LAB 5

Metamorphic Rocks

OBJECTIVES

- To understand how metamorphic rocks form
- To recognize metamorphic textures and understand their origin
- To recognize minerals in metamorphic rocks
- To understand how composition influences metamorphic rocks
- To recognize and be able to identify major metamorphic rock types
- To understand the concepts of metamorphic grade, zones, and facies

Metamorphism, the creation of metamorphic rocks, takes place at high pressure underground, so we never actually see it happening. This makes metamorphic rocks the most mysterious of the three classes of rocks. The heat from Earth's interior that drives plate tectonics (see Lab 12) also causes metamorphism. As a result, the stories told by metamorphic rocks are especially useful to *structural geologists,* Earth scientists who study tectonics and rock deformation.

METAMORPHIC PROCESSES AND TYPES OF METAMORPHISM

Rocks in the Earth's crust may exist unchanged for vast amounts of time. Eventually, however, the continuing motion of the lithospheric plates may cause them to be dragged into a subduction zone, involve them in a continental collision, or stretch them at a divergent plate boundary (Lab 12). Such *tectonic activity*[1] subjects the rocks to substantial increases in temperature and pressure. At the new temperature and pressure, the original minerals in the rocks can become unstable, break down, and recrystallize into a new set of minerals, without melting. This process, known as **metamorphism,** creates metamorphic rocks. Generally, metamorphism changes both the minerals found in a rock and the rock's texture. The new minerals in a metamorphic rock are frequently only stable at the new temperatures and pressures, so we can use them as indicators of the temperature and pressure (depth) of metamorphism. These minerals and the new textures may also reveal where and how the rock was metamorphosed. The composition of the original rock — the **parent-rock** or **protolith** — also influences the mineral composition of the final metamorphic rock.

The temperature of metamorphism can range from about 200°C to about 900°C. The upper limit of metamorphism is melting, which produces igneous rocks, and is usually lower than 900°C. However, the melting temperature depends on pressure and chemical composition, so some rocks can remain solid to 900°C and even higher. Temperatures in the Earth increase about 25°C for every kilometer of depth, and this increase in temperature with depth is one of the major agents of metamorphism. The pressure experienced by a rock at depth, called the **confining pressure,** is caused by the weight of the overlying mass of rock. The general effect of confining pressure is to shrink the rock, causing it to have higher density (■ Figures 5.1 and 5.2). Confining pressure is directly related to depth of

[1] Changes in the broad architecture of the outer part of the Earth, especially movement and deformation of plates.

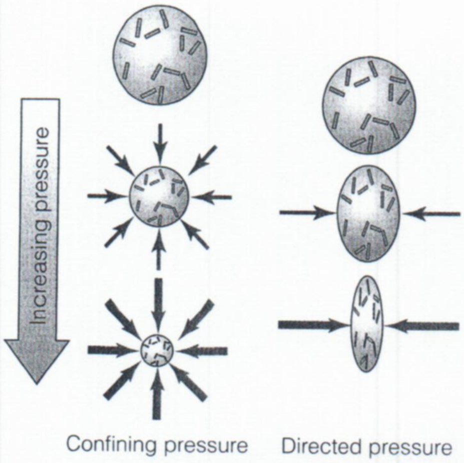


Figure 5.1

The difference between confining pressure and directed pressure

Figure 5.2

Styrofoam cups lowered to 750 m and 1500 m were subjected to the confining pressure of the oceans (called hydrostatic pressure). The pressure, equal in all directions, caused the cups to shrink in size and increase in density, but retain their overall shape. The confining pressure within the crust affects rocks in a similar manner.

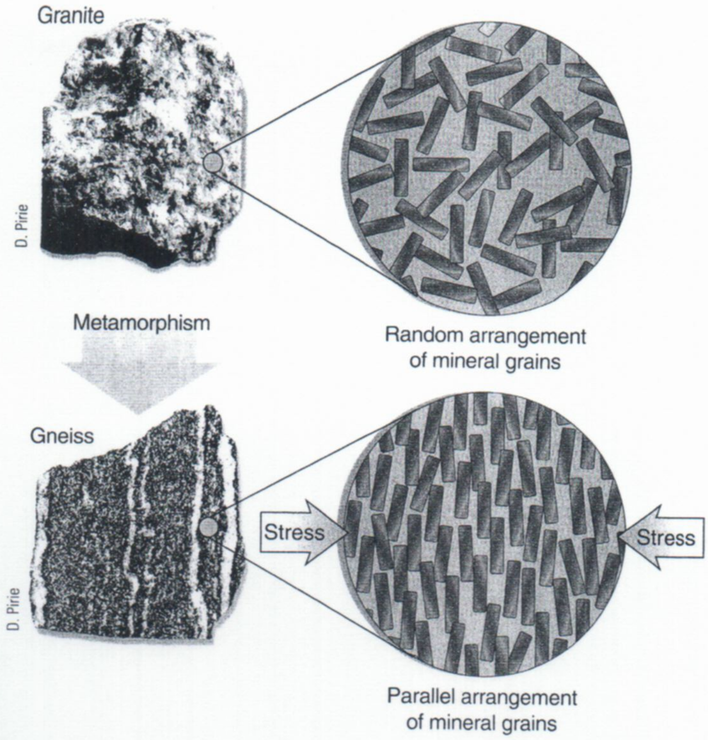


Figure 5.3

Igneous rocks (top) develop randomly oriented mineral grains. This also applies to metamorphic rocks subjected to confining pressure but not directed pressure. Metamorphic rocks subjected to directed pressure (bottom) develop foliation, represented by platy (tabular) and elongate minerals arranged parallel to each other and at right angles to the direction of pressure (stress).

metamorphism and is similar to the pressure experienced by scuba divers as they descend into deep water. The pressure is measured in kilobars (kb), where a kilobar is about 1000 times atmospheric pressure. Pressure increases about 0.3 kb for every kilometer increase in depth; 3 kb corresponds to a depth of about 10 km. The range of pressures is usually 1–12 kb (or about 3–40 km deep). Metamorphism does take place at depths greater than 40 km, but the resulting metamorphic rocks rarely return to the Earth's surface where we can see them.

Confining pressure from the weight of rock above results in a type of pressure that squeezes the rocks in all directions (Figure 5.1). Movement of lithospheric plates can produce another kind of pressure — **directed pressure,** also called **differential stress** (see Figure 5.1) in which the squeezing of the rock is not equal in every direction. Directed pressure flattens the rock, resulting in the formation of a texture with parallel arrangement of mineral grains known as **foliation** (■ Figure 5.3). Thus the texture of a metamorphic rock depends mainly on the presence or absence of directed pressure.

Regional Metamorphism

Mountain building and plate tectonic processes acting over large regions deep within the Earth's crust produce **regional metamorphism.** Two important types of regional metamorphism are *orogenic metamorphism* and *subduction zone metamorphism.*

Orogenic metamorphism results from mountain building during plate collisions (Lab 12). Directed pressure combined with a wide range of temperatures and confining pressure at moderate to great depths produces this type of metamorphism. The deeper in the Earth, the hotter the temperature and the higher the confining pressure are. Rocks that have undergone regional metamor-

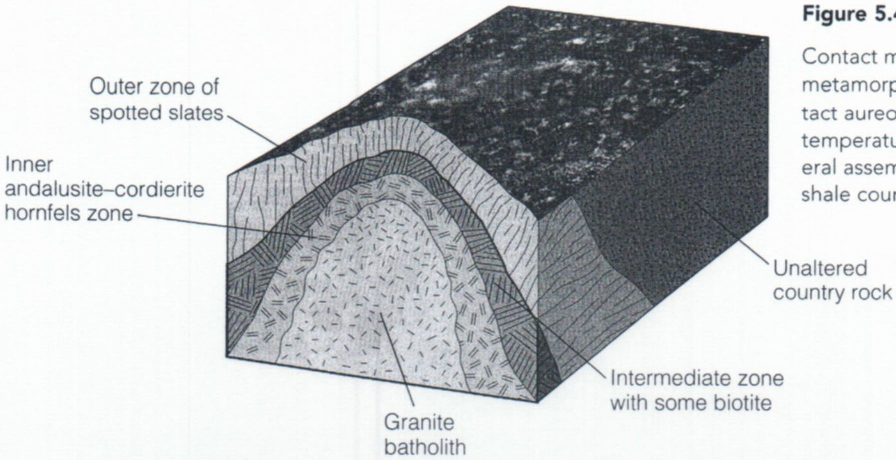


Figure 5.4

Contact metamorphism. The heat from an intrusion metamorphoses the surrounding rocks, known as a contact aureole. Zones of hornfelses showing increasing temperature toward the intrusion contain distinct mineral assemblages. The minerals labeled here are for shale country rock.

phism are commonly the foliated rocks slate, phyllite, schist, and gneiss (see section on foliated rocks, p. 89). As the name suggests, **subduction zone metamorphism** occurs in subduction zones at convergent plate boundaries (Lab 12). The subducting (descending) plate is cold in relation to its surroundings. As a result, this type of regional metamorphism is characterized by minerals that form at high pressures but low temperatures.

Contact Metamorphism

Heat from an intrusion produces **contact metamorphism**, also known as *thermal metamorphism* (■ Figure 5.4). The metamorphic rock produced around the pluton is called the metamorphic **aureole** of the intrusion. The aureole may be a few centimeters to several kilometers thick, depending on the size, composition, and depth of the intrusion. The greater the size and the higher the temperature of the intrusion and its surroundings, the thicker the contact aureole or metamorphosed area will be. Contact metamorphic rocks are often fine grained and are not usually foliated. Most contact metamorphic rocks are hornfelses, quartzites, or marbles (discussed in later sections), depending on the composition of the rock. The type of metamorphism, whether it is regional or contact metamorphism, will influence the texture of the rock.

TEXTURES OF METAMORPHIC ROCKS

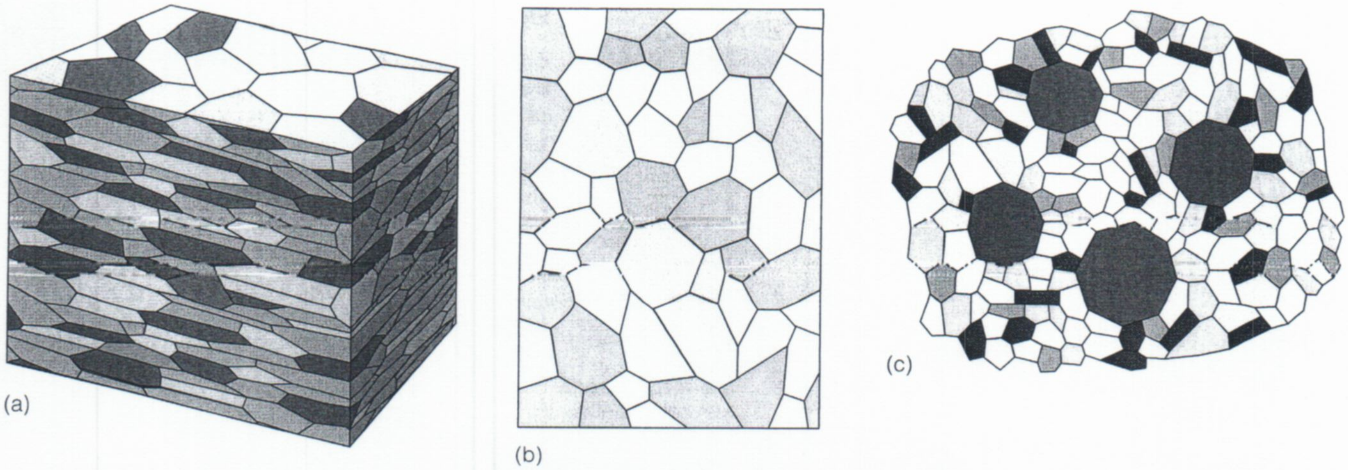
As we have seen, the ***texture*** of a rock — the shape, size, orientation and arrangement of grains — is closely related to the rock's history. For metamorphic rocks, as for all rocks, their classification depends in part on their texture. In fact, foliated texture is the main property used to identify rocks that have undergone directed pressure, commonly during regional metamorphism. Confining pressure, which occurs during contact metamorphism or in other environments without directed pressure, results in different metamorphic textures.

The grain size of metamorphic rocks varies from fine to coarse grained. **Fine grained** rocks have grains too small to see unaided. **Medium grained** rocks have visible grains that are smaller than 2 mm. In **coarse grained** rocks the grains are larger than 2 mm. These grain-size divisions are the same as for sedimentary rocks, for which medium grains are sand-sized. The following sections describe some textures found in metamorphic rocks.

Foliation Textures

Directed pressure during metamorphism causes the arrangement of platy minerals such as micas to orient parallel to planes in the rock (Figure 5.3). This parallelism of mineral grains or preferred orientation is known as **foliation** (■ Figure 5.5a). A number of common metamorphic rocks have foliation, as shown in Figure 5.7. Table 5.1 lists some platy metamorphic minerals. **Lineation** is another type of preferred orientation. A **lineated** rock has elongate minerals (Table 5.1), such as hornblende, arranged parallel to a line within the rock and may be combined with foliation (see Figure 5.9d).[2]

[2]A *foliation* is similar in geometry to a bunch of playing cards scattered on top of each other on a table, or a bunch of pencils similarly scattered on a table every which way. A *lineation* is similar to a bunch of pencils tied up in a bundle. Both foliation and lineation are present if the pencils in the bundle are untied and allowed to roll out onto the table.



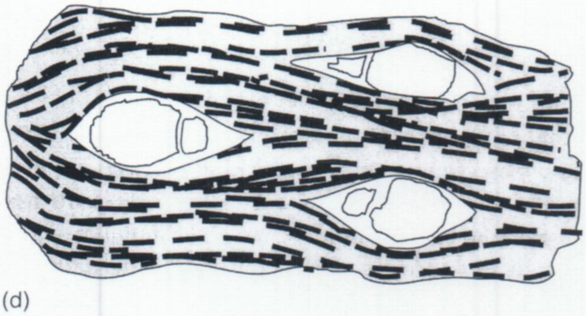


Figure 5.5

Metamorphic textures. (a) Foliation — interlocking mineral grains showing parallelism to planes in the rock. (b) Granoblastic texture — interlocking grains arranged at random in the rock. (c) Porphyroblastic texture — large geometric crystals surrounded by smaller crystals. (d) Porphyroblastic texture in a foliated rock where the porphyroblasts are elongated and eye-shaped *(augen)*.

Experimental Formation of a Foliation Take a half-fist-size blob of Play-Doh® and push the edges of a number of pennies (or buttons, or washers) into it randomly, so about half the penny is sticking out (See ■ Figure 5.6). The pennies represent platy materials. Now squeeze the Play-Doh against the tabletop with your hand. This is a simulation of deformation during metamorphism of a rock.

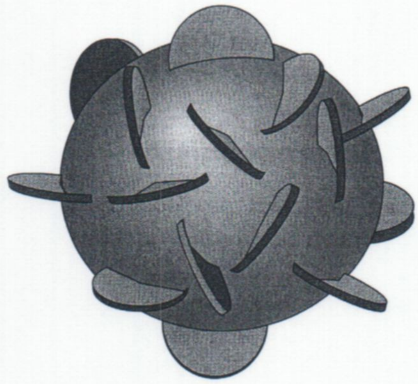


Figure 5.6

Play-Doh® and pennies, buttons, or washers in the configuration suitable for beginning of the Experimental Formation of a Foliation (Exercises 1-3).

1. What type of pressure did you apply to the Play-Doh? (Refer to Figure 5.1.)

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2. Sketch and describe the orientation of the pennies/buttons/washers in the Play-Doh. What is the name of the texture you created?

3. Compare your pennies/buttons/washers in Play-Doh with the marble and schist provided by your instructor. Which of these two rocks exhibits some similarity to your simulated Play-Doh rock? ______________

   Why? ______________________________

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Granoblastic Texture

Not all metamorphic rocks have minerals with preferred orientation. If the mineral grains are visible and are randomly oriented in the rock, the texture is called **gra-**

noblastic, or *nonfoliated* (see Figure 5.5b). Granoblastic texture is visible in the marble and quartzite in Figure 5.9a and c, later in this lab. Granoblastic texture occurs in rocks that have formed under conditions where directed pressure was weak to absent. Granoblastic texture may also result if the rock is composed of only equant minerals such as calcite, quartz, and feldspar that are not easily arranged to form a foliation (Table 5.1). Metamorphic rocks that are commonly granoblastic include *quartzite, marble,* and *eclogite.* We will discuss these rocks later, in the section "Rocks Named for Their Mineral Content."

Nonfoliated Fine-Grained Texture

Other nonfoliated rocks exist without visible minerals and are simply **fine grained.** These rocks are likely to form where heat and confining pressure cause metamorphism without the presence of directed pressure, and where the temperature or the length of metamorphism was insufficient to grow larger crystals. Contact metamorphic environments commonly produce such conditions. Hornfels and some quartzites are fine grained and nonfoliated.

Porphyroblastic Texture

This type of texture (Figure 5.5c, d) occurs in metamorphic rocks that contain large crystals (**porphyroblasts**) surrounded by smaller ones, and is similar in appearance to porphyritic texture in igneous rocks. Porphyroblastic texture can occur in either foliated rocks (Figure 5.5d), granoblastic rocks (Figure 5.5c), or rocks that are otherwise just fine grained (Figure 5.8b). Porphyroblastic texture generally forms because not all metamorphic minerals grow at the same pace.

4. With your lab partners, examine samples provided by your instructor. Without knowing anything more about the metamorphism of these rocks than what you can see, what type of metamorphism may have produced each rock? Explain your reasoning. Refer back to the section on types of metamorphism as needed (pp. 85–87).

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Rocks Defined by Their Specific Textures

Metamorphic petrologists, who study metamorphic rocks, classify some metamorphic rocks based on their texture rather than their composition or mineral content. Some of these rocks have foliated textures and others do not. These textures are visible in hand specimen.

Foliated Rocks

Slate is so *fine grained* that minerals cannot be seen without magnification. This low-grade metamorphic rock breaks along fairly smooth planes of foliation called **slaty cleavage** (■ Figure 5.7a). It may have a wide range of possible colors.

Phyllite is *fine to barely medium grained*. The cleavage of phyllite has a sheen and may have a slightly rippled surface (Figure 5.7b). Micas and chlorite lying parallel to the foliation are responsible for the sheen in this low-grade rock.

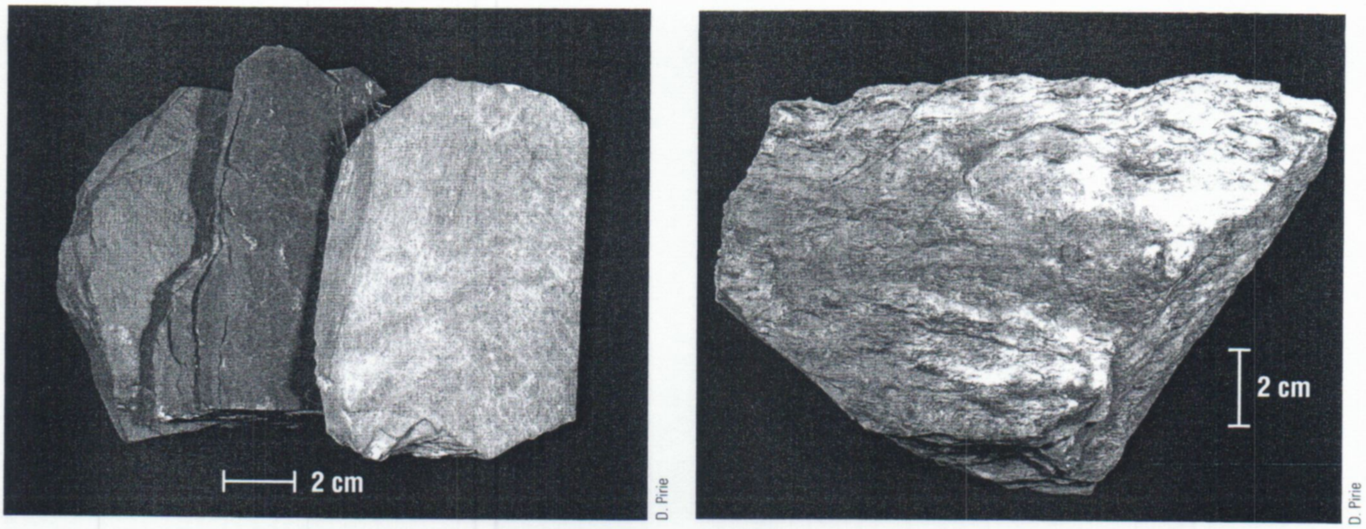
Schist is *medium to medium-coarse grained.* Individual grains are large enough to see. The foliation surface often contains mica and has a sparkly look, like glitter (Figures 5.7c–e, and also Figure 5.9d). Schist breaks parallel to its foliation, which is one of its defining characteristics, and makes the rock flattish. **Schistosity** is a texture with this type of foliation of visible platy minerals. It is common to see schists with porphyroblasts of garnet or other minerals. **Garnet–mica schist** is schist in which the garnets are commonly porphyroblasts, which cause the foliation to be uneven where the micas bend around them (Figure 5.7d).

Gneiss is *medium to coarse grained*, generally coarser than schist. Its foliation, called **gneissic banding,** consists of alternating segregations, streaks, or bands of granular minerals and platy or elongate minerals, often making light and dark streaks (Figure 5.7f, g). Gneissic banding is the defining characteristic of gneiss, with many of the segregations typically wider than about 2 mm or 3 mm. Gneiss does not generally tend to break along its foliation as schist does, so is generally blockier and less flaky than schist. A very common type of gneiss is made up of feldspar and quartz, with streaks of black minerals such as hornblende and biotite. If the felsic minerals predominate, this rock is probably *granite gneiss* formed from deformation of granite.

Augen gneiss is a type of gneiss that has large stretched-out feldspar porphyroblasts or eye-shaped concentrations of minerals. The feldspar porphyroblasts are tapered at the edges, which makes the rock look like it has eyes (*augen* means "eyes" in German; see Figure 5.7g).

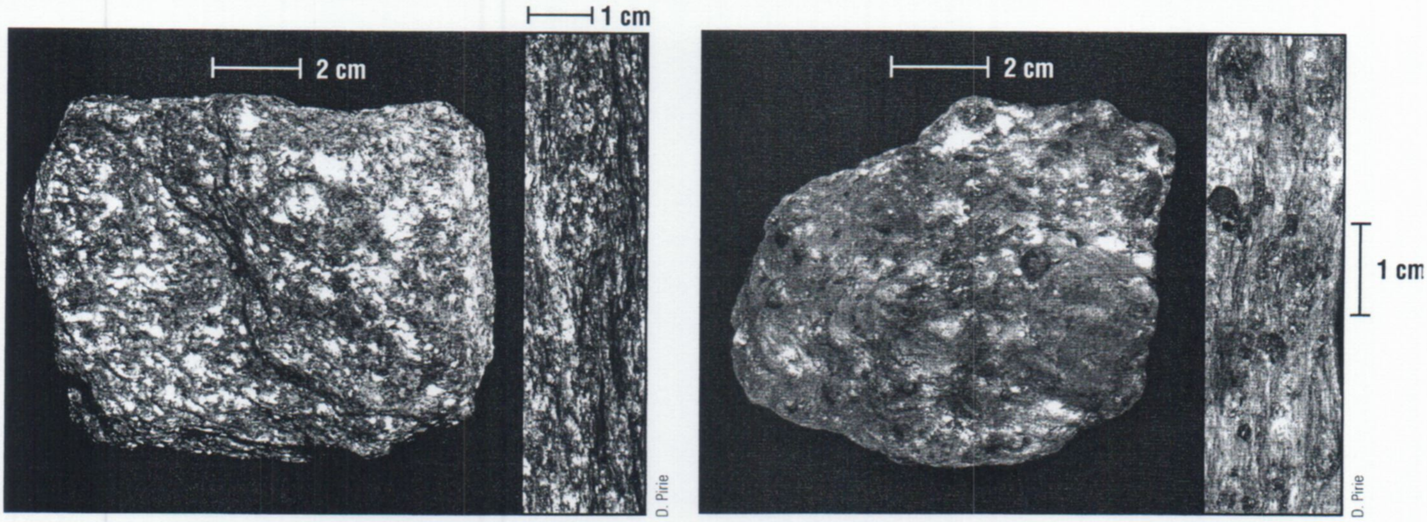
Nonfoliated, Contact Metamorphic Rocks

Hornfels is a fine-grained or porphyroblastic rock produced by contact metamorphism. It is also very tough, because its minerals tend to be intricately



(a) **Slate**: These samples are fine-grained and show their foliation at the edges and by their flatness. Slate has a large number of possible colors. Some of the common colors — gray, red-brown, or gray-green — are shown here.

(b) **Phyllite** has a sheen along foliation planes that results from parallel mica and/or chlorite grains. Wavy foliation of platy minerals is visible in this sample. Chlorite imparts a slightly green cast to this particular phyllite.



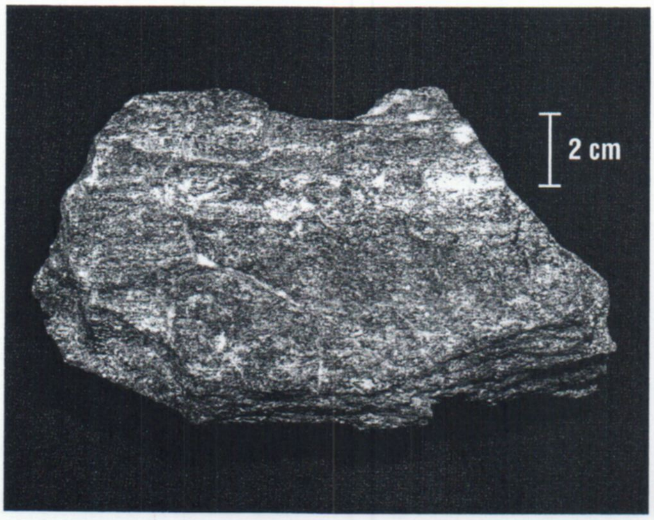
(c) On the sparkly foliation surface of this **mica schist** two types of mica are visible: biotite (black) and muscovite (silvery/pearly). Both micas reflect light as bright white spots where they are parallel to the foliation. *Inset:* a view along the edge of the foliation where micas, quartz, and feldspar are visible. The reflections are much reduced in this view along the mica cleavage edges.

(d) **Garnet-mica schist**, a foliated metamorphic rock with equant porphyroblasts of red-black garnet and two types of mica. Muscovite is much more abundant than biotite in this sample. *Inset:* This view parallel to the foliation shows the garnets more clearly.

Figure 5.7

Foliated metamorphic rocks

interlocking, a feature only visible under a microscope. Hornfelses are difficult to recognize in a lab because they are rather nondescript — fine grained and nonfoliated (■ Figure 5.8a). Their color may vary but they are commonly black and may be mistaken for basalt. Basalt is generally denser and has more magnetite (which makes basalt slightly magnetic) than hornfels. In the field, however, the closeness to an in-



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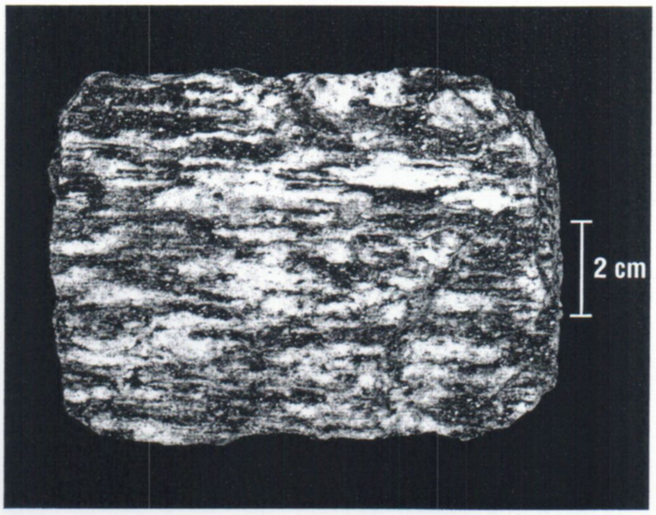
(e) **Blueschist** is a high-pressure, low-temperature foliated metamorphic rock, shown here with blue amphibole and muscovite clearly visible, both of which form the foliation.



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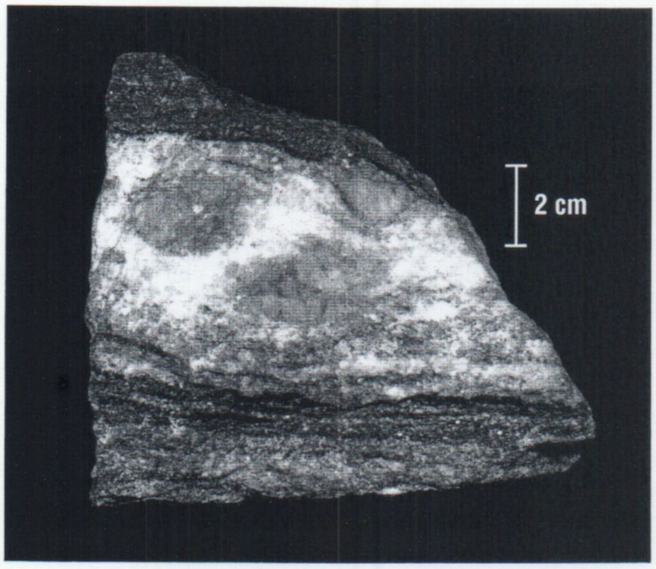
(f) This **gneiss** clearly shows typical gneissic banding with foliation or streaks of light and dark minerals. The black minerals are biotite and hornblende, and the white and light gray minerals are plagioclase feldspar and quartz.



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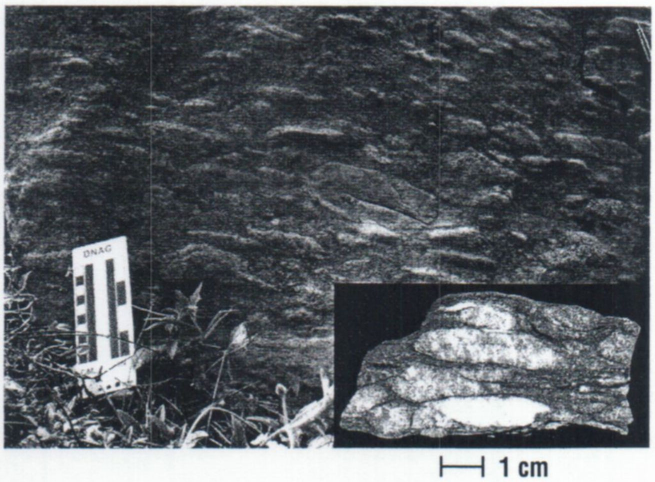
(g) **Augen gneiss,** with buff-colored feldspar *augen* embedded in a matrix of quartz, plagioclase, and more alkali feldspar. The dark layers are biotite and hornblende.



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Inset: Grenville Draper

(h) In the field photograph of this **stretched-pebble conglomerate,** notice how elongated the former pebbles are. *Inset:* In hand sample the pebbles are visibly flattened due to deformation, and the foliation is wrapping partly around them. The pebbles may once have been chert but are now quartzite.

Figure 5.7

Foliated metamorphic rocks *Continued*

trusive igneous rock is a way to confirm the identification of hornfels.

Spotted hornfels is a hornfels with porphyroblasts. You will see larger grains, which may look more like lumps than distinct grains, in a fine-grained and usually black matrix (see Figure 5.8b). Commonly the porphyroblasts are not distinct because they are full of inclusions of other minerals.

D. Pirie

(a)

D. Pirie

(b)

Figure 5.8

Hornfels. (a) *Biotite hornfels*, as in this sample, is fine-grained, unfoliated, and black and thus is difficult to distinguish from basalt, except by its field relations and lower density. (b) Porphyroblastic hornfels is commonly called *spotted hornfels*. This sample has cordierite porphyroblasts that are paler blotches on the otherwise black rock.

COMPOSITION OF METAMORPHIC ROCKS

We can think of the composition of a metamorphic rock in two ways: its mineral makeup and its chemical composition. The **parent rock,** or **protolith** (the rock from which a metamorphic rock forms), significantly influences both the mineral makeup and the chemical composition of the final metamorphic rock, but the minerals in the rock also depend on the temperature and confining pressure of metamorphism.

Common Minerals of Metamorphic Rocks

One useful way to divide up metamorphic minerals is by rock composition (as ■ Table 5.1 does), which is largely dependent on the parent rock. In this system, *carbonate minerals* are from parent rocks such as limestone and dolostone, *high aluminum minerals* from parent rocks such as shale, *felsic minerals* from felsic rocks, *mafic* and associated minerals from mafic rocks, and *ultramafic minerals* from ultramafic rocks. Table 5.1 lists

Table 5.1

Minerals and Their Common Crystal Habits in Metamorphic Rocks

Minerals in bold are especially important.

Rock Composition (parent rocks)	Metamorphic Mineral	Habit
Carbonate (limestone and dolostone)	**Calcite** Dolomite	Equant Equant
High Aluminum (shale, mudstone)	Chlorite **Muscovite mica** **Biotite mica** **Garnet** Staurolite Kyanite Sillimanite	Platy or tabular Platy or tabular Platy or tabular Equant Prismatic Bladed Prismatic or acicular
Silica-rich (quartz sandstone and chert)	**Quartz**	Equant
Felsic (granite, rhyolite, tuff, and obsidian)	**Quartz** **K feldspar** **Plagioclase feldspar** Muscovite Hornblende Biotite	Equant Equant Stubby Platy or tabular Prismatic Platy or tabular
Mafic (Basalt and gabbro parent rocks)	Chlorite Epidote Actinolite (green amphibole) **Hornblende** (black calcium-iron-magnesium-aluminum amphibole) **Plagioclase feldspar** Blue amphibole (blue-black sodium-bearing amphibole) Green pyroxene (sodium-bearing)	Platy or tabular Equant Prismatic or acicular Prismatic Stubby Prismatic Blocky
Ultramafic (peridotite)	Serpentine Talc	Platy or fibrous Platy or tabular

minerals in each of these groups. The metamorphic minerals in a rock reveal the chemical composition of the rock. They also may reveal temperature and pressure, which we will discuss later.

A characteristic of many metamorphic minerals is that they have habits that contribute to the formation of foliation, such as platy (tabular), bladed, prismatic or acicular habits (see Lab 1). Table 5.1 also lists the habits of some common metamorphic minerals.

Rocks Named for the Parent Rocks/Protoliths

Sometimes the metamorphic rock is named for its parent rock by putting the prefix *meta-* in front of the rock name. You would use this naming system to emphasize the parent rock rather than other aspects of the metamorphic rock such as its foliation or its current mineralogy. Naming metamorphic rocks by their parentage ignores other qualities of the rock and is one way to group them.

Metabasalt is metamorphosed basalt (for example, Figures 5.7e, and 5.9d and e). Mafic minerals that form in metabasalts include chlorite, epidote, three types of amphibole (actinolite, hornblende or blue amphibole), and pyroxene (Table 5.1).

Stretched-pebble conglomerate (or **metaconglomerate**) is foliated metamorphic rock in which the pebbles or clasts contained within a former sedimentary conglomerate are still visible, but stretched out into a lineation or foliation (Figure 5.7h).

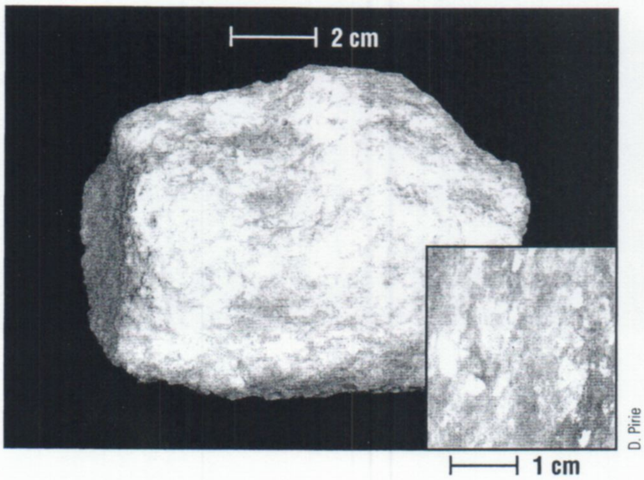
Metapelite (or **metashale**) is metamorphosed shale or mudstone (for example, Figures 5.7a–d and 5.8a and b). The clay minerals common in shale give this group their high aluminum content which allows crystallization of aluminum-rich minerals. As a result, these rocks usually have high mica content and are commonly well foliated (that is, can form slates, phyllites or schists), if formed under directed pressure.

Metalimestone and **Metasandstone**: Metamorphism of limestone over a large range of temperatures produces a rock containing 95% to 100% calcite (marble, occasionally called metalimestone). If quartz sandstone is metamorphosed, it becomes a rock containing 95% to 100% quartz (called quartzite, infrequently called metasandstone). A number of metamorphic rocks are named based on their distinctive mineral content.

Rocks Defined by Their Mineral Content

When classifying metamorphic rocks by composition, we may use the chemical composition of the rock, as described above, or the principal minerals present. The rocks discussed below receive their names from their distinctive mineral makeup.

Marble is a medium- to coarse-grained rock made of calcite, which reacts strongly to dilute hydrochloric acid. *Dolomite marble* consists of dolomite, which reacts when powdered. In both types of marble the grains are large enough to see, with obvious cleavage. Marble may have a foliation, but generally is granoblastic (■ Figure 5.9a and b). Marble forms by metamorphism of limestone or dolostone, but it is distinguished from these rocks by more prominent crystalline grains and a lack of sedimentary textures and fossils.



(a) This **marble** is entirely composed of calcite. *Inset:* a close-up of the crystalline, interlocking *granoblastic* texture of the calcite in the sample.

(b) Foliated **marble.** Green amphibole and black biotite produce the foliation in this sample. Calcite here is pink, white, and gray.

Figure 5.9

Metamorphic rocks defined by their mineral content

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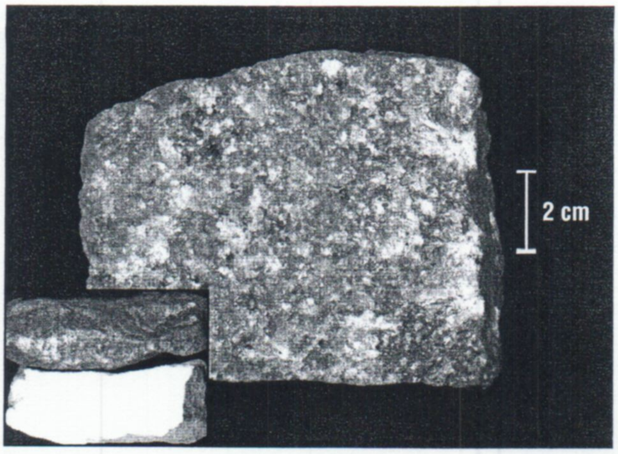

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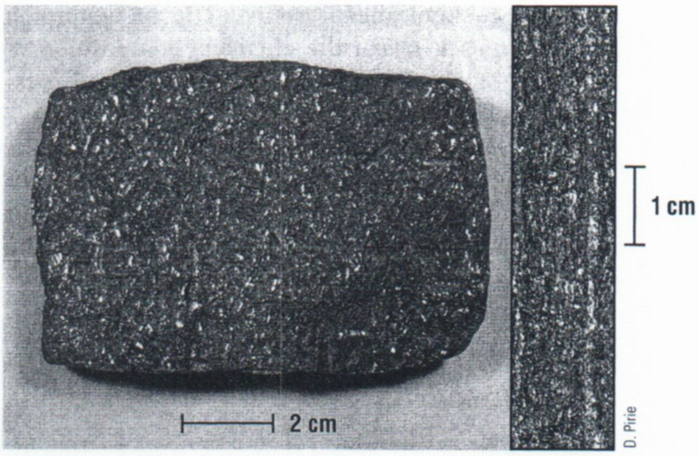
(c) This **quartzite** is a granoblastic metamorphic rock composed primarily of quartz. Quartzite may have a variety of different colors, as seen in the inset.



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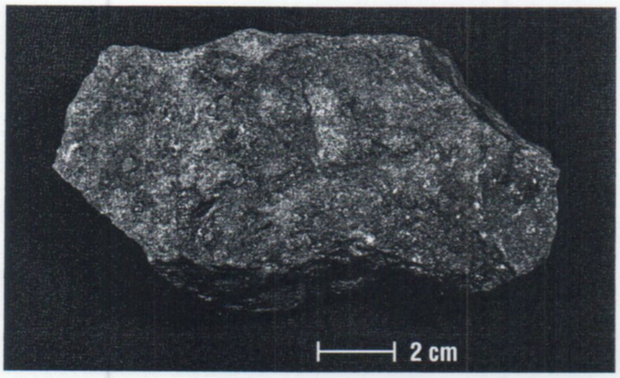
(d) This **amphibolite** is both foliated and lineated and contains hornblende and plagioclase feldspar. On the foliation surface (larger photograph) the lineation is visible as hornblende crystals arranged approximately parallel to each other, up and down. (The hornblende is black, with grains reflecting the light looking bright white.) *Inset:* The edge of the sample where the layering of the foliation is visible. Lighter layers show the plagioclase feldspar clearly.



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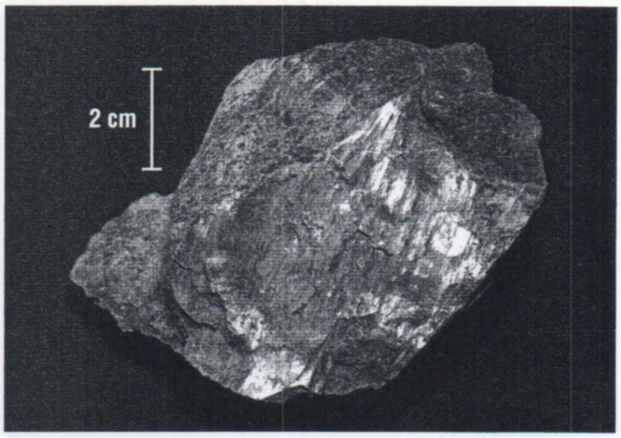
(e) **Eclogite** is a high-pressure metamorphic rock with red garnet porphyroblasts in a green pyroxene matrix. A few grains of white mica are also visible.



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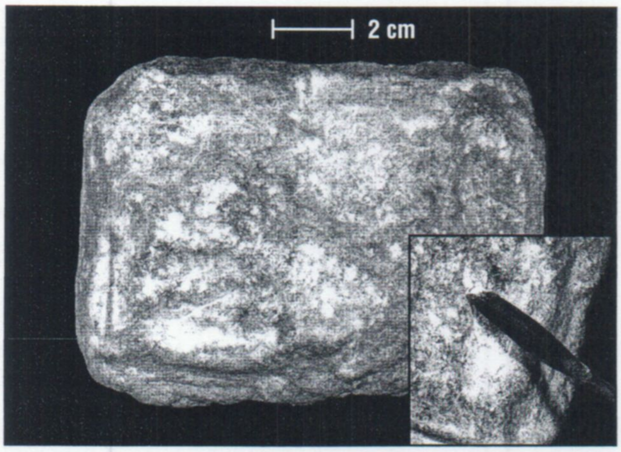
(f) This **serpentinite** sample has *slickensides on the* front surface, showing a region of highly foliated serpentine that formed along a fault zone or a zone of high shear stress. The scaly, or mottled, coloration common to serpentinite is visible along the upper-left side of this metaperidotite sample.



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(g) **Soapstone**, a metamorphosed ultramafic rock composed of talc. Recall that talc has a hardness of 1; thus, the sample can easily be carved with the spatula (*inset*) and even scratched with a fingernail.

Figure 5.9

Metamorphic rocks defined by their mineral content *Continued*

Quartzite is a fine- to coarse-grained, usually granoblastic rock made of crystalline quartz (Figure 5.9c). Most quartzite is medium grained and may occasionally be foliated. With a hand lens you should be able to see the vitreous luster and conchoidal fracture of quartz. The parent rock of quartzite is a rock rich in quartz or silica, such as quartz sandstone or chert.

Amphibolite is a medium- to coarse-grained rock made of hornblende and plagioclase feldspar. Amphibolite commonly has a foliation or lineation, so is sometimes called *hornblende schist*. However, the name amphibolite is more prevalent even for foliated varieties (Figure 5.9d).

Table 5.3

Foliated Metamorphic Rocks (including lineated rocks)

Texture	Grain size	Color or Luster	Other Identifying Characteristics	Rock Name and Grade	Common Parent Rock
Good *slaty cleavage*	Very fine grained (not visible)	Dull luster, gray, black, red, tan, or green	Generally flat	Slate low	Shale
Cleavage (may be wavy)	Fine grained (not to barely visible)	Silky sheen on flat surfaces	Chlorite and muscovite barely discernible with a hand lens	Phyllite low	Shale
Schistosity. Micas oriented parallel to foliation; tends to split parallel to foliation (may be wavy or folded). Some schists are *porphyroblastic*.	Medium (to coarse) grained (visible grains, usually <~4 mm)	Sparkly, especially on flatter surfaces. Many possible colors including greenish, slivery white, gray, black	Minerals visible: biotite, muscovite, *may* see quartz, garnet, or hornblende	Schist Mica schist Garnet mica schist medium grade Hornblende schist medium to high grade	Shale Shale Basalt or Gabbro
Foliated or lineated	Medium grained (visible grains)	Blue or Blue gray	Blue amphibole	Blueschist; high pressure	Basalt
Gneissic banding. Layered, banded or streaked; does not break parallel to foliation	Coarse (to medium) grained (usually > 1 mm)	Bands or segregations of black and white or pink	Light-colored bands of feldspar and quartz, black bands of biotite or hornblende	Gneiss high grade	Granite or shale or basalt

minerals are present, check both systems to find the best match. For example, slate is foliated and fine grained and belongs to the foliated system (Table 5.3), but soapstone is commonly fine grained and may be foliated but is defined in the mineral-based system (■ Table 5.4) based on the presence of the soft mineral talc.

- If the rock is not foliated, use the mineral-based system (see "Composition of Metamorphic Rocks," p. 92, and Table 5.4).
- If the rock is predominately made of one mineral, use the mineral-based system.
- If you are having trouble getting a rock to match a rock name in one system, check the other system.

Actually, this process is not as hard as it sounds if you use the maze in ■ Figure 5.10 and Tables 5.3 and 5.4 to help you to classify metamorphic rocks. Some of the rocks in Table 5.4 may have a foliation or a lineation; in such cases, a reasonable rock name can be used from either table. A typical example is an amphibolite that is lineated or foliated. If it has black and white bands greater than about 3 mm wide, it could be called hornblende gneiss or amphibolite — either name is acceptable. If not banded, hornblende schist or amphibolite is a permissible name.

6. Practice using the maze in Figure 5.10 with some known samples of metamorphic rocks. Pay particular attention to foliation, other textural features, and visible minerals. Hardness, cleavage/fracture and luster will be helpful in mineral identification. When you successfully name the rocks using the maze (without looking at the answers), you are ready to continue to the next exercise.

7. Examine the unknown rocks and fill in the information in ■ Table 5.5, Metamorphic Rock Identification Forms. Use the maze

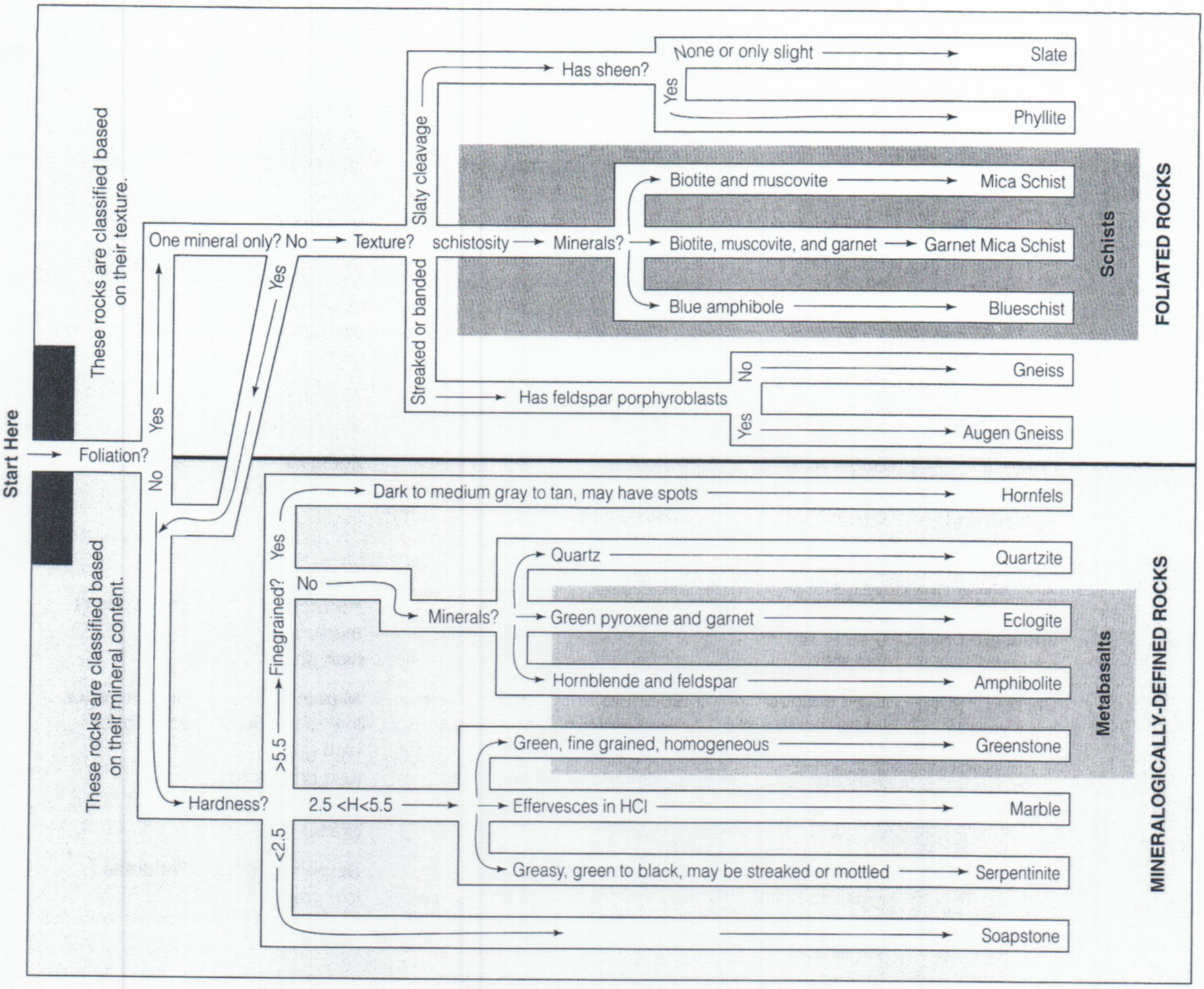

Figure 5.10

Maze for identification of metamorphic rocks

TEMPERATURE AND PRESSURE OF METAMORPHISM

As the temperature and pressure of metamorphism increase, the **metamorphic grade** of the rock also increases. You can think of metamorphic grade as an approximate measure of the amount or degree of metamorphism. To use a cooking analogy, grade refers to how "well done" the rock is. The three metamorphic grades are closely tied to the temperature of metamorphism: **low grade** is mainly low temperature and low pressure, **medium grade** is moderate temperatures and pressures, and **high grade** is for rocks that have undergone metamorphism at high temperatures and pressures. Pressure is of less importance than temperature, so a rock metamorphosed at high temperature and moderate pressure, for example, would still be high grade.

One of the most important concepts to understand about metamorphic rocks is that *different minerals form at different temperatures and pressures*. As temperature and pressure change during metamorphism, new minerals grow within the metamorphic rock, replacing preexisting minerals. This means that the minerals can be clues about the pressure-temperature history of the rock.

Table 5.5

Metamorphic Rock Identification Form (Exercises 7 and 16)

Sample Number	Texture (including foliation and grain size)	Color(s)	Composition (minerals and their colors; porphyroblasts)	Rock Name	Parent Rock	Conditions of Metamorphism (metamorphic grade or best guess for pressure and temperature)

Continued

Table 5.5

Metamorphic Rock Identification Form (Exercises 7 and 16)—continued

Sample Number	Texture (including foliation and grain size)	Color(s)	Composition (minerals and their colors; porphyroblasts)	Rock Name	Parent Rock	Conditions of Metamorphism (metamorphic grade or best guess for pressure and temperature)

Minerals Reveal Metamorphic Temperature

A group of minerals that grow or coexist together at the same temperature and pressure is a **mineral assemblage.** We can therefore use mineral assemblages as our thermometer to measure the temperature of metamorphism. Mineral assemblages operate like medical thermometers used to measure your body temperature in that they record the maximum temperature experienced. In fact, when metamorphic petrologists (people who study metamorphic rocks) use minerals to determine temperatures of metamorphism, they call them *geothermometers.*

Certain mineral assemblages are characteristic of specific ranges in temperature (see ■ Figure 5.11a and ■ Table 5.6). A distinctive assemblage represents a **metamorphic zone.** Simply, a metamorphic zone refers to the group of minerals that would form at certain temperature range in a rock of a certain composition. The zones are named for an especially useful **index mineral,** which is stable at that particular temperature. Clay-rich shales are particularly sensitive in showing progressive mineral changes with increasing temperature during regional metamorphism, and they may display what are known as **Barrovian zones** (see Figure 8.33, on p. 168). Each Barrovian zone is delineated by the first appearance of a distinctive mineral such as chlorite, biotite, or garnet, but you should note that this index mineral generally persists into higher temperature zones (Figure 5.11b). The boundaries between the different zones are called **isograds.** If the region is uplifted and

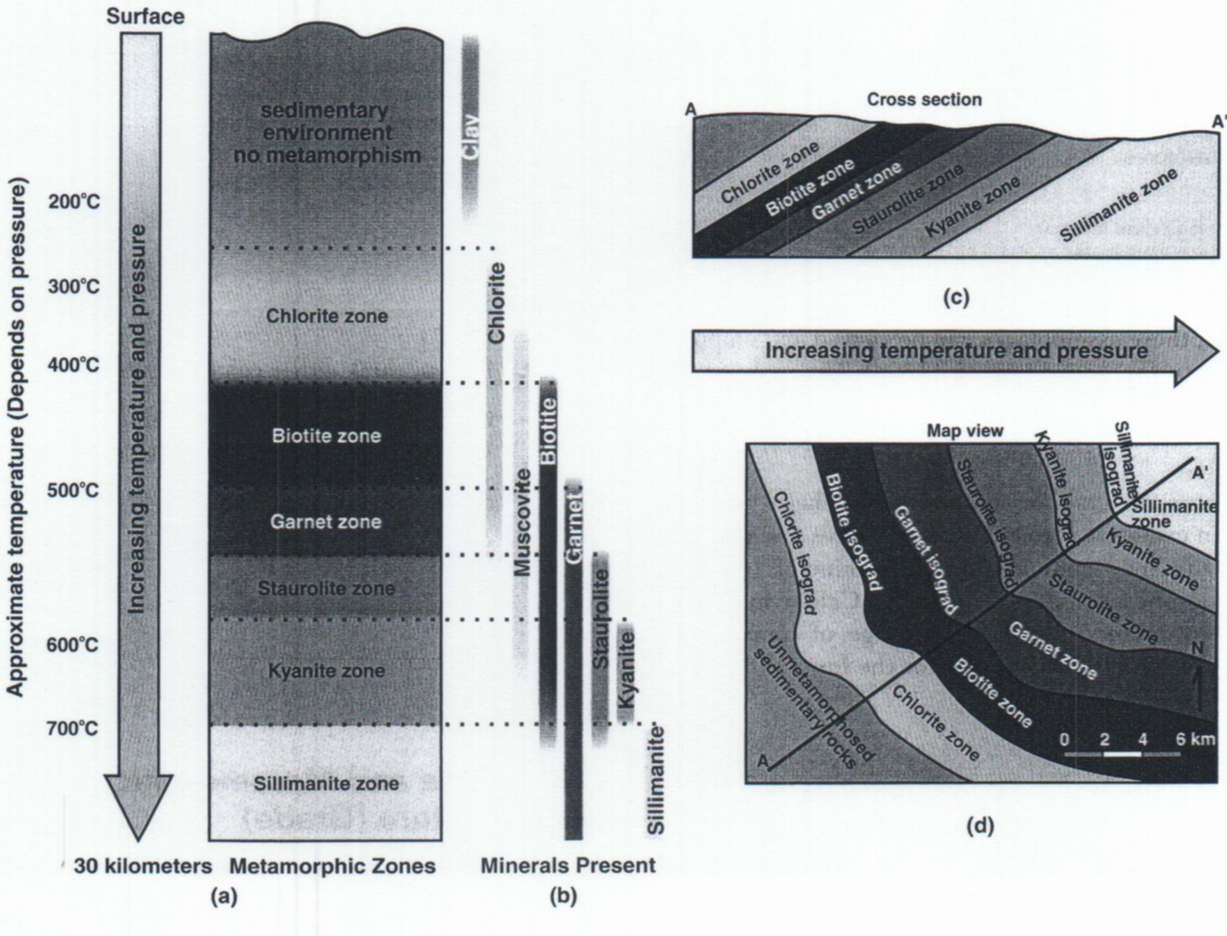

Figure 5.11

Diagrams illustrating the variation in metamorphic zones with depth of burial. (a) Geologic column of a deeply buried succession of shale, with temperature and pressure increasing systematically with depth. Metamorphism is taking place in these rocks, producing different mineral assemblages represented by the metamorphic zones. (b) At these different temperatures different minerals are present. The color streaks represent the range of temperatures at which each mineral is likely to exist. (c) Cross section of an area with more rapid uplift on the right than the left side; erosion on the right exposed rocks formed at greater depths. Minerals that characterize various zones occur at the surface in a progressive sequence from low to high temperature, from left to right. (d) Map view of the area shown in c, with low-grade, low-temperature metamorphism at the southwest and high-grade, high-temperature metamorphism at the northeast. Lines termed **isograds** connect the first appearance of metamorphic index minerals. Moving along an isograd leads you along equal metamorphic temperatures, whereas crossing isograds moves you through changes in metamorphic temperatures.

Table 5.6

Mineral Assemblages in the Barrovian Zones and Comparable Mafic Assemblages

This table shows the temperature and mineral assemblages in metashales for each Barrovian zone. The first appearance of a mineral with increasing temperature is marked in bold. For the equivalent temperature range, the assemblages for mafic rocks are also listed.

Metamorphic Zone	**Chlorite Zone**	**Biotite Zone**	**Garnet Zone**	**Staurolite Zone**	**Kyanite Zone**	**Sillimanite Zone**
Temperature Range	250°–425°C	425°–500°C	500°–530°C	530°–550°C	550°–700°C	≥700°C
Mineral assemblage in metashale (metapelite)	**Chlorite** Muscovite Albite* Quartz	Chlorite Muscovite **Biotite** Albite* Quartz	Chlorite Muscovite Biotite **Garnet** Albite* Quartz	Muscovite Biotite Garnet **Staurolite** Plagioclase Quartz	Muscovite Biotite Garnet Staurolite **Kyanite** Plagioclase Quartz	Biotite Garnet **Sillimanite** Plagioclase Quartz
Mineral assemblage in metabasalt (mafic) at equivalent temperatures	**Chlorite** Actinolite† Albite*	Chlorite **Epidote** Actinolite† Albite*	Chlorite Epidote Actinolite† Albite*	Chlorite Epidote **Garnet** **Hornblende** **Plagioclase**	Epidote Garnet Hornblende Pyroxene Plagioclase	Garnet **Pyroxene** Hornblende Plagioclase

*Na-plagioclase feldspar
†A green amphibole

eroded, these assemblages can be viewed and mapped at Earth's surface (see Figure 5.11c, d). The rocks are now at surface temperature, but the minerals remain to show us the maximum metamorphic temperatures experienced.

Some minerals or mineral assemblages are stable over an extensive variety of temperatures and pressures. Quartzite may contain the same mineral (quartz) if metamorphosed at 200°C or 800°C. Calcite in marble is stable over almost as wide a range of temperatures. Pressure can also vary widely for the formation of these rocks.

8. Examine the metashales provided to demonstrate the Barrovian zones. For each rock, determine what minerals are present and match the rock with one of the Barrovian zones in Table 5.6 (see also Figure 5.11). Enter the rock number and the range of temperature of metamorphism of the appropriate zone in ▪ Table 5.7. *Hint:* In some cases the rock name tells you what important mineral is in the rock. *Note:* Check with your instructor to find out if you need to learn to recognize any new minerals, such as staurolite.

9. Do you think either calcite or quartz would make good index minerals? (Yes/No) _______
Would they make good indicators of pressure or geobarometers? (Yes/No) _______
Why or why not? ______________________
____
____

Grain Size and Metamorphic Temperature (Grade)

10. For Table 5.7, is there a relationship between temperature and grain size?
(Yes/No) _______ If so, describe it.
____
____
____
____

Table 5.7

Temperature of Some Barrovian Metashales (Exercise 8)

Rock Name	Rock Number	Metamorphic Zone	Temperature of Metamorphism
Staurolite mica schist or staurolite quartzite			
Chlorite schist			
Kyanite mica schist or kyanite quartzite			
Mica schist			
Sillimanite gneiss			
Garnet mica schist			

Cooling rate is not as relevant to a metamorphic situation as it is for grain size of igneous rocks. Instead, what other factor would be more pertinent to metamorphic grain size than cooling rate? *Hint:* It also has to do with time.

____

____

As temperature increases, grain size of minerals in the rocks also tends to increase. This is because atoms move faster at higher temperatures and thus can travel farther to attach themselves to a mineral grain. The farther atoms can travel to arrive at one mineral grain, the more atoms can reach the grain and the larger the grain can grow. At low metamorphic temperatures *(low grade)*, atoms move slowly and the rocks are generally fine grained (e.g., slate). As grade increases, the grain size increases to produce phyllite, then schist with medium-size grains or marble with medium-size grains *(medium grade)*. Finally, at the highest temperatures of metamorphism *(high grade)*, atoms within the solid rock become sufficiently mobile to allow for segregation of different minerals into separate bands, such as those seen in gneiss, or to allow for growth of large crystals in a coarse-grained marble.

11. Look at the two samples of either quartzite or marble provided and decide, using their grain size, what metamorphic grades formed each rock.

Sample number? _______

Probable metamorphic grade? ___________

Sample number? _______

Probable metamorphic grade? ___________

Other variables, such as the rock's water content, different rates of growth of different minerals, and time elapsed during the metamorphism, also influence grain size. Thus, there may be considerable variation in grain size of different rocks that experienced the same temperature.

12. Based on the grain size of the porphyroblasts in the metashale samples in Table 5.7, which mineral seems to grow fastest?

____

Pressure and Density

Certain metamorphic rocks are formed under special high-pressure conditions deep (>20 km) in the Earth's crust during subduction zone metamorphism. They have different minerals than rocks from orogenic metamorphism. Remember the concept of mineral assemblages as thermometers; we find that minerals can also be barometers, to measure pressure of metamorphism. Blue amphibole, garnet, and a green pyroxene are high-pressure minerals.

Blueschist is a high-pressure/low-temperature metamorphic rock characterized by the presence of blue amphibole. The blue amphibole gives the rock a bluish-black appearance (Figure 5.7e). Other unusual high-pressure minerals such as *jadeite*, a pyroxene that is the main constituent of the gem jade, occasionally occur in these rocks. These rocks are formed near and within subduction zones[3] at a depth of 20–40 km and between the oceanic trench and the volcanic arc. In the subduction zone, the natural temperatures in the Earth are cooled by subduction of cold oceanic crust; thus the subduction zone setting creates the especially high-pressure/low-temperature conditions that form blueschists (see blueschist facies in ■ Figure 5.12).

Eclogite is a rock of basaltic composition that has recrystallized to high-pressure minerals: a green pyroxene with high sodium and aluminum content and red garnet (Figure 5.9e). Although the pressure of metamorphism of this red and green rock is consistently high, the temperature of metamorphism of eclogite may vary considerably, as shown in Figure 5.12.

13. Measure the density of a piece of eclogite _______ g/ml and a piece of basalt _______ g/ml, as described for minerals in Exercise 13 in Lab 1, on p. 8.

Explain why these rocks have the relative densities they do.

____

____

____

____

[3]A *subduction zone* is an area at some convergent plate boundaries (Lab 12) where oceanic crust moves downward into the mantle. Oceanic trenches occur where the crust first starts to descend, and volcanic arcs occur where the subducting plate generates magma that rises to form the volcanoes at the surface.

Metamorphic Facies

Barrovian zones are based on mineral assemblages in metashales. Since different original rocks may produce different mineral assemblages, it is difficult to compare metamorphic zones of, for instance, metashales and metabasalts. A **metamorphic facies**, on the other hand, is the set of all mineral assemblages that may be found together in a region where the rocks have different chemical composition, but were all metamorphosed at the same conditions of temperature and pressure. Whether a rock is a metashale or a metabasalt (or for that matter a metalimestone), if it formed over a particular range of pressure and temperature, it belongs to the same facies as any other rock formed at the same conditions. The estimated temperature and pressure of formation of different facies are shown in Figure 5.12

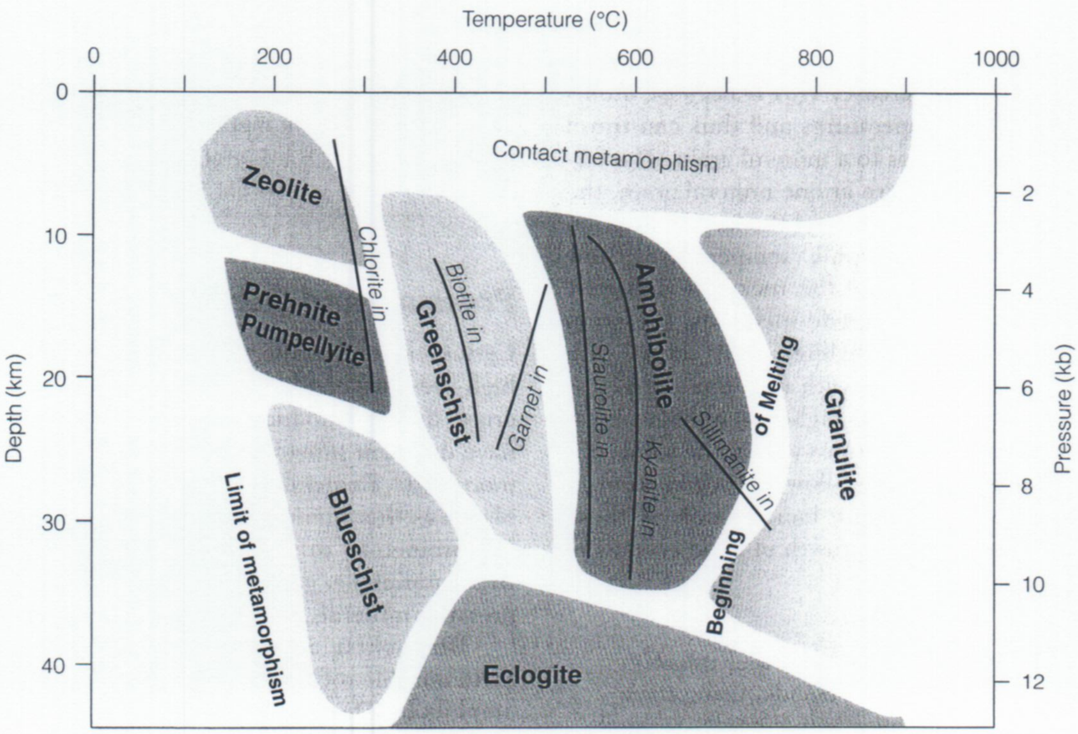

Figure 5.12

Approximate pressure-temperature fields of metamorphic facies. Note also the fields of the Barrovian zones, marked by isograds such as *garnet in*.

along with the conditions for the Barrovian zones of metashales.

14. By reading the graph in Figure 5.12, determine the metamorphic facies of each rock listed here:

Blueschist ____________________

Chlorite muscovite schist ____________________

Staurolite mica schist ____________________

Greenschist ____________________

Kyanite mica schist ____________________

Sillimanite gneiss ____________________

Amphibolite ____________________

Mica schist (biotite and muscovite) ____________________

Eclogite ____________________

Garnet–mica schist ____________________

15. What information do you gain by knowing the metamorphic facies of a rock?

____

____

Now that you know more about the conditions of metamorphism, let's go back and finish filling in the Metamorphic Rock Identification Forms (Table. 5.5).

16. Use Figures 5.10, 5.11, and 5.12 and Tables 5.3, 5.4, and 5.6 to determine the metamorphic grade, temperatures, and/or pressures, if possible, for the rocks you started in Table 5.5. For some rocks, it is not possible to determine the metamorphic grade using minerals. For example, a quartzite with no minerals besides quartz could have formed at almost any temperature and pressure. Its mineral assemblage (quartz) is not diagnostic of temperature or pressure. However, even for a quartzite, the grain size can be used to hypothesize the metamorphic grade as low, medium, or high.

17. In each row in ■ Table 5.8, circle one texture term, choose a rock from the previous exercise that has that texture, and explain how the rock formed. If you found an outcrop of this rock on a mountaintop, what would the rock's presence suggest about the history of the Earth at this location? Don't forget that the beginning of the story is the history of formation of the parent rock.

18. Study the metamorphic rocks so you will be able to recognize them on a quiz. Then take a practice quiz with another set of unknown samples. This time, just jot down the name and the key features of the rock that help you to recognize it. Fill in ■ Table 5.9 with this information.

Table 5.8

Metamorphic Textures and Rock History (Exercise 17)

Texture	Rock Number	Rock Name	Formation and History of the Rock
Slaty cleavage or schistosity or gneissic banding			
Nonfoliated or granoblastic			

Table 5.9

Practice Quiz (Exercise 18)

Sample Number	Key Characteristic 1	Key Characteristic 2	Key Characteristic 3	Rock Name