CHAPTER 3

IGNEOUS ROCKS

MATERIALS NEEDED

- **Pencil**
- **Hand lens**
- **Calculator**
- Samples of igneous rocks

INTRODUCTION

Most **rocks** are aggregates of crystals or grains of one or more minerals. The individual mineral particles in rocks are generally small, with average dimensions less than 1 centimeter (cm). Even so, the minerals are identifiable. They have the same physical properties as the larger mineral specimens you have already studied.

Deciphering the Earth's history begins with rocks because they bear testimony to their origin and subsequent history. Once you have completed the next three chapters, you will be able to use easily observable details to infer at least some of the history reflected in the rocks commonly found all around you.

Rocks are classified as igneous, sedimentary, and metamorphic based on how they formed: **igneous rocks** solidified from melted rock, **sedimentary rocks** represent the accumulation of material released by the disintegration of preexisting rocks at the Earth's surface, and **metamorphic rocks** form when preexisting rocks recrystallized, as solids, under high temperature and pressure beneath the Earth's surface. These basic rock types are linked by a set of processes that routinely converts igneous rocks to sedimentary and metamorphic rocks, sedimentary rocks to igneous and metamorphic rocks, and metamorphic rocks to sedimentary and igneous rocks. This global rock recycling program is called the **rock cycle.**

IGNEOUS ROCKS

The most spectacular way in which igneous rocks form is by volcanic eruption. This happens when molten rock, called **magma,** rises to the surface. The magma then either simply flows onto the surface as **lava** or violently explodes at the surface due to rapid bubble formation within. The forming bubbles increase the volume of the magma so dramatically that it shoots up and out of the volcano. Igneous rocks that cool on the surface are called **extrusive rocks.** Extrusive rocks cool quickly because air, rain, and snow rapidly remove a lot of heat.

Most rising magmas never make it to the surface. They stall deep in the crust and slowly cool. Igneous rocks that cool beneath the surface are termed **intrusive.** The trapped magma cools slowly because the surrounding rocks form an insulating jacket that helps the magma to retain its heat. Because temperature increases with depth in the Earth, the surrounding rocks are themselves warm and this, too, promotes slow cooling.

Igneous rocks are widely studied for many reasons. First, many people live close enough to volcanoes to be killed by explosive eruptions or huge landslides triggered by eruptions. Geologists study the ancient deposits of individual volcanoes to understand their likely future eruptive style. Second, the bulk of the Earth's crust, both continental and oceanic, is made of igneous rocks; thus, we look to igneous rocks to understand how our crust formed and why our planet is so different from the other rocky planets. Third, igneous rocks commonly form at tectonic plate boundaries; hence, the study of ancient igneous rocks tells us a great deal about the history of the Earth. For example, igneous rocks tell us that about one billion years ago North America almost split in two along a zone stretching from Lake Superior to northeastern Kansas. How might this split have changed human history? Finally, hot magmas drive the circulation of a lot of hot water. These hot fluids pick up a number of important metals and can deposit them to create metal ore deposits. These deposits of gold, copper, silver, and a host of other rare metals underpin our modern technological economy.

Although all igneous rocks by definition cool from a liquid magma, they form under such diverse conditions that they differ widely in texture, mineral composition, and appearance. Let's cover these basic differences first.

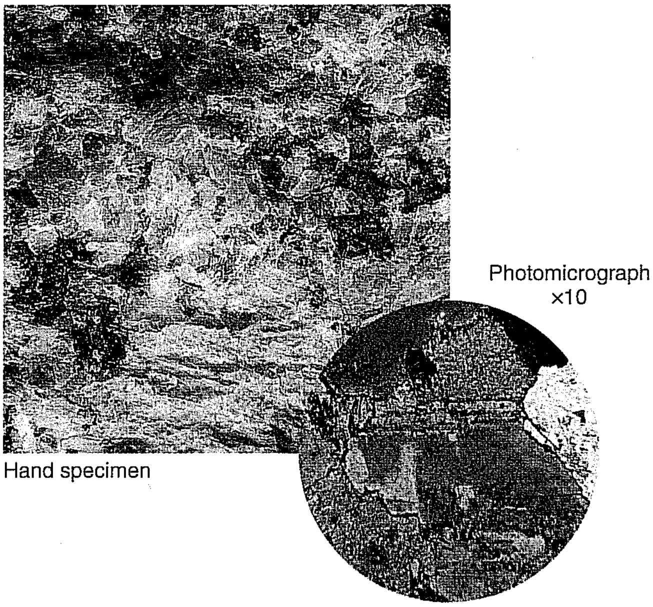

FIGURE 3.1
A coarse-grained crystalline texture clearly shows intergrown mineral crystals. Potassium feldspar, quartz, biotite, and plagioclase are visible. The inset photomicrograph emphasizes how tightly intergrown the crystals are. **The colors in this and most subsequent photomicrographs are not natural; they have been changed by polarizing filters placed on the microscope.**

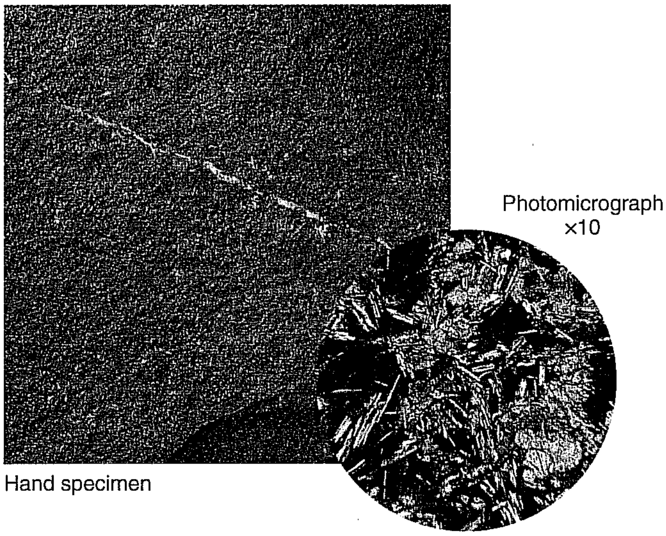

FIGURE 3.2
A fine-grained, or aphanitic, texture is typical of basalt. Its crystalline texture is visible under a microscope (inset photomicrograph).

TEXTURE

Texture refers to the size, shape, and arrangement of the crystals or grains composing the rock. The texture of a rock reflects its composition and how it formed.

Most igneous rocks have a **crystalline** texture (Fig. 3.1), in which the various mineral crystals are interlocked with one another. This texture develops when crystals grow together as a magma solidifies to form solid rock.

The rate at which a magma cools has the greatest effect on the sizes of the crystals in an igneous rock. In general, the more slowly a magma cools, the larger the mineral crystals will be, because slow cooling provides more time for the chemical constituents to migrate to the growing mineral. As you will see shortly, water and gas content can also profoundly affect rock textures.

TEXTURES BASED ON CRYSTAL SIZE

Coarse-grained (phaneritic): An igneous texture in which nearly all crystals are large enough to been seen without a hand lens (Fig. 3.1). For convenience, this is taken to be crystals greater than 1mm (0.04 in). This texture suggests slow cooling of the magma.

Fine-grained (aphanitic): An igneous texture in which most crystals are too small to recognize with the unaided eye (< 1 mm) (Fig. 3.2). This texture suggests fast cooling of the magma.

Glassy: Describes igneous rocks that are made of glass and lack crystals (Fig. 3.3). This texture suggests very fast cooling, such that crystals did not have time to form before the liquid cooled to a solid. Some igneous rocks are part crystals and part glass.

Pegmatitic: Describes igneous rocks with exceptionally large crystals (> 3 cm [1.2 in]). Such rocks are called *pegmatites* (see Fig. 3.7). Large crystals result not only from slow cooling but also from extra water in the magma. Water promotes rapid crystal growth by speeding migration of chemical elements to the growing crystals.

Porphyritic: An igneous texture in which crystals of two different sizes are present in the same rock (Fig. 3.4). The larger crystals, called **phenocrysts,** are surrounded by many smaller crystals, collectively called the **groundmass.** The groundmass can be either coarse grained or fine grained, but the phenocrysts are typically coarse grained. Although both intrusive and extrusive rocks can be porphyritic, it is more typical of extrusive rocks. A porphyritic texture suggests an initial

FIGURE 3.3
Obsidian is easy to identify because of its glassy texture and vitreous (glassy) luster. The excellent conchoidal fracture produces edges that are sharper than any made from metals. This characteristic made obsidian a favorite among Native Americans for arrows and cutting tools and, more recently, it has even been used for very delicate eye surgery. It is most commonly black but may be reddish. *Snowflake obsidian* has white spots that formed where the glass devitrified (crystallized slightly), usually to a variety of silica (SiO_2).

FIGURE 3.4
Porphyritic texture in hand specimen of basalt. Large crystals (plagioclase phenocrysts) are set in a fine-grained groundmass.

period of slow cooling followed by faster cooling. For example, phenocrysts may grow in a slowly cooling magma beneath a volcano. If the volcano then erupts, rapid cooling of the remaining liquid would produce a fine-grained groundmass.

ADDITIONAL EXTRUSIVE-ROCK TEXTURES

Extrusive rocks can develop a range of additional textures if their magmas have high water and gas concentrations. A rising magma experiences a dramatic drop in pressure as it reaches the surface. This release of pressure allows bubbles to form in the magma (or lava), much as bubbles form in soda pop just after the bottle is opened.

Vesicular. Bubbles that form in lava and neither pop nor escape can be frozen into the lava. The cavities left behind are called **vesicles;** the texture is called **vesicular.** Vesicles range from a few millimeters to several centimeters in diameter. Some rocks contain just a few vesicles; others are more vesicle than rock. Some water and gas-rich magmas form so many bubbles that the lavas froth out onto the surface, solidify very rapidly, and form a rock with lots of millimeter-sized vesicles. *Pumice* and *scoria,* described under Fig. 3.15, are examples.

Amygdaloidal. Vesicles in some extrusive rocks are filled with such minerals as calcite, silica, or a useful group of minerals known as the zeolites. Each of these minerals were deposited from water solutions that trickled through the rock after it solidified. Filled vesicles are called **amygdules,** and the texture **amygdaloidal.**

Pyroclastic. Explosive volcanic eruptions expel a lot of gas, glassy volcanic ash, lava, and fragments of rocks and minerals. All of this material comes to rest on the ground following either a free fall through the air or a powerful gas-charged surface flow down the side of the volcano. Either way, the resulting deposit contains a lot of shattered volcanic glass, rock, and mineral fragments, collectively termed **pyroclasts,** that define a **pyroclastic texture.** An extrusive igneous rock with a pyroclastic texture, like that shown in Figure 3.5, is called a **tuff.** Air-fall tuffs frequently show layering, which is otherwise unusual for igneous rocks. Thin pyroclastic deposits formed from flows cool rapidly and, because of their mode of formation, produce unusually soft and lightweight rocks with rather open, porous textures. Thick, hot pyroclastic deposits can retain enough heat for the glassy fragments to fuse (weld) together to form a dense, hard, compacted tuff known as a *welded tuff* or *ignimbrite.*

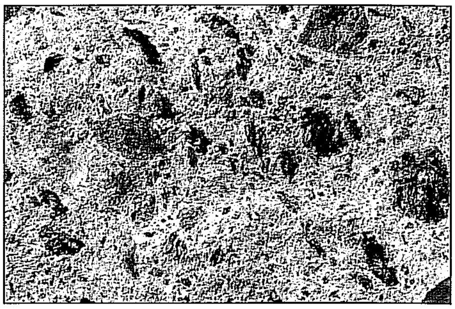

FIGURE 3.5
Pyroclastic texture in hand specimen of rhyolite tuff.

MINERAL COMPOSITION

Relatively few minerals make up most igneous rocks. To correctly identify the rock, you must identify the major minerals. This is fairly easy for coarse-grained rocks, more difficult (but not necessarily impossible) for fine-grained rocks, and impossible for glassy rocks (unless phenocrysts are present). Table 3.1 and the following may be helpful:

1. Most dark-colored igneous rocks are rich in calcium plagioclase and ferromagnesian (iron-magnesium) minerals such as pyroxene or olivine. The word ***mafic*** refers to such rocks. **Ultramafic** igneous rocks are composed entirely of ferromagnesian minerals.
2. Light-colored or **felsic** igneous rocks commonly contain potassium feldspar, sodium plagioclase, and quartz, and only minor amounts of other minerals.
3. **Intermediate** igneous rocks are neither dark nor light and generally contain light-colored minerals (feldspars, some quartz) and dark minerals such as hornblende or biotite.
4. Quartz has a vitreous luster and conchoidal fracture.

TABLE 3.1 RECOGNIZING MINERALS IN IGNEOUS ROCKS

Mineral	*Properties*
Potassium feldspar	Usually white or pink
	Two cleavages at 90°
	Equidimensional crystals
Plagioclase feldspar	Usually white (Na-plagioclase) or gray (Ca-plagioclase)
	Two cleavages at 90°
	Elongate crystals
	Striations
Quartz	Colorless to gray
	Glassy with conchoidal fracture
	Irregular crystals in intrusive rocks
	Equidimensional phenocrysts in extrusive rocks
Biotite	Shiny and black
	One perfect cleavage
	Thin crystals
Muscovite	Shiny and silvery white
	One perfect cleavage
	Thin crystals
Hornblende (amphibole)	Black with shiny, splintery appearance
	Two cleavages at 56° and 124°
	Elongate crystals
Augite (pyroxene)	Black, greenish black, or brownish black
	Vitreous, but rather dull, luster
	Two cleavages at 90°
	Blocky crystals
Olivine	Light green to yellow-green
	Glassy luster
	Small (few millimeters), equidimensional crystals

5. A pink feldspar is usually potassium feldspar; white or gray feldspars may be either potassium feldspar or plagioclase—if striations are present, it is plagioclase.
6. Cleavage and general appearance help to identify amphiboles and pyroxenes. Amphibole cleavages do not intersect at 90°, but pyroxene cleavages do; amphiboles typically are elongate and have a splintery appearance, whereas pyroxenes look blocky.

CLASSIFICATION AND IDENTIFICATION OF IGNEOUS ROCKS

Igneous rocks are classified by their texture and mineral content. The classification scheme in Table 3.2 lists common textures in the left-hand column and typical mineral composition in the top row. Although rock names occupy distinct spaces in the table, it should be understood that these spaces are artificial and that rock types are gradational with each other.

To identify a rock, determine the texture and mineral content, and find the name in the "pigeonhole" that satisfies both. For example, a rock that is coarse grained, porphyritic, and contains quartz and potassium feldspar is a porphyritic granite.

It makes no difference whether texture or mineral content is determined first. Texture is more easily recognized, though, so start with that, as follows:

A. If crystals are not visible or are barely visible with a hand lens (<l mm), and:
    1. The rock looks like glass, the texture is glassy.
    2. It is not glassy, but has a texture similar to fine or medium sandpaper, the texture probably is fine grained.
    3. If the texture is fine grained and vesicles are present, the texture is fine grained and vesicular.
    4. The rock consists of fragments, the texture is pyroclastic.

B. If crystals are visible without a hand lens, and:
    1. Most crystals are larger than 3 cm, the texture is pegmatitic.
    2. Most crystals are smaller than 3 cm, the texture is coarse grained.
    3. Crystals are of two sizes, the texture is porphyritic.
        a. If the groundmass is fine grained, the texture is fine grained and porphyritic.
        b. If the groundmass is coarse grained, the texture is coarse grained and porphyritic.
    4. There are features that look like phenocrysts but have rounded shapes (like the shapes of large vesicles) and the groundmass is fine grained, the texture is amygdaloidal.

Next identify the major minerals. The important mineralogic criteria are:

1. Presence or absence of quartz (only the granites and rhyolites in column 2 contain quartz);
2. The type of feldspar (whether potassium feldspar or plagioclase, and if plagioclase, whether sodium-rich or calcium-rich); and
3. The proportions and kinds of dark-colored minerals (biotite, hornblende, pyroxene, and olivine).

Minerals in the groundmass of fine-grained rocks commonly cannot be identified; however, phenocrysts in such rocks may be helpful. According to Table 3.2, if quartz phenocrysts are present, the rock is rhyolite; if only hornblende phenocrysts are present, it is andesite; if only pyroxene or olivine phenocrysts are present, it is basalt; and if feldspar phenocrysts are present, the feldspar must be identified on the basis of the presence or absence of striations.

Some common igneous rocks are shown in Figures 3.6 through 3.15. **Remember, the photographs are representative examples only, and your samples may differ *considerably* in color and general appearance.** The **texture** and **mineral content** should be similar, so concentrate on those, not on color.

TABLE 3.2
CLASSIFICATION OF IGNEOUS ROCKS*

Mineral Composition ***Texture***	***Felsic*** *>10% quartz, > 50% feldspar with K-feldspar > Na-plagioclase, ± < 15% biotite, muscovite, hornblende*	***Intermediate*** *0–10% quartz, > 50% Na/Ca-plagioclase, 0–10% K-feldspar < 50% hornblende (especially), biotite, augite*	***Mafic*** *20–85% Ca-plagioclase, 15–50% augite, 0–35% olivine*	***Ultramafic*** *Olivine, and/or pyroxene*
Pegmatitic	Granite pegmatite	Diorite pegmatite	Gabbro pegmatite	
Coarse grained (phaneritic)	Granite	Diorite	Gabbro	Peridotite (dunite, if mostly olivine)
Coarse grained and porphyritic	Porphyritic granite	Porphyritic diorite	Porphyritic gabbro	
Fine grained (aphanitic)	Rhyolite	Andesite	Basalt	
Fine grained and porphyritic	Porphyritic rhyolite	Porphyritic andesite	Porphyritic basalt	
Fine grained and vesicular or amygdaloidal		Vesicular or amygdaloidal andesite	Vesicular or amygdaloidal basalt	
Pyroclastic	Rhyolite tuff or breccia	Andesite tuff or breccia	Basalt tuff or breccia	

Texture	***Glass Equivalents of Felsic and Intermediate Rocks***	***Glass Equivalents of Mafic Rocks***	
Glassy	Obsidian		
Glassy with many small vesicles	Pumice	Scoria (may have some crystals)	

*For simplicity, names of less common rocks are omitted and their spaces are left blank.

FIGURE 3.6
Granites are coarse-grained igneous rocks that make up the bulk of the large bodies of intrusive rock called batholiths. Most are light gray or pinkish, but gray and red granite are common too. Gray, glassy-looking quartz is an essential mineral, as is potassium feldspar. Potassium feldspar is commonly pink but may be white. If feldspars of two colors are present, the pink one is probably potassium feldspar, and the white or light gray one is probably sodium plagioclase. Most granites contain some black biotite or hornblende, and some contain muscovite. The fine-grained equivalent of granite is rhyolite. Some granites are very pretty when cut and polished, so they are quarried for use in monuments and buildings.

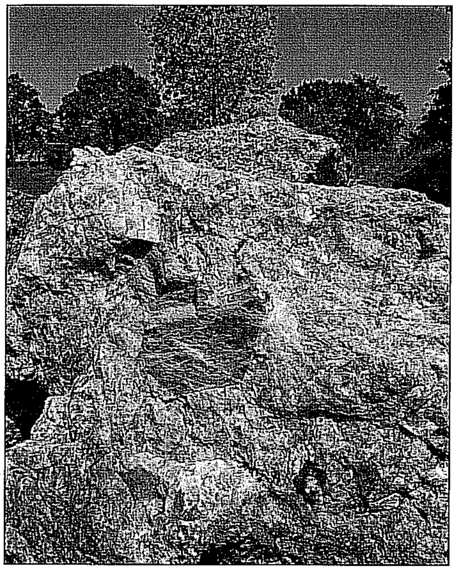

FIGURE 3.7
Pegmatites are very coarse crystalline intrusive rocks that typically occur as small intrusions. Granite pegmatite, like that shown here, is light colored and commonly has large, irregular-shaped crystals of gray quartz and large crystals of potassium feldspar. Some varieties contain white, sodium-rich plagioclase. Big "books" of both biotite and muscovite mica are common. Some pegmatites contain rare minerals such as the silicate minerals tourmaline and beryl, both of which have several gem varieties (for example, emerald is a variety of beryl).

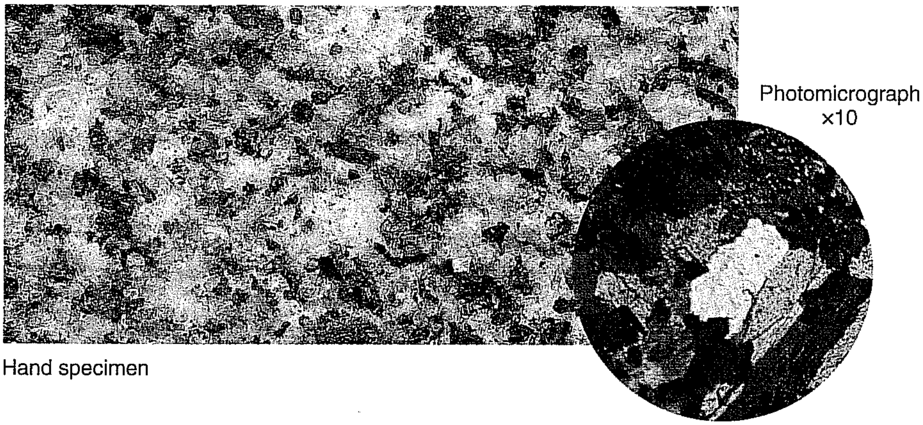

FIGURE 3.8
Diorite is a coarse-grained, intrusive rock usually made of white to light gray sodium-calcium plagioclase and black, splintery-looking hornblende. Finely crystalline diorites look like a mixture of salt and pepper. Some diorites contain biotite as well as hornblende, and possibly a little quartz. The photomicrograph confirms the fully crystalline texture of this rock. Diorite is common in both large (batholith) and small intrusive bodies. Andesite is the fine-grained equivalent of diorite.

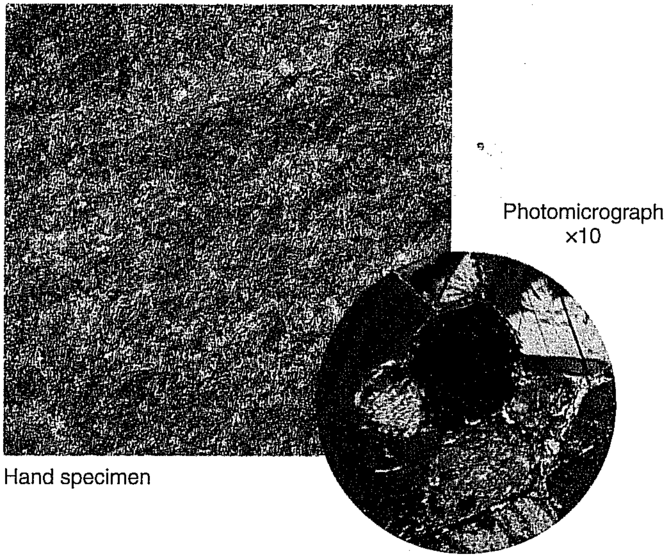

FIGURE 3.9
Gabbro is a coarse-grained intrusive rock composed of light to dark gray calcium plagioclase and black pyroxene. Olivine may be present as well. With so many dark minerals it can be tough to tell one from the other. However, in many gabbros, the plagioclase is easy to identify, because the striations are readily visible on the large elongate crystals. Gabbro is the coarse-grained equivalent of basalt, and it commonly forms thin (dikes and sills) or irregular-shaped, small bodies of intrusive rock. The plagioclase in some gabbros causes a peculiar iridescent blue play of colors that makes the rock valuable for monument or building purposes.

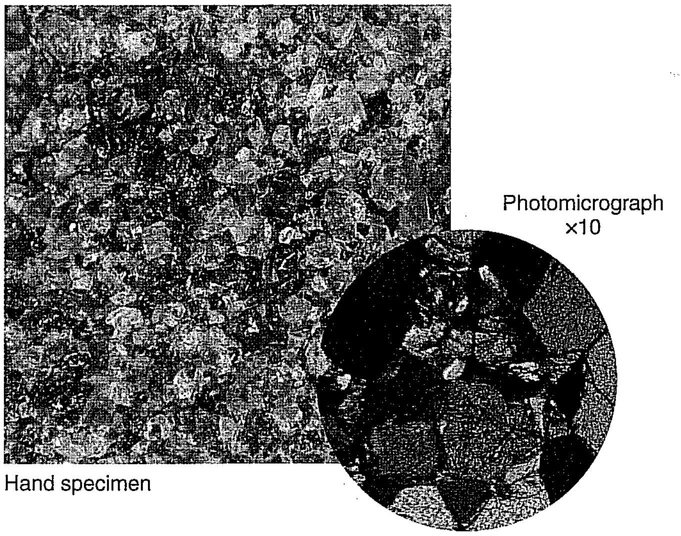

FIGURE 3.10
Peridotite is generally a dark green to black rock, because its principal constituents are pyroxene and olivine. Peridotite consisting almost entirely of olivine is called *dunite,* which usually has the green color of olivine. In fact, the mineral sample of olivine you saw in the lab was probably a piece of dunite (see Figure 2.8). Peridotite rich in pyroxene may have fairly large crystals; in many peridotites, however, the crystals are small, though large enough to identify. Although peridotite is not abundant in the crust, it is the most abundant rock beneath the crust, in the upper part of the Earth's mantle.

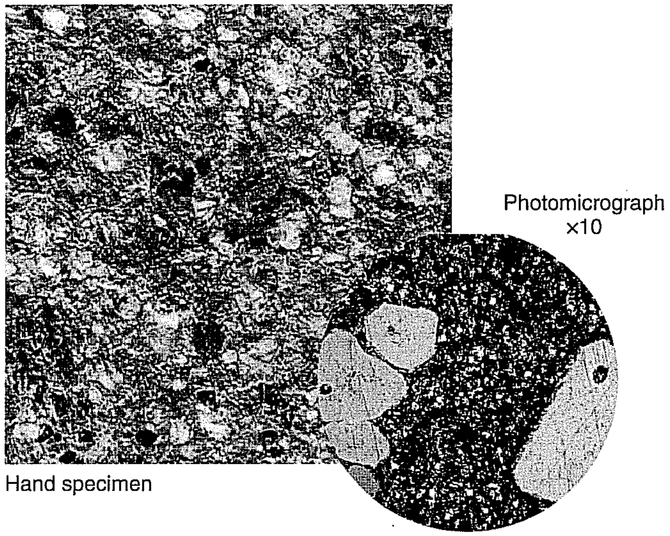

FIGURE 3.11
Rhyolite is a fine-grained extrusive rock that comes in a variety of colors. It is commonly light gray or pink, but red or even black rhyolite is not rare. Many rhyolites, like the one shown here, are porphyritic, so they are identifiable by the glassy quartz phenocrysts and white to salmon potassium feldspar phenocrysts in an aphanitic or even glassy groundmass. In the absence of phenocrysts, a light color suggests, but does not prove, rhyolite. The photomicrograph shows a few phenocrysts (gray) surrounded by a groundmass (black) with tiny crystals (brown to white). Granite is its coarse-grained equivalent.

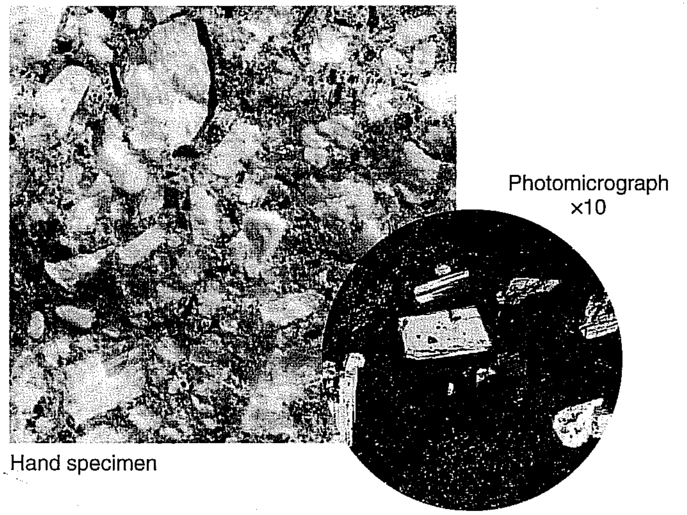

FIGURE 3.12
Andesite is the common extrusive rock of volcanoes formed at convergent plate boundaries. It is typically gray and porphyritic, with phenocrysts of white to light gray plagioclase and black hornblende or biotite. The photomicrograph shows a few phenocrysts (white, yellow, brown) surounded by a glassy groundmass containing very tiny crystals. It is the fine-grained equivalent of diorite.

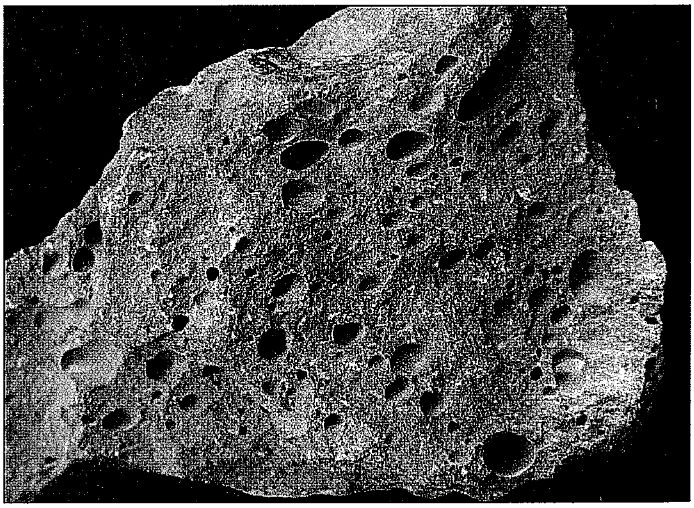

FIGURE 3.13
Basalt is the most abundant extrusive igneous rock, forming the base of the seafloor and large plateaus on land. It is dark gray and fine grained, as in Figure 3.2, and can be vesicular, as shown here, or amygdaloidal. Porphyritic basalt may have phenocrysts of calcium plagioclase, olivine, or both. Olivine phenocrysts are usually small (1 to 5 mm [0.04 to 0.2 in]) and are recognizable by their green color and glassy luster. Basalt is the fine-grained equivalent of gabbro.

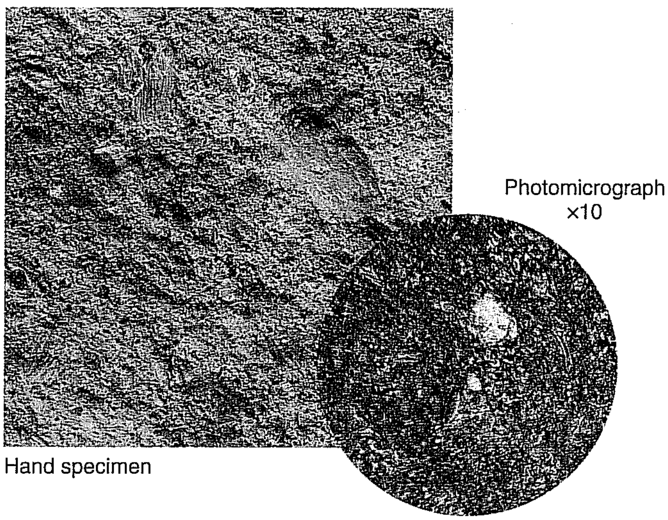

FIGURE 3.14
Tuff is a textural name indicating a pyroclastic texture and particle size less than 6.4 cm (2.5 in). A similar rock with particles bigger than 6.4 cm (2.5 in) is a volcanic breccia. Compositional varieties of tuff or breccia are indicated by using rhyolite, andesite, or basalt as prefixes when possible; for example, rhyolite tuff, basalt breccia. Tuffs vary widely in appearance. Some are made entirely of compacted volcanic glass shards, others have abundant mineral crystals, and others consist of many angular fragments of extrusive rock, especially pumice; most commonly, all three components are present. Just as components and composition are variable, so is color, although many tuffs are light colored, like the rhyolite tuff shown here.

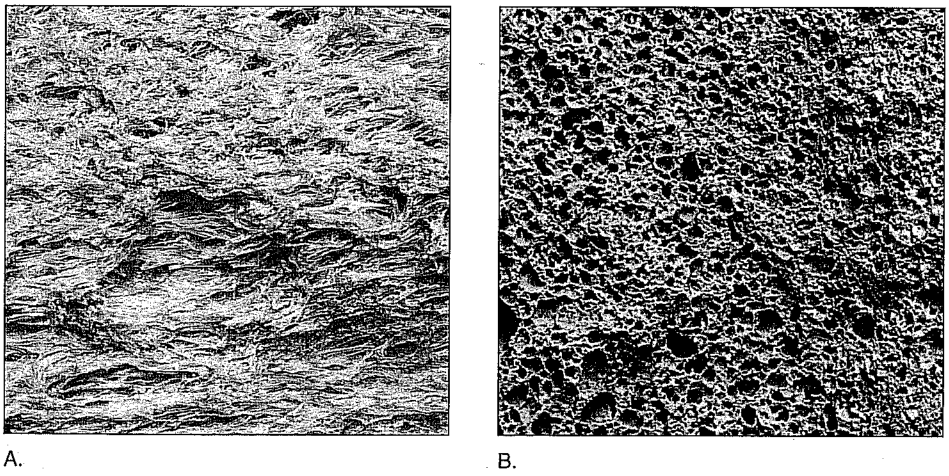

FIGURE 3.15
A. Pumice is the rock that floats because it has so many tiny holes in it. It is a froth of volcanic glass. Look at it with a hand lens to appreciate its character. Pumice is commonly, but not always, white or light gray. It is a good abrasive and is used in Lava® soap and in blocks used to scrape calluses off your feet or to clean griddles. B. Scoria is a basaltic rock with many small holes. You can think of it as being extremely vesicular with small vesicles. It is dark in color, ranging from black to reddish brown. It rarely looks vitreous, although microscopic examination of fresh samples shows that they formed as a bubbly glass. Although it looks as if it might float in water, it is usually too dense. Scoria is sold under the general name "lava rock" for outdoor decorative purposes.

CRYSTALLIZATION OF MAGMA AND BOWEN'S REACTION SERIES

At high temperatures, a magma is completely liquid, but as the temperature drops, crystals begin to form. They don't all form at once, however. At first, crystals of only one or two minerals begin to grow. As the temperature continues to drop, these early-formed crystals may grow to become nicely shaped, they may react with the magma and be partially or wholly dissolved, or new minerals may begin to grow around them, preventing further growth. Continued crystallization increases the proportion of crystals and decreases the amount of liquid. Crystals grow up against one another and form an interlocking, crystalline network. Other minerals may crystallize with further temperature decreases; these will grow in the liquid remaining between earlier-formed crystals.

Because minerals form in a sequence, it is possible to figure out that sequence by carefully studying the textural relations in the rock. This kind of process was done by N.L. Bowen during the early part of the 20th century, but he carried it a giant step further by duplicating the crystallization process in the laboratory. He paid particular attention to reactions between minerals as indicated by textural relations. For example, he commonly found rounded crystals of olivine surrounded by pyroxene (Fig. 3.16) and concluded that olivine formed first, then at a lower temperature, reacted with the liquid (magma) to form pyroxene. He called this a *discontinuous reaction,* because it results in the formation of a completely different mineral (pyroxene). As the pyroxene grows around the olivine, it sometimes prevents further reaction from taking place, and a partially reacted-upon, rounded olivine is left surrounded by pyroxene.

Bowen also observed that plagioclase feldspars gradually changed their chemical composition as magma temperature decreased and plagioclase crystallized. He attributed this to a *continuous reaction* between the magma and the growing crystals of plagioclase: as the temperature of the magma drops and plagioclase crystals grow, they continuously

FIGURE 3.16
Photomicrograph of rounded olivine (green and red) in pyroxene (yellow). The early-formed olivine reacted with the magma to form some of the pyroxene that now surrounds it (×10).

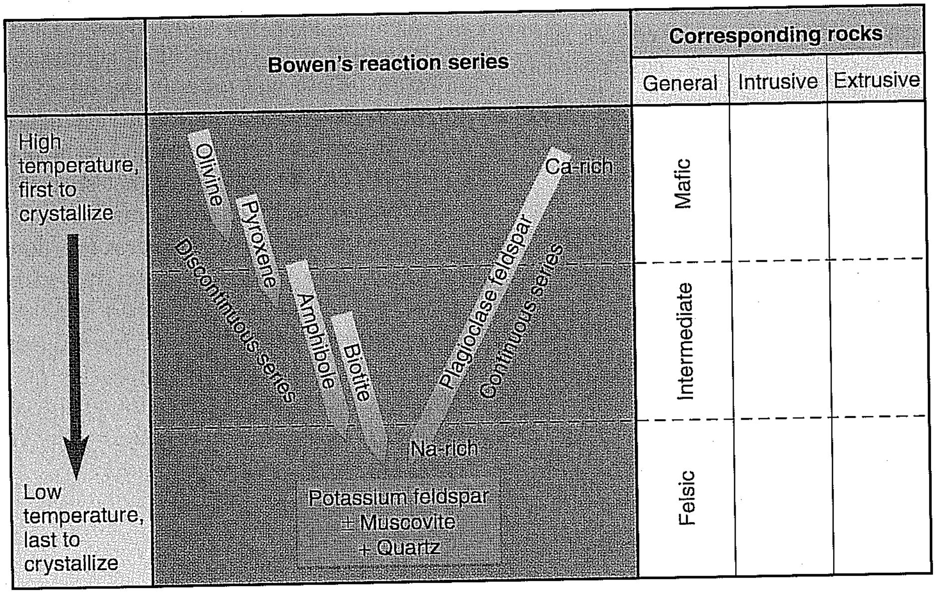

FIGURE 3.17
Bowen's Reaction Series. Minerals at top crystallize first from a magma at high temperatures (1200–1300°C); those at bottom crystallize last at lower temperatures (600–900°C). Ferromagnesian minerals are related by discontinuous reactions with the magma as temperature decreases, whereas plagioclase reacts continuously to form crystals progressively richer in sodium. For names of *Corresponding Rocks,* see Problem 5a.

change their chemical composition and become richer in sodium.

Bowen summarized his studies with a diagram, now called *Bowen's Reaction Series,* which includes all the major rock-forming minerals of common igneous rocks (Fig. 3.17). The *discontinuous reaction series* contains the common iron-magnesium (ferromagnesian) silicate minerals. Plagioclase makes up the *continuous reaction series.* The three minerals at the bottom do not form by reaction. They simply crystallize last, sometimes in the sequence in which they are listed and sometimes simultaneously.

The reaction series shows that when a natural magma cools, certain minerals crystallize earlier and at higher temperatures than others. The common rock-forming minerals form in a regular sequence, with olivine and calcium-rich plagioclase at the top of the list, crystallizing at temperatures some 500–600°C higher than quartz, which is at the bottom of the list. The crystallization temperatures of the plagioclase feldspars fall in the same range as the ferromagnesian minerals. Note, however, that the more calcium-rich plagioclases crystallize at higher temperatures than the less calcium- and more sodium-rich plagioclases. The most sodium-rich one crystallizes at the lowest temperature.

Cautionary note: Although the reaction series is quite instructive, it is not universally applicable in detail; it was designed to summarize the most common reactions and the most common order of crystallization for a specific type of magma (tholeiitic basalt). The overlapping arrows in the discontinuous series suggest the possibility of variation in the sequence.

WHERE AND HOW MAGMAS FORM

Most volcanoes are associated with tectonic plate boundaries (Fig. 3.18). What happens at plate boundaries that allows magmas to form? Are there simply cracks that open into a huge reservoir of magma? Not likely; although part of the Earth's core is molten, the silicate magmas from which igneous rocks form are very different from the molten material in the core.

The most likely way for magmas to form is by **partial melting** of existing rocks. What would happen if a rock made of quartz, potassium feldspar, sodium-plagioclase, biotite, and hornblende began to melt? We can use Bowen's Reaction Series to predict the results. The minerals lowest in the series, such as quartz and potassium feldspar, would melt at lower temperatures than minerals higher in the series. Imagine that the temperature got just high enough to melt the quartz and feldspar, but not high enough to melt the rest of the minerals. Because quartz and potassium feldspar are the main minerals in granite, the partial melt would have a felsic composition similar to that of granite. The liquid, because it is less dense than the surrounding rock, would migrate upward. Drops of liquid would eventually

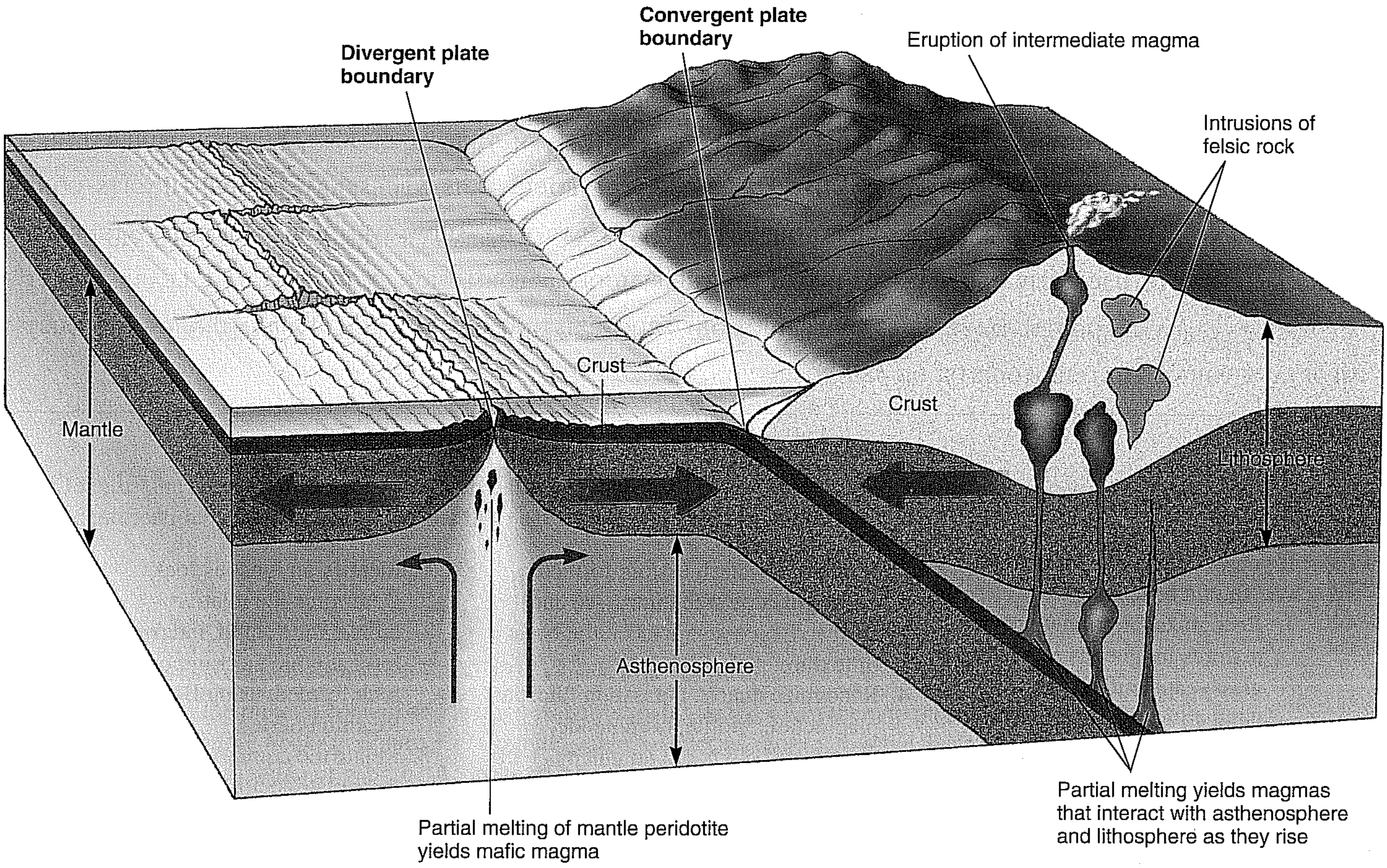

FIGURE 3.18
Most igneous activity takes place at divergent and convergent plate boundaries. Partial melting of peridotite mantle at divergent boundaries yields mafic magmas. Convergent boundaries are more complex; magmas formed by partial melting may interact with a variety of rocks to produce abundant intermediate and felsic magmas.

coalesce to form a body of magma, which would continue to move upward until it either erupted on the surface or crystallized below the surface.

At *divergent plate boundaries* (where plates move away from one another), hot, buoyant peridotite from the mantle rises and, because of its ultramafic composition, partially melts to form a mafic magma that is chemically similar to basalt or gabbro (Fig. 3.18). The magma rises and intrudes into the surrounding lithosphere or is extruded onto the seafloor.

The process at *convergent plate boundaries* (where plates move toward one another) is more complex. When the down-going slab of lithosphere gets hot enough, water-rich fluids are released that trigger partial melting in both the slab and the overlying wedge of mantle. As the magma rises, high-temperature minerals such as olivine may crystallize and be left behind, and the magma may partially dissolve some of the rocks through which it passes. These and other complex processes yield abundant intermediate magma (chemically like andesite or diorite), which erupts at the surface, and felsic magma (chemically like granite or rhyolite), which commonly is trapped below the surface to form large bodies of intrusive igneous rock (Fig. 3.18), but may also reach the surface and erupt explosively.

CHANGES IN MAGMAS

Like the magma formed at convergent plate boundaries, most magmas undergo some kind of change between the time they form and the time they solidify into rock. The changes may result from partially dissolving or melting the surrounding rock, from mixing with other magmas, or from processes within the magma itself.

As an example of a process within the magma, consider what might happen when a gabbro magma crystallizes. According to Bowen's Reaction Series, olivine is the first mineral of the discontinuous series to crystallize. Olivine is denser than the magma, so if there are no currents in the magma, the olivine would sink and form a mush of olivine crystals and magma. This would leave a smaller amount of magma at the top of the chamber, and it would have a different chemical makeup because of the removal of olivine. Should the magma rise, the olivine crystals would be left behind, and the rising magma would be different from the original one. Thus, two different igneous rocks would be formed: one from the olivine-rich mush left behind, and the other from the remaining magma.