A CLOSER LOOK

Naming Igneous Rocks

Igneous rock forms by the cooling and solidification of magma. **Extrusive igneous rocks** are those formed by solidification of lava; **intrusive igneous rocks** are those formed when magma solidifies within the crust or mantle. Both extrusive and intrusive igneous rocks are classified and named on the basis of rock texture and mineral assemblage.

Naming by Texture

The most obvious textural feature of an igneous rock is the size of its mineral grains. Lava cools so rapidly that mineral grains do not have sufficient time to become large. As a result, extrusive igneous rocks are fine-grained (individual grains being less than 2 mm in diameter). Some lavas cool so rapidly that the rocks they form are glassy. Figures C7.1A and B are examples of a glassy and a fine-grained igneous rock, respectively.

Intrusive igneous rock tends to be coarse-grained because magma that solidifies in the crust or mantle cools slowly and has sufficient time to form large mineral grains. Figure C7.1C is an example of a coarse-grained igneous rock.

One special texture involves a distinctive mixture of large and small grains. Rock of such a texture is called a **porphyry**, meaning an intrusive igneous rock consisting of coarse mineral grains scattered through a mixture of fine mineral grains, as shown in Figure C7.1D. The large grains in a porphyry are formed in the same way those of any other coarse-grained igneous rocks are formed—by slow cooling of magma in the crust or mantle; the fine-grained mass that encloses the coarse grains provides evidence that partly solidified magma moved quickly upward. In the new setting, the magma cooled rapidly, and as a result, the later mineral grains are all tiny.

Naming by Mineral Assemblage

When magma or lava of a given composition solidifies, the mineral assemblage that forms is the same for intrusive and extrusive rocks; the only differences are textural. Once the

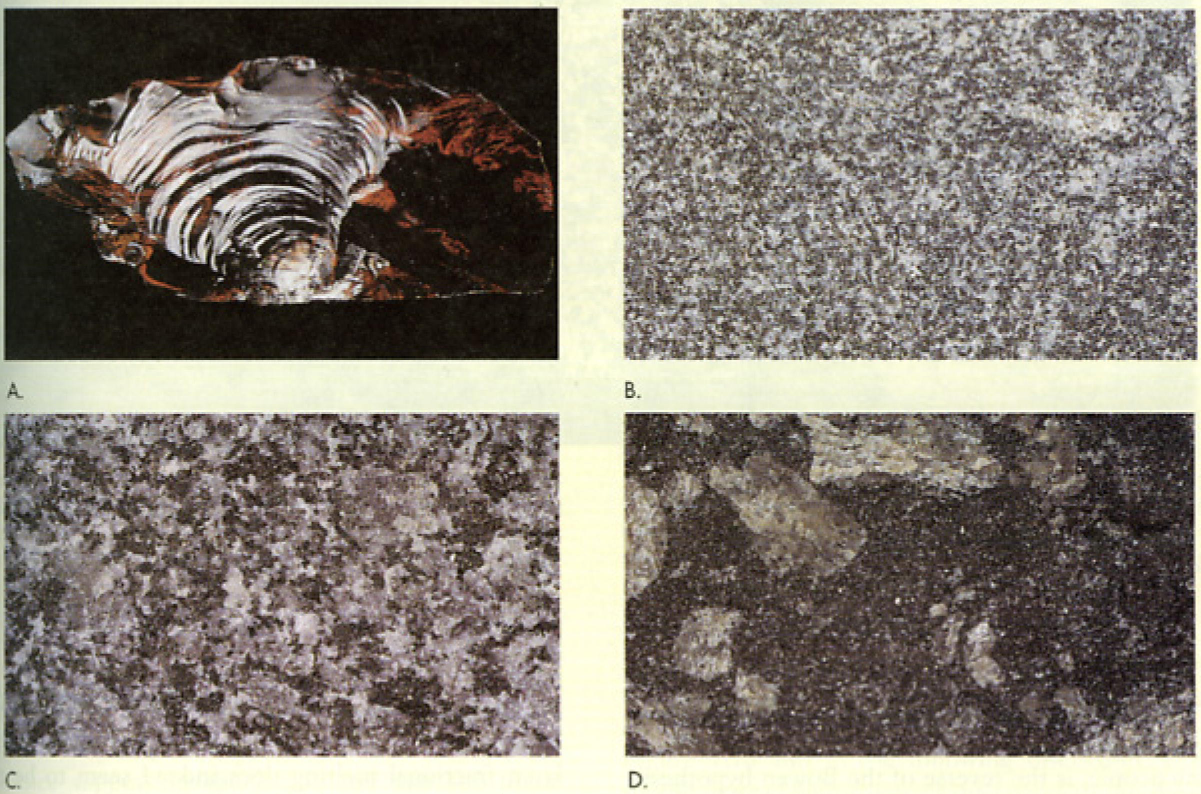


Figure C7.1 Different textures in igneous rock. A. Obsidian, a wholly glassy igneous rock (extrusive). B. Basalt, a fine-grained igneous rock (extrusive). C. Gabbro, a coarse-grained igneous rock (intrusive). D. Basalt porphyry (extrusive). Sample A has the composition of a rhyolite (Table C7.1), but B, C, and D have the same mineral assemblage—feldspar (white), pyroxene (dark green to black), and olivine (pale brown).

texture of an igneous rock has been determined, therefore, specimens are named on the basis of mineral assemblage, as shown in Table C7.1 and Figure C7.2.

All common igneous rocks are composed of one or more of these six minerals or mineral groups: quartz, feldspar, mica (both muscovite and biotite), amphibole, pyroxene, and olivine. Although mineral assemblages are gradational, the common igneous rocks can be divided into four families based on one key feature: the presence or absence of quartz and olivine (Table C7.1).

Varieties of Pyroclastic Rocks

There is an old saying that pyroclasts are igneous on the way up and sedimentary on the way down. As a result, pyroclastic rocks are transitional between igneous and sedimentary. They are called **agglomerates** when tephra is bomb sized, or **tuffs** when the pieces are either lapilli or ash. The igneous origin of a pyroclastic rock is indicated by the name for the mineral assemblage. For example, we refer to a rock of appropriate mineral assemblage as an andesite tuff.

Tephra is converted to pyroclastic rock in two ways. The first, and most common, way is through the addition of a cementing agent, such as quartz or calcite introduced by groundwater. Figure C7.3A is an example of a rhyolitic tuff formed by cementation. The second way tephra is transformed to pyroclastic rock is through the welding of hot, glassy, ash particles. When ash is very hot and plastic, the individual particles can fuse together to form a glassy pyroclastic rock. Such a rock is called **welded tuff** (Fig. C7.3B).

Uses of Igneous Rock

Igneous rocks have many uses. Granites, diorites, and gabbros are very attractive when polished and are widely used

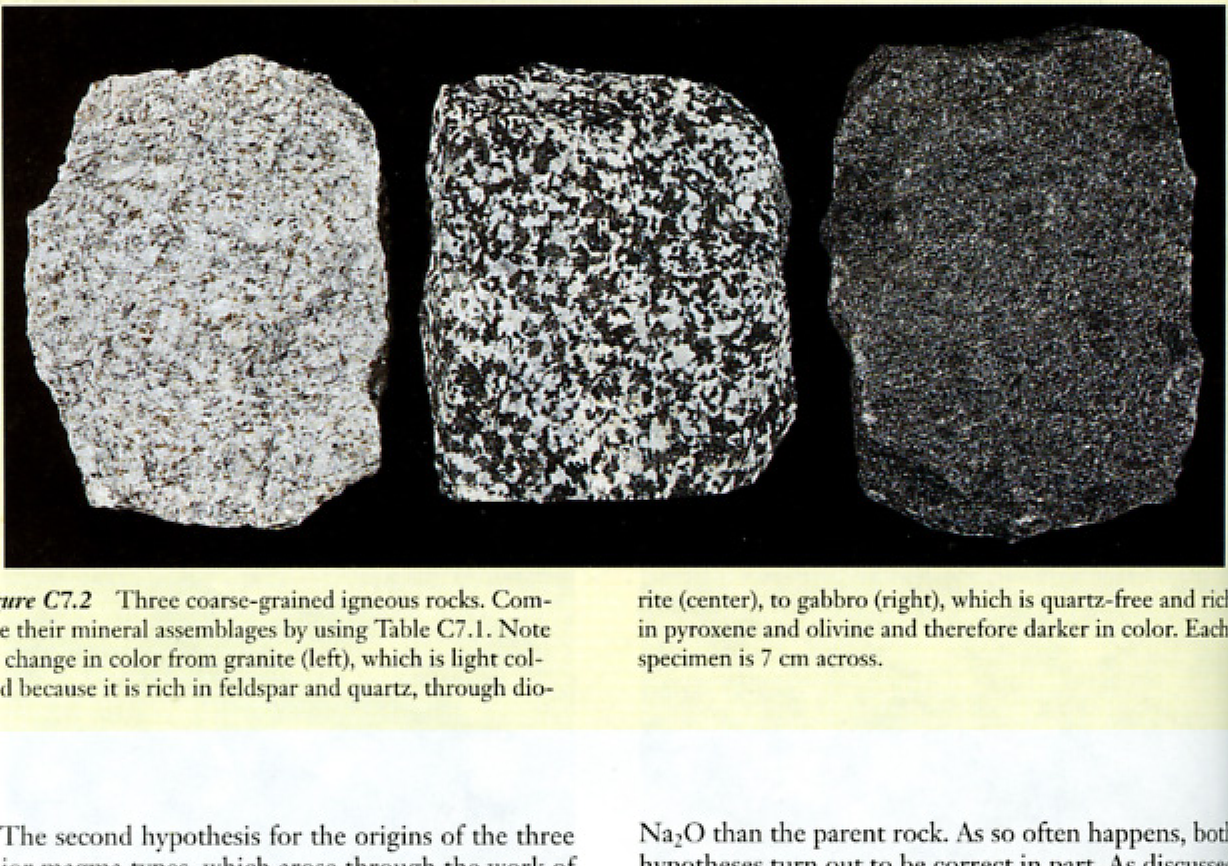


Figure C7.2 Three coarse-grained igneous rocks. Compare their mineral assemblages by using Table C7.1. Note the change in color from granite (left), which is light colored because it is rich in feldspar and quartz, through diorite (center), to gabbro (right), which is quartz-free and rich in pyroxene and olivine and therefore darker in color. Each specimen is 7 cm across.

The second hypothesis for the origins of the three major magma types, which arose through the work of many people, is the reverse of the Bowen hypothesis. Instead of seeking the answer in cooling processes (the Bowen approach), one can look at melting processes—*fractional melting* rather than fractional crystallization. When a rock starts to melt, the first liquid to form contains more SiO_2, Al_2O_3, K_2O, and Na_2O than the parent rock. As so often happens, both hypotheses turn out to be correct in part. As discussed later, fractional melting does indeed seem to be the reason there are three major kinds of magma. However, many of the subtle variations in igneous rocks are best explained by the reaction series identified by Bowen.

Table C7.1 Mineral Assemblages of Common Igneous Rocks

		Name[a]	
Key Feature	**Mineral Assemblage**	**Coarse (intrusive)**	**Fine (extrusive)**
Quartz yes, olivine no	Quartz, feldspar, muscotive, biotite, amphibole	Granite	Rhyolite
Quartz no, olivine no	Feldspar, amphibole, pyroxene, biotite	Diorite	Andesite
Quartz no, olivine yes	Feldspar, pyroxene, olivine, biotite	Gabbro	Basalt
Quartz no, olivine yes	Olivine (abundant), pyroxene, feldspar	Peridotite	(none)

[a]When a rock has a porphyritic texture, we use the name determined by the mineral assemblage as an adjective and the term for the texture of the groundmass as the noun. For example, if the groundmass is fine, we call it a rhyolite porphyry; if the groundmass is course, we call it a granite porphyry.

for facing buildings and for ornamental purposes. Basalt is a very tough rock, and fragments of crushed basalt are widely used as the aggregate in concrete and for roadways. Crushed basalt of commerce is sometimes called trap rock. Rhyolite and andesite are sometimes used for roadways, but when rhyolite is glassy (obsidian) it is also used for jewelry and other ornamental purposes.

A.

B.

Figure C7.3 Two ways of forming a pyroclastic rock. A. Rhyolite tuff, formed by cementation of lapilli and ash, from Clark County, Nevada. B. Welded tuff from the Jemez Mountains, New Mexico. The dark patches are glassy fragments flattened during welding. Note the fragments of other rocks in the specimen. Both samples are 4 cm across.

Fractional Melting and Magma Types

Evidence supporting the hypothesis that the three types of magma originate through fractional melting comes both from laboratory experiment and from the distribution of the different kinds of volcanoes on our planet. A close relationship exists between plate tectonics and the volcano locations. A summary of present thinking about the distribution is presented in Figure 7.18 and in the following discussion, which should be read with frequent references to this figure.

It has long been known that volcanoes that erupt rhyolitic magma are abundant on the continental crust but are not known on the oceanic crust. This observation suggests that the processes that form rhy-

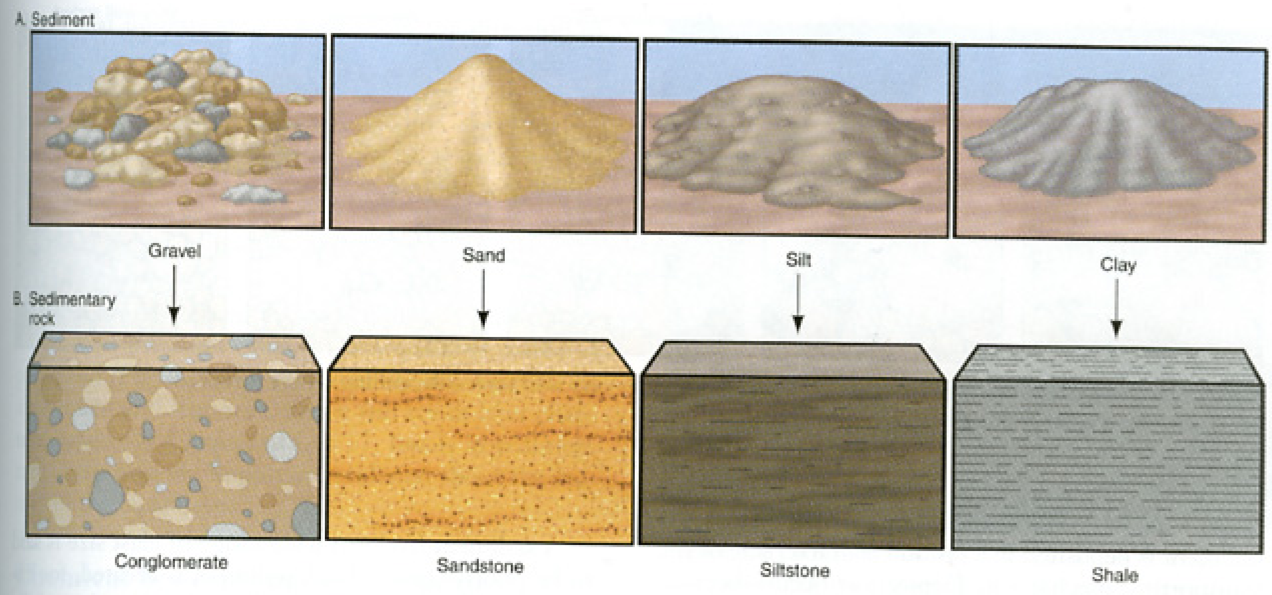


Figure 8.4 Principal kinds of clastic sediment and the sedimentary rocks formed from them. A. Sediment is classified and named for the sizes of the clasts. B. Rock is formed from clastic sediment.

The transformation of sediment to sedimentary rock is called *lithification* (from the Greek *lithos*, meaning stone; hence stone-making). As discussed in Chapter 6, lithification happens either by the addition of a cement or by recrystallization of the sediment particles to a firm, coherent mass.

Clastic Sediment and Clastic Sedimentary Rock

Clast size is the primary basis for classifying clastic sediment and clastic sedimentary rock. Clastic sediment can be divided into four main classes, which from coarsest to finest are gravel, sand, silt, and clay (Fig. 8.4). Gravel is further classified on the basis of dominant clast size into boulder gravel, cobble gravel, and pebble gravel (Table 8.2). The names of the clastic sedimentary rocks corresponding to the various clastic sediments are **conglomerate, sandstone, siltstone,** and **shale** as listed in Figure 8.4 and Table 8.2.

Clastic sediment is transported in many ways. It may slide or roll down a hillside under the pull of gravity or be carried by a glacier, by the wind, or by flowing water. In each case, when transport ceases, the

Table 8.2. Definition of Clastic Particles, Together with the Sediments and Sedimentary Rocks Formed from Them

Name of Particle	Size Limits of Diameter (mm)[a]	Names of Loose Sediment	Name of Consolidate Rock
Boulder	More than 256	Boulder gravel	Boulder conglomerate[c]
Cobble	64 to 256	Cobble gravel	Cobble conglomerate[c]
Pebble	2 to 64	Pebble gravel	Pebble conglomerate
Sand	1/16 to 2	Sand	Sandstone
Silt	1/256 to 1/16	Silt	Siltstone
Clay[b]	Less than 1/256	Clay	Shale

[a]Note that size limits of sediment classes are powers of 2, just as are memory limits in microcomputers (for example, 2K, 64K, 256K, 512K).

[b]Clay, used in the context of this table, refers to particle size. The term should not be confused with clay minerals, which are definite mineral species.

[c]If the clasts are angular, the rock is called a *breccia* rather than a conglomerate.

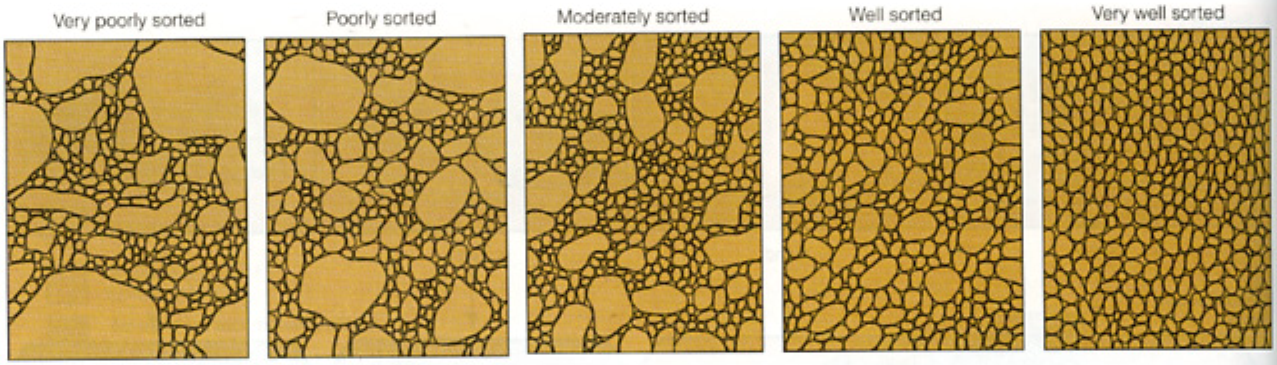


Figure 8.5 Clastic sediment ranges from very poorly sorted to very well sorted depending on the extent to which the constituent grains are of equal size.

sediment is deposited in a fashion characteristic of the transporting mechanism. Deposition occurs because of a drop in energy. Sediment transported by wind or water is deposited when the moving air or flowing water slows to a speed at which clasts can no longer be carried. In a general way, grain size in sediment moved by wind or water is related to the speed of the transporting agent: the faster the speed, the larger the clasts that can be moved. When the speed fluctuates, clast sorting occurs. For example, a rapidly flowing river will remove all the fine particles, leaving behind only the largest clasts. As the speed of the flowing water slows, smaller and smaller clasts are dropped, and well-sorted sediment is the result (Fig. 8.5).

Figure 8.6 Varves deposited in a glacial-age lake in southern Connecticut. Each pair of layers in a sequence of varves represents an annual deposit. Light-colored silty layers were deposited in summer, and the dark-colored clayey layers accumulated in winter.

A sediment having a wide range of clast size is said to be poorly sorted. Such sediment is created, for example, by rockfalls, by the sliding of debris down hillslopes, by slumping of loose deposits on the seafloor, by mudflows, and by deposition of debris from glaciers or from floating ice. Some poorly sorted sediments are given specific names. (For example, *till* is a poorly sorted sediment of glacial origin, while the corresponding rock is a *tillite*.)

Some clastic sediment displays a distinctive *alternation* of parallel layers having different clast sizes (Fig. 8.6). Such alternation suggests that some naturally occurring rhythm has influenced sedimentation. A pair of such sedimentary layers deposited over the cycle of a single year is termed a **varve** (Swedish for cycle). Varves are most common in deposits of high-latitude or high-altitude lakes, where there is a strong contrast in seasonal conditions. In spring, as the ice of nearby glaciers starts to melt, the inflow of sediment-laden water in a lake increases and coarse sediment is deposited throughout the spring and summer. With the onset of colder conditions in the autumn, streamflow decreases and ice forms over the lake surface. During autumn and winter, very fine sediment that has remained suspended in the water column slowly settles to form a thinner, darker layer above the coarse, lighter-colored summer layer. Varved lake sediments are common in Scandinavia and New England where they formed beyond the retreating margins of Ice Age glaciers.

Cross bedding refers to sedimentary beds that are inclined with respect to a thicker stratum within which they occur (Fig. 8.7). Cross beds consist of clasts coarser than silt and are the work of turbulent flow in streams, wind, or ocean waves. As they are moved along, the clasts tend to collect in ridges, mounds, or heaps in the form of ripples, waves, or dunes that migrate slowly forward in the direction of the current. Clasts accumulate on the downstream slope of the pile to produce beds having inclinations as great as 35°. The direction in which cross bedding is inclined tells the direction in which the related current of water or air was flowing at the time of deposition.

Many bodies of sediment contain **fossils**, the remains of plants and animals that died and were incorporated and preserved as the sediment accumulated. Sometimes the form of an original plant or animal is preserved (Fig. 8.8), but more commonly the remains are broken and scattered. As we will see in later chapters, especially Chapters 15 to 17, fossils in sedimentary rocks provide important evidence about the history of the biosphere.

Figure 8.7 Ancient cross-bedded sand dunes that have been converted to sedimentary rock that crops out near Kanab, Utah. The inclination of the cross beds shows that the ancient prevailing winds were blowing from left to right.

Chemical Sediment and Chemical Sedimentary Rock

Chemical sediment forms when dissolved substances precipitate. One common example of precipitation involves the evaporation of seawater or lake water; as the water evaporates, dissolved matter is concentrated, and salts begin to precipitate out as chemical sediment. Chemical sediment formed as the result of evaporation is called an *evaporite*. The most important are halite (NaCl) and gypsum ($CaSO_4 \cdot 2H_2O$); the corresponding rocks are salt and gyprock, respectively. Most of the salt we use in our cooking is mined from beds of salt formed by evaporation.

When chemical sediment forms as a result of biochemical reactions in water, the resulting sediment is said to be *biogenic*. One common example of a biogenic reaction involves the formation of calcium carbonate shells by clams and other aquatic animals. The clams extract both calcium and carbonic acid from the water and use them to lay down layers of solid calcium carbonate. In effect, they make a home for themselves by a biogenic reaction. When the animals die, their shells become biogenic sediment.

Limestone and **dolostone**, containing the minerals calcite and dolomite, respectively, are the most important of the biogenic rocks. Limestone composed entirely of shelly debris is called *coquina*. Other limestones consist of cemented reef organisms *(reef limestone)*, the compacted carbonate shells of minute floating organisms *(chalk)*, and accumulations of tiny round, calcareous accretionary bodies (ooliths) that are 0.5 to 1 mm in diameter *(oolitic limestone)*.

Biogenic sediment can form both in the sea and on land. Trees, bushes, and grasses contribute most of the biogenic material on land. In water-saturated environments, such as bogs or swamps, plant remains accumulate to form **peat**, a sediment with a carbon content of about 60 percent. Peat is the initial stage in the development of the biogenic sedimentary rock we call **coal.**

As peat is buried beneath more plant matter and accumulating sand, silt, or clay, both temperature and pressure rise. As millions of years pass, the increased temperature and pressure bring about a series of

Figure 8.8 The fossil remains of a kauri pine lie next to the skeleton of a fossil fish on a bedding plane of a 175-million-year-old shale in Australia.

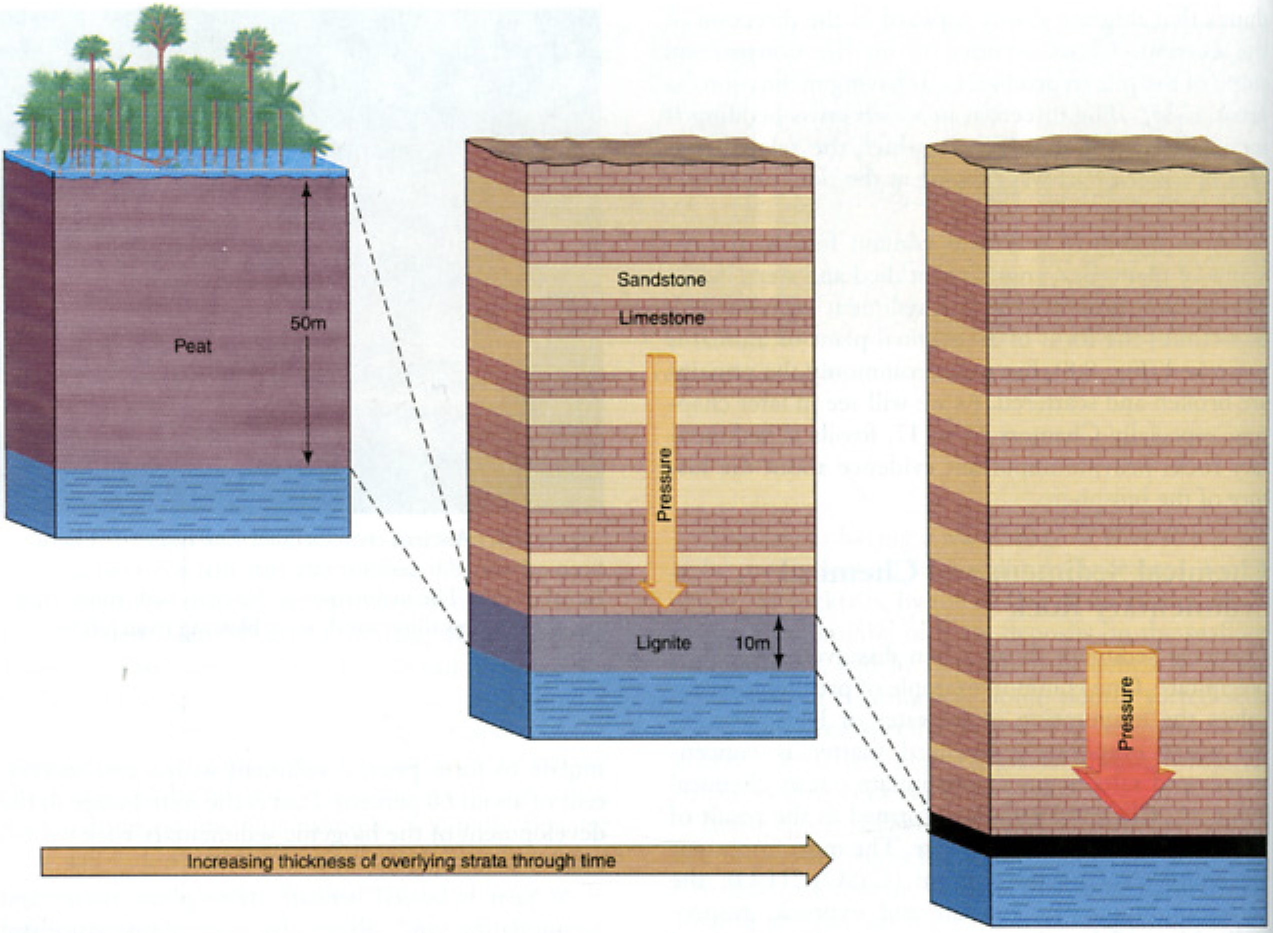


Figure 8.9 Plant matter in peat (a biogenic sediment) is converted to coal (a biogenic sedimentary rock) by decomposition and increasing pressure and temperature as overlying sediments build up. By the time a layer of peat 50 m thick is converted to bituminous coal, its thickness has been reduced by 90 percent. In the process, the proportion of carbon has increased from 60 to 80 percent.

changes. The peat is compressed, water is squeezed out, and the gaseous organic compounds such as methane (CH_4) escape, leaving an increased proportion of carbon. The peat is thereby converted into *lignite* and eventually into *bituminous coal* (Fig. 8.9).

METAMORPHISM: NEW ROCKS FROM OLD

Metamorphic rocks are of particular interest because the changes they undergo happen in the solid state. When tectonic plates move and crustal fragments collide, rocks are squeezed, stretched, bent, heated, and changed in complex ways. Even when a rock has been altered two or more times, however, vestiges of its earlier forms are usually preserved because the changes occurred in the solid state. Solids, unlike liquids and gases, tend to retain a "memory" of the events that changed them. In many ways, therefore, metamorphic rocks are the most complex but also the most interesting of the rock families. In them is preserved the story of all the collisions that have happened to the crust. Deciphering the record is an exceptional challenge for geologists. For example, when continental masses collide because of moving plates, distinctive kinds of metamorphic rocks form along the plate edges. Therefore, it is possible to determine where the boundaries of ancient continents once were by studying the distribution of metamorphic rocks. Geologists also use evidence derived from metamorphic rocks to determine how long plate tectonics has been active on the Earth. So far the evidence suggests that plate tectonics has been operating for at least 2 billion years and probably 3 billion years.

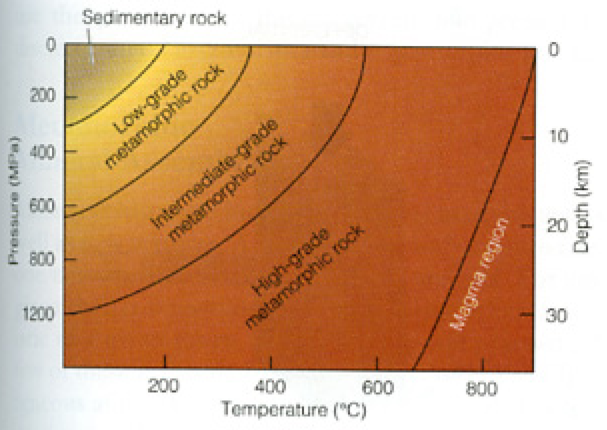


Figure 8.10 Ranges of temperature and pressure (equivalent to depth) under which metamorphism occurs in the crust. At lowest temperatures and pressure, sediment is converted to sedimentary rock. At the highest temperature and pressure, melting commences and the result is magma rather than rock.

The Limits of Metamorphism

Metamorphism describes changes in mineral assemblage and texture in sedimentary and igneous rocks subjected to temperatures above 200°C and pressure in excess of about 300 MPa (the pressure caused by a few thousand meters of overlying rock). There is, of course, an upper limit to metamorphism because at sufficiently high temperatures rock will melt. Remember then: metamorphism refers only to changes in solid rock, not to changes caused by melting. Changes due to melting involve igneous phenomena, as discussed in Chapter 7.

Low-grade metamorphism refers to metamorphic processes that occur at temperatures from about 200°C to 320°C and at relatively low pressures (Fig. 8.10). High-grade metamorphism refers to metamorphic processes at high temperature (above about 550°C) and high pressure. Intermediate-grade metamorphism lies between low and high grade.

Controlling Factors in Metamorphism

In a simplistic way, you can think of metamorphism as cooking. When you cook, what you get to eat depends on what you start with and on the cooking conditions. So too with rocks; the end product is controlled by the initial composition of the rock and by the metamorphic (or cooking) conditions. The chemical composition of a rock undergoing metamorphism plays a controlling role in the new mineral assemblage; so do changes in temperature and pressure. The ways in which temperature and pressure control metamorphism are not entirely straightforward, however, because they are strongly influenced by such factors as the presence or absence of fluids, how long a rock is subjected to high pressure or high temperature, and whether the rock is simply compressed or is twisted and broken as well as compressed during metamorphism.

Chemical Reactivity Induced by Fluids

The innumerable open spaces between grains in a sedimentary rock and the tiny fractures in many igneous rocks are called pores, and all pores are filled by a watery fluid. The fluid is never pure water, for it always has dissolved in it small amounts of gases such as CO_2 and salts such as NaCl and $CaCl_2$, as well as traces of all the mineral constituents present in the enclosing rock. At high temperature the fluid is more likely to be a vapor than a liquid. Regardless of its composition or state, the *pore fluid* (for that is its best designation) plays a vital role in metamorphism.

When the temperature of, and pressure on, a rock undergoing metamorphism change, so does the composition of the pore fluid. Some of the dissolved constituents move from the pore fluid to the new minerals growing in the metamorphic rock. Other constituents move in the other direction, from the minerals to the pore fluid. In this way the pore fluid serves as a transporting medium that speeds up chemical reactions in much the same way that water in a stew pot speeds up the cooking of a tough piece of meat.

Pressure and Temperature

When a mixture of flour, salt, sugar, yeast, and water is baked, the high temperature causes a series of chemical reactions—new compounds are formed, and the result is a loaf of bread. When rocks are heated, new minerals grow and the result is a metamorphic rock. In the case of the rocks, the cooking is brought about by the Earth's internal heat. Rocks can be heated by burial, by a nearby igneous intrusion, or by a thickening of the crust owing to collision. But burial, collision, and intrusion can also cause a change in pressure. Therefore, whatever the cause of the heating, metamorphism can rarely be considered to be entirely due to the rise in temperature. The effects attributable to changing temperature and pressure must be considered together.

When discussing metamorphic rocks, scientists often use the term *stress* in place of pressure. They do so because stress has the connotation of direction.

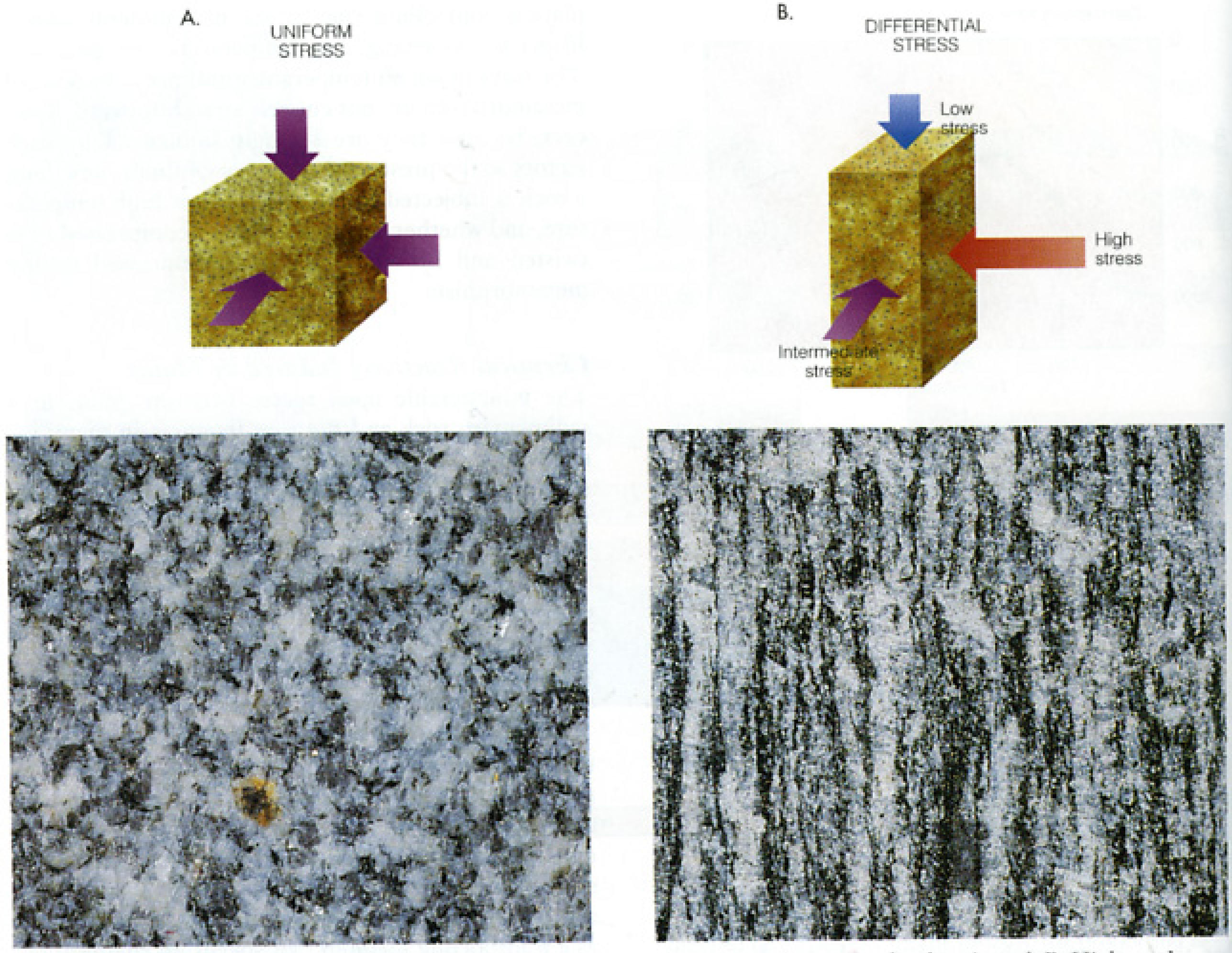


Figure 8.11 Comparison of textures developed in rocks of the same composition under uniform and differential stress. A. Granite, consisting of quartz, feldspar, and mica (the dark mineral) that crystallized under a uniform stress. Note that mica grains are randomly oriented. B. High-grade metamorphic rock, also consisting of quartz, feldspar, and mica, that crystallized under a differential stress. Mica grains are parallel, giving the rock a distinct foliation.

Rocks are solids, and solids can be squeezed more strongly in one direction than another; that is, stress in a solid, unlike stress in a liquid, can be different in different directions. The textures in many metamorphic rocks record **differential stress** (meaning not equal in all directions) during metamorphism. In contrast, igneous rocks have textures formed under **uniform stress** (meaning equal in all directions) because igneous rocks crystallize from liquids.

The most visible effect of metamorphism in a differential stress field involves the texture of silicate minerals, such as micas and chlorites, that contain polymerized $(Si_4O_{10})^{4-}$ sheets. Compare Figures 8.11A and B. Figure 8.11A is a granite that has a typical texture of randomly oriented mineral grains that grew in a uniform stress field. Figure 8.11B is a metamorphic rock containing the same minerals as in A, but this rock formed in a differential stress field. Note that in Figure 8.11B all the biotite (mica) grains (black) are parallel, giving the rock a distinctive texture.

In a metamorphic rock containing sheet-structure minerals, the sheets are oriented perpendicular to the direction of maximum stress, as shown in Figure 8.11B. The parallel sheets produce a planar texture called **foliation**, named from the Latin word *folium*, meaning leaf. Foliated rock tends to split into thin flakes.

It is important to understand that stress can be high or low. It is the magnitude of the stress that determines a mineral assemblage (refer back to Chapter 6 for a discussion of mineral assemblages). Texture, on the other hand, is controlled by differential versus uniform stress. To avoid confusion, geologists often use the term *stress* to discuss texture and *pressure* to discuss mineral assemblages and metamorphic grades.

Metamorphic Mineral Assemblages

Metamorphism produces new mineral assemblages as well as new textures. As temperature and pressure rise, one new mineral assemblage follows another. For any given rock composition, each assemblage is characteristic of a given range of temperature and pressure. A few of these minerals are found rarely (or not at all) in igneous and sedimentary rocks. Therefore their presence in a rock is usually evidence enough that the rock has been metamorphosed. Examples of these metamorphic minerals are chlorite, serpentine, talc, and the three Al_2SiO_5 minerals andalusite, kyanite, and sillimanite. Figure 8.12 illustrates the way mineral assemblages change with the grade of metamorphism as a shale is metamorphosed.

Kinds of Metamorphism

The processes that result from changing temperature and pressure, and that cause the metamorphic changes observed in rocks, can be grouped under the terms *mechanical deformation* and *chemical recrystallization*. Mechanical deformation includes grinding, crushing, and the development of foliation (Fig. 8.13). Chemical recrystallization includes all the changes in mineral composition, in the growth of new minerals, and the losses of H_2O and CO_2 that occur as rock is heated and squeezed. Different kinds of metamorphism reflect the different levels of importance of the two processes. The two most important kinds of metamorphism are burial and regional metamorphism.

Burial Metamorphism

Sediments, together with interlayered pyroclastics, may attain temperatures in excess of 200°C or more when buried deeply in a sedimentary basin and thus subjected to metamorphism. Abundant pore water is present in buried sediment, and this water speeds up chemical recrystallization and helps new minerals to grow. Because water-filled sediment is weak and acts more like a liquid than a solid, however, the stress during **burial metamorphism** tends to be uniform. As a result, burial metamorphism involves little mechanical deformation, and the metamorphic rock that results lacks foliation. The texture looks like that of an essentially unaltered sedimentary rock, even though the mineral assemblages in the two are completely different from one another.

Burial metamorphism is the first stage of metamorphism in deep sedimentary basins, such as deep-sea trenches on the margins of tectonic plates, in the great

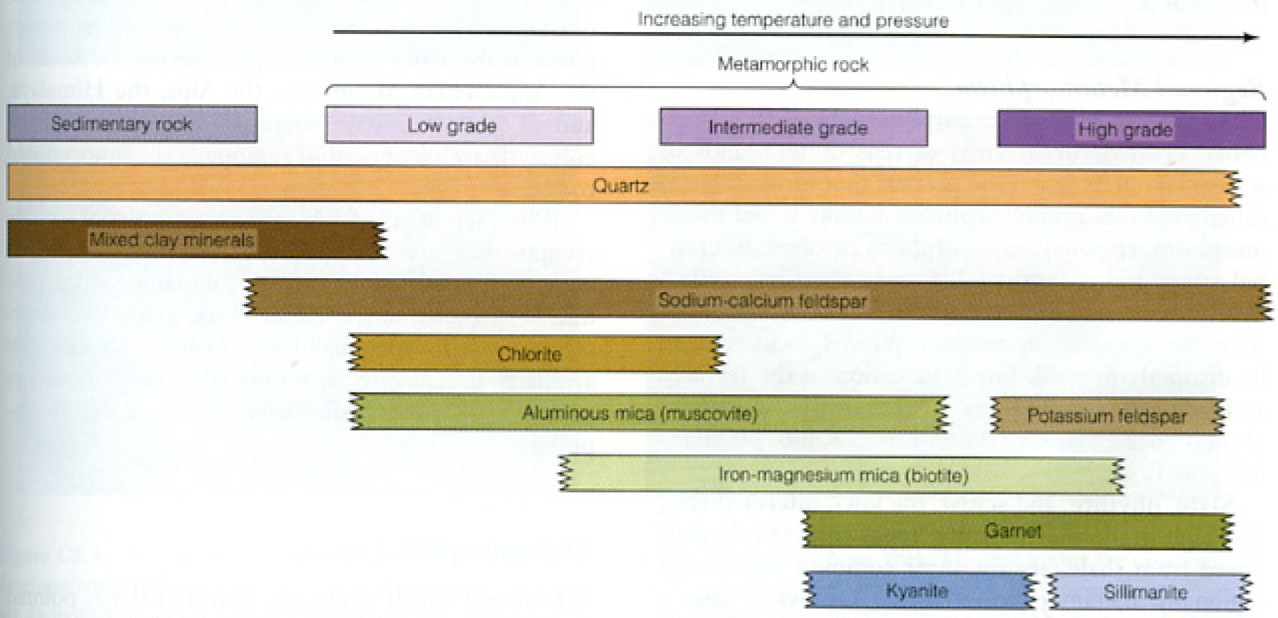


Figure 8.12 Changing mineral assemblages as a shale is metamorphosed from low to high grade. Kyanite and sillimanite have the same composition (Al_2SiO_5) but different crystal structures. They are found only in metamorphic rocks.

A.

B.

Figure 8.13 Development of foliation in a granite by mechanical deformation—the mineral assemblage is unchanged, but the texture changes. From Groothoek, South Africa. A. Undeformed granite consisting of quartz, feldspar, and mica. The dark patch in the center of the field of view is a fragment of amphibolite (a metamorphic rock consisting largely of amphibole) that fell into the magma during intrusion. Foliation is not present. B. The original granitic texture has been completely changed, and the granite has been metamorphosed to a gneiss with a distinct foliation. The dark streak above the hammer handle was originally an inclusion of amphibolite like that in A. The amphibolite fragment has been crushed and stretched by the differential stress during the metamorphic processes.

piles of sediment that accumulate at the foot of the continental shelf along passive continental margins, such as the east coast of North America, and off the mouths of great rivers. Burial metamorphism is known to be happening today in the great pile of sediments accumulated in the Gulf of Mexico, off the mouth of the Mississippi River.

Regional Metamorphism

The most common metamorphic rocks of the continental crust occur in areas of tens of thousands of square kilometers, and the process that forms them is called **regional metamorphism.** Unlike burial metamorphism, regional metamorphism involves differential stress and a considerable amount of mechanical deformation in addition to chemical recrystallization. As a result, regionally metamorphosed rocks tend to be distinctly foliated. For a discussion of the textures and mineral assemblages of regionally metamorphosed rocks, see "A Closer Look: Kinds of Metamorphic Rock."

Slate, **phyllite**, and **schist**, the low-, intermediate-, and high-grade metamorphic rocks respectively produced from shale, are the most common varieties of regionally metamorphosed rocks. **Gneiss** is also a high-grade metamorphic rock produced from shale; it has more quartz and feldspar and less mica than is present in schist. Regionally metamorphosed rocks are usually found in mountain ranges formed as a result of either subduction or collision between fragments of continental crust. During both subduction and collision between continents, sedimentary rock along the margin of a continent is subjected to intense differential stresses. The foliation that is so characteristic of slates, phyllites, schists, and gneisses is a consequence of those intense stresses. Regional metamorphism is therefore a result of plate tectonics. Rocks of the Appalachian Mountains, the Alps, the Himalaya, and all other mountain ranges formed by continental collisions are composed of regionally metamorphosed rocks.

When segments of ancient oceanic crust of basaltic composition are incorporated into the continental crust as a result of subduction, metamorphism produces two distinctive rocks. Low-grade metamorphism produces **greenschists**, so named because they are rich in chlorite. Intermediate-grade metamorphism produces **amphibolites**, which are rich in amphiboles.

Metamorphic Facies

A famous Finnish geologist, Pennti Eskola, pointed out in 1915 that the same metamorphic mineral assemblages are observed again and again. This led him to propose a concept known as **metamorphic facies**.

A CLOSER LOOK

Kinds of Metamorphic Rock

Metamorphic rocks are named partly on the basis of texture, partly on mineral assemblage. The most widely used names are those applied to metamorphic derivatives of shales, sandstones, limestones, and basalts. This is because shales, sandstones, and limestones are the most abundant sedimentary rock types, whereas basalt is by far the most abundant igneous rock.

Metamorphism of Shale

Slate The low-grade metamorphic product of shale is *slate* (Fig. C8.3). The minerals usually present in shale include quartz, clays, calcite, and feldspar. Slate contains quartz, feldspar, and mica or chlorite. Although a slate may still look like a shale, the tiny mica and chlorite grains give slate a distinctive foliation called slaty cleavage. The presence of slaty cleavage is clear proof that a rock has changed from a sedimentary rock (shale) to a metamorphic rock (slate).

Phyllite Continued metamorphism of a slate to an intermediate grade of metamorphism produces both larger grains of mica and a changing mineral assemblage; the rock develops a pronounced foliation (Fig. C8.3) and is called *phyllite* (from the Greek *phyllon*, a leaf). In a slate it is not possible to see the new grains of mica with the unaided eye, but in a phyllite they are just large enough to be visible.

Schist and Gneiss Still further metamorphism beyond that which produces a phyllite leads to a coarse-grained rock with pronounced schistosity, called *schist* (Fig. C8.3). The most obvious differences between slate, phyllite, and schist are in grain size (Fig. C8.4). At the high grades of metamorphism characteristic of schists, minerals may start to segregate into separate bands. A high-grade rock with coarse grains and pronounced foliation,

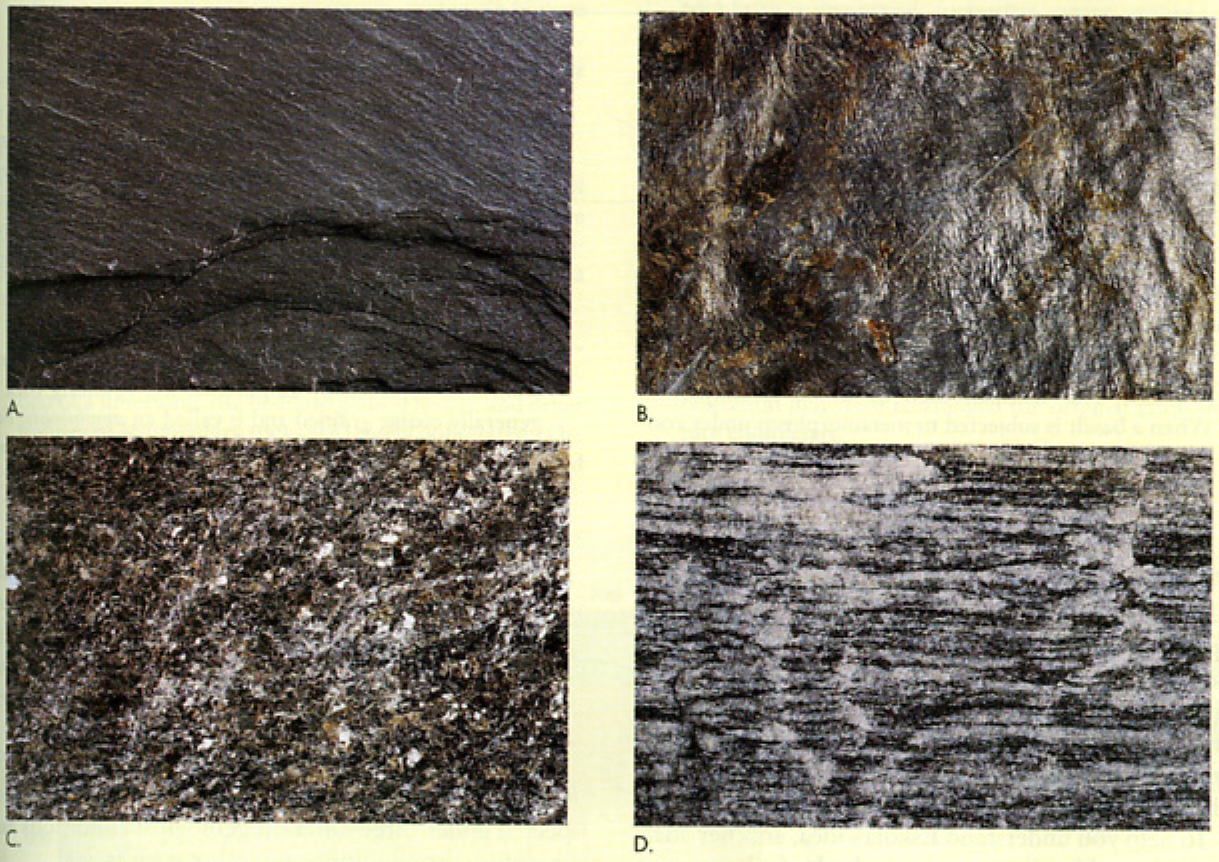


Figure C8.3 Progressive metamorphism of shale and the development of foliation. A. Slate from Bangor, Pennsylvania. Individual mineral grains are too small to be visible. Slaty cleavage records the beginning of metamorphism. B. Phyllite from Woodbridge, Connecticut. Mineral grains are just visible. Foliation is more pronounced. C. Schist, from Manhattan, New York. Mineral grains are now easily visible and foliation is pronounced. D. Gneiss, from Uxbridge, Massachusetts. Quartz and feldspar layers (light) are segregated from mica-rich layers (dark). Foliation is pronounced.

A.

Intensity of metamorphism →	Not metamorphosed	Low grade	Intermediate grade	High grade
Rock name	Shale →	Slate →	Phyllite →	Schist / Gneiss
Foliation	None	Subtle	Distinct; schistosity apparent	Conspicuous; schistosity and compositional layering
Size of mica grains	Microscopic	Microscopic	Just visible with hand lens	Large and obvious

B.

Intensity of metamorphism →	Not metamorphosed	Low grade	Intermediate grade	High grade
Rock name	Basalt → ($+H_2O$)	Greenschist →	Amphibolite →	Granulite
Foliation	None	Distinct	Indistinct;, when present due to parallel grains of amphibole	Indistinct because of absence of micas
Size of mica grains	Not present	Visible with hand lens	Obvious if present	Not present

Figure C8.4 Progressive metamorphism of shale and basalt. Both foliation and mica grain size change as a result of increasing temperature and differential stress.

but with layers of micaceous minerals segregated from layers of minerals such as quartz and feldspar, is called a *gneiss* (pronounced nice, from the German *gneisto*, meaning to sparkle) (Fig. C8.3).

Metamorphism of Basalt

Greenschist The main minerals in basalt are olivine, pyroxene, and feldspar, each of which is anhydrous. When a basalt is subjected to metamorphism under conditions where H_2O can enter the rock and form hydrous minerals, distinctive mineral assemblages develop. At low grades of metamorphism, mineral assemblages such as chlorite + feldspar + epidote + calcite form. The resulting rock is equivalent in metamorphic grade to a slate but has a very different appearance. It has pronounced foliation as a phyllite does, but it also has a very distinctive green color because of its chlorite content: it is termed *greenschist*.

Amphibolite and Granulite When a greenschist is subjected to an intermediate grade of metamorphism, chlorite is replaced by amphibole; the resulting rock is generally coarse grained and is called an *amphibolite*. Foliation is present in amphibolites but is not pronounced

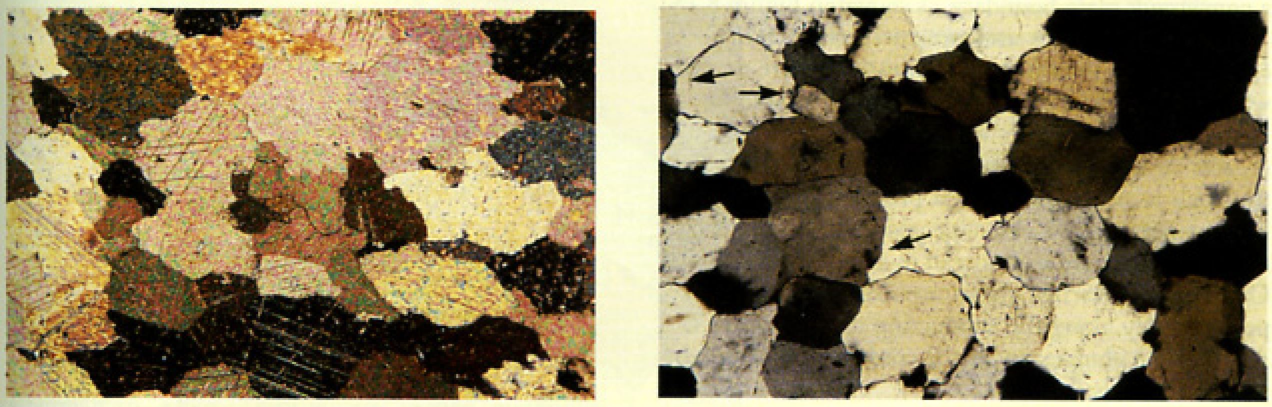
(The term *facies* comes from the Latin for *face*, or appearance.) According to the metamorphic facies concept, for a given range of temperature and pressure, and for a given rock composition, the assemblage of minerals formed during metamorphism is always the same. Based on mineral assemblages, Eskola defined a series of pressure and temperature ranges that he called metamorphic facies.

To help you understand Eskola's idea, another analogy with cooking is appropriate; think of a large roast of beef. When it is carved, one sees that the center is rare, the outside is well done, and in between is a region of medium rare meat. The differences occur because the temperature was not uniform throughout. The center, rare-meat facies is a low-temperature facies; the outside, well-done facies is a high-temperature one. The composition of beef varies little, if at all, from roast to roast, and so the facies must depend not on composition but on the temperature. So too with rocks, although in any rock of given composition, pressure as well as temperature determines mineral assemblage.

Figure 8.14 shows the principal metamorphic facies, together with geothermal gradients to be expected under three different geological conditions and therefore the conditions typical of each facies.

Plate Tectonics and Metamorphism

One of the triumphs of plate tectonics is that, for the first time, it explains the distribution of metamorphic



A.

B.

Figure C8.5 Texture of nonfoliated metamorphic rocks seen in thin section and viewed in polarized light. Notice the interlocking grain structure produced by recrystallization during metamorphism. Each specimen is 2 cm across. A. Marble, composed entirely of calcite. All vestiges of sedimentary structure have disappeared. B. Quartzite. Arrows point to faint traces of the original rounded quartz grains in some of the grains.

because micas and chlorite are usually absent. At highest grade metamorphism, amphibole is replaced by pyroxene and an indistinctly foliated rock called a *granulite* develops.

Metamorphism of Limestone and Sandstone

Marble and **quartzite** are the metamorphic derivatives of limestone and sandstone, respectively. Neither limestone nor quartz sandstone (when pure) contains the necessary ingredients to form sheet- or chain-structure minerals. As a result, marble and quartzite commonly lack foliation.

Marble Marble consists of a coarsely crystalline, interlocking network of calcite grains. During recrystallization of a limestone, the bedding planes, fossils, and other features of sedimentary rocks are largely obliterated. The end result, as shown in Figure C8.5A, is an even-grained rock with a distinctive, somewhat sugary texture. Pure marble is snow white and consists entirely of pure grains of calcite. Such marbles are favored for marble gravestones and statues in cemeteries, perhaps because white is considered to be a symbol of purity. Many marbles contain impurities such as organic matter, pyrite, goethite, and small quantities of silicate minerals, which impart various colors.

Quartzite Quartzite is derived from sandstone by the filling in of the spaces between the original grains with silica, and by recrystallization of the entire mass (Fig. C8.5B). Sometimes, the ghostlike outlines of the original sedimentary grains can still be seen, even though recrystallization may have rearranged the original grain structure completely.

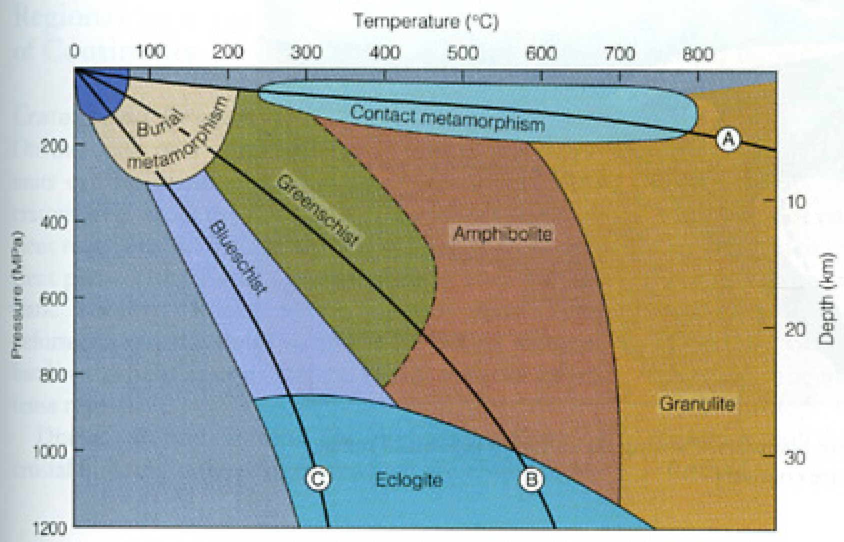


Figure 8.14 Metamorphic facies plotted with respect to temperature and pressure. Curve A is a typical thermal gradient around an intrusive igneous rock that causes low-pressure metamorphism. Curve B is a normal continental geothermal gradient. Curve C is the geothermal gradient developed in a subduction zone.