Lab 6: Metamorphic Rocks

Introduction

The Earth's crust is in a constant state of change. For example, plutonic igneous rocks are exposed at the surface through uplift and erosion. Many minerals within igneous rocks are unstable at the surface of the Earth and decompose by weathering. Similarly, sedimentary or volcanic rocks are frequently buried by accumulations of younger material. As a result of burial, they experience physical conditions different from those at the Earth's surface. Many minerals from the surface are unstable at this depth and chemically react to produce more stable minerals. Also, the weight of the overlying material imposes direct pressure on buried rocks and they become more compact by internal rearrangement of minerals. The mineralogical and textural changes produced by increased temperature and pressure are collectively called metamorphism. The rocks produced by these processes are called metamorphic rocks.

Metamorphism takes place at temperatures and pressures that fall between those in which sediments are lithified (become rock) and those in which rocks begin to melt and form magmas. Figure 6-1 shows the approximate upper and lower boundaries of metamorphic conditions. It is important to note that these boundaries represent "average" rocks. Some rocks, such as granite, are not affected much by metamorphism until temperatures and pressures are well within the field of metamorphic conditions. Similarly, actual melting begins at different temperature and pressure conditions for different rocks.

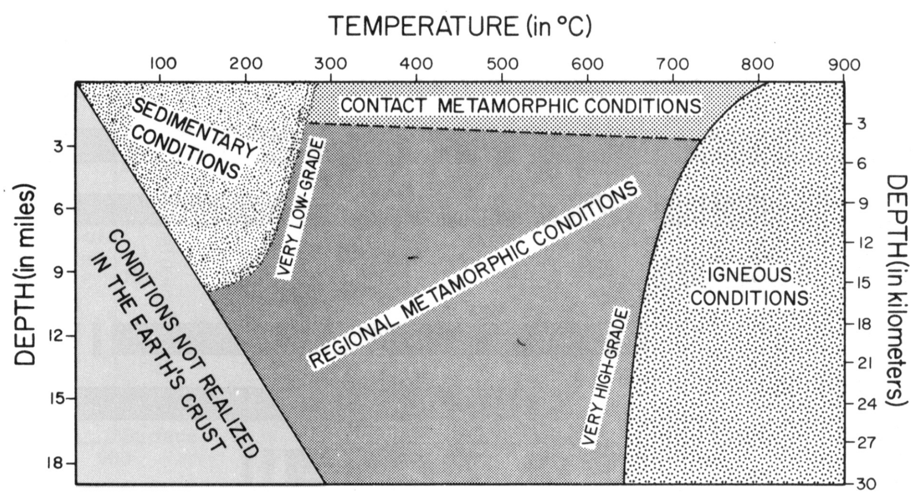

Figure 6-1. Diagram illustrating the pressure and temperature conditions of metamorphism. Note that there is a gradual transition between the sedimentary processes of diagenesis and low-grade metamorphism and that high-grade metamorphism grades into igneous (rock melting) processes at higher

Water and other fluids, such as carbon dioxide, are generally present during metamorphism, because they are contained in the rocks undergoing metamorphism and/or they are released by metamorphic reactions. These fluids are important in metamorphism because they allow ions to move about more readily, thereby speeding up metamorphic reactions and enabling the growth of mineral crystals.

There are two common types of metamorphism: regional and contact metamorphism. Regional metamorphism can occur over an area of hundreds to thousands of square kilometers. Regionally metamorphosed rocks are buried beneath thick accumulations of sediment and rock sometime during their history. During this period of burial, they are subjected to higher temperatures and pressures than present at the surface (Figure 6-1). The weight of the overlying sediment and rock provides most of the pressure, but tectonic forces within the Earth, such as those at convergent plate margins, also may contribute.

Heat from intruding bodies of magma may cause contact metamorphism of the surrounding rock. Fluids released from the magma or the surrounding rocks may accentuate the changes. Contact metamorphism is most evident around igneous intrusions that formed within a few kilometers of the surface (Figure 6-1); at greater depths, it becomes difficult to differentiate the effects of contact and regional metamorphism.

A. Identifying and Understanding Metamorphic Rocks

The important changes that take place during metamorphism are:

(1) recrystallization of existing minerals, especially into larger crystals;
(2) chemical breakdown of unstable original minerals and crystallization and growth of new minerals that are stable in the metamorphic environment; and
(3) deformation and reorientation of existing mineral crystals and growth of new ones with a distinctive orientation. This alignment is called foliation.

The extent to which each of these processes operates during metamorphism depends upon the mineralogy of the original rock (parent rock, or "**protolith**") and the depth and temperature at which the alteration occurred. The combined effects of these metamorphic processes generally produce rocks that have larger crystals than their protoliths (are coarser-grained) and/or have a foliated (layered) texture.

The term metamorphic grade refers to the pressure/temperature conditions in metamorphic rocks. High-grade rocks were subjected to high temperatures (550-700°C) and high pressures (equivalent to a depth of 15-35 km), whereas low-grade rocks were subjected to low temperatures (250-400°C) and pressures (6-12 km depth). The texture and mineralogical composition of a metamorphic rock is a function of the metamorphic grade and the composition of the protolith.

Metamorphic Rock Composition

Metamorphic rocks contain many of the same minerals found in igneous and sedimentary rocks. Certain minerals however, occur almost exclusively in metamorphic rocks. Diagnostic properties used to identify the common metamorphic rock-forming minerals are shown in Table 6-1.

Each mineral found in metamorphic rocks is stable within a specific range of pressure and temperature conditions. If that range is exceeded, the mineral begins to break down into its constituent chemical components. A new mineral that is stable under these new temperature and pressure conditions will then form from these components. Minerals that form within a specific range of pressure and temperature conditions are called index minerals. The presence or absence of specific index minerals in a metamorphic rock can therefore help us constrain the approximate temperature and pressure conditions at which the rock formed.

Mineral	Properties
Orthoclase	Usually pink; 2 cleavages at 90°
Plagioclase	Usually white or gray; 2 cleavages at 90°; elongate grains; striations
Quartz	variable color, often clear; glassy with conchoidal fracture; irregularly-shaped grains
Biotite	Shiny, black sheets; one perfect cleavage; may define foliation
Muscovite	Shiny, transparent sheets; one perfect cleavage; may define foliation
Amphibole	Black with shiny, splintery appearance; two cleavages at 60° and 120°; elongate parallel grains
Garnet	Usually pink, red, or reddish-brown; vitreous to resinous luster; 12-sided crystals are common
Kyanite	Light to greenish blue; long blade-shaped crystals
Graphite	Gray to black; metallic; soft, marks paper; greasy feel
Talc	White, gray, or apple green; pearly luster; greasy feel; can be scratched by fingernail
Chlorite	Green to blackish green; 1 good cleavage; commonly small, flaky sheets; may define foliation
Calcite	Often white, gray, or black; reacts to acid; doesn't scratch glass

Table 6-1. Diagnostic properties of the common metamorphic rock-forming minerals.

The mineralogy of a particular metamorphic rock also depends upon the chemical composition of its protolith. For example, aluminum- and potassium-rich minerals such as muscovite and biotite cannot form during the metamorphism of a pure quartz sandstone. Protolith compositions can be extremely varied; they can be grouped, however, into four distinct chemical types:

(1) Protoliths that are rich in aluminum and potassium. Possible protoliths include clay-rich sedimentary rocks such as shale and siltstone, and some felsic volcanic rocks. Metamorphic rocks formed from these rock types tend to contain abundant biotite and muscovite. They also contain one or more of the following minerals: quartz, plagioclase, garnet, andalusite, staurolite, and/or kyanite.

(2) Protoliths that are rich in iron, magnesium, and calcium. Possible protoliths include various types of mafic igneous rocks, such as basalt. Metamorphic rocks formed from these rock types tend to contain abundant talc, chlorite, epidote, biotite, amphibole, garnet, and/or plagioclase.

(3) Protoliths composed mostly of quartz, such as sandstone. Because quartz is stable over a wide range of temperatures and pressures, metamorphic rocks formed from quartz-rich protoliths show little mineralogical change and contain abundant recrystallized quartz.

(4) Protoliths composed mainly of calcite, such as limestone. Like quartz, calcite is stable over a wide range of temperatures and pressures; therefore, metamorphic rocks formed from calcite-rich protoliths contain abundant recrystallized calcite.

Table 6-2 lists the common minerals produced from different protoliths during metamorphism.

Protolith	**Contact Metamorphism**	**Low Grade**	**Medium Grade**	**High Grade**
Al and K rich (e.g., shales)	Mica*, Feldspar*, Amphibole	Clay, Mica*	Mica*, Garnet, Quartz	Feldspar*, Quartz, Garnet, Amphibole
Fe, Mg, Ca rich (e.g., mafic igneous rocks)	Pyroxene, Amphibole	Talc, Chlorite	Amphibole, Plagioclase	Pyroxene, Amphibole, Plagioclase, Garnet
Quartz rich rocks	Quartz	Quartz	Quartz	Quartz
Calcite rich rocks	Calcite	Calcite	Calcite	Calcite, Feldspar*

Table 6-2. Common minerals produced from different protoliths exposed to different grades of metamorphism. (***** Note that "mica" includes muscovite and biotite and "feldspar" includes orthoclase and plagioclase.)

1. **Identify eight of the common metamorphic rock-forming minerals** (specimens M-1 through M-8). You identified many of these minerals in previous labs. Refer to your mineral identification charts (Tables A-1, A-2, and A-3) and the diagnostic properties of metamorphic rock-forming minerals (Table 6-1).

Specimen #	Mineral Name	Specimen #	Mineral Name
M-1		M-5	
M-2		M-6	
M-3		M-7	
M-4		M-8	

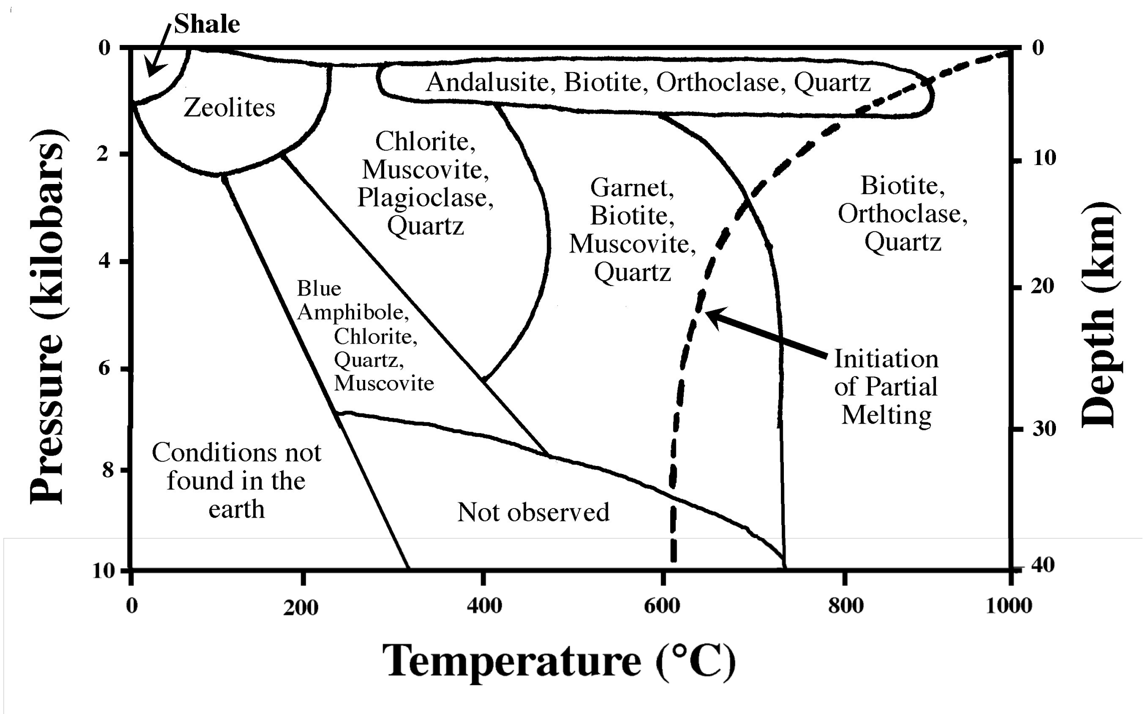

Figure 6-2. Mineralogical changes during the metamorphism of a shale.

2. **Look at rock A, a metamorphosed shale, which your TA has set up somewhere in your lab room.** Use Figure 6-2, which shows the changes in mineral assemblage in a shale due to metamorphism, to assist in answering the following questions.

   (a) **Name two or more minerals in this metamorphic rock**.

(b) Use the minerals you have identified and Figure 6-2 to determine the likely range of pressures and temperatures at which this rock formed. **List the *range* of temperatures and the *range* of pressures below (in °C and kilobars).**

(c) **Do these minerals form under conditions of low-, medium-, or high-grade metamorphism?**

(d) **If the pressure during metamorphism dropped below 1 kilobar, what minerals would you expect to find in this metamorphic rock?** (Use Figure 6-2.)

3. Which would be more useful to infer the given information about a metamorphic rock: its *mineral composition* or its *chemical (elemental) composition*? **Explain your answer**.
   (a) the protolith of the rock before metamorphism?

   (b) the pressure and temperature conditions experienced during metamorphism?

4. To the best of your ability, **identify the minerals present in each of the rock specimens in your tray (R-1 to R-7).** Write your answer on the Metamorphic Rock ID Chart (page 9) under "composition." Along with the diagnostic minerals (Table 6-1), the composition may also include "clay minerals" and "rock fragments".

Metamorphic Rock Texture

Many metamorphic rocks are classified on the basis of their foliation. <u>Foliation</u> is a planar feature found throughout the rock (resembling the pages of a closed book) caused by the parallel orientation of elongate or platy minerals such as clays or mica, or by the segregation of minerals of different compositions into distinct layers. The orientation of foliation will be perpendicular to the direction from which pressure was applied. We will examine three different types of foliation: slaty cleavage, schistosity, and gneissic banding (Figure 6-3).

(1) <u>Slaty cleavage</u> is the tendency of a rock to split along regular parallel planes (which are not to be confused with sedimentary bedding planes). This cleavage results from the parallel orientation of clays and/or very fine-grained micas. The resultant low grade metamorphic rock, <u>slate</u>, is generally formed by the regional metamorphism of shale or siltstone.

(2) A <u>schist</u> is a rock characterized by the parallel alignment of mica crystals. This planar fabric is called <u>schistosity</u> and generally results from medium-grade metamorphism. Schists contain minerals with a larger grain size than slate.

(3) High-grade metamorphism leads to the segregation of different minerals into distinct layers, resulting in a rock with a banded appearance, called a <u>gneiss</u>. Gneiss typically

occurs at a significant depth within the Earth's crust. The compositional layering is called gneissic banding.

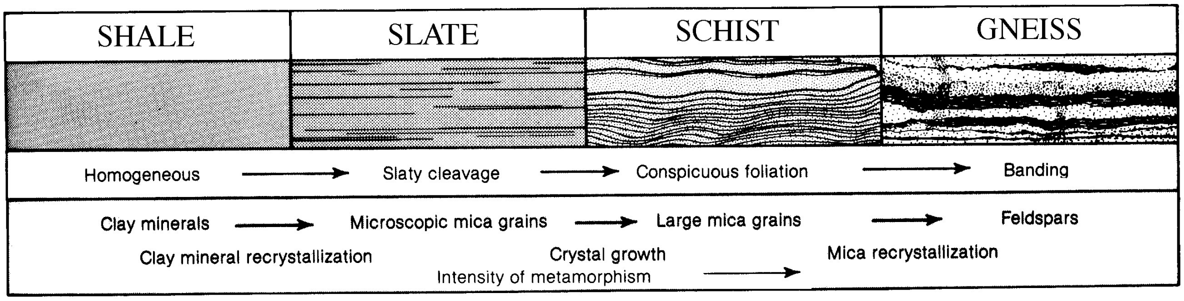

Figure 6-3. The textural changes associated with the metamorphism of a shale, a sedimentary rock, with increasing metamorphic grade.

At even higher temperatures and pressures, the felsic component of a metamorphic rock begins to melt, resulting in a rock with mixed igneous and metamorphic characteristics known as a migmatite. (A good example of a migmatite can be seen on the first floor of Johnson Hall, on the wall near the southeast staircase.) If temperatures and pressures continue to increase, the entire rock will melt.

Metamorphic rocks that do not exhibit foliation have a non-foliated or crystalline texture. In these instances, the rock is named based on its composition rather than its texture. Marble, for instance, is composed of recrystallized calcite ($CaCO_3$), or dolomite ($(Ca,Mg)(CO_3)_2$), and results from the metamorphism of limestone. Quartzite is composed of recrystallized quartz grains and is formed by the metamorphism of a quartz sandstone. These rocks do not usually have foliation because they contain only equidimensional (not elongate or platy) minerals, which cannot align into layers, and have a simple chemical composition, so they cannot segregate into bands of different composition.

6. **Identify the metamorphic textures of specimens R-1 to R-3** as “slaty cleavage”, “schistosity”, or “gneissic banding”. **Interpret their grade of metamorphism** (“low”, “medium”, or “high”) based on the texture.

Specimen #	**Texture**	**Metamorphic Grade**
R-1		
R-2		
R-3		

7. (a) **What changes would you expect to see in a shale as it is subjected to increasingly higher temperatures and pressures?**

(b) How does the rock's grain size change during this process?

8. **Describe the texture of specimens R-1 through R-7 on your Metamorphic Rock ID Chart.** First determine if they are foliated or nonfoliated and write "F" or "NF" in the appropriate column. Then describe their texture in the column labeled "texture". If they are nonfoliated, you can describe the texture as "crystalline". If foliated, describe the texture as consisting of "slaty cleavage", "schistosity", or "gneissic banding".

Identifying Metamorphic Rocks

A metamorphic rock may be classified by comparing its textural and mineralogical properties with the Metamorphic Rock ID Chart (Table 6-3). Be aware that metamorphic rock types are texturally and mineralogically gradational. Therefore, the subdivisions between rock types are somewhat arbitrary.

9. **Use your Metamorphic Rock ID Chart (Table 6-3) to name the seven rock specimens in your tray.** *Please note that we do not include a sample of *phyllite* in the metamorphic rock collection for this lab. It is an intermediate grade of metamorphism between slate and schist. The microscopic minerals, such as, muscovite, chlorite and graphite give it a silky to golden sheen called the "phyllitic luster."

Specimen #	Composition	Foliated (F) or Nonfoliated (NF)	Texture	Rock Name
R-1				
R-2				
R-3				
R-4				
R-5				
R-6				
R-7				

Table 6-3

Scheme for Metamorphic Rock Identification

TEXTURE		GRAIN SIZE	COMPOSITION	TYPE OF METAMORPHISM	COMMENTS	ROCK NAME
FOLIATED	MINERAL ALIGNMENT	Fine	MICA; clay minerals	Regional	Low-grade metamorphism of shale	Slate
FOLIATED	MINERAL ALIGNMENT	Fine to medium	MICA, QUARTZ, FELDSPAR, AMPHIBOLE, GARNET	Regional (Heat and pressure increase with depth)	Foliation surfaces shiny from microscopic mica crystals	Phyllite
FOLIATED	MINERAL ALIGNMENT	Fine to medium	MICA, QUARTZ, FELDSPAR, AMPHIBOLE, GARNET, PYROXENE	Regional (Heat and pressure increase with depth)	Platy mica crystals visible from metamorphism of clay or feldspars	Schist
FOLIATED	BAND-ING	Medium to coarse	MICA, QUARTZ, FELDSPAR, AMPHIBOLE, GARNET, PYROXENE	Regional (Heat and pressure increase with depth)	High-grade metamorphism; some mica changed to feldspar; segregated by mineral type into bands	Gneiss
NONFOLIATED		Fine	Variable	Contact (Heat)	Various rocks changed by heat from nearby magma/lava	Hornfels
NONFOLIATED		Fine to coarse	Quartz	Regional or Contact	Metamorphism of quartz sandstone	Quartzite
NONFOLIATED		Fine to coarse	Calcite and/or dolomite	Regional or Contact	Metamorphism of limestone or dolostone	Marble
NONFOLIATED		Coarse	Various minerals in particles and matrix	Regional or Contact	Pebbles may be distorted or stretched	Metaconglomerate

10. **List two reasons why specimen R-4 does not have a foliation**. (Consider its mineralogy.)

11. (a) **Use the metamorphic minerals present in the following rock specimens to determine a possible protolith**. Choose between a shale, a basalt, a limestone, and a quartz sandstone.

Specimen #	**Protolith type**
R-2	
R-4	
R-6	

12. (a) Rock B on the side table is the protolith of specimen R-7. **Identify Rock B**.

(b) **What physical characteristic could you use to distinguish specimen R-7 from Rock B?**

B. Metamorphic Rocks and Plate Tectonics

Most metamorphic rocks were probably formed in orogenic (mountain) belts at convergent plate margins. A subducting oceanic plate sets in motion a series of processes, each of which is related to one or more kinds of metamorphism.

(1) First, the subducting oceanic plate creates a trench that collects sediments eroding from the continent. These sediments get dragged down with the subducting plate and become exposed to increasing pressures. (A in Figure 6-4.)

(2) Second, the cold ocean plate and the "wet" sediments it carries begin to heat as they subduct. At a depth of about 120 km the "wet" sediments are hot enough to melt, releasing magma that rises into the overlying continental crust. (B in Figure 6-4.)

(3) Third, the heat from the rising magmas and the compression of the two plates coming together cause the crust to buckle upward and form a mountain range. Each of these processes are responsible for a specific kind of metamorphism.

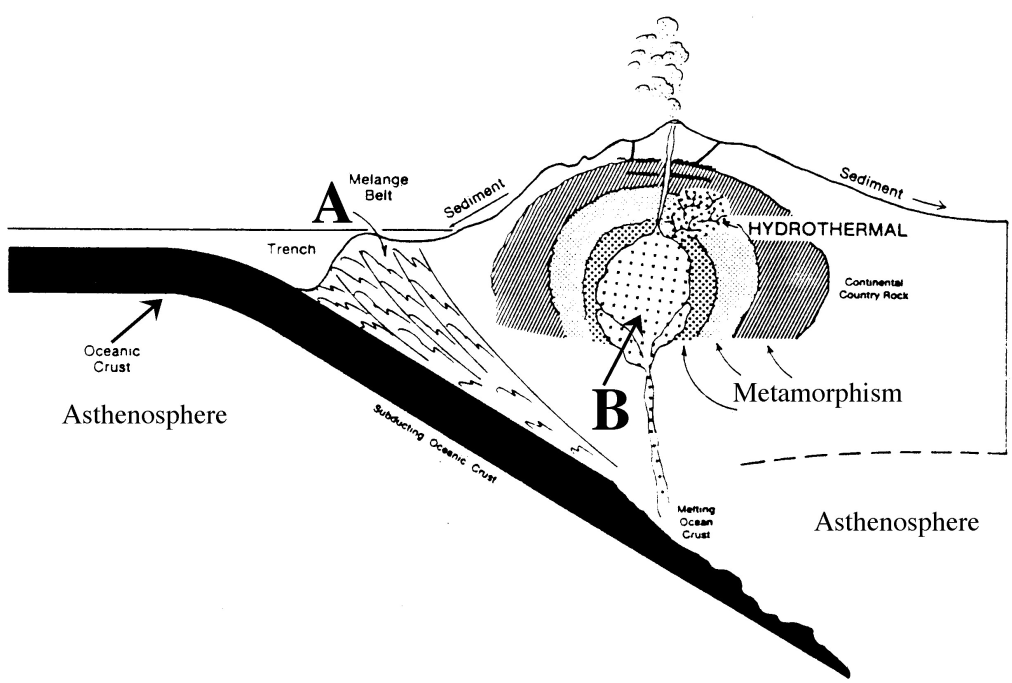

Figure 6-4. Zones of metamorphism associated with a convergent plate margin.

13. **Look at Rock C on the side table of the lab room**. This rock is a "blueschist", a unique type of metamorphic rock that forms under conditions of high pressure and low temperature.
    (a) **In what type of plate-tectonic setting might this rock form?**

    (b) **Label this region "blueschist" on Figure 6-4.**

14. **Look at Rock D on the side table of the lab room**. This rock is a "hornfels", a metamorphic rock that forms under conditions of high temperature and low pressure.
    (a) **In what type of plate-tectonic setting does this rock form?**

    (b) **Label this region "hornfels" on Figure 6-4.**

15. **What types of metamorphism (contact, regional, or both) is associated with a continent/continent convergent margin?**

16. Each group will receive a single metamorphic rock from their TA. The students will then **describe the composition, texture, name, and protolith of the rock**. After identifying the rock, each group will then **approximate the temperature and pressure conditions under which the rock formed**. Each group will then **discuss the geologic history of this rock, and include such things as the setting in which the original rock might have formed and the tectonic history which led to metamorphism of the rock**.