Chapter 8:
Metamorphism and Metamorphic Rocks

Chapter Outline,

8.1 Introduction
8.2 The Agents of Metamorphism
8.3 The Three Types of Metamorphism
8.4 How Are Metamorphic Rocks Classified?
8.5 Metamorphic Zones and Facies
8.6 Plate Tectonics and Metamorphism
8.7 Metamorphism and Natural Resources

Key Concepts Review

Learning Objectives

Upon completion of this material, the student should understand the following.

• Metamorphic rocks result from the transformation of other rocks by various processes occurring beneath Earth’s surface.
• Heat, pressure, and fluid activity are the three agents of metamorphism.
• Contact, dynamic, and regional metamorphism are the three types of metamorphism.
• Metamorphic rocks are typically divided into two groups, foliated and nonfoliated, primarily on the basis of texture.
• Metamorphic rocks with a foliated texture include slate, phyllite, schist, gneiss, amphibolite, and migmatite.
• Metamorphic rocks with a nonfoliated texture include marble, quartzite, greenstone, hornfels, and anthracite.
• Metamorphic rocks can be grouped into metamorphic zones based on the presence of index materials that form under specific temperature and pressure conditions.
• The successive appearance of particular metamorphic minerals indicates increasing or decreasing metamorphic intensity.

Chapter Summary

• Metamorphic rocks result from the transformation of other rocks, usually beneath Earth's surface, as a consequence of one, or a combination, of three agents: heat, pressure, and fluid activity.
• Heat for metamorphism comes from intrusive magmas, extrusive lava flows, or deep burial. Pressure is either lithostatic (uniformly applied stress) or differential (stress unequally applied from different directions). Fluids trapped in sedimentary rocks or emanating from intruding magmas can enhance chemical changes and the formation of new minerals.
• The three major types of metamorphism are contact, dynamic, and regional.
• Contact metamorphism results when a magma or lava alters the surrounding country rock.
• Dynamic metamorphism is associated with fault zones where rocks are subjected to high differential pressure.
• Most metamorphic rocks result from regional metamorphism, which occurs over a large area and is usually caused by tremendous temperatures, pressures, and deformation within the deeper portions of the crust.
• Metamorphic grade generally characterizes the degree to which a rock has undergone metamorphic change.
• Index minerals—minerals that form only within specific temperature and pressure ranges—allow geologists to recognize low-, intermediate-, and high-grade metamorphism.
• Metamorphic rocks are primarily classified according to their texture. In a foliated texture, platy and elongate minerals have a preferred orientation. A nonfoliated texture does not exhibit any discernable preferred orientation of the mineral grains.
• Foliated metamorphic rocks can be arranged in order of increasing grain size, perfection of their foliation, or both. Slate is fine grained, followed by (in increasingly larger grain size) phyllite and schist; gneiss displays segregated bands of minerals. Amphibolite is another fairly common foliated metamorphic rock. Migmatities have both igneous and high-grade metamorphic characteristics.
• Marble, quartzite, greenstone, hornfels, and anthracite are common nonfoliated metamorphic rocks.
• Metamorphic zones are based on index minerals and are areas of rock that all have similar grades of metamorphism; that is, they have all experienced the same intensity of metamorphism.
• A metamorphic facies is a group of metamorphic rocks whose minerals all formed under a particular range of temperatures and pressures. Each facies is named after its most characteristic rock or mineral.
• Metamorphism occurs along all three types of plate boundaries but is most common at convergent plate margins.
• Many metamorphic rocks and minerals, such as marble, slate, graphite, talc, and asbestos, are valuable natural resources. In addition, many ore deposits are the result of metamorphism and include copper, tin, tungsten, lead, iron, and zinc.

Enrichment Topics

Topic 1. The Oldest Rocks. Considering the amount of time that has past since Earth first formed rocks it’s no surprise that the oldest rocks are metamorphic. It’s probably also not surprising that these rocks would be metamorphosed volcanic rocks since the early Earth was very hot and volcanically active. The rocks are an ancient greenstone belt. What is surprising is how old these rocks are. The Nuvvagittuq Belt on the coast of Hudson Bay in Northern Quebec is 4.28 billion years old. Since Earth formed 4.6 billion years ago and was very, very hot, that seems pretty old. http://www.livescience.com/2896-oldest-rocks-earth.html
**Topic 2. Shock Metamorphism.** One of the great mass extinctions came at the end of the last Ice Age when a sudden cold snap reversed the warming trend that had been taking place. The cold lasted for 1,300 years and coincided with the extinction of large animals such as mammoths, mastodons, saber-toothed cats and others. The possibility that a comet airburst or meteorite impact caused the cold snap was explored by scientists who looked for nanodiamonds to indicate that an impact had taken place. Nanodiamonds are the result of shock metamorphism that occurs from an impact; they found none. Other lines of evidence for an impact have also been rejected and so other causes of the cold snap must be found. [http://www.sciencedaily.com/releases/2010/08/100830152530.htm](http://www.sciencedaily.com/releases/2010/08/100830152530.htm)

**Topic 3. Useful Garnets.** Garnets are useful as gemstones and for industrial purposes, but they are also useful for geologists. Garnets are important minerals for geothermaobarometry, the measure of the previous temperature and pressure history of a metamorphic rock, since temperature-time histories are preserved in the compositional zonations that are typical of their growth pattern. A garnet with no zonation was likely homogenized by diffusion, which tells geologists something of the time-temperature history of the host rock. Garnets are also useful for determining the metamorphic facies of a rock. Rocks that had basalt composition often contain eclogite garnet. Pyrope is formed at high pressures, which means that a pyrope-containing peridotite formed at great depth, possibly as deep as 100 km. Silica-rich garnets are formed at even greater depths; if they are found as inclusions within diamonds they likely originated at 300 to 400 km depth in the crust.

**Common Misconceptions**

**Misconception 1.** Marble is forever. Marble is a good stone to use for permanent monuments, tombstones, sculpture, and other art objects because it will last for such a long time.

**Fact:** Marble is made of the mineral calcite, CaCO₃, and is not all that stable. Calcite has a low hardness (#3 on the hardness scale), and so can be scratched or abraded by anything harder. This, of course, is why marble has long been a favorite with sculptors, who can use tools made of harder stones or metals. In addition, calcite is easily cleavable, and it reacts to acid. This last property means that it is susceptible to solution by even mildly acid solutions, such as acid rain. Even normal rainwater, which is slightly acidic, will weather marble over time.

**Misconception 2.** A preexisting rock can melt all the way and still become a metamorphic rock. Once a rock is completely molten, it is a magma. When it cools it becomes an igneous rock. Migmatite is the rock at that borderline place where some has melted all the way but some has not so it is still considered a metamorphic rock.

**Lecture Suggestions**

1. When describing metamorphic rocks, it is important to stress that: a) foliation results from the preferred orientation of minerals; b) schist appears to be layered because its principle minerals (biotite and muscovite) are oriented with their flat cleavage surfaces parallel to one another; and c) the banded foliation of gneiss can be distinguished from other foliation types and from stratification by its coarse crystals and the differences in mineral composition from one layer to another.
2. Point out that foliation in a metamorphic rock does not have any necessary relationship to any preexisting layering, such as stratification, which may have been present in the parent rock. You could use a thick stack of cards (perhaps 5”x7” size) on the sides of which you rule a series of parallel lines to represent stratification. Be sure the “stratification” is at a distinct angle to the layered edges of the cards, which will represent “foliation.”

3. Note that metamorphic rocks can form from any parent rock type, even another metamorphic rock. Make frequent reference to the parent rock type(s) from which a given metamorphic rock formed. Make clear that although parent rock type is easily identified in some metamorphic rocks such as quartzite and marble, the parent rock types of others often cannot be identified without a whole-rock chemical analysis of the rock’s composition (e.g., gneiss can form from impure sandstones or from granitic igneous rocks).

4. Review the rock cycle, focusing on metamorphism and metamorphic rocks, and emphasize the link of metamorphism to plate tectonics.

5. Note that nonfoliated rock types also exhibit recrystallization, which usually results in increased crystal size, but often without changes in mineral or chemical composition.

6. Stress that although heat is involved in the metamorphism of rocks, the heat never, by definition, is great enough to melt all or even a significant portion of the parent rock.

7. Note that new minerals can form in metamorphic rocks without introduction of new or additional elements, because the rock is transformed as a new equilibrium adjustment to increased pressure and temperature is reached. When hot fluids are involved, however, these may introduce new or additional elements and remove others. Thus, in some metamorphic rocks, new minerals are formed by additions and losses of various elements.

8. When discussing the causes and tectonic contexts of metamorphism, stress that low-temperature, high-pressure metamorphism is usually associated with disruptions of the crust such as folds and faults which result from compressional forces.

**Consider This**

1. Why can a glacier be considered a metamorphic rock?

2. How reasonable is it to assume that any metamorphic rock must be older than the igneous or sedimentary rock found in the same region?

3. Are diamonds the product of the metamorphism of anthracite coal?

4. What type(s) of metamorphism are likely to occur along continental-continental convergent plate boundaries?
Important Terms

- aureole
- contact (thermal) metamorphism
- differential pressure
- dynamic metamorphism
- fluid activity
- foliated texture
- heat
- index mineral
- lithostatic pressure
- metamorphic facies
- metamorphic grade
- metamorphic rock
- metamorphic zone
- metamorphism
- nonfoliated texture
- regional metamorphism

Internet Sites, Videos, and Demonstration Aids

Internet Sites
1. Volcano World: Metamorphic Rocks
   http://volcano.oregonstate.edu/vwdocs/vwlessons/lessons/Metrocks/Metrocks2.html
   Basics of the rock cycle and metamorphic rocks and how they form.

2. Metamorphic Rocks http://csmres.jmu.edu/geolla/Fichter/MetaRx/
   More basics of metamorphic rocks and how they form. Other rock types also. From James Madison University.

Videos
   (1992, 30 mins., free video):
   - #18: Metamorphic Rocks. How metamorphic rocks form and the relationship of these rocks to plate tectonics processes.

   The causes of metamorphism and the types of rocks produced by metamorphic processes.

   How minerals form rocks and how rocks alter from one type to another.

Slides and Demonstration Aids

   - Metamorphic Rock Collection
   - Ores of Common Metals Collection
Answers to Figure-Related Critical Thinking Questions

☐ Critical Thinking Question Figure 8.2
If the Acasta Gneiss (a metamorphic rock) is one of the oldest known rocks on Earth, why does Earth have to be older than 4 billion years?

Age dating of the Acasta Gneiss dates back to the development of the highest grade of Metamorphism. This rock reached that grade ~4 Ga. The process of Progressive Metamorphism (Regional) takes a considerable period of time – often 100’s of millions of years. The process must also consider the “parent” rocks. The “parent” process most likely started with granite in the earliest of the Greenstone belts (Hadean?) with a weathering process to form some of the earliest sediments in fore arch basins, preparing to be crushed up against the oldest of North America’s cratons. Wow! Older than ~4 Ga? You bet!

☐ Critical Thinking Question Figure 8.7
What criteria would you use to determine that what you see is indeed spheroidal weathering and not weathered pillow lavas?

Joint patterns and crystal textures will be different. Joints should not be present between pillows (welded together during initial cooling). Pillows also show a crystal size zoning: very fine grain exterior and coarse interiors.

☐ Critical Thinking Question Figure 8.9
Why aren’t quartz or calcite index minerals that can be used to determine the metamorphic grade of a rock?

Quartz may be found in metamorphic rocks, but is not necessarily the result of the process of metamorphism. Quartz formed during the crystallization of igneous rocks. It is stable at high temperatures and pressures and may remain chemically unchanged during the metamorphic process. The calcite found in limestone has no value as an index mineral because it never changes.

☐ Critical Thinking Question Figure 8.12
How do you distinguish between bedding and cleavage in a metamorphic rock?

This can be particularly interesting with the compressed, folded metasediments in the UP of Michigan like the Siamo Slate. You can see the uniform layers, in some places even vertical, criss-crossed in some places by slaty cleavage oriented east-west relative to north-south compression. As metamorphic grade increases the vestiges of sedimentary layering become obscure.

☐ Critical Thinking Question Figure 8.19
Go to a point that is represented by 200°C and 2 kbar of pressure. What metamorphic facies is represented by those conditions? If the pressure is raised to 12 kbar, what facies is represented by the new conditions? What change in depth of burial is required to effect the pressure change from 2 to 12 kbar?

I would turn this chart bottom to top to suggest pressure increase with depth.

At 200°C and 2 kilobars, your sample is in approximately the Zeolite facies.
Pressure increase to 12 kilobars puts the sample in the Blue Schist facies; equal to an increase in burial depth of about 30 km; conditions common at subduction zones.

**Suggested Answer to Selected Short Answer Question**  
*(Answers to question 8 and question 9 provided in the appendix to the text)*

7. Why is it important for people to know something about metamorphism, metamorphic rocks, and how they form?

**Suggested Answer:** Not only do metamorphic rocks provide a tectonic history of a landscape, they also provide humans with valuable resources:

- Marble, used for statuary and ornamental building stone
- Slate, used for roofing, flooring, billiard/pool tables, and blackboards
- Graphite, used in pencils and lubricants
- Garnet and Corundum, used as gemstones and abrasives
- Asbestos, formerly used as a heat insulator
- Kyanite, Andalusite, and Sillimanite (aluminum silicates), used as raw materials in the ceramics industry
- Iron and tin oxides deposits (hematite, magnetite, and cassiterite)
- Precious metal deposits (gold)