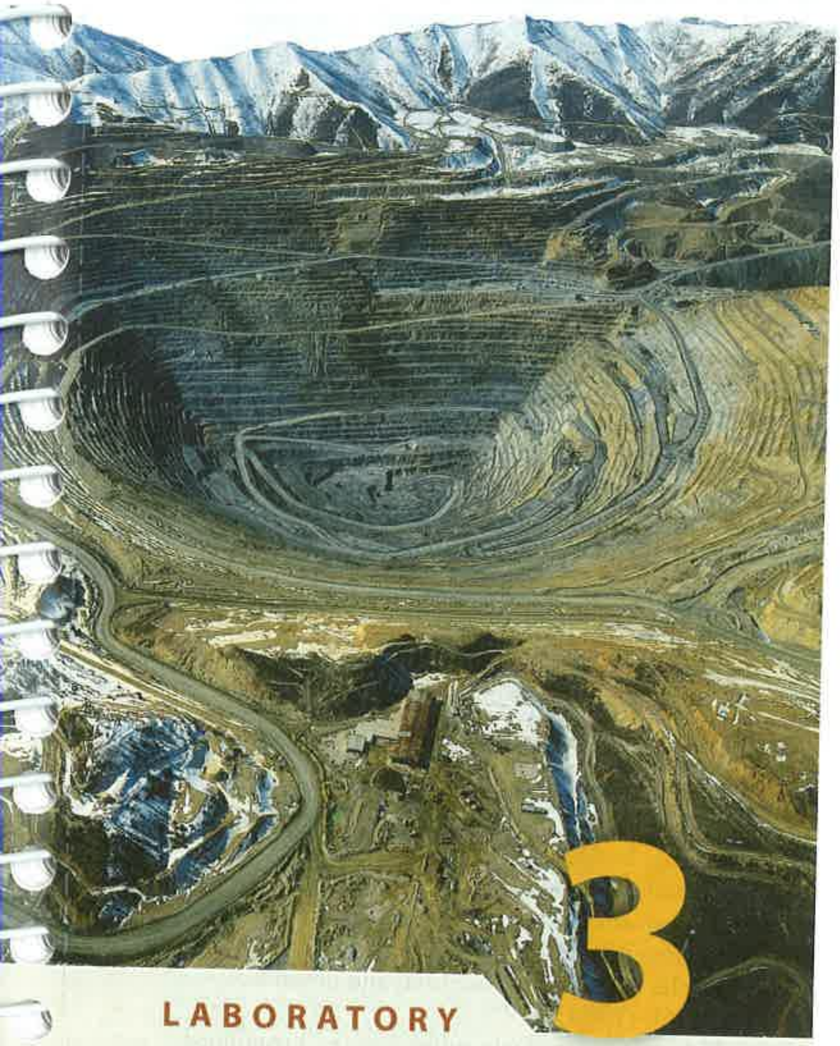

LABORATORY

3 Mineral Properties, Identification, and Uses

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Bingham Canyon Mine, southwest of Salt Lake City, Utah. It is primarily a copper mine, but gold, silver, and other metals have also been extracted from the ore here for over a century. (Michael Collier)

BIG IDEAS

Minerals comprise rocks and are described and classified on the basis of their physical and chemical properties. Every person depends on minerals and elements refined from them, but the supply of minerals is nonrenewable, and the magnitude of their use may be unsustainable.

FOCUS YOUR INQUIRY

THINK About It | What are minerals and crystals, and how are they related to rocks and elements?

ACTIVITY

3.1 Mineral and Rock Inquiry

THINK About It | **What are minerals and crystals, and how are they related to rocks and elements?**

OBJECTIVE Analyze rock samples, and infer how minerals are related to and distinguished from rocks, crystals, and chemical elements.

PROCEDURES

1. **Before you begin,** do not look up definitions and information. Use your current knowledge, and complete the worksheet with your current level of ability. Also, this is **what you will need** to do the activity:

    ____ Activity 3.1 Worksheet (p. 101) and pencil
2. **Then answer every question on the worksheet in a way that makes sense to you** and be prepared to compare your ideas with others.
3. **After you complete the worksheet,** read about minerals and rocks below and be prepared to discuss your observations, interpretations, and inferences with others.

Minerals and Rocks

Many people think of minerals as the beautiful natural crystals mined from the rocky body of Earth and displayed in museums or mounted in jewelry. But table salt, graphite in pencil leads, and gold nuggets are also minerals.

What Are Minerals?

According to geologists, **minerals** are inorganic, naturally occurring solids that have a definite chemical composition, distinctive physical properties, and crystalline structure. In other words, each mineral

- occurs in the solid, rocky body of Earth, where it formed by processes that are inorganic (not involving life).
- has a definite chemical composition of one or more chemical elements that can be represented as a chemical formula (like NaCl for halite, FeS_2 for pyrite, and Au for pure "native gold").
- has physical properties (like hardness, how it breaks, and color) that can be used to identify it.
- has crystalline structure—an internal patterned arrangement or geometric framework of atoms that can be revealed by external crystal faces (**FIGURES 3.1A, B**), the way a mineral breaks (**FIGURE 3.2B**), and in atomic-resolution images (**FIGURE 3.2C**).

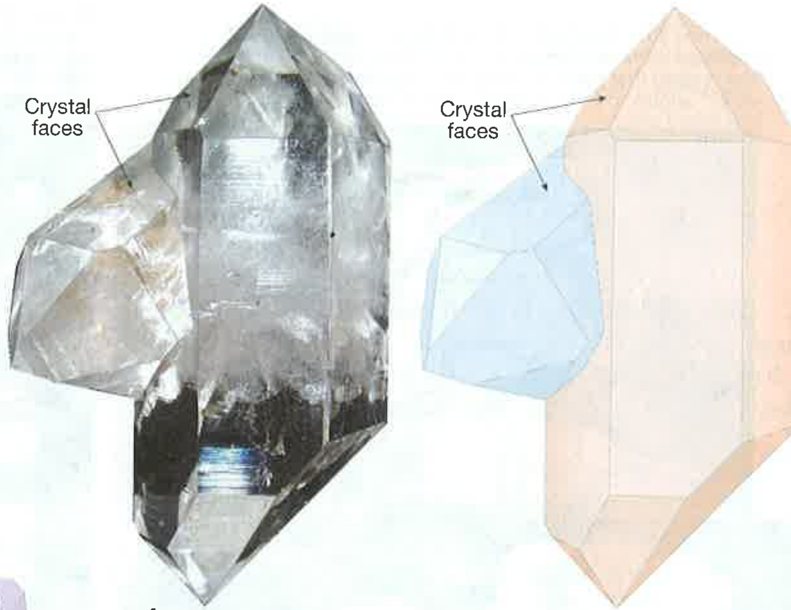
A few "minerals," such as limonite (rust) and opal (**FIGURE 3.3**) never form crystals, so they do not have crystalline structure. They are mineral-like materials (*mineraloids*) rather than true minerals. And even though all true minerals normally form by inorganic processes, some organisms make them as shells or other parts of their bodies. These so-called *biominerals* are of obvious organic origin (made by plants and animals). Examples include aragonite mineral crystals in clam shells and tiny magnetite crystals in the human brain. People make *cultured* mineral crystals in laboratories. Their chemical and physical properties are identical to naturally-formed mineral crystals, but they are not true minerals because they are *synthetic* (man-made, not natural).

How Are Minerals Classified?

Geologists have identified and named thousands of different kinds of minerals, but they are often classified into smaller groups according to their importance, use, or chemistry. For example, a group of only about twenty are known as **rock-forming minerals,** because they are the minerals that make up most of Earth's crust. Another group is called the **industrial minerals**, because they are the main non-fuel raw materials used to sustain industrialized societies like ours. Some industrial minerals are used in their raw form, such as quartz (quartz sand), muscovite (used in computer chips), and gemstones. Most are refined to obtain specific elements such as iron, copper, and sulfur. All minerals are also classified into the following chemical classes:

- **Silicate minerals** are composed of pure silicon dioxide (SiO_2, called quartz) or silicon-oxygen ions $(SiO_4)^{4-}$ combined with other elements. Examples are olivine: $(Fe, Mg)_2SiO_4$, potassium feldspar: $KAlSi_3O_8$, and kaolinite: $Al_2(Si_4O_{10})(OH)_8$.
- **Oxide minerals** contain oxygen (O^{2-}) combined with a metal (except for those containing silicon, which are silicate minerals). Examples are hematite: Fe_2O_3, magnetite: Fe_2O_3, and corundum: Al_2O_3.
- **Hydroxide minerals** contain hydroxyl ions $(OH)^-$ combined with other elements (except for those containing silicon, which are silicate minerals). Examples are goethite: FeO(OH) and limonite: $FeO(OH) \cdot nH_2O$.
- **Sulfide minerals** contain sulfur ions (S^{2-}) combined with metal(s) and no oxygen. Examples are pyrite: FeS_2, galena: PbS, and sphalerite: ZnS. When they are scratched or crushed, one can usually smell the sulfur in these minerals.
- **Sulfate minerals** contain sulfate ions $(SO_4)^{2-}$ combined with other elements. Examples include gypsum: $CaSO_4 \cdot H_2O$ and barite: $BaSO_4$.
- **Carbonate minerals** contain carbonate ions $(CO_3)^{2-}$ combined with other elements. Examples include calcite: $CaCO_3$ and dolomite: $CaMg(CO_3)_2$. These minerals react with acid, the way baking soda (which is the mineral named nahcolite and the chemical compound named sodium bicarbonate: $NaHCO_3$) reacts with acetic acid (CH_3COOH) in vinegar. Geologists use dilute hydrochloric acid (HCl) to detect carbonate minerals because the reaction makes larger bubbles. If a mineral reacts with the dilute HCl, then it is a carbonate mineral.

Top view: Crystal growth was unobstructed so crystal faces are developed (x1).



A.
A rock made of two large, visible, quartz mineral crystals. *Crystal faces* (flat outside surfaces) merge into three dimensional *crystal forms* (geometric shapes). Crystal growth was unobstructed, except where the two crystals touched and grew together (x1).

Side view: Deformed crystal faces among crowded intergrown crystals (x1).

B.
Rock made of many quartz mineral crystals. Note how crystal growth was obstructed as the sides of many crystals grew together (side view), but tips of the crystals (top view) grew unobstructed into six-sided pyramids. Iron impurity gives the purple amethyst variety of quartz its color.

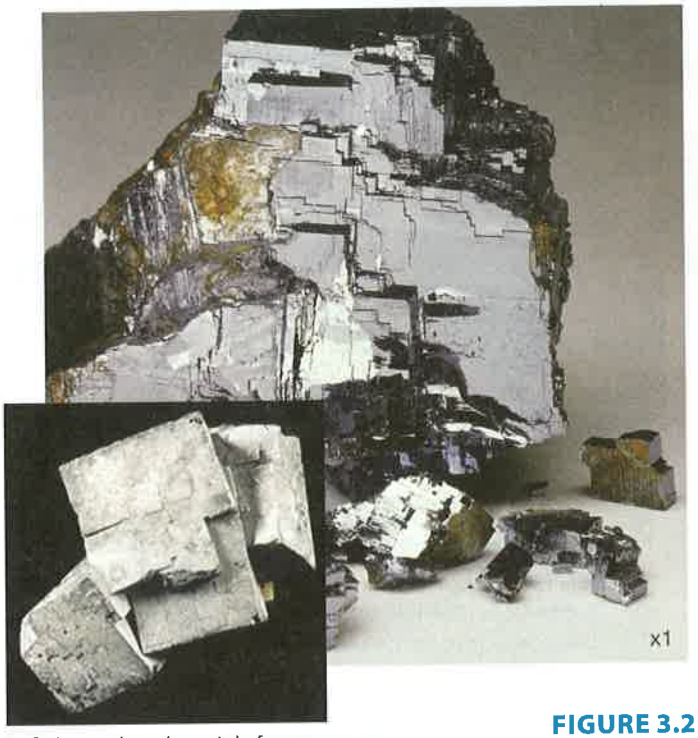
C.
Crystal growth of the calcite mineral crystals in this rock (marble) was obstructed in every direction. The crystals grew together as a dense mass of odd-shaped crystals instead of perfect crystal forms.

Thin section (x30). The layers of agate are made of long intergrown quartz mineral crystals.

D.
Slice of rock (agate) cut with a diamond saw and polished. The layers are made of quartz mineral crystals that are *cryptocrystalline* (not visible in hand sample). They can only be seen in a thin section (thin transparent slice of the rock mounted on a glass slide) magnified with a microscope to 30 times larger than their actual size (x30).

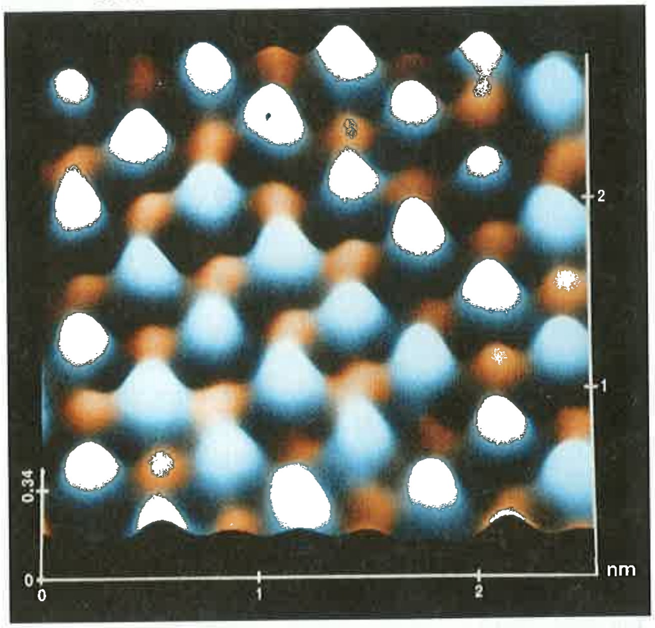
FIGURE 3.1 Minerals and rocks. Most rocks are made of one or more mineral crystals.

B. When struck with a hammer, galena breaks along flat *cleavage surfaces* (planes of weak chemical bonding within the crystal) that have a silvery color, like metal, and intersect at 90° angles to form shapes made of cubes.



A. Galena mineral crystals form cubic shapes that tarnish to a dull gray color.

C. Scanning tunneling microscope (STM) image of galena showing the orderly arrangement of its lead and sulfur atoms. Each sulfur atom is bonded to four lead atoms in the image, plus a lead atom beneath it. Similarly, each lead atom is bonded to four sulfur atoms in the image, plus a sulfur atom beneath it.



Blue = S (sulfur) atoms, Orange = Pb (lead) atoms
nm = nanometer = 1 millionth of a millimeter

FIGURE 3.2 Crystal shape, cleavage, and atomic structure. Galena is lead sulfide—PbS. It is an ore mineral from which lead (Pb) and sulfur (S) are extracted. (STM image by C.M. Eggleston, University of Wyoming)

- **Halide minerals** contain a halogen ion (F^-, Cl^-, Br^-, or I^-) combined with a metal. Examples are halite: NaCl and fluorite: CaF_2.
- **Phosphate minerals** contain phosphate ions $(PO_4)^{3-}$ combined with other elements. An example is apatite: $Ca_5F(PO_4)_3(OH, F, Cl)$.
- **Native elements** are elements in pure form, not combined with different elements. Examples include graphite: C, copper: Cu, sulfur: S_2, gold: Au, and silver: Ag.

How Are Minerals Related to Rocks?

Most **rocks** are aggregates of one or more mineral crystals. For example, mineral crystals comprise all of the rocks in **FIGURE 3.1**. Notice that you can easily detect the mineral crystals in **FIGURES 3.1A** and **3.1B** by their flat **faces**, which are an external feature of the internal geometric framework of their atoms. However, the crystals in many rocks have grown together in such a crowded way that few faces are visible (**FIGURES 3.1C**). Some rocks are also **cryptocrystalline**, made of crystals that are only visible under a microscope (**FIGURE 3.1D**).

Earth is sometimes called the "third rock" (rocky planet) from the Sun, because it is mostly made of rocks. But rocks are generally made of one or more minerals, which are the natural materials from which every inorganic item in our industrialized society has been manufactured. Therefore, minerals are the physical foundation of both our rocky planet and our human societies.

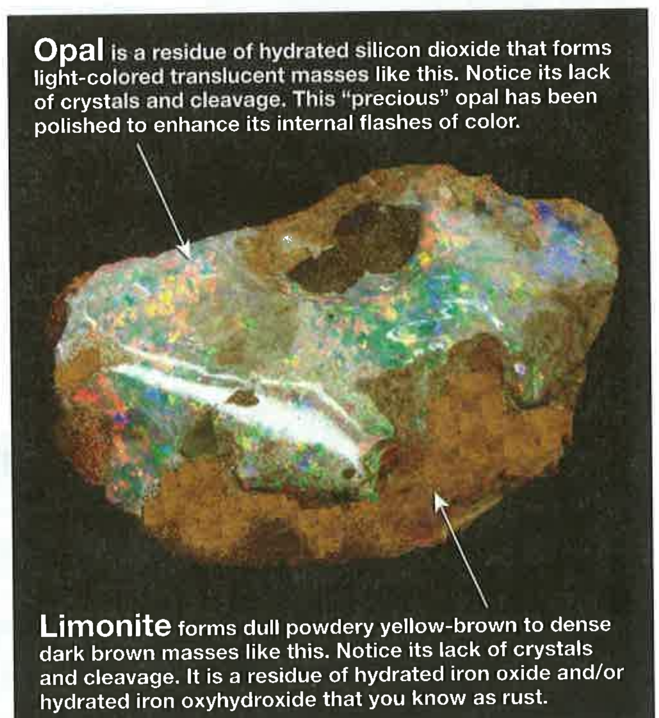


FIGURE 3.3 Mineraloids. Opal and limonite are naturally-occurring inorganic materials, but they are *amorphous* (non-crystalline; they never form crystals). This makes them *mineraloids* (amorphous mineral-like materials), rather true minerals, but they are described, identified, and listed as minerals.

ACTIVITY

3.2 Mineral Properties

THINK About It | **How and why do people study minerals?**

OBJECTIVE Analyze and describe the physical and chemical properties of minerals.

PROCEDURES

1. **Before you begin**, read the following background information. This is **what you will need**:
   - ____ Activity 3.2 Worksheets (pp. 102–103) and pencil
   - ____ set of mineral samples (obtained as directed by your instructor)
   - ____ set of mineral analysis tools (obtained as directed by your instructor)
   - ____ cleavage goniometer cut from GeoTools Sheet 1 at the back of the manual
2. **Then follow your instructor's directions** for completing the worksheets.

What Are a Mineral's Chemical and Physical Properties?

The **chemical properties** of a mineral are its characteristics that can only be observed and measured when or after it undergoes a chemical change due to reaction with another material. This includes things like if or how it tarnishes (reacts with air or water) and whether or not it reacts with acid. For example, calcite and other carbonate (CO_3-containing) minerals react with acid, and native copper tarnishes to a dull brown or green color when it reacts with air or water.

The **physical properties** of a mineral are its characteristics that can be observed (and sometimes measured) without changing its composition. This includes things like how it looks (color, luster, clarity) before it tarnishes or weathers by reacting with air or water, how well it resists scratching (hardness), how it breaks or deforms under stress (cleavage, fracture, tenacity), and the shapes of its crystals. For example, quartz crystals are hard to scratch, glassy, and transparent, while talc is easily scratched, opaque, and feels greasy.

In this activity, you will use the properties of color and clarity (before and after tarnishing), crystal form, luster (before and after tarnishing), streak, hardness, cleavage, and fracture to describe mineral samples. Additional properties—such as tenacity, reaction with acid, magnetic attraction, specific gravity, striations, and exsolution lamellae—can also be helpful in analyzing particular minerals.

Color and Clarity. A mineral's **color** is usually its most noticeable property and may be a clue to its identity. Minerals normally have a typical color, like gold. A rock made up of one color of mineral crystals is usually made up of one kind of mineral, and a rock made of more than one color of mineral crystals is usually made up of more than one kind of mineral. However, there are exceptions, like the agate in FIGURE 3.1D. It has many colors, but they are simply *varieties* (var.)—different colors—of the mineral quartz. This means that a mineral cannot be identified solely on the basis of its color. The mineral's other properties must also be observed, recorded, and used collectively to identify it. Most minerals also tend to exhibit one color on freshly broken surfaces and a different color on tarnished or weathered surfaces. Be sure to note this difference, if present, to aid your identification.

Mineral crystals may vary in their **clarity**: degree of transparency or their ability to transmit light. They may be *transparent* (clear and see-through, like window glass), *translucent* (foggy, like looking through a steamed-up shower door), or *opaque* (impervious to light, like concrete and metals). It is good practice to record not only a mineral's color, but also its clarity. For example, the crystals in FIGURE 3.1B are purple in color and have transparent to translucent clarity. Galena mineral crystals (FIGURE 3.2) are opaque.

Crystal Forms and Mineral Habits. The geometric shape of a crystal is its **crystal form**. Each form is bounded by flat **crystal faces** that intersect at specific angles and in symmetrical relationships (FIGURE 3.1A and B). The crystal faces are the outward reflection of the way that atoms or groups of atoms bonded together in a three-dimensional pattern as the crystal grew under specific environmental conditions. There are many named crystal forms (FIGURE 3.4). Combinations of two or more crystals can also form named patterns, shapes, or twins (botryoidal, dendritic, radial, fibrous: FIGURE 3.4). A mass of mineral crystals lacking a distinctive pattern of crystal growth is called *massive*.

Development of Crystal Faces. The terms euhedral, subhedral, and anhedral describe the extent to which a crystal's faces and form are developed. *Euhedral crystals* have well developed crystal faces and clearly defined and recognizable crystal forms (FIGURE 3.1A). They develop only if a mineral crystal is unrestricted as it grows. This is rare. It is more common for mineral crystals to crowd together as they grow, resulting in a massive network of intergrown crystals with deformed crystal faces and odd shapes or imperfect crystal forms (FIGURE 3.1B). *Subhedral* crystals are imperfect but have enough crystal faces that their forms are recognizable. *Euhedral* crystals have no crystal faces, so they have no recognizable crystal form (FIGURE 3.1C). Most of the laboratory samples of minerals that you will analyze do not exhibit their crystal forms because they are small broken pieces of larger crystals. But whenever the form or system of crystals in a mineral sample can be detected, then it should be noted and used as evidence for mineral identification.

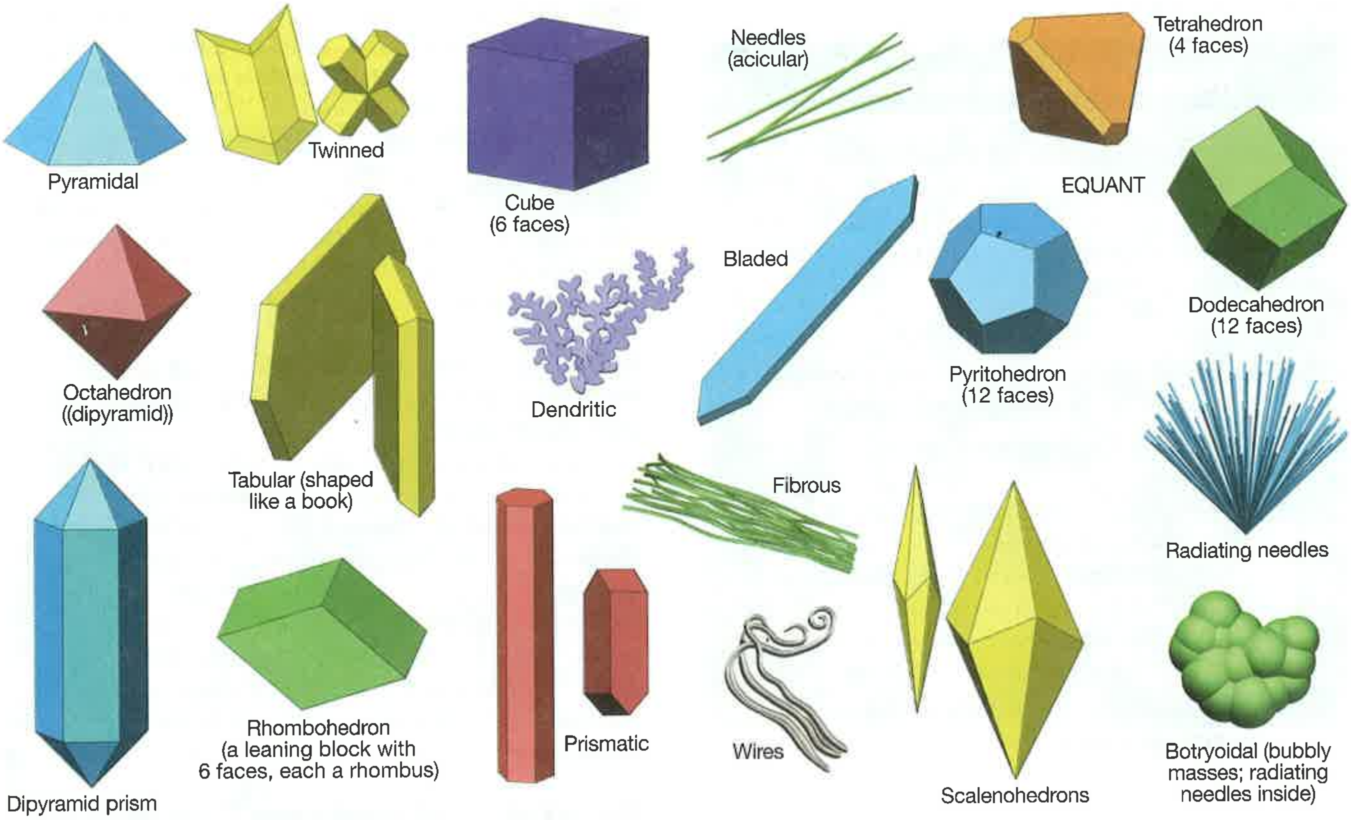


FIGURE 3.4 Crystal forms and combinations. *Crystal form* is the geometric shape of a crystal, and is formed by intersecting flat outer surfaces called *crystal faces*. Combinations of two or more crystals can form patterns, shapes, or twins that also have names. *Massive* refers to a combination of mineral crystals so tightly inter-grown that their crystal forms cannot be seen in hand sample.

Crystal Systems. Each specific crystal form can be classified into one of six *crystal systems* (FIGURE 3.5) according to the number, lengths, and angular relationships of imaginary geometric axes along which its crystal faces grew. The crystal systems comprise 32 classes of crystal forms, but only the common crystal forms are illustrated in FIGURE 3.5.

Mineral Habit. A mineral's **habit** is the characteristic crystal form(s) or combinations (clusters, coatings, twinned pairs) that it habitually makes under a given set of environmental conditions. Pyrite forms under a variety of environmental conditions so it has more than one habit. Its habit is cubes, pyritohedrons, octahedrons, or massive (FIGURE 3.4).

Luster. A mineral's **luster** is a description of how light reflects light from its surfaces. Luster is of two main types—metallic and nonmetallic—that vary in intensity from bright (very reflective, shiny, polished) to dull (not very reflective, not very shiny, not polished). For example, if you make a list of objects in your home that are made of metal (e.g., coins, knives, keys, jewelry, door hinges, aluminum foil), then you are already familiar with metallic luster. Yet the metallic objects can vary from bright (very reflective—like polished jewelry, the polished side of aluminum foil, or new coins) to dull (non-reflective—like unpolished jewelry or the unpolished side of aluminum foil).

Metallic Luster. Minerals with a **metallic luster (M)** reflect light just like the metal objects in your home—they have opaque, reflective surfaces with a silvery, gold, brassy, or coppery sheen (FIGURES 3.2B, 3.6A, 3.7A).

Nonmetallic Luster. All other minerals have a **nonmetallic luster (NM)**—a luster unlike that of the metal objects in your home (FIGURES 3.1, 3.2A, 3.3). The luster of nonmetallic minerals can also be described with the more specific terms below:

- Vitreous—very reflective luster resembling freshly broken glass or a glossy photograph
- Waxy—resembling the luster of a candle
- Pearly—resembling the luster of a pearl
- Earthy (dull)—lacking reflection, like dry soil
- Greasy—resembling the luster of grease, oily

Tarnish and Submetallic Luster. Most metallic minerals will normally tarnish (chemically weather) to a more dull nonmetallic luster, like copper coins. Notice how the exposed metallic copper crystals in FIGURE 3.6 and the galena crystals in FIGURE 3.2A have tarnished to a nonmetallic luster. Always observe freshly broken surfaces of a mineral (e.g., FIGURE 3.2B) to determine whether it has a metallic or nonmetallic luster. It is also useful to note a mineral's luster on fresh versus tarnished

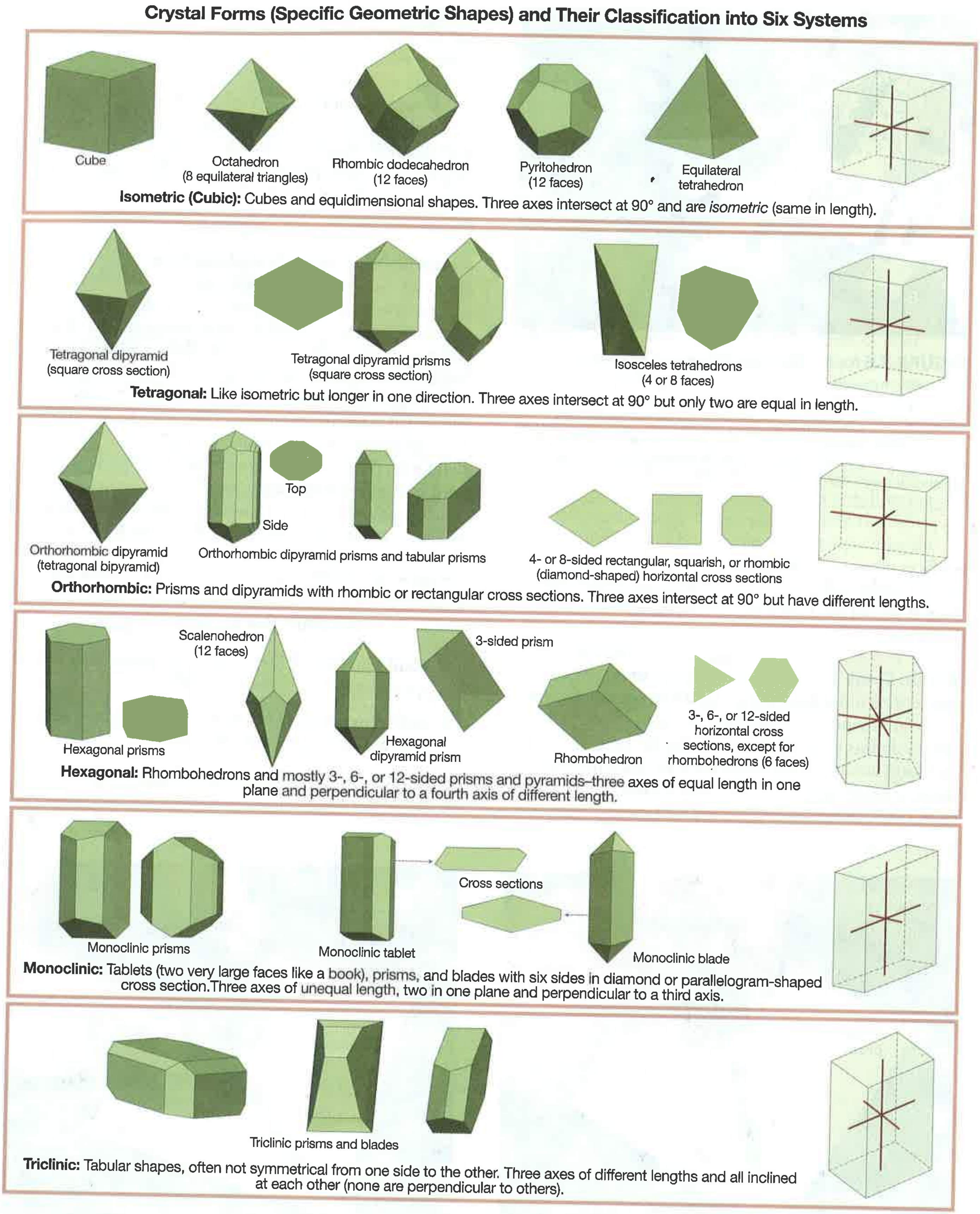


FIGURE 3.5 Crystal systems. Each specific crystal form can be classified into one of six *crystal systems* (major groups) according to the number, lengths, and angular relationships of imaginary geometric axes along which its crystal faces grew (red lines in the right-hand models of each system above). Only the common crystal forms of each class are illustrated and named above.

FIGURE 3.6 Native elements. The native elements are minerals composed of just one element, like gold nuggets. A. When freshly formed or broken, native copper (Cu, naturally-occurring pure copper) has a reflective metallic luster like this freshly-minted copper coin. However, these dendritic clusters of native copper crystals have tarnished to nonmetallic dull brown (A) and/or green (B) colors.

surfaces when possible. If you think that a mineral's luster is *submetallic*, between metallic and nonmetallic, then it should be treated as metallic for identification purposes.

Streak. Streak is the color of a mineral or other substance after it has been ground to a fine powder (so fine that you cannot see the grains of powder). The easiest way to do this is simply by scratching the mineral back and forth across a hard surface such as concrete, or a square of unglazed porcelain (called a *streak plate*). The color of the mineral's fine powder is its streak. Note that the brassy mineral in FIGURE 3.7 has a dark gray streak, but the reddish silver mineral has a red-brown streak. A mineral's streak is usually similar even among all of that mineral's varieties.

If you encounter a mineral that is harder than the streak plate, it will scratch the streak plate and make a white streak of powder from the streak plate. The streak of such hard minerals can be determined by crushing a tiny piece of them with a hammer (if available). Otherwise, record the streak as unknown.

Hardness (H). A mineral's **hardness** is a measure of its resistance to scratching. A harder substance will scratch a softer one (FIGURE 3.8). German mineralogist Friedrich Mohs (1773–1839) developed a quantitative scale of relative mineral hardness on which the softest mineral (talc) has an arbitrary hardness of 1 and the hardest mineral (diamond) has an arbitrary hardness of 10. Higher-numbered minerals will scratch lower-numbered minerals (e.g., diamond will scratch talc, but talc cannot scratch diamond). **Mohs Scale of Hardness** (FIGURE 3.9) is widely used by geologists and engineers. When identifying a mineral, you should mainly be able to distinguish minerals that are relatively hard (6.0 or higher on Mohs Scale) from minerals that are relatively soft (less than or equal to 5.5 on Mohs Scale). You can use common objects such as a glass plate (FIGURE 3.9), pocket knife, or steel masonry nail to make this distinction as follows.

- **Hard minerals:** Will scratch glass; cannot be scratched with a knife blade or masonry nail.
- **Soft minerals:** Will not scratch glass; can be scratched with a knife blade or masonry nail.

You can determine a mineral's hardness number on Mohs Scale by comparing the mineral to common objects

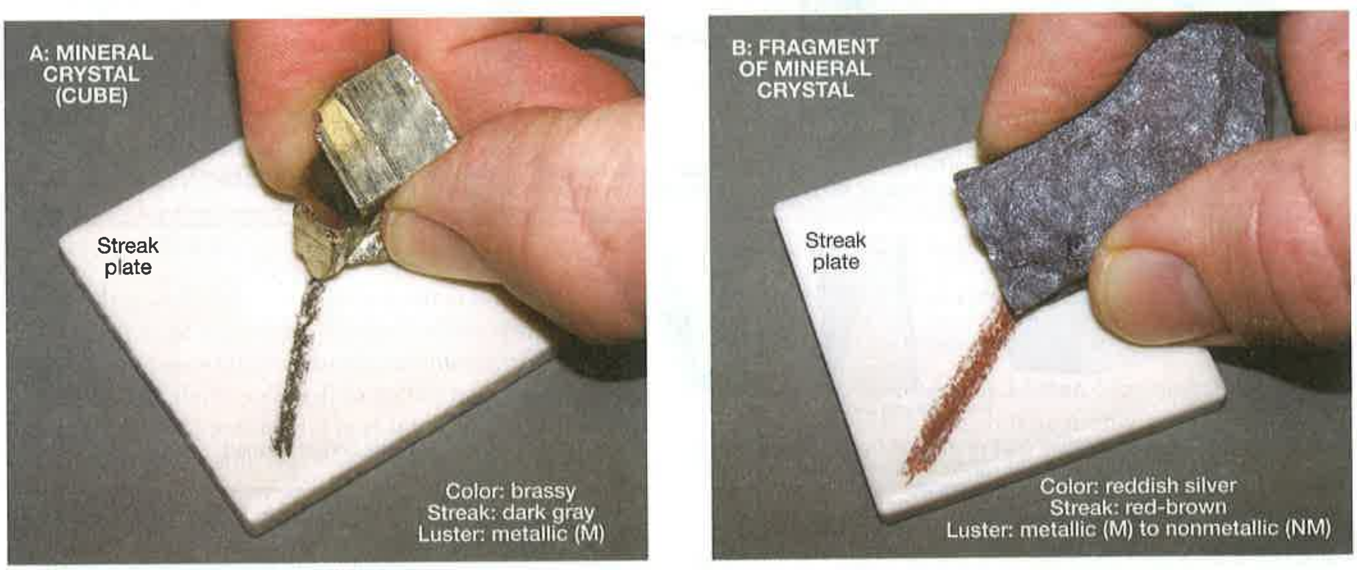


FIGURE 3.7 Streak tests. Determine a mineral's streak (color in powdered form) by scratching it across a streak plate with significant force, then blowing away larger pieces of the mineral to reveal the color of the powder making the streak. If you do not have a streak plate, then determine the streak color by crushing or scratching part of the sample to see the color of its powdered form.

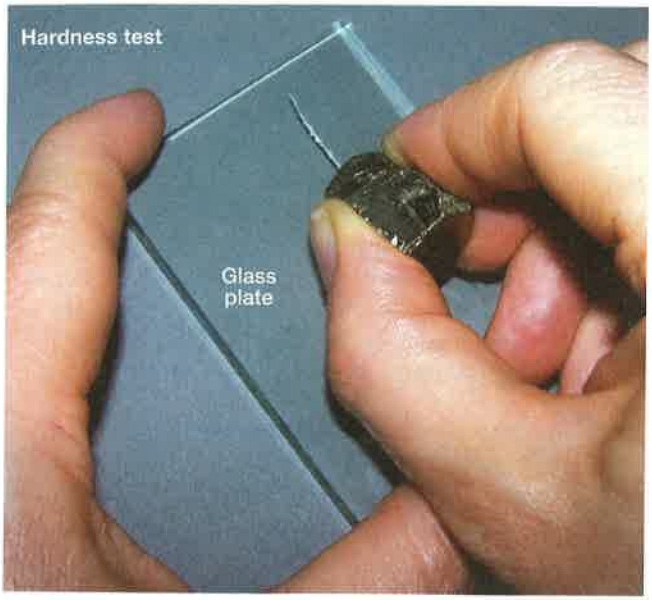
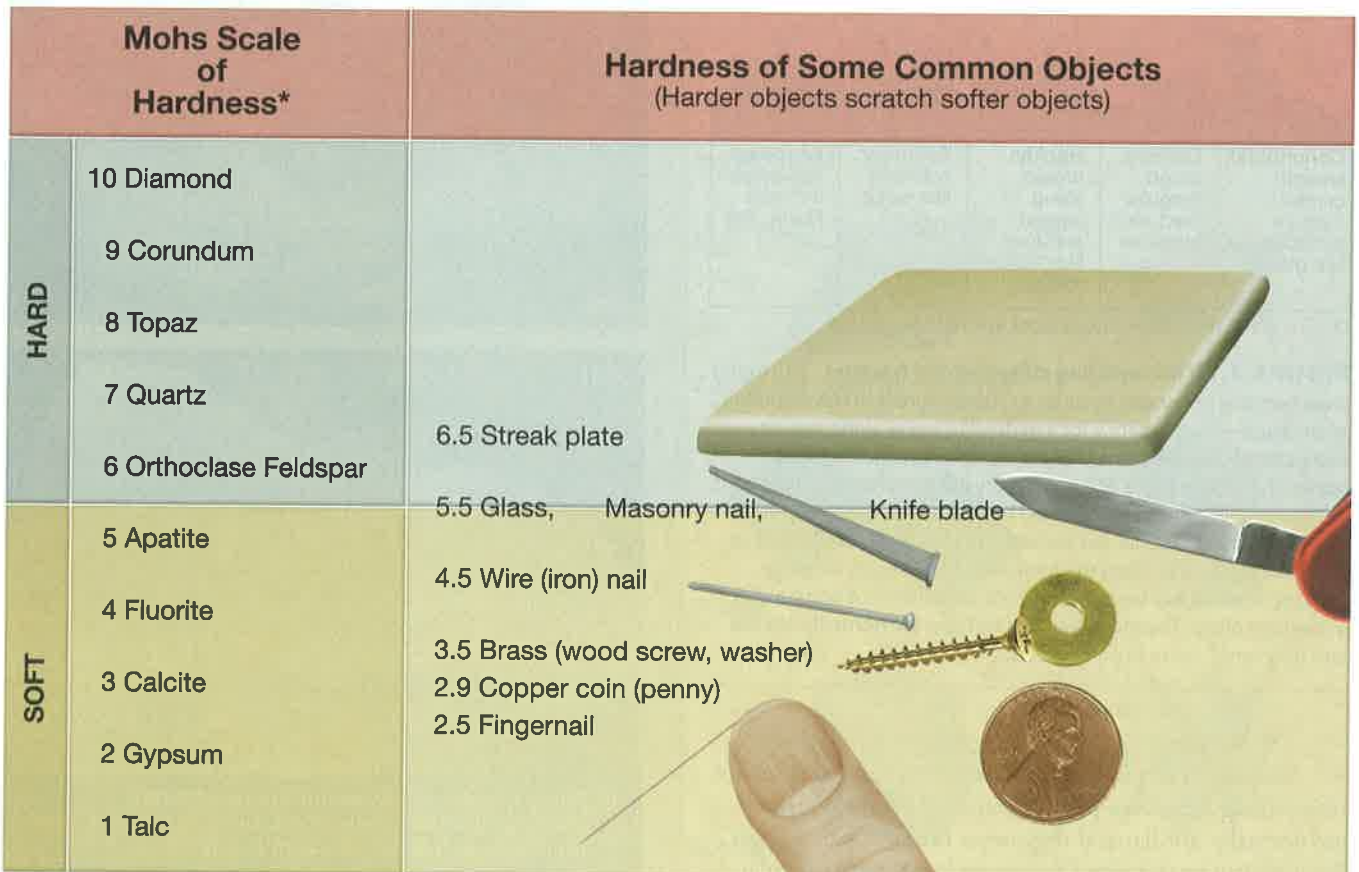


FIGURE 3.8 Hardness test. You can test a mineral's hardness (resistance to scratching) using a glass plate, which has a hardness of 5.5 on Mohs Scale of Hardness (FIGURE 3.9). Be sure the edges of the glass have been dulled. If not, then wrap the edges in masking tape or duct tape. Hold the glass plate firmly against a flat table top, then forcefully try to scratch the glass with the mineral sample. A mineral that scratches the glass is a *hard* mineral (i.e., harder than 5.5). A mineral that does not scratch the glass is a *soft* mineral (i.e., less than or equal to 5.5).

shown in FIGURE 3.9 or pieces of the minerals in Mohs Scale. Commercial *hardness kits* contain a set of all of the minerals in FIGURE 3.9 or a set of metal scribes of known hardnesses. When using such kits to make hardness comparisons, remember that the harder mineral/object is the one that scratches, and the softer mineral/object is the one that is scratched.

Cleavage and Fracture. Cleavage is the tendency of some minerals to break (*cleave*) along flat, parallel surfaces (**cleavage planes**) like the flat surfaces on broken pieces of galena (FIGURE 3.2B). Cleavage planes are surfaces of weak chemical bonding (attraction) between repeating, parallel layers of atoms in a crystal. Each different set of parallel cleavage planes is referred to as a *cleavage direction.* Cleavage can be described as excellent, good, or poor (FIGURE 3.10). An *excellent cleavage* direction reflects light in one direction from a set of obvious, large, flat, parallel surfaces. A *good cleavage* direction reflects light in one direction from a set of many small, obvious, flat, parallel surfaces. A *poor cleavage* direction reflects light from a set of small, flat, parallel surfaces that are difficult to detect. Some of the light is reflected in one direction from the small cleavage surfaces, but most of the light is scattered randomly by fracture surfaces separating the cleavage surfaces.



* A scale for measuring relative mineral hardness (resistance to scratching).

FIGURE 3.9 Mohs Scale of Hardness (resistance to scratching). *Hard minerals* have a Mohs hardness number greater than 5.5, so they scratch glass and cannot be scratched with a knife blade or masonry (steel) nail. *Soft minerals* have a Mohs hardness number of 5.5 or less, so they do not scratch glass and are easily scratched by a knife blade or masonry (steel) nail. A mineral's hardness number can be determined by comparing it to the hardness of other common objects or minerals of Mohs Scale of Hardness.

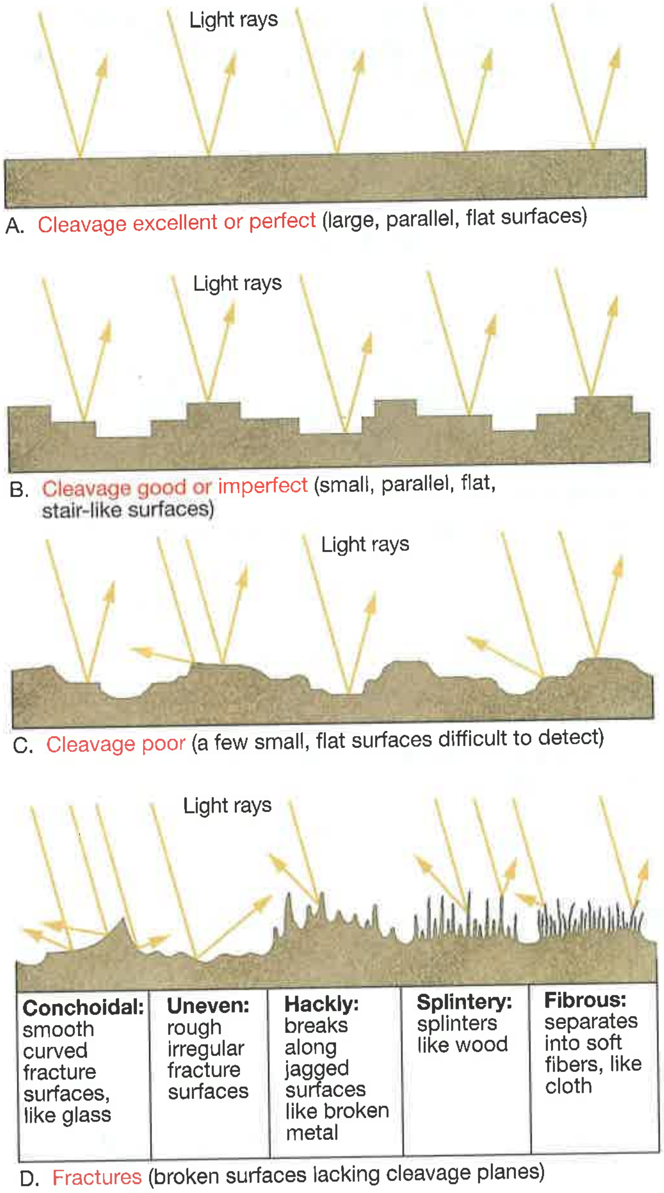


FIGURE 3.10 Recognizing cleavage and fracture. Illustrated cross sections of mineral samples to show degrees of development of cleavage—the tendency for a mineral to break along one or more sets of parallel, planar, reflective surfaces called *cleavage planes*. If a broken piece of a mineral crystal is rotated in bright light, its cleavage planes will be revealed by periodic flashes of light from one large, or many small, flat parallel surfaces. If no such reflective flashes of light occur, then the mineral sample has no cleavage. *Fracture* refers to any break in a mineral that does not occur along a cleavage plane. Therefore, fracture surfaces are normally not flat and they never occur in parallel sets.

Fracture refers to any break in a mineral that does not occur along a cleavage plane. Therefore, fracture surfaces are normally not flat and they never occur in parallel sets. Fracture can be described as *uneven* (rough and irregular, like the milky quartz in FIGURE 3.11B), *splintery* (like splintered wood), or *hackly* (having jagged edges, like broken metal). Pure quartz (FIGURE 3.11A) and mineraloids like opal (FIGURE 3.3) tend to fracture like glass—along ribbed, smoothly curved surfaces called *conchoidal fractures*.

Cleavage Direction. Cleavage planes are parallel surfaces of weak chemical bonding (attraction) between repeating parallel layers of atoms in a crystal, and more than one set of cleavage planes can be present in a crystal. Each different set has an orientation relative to the crystalline structure and is referred to as a **cleavage direction** (FIGURE 3.12). For example, muscovite (FIGURE 3.13) has one excellent cleavage direction and splits apart like pages of a book (book cleavage). Galena (FIGURE 3.2) breaks into small cubes and shapes made of cubes, so it has three cleavage directions developed at right angles to one another. This is called cubic cleavage (FIGURE 3.12).

Cleavage Direction in Pyriboles. Minerals of the pyroxene (e.g., augite) and amphibole (e.g., hornblende) groups generally are both dark-colored (dark green to black), opaque, nonmetallic minerals that have two good

A: Pure quartz (var. rock crystal) is colorless, transparent, nonmetalic, and has conchoidal fracture (like glass).

B: Milky quartz forms when the quartz has microscopc fluid inclusions, usually water. It has an irregular (rough, uneven) fracture.

FIGURE 3.11 Fracture in quartz—SiO_2 (silicon dioxide). These hand samples are broken pieces of quartz mineral crystals so no crystal faces are present. Note the absence of cleavage and the presence of conchoidal (like glass) to uneven fracture.

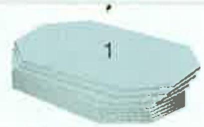
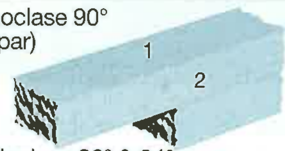
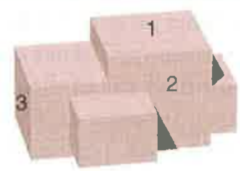
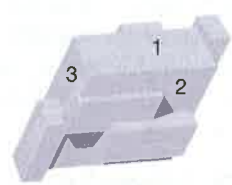
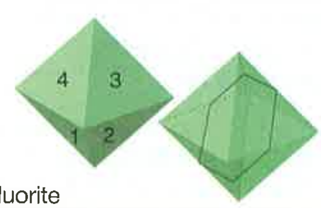
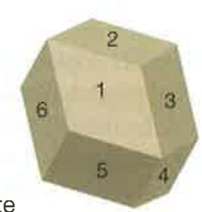
Number of Cleavages and Their Directions	Name and Description of How the Mineral Breaks	Shape of Broken Pieces (cleavage directions are numbered)	Illustration of Cleavage Directions
No cleavage (fractures only)	No parallel broken surfaces; may have conchoidal fracture (like glass)	 Quartz	None (no cleavage)
1 cleavage	**Basal (book) cleavage** "Books" that split apart along flat sheets	 Muscovite, biotite, chlorite (micas)	
2 cleavages intersect at or near 90°	**Prismatic cleavage** Elongated forms that fracture along short *rectangular* cross sections	Orthoclase 90° (K-spar)  Plagioclase 86° & 94°, pyroxene (augite) 87° & 93°	
2 cleavages do not intersect at 90°	**Prismatic cleavage** Elongated forms that fracture along short *parallelogram* cross sections	 Amphibole (hornblende) 56° & 124°	
3 cleavages intersect at 90°	**Cubic cleavage** Shapes made of cubes and parts of cubes	 Halite, galena	
3 cleavages do not intersect at 90°	**Rhombohedral cleavage** Shapes made of rhombohedrons and parts of rhombohedrons	 Calcite and dolomite 75° & 105°	
4 main cleavages intersect at 71° and 109° to form octahedrons, which split along hexagon-shaped surfaces; may have secondary cleavages at 60° and 120°	**Octahedral cleavage** Shapes made of octahedrons and parts of octahedrons	 Fluorite	
6 cleavages intersect at 60° and 120°	**Dodecahedral cleavage** Shapes made of dodecahedrons and parts of dodecahedrons	 Sphalerite	

FIGURE 3.12 **Cleavage in minerals.**

FIGURE 3.13 Cleavage in mica. Mica is a group of silicate minerals that form very reflective (vitreous) tabular crystals with one excellent cleavage direction. The crystals split easily into thin sheets, like pages of a book. This is called *book cleavage*. Muscovite mica is usually silvery brown in color. Biotite mica is always black.

cleavage directions. The two groups of minerals are sometimes difficult to distinguish, so some people identify them collectively as *pyriboles*. However, pyroxenes can be distinguished from amphiboles on the basis of their cleavage. The two cleavages of pyroxenes intersect at 87° and 93°, nearly at right angles (**FIGURE 3.14A**). The two cleavages of amphiboles intersect at angles of 56° and 124° (**FIGURE 3.14B**). These angles can be measured in hand samples using the cleavage goniometer from GeoTools Sheet 1 at the back of this manual. Notice how a green cleavage goniometer was used to measure angles between cleavage directions in **FIGURE 3.14**.

Cleavage Direction in Feldspars. Feldspars have two excellent to good cleavage directions, plus uneven fracture (**FIGURE 3.15**). The cleavage goniometer from GeoTools Sheet 1 can be used to distinguish potassium feldspar (orthoclase) from plagioclase (**FIGURE 3.15**).

Other Properties. There are additional mineral properties, too numerous to review here. However, the following other properties are typical of specific minerals or mineral groups:

Tenacity is the manner in which a substance resists breakage. Terms used to describe mineral tenacity include *brittle* (shatters like glass), *malleable* (like modeling clay or gold; can be hammered or bent permanently into new shapes), *elastic* or *flexible* (like a plastic comb; bends but returns to its original shape), and *sectile* (can be carved with a knife).

Reaction to acid differs among minerals. Cool, dilute hydrochloric acid (1–3% HCl) applied from a dropper bottle is a common "acid test." All of the so-called *carbonate minerals* (minerals with a chemical composition including carbonate, CO_3) will effervesce ("fizz") when a drop of such dilute HCl is applied to one of their freshly exposed surfaces (**FIGURE 3.16**). Calcite ($CaCO_3$) is the most commonly encountered carbonate mineral and effervesces in the acid test. Dolomite $[Ca,Mg(CO_3)_2]$ is

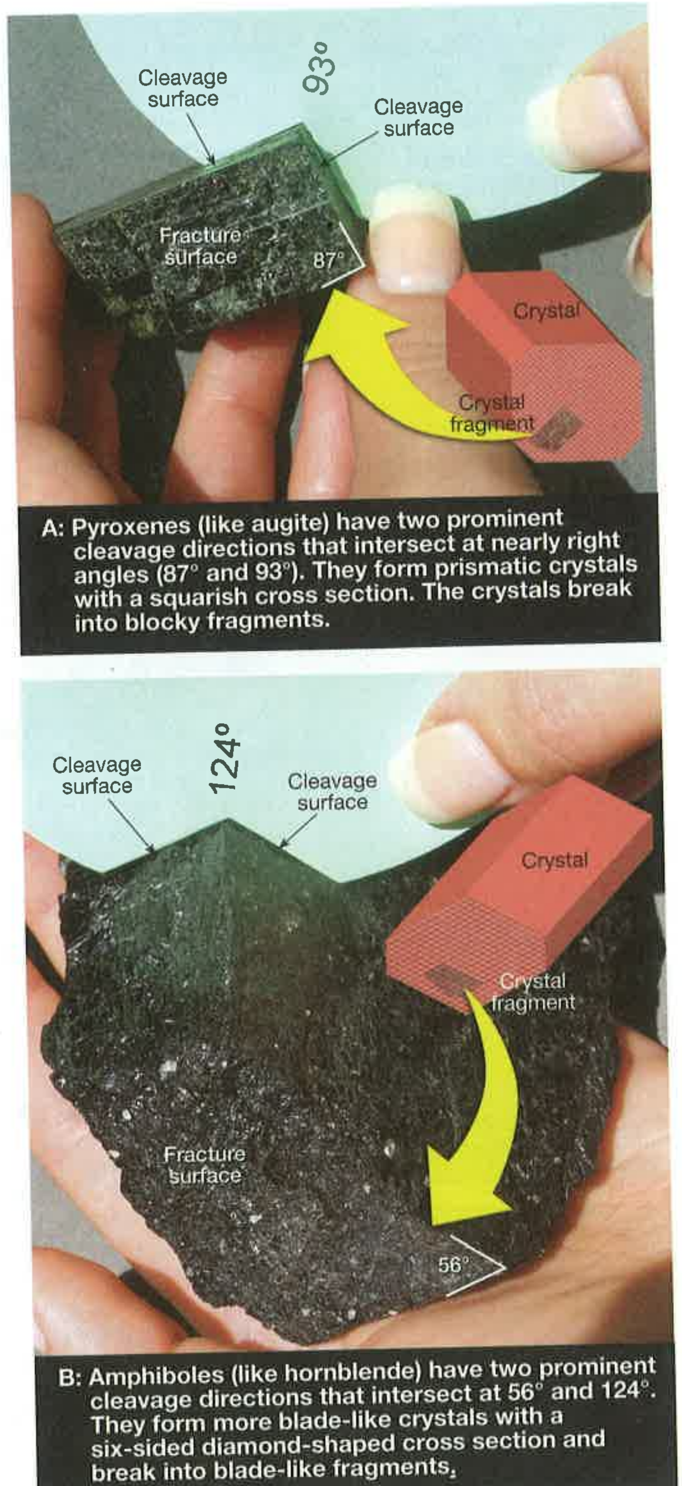


FIGURE 3.14 Cleavage in pyroxenes and amphiboles. Pyroxenes and amphiboles are two groups of dark colored silicate minerals with many similar properties. The main feature that distinguishes them is their cleavage.

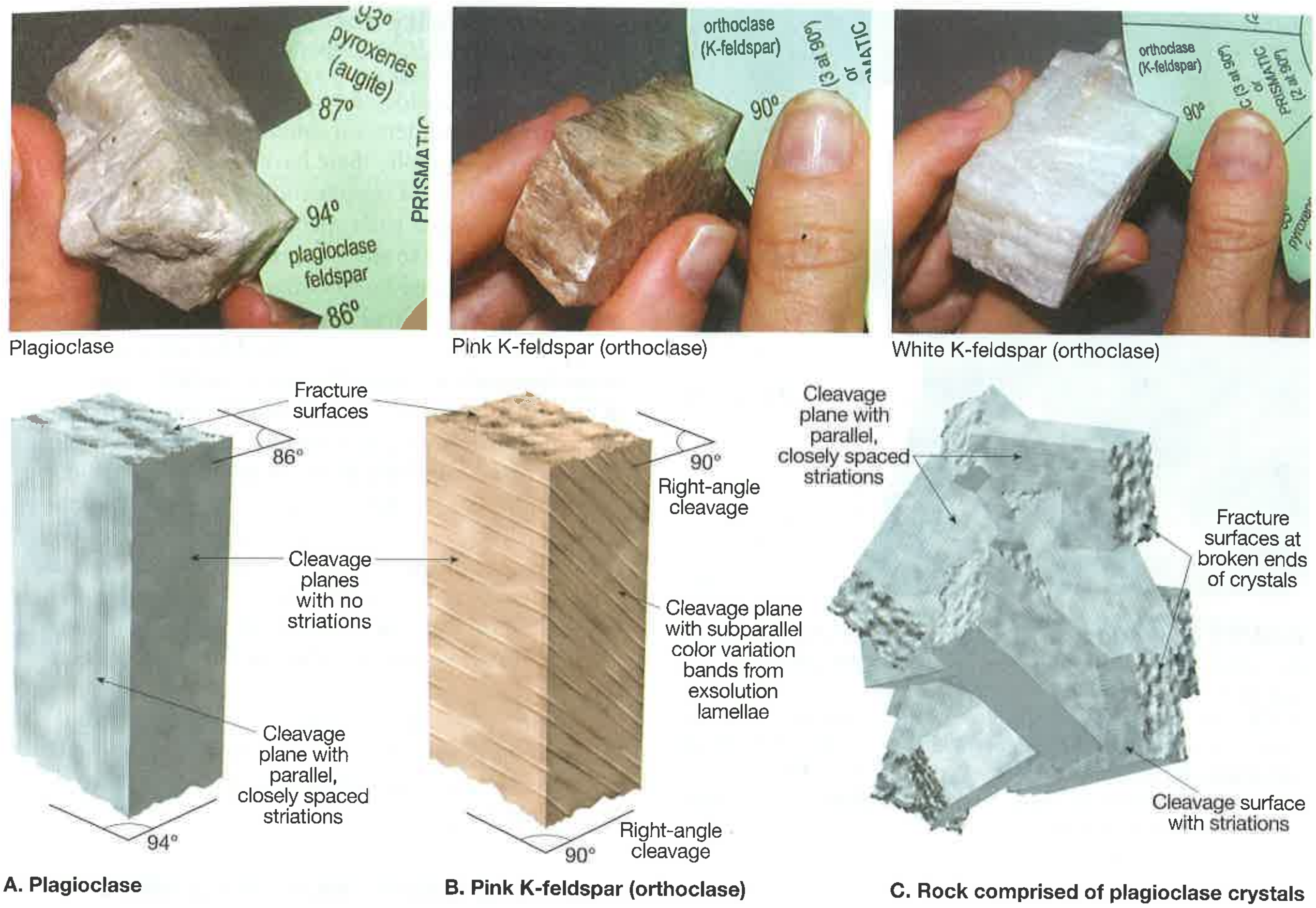


FIGURE 3.15 Common feldspars. Note how the cleavage goniometer can be used to distinguish potassium feldspar (K-spar, orthoclase) from plagioclase. The K-spar or orthoclase (Greek, *ortho*—right angle and *clase*—break) has perfect right-angle (90º) cleavage. Plagioclase (Greek, *plagio*—oblique angle and *clase*—break) does not. A. Plagioclase often exhibits *hairline striations* on some of its cleavage surfaces. They are caused by *twinning*: microscopic intergrowths between symmetrically-paired microcrystalline portions of the larger crystal. B. K-par (orthoclase) crystals may have intergrowths of thin, discontinuous, *exsolution lamellae*. They are actually microscopic layers of plagioclase that form as the K-spar cools, like fat separates from soup when it is refrigerated. C. Hand sample of a rock that is an aggregate of intergrown plagioclase mineral crystals. Individual mineral crystals are discernible within the rock, particularly the cleavage surfaces that have characteristic hairline striations.

another carbonate mineral that resembles calcite, but it will fizz in dilute HCl only if the mineral is first powdered. (It can be powdered for this test by simply scratching the mineral's surface with the tip of a rock pick, pocket knife, or nail.) If HCl is not available, then undiluted vinegar can be used for the acid test. It contains acetic acid (but the effervescence will be much less violent).

Striations are straight "hairline" grooves on the cleavage surfaces or crystal faces of some minerals. This can be helpful in mineral identification. For example, you can use the striations of plagioclase feldspar (**FIGURE 3.15A**) to distinguish it from potassium feldspar (K-feldspar, **FIGURE 3.15B**). *Plagioclase feldspar* has faint hairline striations on surfaces of one of its two cleavage directions. In contrast, *K-feldspar* (orthoclase) sometimes has internal *exsolution lamellae*, which are faint streaks of plagioclase that grew inside of it.

Magnetism influences some minerals, such as magnetite. The test is simple: check to see if the mineral is attracted to a magnet. Lodestone is a variety of magnetite that is itself a natural magnet. It will attract steel paperclips. Some other minerals may also be weakly attracted to a magnet (e.g., hematite, bornite, and pyrrhotite).

Specific Gravity (SG). Density is a measure of an object's mass (weighed in grams, g) divided by its volume (in cubic centimeters, cm^3). **Specific gravity** is the ratio of the density of a substance divided by the density of water. Since water has a density of 1 g/cm^3 and the units cancel out, specific gravity is the same number as density but without any units. For example, the mineral quartz has a density of 2.65 g/cm^3 so its specific gravity is 2.65 (i.e., SG = 2.65). **Hefting** is an easy way to judge the specific gravity of one mineral relative to another. This is done by holding a piece of the first mineral in one hand and holding an equal-sized piece of the second mineral in your other hand. Feel the difference in weight between the two samples (i.e., heft the samples). The sample that feels heavier has a higher specific gravity than the other. Most metallic minerals have higher specific gravities than nonmetallic minerals.

METALLIC AND SUBMETALLIC (M) MINERAL IDENTIFICATION

STEP 1: What is the mineral's hardness?	STEP 2: Does the mineral have cleavage?	STEP 3: What is the mineral's streak?	STEP 4: Match the mineral's physical properties to other characteristic properties below.	STEP 5: Mineral name. Find out more about it in the mineral database (Fig.3.21).
HARD (H > 5.5) Scratches glass Not scratched by masonry nail or knife blade	Cleavage absent, poor, or not visible	Dark gray to black	Color silvery gold; Tarnishes brown; H 6–6.5; Brittle; conchoidal to uneven fracture; Crystals: cubes (may be striated), pyritohedrons, or octahedrons; Distinguished from chalcopyrite, which is soft	Pyrite
			Silvery dark gray to black; Tarnishes gray or rusty yellow-brown; Strongly attracted to a magnet and may be magnetized; H 6–6.5; Crystals: octahedrons	Magnetite
HARD or SOFT		Yellow-brown	Color submetallic silvery brown; Tarnishes to dull and earthy yellow-brown to brown rust colors; H 1–5.5; More commonly occurs in its nonmetallic yellow to brown forms (H 1–5)	Limonite
		Brown	Color silvery black to black; Tarnishes gray to black; H 5.5–6; May be weakly attracted to a magnet; Crystals: octahedrons	Chromite
		Red to red-brown	Color steel gray, reddish-silver, to glittery bright silver (var. specular); Both metallic varieties have the characteristic red-brown streak; May be attracted to a magnet; H 5–6; Also occurs in nonmetallic, dull to earthy, red to red-brown forms	Hematite
SOFT (H ≤ 5.5) Does not scratch glass Scratched by masonry nail or knife blade	Cleavage good to excellent	Dark gray to black	Color bright silvery gray; Tarnishes dull gray; Brittle; breaks into cubes and shapes made of cubes; H 2.5; Crystals: cubes or octahedrons; Feels heavy for its size because of high specific gravity	Galena
		White to pale yellow-brown	Color silvery yellow-brown, silvery red, or black with submetallic to resinous luster; Tarnishes brown or black; H 3.5–4.0; smells like rotten eggs when scratched, powdered, or in acid test	Sphalerite
	Cleavage absent, poor, or not visible	Dark gray to black	Color bright silvery gold; Tarnishes bronze brown brassy gold, or iridescent blue-green and red; H 3.5–4.0; Brittle; uneven fracture; Crystals: tetrahedrons	Chalcopyrite
			Color characteristically brownish-bronze; Tarnishes bright iridescent purple, blue, and/or red, giving it its nickname "peacock ore"; May be weakly attracted to a magnet; H 3; Usually massive, rare as cubes or dodecahedrons	Bornite
			Color opaque brassy to brown-bronze; Tarnishes dull brown, may have faint iridescent colors; Fracture uneven to conchoidal; No cleavage; Attracted to a magnet; H 3.5–4.5; Usually massive or masses of tiny crystals; Resembles chalcopyrite, which is softer and not attracted to a magnet	Pyrrhotite
			Color dark silvery gray to black; Can be scratched with your fingernail; Easily rubs off on your fingers and clothes, making them gray; H 1–2	Graphite
		Yellow-brown	Metallic or silky submetallic luster, Color dark brown, gray, or black; H 5–5.5; Forms layers of radiating microscopic crystals and botryoidal masses	Goethite
		Copper	Color copper; Tarnishes dull brown or green; H 2.5–3.0; Malleable and sectile; Hackly fracture; Usually forms dendritic masses or nuggets	Copper (native copper)
		Gold	Color yellow gold; Does not tarnish; Malleable and sectile; H 2.5–3.0; Forms odd-shaped masses, nuggets, or dendritic forms	Gold (native gold)
		Silvery white	Color silvery white to gray; Tarnishes gray to black; H 2.5–3.0; Malleable and sectile; Forms dendritic masses, nuggets, or curled wires	Silver (native silver)

FIGURE 3.18 Identification chart for opaque minerals with metallic or submetallic luster (M) on freshly broken surfaces.

DARK TO MEDIUM-COLORED NONMETALLIC (NM) MINERAL IDENTIFICATION

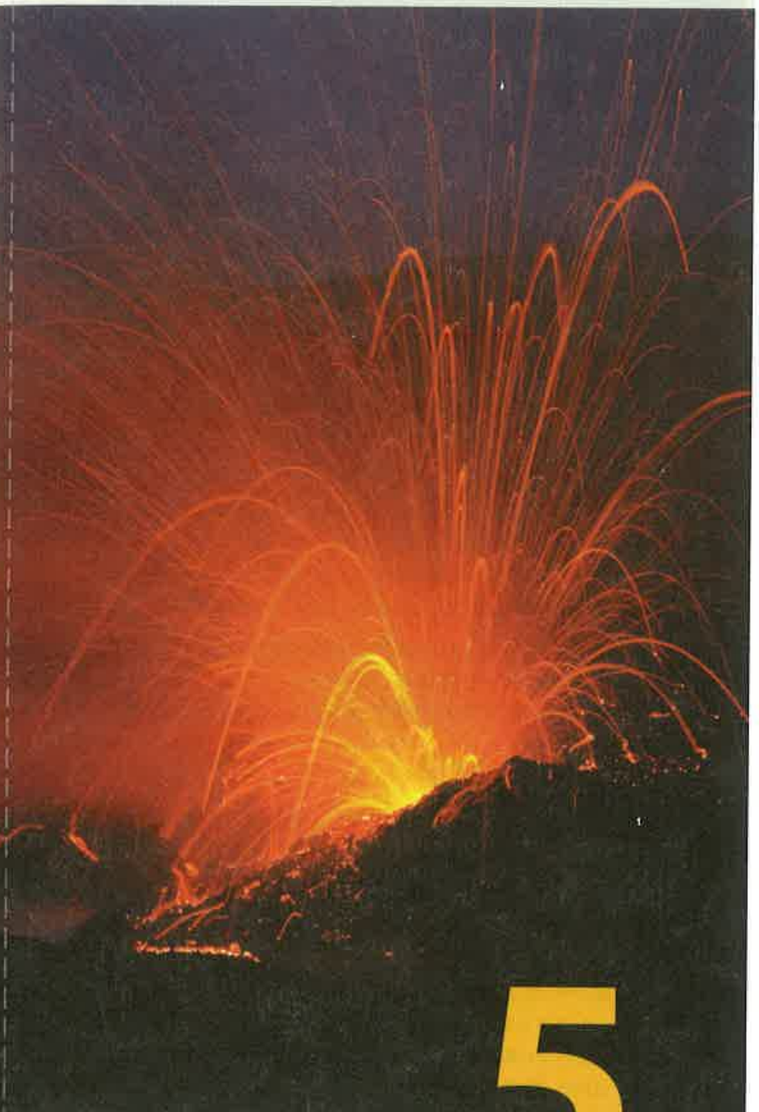
STEP 1: What is the mineral's hardness?	STEP 2: What is the mineral's cleavage?	STEP 3: Compare the mineral's physical properties to other distinctive properties below.	STEP 4: Find mineral name(s) and check the mineral database for additional properties (Figure 3.21).
HARD (H > 5.5) Scratches glass Not scratched by masonry nail or knife blade	Cleavage excellent or good	Translucent to opaque dark gray; blue-gray, or black; May have silvery iridescence; 2 cleavages at nearly 90° and with striations; H 6	Plagioclase feldspar
		Translucent to opaque brown, gray, green, or red; 2 cleavages at nearly right angles; Exsolution lamellae; H 6	Potassium feldspar (K-spar)
		Green to black; Vitreous luster; H 5.5–6.0; 2 cleavages at about 124° and 56° plus uneven fracture; Usually forms long blades and masses of needle-like crystals	Actinolite (amphibole)
		Dark gray to black; Vitreous luster; H 5.5–6.0; 2 cleavages at about 124° and 56° plus uneven fracture; Forms long crystals that break into blade-like fragments	Hornblende (amphibole)
		Dark green to black; Dull to vitreous luster; H 5.5–6.0; two cleavages at nearly right angles (93° and 87°) plus uneven fracture; Forms short crystals with squarish cross sections; Breaks into blocky fragments	Augite (pyroxene)
	Cleavage absent, poor, or not visible	Transparent or translucent gray, brown, or purple; Greasy luster; Massive or hexagonal prisms and pyramids; H 7	Quartz Smoky quartz (black/brown var.), Amethyst (purple var.)
		Gray, black, or colored (dark red, blue, brown) hexagonal prisms with flat striated ends; H 9	Corundum Emery (black impure var.), Ruby (red var.) Sapphire (blue var.)
		Opaque red-brown or brown; Luster waxy; Cryptocrystalline; H 7	Jasper (variety of quartz)
		Transparent to translucent dark red to black; Equant (dodecahedron) crystal form or massive; H 7	Garnet
		Opaque gray; Luster waxy; Cryptocrystalline; H 7	Chert (gray variety of quartz)
		Opaque black; Luster waxy; Cryptocrystalline; H 7	Flint (black variety of quartz)
		Black or dark green; Long striated prisms; H 7–7.5	Tourmaline
		Olive green, Transparent or translucent; No cleavage; Usually has many cracks and conchoidal to uneven fracture; Single crystals or masses of tiny crystals resembling green granulated sugar or aquarium gravel; The crystals have vitreous (glassy) luster	Olivine
		Opaque dark gray to black; Tarnishes gray to rusty yellow-brown; Cleavage absent; Strongly attracted to a magnet; May be magnetized; H 6–6.5	Magnetite
		Opaque green; Poor cleavage; H 6–7	Epidote
		Opaque brown prisms and cross-shaped twins; H 7	Staurolite
SOFT (H ≤ 5.5) Does not scratch glass Scratched by masonry nail or knife blade	Cleavage excellent or good	Yellow-brown, brown, or black; vitreous to resinous luster (may also be submetallic); Dodecahedral cleavage; H 3.5–4.0; Rotten egg smell when scratched or powdered	Sphalerite
		Purple cubes or octahedrons; Octahedral cleavage; H 4	Fluorite
		Black short opaque prisms; Splits easily along 1 excellent cleavage into thin sheets; H 2.5–3	Biotite (black mica)
		Green short opaque prisms; Splits easily along 1 excellent cleavage into thin sheets; H 2–3	Chlorite
	Cleavage absent, poor, or not visible	Opaque rusty brown or yellow-brown; Massive and amorphous; Yellow-brown streak; H 1–5.5	Limonite
		Rusty brown to red-brown, may have shades of tan or white; Earthy and opaque; Contains pea-sized spheres that are laminated internally; H 1–5; Pale brown streak	Bauxite
		Deep blue; Crusts, small crystals, or massive; Light blue streak; H 3.5–4	Azurite
		Opaque green or gray-green; Dull or silky masses or asbestos; White streak; H 2–5	Serpentine
		Opaque green in laminated crusts or massive; Streak pale green; Effervesces in dilute HCl; H 3.5–4	Malachite
		Translucent or opaque dark green; Can be scratched with your fingernail; Feels greasy or soapy; H 1	Talc
		Transparent or translucent green, brown, blue, or purple; Brittle hexagonal prisms; Conchoidal fracture; H 5	Apatite
		Opaque earthy brick red to dull red-gray, or gray; H 1.5–5; Red-brown streak; Magnet may attract the gray forms	Hematite

FIGURE 3.19 Identification chart for dark to medium-colored minerals with nonmetallic (NM) luster on freshly broken surfaces.

LIGHT-COLORED NONMETALLIC (NM) MINERAL IDENTIFICATION

STEP 1: What is the mineral's hardness?	STEP 2: What is the mineral's cleavage?	STEP 3: Compare the mineral's physical properties to other distinctive properties below.	STEP 4: Find mineral name(s) and check the mineral database for additional properties (Figure 3.21).
HARD (H > 5.5) Scratches glass Not scratched by masonry nail or knife blade	Cleavage excellent or good	White or pale gray; 2 good cleavages at nearly 90° plus uneven fracture; May have striations; H 6	Plagioclase feldspar
		Orange, pink, pale brown, green, or white; H 6; 2 good cleavages at 90° plus uneven fracture; exsolution lamellae	Potassium feldspar
		Pale brown, white, or gray; Long slender prisms; 1 excellent cleavage plus fracture surfaces; H 6–7	Sillimanite
		Blue, very pale green, white, or gray; Crystals are blades; H 4–7	Kyanite
	Cleavage absent, poor, or not visible	Gray, white, or colored (dark red, blue, brown) hexagonal prisms with flat striated ends; H 9	Corundum vars. ruby (red), sapphire (blue)
		Colorless, white, gray, or other colors; Greasy luster; Massive or hexagonal prisms and pyramids; Transparent or translucent; H 7	Quartz: vars. rose (pink), rock crystal (colorless), milky (white), citrine (amber)
		Opaque gray or white; Luster waxy; H 7	Chert (variety of quartz)
		Colorless, white, yellow, light brown, or pastel colors; Translucent or opaque; Laminated or massive; Cryptocrystalline; Luster waxy; H 7	Chalcedony (variety of quartz)
		Pale green to yellow; Transparent or translucent; H 7; No cleavage; Usually has many cracks and conchoidal to uneven fracture; Single crystals or masses of tiny crystals resembling green or yellow granulated sugar or aquarium gravel; Crystals vitreous (glassy)	Olivine
SOFT (H ≤ 5.5) Does not scratch glass Scratched by masonry nail or knife blade	Cleavage excellent or good	Colorless, white, yellow, green, pink, or brown; 3 excellent cleavages; Breaks into rhombohedrons; Effervesces in dilute HCl; H 3	Calcite
		Colorless, white, gray, creme, or pink; 3 excellent cleavages; Breaks into rhombohedrons; Effervesces in dilute HCl only if powdered; H 3.5–4	Dolomite
		Colorless or white with tints of brown, yellow, blue, black; Short tabular crystals and roses; Very heavy; H 3–3.5	Barite
		Transparent, colorless to white; H 2, easily scratched with your fingernail; White streak; Blade-like crystals or massive	Gypsum var. selenite
		Colorless, white, gray, or pale green, yellow, or red; Spheres of radiating needles; Luster silky; H 5–5.5	Natrolite (zeolite)
		Colorless, white, yellow, blue, brown, or red; Cubic crystals; Breaks into cubes; Salty taste; H 2.5	Halite
		Colorless, purple, blue, gray, green, yellow; Cubes with octahedral cleavage; H 4	Fluorite
		Colorless, yellow, brown, or red-brown; Short opaque prisms; Splits along 1 excellent cleavage into thin flexible transparent sheets; H 2–2.5	Muscovite (white mica)
	Cleavage absent, poor, or not visible	White, gray or yellow; Earthy to pearly; massive form; H 2, easily scratched with your fingernail; White streak	Gypsum var. alabaster
		White to gray; Fibrous form with silky or satiny luster; H 2, easily scratched with your fingernail	Gypsum var. satin spar
		Yellow crystals or earthy masses; Luster greasy; H 1.5–2.5; Smells like rotten eggs when powdered	Sulfur (Native sulfur)
		Opaque pale blue to blue-green; Conchoidal fracture; H 2-4; Massive or amorphous earthy crusts; Very light blue streak	Chrysocolla
		Opaque green, yellow, or gray; Dull or silky masses or asbestos; White streak; H 2–5	Serpentine
		Opaque white, gray, green, or brown; Can be scratched with fingernail; Greasy or soapy feel; H 1	Talc
		Opaque earthy white to very light brown masses of "white clay"; H 1–2; Powdery to greasy feel	Kaolinite
		Mostly pale brown to tan or white; Earthy and opaque; Contains pea-sized spheres that are laminated internally; H 1–5; Pale brown to white streak	Bauxite
		Colorless to white, orange, yellow, blue, gray, green, or red; May have internal play of colors; H 5.0–5.5; Amorphous; Often has many cracks; Conchoidal fracture	Opal
		Colorless or pale green, brown, blue, white, or purple; Brittle hexagonal prisms; Conchoidal fracture; H 5	Apatite

FIGURE 3.20 Identification chart for light-colored minerals with nonmetallic (NM) luster on freshly broken surfaces.



LABORATORY

5

Igneous Rocks and Processes

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Explosive volcanic eruptions like this one eject partially molten volcanic bombs that become rounded and cool as they fly through the air. (Superstock)

BIG IDEAS

Igneous rocks form wherever magma or lava cool to a solid state. The composition and texture of igneous rock samples, and the shapes of bodies of igneous rock, can be used to classify them and infer their origin. Lava and igneous rock-forming processes can be observed at volcanoes, which occur along lithospheric plate boundaries and hot spots, are linked to underground bodies of magma, and can pose hazards to humans.

FOCUS YOUR INQUIRY

THINK About It | What do igneous rocks look like? How can they be classified into groups?

THINK About It | What are igneous rocks composed of? How is composition used to classify and interpret igneous rocks?

THINK About It | What are igneous rock textures? How is texture used to classify and interpret igneous rocks?

THINK About It | How are rock composition and texture used to classify, name, and interpret igneous rocks?

THINK About It | How can the shapes of bodies of igneous rock be used to classify them and infer their origin?

Introduction

Right now, there are more than a hundred volcanoes erupting or threatening to erupt on continents and islands around the world. Some pose direct threats to humans. Others pose indirect threats, such as earthquakes and episodic melting of glaciers. In the oceans, deep under water and far from direct influence on humans, there are likely hundreds more volcanoes. The exact number is unknown, because they are erupting at places on the sea floor that humans rarely see.

Most of the world's volcanoes occur along its 260,000 kilometers of linear boundaries between lithospheric plates. The rest are largely associated with hot spots. All of the volcanoes overlie bodies of molten (hot, partly or completely melted) rock called **magma**, which is referred to as **lava** when it reaches Earth's surface at the volcanoes. In addition to their liquid rock portion, or *melt*, magma and lava contain dissolved gases (e.g., water, carbon dioxide, sulfur dioxide) and solid particles. The solid particles may be pieces of rock that have not yet melted and/or mineral crystals that may grow in size or abundance as the magma cools. **Igneous rocks** form when magma or lava cool to a solid state. The bodies of igneous rock may be as large as those in Yosemite Park, where bodies of magma cooled underground to form batholiths of igneous rock, tens of kilometers in diameter. They may be as small as centimeter-thick layers of volcanic ash, which is composed of microscopic fragments of igneous rock (mostly volcanic glass pulverized by an explosive volcanic eruption).

ACTIVITY 5.1 Igneous Rock Inquiry

THINK About It What are igneous rocks composed of, and how can they be classified into groups?

OBJECTIVE Analyze and describe samples of igneous rock, then infer how they can be classified into groups.

PROCEDURES

1. **Before you begin**, do not look up definitions and information. Use your current knowledge, and complete the worksheet with your current level of ability. Also, this is **what you will need** to do the activity:
   ____ Activity 5.1 Worksheet (p. 143) and pencil
   ____ optional: a set of igneous rock samples (obtained as directed by your instructor)
2. **Analyze the rocks, and complete the worksheet in a way that makes sense to you.**
3. **After you complete the worksheet**, be prepared to discuss your observations, interpretations, and inferences with others.

ACTIVITY 5.2 Minerals That Form Igneous Rocks

THINK About It What are igneous rocks composed of? How is composition used to classify and interpret igneous rocks?

OBJECTIVE Identify samples of eight minerals that form most igneous rocks and categorize them as mafic or felsic.

PROCEDURES

1. **Before you begin**, read Mafic and Felsic Rock-Forming Minerals below. Also, this is **what you will need:**
   ____ Activity 5.2 Worksheet (p. 144) and pencil
   ____ optional: a set of mineral samples (obtained as directed by your instructor)
   ____ optional: a set of mineral analysis tools (obtained as directed by your instructor)
2. **Then follow your instructor's directions** for completing the worksheet.

Mafic and Felsic Rock-Forming Minerals

There are eight silicate minerals that form most igneous rocks. This is because silicon and oxygen are the most common elements in magma and lava. The silicon and oxygen naturally forms silicon-oxygen tetrahedra, in which one silicon atom shares electrons with four oxygen atoms (FIGURE 5.1). This creates a silicon-oxygen tetrahedron (four-pointed pyramid) with four electrons too many, so each oxygen atom also shares an electron with another adjacent silicon atom. The simplest ratio of silicon to oxygen is 1:2, written SiO_2 and called **silica.** The mineral quartz is a crystalline form of pure silica. However, with the abundance of other chemicals in magma and lava, silicon-oxygen tetrahedra often bond with other kinds of metal atoms to make the other silicate minerals commonly found in igneous rocks. Although each one has its own unique properties that can be used to identify it, the minerals are also categorized into two chemical groups.

Felsic Minerals

The name *felsic* refers to feldspars (*fel-*) and other silica-rich (*-sic*) minerals. The common felsic minerals in igneous rocks are gray translucent *quartz*, light gray opaque *plagioclase feldspar*, pale-orange to pink opaque *potassium feldspar*, and glossy pale-brown to silvery-white *muscovite.* They are all light colored because their chemical composition lacks iron and magnesium.

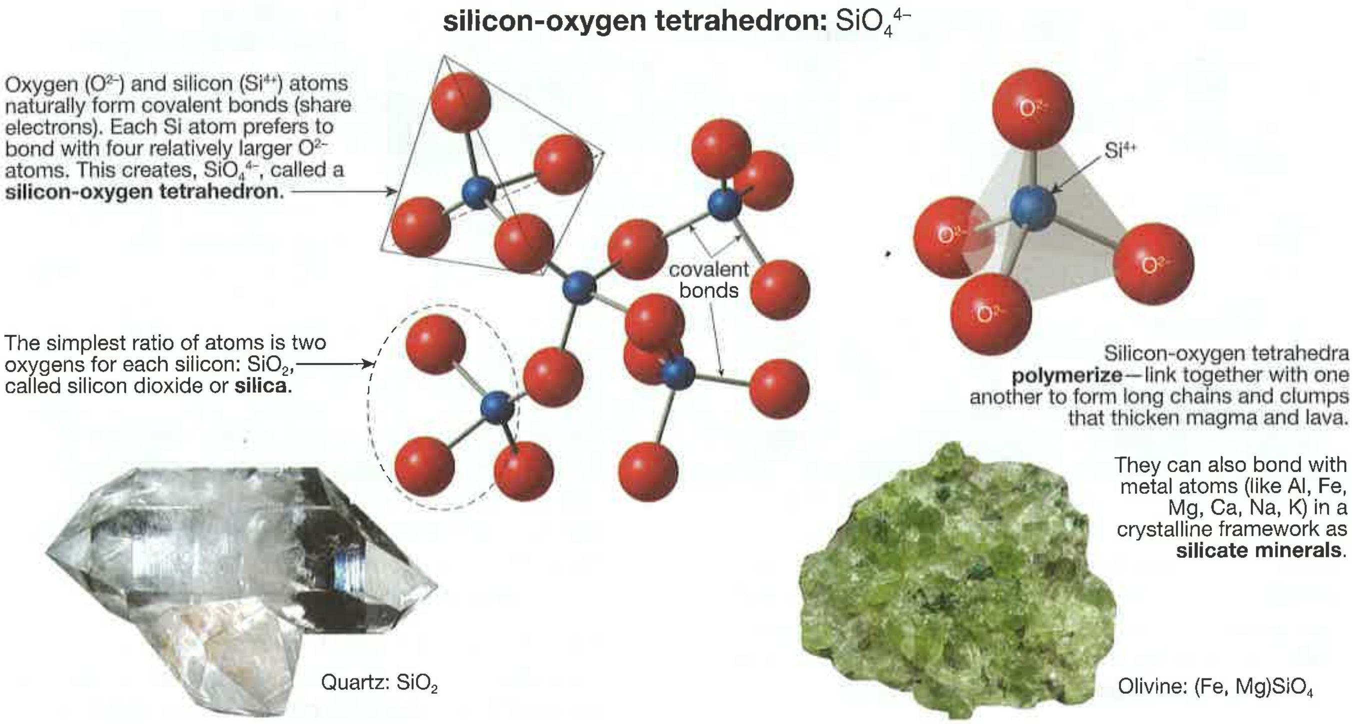


FIGURE 5.1 Silica and silicate minerals. Silicon (Si) and oxygen (O) are, by far, the most abundant chemical elements in magma, lava, and igneous rocks. They form silica (SiO_2), which thickens magma and lava (makes it more viscous) and bonds togther, alone (as quartz), or with metal atoms to make silicate minerals besides quartz in igneous rocks.

Mafic Minerals

The name *mafic* refers to minerals with magnesium (*ma-*) and iron (*-fic*) in their chemical formulas, so they are also called *ferromagnesian* minerals. They get their dark color from the abundant proportion of iron and magnesium in their chemical composition. The common mafic minerals in igneous rocks are glossy black *biotite*, dark gray to black *amphibole*, dark green to green-gray *pyroxene*, and olive-green *olivine*.

ACTIVITY

5.3 Estimate Rock Composition

THINK About It **What are igneous rocks composed of? How is composition used to classify and interpret igneous rocks?**

OBJECTIVE Determine the compositional group of an igneous rock using methods of visual estimation and point counting.

PROCEDURES

1. **Before you begin**, read about Composition of Igneous Rocks and How to Assign Rock Samples to Chemical Groups (p. 145). Also, this is **what you will need:**

   _____ Activity 5.3 Worksheet (p. 145) and pencil

2. **Then follow your instructor's directions** for completing the worksheet.

Composition of Igneous Rocks

Composition of a rock refers to what it is made of. *Chemical compositon* refers to the chemical elements that make up the rock. This determines how the rock will react with materials of different compositon, such as whether or not it will react with and decay (tarnish, dissolve, chemically disintegrate) in air or water. It also determines rock color. For example, ferromagnesian-rich rocks (iron- and magnesium-rich rocks) generally have a dark color and ferromagnesian-poor rocks generally have a light color. But the chemical elements in a rock are normally bonded together in tangible materials like minerals that, in turn, make up most rocks. So the *phsyical composition* of rocks is a description of what visible materials they are made of, in whole or part. It is your job as a geologist, using your eyes and simple tools (like a hand magnifying lens), to describe and identify what physical materials igneous rocks are made of.

Chemical Composition—Four Groups

Magmas, lavas, and igneous rocks are composed mostly of the same eight elements that characterize the average composition of Earth's crust. They are oxygen (O), silicon (Si), aluminum (Al), iron (Fe), magnesium (Mg), calcium (Ca), sodium (Na), and potassium (K).

COMPOSITION OF IGNEOUS ROCKS		
Chemical Composition		Physical Composition
Compositional Group Name	Silica % (by weight) in the magma, lava, or rock	Mafic Color Index (MCI): Percent of mafic (green, dark gray, and black) mineral crystals in the rock
Felsic (acidic)	above 65%	below 15%
Intermediate	54 – 64%	16 – 45%
Mafic	45 - 53%	46 – 85%
Ultramafic	below 45%	above 85%

FIGURE 5.2 Composition of igneous rocks. Magma, lava, and igneous rocks are classified into one of four compositional groups on the basis of their chemical composition (percentage of silica, by weight). The same names are used to describe the physical compositon of igneous rocks, based on their mafic color index (MCI).

All of these elements are cations (positively-charged atoms), except for oxygen (a negatively-charged atom, or anion); oxygen combines with the cations. The most abundant cation is silicon, so silica is the most abundant chemical compound in magmas, lavas, and igneous rocks (FIGURE 5.1). Chemical classification of magmas, lavas, and igneous rocks is based on the amount (percentage by weight) of silica they contain, which is used to assign them to one of four chemical **compositonal groups** (FIGURE 5.2):

- **Felsic (acidic) Compositional Group**. The name *felsic* refers to feldspars (*fel-*) and other silica-rich (*-sic*) minerals, but it is now also used (in place of "acidic") to decsribe magmas, lavas, and igneous rocks containing more than 60% silica.
- **Mafic (basic) Compositional Group.** The name *mafic* refers to minerals with magnesium (*ma-*) and iron (*-fic*) in their chemical formulas (also called *ferromagnesian* minerals), but it is now also used (in place of "basic") to describe magmas, lavas, and igneous rocks containing 45–53% silica.
- **Ultramafic (ultrabasic) Compositional Group.** As the name implies, this term was originally used to describe igneous rocks made almost entirely of mafic minerals. However, it now also is used (in place of "ultrabasic") to describe magmas, lavas, and igneous rocks containing less than 45% silica.
- **Intermediate Compositional Group**. This name refers to magmas, lavas, and igneous rocks that contain 54–64 % silica; a composition between mafic and felsic.

Physical Composition

The visible materials that comprise igneous rocks include volcanic glass and **grains**—mineral crystals and other hard discrete particles.

- **Volcanic glass.** Glass is an amorphous (containing no definite form; not crystalline) solid that forms by cooling viscous molten materials like melted rock (magma, lava) or quartz sand (the main ingredient that is melted to make window glass. Volcanic glass (obsidian) looks and breaks just like window glass, and it is transparent to translucent when held up to a light. It is mostly associated with felsic rocks, because they have a high percentage of silica that can polymerize into glass rather than mineral crystals (FIGURE 5.1). It may be tan, gray, black, or red-brown. The black and red-brown varieties get their dark color from the oxidation of minute amounts of iron in the lavas from which they cooled. It takes just a tiny amount of magnetite or hematite to darken the glass.
- **Mineral grains (crystals).** Most igneous rocks, even pieces of volcanic glass, contain some proportion of mineral crystals—either mafic (dark-colored ferromagnesian minerals) or felsic (light-colored silica-rich minerals). If you have not read Mafic and Felsic Rock-Forming Minerals on page 130, then you should do so now.
- **Pyroclasts (tephra).** *Pyroclasts* (from Greek meaning "fire broken") are rocky materials that have been fragmented and/or ejected by explosive volcanic eruptions (FIGURE 5.3). They include *volcanic ash* fragments (pyroclasts < 2 mm), *lapilli* or *cinders* (pyroclasts 2–64 mm), and *volcanic bombs* or *blocks* (pyroclasts > 64 mm). A mass of pyroclastic debris is called *tephra.*
- **Xenoliths.** Magma is physically contained within the walls of bedrock (crust, mantle) through which it moves. Fragments of the wall rock occasionally break free and become incorporated into the magma. When the magma cools, the fragments of wall rock are contained within the younger igneous rock as xenoliths.

How to Assign Rock Samples to Chemical Groups

The process of chemically anaylzing rocks to determine their proportions of specific elements is generally time consuming and expensive. Therefore, geologists have devised methods of hand sample analysis that enable them to assign igneous rocks to their compositional groups.

Using a Visual Estmation of Percent Chart

You can estimate the abundance of any mineral or other type of grain in a rock by using a Visual Estimation of Percent Chart provided at the back of the manual (GeoTools Sheets 1 and 2). The percentage of the circle that is black is noted on the charts (5%, 15%, 45%, 85%) for both small and large visible grains. The charts on GeoTools Sheet 2 are transparent, so you can lay them directly onto the rock.

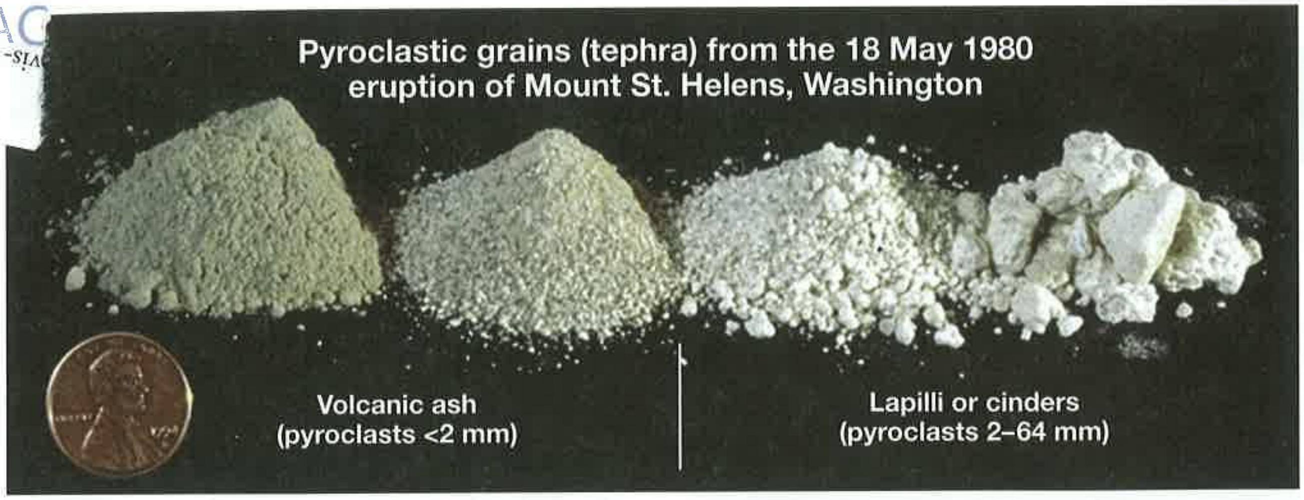


FIGURE 5.3 Pyroclastic grains (tephra). These samples of volcanic ash and lapilli (cinders) were ejected from Mount St. Helens, then collected and photographed by D. Wieprecht. (Image courtesy of U.S. Geological Survey. Scale x1.)

Using the Mafic Color Index (MCI)

The **mafic color index (MCI)** of an igneous rock is the percentage of its green, dark gray, and black mafic (ferromagnesian) mineral crystals. If the rock has no visible mineral crystals, then the overall color of the rock is used to estimate its mafic color index and corresponding compositional group. A white, pale gray, or pink rock has a felsic MCI (0–15%) and compositonal group. A moderately medium-gray rock has an intermediate MCI (16–45%) and compositional group. A very dark gray rock has a mafic MCI (46–85%) and compositional group. A black or dark green rock has a mafic MCI (above 85%) and compositional group.

If the rock has visible crystals, then you should use a Visual Estimation of Percent chart to estimate the mafic color index as closely as possible.

The mafic color index of an igneous rock is only an approximation of the rock's mineral composition, because there are some exceptions to the generalization that "light-colored equals felsic" and "dark-colored equals mafic." For example, labradorite feldspar (felsic) can be dark gray to black. Luckily, it can be identified by its characteristic play of iridescent colors that flash on and off as the mineral is rotated and reflects light. Olivine (mafic) is sometimes a pale yellow-green color (instead of medium to dark green). Volcanic glass (obsidian) is also an exception to the mafic color index rules. Its dark color suggests that it is mafic when, in fact, most obsidian has a very high weight percentage of silica and less than 15% ferromagnesian constituents. (Ferromagnesian-rich obsidian does occur, but only rarely.)

Using Point Counting

Point counting is counting the number of times that each kind of mineral crystal occurs in a specified area of the sample, or along a line randomly drawn across the sample, then calculating the relative percentage of each mineral.

ACTIVITY 5.4 Glassy and Vesicular Textures of Igneous Rocks

THINK About It What are igneous rock textures? How is texture used to classify and interpret igneous rocks?

OBJECTIVE Experiment with molten sugar to produce glassy and vesicular textures, then apply your knowledge to interpret rock samples.

PROCEDURES

1. **Before you begin**, read about Textures of Igneous Rocks below. Also, this is **what you will need:**
   ____ Activity 5.4 Worksheet (p. 146) and pencil
   ____ sugar
   ____ materials provided in lab: hot plate, small metal sauce pan with handle or 500 mL Pyrex™ beaker and tongs, water (~50 mL), safety goggles, aluminum foil, hand lens, sugar (~50 mL, 1/8 cup), and hot plate
   ____ collection of numbered igneous rock samples
2. **Then follow your instructor's directions** for completing the worksheet.

Textures of Igneous Rocks

Texture of an igneous rock is a description of its constituent parts and their sizes, shapes, and arrangement. You must be able to identify the common textures of igneous rocks described below and understand how they form. Notice the list of textures and their origins in FIGURE 5.4.

ACTIVITY

5.5 Crystalline Textures of Igneous Rocks

THINK About It | **What are igneous rock textures? How is texture used to classify and interpret igneous rocks?**

OBJECTIVE Review a crystallization experiment, infer how rate of cooling affects crystal size, and then apply your knowledge to interpret a rock with porphyritic texture.

PROCEDURES

1. **Before you begin**, read about Textures of Igneous Rocks (p. 133). Also, this is **what you will need:**

    ____ Activity 5.5 Worksheet (p. 147) and pencil

2. **Then follow your instructor's directions** for completing the worksheet.

Igneous rocks are also classified into *two textural groups*: intrusive (plutonic) versus extrusive (volcanic).

Intrusive (plutonic) rocks form deep underground, where they are well insulated (take a long time to cool) and pressurized. The pressure prevents gases from expanding, just like carbonation in a sealed soft drink. The cap seals in the pressure—an intrusive process. If you remove the cap, then the carbon dioxide inside the bottle expands and bubbles—an extrusive process. Therefore, **extrusive (volcanic) rocks** form near and on Earth's surface, where the confining pressure is low and gases begin to bubble out of the magma. This can help cause explosive eruptions and textures related to fragmenting of rocks. Cooler surface temperatures also rob thermal energy from magma, so it cools quickly.

The size of mineral crystals in an igneous rock generally indicates the rate at which the lava or magma cooled to form a rock and the availability of the chemicals required to form the crystals. Large crystals require a long time to grow, so their presence generally means that a body of molten rock cooled slowly (an intrusive process) and contained ample atoms of the chemicals required to form the crystals. Tiny crystals generally indicate that the magma cooled more rapidly (an extrusive process). Volcanic glass (no crystals) can indicate that a magma was quenched (cooled immediately), but most volcanic glass is the result of poor nucleation as described below.

Nucleation and Rock Texture

The crystallization process depends on the ability of atoms in lava or magma to *nucleate*. *Nucleation* is the initial formation of a microscopic crystal, to which other atoms progressively bond. This is how a crystal grows. Atoms are mobile in a fluid magma, so they are free to nucleate. If such a fluid magma cools slowly, then crystals have time to grow—sometimes to many centimeters in length. However, if a magma is very viscous (thick and resistant to flow), then atoms cannot easily move to nucleation sites. Crystals may not form even by slow cooling. Rapid cooling of very viscous magma (with poor nucleation) can produce igneous rocks with a **glassy texture** (see FIGURE 5.4), which indicates an extrusive (volcanic) origin.

Textures Based on Crystal Size

Several common terms are used to describe igneous rock texture on the basis of crystal size (FIGURE 5.4). Igneous rocks made of crystals that are too small to identify with the naked eye or a hand lens (generally <1 mm) have a very fine-grained **aphanitic texture** (from the Greek word for *invisible*). Those made of visible crystals that can be identified with a hand lens or unaided eye are said to have a **phaneritic texture** (coarse-grained; crystals 1–10 mm) or **pegmatitic texture** (very coarse-grained; >1 cm).

Some igneous rocks have two distinct sizes of crystals. This is called **porphyritic texture** (see FIGURE 5.4). The large crystals are called *phenocrysts,* and the smaller, more numerous crystals that surround them form the *groundmass,* or *matrix* (FIGURE 5.4). Porphyritic textures may generally indicate that a body of magma cooled slowly at first (to form the large crystals) and more rapidly later (to form the small crystals). However, recall from above that crystal size can also be influenced by changes in magma composition or viscosity.

Combinations of igneous-rock textures also occur. For example, a *porphyritic-aphanitic* texture signifies that phenocrysts occur within an aphanitic matrix. A *porphyritic-phaneritic* texture signifies that phenocrysts occur within a phaneritic matrix.

Vesicular and Pyroclastic Textures

When gas bubbles get trapped in cooling lava they are called *vesicles,* and the rock is said to have a **vesicular texture**. Scoria is a textural name for a rock having so many vesicles that it resembles a sponge. Pumice has a glassy texture and so many tiny vesicles (like frothy meringue on a pie) that it floats in water.

Recall that *pyroclasts* (from Greek meaning *fire broken*) are rocky materials that have been fragmented and/or ejected by explosive volcanic eruptions (FIGURE 5.3). They include *volcanic ash* fragments (pyroclasts < 2 mm), *lapilli* or *cinders* (pyroclasts 2–64 mm), and *volcanic bombs* or *blocks* (pyroclasts > 64 mm). Igneous rocks composed mostly of pyroclasts have a **pyroclastic texture** (see FIGURE 5.4).

How to Identify Igneous Rocks

The identification and interpretation of an igneous rock is based on its composition and texture (FIGURES 5.4 and 5.5). ***Follow these steps to classify and identify an igneous rock:***

Steps 1 and 2: Identify the rock's mafic color index (MCI). Then, if possible, identify the minerals that make up the rock and estimate the percentage of each.

IGNEOUS ROCK ANALYSIS AND CLASSIFICATION

STEP 1 & 2: MCI and Mineral Composition

Mafic Color Index (MCI): the percent of mafic (green, dark gray, black) minerals in the rock. See the top of Figure 5.2 and GeoTools Sheets 1 and 2 for tools to visually estimate MCI.

FELSIC MINERALS

Quartz
hard, transparent, gray, crystals with no cleavage

Plagioclase Feldspar
hard, opaque, usually pale gray to white crystals with cleavage, often striated

Potassium Feldspar
hard, opaque, usually pastel orange, pink, or white crystals with exsolution lamellae

Muscovite Mica
flat, pale brown, yellow, or colorless, crystals that scratch easily and split into sheets

MAFIC MINERALS

Biotite Mica
flat, glossy black crystals that scratch easily and split into sheets

Amphibole
hard, dark gray to black, brittle crystals with two cleavages that intersect at 56 and 124 degrees

Pyroxene (augite)
hard, dark green to green-gray crystals with two cleavages that intersect at nearly right angles

Olivine (gemstone peridot)
hard, transparent to opaque, pale yellow-green to dark green crystals with no cleavage

STEP 3: Texture

INTRUSIVE ORIGIN

EXTRUSIVE (VOLCANIC) ORIGIN

Pegmatitic
mostly crystals larger than 1 mm: very slow cooling of magma

Phaneritic
crystals about 1–10 mm, can be identified with a hand lens: slow cooling of magma

Porphyritic
large and small crystals: slow, then rapid cooling and/or change in magma viscosity or composition

Aphanitic
crystals too small to identify with the naked eye or a hand lens; rapid cooling of lava

Glassy
rapid cooling and/or very poor nucleation

Vesicular
like meringue: rapid cooling of gas-charged lava

Vesicular
some bubbles: gas bubbles in lava

Pyroclastic or Fragmental:
particles emitted from volcanoes

STEP 4: Igneous Rock Classification Flowchart

- **Texture is pegmatitic or phaneritic**
  - Feldspar > mafic minerals
    - K-spar > Plagioclase
      - quartz present... GRANITE[1,2]
      - no quartz.......... SYENITE[1,2]
    - K-spar < Plagioclase.................. DIORITE[1,2]
  - Feldspar < mafic minerals
    - MCI = 45–85.................. GABBRO[1,2]
    - MCI = 85–100 (< 15% felsic minerals) .... PERIDOTITE
- **Texture is aphanitic and/or vesicular**
  - felsic (MCI = 0–15) and/or pink, white, or pale brown.................. RHYOLITE[2,3]
  - intermediate (MCI = 15–45) and/or green to gray.................. ANDESITE[2,3]
  - mafic (MCI ≥ 45) and/or dark gray to black.................. BASALT[2,3]
  - mafic with abundant vesicles (resembles a sponge).................. SCORIA
  - intermediate or felsic with abundant tiny vesicles—like meringue, floats in water.. PUMICE
- **Glassy texture** .... OBSIDIAN
- **Pyroclastic (fragmental) texture**
  - fragments ≤ 2mm.................. TUFF
  - fragments > 2mm.................. VOLCANIC BRECCIA

(GRANITE through OBSIDIAN:) Also refer to Figure 5.2

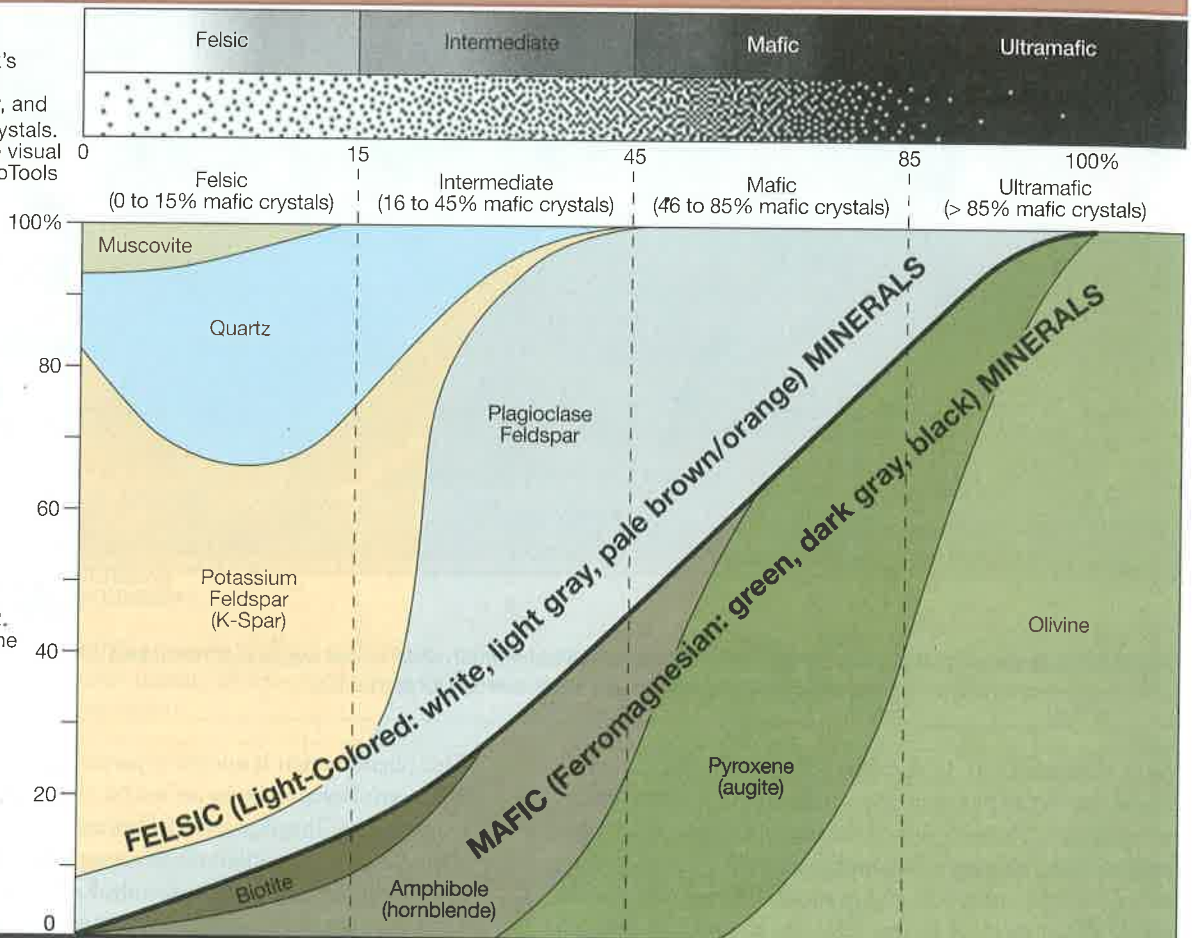
[1]Add *pegmatite* to end of name if crystals are > 1 cm (e.g., granite-pegmatite).
[2]Add *porphyritic* to front of name when present (e.g., porphyritic granite, porphyritic rhyolite).
[3]Add *vesicular* to front of name when present (e.g., vesicular basalt).

FIGURE 5.4 Igneous rock analysis and classification. Step 1—Estimate the rock's mafic color index (MCI). Step 2—Identify the main rock-forming minerals if the mineral crystals are large enough to do so, and estimate the relative abundance of each mineral (using a Visual Estimation of Percent chart from GeoTools Sheet 1 or 2). Step 3—Identify the texture(s) of the rock. Step 4—Use the Igneous Rock Classification Flowchart to name the rock. Start on the left side of the flowchart, and work toward the right side to the rock name.

IGNEOUS ROCKS CLASSIFICATION

1. Mafic Color Index (MCI)
Estimate the rock's percent of mafic (green, dark gray, and black) mineral crystals. You can also use visual estimators in GeoTools 1 and 2.

2. Minerals
Identify minerals in the rock, if possible, and the percent of each one. You can use visual estimators in GeoTools 1 and 2. Skip this step if the rock is glassy or aphanitic.



3. Texture(s) Identify the rock's texture(s).

4. Rock Name: Select name below, based on data from steps 1–3.

Origin	Texture	Felsic	Intermediate	Mafic	Ultramafic
INTRUSIVE ORIGIN	Pegmatitic: very coarse-grained	PEGMATITIC GRANITE	PEGMATITIC DIORITE	PEGMATITIC GABBRO	PEGMATITIC PERIDOTITE
INTRUSIVE ORIGIN	Phaneritic: coarse-grained	**GRANITE** (SYENITE, if no quartz)	**DIORITE**	**GABBRO**	**PERIDOTITE**
INTRUSIVE ORIGIN	Phenocrysts[1] in a phaneritic groundmass	PORPHYRITIC GRANITE	PORPHYRITIC DIORITE	PORPHYRITIC GABBRO	PORPHYRITIC PERIDOTITE
EXTRUSIVE ORIGIN	Phenocrysts[1] in an aphanitic groundmass	PORPHYRITIC RHYOLITE	PORPHYRITIC ANDESITE	PORPHYRITIC BASALT	KOMATIITE (resembles basalt but has 1–10 cm long criss-crossing needles of olivine or pyroxene)
EXTRUSIVE ORIGIN	Aphanitic: fine-grained	**RHYOLITE**	**ANDESITE**	**BASALT**	
EXTRUSIVE ORIGIN	Glassy	OBSIDIAN			
EXTRUSIVE ORIGIN	Vesicular	PUMICE (abundant tiny vesicles–like meringue; very lightweight; white or gray; floats in water)		SCORIA (resembles a sponge) VESICULAR BASALT (has few scattered vesicles)	
EXTRUSIVE ORIGIN	Pyroclastic or Fragmental	VOLCANIC TUFF (fragments < 2 mm) VOLCANIC BRECCIA (fragments > 2 mm)			

[1]Phenocrysts are crystals conspicuously larger than the finer grained groundmass (main mass, matrix) of the rock.

FIGURE 5.5 Igneous Rock Classification Chart. Obtain data about the rock in Steps 1–3, then use that data to select the name of the rock (Step 4). Also refer to FIGURE 5.4 and the examples of classified igneous rocks in FIGURES 5.8–5.14.

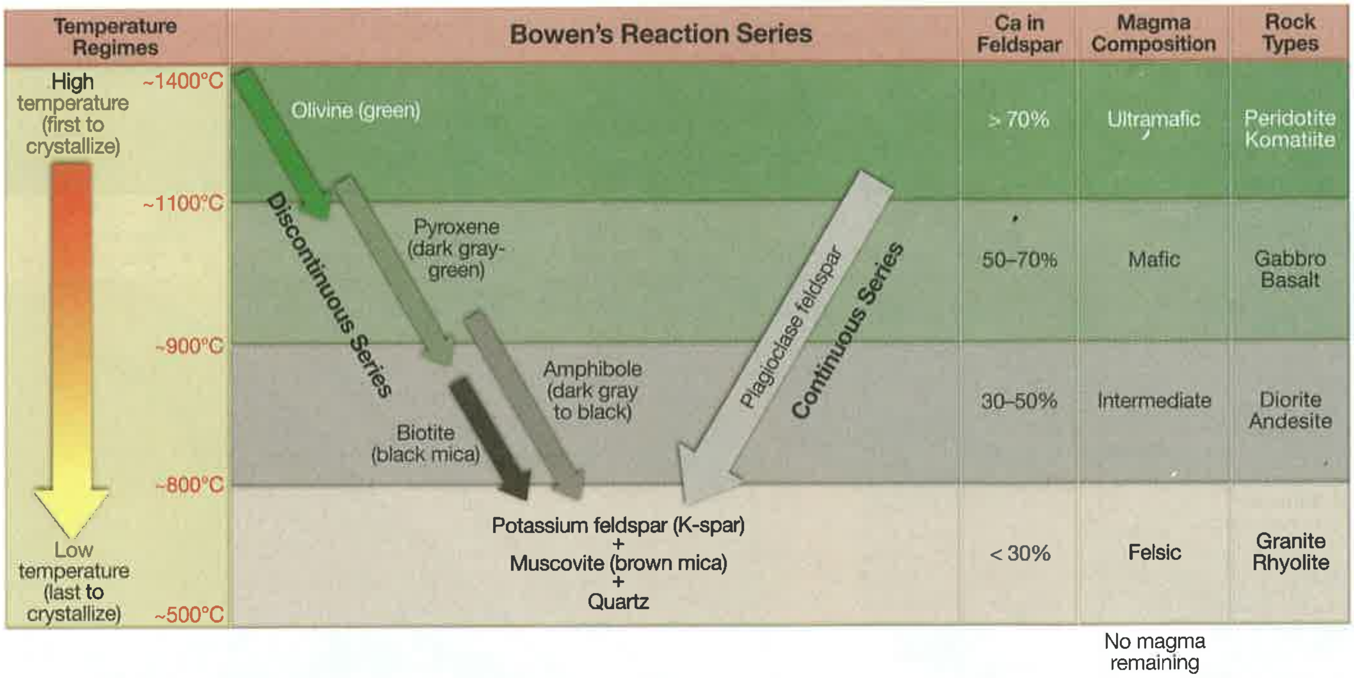


FIGURE 5.6 Bowen's Reaction Series—A laboratory-based conceptual model of one way that different kinds of igneous rocks can differentiate from a single, homogeneous body of magma as it cools. See text for discussion.

cools to about 1100° C, then the olivine starts to react with it and dissolve as pyroxene (next mineral in the series) starts to crystallize. More cooling of the magma causes pyroxene to react with the magma as amphibole (next mineral in the series) starts to crystallize, and so on. If the magma cools too quickly, then rock can form while one reaction is in progress and before any remaining reactions even have time to start.

Continuous Crystallization of Plagioclase (Right Branch). The right branch of Bowen's Reaction Series (FIGURE 5.6) shows that plagioclase feldspar crystallizes continuously from high to low temperatures (~1100–800° C), but this is accompanied by a series of continuous change in the composition of the plagioclase. The high temperature plagioclase is calcium rich and sodium poor, and the low temperature plagioclase is sodium rich and calcium poor. If the magma cools too quickly for the plagioclase to react with the magma, then a single plagioclase crystal can have a more calcium rich center and a more sodium rich rim.

Crystallization of Quartz (Bottom of the Series). Finally, notice what happens at the bottom of Bowen's Reaction Series (FIGURE 5.6). At the lowest temperatures, where the last crystallization of magma occurs, the remaining elements form abundant potassium feldspar (K-spar), muscovite, and quartz.

Partial Melting and Bowen's Reaction Series. When a plastic tray of ice cubes is heated in an oven, the ice cubes melt long before the plastic tray melts (i.e., the ice cubes melt at a much lower temperature). As rocks are heated, their different mineral crystals also melt at different temperatures. Therefore, at a given temperature, it is possible to have rocks that are partly molten and partly solid. This phenomenon is known as *partial melting*. When minerals of Bowen's Reaction Series are heated, they melt at different temperatures. The plagioclase feldspars melt continuously from about 1100–1500° C, but the ferromagnesian minerals, quartz, and K-feldspar melt discontinuously. K-feldspar melts at about 1250° C, pyroxene at 1400° C, quartz at 1650° C, and olivine at 1800° C. Because feldspars tend to melt at lower temperatures than the ferromagnesian minerals, partial melting of an igneous rock tends to produce magma of more felsic composition than the original rock from which it melted. So when a rock like basalt partially melts, it tends to form a magma that is more felsic and would cool to form andesite.

Magmatic Differentiation. Bowen's Reaction Series is an example of one way that more than one rock type can form from a single body of magma. It was generated under controlled laboratory conditions. There is no known natural location where an ultramafic magma evolved to a felsic one according to Bowen's Reaction Series. However, there are many examples where parts of Bowen's Reaction Series have occurred in nature.

Bowen's continuous series of crystallization leads to the depletion of calcium and sodium from the magma, so the composition of the magma changes. However, along the discontinuous series, early-formed mafic mineral crystals in a cooling body of magma have been shown to react with the magma at lower temperatures to form new mafic minerals. If this recycling of elements occurred perfectly, then the concentrations of iron and magnesium in the magma would never change. In nature, some of the early-formed crystals either settle out of the magma or are encrusted with different minerals before they can react, so they can no longer react with the original magma. This is called *fractional crystallization*. On the other hand,

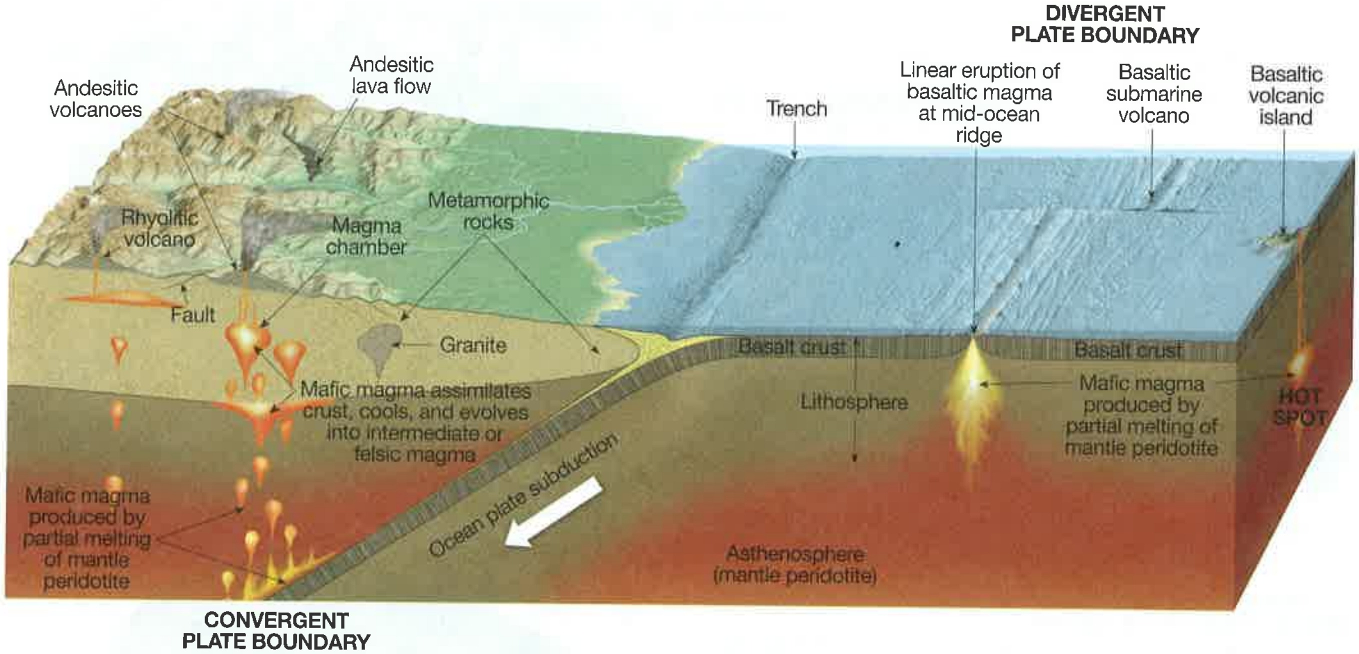


FIGURE 5.7 Tectonic settings where igneous rocks form. Different types of igneous rocks are formed in different geologic settings: a hot spot (such as the Hawaiian Islands), divergent plate boundary (mid-ocean ridge), convergent plate boundary (subduction zone), and Earth's mantle. See text for discussion.

a magma may melt some of the wall rocks surrounding it and assimilate its elements. This is called *assimilation. Magma mixing* may also occur. Bowen's continuous series of crystallization, fractional crystallization, assimilation, and magma mixing are all factors that can contribute to **magmatic differentiation** (any process that causes magma composition to change). Magmatic differentiation produces more than one rock type from a single body of magma.

Plate Tectonics and Igneous Rocks

The four compositional groups of igneous rocks occur in specific tectonic settings (FIGURE 5.7).

Ultramafic Rocks Occur in the Mantle

Ultramafic igneous rocks, like peridotite, are associated with Earth's mantle. They are denser than rocks of the crust, so they are not normally found at Earth's surface. Billions of years ago, when the body of Earth was much hotter and the crust was thinner, ultramafic magmas occasionally erupted to the surface. However, no such eruptions have occurred for more than 60 million years. Xenoliths of peridotite found in some volcanic rocks are thought to have originated in the mantle (FIGURE 5.8).

Mafic Rock at Divergent Plate Boundaries and Ocean Hot Spots

Partial melting of mantle peridotite beneath ocean hot spots and mid-ocean ridges produces mafic magma rather than ultramafic magma (FIGURE 5.7). When the mafic magma cools along the mid-ocean ridges and ocean hot spots (e.g., Hawaiian Islands), it forms gabbro (FIGURE 5.9) and seafloor basalt (FIGURE 5.10).

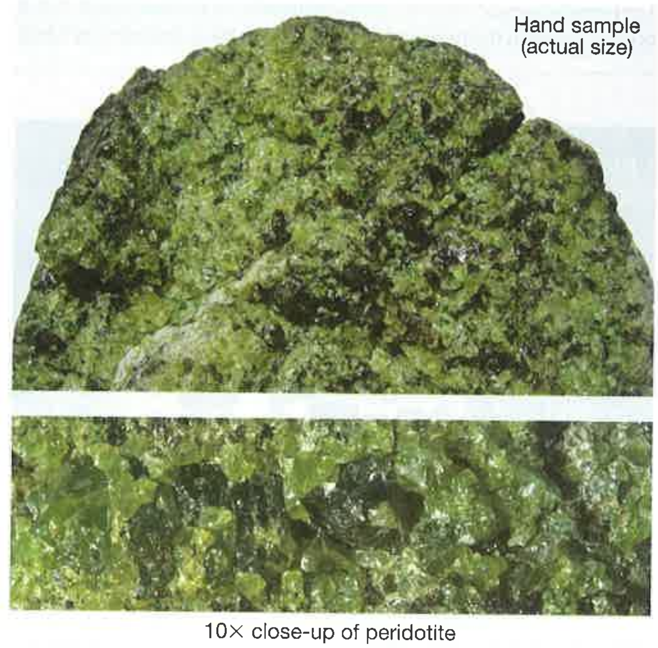


FIGURE 5.8 Peridotite (ultramafic, intrusive, phaneritic). Peridotite—an intrusive, phaneritic igneous rock having a very high MCI (>85%) and mostly made of ferromagnesian mineral crystals. This sample is a peridotite xenolith extracted from a basaltic volcanic rock. It is made mostly of olivine mineral crystals.

LABORATORY 7

Metamorphic Rocks, Processes, and Resources

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Marble is metamorphosed limestone. It is being quarried here for use in construction, table tops, decorative tiles, and sculptures. (Fotografiche/Shutterstock)

BIG IDEAS

Metamorphic rocks are rocks that have changed to a new and different form as a result of intense heat, intense pressure, and/or the action of watery hot fluids. The mineralogy and texture of a metamorphic rock can be used to deduce its original form (parent rock) and infer the geologic history of how and why it changed. Metamorphic rocks are widely used in the arts and construction industries and are sources of industrial minerals and energy.

FOCUS YOUR INQUIRY

THINK About It | What do metamorphic rocks look like? How can they be classified into groups?

ACTIVITY 7.1 Metamorphic Rock Inquiry *(p. 188)*

THINK About It | What are the characteristics of metamorphic rocks, and how are they formed?

ACTIVITY 7.2 Metamorphic Rock Analysis and Interpretation *(p. 189)*

THINK About it | How are rock composition and texture used to classify, name, and interpret metamorphic rocks?

ACTIVITY 7.3 Hand Sample Analysis, Classification, and Origin *(p. 196)*

THINK About it | What can metamorphic rocks tell us about Earth's history and the environments in which the rocks formed?

ACTIVITY 7.4 Metamorphic Grades and Facies *(p. 198)*

Introduction

The word *metamorphic* is derived from Greek and means "of changed form." **Metamorphic rocks** are rocks changed from one form to another (metamorphosed) by intense heat, intense pressure, or the action of watery hot fluids. Think of metamorphism as it occurs in your home. *Heat* can be used to metamorphose bread into toast, *pressure* can be used to compact an aluminum can into a flatter and more compact form, and the chemical action of *watery hot fluids* (boiling water, steam) can be used to change raw vegetables into cooked forms. Inside Earth, all of these metamorphic processes are more intense and capable of changing a rock from one form to another. Thus metamorphism can change a rock's size, shape, texture, color, and/or mineralogy.

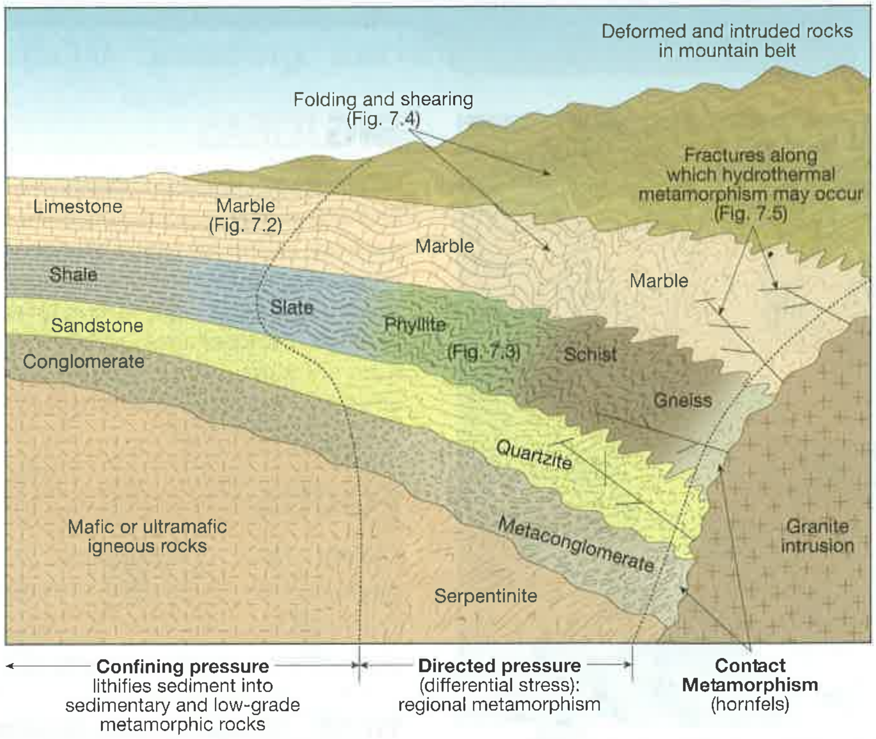


FIGURE 7.1 Generalized diagram of metamorphism. This hypothetical diagram shows how heat (from a body of granitic magma), directed pressure (as in a mountain belt at a convergent plate boundary), and the chemical action of watery hot (hydrothermal) fluids drive the process of metamorphism. *Parent rocks* far from the intrusion and directed pressure remain unchanged. In the region of folding and igneous intrusion, mafic igneous rocks were metamorphosed to serpentinite. Sedimentary conglomerate, sandstone, and limestone parent rocks were metamorphosed to *metaconglomerate, quartzite,* and *marble*. Shale was metamorphosed to *slate, phyllite, schist,* and *gneiss* depending on the grade (intensity) of metamorphism from low-grade (slate) to medium-grade (phyllite, schist), to high-grade (gneiss). *Contact metamorphism* occurred in narrow zones next to the contact between parent rock and intrusive magma. Hydrothermal metamorphism occurred along fracture systems along which the fluids migrated through the rocks.

Every metamorphic rock has a **parent rock** (or *protolith*), the rock type that was metamorphosed. Parent rocks can be any of the three main rock types: igneous rock, sedimentary rock, or even metamorphic rock (i.e., metamorphic rock can be metamorphosed again), and the degree that a parent rock is metamorphosed can vary. As temperature and pressure increases, so does the metamorphic grade. **Metamorphic grade** refers to the intensity of metamorphism, from low grade (least intense metamorphism) to high grade (most intense metamorphism).

FIGURE 7.1 is a highly generalized illustration of metamorphism at part of a convergent plate boundary, where rocks were highly compressed at great depths within a mountain belt. A body of granitic magma also intruded part of the region. Note how the rocks were folded and changed. Mafic and ultramafic igneous rocks were metamorphosed to serpentinite. Sedimentary conglomerate, sandstone, and limestone parent rocks were metamorphosed to *metaconglomerate*, *quartzite*, and *marble*. Shale was metamorphosed to *slate*, *phyllite*, *schist*, and *gneiss*, depending on the grade of metamorphism from low-grade (slate) to medium-grade (phyllite, schist), to high-grade (gneiss). *Hornfels* formed only in a narrow zone of "contact" metamorphism next to the intrusion of magma. Watery hot fluids, called **hydrothermal fluids**, traveled along faults and fractures, where they leached chemicals from the rocks while hot and deposited mineral crystals as they cooled.

ACTIVITY 7.1 Metamorphic Rock Inquiry

THINK About it | **What do metamorphic rocks look like, and how can they be classified into groups?**

OBJECTIVE Analyze and describe samples of metamorphic rock, then infer how they can be classified into groups.

PROCEDURES

1. **Before you begin**, do not look up definitions and information. Use your current knowledge, and complete the worksheet with your current level of ability. Also, this is **what you will need** to do the activity:
   - ____ Activity 7.1 Worksheet (p. 199) and pencil
   - ____ optional: a set of metamorphic rock samples (obtained as directed by your instructor)
2. **Analyze the rocks, and complete the worksheet in a way that makes sense to you.**
3. **After you complete the worksheet**, be prepared to discuss your observations, interpretations, and inferences with others.

ACTIVITY

7.2 Metamorphic Rock Analysis and Interpretation

THINK About it What are metamorphic rocks composed of? How is composition used to classify and interpret igneous rocks?

OBJECTIVE Be able to describe and interpret textural and compositional features of metamorphic rocks.

PROCEDURES

1. **Before you begin**, read about Metamorphic Processes and Rocks below. Also, this is **what you will need:**
   - ___ Activity 7.2 Worksheets (pp. 200–201) and pencil
   - ___ optional: a set of mineral samples (obtained as directed by your instructor)
   - ___ optional: a set of mineral analysis tools (obtained as directed by your instructor)
2. **Then follow your instructor's directions** for completing the worksheets.

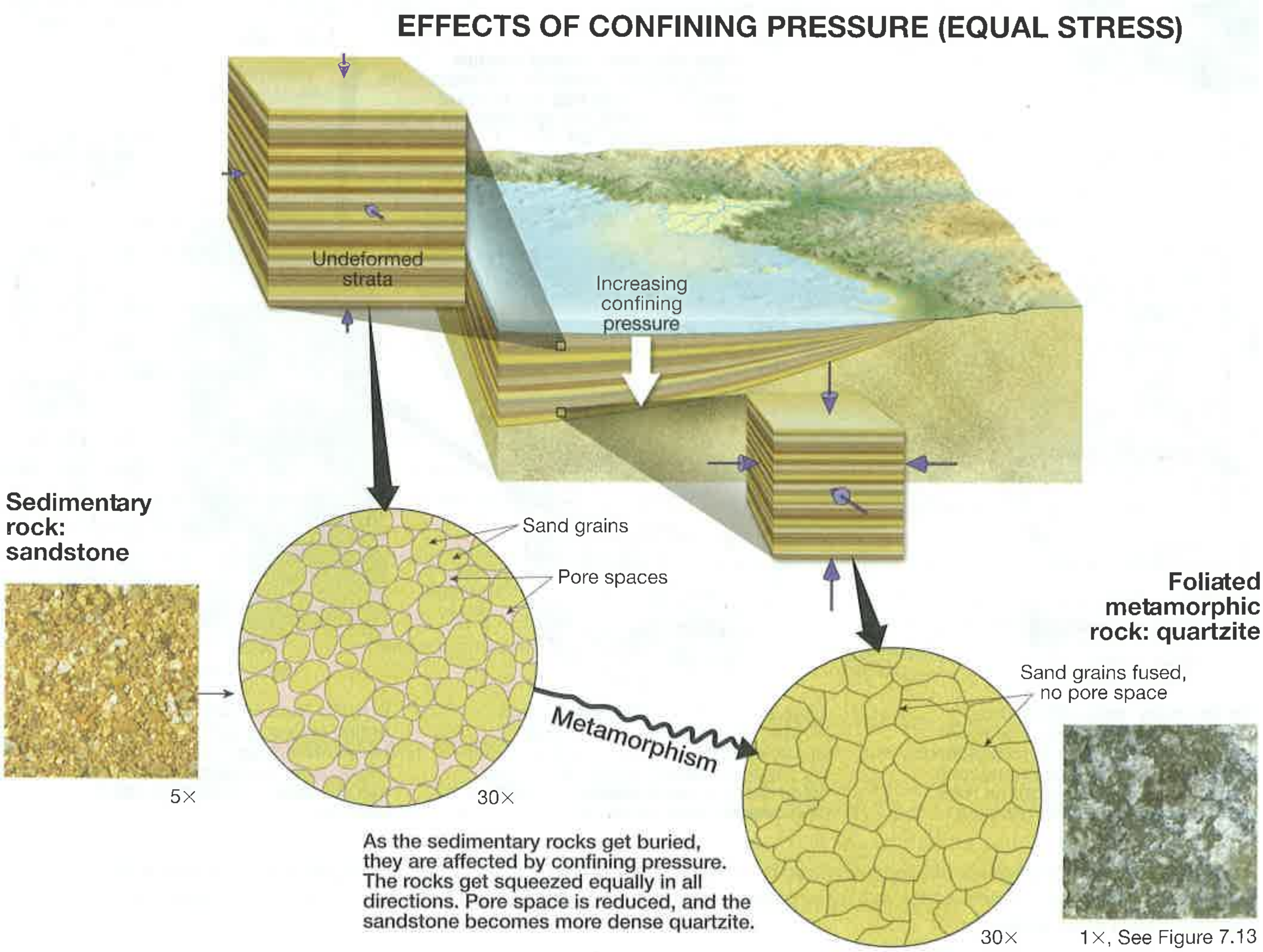
Agents of Metamorphism

Temperature, pressure, and hydrothermal fluids (watery hot fluids) are known as agents of metamorphism. Wherever metamorphism is occurring, one or more of these agents is involved in the metamorphic process.

Pressure Effects on Rocks

Confining Pressure is pressure (stress) applied equally in all directions (FIGURE 7.2). When you jump into a swimming pool you feel the confining pressure of the water pushing on every part of your body with equal force. If you dive down deep under the water, the pressure increases all around you. The same thing happens with rocks. Confining pressure increases with depth below Earth's surface and is equal in all directions. The deeper the rocks, the greater the confining pressure. This is what compacts rocks from sediment into sedimentary rock. The rock gets more dense because it is squeezed into less space. Unequal-sized

FIGURE 7.2 Effects of confining pressure (equal stress). As rocks get buried, they experience confining pressure that is equal in all directions (equal stress). The rocks become more dense as pore space is squeezed, may recrystallize to crystals of equal size, and remain nonfoliated.



aragonite seashells or calcite mineral crystals will both recrystallize to a mass of small equal-sized crystals in the metamorphic rock called marble. Quartz sandstone becomes quartzite.

Directed pressure (differential stress) is pressure that is not equal in all directions. This causes the rock to get more compressed in one direction than any other (FIGURE 7.3). If you roll a lump of dough into a ball, then you are rolling and squeezing it equally in all directions to make the ball. But if you place the dough on a table and press on it with your hand, it gets squashed and shortened in the direction of the directed pressure. This causes flat minerals to get **foliated**—flatten out parallel to one another and perpendicular to the stress.

Directed stress occurs on a large scale at convergent plate boundaries, where the edges of two plates push together.

Temperature Effects on Rocks

Temperature is a measure of thermal energy. The greater the thermal energy, the higher the temperature and more energized the atoms and molecules are in the rock. When temperature exceeds 200°C (twice the boiling point of water), the molecules get highly energized. If the rock is under directed pressure, then it may fold in a ductile (like plastic) manner and become foliated. (FIGURE 7.4). Some bonds in the minerals begin to break and reform in more stable configurations. This may cause recrystallization or neomorphism.

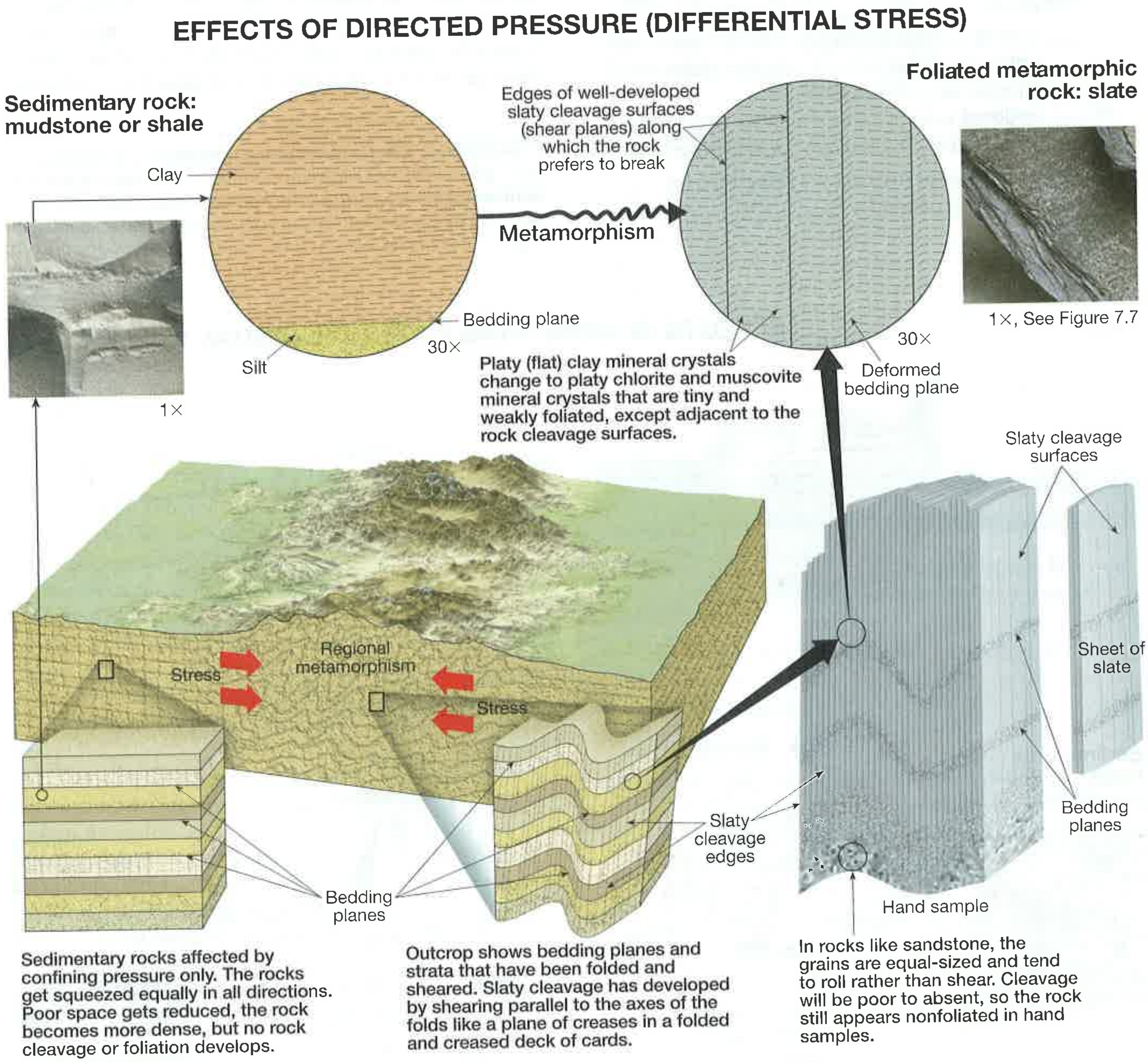


FIGURE 7.3 Effects of directed pressure (unequal stress). In places like convergent plate boundaries, rocks experience directed pressure, also known as *differential stress*, as they collide. They may fracture (brittle rocks) or fold (ductile rocks) and develop rock cleavage and foliation of platy (flat) minerals.

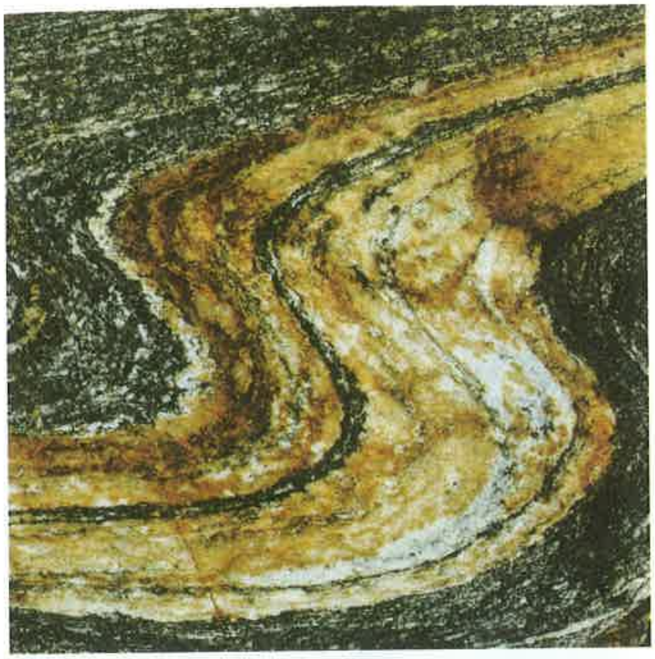


FIGURE 7.4 Folded and foliated (layered) gneiss. The dark minerals are muscovite, and the white minerals are quartz. Some of the quartz has been stained brown by iron. Regional metamorphism caused this normally rigid and brittle rock to be bent into *folds* without breaking. Pressure applied to the flat mica mineral grains has caused them to shear (slide parallel to and past one another) into layers called *foliations*. Metamorphic rocks with a layered appearance or texture are *foliated* metamorphic rocks. FIGURE 7.5 is a *nonfoliated* metamorphic rock because it lacks layering.

FIGURE 7.5 Hydrothermal mineral deposits. The dark part of this rock is chromite (chromium ore) that was precipitated from *hydrothermal fluids* (watery hot fluids). The light-colored minerals form a *vein of* zeolites (a group of light-colored hydrous aluminum silicates formed by low-grade metamorphism). The vein formed when directed pressure fractured the chromite deposit, hydrothermal fluids intruded the fracture, and the zeolites precipitated from the hydrothermal fluids as they cooled (making a *healed* fracture and a *vein* of zeolites).

Recrystallization is a process whereby unequal-sized crystals of one mineral slowly convert to equal-sized crystals of the same mineral, without melting of the rock. The longer the process continues, the larger the crystals become. For example, microscopic calcite crystals in chemical limestone (travertine, as in a cave stalactite) can recrystallize to form a mass of visible calcite crystals in metamorphic marble. Mineral composition of the rock stays the same, but texture of the rock changes.

Neomorphism is a process whereby mineral crystals not only recrystallize but also form different minerals from the same chemical elements. This happens when bonds of the original minerals break, and the chemical elements rearrange themselves into different crystalline structures and/or different molecules. For example, shales consisting mainly of clay minerals, quartz grains, and feldspar grains may change to a metamorphic rock consisting mainly of muscovite and garnet.

Hydrothermal Fluid Effects on Rocks

Just as hot water can cook vegetables and remove their color by breaking down molecules within them, it can also change the composition and form of rocks. Thus, water is an important agent of **metasomatism**, the loss or addition of new chemicals during metamorphism. Hornfels sometimes has a spotted appearance caused by the partial decomposition of just some of its minerals. In still other cases, one mineral may decompose (leaving only cavities or molds where its crystals formerly existed) and be simultaneously replaced by a new mineral of slightly or wholly different composition. When the hydrothermal fluids cool, minerals precipitate in the fractures and "heal" them (FIGURE 7.5).

Types of Metamorphism

Metamorphism can occur at different scales and in different types of environments.

Burial metamorphism is the most common type of metamorphism and occurs on a regional scale as rocks form and get buried. The metamorphism is caused by confining pressure (FIGURE 7.2).

Regional metamorphism, as the name implies, occurs on a regional scale, but the term now refers specifically to large-scale metamorphism at convergent plate boundaries, where there is directed pressure (differential stress) and high temperature that causes folding and foliation of the rocks. It is also called dynamothermal (pressure-temperature) metamorphism.

Contact metamorphism occurs locally, adjacent to igneous intrusions. It involves conditions of low to moderate pressure and intense heating. The intensity of contact metamorphism is greatest at the contact between parent rock and intrusive magma. The intensity then decreases rapidly over a short distance from the magma or hydrothermal fluids. Thus, zones of contact metamorphism are usually narrow, on the order of millimeters to tens-of-meters thick but some are kilometers wide.

The intruding magma thermally metamorphoses the rock in a narrow zone adjacent to the heat source (magma).

Hydrothermal metamorphism occurs along fractures that are in contact with the watery hot (hydrothermal) fluids. Like contact metamorphism, there is high heat and low pressure.

Dynamic metamorphism occurs along fault zones where there is local-to-regional shearing and crushing of rocks. If the rocks are brittle, then shearing produces fault breccia. But if the rocks are hot and ductile, then a fine-grained metamorphic rock called mylonite may result. Mylonite is a hard, dense, fine-grained rock that lacks cleavage but may have a banded coloration.

Minerals of Metamorphic Rocks

The **mineralogical composition** of a metamorphic rock is a description of the kinds and *relative* abundances of mineral crystals that make up the rock. Information about the relative abundances of the minerals is important for constructing a complete name for the rock and understanding metamorphic changes that formed the mineralogy of the rock.

Mineralogical composition of a parent rock may change during metamorphism as a result of changing pressure, changing temperature, and/or the chemical action of hydrothermal fluids, and processes like neomorphism and metasomatism. In general, as temperature and pressure increase, so does the **metamorphic grade**—the intensity of metamorphism, from low grade (least intense metamorphism) to high grade (most intense metamorphism). One group of minerals that was stable at a low temperature and/or pressure will eventually neomorphose to different minerals at a higher temperature and/or pressure. An **index mineral** is a mineral that is stable under a specific range of temperature and pressure and thus characterizes a grade of metamorphism (**FIGURE 7.6**).

Textures of Metamorphic Rocks

Texture of a metamorphic rock is a description of its constituent parts and their sizes, shapes, and arrangements. Two main groups of metamorphic rocks are distinguished on the basis of their characteristic textures, *foliated* and *nonfoliated*.

Foliated Metamorphic Rocks

Foliated metamorphic rocks (foliated textures) exhibit **foliations**—*layering* and parallel alignment of platy (flat) mineral crystals, such as micas. The foliations form when directed pressure causes the platy (flat) mineral crystals to slide parallel to and past one another (shear). This can happen as they recrystallize. Crystals of minerals such as tourmaline, hornblende, and kyanite can also be foliated because their crystalline growth occurred during metamorphism and had a preferred orientation in relation to the directed pressure. Specific kinds of foliated textures are described below:

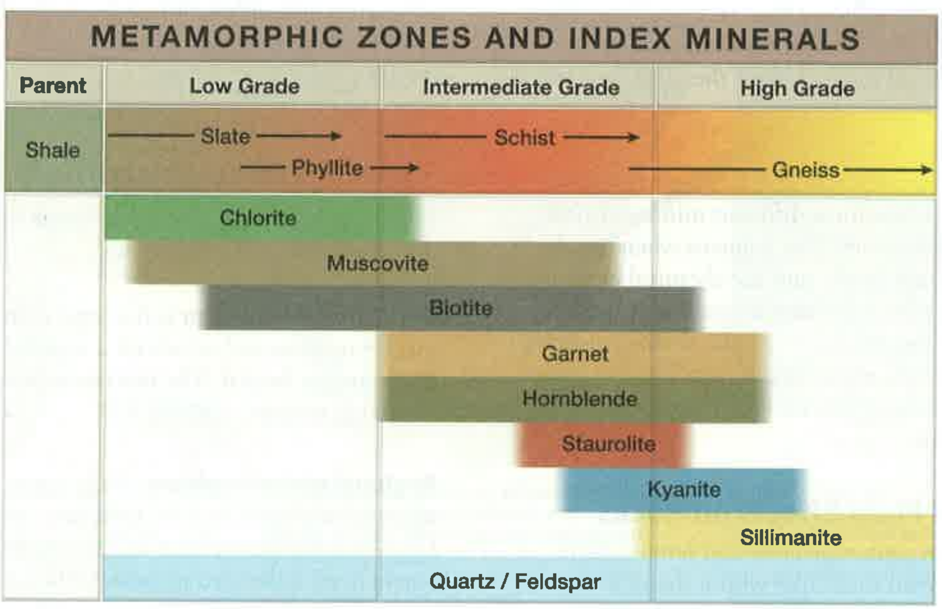


FIGURE 7.6 Index minerals of regionally-metamorphosed clay and mica-rich rocks. Sedimentary rocks rich in clay minerals neomorphose at low grades to larger foliated crystals of platy (flat) minerals like chlorite, muscovite, and biotite. These minerals neomorphose to garnet and staurolite at an intermediate grade, and then to sillimanite at a high grade of metamorphism.

- **Slaty rock cleavage**—*a very flat foliation* (resembling mineral cleavage) developed along flat, parallel, closely spaced shear planes (microscopic faults) in tightly folded clay- or mica-rich rocks (**FIGURE 7.3**). Rocks with excellent slaty cleavage are called *slate* (**FIGURE 7.7**), which is used to make roofing shingles and classroom blackboards. The flat surface of a blackboard or sheet of roofing slate is a slaty cleavage surface.
- **Phyllitic texture**—*a wavy and/or wrinkled foliation* of fine-grained *platy minerals* (mainly muscovite or chlorite crystals) that gives the rock a satiny or metallic luster. Rocks with phyllite texture are called *phyllite* (**FIGURE 7.8**). The phyllite texture is normally developed oblique or perpendicular to a weak slaty cleavage, and it is a product of intermediate-grade metamorphism.

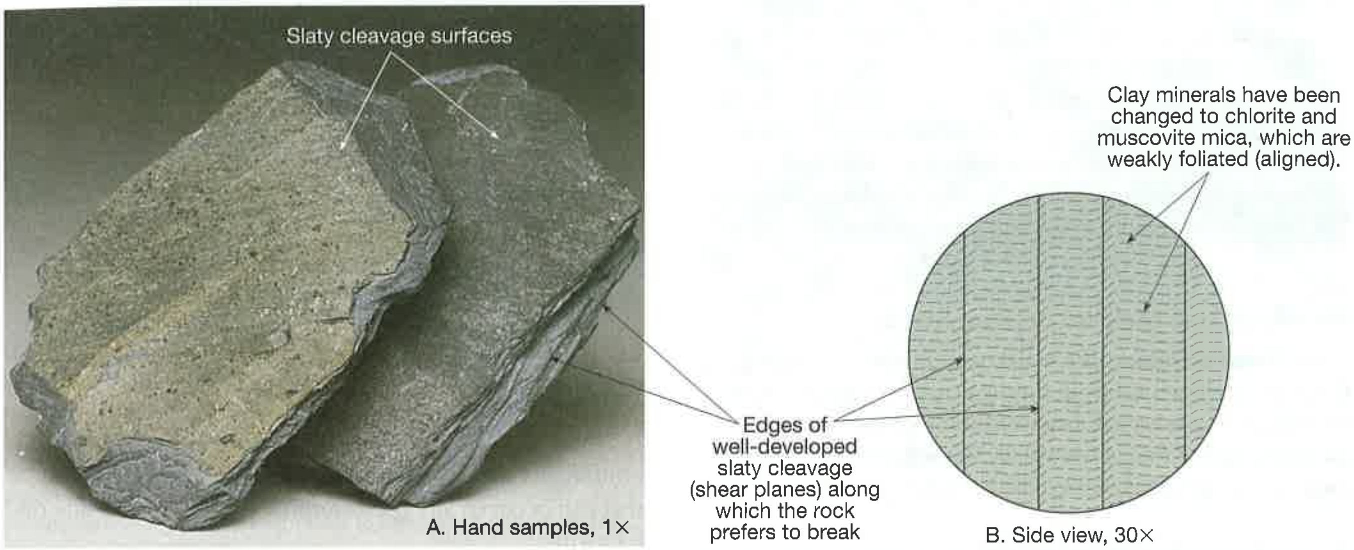


FIGURE 7.7 Slate. Slate is a foliated metamorphic rock with dull luster, excellent slaty cleavage, and no visible grains. Slate forms from low-grade metamorphism of mudstone (shale, claystone). Clay minerals of the mudstone parent rock change to foliated chlorite and muscovite mineral crystals. Slate splits into hard, flat sheets (usually less than 1 cm thick) along its well-developed *slaty cleavage* (**FIGURE 7.3**). It is used to make roofing shingles and classroom blackboards.

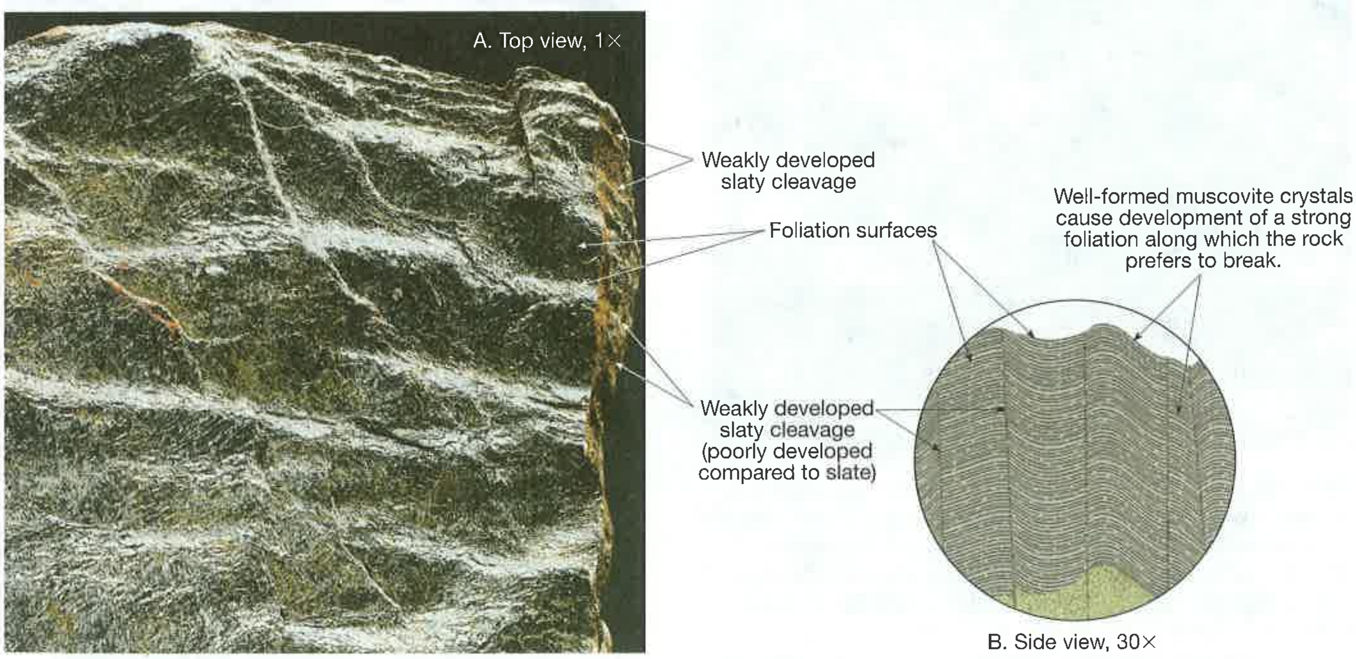


FIGURE 7.8 Phyllite. Phyllite is a foliated, fine-grained metamorphic rock, with a satiny, green, silver, or brassy metallic luster and a wavy foliation with a wrinkled appearance (*phyllite texture*). Phyllite forms from low-grade metamorphism of mudstone (shale, claystone), slate, or other rocks rich in clay, chlorite, or mica. When the very fine-grained mineral crystals of clay, chlorite, or muscovite in dull mudstone or slate are metamorphosed to form the phyllite, they become recrystallized to larger sizes and are aligned into a wavy and/or wrinkled foliation (*phyllite texture*) that is satiny or metallic. This is the wavy foliation along which phyllite breaks. Slaty cleavage may be poorly developed. It is not as obvious as the wavy and/or wrinkled foliation surfaces. The phyllite grade of metamorphism is between the low grade that produces slate (**FIGURE 7.7**) and the intermediate grade that produces schist (**FIGURE 7.9**).

- **Schistosity**—*a scaly glittery layering* of visible (medium- to coarse-grained) *platy minerals* (mainly micas and chlorite) *and/or linear alignment of long prismatic crystals* (tourmaline, hornblende, kyanite). Rocks with schistosity break along scaly, glittery foliations and are called *schist* (**FIGURE 7.9**). Schists are a product of intermediate-to-high grades of metamorphism.
- **Gneissic banding**—*alternating layers or lenses of light and dark medium- to coarse-grained minerals.* Rock with gneissic banding is called *gneiss* (**FIGURES 7.4** and **7.10**). Ferromagnesian minerals usually form the dark bands. Quartz or feldspars usually form the light bands. Most gneisses form by high-grade metamorphism (including recrystallization) of clay- or mica-rich rocks such as shale (see **FIGURE 7.1**), but they can also form by metamorphism of igneous rocks such as granite and diorite.

Nonfoliated Metamorphic Rocks

Nonfoliated metamorphic rocks have no obvious layering (i.e., no foliations), although they may exhibit stretched fossils or long, prismatic crystals (tourmaline, amphibole) that have grown parallel to the pressure field. Nonfoliated metamorphic rocks are mainly characterized by the following textures:

FIGURE 7.9 Schist. Schist is a medium- to coarse-grained, scaly (like fish scales), foliated metamorphic rock formed by intermediate-grade metamorphism of mudstone, shale, slate, phyllite, or other rocks rich in clay, chlorite, or mica. Schist forms when clay, chlorite, and mica mineral crystals are foliated as they recrystallize to larger, more visible crystals of chlorite, muscovite, or biotite. This gives schist its scaly foliated appearance called *schistosity*. Slaty cleavage or *crenulations* (sets of tiny folds) may be present, but schist breaks along its scaly, glittery schistosity. It often contains porphyroblasts of garnet, kyanite, sillimanite, or tourmaline mineral crystals. The schist grade of metamorphism is intermediate between the lower grade that produces phyllite (**FIGURE 7.8**) and the higher grade that produces gneiss (**FIGURES 7.10**). Also see chlorite schist in **FIGURE 7.15**.

- **Crystalline texture (nonfoliated)**—a medium- to coarse-grained aggregate of intergrown, usually equal-sized (equigranular), visible crystals. *Marble* is a nonfoliated metamorphic rock that typically exhibits an equigranular crystalline texture (**FIGURE 7.11**).
- **Microcrystalline texture**—a fine-grained aggregate of intergrown microscopic crystals (as in a sugar cube). *Hornfels* (**FIGURE 7.12**) is a nonfoliated metamorphic rock that has a microcrystalline texture.
- **Sandy texture**—a medium- to coarse-grained aggregate of fused, sand-sized grains that resembles sandstone. *Quartzite* is a nonfoliated metamorphic rock with a sandy texture (**FIGURE 7.13**) remaining from its sandstone parent rock, but the sand grains cannot be rubbed free of the rock because they are fused together.
- **Glassy texture**—a homogeneous texture with no visible grains or other structures and breaks along glossy surfaces; said of materials that resemble glass, such as *anthracite coal* (**FIGURE 7.14**).

Besides the main features that distinguish foliated and nonfoliated metamorphic rocks, there are some features that can occur in any metamorphic rock. They include the following:

- **Stretched or sheared grains**—deformed pebbles, fossils, or mineral crystals that have been stretched out, shortened, or sheared.

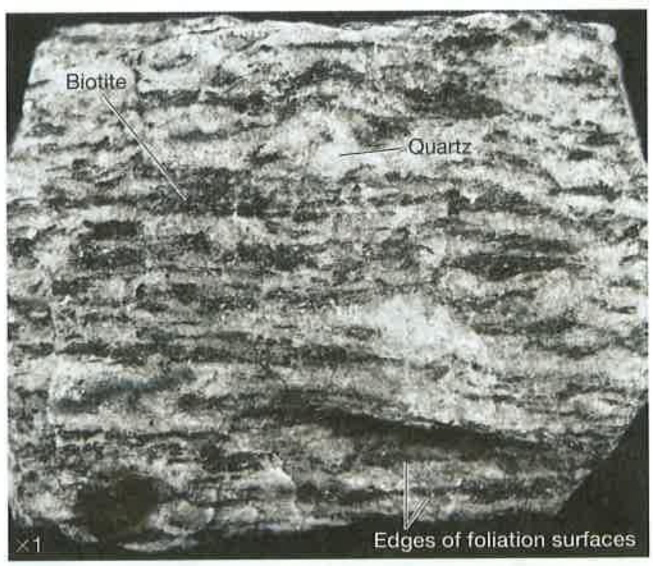


FIGURE 7.10 Gneiss. Gneiss is a medium- to coarse-grained metamorphic rock with *gneissic banding* (alternating layers or lenses of light and dark minerals). Generally, light-colored layers are rich in quartz or feldspars and alternate with dark in biotite mica, hornblende, or tourmaline. Most gneisses form by high-grade metamorphism (including recrystallization) of clay or mica-rich rocks such as shale (**FIGURE 7.1**), mudstone, slate, phyllite, or schist. However, they can also form by metamorphism of igneous rocks such as granite and diorite. The compositional name of the rock in this picture is biotite quartz gneiss.

FIGURE 7.11 Marble. Marble is a fine- to coarse-grained, nonfoliated metamorphic rock with a crystalline texture formed by tightly interlocking grains of calcite or dolomite. Marble forms by intermediate- to high-grade metamorphism of limestone or dolostone. Marble is a dense aggregate of nearly equal-sized crystals (see photograph), in contrast to the porous texture and/or odd-sized grains of its parent rock.

FIGURE 7.12 Hornfels. Hornfels is a fine-grained, nonfoliated metamorphic rock having a dull luster and a microcrystalline texture (that may appear smooth or sugary). It is usually very hard and dark in color, but it sometimes has a spotted appearance caused by patchy chemical reactions with the metamorphosing magma or hydrothermal fluid. Hornfels forms by contact metamorphism of any rock type.

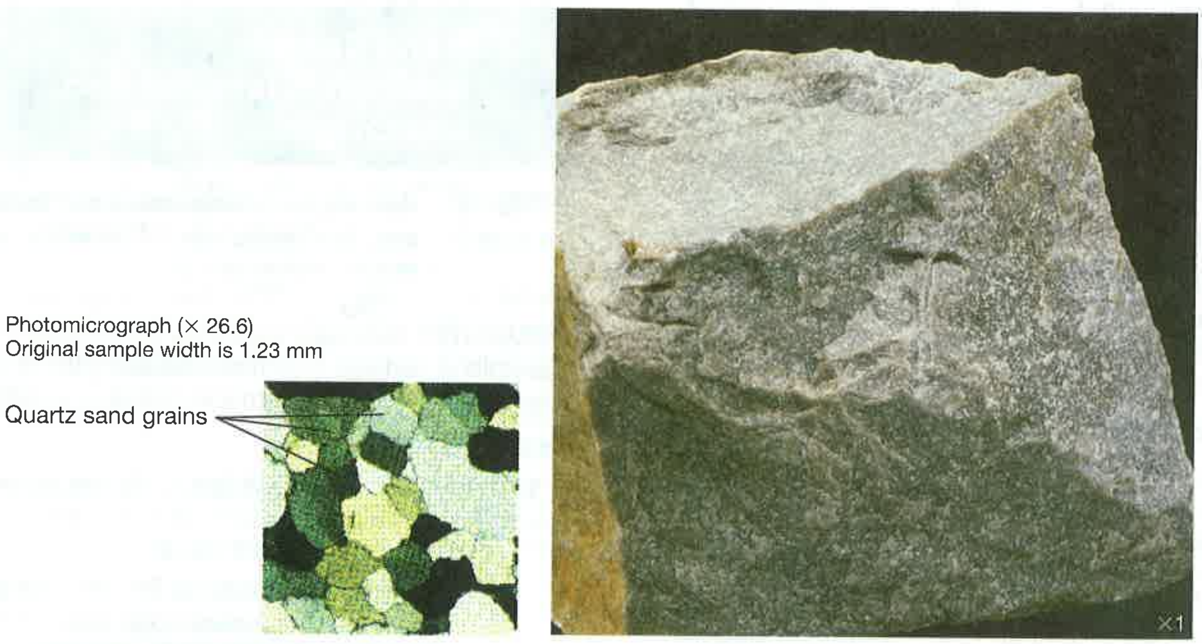


FIGURE 7.13 Quartzite. Quartzite is a medium- to coarse-grained, nonfoliated metamorphic rock consisting chiefly of fused quartz grains that give the rock its *sandy texture*. Compare the fused quartz grains of this quartzite sample (see photomicrograph) with the porous sedimentary fabric of quartz sandstone in FIGURE 7.2. Sand grains can often be rubbed from the edges of a sandstone sample, but never from quartzite (because the grains are fused together).

FIGURE 7.14 Anthracite coal. Anthracite is a fine-grained, nonfoliated metamorphic rock, also known as *hard coal* (because it cannot easily be broken apart like its parent rock, bituminous or soft coal). Anthracite has a smooth, homogeneous, glassy texture and breaks along glossy, curved (conchoidal) fractures. It is formed by low- to intermediate-grade metamorphism of bituminous coal, lignite, or peat.

FIGURE 7.15 Porphyroblastic texture. This texture is characterized by large, visible crystals of one mineral occur in a fine-grained groundmass of one or more other minerals. This medium-grained chlorite schist contains porphyroblasts of pyrite (brassy metallic cubes) in a groundmass of chlorite. The rock can be called porphyroblastic chlorite schist or pyrite chlorite schist or pyrite greenschist.

- **Porphyroblastic texture**—an arrangement of large crystals, called *porphyroblasts*, set in a finer-grained groundmass (FIGURE 7.15). It is analogous to porphyritic texture in igneous rocks.
- **Hydrothermal veins**—fractures "healed" (filled) by minerals that precipitated from hydrothermal fluids (see FIGURE 7.5).
- **Folds**—bends in rock layers that were initially flat, like a folded stack of paper (see FIGURE 7.4).
- **Lineations**—lines on rocks at the edges of foliations, shear planes, slaty cleavage, folds, or aligned crystals.

Classification of Metamorphic Rocks

Metamorphic rocks are mainly classified according to their texture and mineralogical composition. This information is valuable for naming the rock and determining how it formed from a parent rock (protolith). It is also useful for inferring how the metamorphic rock could be used as a commodity for domestic or industrial purposes. You can analyze and classify metamorphic rocks with the aid of FIGURE 7.16, which also provides information about parent rocks and how the metamorphic rocks are commonly used.

ACTIVITY 7.3 Hand Sample Analysis, Classification, and Origin

THINK About It **How are rock composition and texture used to classify, name, and interpret metamorphic rocks?**

OBJECTIVE Determine the names, parent rocks (protoliths), and uses of common metamorphic rocks, based on their textures and mineralogical compositions.

PROCEDURES

1. **Before you begin**, read about Description and Interpretation of Metamorphic Rock Samples. Also, this is **what you will need:**
   ___ Activity 7.3 Worksheets (pp. 202–204) and pencil
   ___ optional: a set of metamorphic rock samples (obtained as directed by your instructor)
2. **Then follow your instructor's directions** for completing the worksheets.

METAMORPHIC ROCK ANALYSIS AND CLASSIFICATION

		STEP 1: What are the rock's textural features?	STEP 2: What are the rock's mineralogical composition and/or other distinctive features?	STEP 3: Metamorphic rock name		STEP 4: What was the parent rock?	STEP 5: What is the rock used for?
FOLIATED	Fine-grained or no visible grains	Flat slaty cleavage is well developed	Dull luster; breaks into hard flat sheets along the slaty cleavage	SLATE[1]	INCREASING METAMORPHIC GRADE (↓)	Mudstone or shale	Roofing slate, table tops, floor tile, and blackboards
		Phyllite texture well developed more than slaty cleavage	Breaks along wrinkled or wavy foliation surfaces with shiny metallic luster	PHYLLITE[1]		Mudstone, shale, or slate	Construction stone, decorative stone, sources of gemstones
	Medium- to coarse-grained	Schistosity: foliation formed by alignment of visible crystals; rock breaks along scaly foliation surfaces; crystalline texture	Mostly blue or violet needle-like crystals (blue amphibole)	Blueschist	SCHIST[1]	Mudstone, shale, slate, or phyllite	
			Mostly visible sparkling crystals of chlorite +/– actinolite (green amphibole)	Greenschist			
			Mostly visible sparkling crystals of muscovite	Muscovite schist			
			Mostly visible sparkling crystals of biotite	Biotite schist			
		Gneissic banding: minerals segregated into alternating layers gives the rock a banded texture in side view; crystalline texture	Visible crystals of two or more minerals in alternating light and dark foliated layers	GNEISS[1]		Mudstone, shale, slate, phyllite, schist, granite, or diorite	Construction stone, decorative stone, sources of gemstones
FOLIATED OR NONFOLIATED		Medium- to coarse-grained crystalline texture	Mostly visible glossy black amphibole (hornblende) in blade-like crystals	AMPHIBOLITE		Basalt, gabbro, or ultramafic igneous rocks	Construction stone
		Crystalline texture	Green pyroxene + red garnet	ECLOGITE		Basalt, gabbro	Titanium ore
NONFOLIATED	Fine-grained or no visible grains	Glassy texture; slaty cleavage may barely be visible	Black glossy rock that breaks along uneven or conchoidal fractures (Figure 7.12)	ANTHRACITE COAL		Peat, lignite, bituminous coal	Highest grade coal for clean burning fossil fuel
		Microcrystalline texture	Usually a dull dark color; very hard	HORNFELS		Any rock type	
		Microcrystalline texture or no visible grains. May have fibrous asbestos form	Serpentine; dull or glossy; color usually shades of green	SERPENTINITE		Basalt, gabbro, or ultramafic igneous rocks	Decorative stone
		Microcrystalline or no visible grains	Talc; can be scratched with your fingernail; shades of green, gray, brown, white	SOAPSTONE		Basalt, gabbro, or ultramafic igneous rocks	Art carvings, electrical insulators, talcum powder
	Fine- to coarse-grained	Sandy texture	Quartz sand grains fused together; grains will not rub off like sandstone; usually light colored	QUARTZITE[1]		Sandstone	Construction stone, decorative stone
		Microcrystalline (resembling a sugar cube) or medium to coarse crystalline texture	Calcite (or dolomite) crystals of nearly equal size and tightly fused together; calcite effervesces in dilute HCl; dolomite effervesces only if powdered	MARBLE[1]		Limestone	Art carvings, construction stone, decorative stone, source of lime for agriculture
		Conglomeratic texture, but breaks across grains	Pebbles may be stretched or cut by rock cleavage	META-CONGLOMERATE		Conglomerate	Construction stone, decorative stone

[1]Modify rock name by adding names of minerals in order of increasing abundance. For example, garnet muscovite schist is a muscovite schist with a small amount of garnet.

FIGURE 7.16 Five-step chart for metamorphic rock analysis and classification. See text for description of steps (page 198).