspars, and quartz, may be found in metamorphic rocks, but are not necessarily the result of the process of metamorphism. These minerals formed during the crystallization of igneous rocks. They are stable at high temperatures and pressures and may remain chemically unchanged during the metamorphic process. However, all minerals are stable only within certain limits, and the presence of some minerals in metamorphic rocks indicates the approximate temperatures and pressures at which they formed.

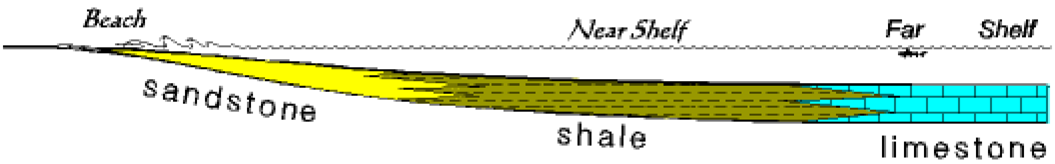
The change in the particle size of the rock during the process of metamorphism is called recrystallization. For instance, the small calcite crystals in the sedimentary rock limestone and chalk change into larger crystals in the metamorphic rock marble; in metamorphosed sandstone, recrystallization of the original quartz sand grains results in very compact quartzite, also known as metaquartzite, in which the often larger quartz crystals are interlocked. Both high temperatures and pressures contribute to recrystallization. High temperatures allow the atoms and ions in solid crystals to migrate, thus reorganizing the crystals, while high pressures cause solution of the crystals within the rock at their point of contact.

Metamorphic Rocks Classification on basis of Mineralogical Composition

Metamorphic Rock Composition

Metamorphism is the alteration of a parent rock into a metamorphic rock. There are as many parent rocks as there are igneous, sedimentary, and metamorphic rocks, since any of these can be metamorphosed.

But, the simplest way to examine compositional changes during metamorphism is to start with the three end products of the Simple Model For Sedimentary Rocks, shown in the illustration below (click picture for full model). These weathering products are also the most common sedimentary rocks and form a very large percentage of the metamorphic rocks we see.



These three end products (Attractors) in the sedimentary model (Quartz Sandstone, Shale, and Limestone) become the three parent rocks of metamorphism. All the metamorphic rocks discussed here, and included in the identification key (see below) come from these three parents.

The Changes We See

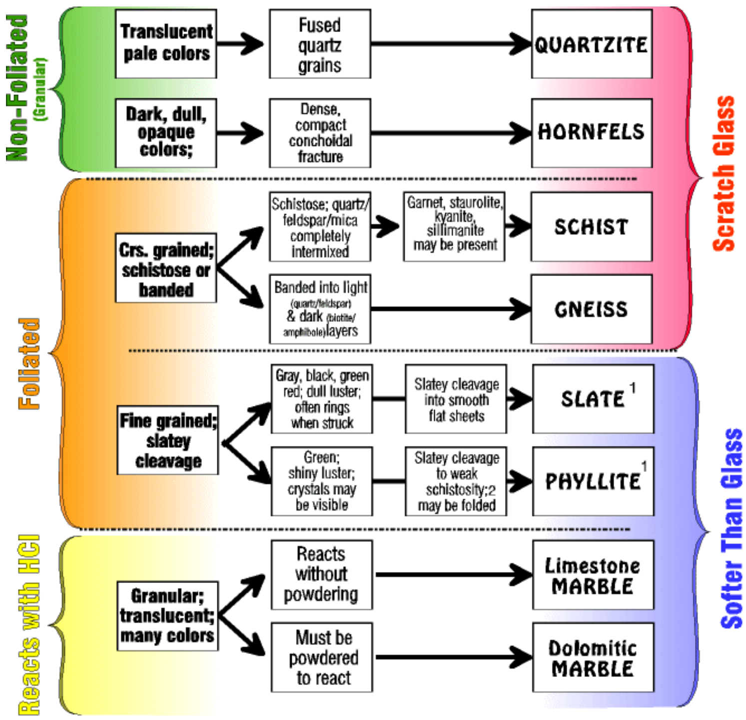
Compositionally simple sedimentary rocks, such as quartz sandstone and limestone (calcite) do not change composition with metamorphism - their chemistry is too simple. Quartz remains quartz, and calcite remains calcite. The rocks do recrystallize, though, forming granular rocks with fused grains; the rocks quartzite and marble. It does not matter by what process you metamorphose quartz sandstone and limestone, their composition does not change, and they produce the same kind of metamorphic rock.

Rocks with a more complex chemical composition, such as shale (the mineral clay), however, undergo many compositional, and textural changes. Shale produces the greatest diversity of metamorphic rocks, so many changes in fact that it is sometimes hard to believe they could all come from the same parent. We can see this in the chart below where sedimentary shale turns into Slate, then Phyllite, then Schist, then Gneiss. These rocks look so different that it can be hard to imagine they are all derived from the same shale parent (and this does not even include the Hornfels produced when shale is contact metamorphosed).

IDENTIFICATION KEY TO COMMON METAMORPHIC ROCKS

Rocks are identified by making a series of decisions about their properties, such as texture, composition, hardness, etc. This requires the ability to observe and recognize these properties - one of the skills of science that must be learned for each group of rocks.

The Key To Common Metamorphic Rocks allows someone to identify a rock based on its properties. We are able to do this because the properties do not overlap completely. You can see this on the key through the color coding for the properties. None of the colors overlap completely.



1 (Shale), slate, and phyllite complete intergrade with each other. Distinctions may be difficult.

The Relationships between Rock and Process

One final observation. It would be nice if there was a simple relationship between the processes of metamorphism and the rocks produced. For example, if all schist rocks were produced by the same kind of metamorphism. Or, if a particular kind of metamorphism produced rocks not found in any other kind of metamorphism. Unfortunately, such simple relationships do not exist. True, some rocks are confined to one kind of metamorphic process, but other rocks result from more than one kind of metamorphism. Eventually these relationships have to be learned, but they can be easily summarized in the table to the right for this simple classification.

Observe that hornfels, quartzite, and marble are contact metamorphic rocks, but that hornfels is the only strictly contact metamorphic rock. And, note that quartzite and marble can be formed by both contact and Barrovian metamorphism.

One lesson might be that simple parent rocks undergo simple metamorphism, regardless of the kind or intensity of metamorphism. Another lesson is, quartzite and marble cannot tell you the kind of metamorphism, although hornfels, slate, phyllite, schist, and gneiss can.