Welcome

This is

CE181404
Engineering Geology

Metamorphic Rocks

What is Metamorphism

- Metamorphism is the transformation of one rock type into another.
- Metamorphic rocks are produced from pre-existing igneous, sedimentary, or even other metamorphic rocks. Thus, every metamorphic rock has a parent rock—the rock from which it was formed.
- Metamorphism, which means to “change form,” is a process that leads to changes in the mineral content, texture, and sometimes the chemical composition of rocks.
- Metamorphism takes place where pre existing rock is subjected to new conditions, usually elevated temperatures and pressures, that are significantly different from those in which it initially formed.

What Drives Metamorphism?

Agents of Metamorphism

- *heat,*
- *pressure (stress), and*
- *chemically active fluids.*

Heat as a Metamorphic Agent

- The most important factor driving metamorphism is *heat* because it provides the energy needed to drive the chemical reactions that result in the recrystallization of existing minerals and/or the formation of new minerals.
- Increase in temperature causes the ions within a mineral to vibrate more rapidly. Even in a crystalline solid, where ions are strongly bonded, this elevated level of activity allows individual atoms to migrate more freely between sites in the crystalline structure.

Changes caused by Heat.

- When Earth materials are heated, especially those that form in low-temperature environments, they are affected in two ways.
- First, heating promotes recrystallization of mineral grains. This is particularly true of sedimentary and volcanic rocks that are composed of fine-grained clay and silt sized particles. Higher temperatures promote crystal growth in which fine particles join together to form larger grains with the ***same mineral composition***.
- Second, when rocks are heated, they eventually reach a temperature at which one or more minerals become chemically unstable. When this occurs, the constituent atoms begin to arrange themselves into crystalline structures that are more stable in the new high-temperature environment. These chemical reactions create ***new minerals*** with stable configurations that have an overall composition roughly equivalent to that of the original rock.

What is the source of heat?

Earth's internal heat comes mainly from energy that is continually being released by radioactive decay and thermal energy that remains from the time when our planet was forming.

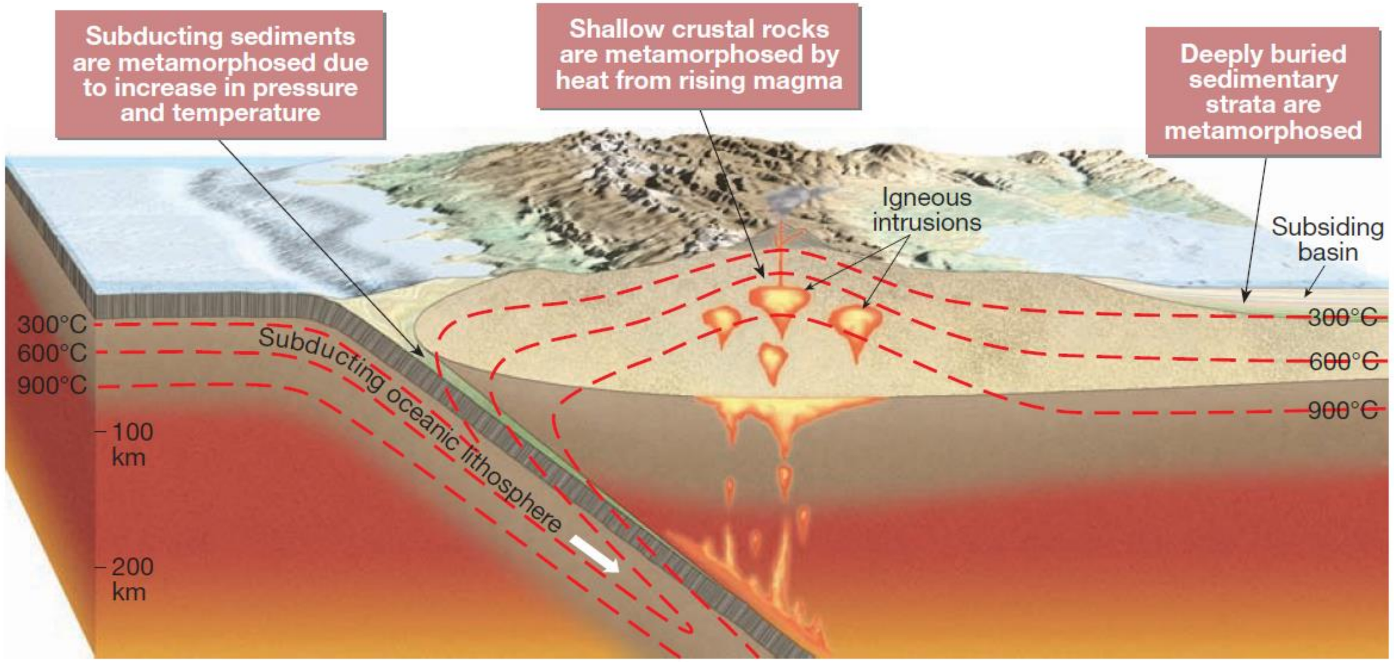


FIGURE 7.2 The geothermal gradient and its role in metamorphism. Notice how the geothermal gradient is lowered by the subduction of relatively cool oceanic lithosphere. By contrast, thermal heating is evident where magma intrudes the upper crust.

Confining Pressure and Differential Stress

Pressure, like temperature, also increases with depth as the thickness of the overlying rock increases. Buried rocks are subjected to confining pressure.

Confining pressure causes the spaces between mineral grains to close, producing a more compact rock having a greater density.

As confining pressure increases some minerals recrystallize into ***new minerals*** that have the ***same chemical composition*** but a more compact crystalline form.

In addition to confining pressure, rocks may be subjected to directed pressure. This occurs, for example, at convergent plate boundaries where slabs of lithosphere collide. Here the forces that deform rock are unequal in different directions and are referred to as differential stress.

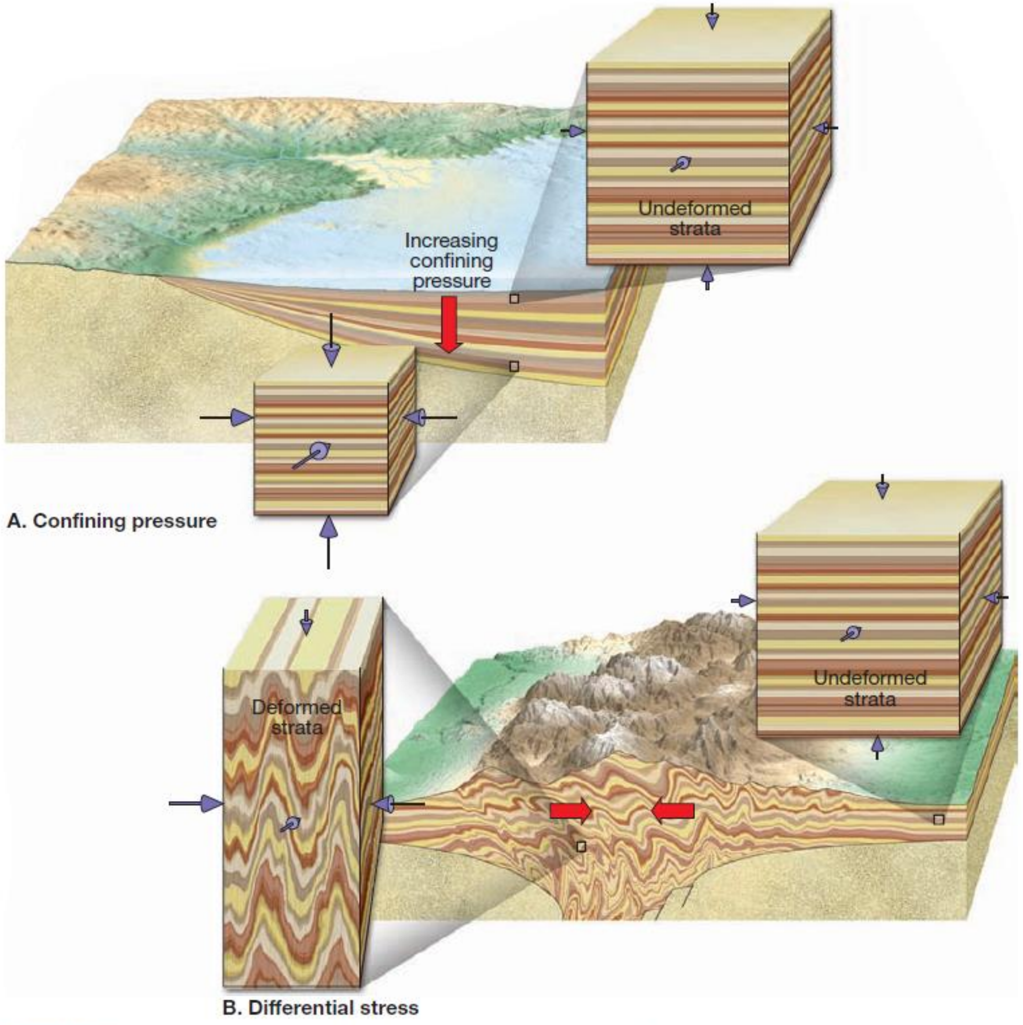


FIGURE 7.3 Confining pressure and differential stress as metamorphic agents. **A.** In a depositional environment, as confining pressure increases, rocks deform by decreasing in volume. **B.** During mountain building, rocks subjected to differential stress are shortened in the direction that pressure is applied and lengthened in the direction perpendicular to that force.

Chemically Active Fluids

- Many minerals, including clays, micas, and amphiboles, are hydrated—meaning they contain water in their crystalline structures. Elevated temperatures and pressures cause the dehydration of these minerals. Once expelled, these hot fluids promote recrystallization by enhancing the migration of mineral matter.

Metamorphic Textures

the term texture is used to describe the size, shape, and arrangement of grains within a rock. Most igneous and many sedimentary rocks consist of mineral grains that have a random orientation and thus appear the same when viewed from any direction. By contrast, deformed metamorphic rocks that contain platy minerals (micas) and/or elongated minerals (amphiboles), typically display some kind of *preferred orientation* in which the mineral grains exhibit a parallel to subparallel alignment.

A rock that exhibits a preferred orientation of its minerals is said to possess *foliation*.

Foliation

The term foliation refers to any planar (nearly flat) arrangement of mineral grains or structural features within a rock.

Foliation can form in many different ways, including:

1. Rotation of platy and/or elongated mineral grains into a parallel or nearly parallel orientation.

2. Recrystallization that produces new minerals with grains that exhibit a preferred orientation.

3. Mechanisms that change spherically shaped grains into elongated shapes that are aligned in a preferred orientation.

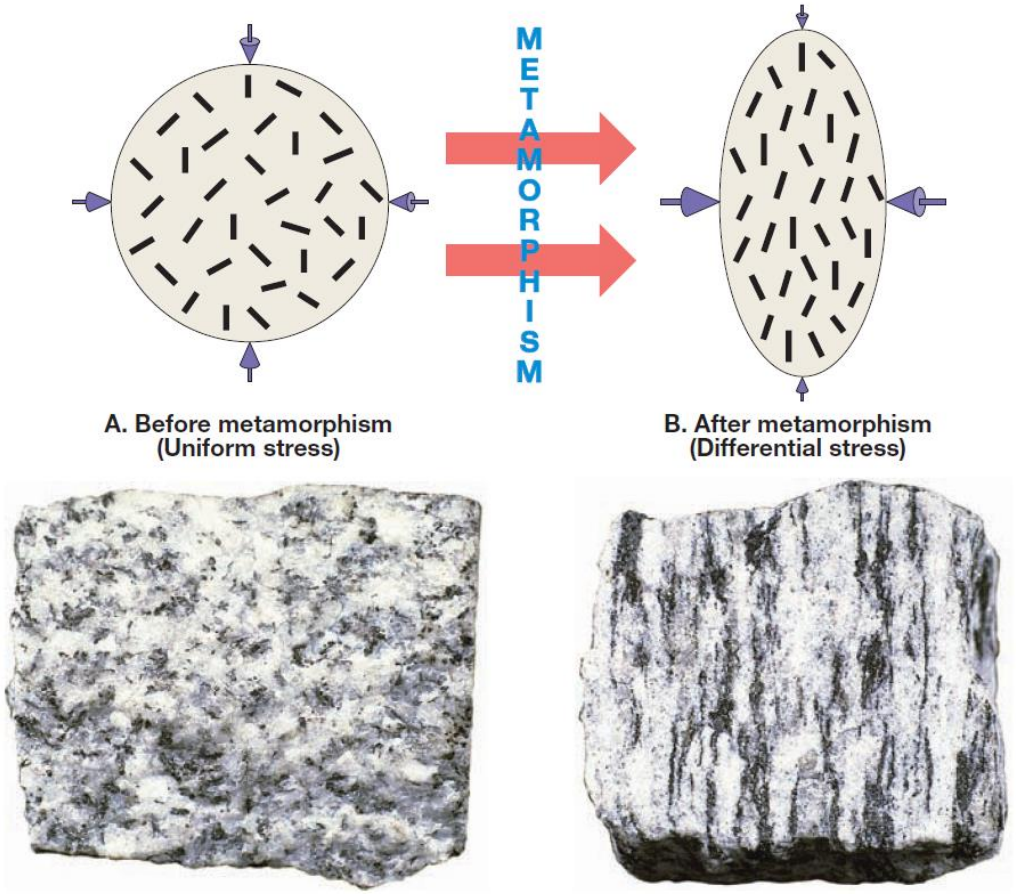


FIGURE 7.5 Mechanical rotation of platy or elongated mineral grains. **A.** Existing mineral grains keep their random orientation if force is uniformly applied. **B.** As differential stress causes rocks to flatten, mineral grains rotate toward the plane of flattening. *(Photos by E. J. Tarbuck)*

Foliation

A change in grain shape can occur as units of a mineral's crystalline structure slide relative to one another along discrete planes, thereby distorting the grain as shown in FIGURE 7.6. This type of gradual solid-state flow involves slippage that disrupts the crystal lattice as atoms shift positions. This process involves the breaking of existing chemical bonds and the formation of new ones.

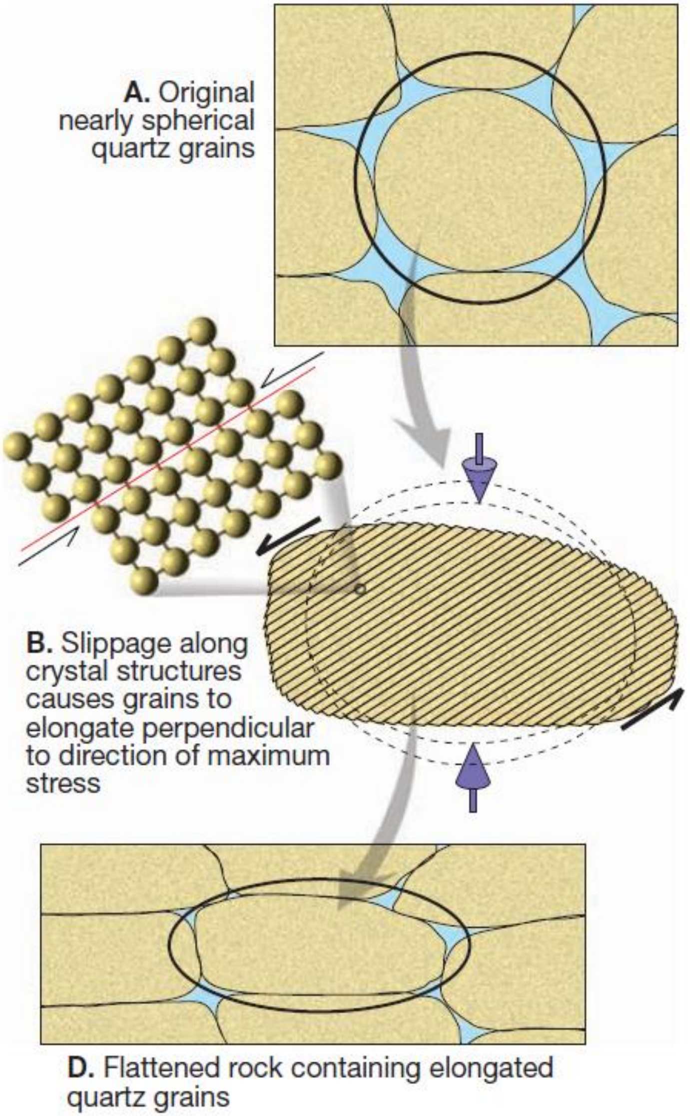


FIGURE 7.6 Development of preferred orientations of minerals that have roughly spherical crystals, such as quartz. This mechanism for changing the shape of mineral grains occurs when units of the mineral's crystalline structure slide relative to one another.

Foliated Textures

- Various types of foliation exist, depending largely upon the grade of metamorphism and the mineral content of the parent rock.

We will look at three:

- *rock* or *slaty cleavage,*
- *schistosity,* and
- *gneissic texture.*

Rock or Slaty Cleavage

Rock cleavage refers to closely spaced, flat surfaces along which rocks split into thin slabs when hit with a hammer. Rock cleavage develops in various metamorphic rocks but is best displayed in slates, which exhibit an excellent splitting property *called slaty cleavage*.

Depending on the metamorphic environment and the composition of the parent rock, rock cleavage develops in a number of ways. In a low-grade metamorphic environment, rock cleavage is known to develop where beds of shale (and related sedimentary rocks) are strongly folded and metamorphosed to form slate. The process begins as platy grains are kinked and bent—generating microscopic folds having limbs (sides) that are roughly aligned (FIGURE 7.7).

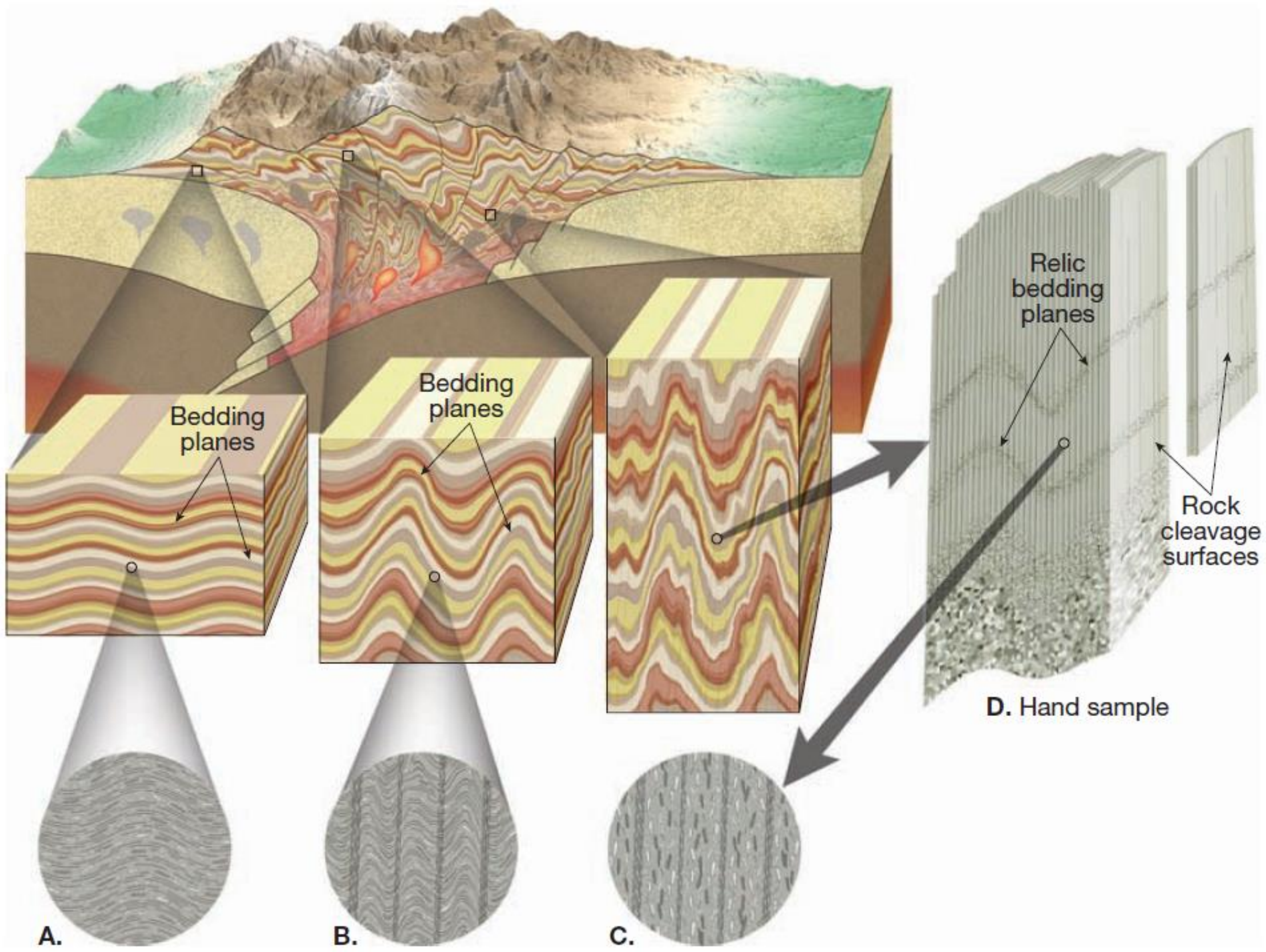


FIGURE 7.7 Development of rock cleavage. As shale is strongly folded (**A.**, **B.**) and metamorphosed to form slate, the developing mica flakes are bent into microfolds. **C.** Further metamorphism results in the recrystallization of mica grains along the limbs of these folds to enhance the foliation. **D.** This hand sample of slate illustrates rock cleavage and its orientation to relic bedding surfaces.

Rock or Slaty Cleavage

With further deformation, this new alignment is enhanced as old grains break down and recrystallize preferentially in the direction of the newly developed orientation. In this manner the rock develops narrow parallel zones where mica flakes are concentrated. These features alternate with zones containing quartz and other mineral grains that do not exhibit a pronounced linear orientation. It is along these very thin zones of platy mineral that slate splits (FIGURE 7.8).

FIGURE 7.8 Excellent slaty cleavage is exhibited by the rock in this slate quarry. Because slate breaks into flat slabs, it has many uses. *(Photo by Fred Bruemmer/Photolibrary)* The inset photo shows the use of slate for the roof of this house in Switzerland. *(Photo by E. J. Tarbuck)*

Schistosity

Under higher temperature pressure regimes, the minute mica and chlorite crystals in slate begin to grow. When these platy minerals are large enough to be discernible with the unaided eye and exhibit a planar or layered structure, the rock is said to exhibit a type of foliation called schistosity**.**

Rocks having this texture are referred to as *schists.*

Two, of several, schists that form from shale are *mica schist* and *garnet-mica schist* (figure 15.12).

FIGURE 15.12

Garnet-mica schist. Small, subparallel flakes of muscovite mica reflect light. Garnet crystals give the rock a "raisin bread" appearance. *Photo by C. C. Plummer*

Gneissic Texture

During high-grade metamorphism, ion migration can result in the segregation of minerals.

Notice that the dark biotite crystals and light silicate minerals (quartz and feldspar) have separated, giving the rock a banded appearance called gneissic texture**.**

A metamorphic rock with this texture is called *gneiss* (pronounced “nice”).

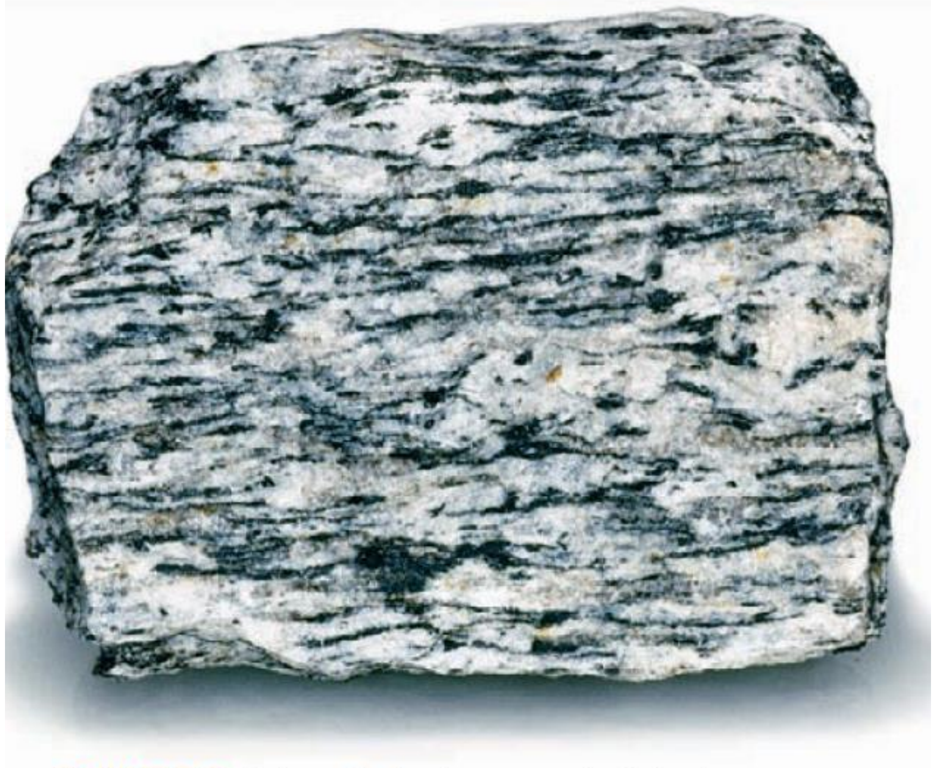


FIGURE 7.9 This rock displays a gneissic texture. Notice that the dark biotite flakes and light silicate minerals are segregated, giving the rock a banded or layered appearance. *(Photo by E. J. Tarbuck)*

Other Metamorphicn Textures

Not all metamorphic rocks exhibit a foliated texture. Those that *do not* are referred to as nonfoliated**.** Nonfoliated metamorphic rocks typically develop in environments where deformation is minimal and the parent rocks are composed of minerals that exhibit equidimensional crystals, such as quartz or calcite.

For example, when a fine-grained limestone (made of calcite) is metamorphosed by the intrusion of a hot magma body, the small calcite grains recrystallize to form larger interlocking crystals. The resulting rock, *marble,* exhibits large, equidimensional grains that are randomly oriented, similar to those in a coarse-grained igneous rock.

Porphyroblastic textures

Another texture common to metamorphic rocks consists of unusually large grains, called *porphyroblasts,* that are surrounded by a fine-grained matrix of other minerals.

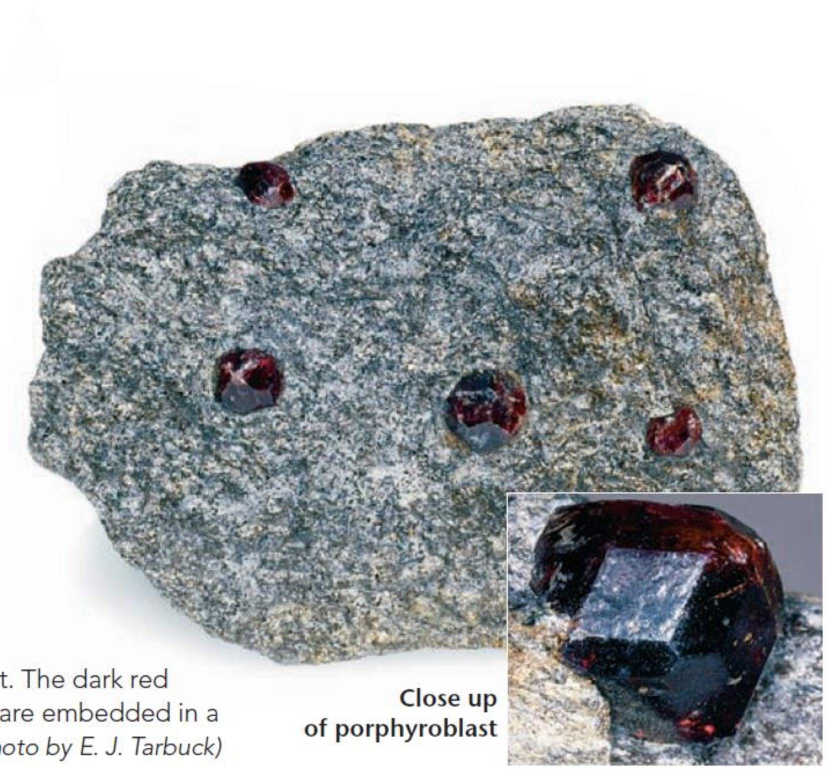


FIGURE 7.10 Garnet-mica schist. The dark red garnet crystals (porphyroblasts) are embedded in a matrix of fine-grained micas. *(Photo by E. J. Tarbuck)*

Common Metamorphic Rocks

- Recall that metamorphism causes many changes in rocks, including increased density, change in grain size, reorientation of mineral grains into a planar arrangement known as foliation, and the transformation of low-temperature minerals into high-temperature minerals.
- Notice that metamorphic rocks can be broadly classified by the type of foliation exhibited and to a lesser extent on the chemical composition of the parent rock.

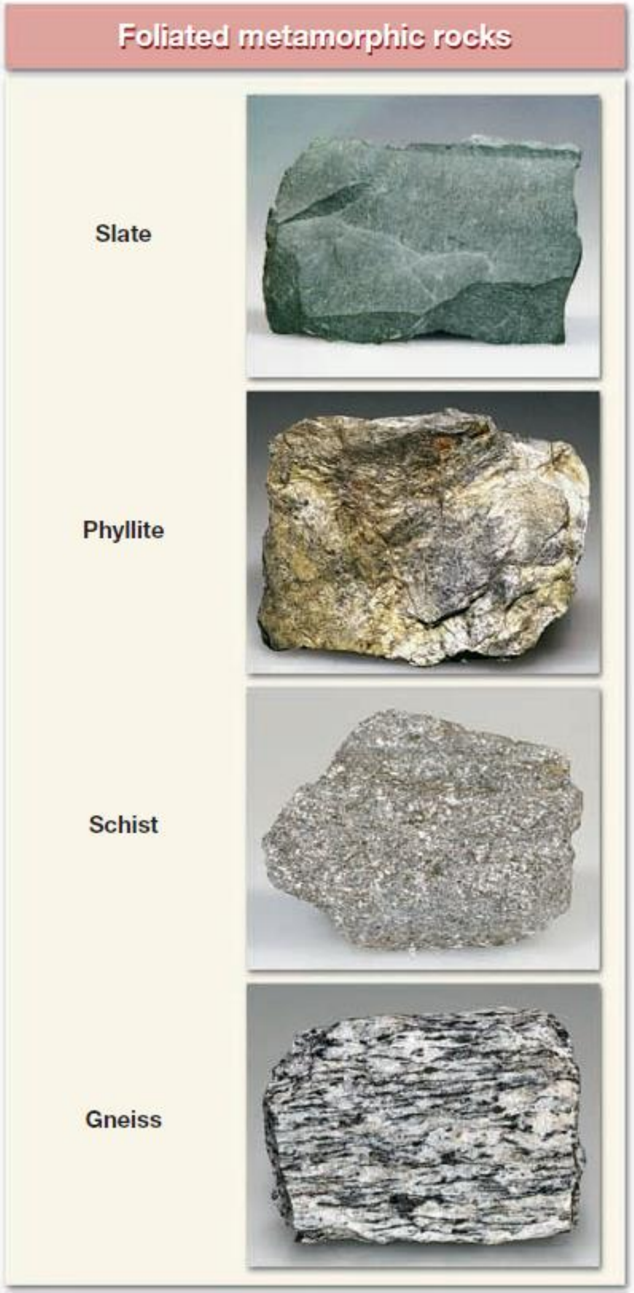
Common Metamorphic Rocks

(Slate → Migmatite: Increasing Metamorphism)

Rock Name	Texture	Grain Size	Comments	Original Parent Rock
Slate	Foliated	Very fine	Excellent rock cleavage, smooth dull surfaces	Shale, mudstone, or siltstone
Phyllite	Foliated	Fine	Breaks along wavy surfaces, glossy sheen	Shale, mudstone, or siltstone
Schist	Foliated	Medium to Coarse	Micaceous minerals dominate, scaly foliation	Shale, mudstone, or siltstone
Gneiss	Foliated	Medium to Coarse	Compositional banding due to segregation of minerals	Shale, granite, or volcanic rocks
Migmatite	Foliated	Medium to Coarse	Banded rock with zones of light-colored crystalline minerals	Shale, granite, or volcanic rocks
Mylonite	Weakly Foliated	Fine	When very fine-grained, resembles chert, often breaks into slabs	Any rock type
Metaconglomerate	Weakly Foliated	Coarse-grained	Stretched pebbles with preferred orientation	Quartz-rich conglomerate
Marble	Nonfoliated	Medium to coarse	Interlocking calcite or dolomite grains	Limestone, dolostone
Quartzite	Nonfoliated	Medium to coarse	Fused quartz grains, massive, very hard	Quartz sandstone
Hornfels	Nonfoliated	Fine	Usually, dark massive rock with dull luster	Any rock type
Anthracite	Nonfoliated	Fine	Shiny black rock that may exhibit conchoidal fracture	Bituminous coal
Fault breccia	Nonfoliated	Medium to very coarse	Broken fragments in a haphazard arrangement	Any rock type

FIGURE 7.11 Classification of common metamorphic rocks.

Foliated Rocks



Nonfoliated Rocks

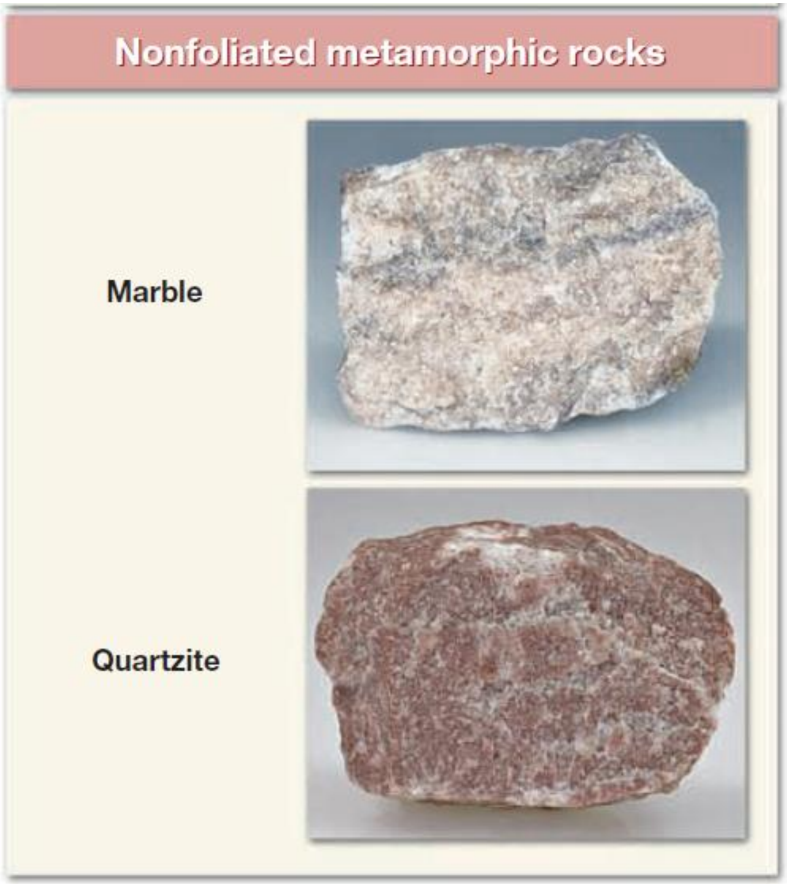


FIGURE 7.12 Common metamorphic rocks.
(Photos by E. J. Tarbuck)

Slate

Slate is most often generated by the low-grade metamorphism of shale, mudstone, or siltstone.

Phyllite

Phyllite represents a gradation in the degree of metamorphism between slate and schist.

Schist

Schists are medium to coarse-grained metamorphic rocks in which platy minerals predominate. These flat components commonly include the micas (muscovite and biotite), which display a planar alignment that gives the rock its foliated texture.

Schist

Gneiss

Gneiss is the term applied to medium- to coarse-grained banded metamorphic rocks in which granular and elongated (as opposed to platy) minerals predominate.

Nonfoliated Rocks

MARBLE

Marble is a coarse, crystalline metamorphic rock whose parent was limestone or dolostone.

Pure marble is white and composed essentially of the mineral calcite.

QUARTZITE

Quartzite is a very hard metamorphic rock formed from quartz sandstone . Under moderate to high-grade metamorphism, the quartz grains in sandstone fuse together.

Metamorphic Environments

- There are many environments in which metamorphism occurs. Most are in the vicinity of plate margins, and several are associated with igneous activity.
- We will consider the following types of metamorphism:

(1) *contact* or *thermal metamorphism;*

(2) *hydrothermal metamorphism;*

(3) *burial and subduction zone metamorphism;*

(4) *regional metamorphism;*

(5) *metamorphism along faults;*

(6) *impact metamorphism*

and with the exception of impact metamorphism, there is considerable overlap among the types.

Contact or Thermal Metamorphism

Contact or thermal metamorphism occurs when rocks immediately surrounding a molten igneous body are “baked” and therefore altered from their original state. The altered rocks occur in a zone called a metamorphic aureole.

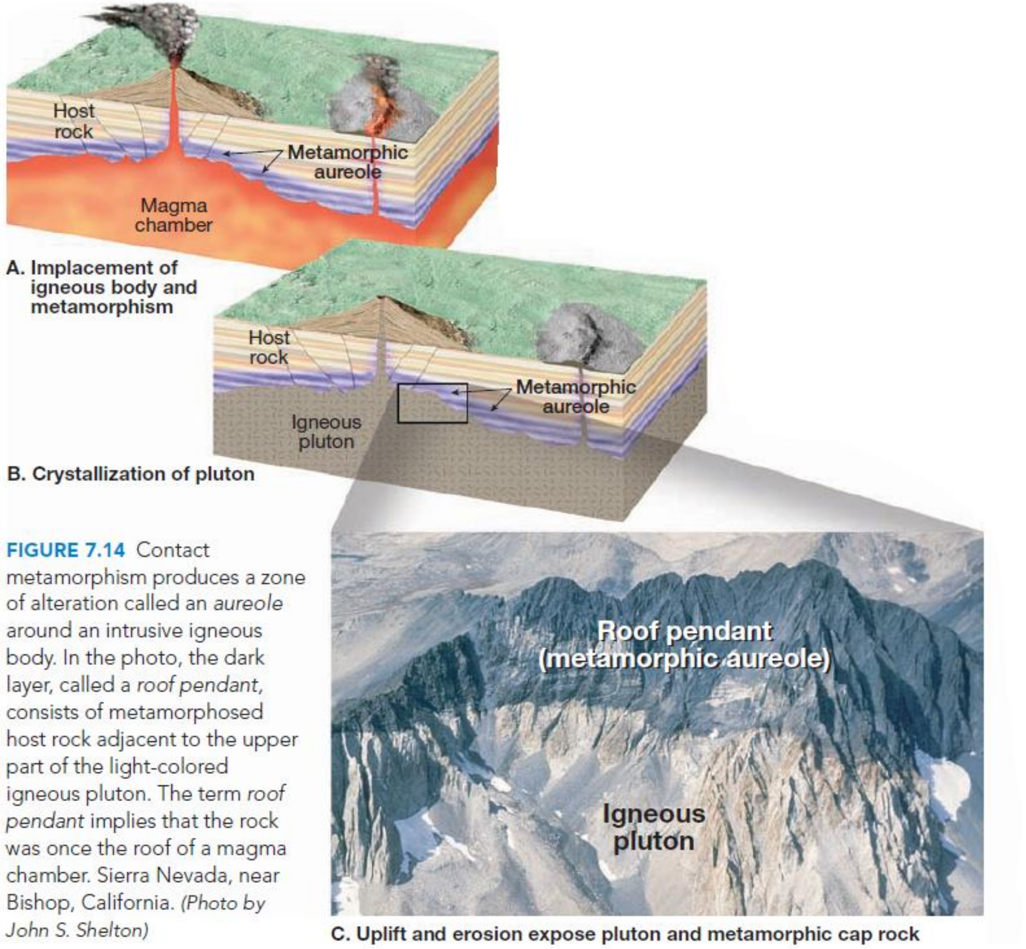


FIGURE 7.14 Contact metamorphism produces a zone of alteration called an *aureole* around an intrusive igneous body. In the photo, the dark layer, called a *roof pendant*, consists of metamorphosed host rock adjacent to the upper part of the light-colored igneous pluton. The term *roof pendant* implies that the rock was once the roof of a magma chamber. Sierra Nevada, near Bishop, California. *(Photo by John S. Shelton)*

Contact or Thermal Metamorphism

During contact metamorphism of mudstones and shales, the clay minerals are baked as if placed in a kiln. The result is a very hard, fine-grained metamorphic rock called *hornfels.*

Hornfels can form from a variety of materials including volcanic ash and basalt.

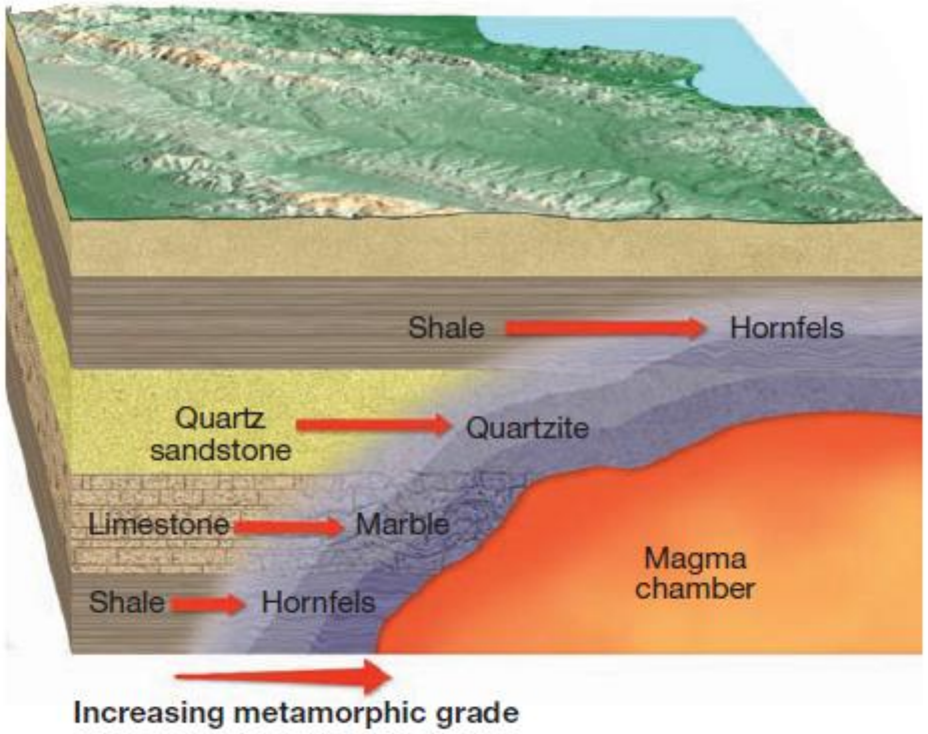


FIGURE 7.15 Contact metamorphism of shale yields hornfels, while contact metamorphism of quartz sandstone and limestone produces quartzite and marble, respectively.

Hydrothermal Metamorphism

When hot, ion-rich fluids circulate through fissures and cracks in rock, a chemical alteration called hydrothermal metamorphism occurs

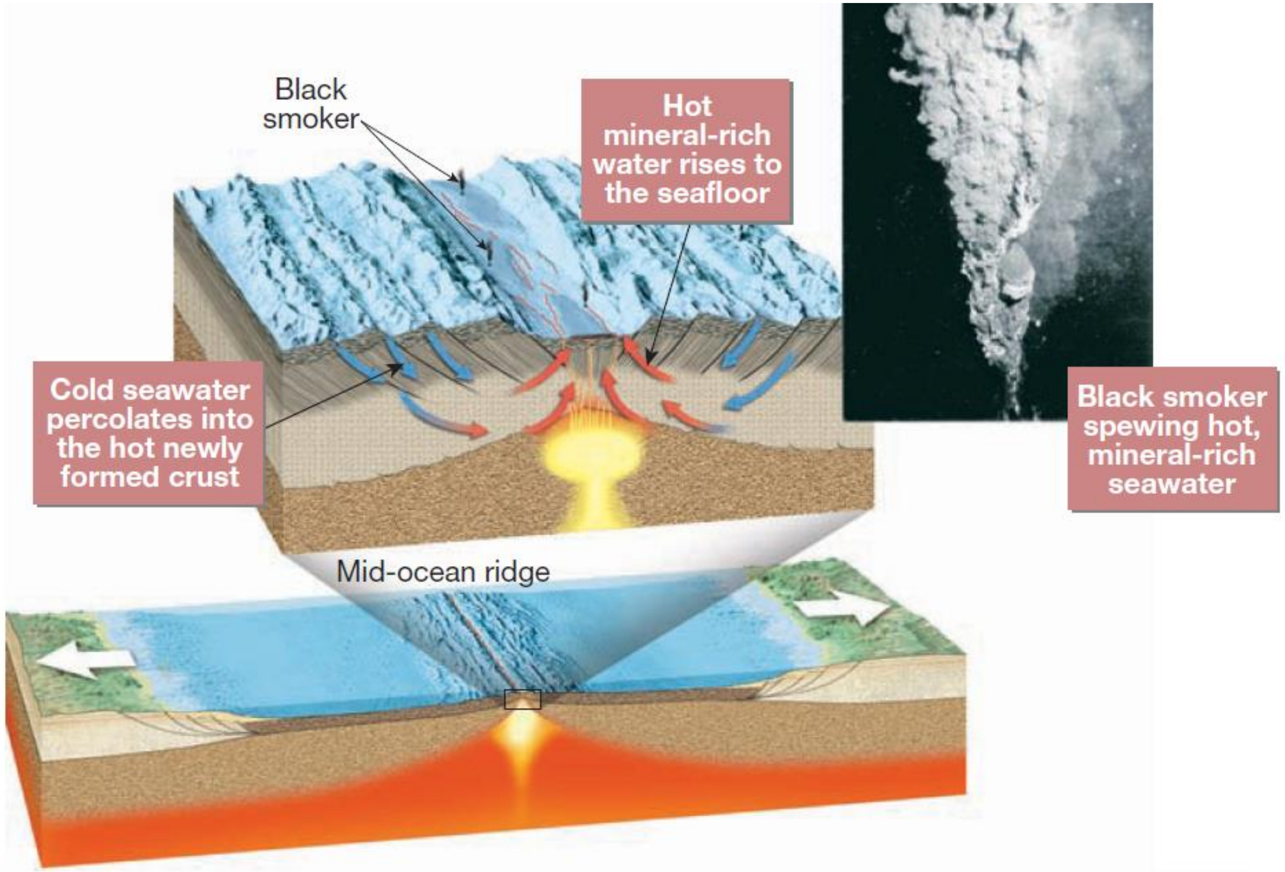


FIGURE 7.17 Hydrothermal metamorphism along a mid-ocean ridge. *(Photo by R. Ballard/Woods Hole)*

Burial and Subduction Zone Metamorphism

Burial metamorphism tends to occur where massive amounts of sedimentary or volcanic material accumulates in a subsiding basin.

Here, low-grade metamorphic conditions may be attained within the deepest layers. Confining pressure and geothermal heat drive the recrystallization of the constituent minerals— changing the texture and/or mineral content of the rock without appreciable deformation.

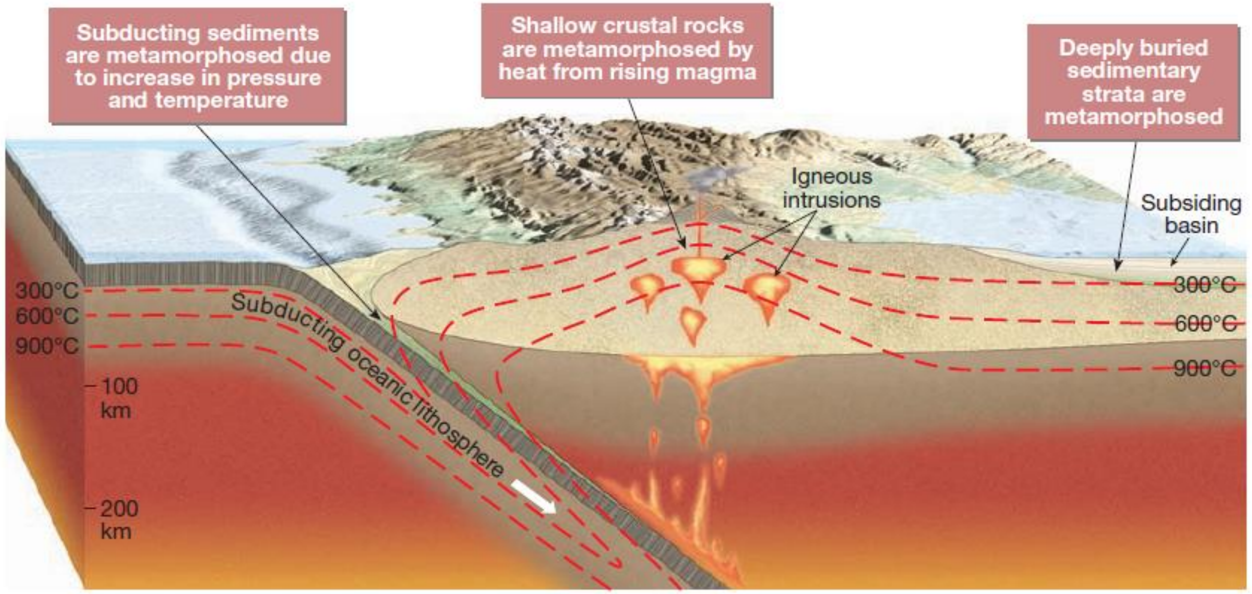


FIGURE 7.2 The geothermal gradient and its role in metamorphism. Notice how the geothermal gradient is lowered by the subduction of relatively cool oceanic lithosphere. By contrast, thermal heating is evident where magma intrudes the upper crust.

Regional Metamorphism

Most metamorphic rock is produced by regional metamorphism during mountain building when large segments of Earth's crust are intensely deformed along convergent plate boundaries.

This activity occurs most often during continental collisions.

Sediments and crustal rocks that form the margins of the colliding continental blocks are folded and faulted, causing them to shorten and thicken like a rumpled carpet

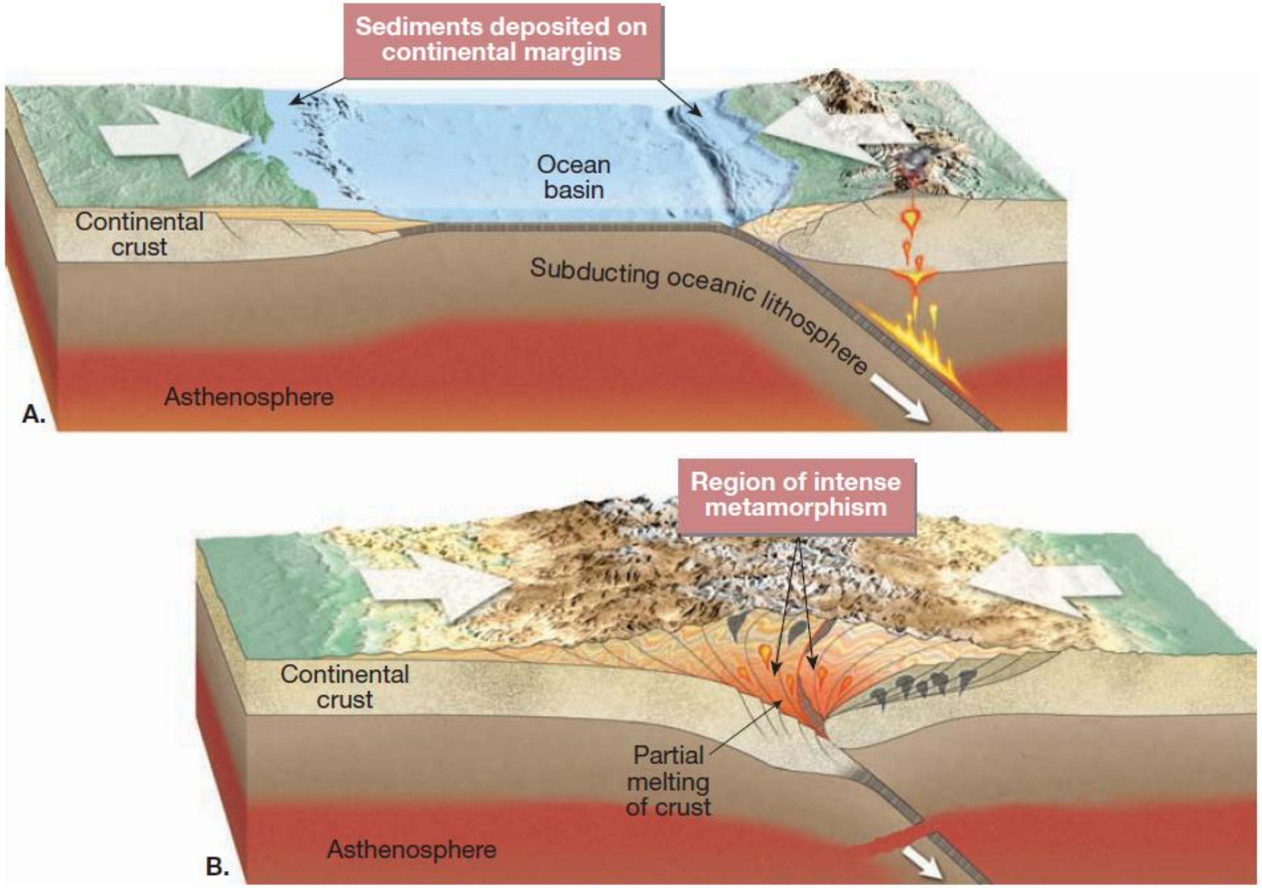


FIGURE 7.18 Regional metamorphism occurs where rocks are squeezed between two converging lithospheric plates during mountain building.

Metamorphism along Fault Zones

Near the surface, rock behaves like a brittle solid. Consequently, movement along a fault zone fractures and pulverizes rock.

The result is a loosely coherent rock called *fault breccia* that is composed of broken and crushed rock fragments.

Deformation associated with fault zones occurs at great depth and thus at high temperatures. In this environment preexisting minerals deform by ductile flow. As large slabs of rock move in opposite directions, the minerals in the fault zone between them tend to form elongated grains that give the rock a foliated or lineated appearance .

Rocks formed in these zones of intense ductile deformation are termed *mylonites* (*mylo* = a mill, *ite* = a stone).

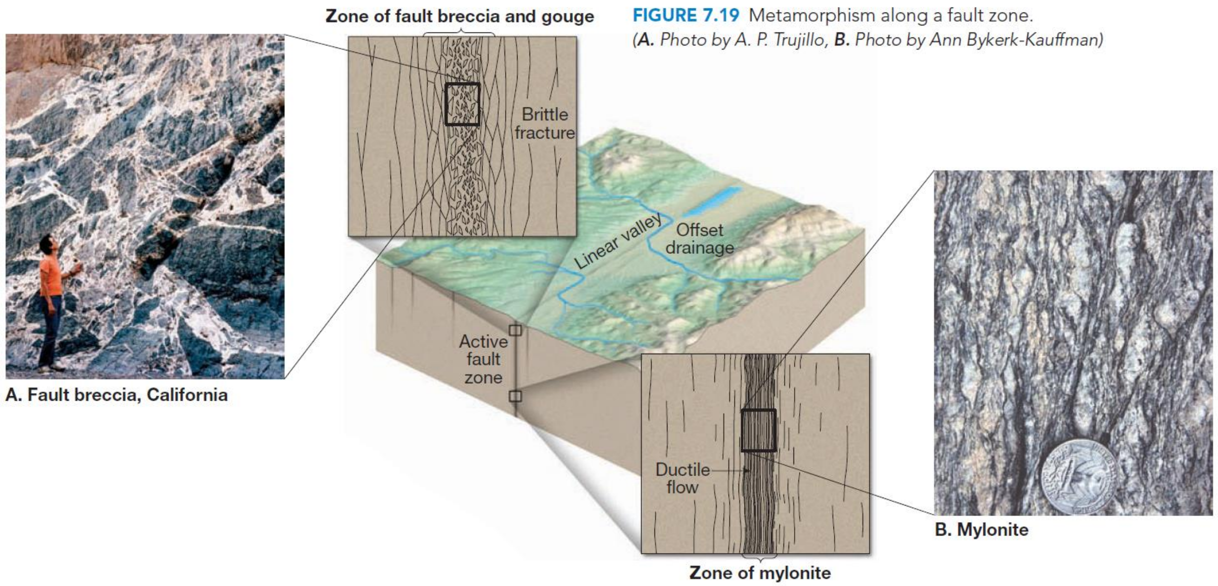


FIGURE 7.19 Metamorphism along a fault zone. (*A.* Photo by A. P. Trujillo, *B.* Photo by Ann Bykerk-Kauffman)

Impact Metamorphism

- Impact (or shock) metamorphism occurs when high-speed projectiles called *meteorites* (fragments of comets or asteroids) strike Earth's surface.
- Upon impact the energy of the once rapidly moving meteorite is transformed into heat energy and shock waves that pass through the surrounding rocks.
- The result is pulverized, shattered, and sometimes melted rock.

Metamorphic Zones

Textural Variations

When we begin with a clay-rich sedimentary rock such as shale or mudstone, a gradual

increase in metamorphic intensity is accompanied by a general coarsening of the grain size.

Thus, we observe shale changing to a fine-grained slate, which then forms phyllite and, through continued recrystallization, generates a coarse-grained schist.

Under more intense conditions a gneissic texture that exhibits layers of dark and light minerals may develop.

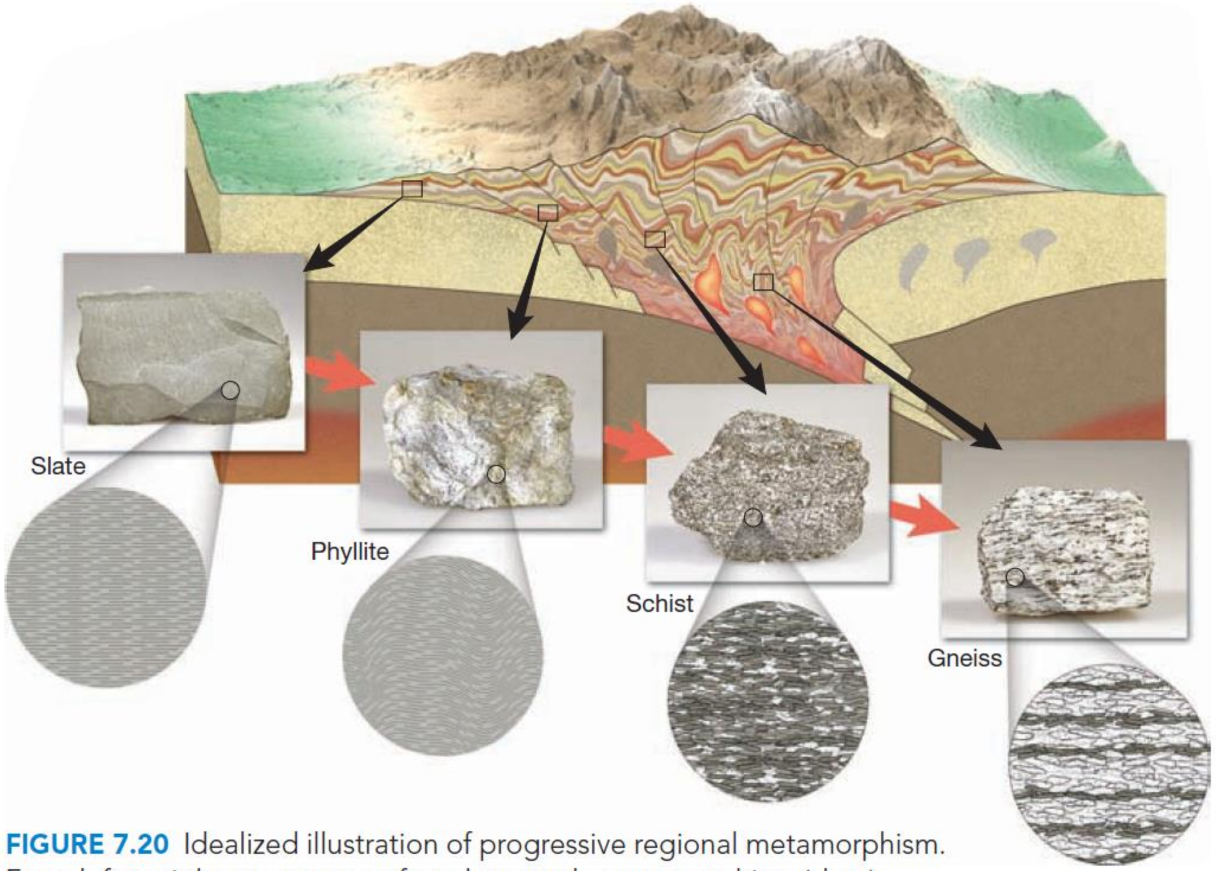


FIGURE 7.20 Idealized illustration of progressive regional metamorphism. From left to right, we progress from low-grade metamorphism (slate) to high-grade metamorphism (gneiss). *(Photos by E. J. Tarbuck)*

Metamorphic Zones

Index Minerals and Metamorphic Grade

Changes in mineral content as we shift from regions of low-grade metamorphism to regions of high-grade metamorphism. An idealized transition in mineralogy that results from the regional metamorphism of shale.

The first new mineral to form as shale changes to slate is chlorite. At higher temperatures flakes of muscovite and biotite begin to dominate. Under more extreme conditions, metamorphic rocks may contain garnet and staurolite crystals. At temperatures approaching the melting point of rock, sillimanite forms.

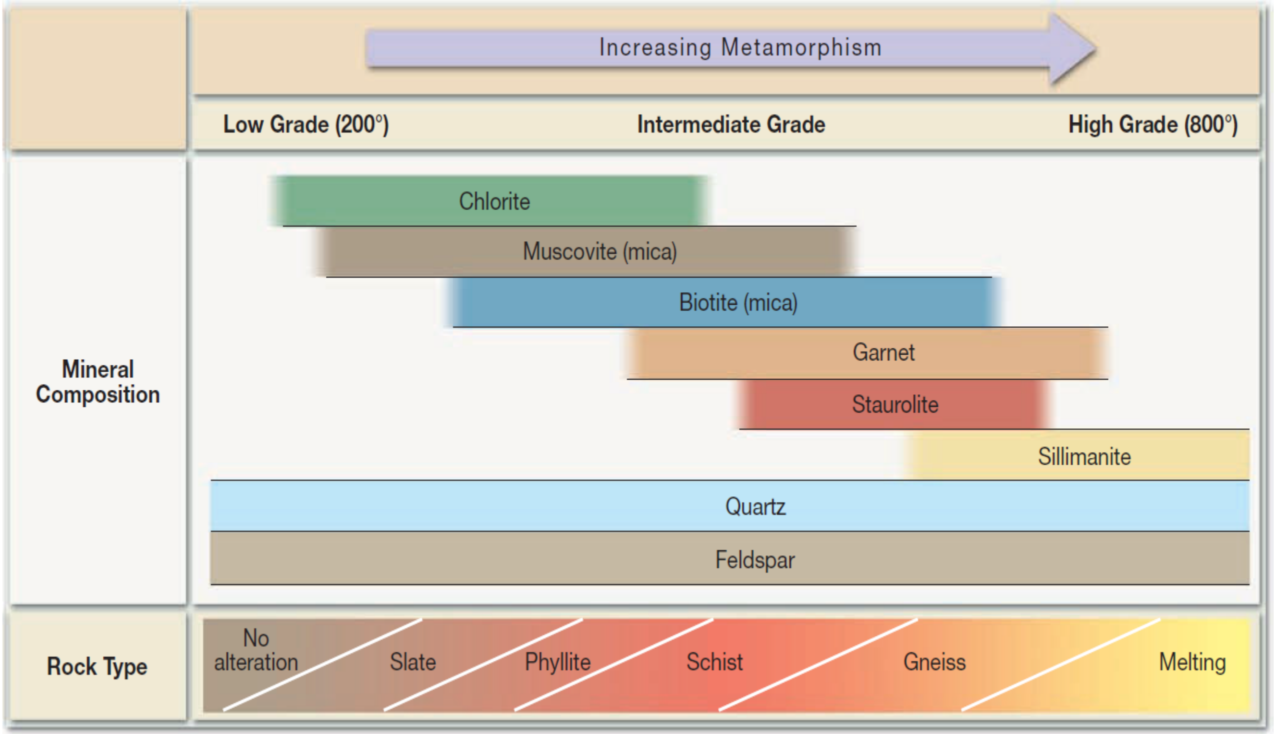


FIGURE 7.21 The typical transition in mineral content that results from the progressive metamorphism of shale.