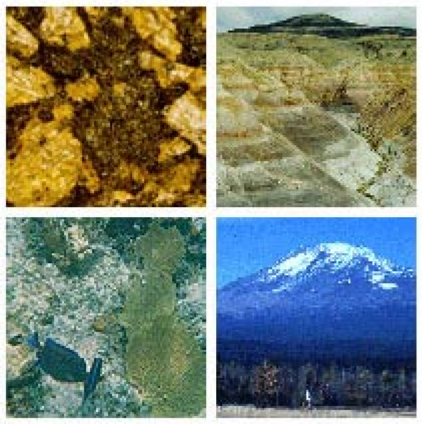
Rocks & Minerals



> This curious world we inhabit is more wonderful than convenient; more beautiful than it is useful; it is more to be admired and enjoyed than used.
>
> Henry David Thoreau

> My words are tied in one, with the great mountains, with the great rocks, with the great trees, in one with my body, and my heart.
>
> Yokuts Indian Prayer

Introduction

- Understanding the composition of rocks on other planets provides clues to the geologic development of those planets.
- Rocks analyzed during NASA's Pathfinder expedition to Mars were found to be similar to common rocks on Earth.

When NASA's Pathfinder spacecraft landed on **Mars** on July 4, 1997, it released a "rover," a small vehicle called Sojourner (Fig. 1). Sojourner spent the next few days getting up close and personal with several big rocks around the landing site. Why travel 100,000,000 miles to look at rocks? Scientists knew that the best way to learn about Mars was to understand its most basic components, the rocks that made up the planet. The rocks, and the minerals they contain, provided clues to the evolution of Mars.

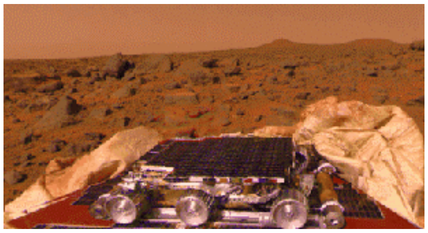


Figure 1. View of Mars from Pathfinder lander and landing site with "Twin Peaks" on horizon. Rover vehicle is in foreground of the picture. Image from NASA's Planetary Photojournal.

Scientists were surprised to learn that the first rock they analyzed, nicknamed Barnacle Bill, contained many of the same minerals that were common on Earth. The rock composition was similar to **andesite**, a rock formed by volcanic activity. Andesite on Mars was an unexpected find as volcanoes are rare on the red planet. The composition of other samples (Fig. 2) confirmed the resemblance with other volcanic rocks on Earth and scientists began to rethink their view of Mars' origins.

The boulder-studded landing site was interpreted as the site of catastrophic floods. Other features suggested later modification by wind action. The compositions of soil and rocks at the landing site are chemically distinct, suggesting the rocks were transported into the area from another location.

Figure 2. Yogi, one of the rocks analyzed during the Mars exploration was found to have a composition closer to basalt than andesite - both are volcanic rocks. Image from NASA's Planetary Photojournal.

Rocks on the Earth may be composed of hundreds of possible minerals but only 20 to 30 minerals are common in the majority of rocks. Minerals are made up of combinations of nearly a hundred different elements, yet only eight elements make up over 98% of the Earth's crust. Atoms represent the basic building blocks of the elements and the next section of the chapter, **Atoms and Elements**, discusses how atoms of different elements combine to form minerals. The same mineral found in different parts of the world, will always look the same and will have a consistent chemical composition. Minerals can be identified in rocks by a variety of features described in the **Minerals** section of the chapter, including crystal form, cleavage, hardness, color, and luster.

Rocks are classified into three distinct groups - igneous, sedimentary, and metamorphic - and each is discussed in a separate section. Each rock group is further subdivided into subgroups that are defined by the mode of origin of the rocks. **Igneous rocks** form when magma, molten rock, rises upward toward the surface and are classified into two types on the basis of texture (grain size) and composition. **Metamorphic rocks** form when changes in the composition and/or texture of a rock occur as a result of increasing pressure or temperature but stop short of melting minerals. Two groups of metamorphic rocks can be identified based upon the presence or absence of a specific texture (foliation) in the rocks. **Sedimentary rocks**, the most common rocks on the Earth's surface, are readily identified by the presence of layers (beds). Although layering is sometimes present in igneous and metamorphic rocks, it is much more common in sedimentary rocks.

Most sedimentary rocks are deposited under water so the presence of layering in rocks is often taken as an indication of ancient oceans or lakes. On Earth the boundary between ocean and continent is represented by a global shoreline. Broad expanses of the ocean floor are characterized by flat surfaces, unmarked by the erosion that generates the irregular land surfaces above sea level. Recent maps of the martian surface from data generated by NASA's **Mars Global Surveyor** (MGS) spacecraft show a large low region around the planet's north pole that is much flatter and smoother than the surrounding terrain. Early interpretations that this may be the floor of an **ancient ocean** are bolstered by the presence of a level surface that rings the region, perhaps the remnants of an ancient coastline. More detailed analyses of images from the MGS have cast doubt on the existence of the shoreline but have

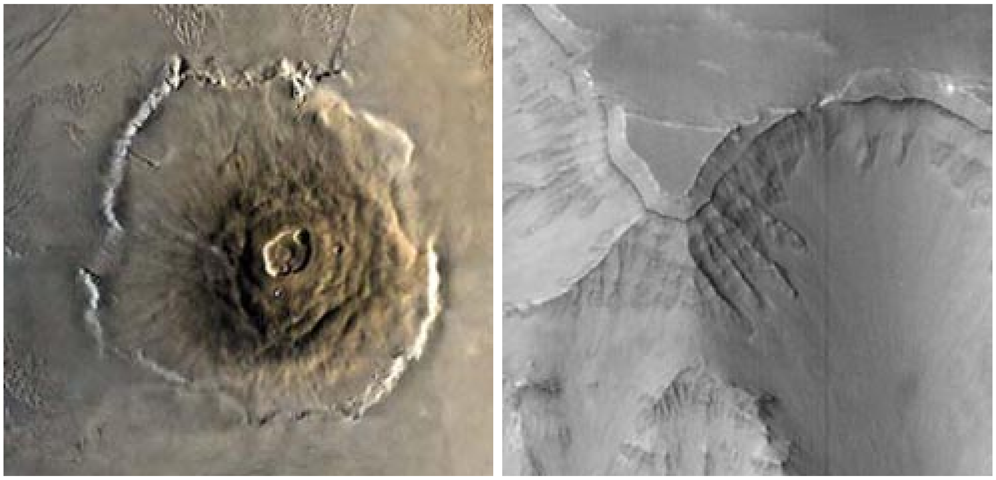


Figure 3. Left: Olympus Mons, the largest volcano in the solar system, is 27 km high and covers an area approximately the size of Arizona. It is part of a volcanic field that produced huge amounts of lava, gases, and water vapor. The release of great volumes of gases such as carbon dioxide and water vapor would have altered the martian climate and may have provided the source for surface streams and oceans. Right: Part of the Valles Marinaris (the "Grand Canyon" of Mars) showing indications of layering perhaps indicating the presence of sedimentary rocks or volcanic flows. Images courtesy of NASA's Observatorium Gallery.

revealed numerous sites characterized by **layered rocks** (Fig. 3). Elsewhere there are deep channels and networks of dry valleys, tantalizing clues that there may have once been water on Mars. Equivalent layers on Earth contain fossil evidence of past life. The great age (3.5 billion years old) of the Martian rocks probably rules out the prospect that fossils will be found, but if there is any evidence of primitive life on the red planet it is most likely in these layers. Missions to Mars by the European Space Agency and NASA in the next few years will provide further information on the presence of water and the complex organic molecules necessary for life.

We tie the three major rock groups together in the **Rock Cycle**, a simplified view of the formation of different rocks to illustrate the potential interaction between rock types. The chapter ends with a discussion of the geologic processes associated with the concentration of mineral resources. Geologists are not just interested in using rock types to understand the geologic history of a region. It is also important to understand the distribution of rocks and minerals for practical applications. Mineral resources include nonfood, nonfuel materials such as metals (e.g., aluminum, gold) and industrial minerals (e.g., gypsum, phosphate). Mineral resources become concentrated in Earth's crust as a result of specific geologic processes associated with the formation of rocks. Exploration for minerals requires that geologists recognize the telltale evidence that signals the presence of useful mineral deposits. The section on the **Geology of Mineral Resources** describes the geologic associations that are characteristic of some of the more common mineral deposits.

Think about it . . .

1. Where is the nearest outcrop of bedrock?
2. Where is the nearest example of a rock that is not part of the local bedrock?
3. Give three examples of how minerals and/or rocks are used in your daily life?

Atoms & Elements

- Rocks are made up of minerals.
- Minerals are composed of elements.
- Elements can be separated into atoms.
- Atoms are composed of protons, neutrons, and electrons.
- Each element has a unique atomic number that represents the number of protons in its nucleus.
- Elements in the foods we eat originate in the rocks of Earth's crust.

Rocks are generally composed of an assemblage of minerals. For example, the andesite from Mars contains quartz, feldspar, amphibole, and other minerals.

Minerals can be divided into their constituent elements. The mineral quartz is composed of two elements, silicon and oxygen. Other minerals may contain many elements. For example, the mineral amphibole is made up of a laundry list of elements including sodium, calcium, magnesium, iron, aluminum, silicon, and oxygen.

Elements are the last stop; they cannot be further divided into other materials but they can be separated into individual atoms. An **atom** is the smallest particle of an element that retains the characteristics of the element. All atoms are composed of **neutrons, protons, and electrons**. The protons and neutrons are present in the atom’s nucleus that is surrounded by electrons.

The number of protons in an atom is unique for each element and represents the element's **atomic number**. For example, oxygen has 8 protons, silicon has 14 (Fig. 4). Protons have a positive charge that is balanced by the negatively charged electrons. Neutrons are neutral, they have no charge.

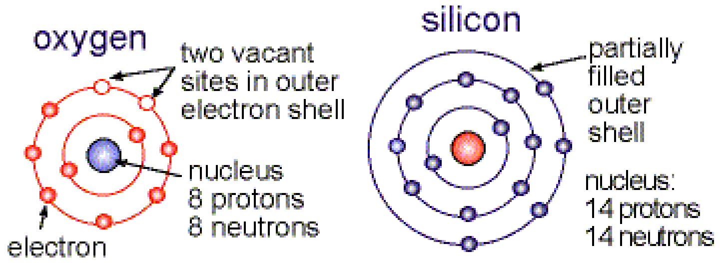


Figure 4. Oxygen (left), atomic number = 8, has 8 protons; silicon (right), atomic number = 14, has 14 protons.

Electrons are located in a series of "**shells**" around the nucleus. Different shells hold different numbers of electrons. The two innermost shells hold two and eight electrons respectively. Outer shells can hold more electrons but are considered stable when they contain eight electrons. The number of electrons should ideally equal the number of protons. However, atoms may lose or gain electrons to reach a configuration with a stable outer shell. This results in the formation of a negatively or positively charged atom known as an **ion**.

Ions may be either positive (**cation**) where an atom has lost electrons, or negative (**anion**) where an atom has gained electrons. Anions may form where an atom with a nearly full outer shell gains electrons. Oxygen atoms will add two electrons to complete its outer shell (Fig. 5); oxygen ions therefore have two negative charges (O^{2-}). The silicon atom's 14 protons are balanced with an equal number of electrons. However, silicon forms a cation (Si^{4+}) due to the loss of four electrons in its outer shell (Fig. 5).

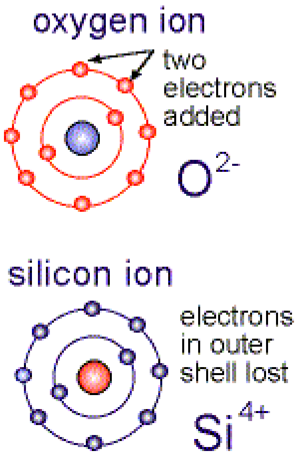


Figure 5. Oxygen and silicon ions with negative and positive charges, respectively. The oxygen anion has gained two electrons whereas the silicon cation has lost four electrons.

Ions of individual elements combine together to form mineral compounds by **chemical bonding**. Bonds form when elements balance each other's electrical charge (**ionic bonds**) or share electrons (**covalent bonds**). Ionic bonding occurs because of electrical attraction between oppositely charge ions (proving again that opposites attract).

Water (H_2O, Fig. 6) is formed by covalent bonding of hydrogen (H) and oxygen (O) when two hydrogen ions (H^{1+})

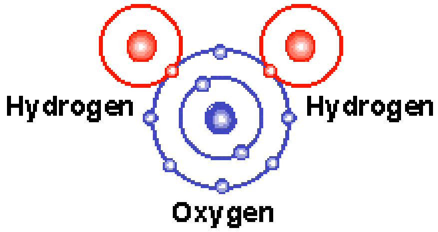


Figure 6. Hydrogen and oxygen atoms share two electrons by covalent bonding to form water. (And yes, we know it looks like Mickey Mouse).

share electrons with an oxygen ion (O^{2-}). Covalent bonds are typically stronger than ionic bonds. For example, **quartz**, formed by covalent bonding between silicon and oxygen, is one of the most resistant common minerals and **diamond**, the hardest mineral, is formed by covalent bonding between carbon atoms.

Rocks and Breakfast Cereal

Although at first they may appear to have nothing in common, a bowl of breakfast cereal and a pile of rocks share common elements. Rocks and breakfast cereal represent components of a **geochemical cycle** that begins when elements are naturally extracted from rocks as minerals break down at Earth's surface to form soil. The elements are absorbed by crops growing in the soils and may find their way to us in the foods we eat. The continental crust, the rock below our feet, contains 88 naturally occurring elements but only 8 make up over 98% of the crust by weight. Many of these are essential for human health.

Most Common Elements in Continental Crust

Element	Ion	% by weight
Oxygen (O)	O^{2-}	46.6
Silicon (Si)	Si^{4+}	27.7
Aluminum (Al)	Al^{3+}	8.1
Iron (Fe)	Fe^{2+}, Fe^{3+}	5.0
Calcium (Ca)	Ca^{2+}	3.6
Sodium (Na)	Na^{+}	2.8
Potassium (K)	K^{+}	2.6
Magnesium (Mg)	Mg^{2+}	2.1
Other	-	1.5

Specific elements may be added to the food we eat or the water we drink to promote good health:

- **Fluorine** is added to municipal drinking water and toothpaste to prevent tooth decay.
- **Calcium** supplements in foods such as milk and orange juice prevent bone disease.
- Iodized salt contains **iodine** needed to regulate thyroid gland activity.

Not all elements are beneficial. Elements that promote good health in low concentrations may cause harm if those concentrations are increased. Even when measured in parts per million, some elements can be harmful to humans or the natural environment:

- Legislation has removed **lead** from gasoline and paint because it was shown to harm the human nervous system and cause mental retardation in children
- High concentrations of **selenium** at the Kesterson Wildlife Refuge, California, produced deformities in birds
- **Mercury** poisoning affects the human nervous system.

Elements may enter the environment as a result of human actions (agriculture, waste disposal, mining, pollution) or from natural processes (weathering of rocks and minerals). Their passage through the environment makes up a geochemical cycle that may ultimately take millions of years to complete.

Think about it . . .

1. The atomic number of carbon is six. How many protons are present in the nucleus and how many electrons are in the atom's outer shell?
2. Four elements and their atomic numbers are listed below. Which has a stable atomic configuration?
   a) Hydrogen (1)
   b) Neon (10)
   c) Magnesium (12)
   d) Calcium (20)
3. Calcium's atomic number is 20: Will it form an anion or cation?
4. Rock salt is formed by ionic bonding between Sodium (Na, atomic number 11) and chlorine (Cl, atomic number 17). What is the chemical formula for rock salt?

Minerals

- Silicon and oxygen are the most common constituents in most common minerals known as silicates.
- Positive and negative charges of cations and anions must cancel out for elements to combine to form minerals.
- A mineral is a naturally occurring, inorganic solid, with a definite chemical composition and uniform atomic structure, and is made up of elements.
- Minerals can be identified on the basis of features such as cleavage, color, hardness, and luster.

Figure 7. Quartz crystals form prisms; columns with pyramids at either end.

Elements combine to form thousands of **minerals**, mercifully there are relatively few minerals (~20) that are present in most rocks. Minerals share some key characteristics:

- Naturally occurring - not formed in a lab
- Inorganic - not formed by organisms
- A solid - not a liquid or gas
- Definite chemical composition – consistent chemical formula
- Uniform atomic structure – a three dimensional organization of atoms
- Made up of one or more elements

The most common minerals are composed of the most common elements. Silicon and oxygen make up over 70% of the continental crust by weight so it stands to reason that these elements would be present in many minerals. Minerals that contain both silicon and oxygen are known as **silicates**.

Just as we can use similar bricks to build many different structures, these basic building blocks, silicon and oxygen, can be joined together in a variety of ways in combination with other elements to form different silicate minerals such as quartz (Fig. 7) and feldspar.

Mineral Characteristics

Although there are thousands of minerals in Earth, there are only about 20 common minerals. The same mineral found in different parts of the world will always look the same and will have a characteristic crystal form and a consistent chemical formula. Minerals can be identified in rocks by a process of elimination. A variety of features can be used to identify specific minerals. Some of the most common are listed below.

Crystal Form

Minerals form crystals with specific shapes (Fig. 8) when they have been able to grow without obstruction. Common shapes

Figure 8. A range of crystal shapes including pyramid (calcite, left) and acicular (needle-like, tourmaline, right).

are prisms, pyramids, needles, cubes, and sheets.

Cleavage

Minerals break along specific planes of weakness related to their atomic structure (Fig. 9). Amphibole's cleavage planes intersect at 120 degrees; pyroxene has a distinctive 90 degree cleavage intersection. Quartz has no cleavage planes but fractures irregularly.

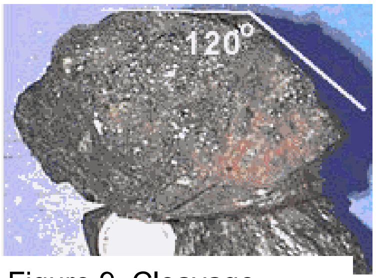


Figure 9. Cleavage planes in amphibole intersect at an angle of 120 degrees.

Moh's Hardness Scale

Minerals are ranked from 1 to 10 based upon their relative hardness (Fig. 10). Harder minerals can scratch softer minerals. Ten index minerals make up Moh's scale and other minerals are ranked relative to these. For example, a mineral that could scratch feldspar but not quartz would have a hardness of approximately 6.5.

	Moh's Hardness Scale	
Softest	1	Talc
	2	Gypsum
	3	Calcite
	4	Fluorite
	5	Apatite
	6	Feldspar
	7	Quartz
	8	Topaz
	9	Corundum
Hardest	10	Diamond

Figure 10. Corundum ranks 9th on Moh's hardness scale

Color

Minerals come in a variety of colors (Fig. 11). Examples of common dark-colored minerals (black, dark brown, dark green) are amphibole, olivine, pyroxene, biotite mica. Light-colored minerals (white, pink, gray, translucent) are represented by quartz, feldspar (orthoclase, plagioclase), muscovite mica, gypsum, halite, calcite. However, we must be careful in using color to identify minerals because some minerals can be found in a wide range of colors.

Figure 11. Brightly colored Azurite (blue) and malachite (green).

Luster

Characteristics of light reflected from mineral is luster (Fig. 12). Types of luster include earthy, silky, glassy, and metallic.

Figure 12. Metallic luster of galena.

Figure 13. Brown streak on white porcelain streak plate from metallic iron mineral hematite.

Streak

Minerals will leave a mark when pulled across an unglazed porcelain streak plate (Fig. 13). The streak represents the mineral in powdered form and is often constant even when mineral color changes. This property is most useful for metallic minerals that leave a dark-colored streak.

Other

Calcite reacts (bubbles) with weak acids (Fig. 14); halite (rock salt) has a salty taste.

Figure 14. Left: Calcite and dropper prior to addition of acid. Right: Reaction of calcite and weak hydrochloric acid.

Think about it . . .

Finish the partially completed concept map for minerals found at the end of the chapter. Fill in the blanks with appropriate terms.

Igneous Rocks

- Magma is molten rock below Earth's surface.
- Volcanic (extrusive) igneous rocks form when magma solidifies on Earth's surface.

- Plutonic (intrusive) igneous rocks form when magma solidifies below the surface.
- Volcanic and plutonic rocks can be identified on the basis of texture.
- The composition of igneous rocks varies with silica content.
- Silica-rich rocks contain the minerals quartz, feldspar, mica, and amphibole.
- Silica-poor rocks do not contain quartz but feldspar, olivine, and pyroxene are relatively common.

Rocks can be subdivided into three principal types: igneous rocks, sedimentary rocks, and metamorphic rocks. This section will examine what happens when **magma**, molten rock, solidifies on or below Earth's surface to form igneous rocks. Igneous rocks are subdivided on the basis of whether they formed on Earth's surface or within Earth's interior.

- **Volcanic (extrusive) igneous rocks** form when molten rock (magma) in Earth's interior rises to the surface through pipes or fractures in the crust. Volcanic landforms are the most readily recognized representation of igneous rocks (Fig. 15).
- **Plutonic (intrusive) igneous rocks** form when magma cools within Earth. Igneous rocks that cool below Earth's surface are termed plutonic (or intrusive) igneous rocks. The features they form are **plutons** (or intrusions). These features remain hidden from sight until erosion removes the overlying rocks (Fig. 15). The characteristics of the intrusions are largely controlled by the volume of magma involved and the character of the surrounding rocks. Magma moving within Earth's crust will often follow the path of least resistance such as fractures.

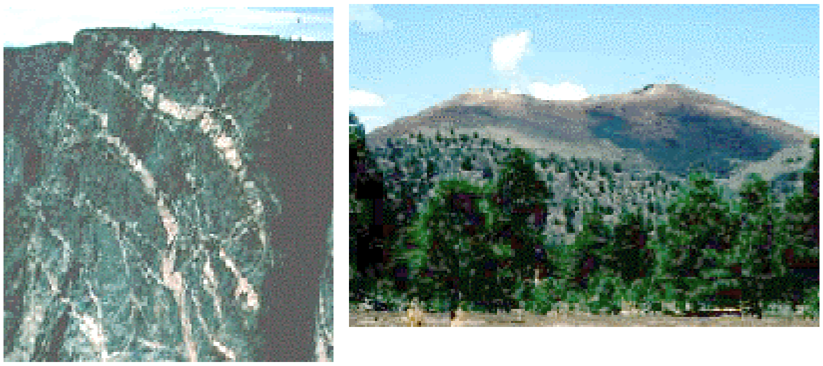


Figure 15. Left: Multiple plutons (intrusions - light rock) in the Black Canyon of the Gunnison river, Colorado. Right: Sunset Crater, northern Arizona, a small volcano.

Magma and the Classification of Igneous Rocks

Igneous activity occurs when magma rises toward the surface through pipes and fissures (fractures) in Earth's crust. The three major types of magma (**basalt magma**, **andesite magma**, and **rhyolite magma**) solidify to form volcanic rocks of the same name on the surface. Igneous rocks can be classified on the basis of texture (volcanic vs. plutonic) and composition (basalt vs. andesite vs. rhyolite).

Plutonic rocks can be distinguished from volcanic rocks by **texture** (Fig. 16). Texture is most readily apparent as **grain size**. Hot magmas (700-1,200^{o}C) cool rapidly on Earth's surface and more slowly below the surface. Individual mineral grains (crystals) do not have much time to grow when magma cools rapidly. Consequently, grain sizes in all volcanic rocks are small, too small to be seen with the naked eye.

In contrast, plutonic rocks cooled slowly under relatively warm conditions and the mineral grains had sufficient time to grow large. Individual grains can be readily seen in specimens of plutonic rocks (see close up of granite or gabbro). Plutonic rocks equivalent to basalt, andesite, and rhyolite, are **gabbro**, **diorite**, and **granite**, respectively. Keep in mind that the same minerals are present in both volcanic and plutonic igneous rocks formed from the same magma.

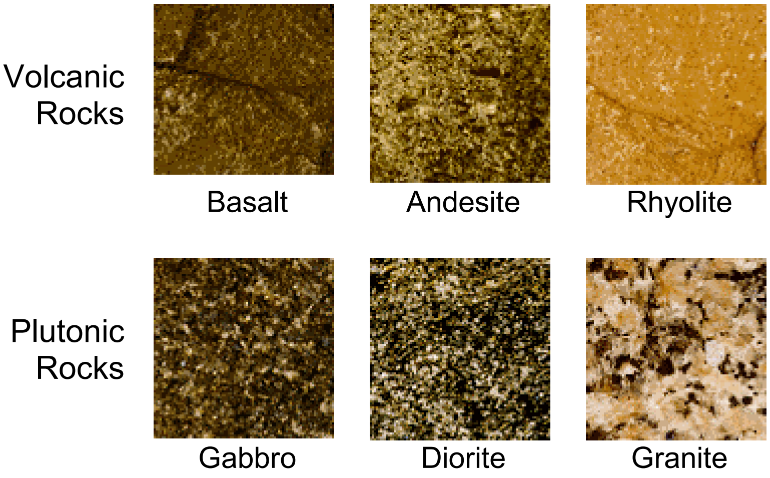


Figure 16. Principal forms of igneous rocks.

Magma that rises to the surface in stages may contain two discrete grain sizes and this texture is termed a **porphyry**. Large grains form initially at depth but are surrounded by a fine-grained matrix formed when the remainder of the magma cools near the surface. Magma that cools very rapidly on the surface (e.g., in the presence of water) forms a glassy textured rock, **obsidian**.

Silica Content	Volcanic Rocks	Plutonic Rocks
High	Rhyolite	Granite
Intermediate	Andesite	Diorite
Low	Basalt	Gabbro

The composition of the magma can be determined by the assemblage of minerals present in the rock (Figs. 16, 17). Light-colored igneous rocks are formed from silica-rich magmas (rhyolite, granite) and contain abundant (~80%) white, pink, or translucent minerals such as quartz and feldspar. In contrast, silica-poor rocks (basalt, gabbro) are dominated by olivine, pyroxene, and biotite mica, all dark-colored minerals (black, brown, dark green). Rocks of intermediate composition lie somewhere between the light and dark rocks depending upon the minerals present.

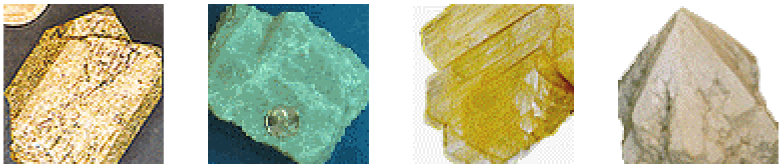
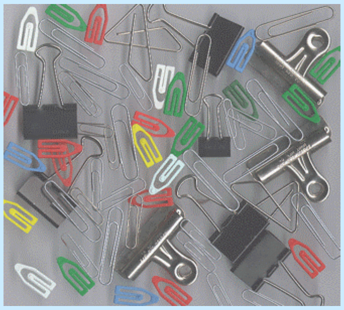


Figure 17. Minerals in light-colored silica-rich igneous rocks such as granite and rhyolite. From left to right, orthoclase feldspar, plagioclase feldspar, muscovite mica, milky quartz.

Think about it . . .

1. Is there any significant difference in the way we classify igneous rocks and the objects in the image below?



2. Finish the partially completed concept map for igneous rocks found at the end of the chapter. Fill in the blanks with appropriate terms.

Sedimentary Rocks

- Sedimentary rocks form as layers known as beds.
- Clastic sedimentary rocks are formed from fragments of rocks and minerals.
- Chemical sedimentary rocks are precipitated from solutions.
- Biochemical sedimentary rocks are formed by the actions of organisms or from the remains of dead organisms.

Sedimentary rocks characteristically form as a series of layers of different composition and thickness (Fig. 18). The layers, called **beds**, can be readily identified in nature on the basis of different colors or resistance to erosion, both properties that are linked to the composition of the rocks.

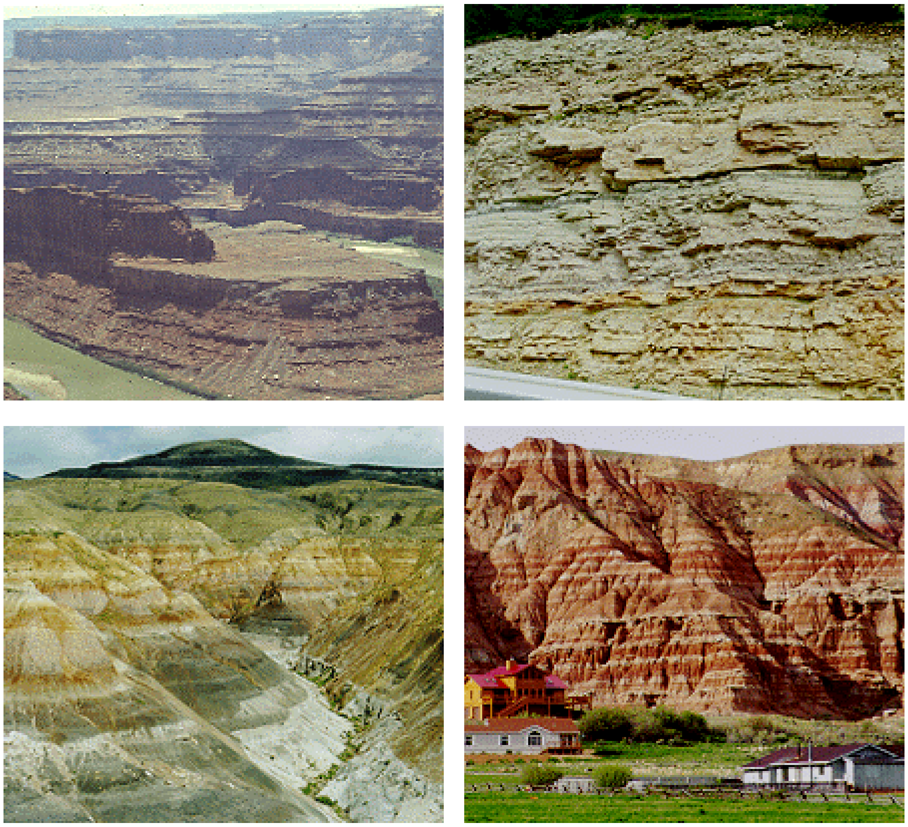


Figure 18. A variety of horizontal beds of sedimentary rocks exposed at Dead Horse Point, Utah, (top left); along U.S. 14, Bighorn Mountains, Wyoming (top right); in Rainbow Canyon, Bighorn Basin, near Lovell, Wyoming (bottom left); and near Dubois, Wyoming (bottom right).

Sedimentary rocks can be divided into three fundamental types:

- **Clastic** sedimentary rocks composed of **sediments**, rock and mineral fragments formed when rocks disintegrate at or near Earth's surface.

- **Chemical** sedimentary rocks precipitated from a solution (e.g., seawater) as a result of changing physical conditions (e.g., evaporation).
- **Biochemical** sedimentary rocks formed by the actions of living organisms or composed of the remains of dead organisms.

Clastic Sedimentary Rocks

The basic building blocks of clastic sedimentary rocks are **sediments**, rock and mineral fragments formed when rocks disintegrate on the earth's surface. Clastic sedimentary rocks are formed in three steps that require the generation, transportation, and deposition of sediments.

Weathering: Rocks physically disintegrate into smaller pieces and the constituent minerals may undergo decomposition to form alternate minerals. The process of disintegration and decomposition is termed weathering and is influenced by the original rock type and climatic conditions. Weathered material forms sediments that are classified by increasing grain size as **mud**, **silt**, **sand**, and **gravel**.

Erosion: Sediment is removed (**transported**) from its place of origin by **running water**, **winds**, and/or **glaciers**. A muddy river (Fig. 19) is an indication that the river is carrying a large load of sediment. Clastic sediments are divided into coarse grain-size particles (Fig. 19; **gravel**, includes pebbles, cobbles and boulders), medium grain-size (**sand**), fine grain-size (**silt**), or very fine sediment (**clay**). The process of erosion shapes the landscape and contributes to the formation of many of the distinctive landforms of a region (valleys, canyons, mountains).

Figure 19. Left: Slow-flowing muddy stream (left) near Graybull, Wyoming, transports fine-grained sediment. Sand bars on inner banks was formed when flow velocity decreased and larger sediment was deposited. Center: Fast-flowing stream in Wyoming. Right: Pebbles and boulders deposited in stream channel. The largest boulder is 0.4 meters (15 inches) across.

Deposition: Clastic sediments are **deposited** when the velocity of the transporting medium drops. For example, rivers dump much of their sediment where they enter the relatively quiet waters of an ocean or lake; the landform that is created is a **delta** (Fig. 20). This material may be redistributed along the coastline to form beaches. Winds in deserts may shape sand into dunes.

Deposition concentrates sediments of the same size together. As the pile of sediment grows, sediment at the base of the pile becomes **compacted**, squeezing out water and forcing the grains closer together. Fluids circulating through the pile precipitate minerals to **cement** the grains together, converting the sediment into a cohesive aggregate, i.e., a rock. The processes of compaction and cementation that convert sediment into sedimentary rock are termed **lithification**.

Sediment	Grain Size (diameter)	Rock
Clay	Less than 0.0039 mm	Shale, Mudstone
Silt	0.0039 to 0.0625 mm	Siltstone
Sand	0.0625 to 2 mm	Sandstone
Gravel	More than 2 mm	Conglomerate

Figure 20. Top: Delta of the Ebro River, Spain, which deposits sediment into the western Mediterranean Sea. Growth of the delta landform has slowed in recent years because of the construction of dams upstream. Light-colored sediment in water around the delta indicates ongoing deposition. Bottom: Sand dunes (center) deposited in southeast Algeria were derived from weathering and erosion of the surrounding sandstone bedrock (dark brown). Images courtesy of NASA's Earth from Space.

Think about it . . .
What observations can you make about the image below that would help make an interpretation of the origin of the pictured sediments?

Chemical Sedimentary Rocks

Relative proportion of sedimentary rock types

Clastic sedimentary rocks:
86%

Chemical and biochemical sedimentary rocks:
14%

Chemical sedimentary rocks are **precipitated from a solution** as a result of changing physical conditions. The most common solution is seawater. These minerals are dissolved from rocks on the continents and transported to the oceans in solution in streams. Vast shallow tropical oceans were the source for the bulk of the chemical sedimentary rocks that are present at the surface across North America today.

Rock salt forms as a result of changing physical conditions (increasing temperature). Minerals dissolved in seawater are precipitated when the water evaporates to form rocks such as **gypsum** and rock salt (halite). Evaporation typically occurred in restricted basins in arid climates. Thick salt deposits are interpreted to indicate that there must have been a constant supply of additional seawater to ensure the steady deposition of salts. These rock types are collectively termed **evaporites**.

Biochemical Sedimentary Rocks

Biochemical sedimentary rocks involve the actions of living organisms that cause minerals to be **precipitated from a solution** or are composed of the remains of dead organisms.

Figure 21. Coral reef in clear, shallow water, Bahamas.

Figure 22. Close-up of coquina limestone, note shell fragments (penny for scale).

Limestone forms when living marine organisms precipitate minerals from seawater to build their skeletons. The actions of organisms in seawater change the composition of the water resulting in the precipitation of the mineral **calcite** (calcium carbonate), the principal ingredient in limestone. Massive limestone **coral reefs** around the world were built up because of the actions of the coral organisms (Fig. 21). The skeletons of some microorganisms collect on the sea floor to form deposits of **chalk**, a type of limestone. The shells of larger organisms may be broken down and sorted by wave action to form a clastic form of limestone known as **coquina** (Fig. 22). Additional disintegration may form sand- or mud-size particles that become lithified into medium- to fine-grained limestones, respectively.

Some biochemical rocks are composed of the remains of **dead organisms**. The most common example is **coal** (Fig. 23), the compacted remains of dead plants that grew in a tropical swamp environment. These rocks are sometimes termed **organic** sedimentary rocks.

Figure 23. Massive coal seam in Tertiary rocks of the Powder River basin, northern Wyoming. The seam is up to 200 feet (60 meters) thick in places (note large coal-hauling truck for scale).

Think about it . . .
Make a concept map for sedimentary rocks using the terms here. Generate your own linking phrases that connect these terms together.

clastic rocks
gravel
streams
biochemical rocks
lithification
precipitation
weathering
chemical rocks
deposition
grain size
sedimentary rocks
living organisms

Metamorphic Rocks

- Metamorphism occurs when a rock changes because of changing physical conditions (temperature, pressure).
- The temperature range for metamorphism is approximately 200-1,000°C.
- Contact metamorphism occurs in relatively narrow zones around heat sources (e.g., magma).
- Regional metamorphism occurs over large areas in association with the formation of mountain belts.
- Rocks subjected to regional metamorphism may develop a texture termed foliation.

Metamorphism represents the changes in the composition and/or texture of a rock that occurs in solid rocks as a result of increasing pressure and/or temperature.

The chemical reactions associated with metamorphism are practically inactive below approximately 200°C. Depending upon their composition, most minerals will melt at temperatures ranging from 600-1,000°C. When melting occurs the rock is no longer in the solid state. Consequently the temperature "window" for metamorphism is from 200 to 1,000°C. There are two types of metamorphism: **contact metamorphism** and **regional metamorphism**.

Contact Metamorphism

Contact metamorphism occurs when rocks undergo metamorphism because they come in contact with a heat source

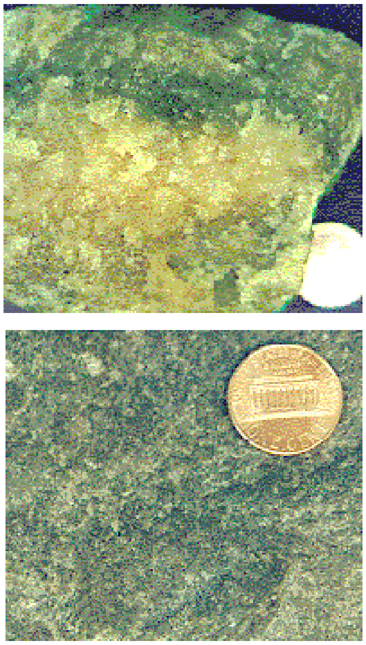


Figure 24. Two examples of rocks that may form as a result of contact metamorphism of limestone (top, marble) or sandstone (bottom, quartzite.)

(usually a magma body). Essentially the rocks are getting cooked. A comparable change occurs in roasting meat or baking bread - the initial composition does not change but the texture of the material does.

Rocks do not conduct heat well (they are good insulators) so the zone of contact metamorphism is usually relatively narrow and occurs in the rock (**country rock**) immediately surrounding the heat source.

Marble is an example of a rock that may be formed by contact metamorphism. Marble (Fig. 24) forms when limestone is heated to high temperatures. Both marble and limestone may have the same composition but marble typically has larger grains.

Regional Metamorphism

Regional metamorphism occurs when rocks undergo increased temperatures and pressures and is typically associated with the formation of mountain belts. In these areas rocks may be buried to great depths (10-20 km).

The additional pressure causes tabular minerals (e.g., mica) in the rock to grow parallel to each other and perpendicular to the direction of pressure (stress), generating a mineral alignment termed **foliation** (Fig. 25)

Increased temperatures and/or pressures generate more intense grades of metamorphism. Foliated metamorphic rocks in order of increasing metamorphic grade (low to high temperature) are slate, phyllite (Fig. 26), schist, and/or gneiss (Fig. 27).

Figure 25. Tabular or sheetlike minerals grow perpendicular to the direction of pressure to form a foliation.

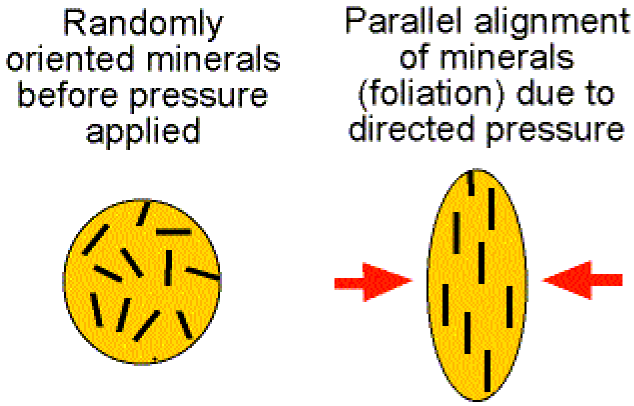


Figure 26. Foliation in a phyllite from New Mexico; the foliation is the series of surfaces that are inclined from the top right to the bottom left.

Not all rocks that undergo regional metamorphism will form a foliation. Rocks that lack tabular minerals such as mica will not generate the parallel alignment of minerals necessary to create a foliation. Sandstone, composed mainly of quartz grains, will be converted to quartzite (Fig. 24) by regional metamorphism; limestone may form marble. Neither metamorphic rock contains a foliation.

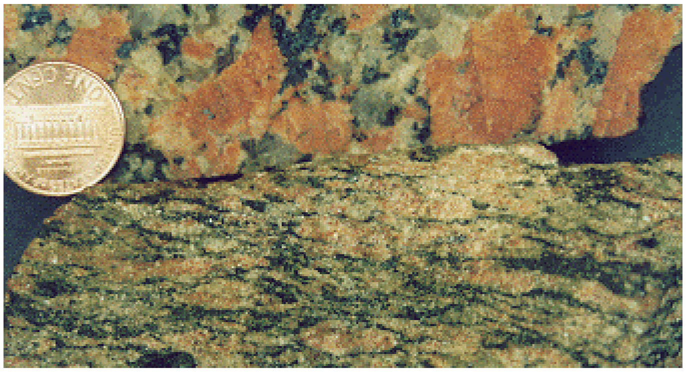


Figure 27. Granite (above) and gneiss (below) are composed of similar minerals. Note the irregular horizontal foliation in the gneiss defined by light and dark minerals.

Think about it . . .
Make a concept map that summarizes the characteristics of metamorphic rocks.

The Rock Cycle

- The rock cycle links the principal sedimentary, metamorphic, and igneous rocks together in an idealized view of the sequential evolution of rocks in Earth's crust.

The rock cycle (Fig. 28) represents a simplified view of the formation of different rocks to illustrate the potential interaction between rock types. Minerals and elements in Earth's crust can be recycled through several different rocks during their lifetime.

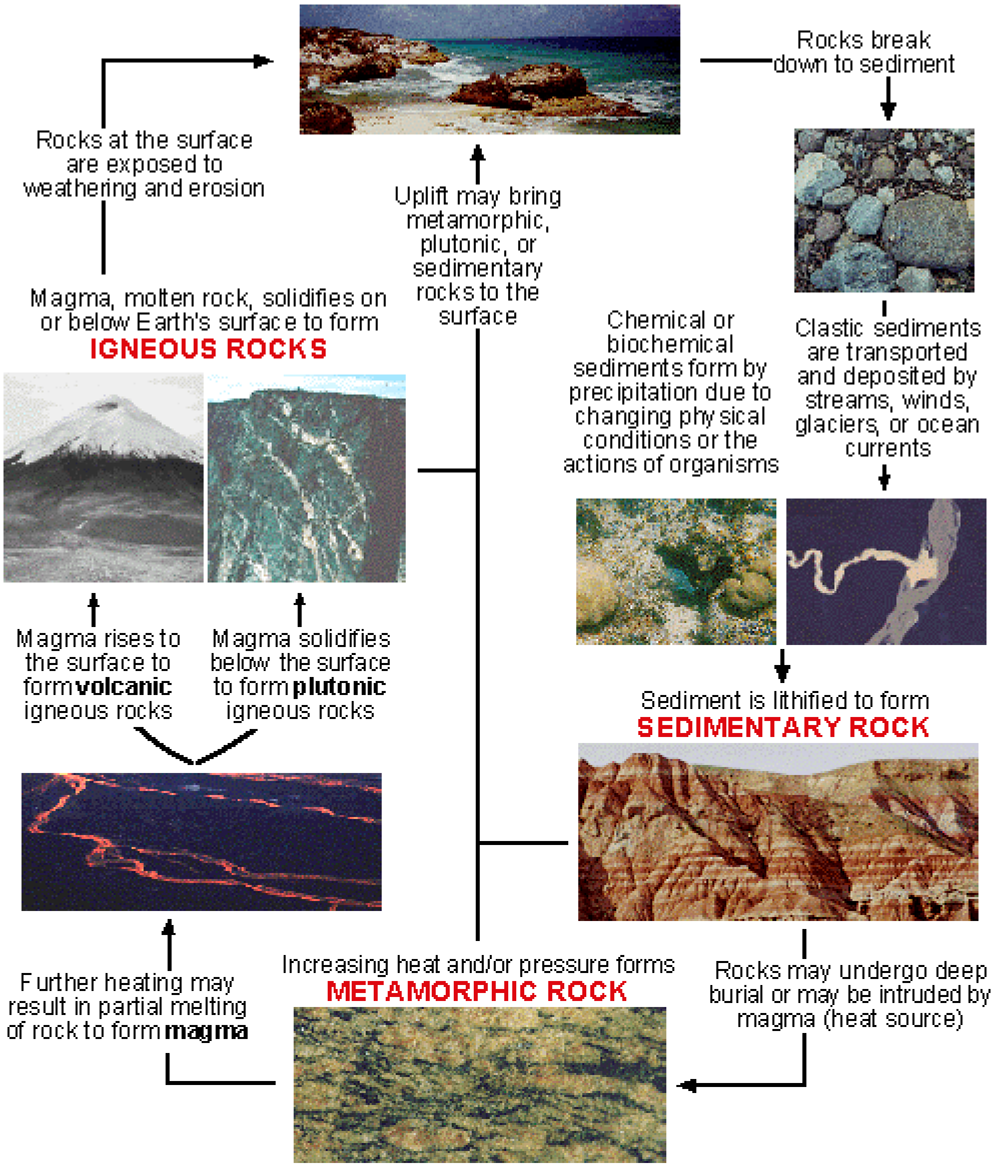


Figure 28. A summary diagram of the rock cycle.

For example, a grain of **quartz** sand on a beach may be incorporated into a clastic sedimentary rock such as **sandstone**. Regional metamorphism may result in the sand grain and its host rock being buried several kilometers below the surface, where higher temperatures and pressures convert the sandstone to **quartzite**. Magma rising from the mantle may melt the adjacent quartzite, assimilating the quartz grain into the magma. The elements of the quartz grain (**silicon, oxygen**) may recombine with other elements to form new minerals as the magma solidifies to form **granite** deep within the crust. Erosion eventually exposes the rock, breaking it down to its constituent minerals and rock fragments (**sediment**) that are carried by streams to the coast where the grains are deposited on a beach. And the cycle begins again.

Each cycle may last millions or even billions of years but keep in mind that we are not adding new material to Earth so any rocks forming today must be recycling elements from rocks formed at some time in the planet's history.

Think about it . . .

1. Use the Venn diagram at the end of the chapter to compare and contrast the similarities and differences between igneous, sedimentary, and metamorphic rocks.
2. Complete the diagram of the rock cycle at the end of the chapter by filling in the blanks.
3. Describe how you might use beach sands to understand the geology of a landmass surrounded on several sides by ocean.

Geology of Mineral Resources

- Ore is rock that contains economic concentrations of metallic minerals.
- Gangue are noneconomic minerals associated with ores
- Concentration factor is the increase in concentration of a mineral required to form an ore.
- Minerals form in a range of geologic settings associated with the formation of the most common rock types.

Introduction

A rock containing economic concentrations (reserves) of metallic minerals is known as **ore**. Noneconomic minerals (e.g., quartz, feldspar, calcite) found in association with ore minerals are known as **gangue** (pronounced "gang") and are considered waste. The average concentration of minerals in the crust is insufficient to form an ore. Various geologic processes (see below) concentrate minerals within the crust.

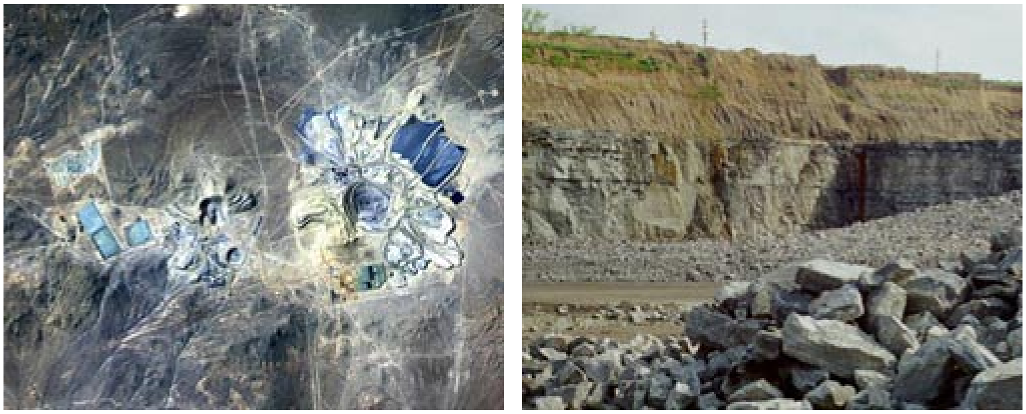


Figure 29. Left: Escondida mine, Chile, at an elevation of over 3 km in the Andes Mountains produces copper, silver, and gold. Image courtesy of NASA. Right: Martin Marietta limestone quarry, Columbus, Ohio, produces crushed stone, the most valuable mined resource in the U.S.

The **concentration factor** (CF) is the increase in the concentration of a mineral required to generate an ore. The concentration factor necessary to generate an economic mineral deposit can be determined by dividing the economic concentration by the average concentration of the mineral in the crust. For example **copper** makes up 55 parts per million (ppm, 0.0055%) of Earth's crust. Copper ores from the Bingham Canyon mine, Utah, are composed of 0.6% copper (6,000 ppm), equivalent to a concentration factor of 109 (6,000/55). In contrast, copper ores from the Escondida mine, Chile, range in concentration from 0.2-1% (2,000-10,000 ppm), equivalent to concentration factors of 36-181. Relatively rare minerals have large CF values (e.g., gold, CF = >2,000), whereas more common elements have low CF values (e.g., silicon, CF = 2).

Minerals are deposited in a variety of geologic settings that fall under two general headings:

- **Igneous mineral deposits** form in association with magma and water or when minerals concentrate during the formation of igneous rocks.
- **Sedimentary mineral deposits** are precipitated from a solution, typically seawater, formed by weathering reactions that break down rocks at Earth’s surface, or are sorted and redistributed by the flow of water, wind, or ice.

Igneous Mineral Deposits

Hydrothermal mineral deposits: Magma and water are the key ingredients in the generation of hydrothermal mineral deposits. Water becomes scarce with depth so most of these

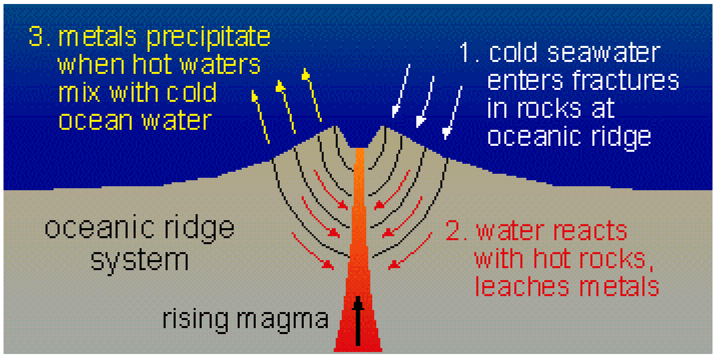


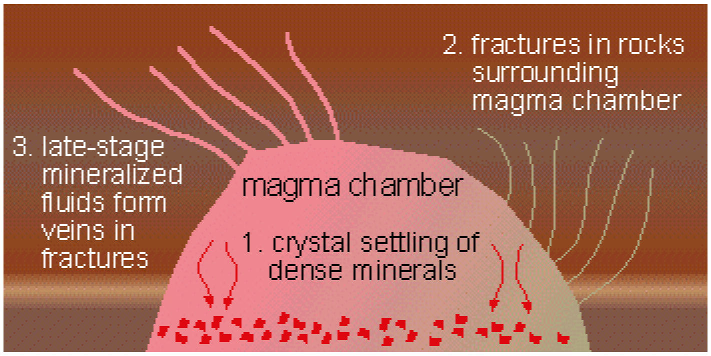
Figure 30. Geologic setting for the formation of hydrothermal mineral deposits along oceanic ridges.

minerals form as magma makes it way up through the crust toward Earth's surface. One location where water is readily available is the ocean floor. Magma rises along topographic high areas of the ocean floor known as oceanic ridges (Fig. 30). Cold bottom **waters** from the ocean floor can infiltrate the oceanic crust through networks of narrow fractures. The waters are heated to high temperatures (300-400°C) by the rising magma and chemical reactions occur that leach out metals from the surrounding rocks. These mixtures of **dissolved metals** are transported to the ocean floor where they meet much colder waters (2°C). The sudden decrease in temperature causes the minerals to precipitate from solution and they are incorporated into sediments deposited along the ocean ridge system.

Exploration of the ocean floor by Woods Hole Oceanographic Institute using submersible craft discovered plumes of hot waters expelled along the oceanic ridge. The plumes contained dissolved **sulfide metals** such as **manganese**, **iron**, **copper,** and **zinc**, and the mineral deposits they produced were termed **massive sulfides**. The hydrothermal vents have been informally named "black smokers" because the precipitating minerals make the water coming from tall vents resemble smoke rising from a chimney when viewed in the lights of the submersible craft (the floor of the ocean is normally in complete darkness). Scientists discovered populations of previously unknown organisms living near the vents.

Hydrothermal deposits also form on land when metal-rich fluids are expelled from magma chambers. These fluids form **veins** that fill fractures in the rock and may contain concentrations of economic minerals. One of the last minerals to form during the cooling of a magma chamber is quartz. Quartz-rich fluids expelled from magma chambers often form associations with **gold** deposits.

Figure 31. Metallic minerals may form as a result of crystal settling of dense minerals or through the late-stage expulsion of mineralized hydrothermal fluids from the magma chamber.



Magmatic mineral deposits: Igneous processes may result in the concentration of minerals in specific locations within **plutonic igneous rocks**. Metal-rich minerals (e.g., platinum-group minerals, chromium) may form early in the crystallization of a magma chamber and sink to the bottom of the chamber (**crystal settling**), forming an enriched layer (Fig. 31). Late-stage fluids may form large-grained plutons, **pegmatites**, that have concentrations of relatively rare minerals such as lithium and beryllium. Slow cooling of residual magma to form pegmatites may yield crystals of individual minerals that are meters across.

Sedimentary Mineral Deposits

Sedimentary iron deposits: The largest U.S. iron deposits are found in ancient (more than 2 billion years old) sedimentary rocks that formed when the **chemistry of Earth's oceans** was considerably different than today. The greatest concentration of these deposits in the U.S. is in the Upper Peninsula of Michigan and northern Minnesota. Nearly two billion tons or iron ore have been mined in northern Michigan alone. The iron deposits were precipitated from seawater like modern evaporite deposits such as salt. The iron is present in association with a variety of silica-rich gangue minerals such as quartz and feldspar. The iron must be concentrated by additional geologic processes before these deposits can be considered an ore. Two potential concentration methods are:

- The leaching of silica from the rocks (leaving iron behind in greater relative concentrations) by weathering processes that occur on Earth's surface.
- Metamorphism that causes an increase in grain size and the formation of new iron minerals that are easier to separate from the rock.

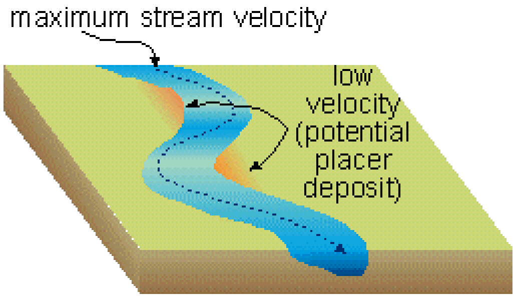


Figure 32. Placer deposits collect on the inside of stream bends (meanders) where flow velocity is least.

Placer deposits: Placers represent a natural recycling of older mineral deposits. Minerals that are weathered out of veins may be carried downslope by streams. Stream flow serves to sort and concentrate the minerals (Fig. 32). Metal-rich minerals are heavier than the rest of the material carried by the stream. Consequently, when flow velocity decreases the heavy minerals are among the first materials to be deposited. Suitable sites for deposition are the insides of stream bends (meanders) or at the stream mouth (delta).

Placer deposits can be extracted relatively easily and have often held the imagination of would-be millionaires seeking to strike it rich quick. The gold rushes of the West began in California in 1848 and almost always began with thousands of hopeful miners descending upon streams with gold pans in search of placer deposits. The top three placer gold-producing states were **California** (60% of all placer gold), **Alaska** (18%), and **Montan**a (8%).

Residual mineral deposits: Water flowing through rocks on or near the land surface may remove soluble minerals to leave behind sufficient concentrations of economic minerals to form an ore. This process is most rapid in areas of high rainfall and high temperatures such as the tropics. Iron- and aluminum-rich **laterite** forms as a result of leaching of minerals from thick soils in tropical regions. The world’s principal source of aluminum ore is from a form of laterite known as **bauxite**. Most of the world’s bauxite is mined in Australia, Guinea, and Jamaica.

Metals vs. Industrial Minerals

Metallic mineral deposits (Fig. 33) form when minerals are concentrated as a result of igneous or sedimentary processes described above. However, many sediments and rocks are

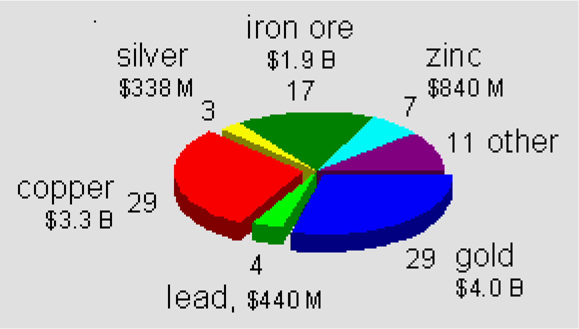


Figure 33. Annual value (B, billions; M, millions) and relative proportions (%) of U.S. metal resources (1998). Gold and copper represent nearly 60% of the value of U.S. metal resources.

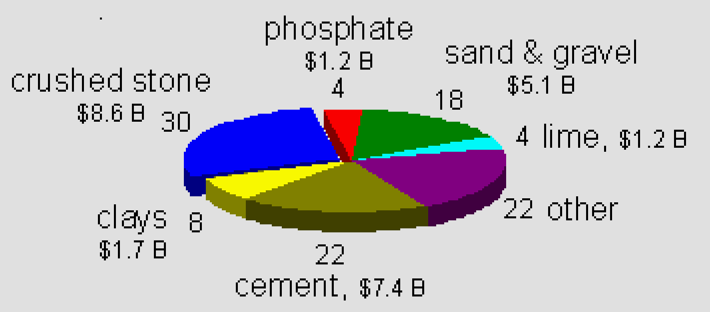


Figure 34. Annual value (1999; B, billions; M, millions) and relative proportions (%) of U.S. nonfuel mineral production for industrial minerals.

mined for nonmetallic industrial minerals for a variety of uses (Fig. 34). Although they are relatively inexpensive in comparison to metals, **industrial minerals** are commonly mined everywhere people live and the sheer volume of materials produced makes them the most valuable mineral resources in the U.S.

Aggregates represent a subgroup of industrial minerals that are typically used for construction. Aggregates include sand, gravel, crushed stone, dolomite, and sandstone. Some of the uses of industrial minerals are:

- **Limestone** used for crushed stone (construction) or lime (steel production).
- **Sand and gravel** (construction).
- **Sandstone** for building stone (construction), as a source for silicon (computer chips), for use in glass making.
- **Clay** is used to make bricks and ceramics and in the manufacture of glossy paper, paint, toothpaste and antacid medications.
- **Gypsum** used in making wallboard, plaster of Paris, and cement.
- **Salt** deposits are mined for table salt, used in water. softeners, animal feed, and for ice control on roadways
- **Phosphate** rock is used in manufacture of fertilizers.

Crushed stone represents the most valuable nonfuel mineral produced in the U.S. (~$9 million annually) and 22% of total nonfuel mineral production ($40 million). The total annual value of industrial minerals ($28.8 million) mined in the U.S. is more than twice the value of mined metals ($11.3 million).

Summary

1. How do rocks on Mars compare to those on Earth?

The rocks, and the minerals they contain, provided clues to the evolution of the planet. Rocks on Mars were determined to have a composition similar to andesite, a common igneous rock on earth.

2. What is the relationship among atoms, elements, and minerals?

Rocks are made up of minerals. Minerals can be divided into their constituent elements. Elements cannot be further divided into other materials but they can be separated into individual atoms, the smallest particles that retain the characteristics of the element.

3. What are protons, neutrons, and electrons?

Atoms are composed of neutrons, protons, and electrons. The protons and neutrons are present in the atom's nucleus which is surrounded by electrons.

4. What is an ion?

Atoms may loose or gain electrons to reach a more stable configuration. This results in the formation of a negatively or positively charged atom known as an ion. Ions may be either positive (cation) where an atom has lost electrons, or negative (anion) where an atom has gained electrons.

5. What are the most common elements in the continental crust?

Eight elements (oxygen, silicon, aluminum, iron, calcium, magnesium, sodium, potassium) make up more than 98% of the continental crust.

6. What are silicates?

The most common minerals are composed of the most common elements. Silicon and oxygen make up over 70% of the continental crust by weight; minerals that contain both silicon and oxygen are known as silicates.

7. What is the definition for a mineral?

A mineral is a naturally occurring, inorganic solid with a definite chemical composition and uniform atomic structure made up of an element or compound of elements.

8. What characteristic properties can be used to identify minerals?

Minerals can be identified by crystal form, color, cleavage, hardness, streak, and luster.

9. What are the three main groups of rocks?

Rocks can be divided into igneous, sedimentary, and metamorphic rocks.

10. How are igneous rocks classified?

Igneous rocks are subdivided based upon whether magma cooled on Earth’s surface (volcanic igneous rocks) or within Earth’s interior (plutonic igneous rocks).

11. What are the most common igneous rocks?

Rhyolite (volcanic) and granite (plutonic) are igneous rocks formed from silica-rich magmas. Basalt (volcanic) and gabbro (plutonic) form from silica-poor magmas. Andesite (volcanic) and diorite (plutonic) form from magmas of intermediate composition.

12. What are the three basic types of sedimentary rocks?

Clastic sedimentary rocks are composed of rock and mineral fragments. Chemical sedimentary rocks are precipitated from a solution. Organic sedimentary rocks are composed of the remains of dead organisms.

13. What controls the grain size of clastic sediments?

The velocity of transport may control the size of the sediment that can be carried (the exception is glaciers that carry sediment of all sizes trapped in the ice). Fast-flowing streams and strong winds can transport the largest grains. Transport velocity therefore results in sediments being sorted (arranged) by grain size.

14. What are the three size classes for clastic sediments?

Clastic sediments are divided into large grain-size particles (gravel), medium grain-size (sand), or fine grain-size (mud, silt, clay).

15. What is lithification?
Lithification represents the compaction and cementation that converts sediment to sedimentary rock.

16. How do chemical sedimentary rocks form?
Chemical sedimentary rocks are precipitated from a solution as a result of changing physical conditions or due to the actions of living organisms. The most common solution is seawater.

17. How would coal be classified as a sedimentary rock?
Coal is an organic sedimentary rock composed of the remains of dead organisms (plant remains).

18. What is metamorphism?
Metamorphism represents changes in the composition and/or texture of a rock that occurs in the solid state as a result of increasing temperature and/or pressure.

19. What is the temperature range for metamorphism?
The chemical reactions associated with metamorphism are practically inactive below approximately 200^{o}C. Depending upon their composition, most minerals will melt at temperatures ranging from 600 to 1,000^{o}C.

20. How does contact metamorphism occur?
Contact metamorphism occurs when rocks undergo metamorphism because they come in contact with a heat source (usually a magma body).

21. Where does regional metamorphism occur?
Regional metamorphism occurs when rocks undergo increased temperatures and pressures and is typically associated with the formation of mountain belts. In these areas rocks may be buried to great depths (10-20 km).

22. What factors influence the development of a foliation?
Foliations form when pressure causes tabular minerals in metamorphic rocks to grow parallel to each other and perpendicular to the direction of pressure (stress), generating an alignment of minerals.

23. What is the rock cycle?
The rock cycle represents a simplified view of the formation of different rocks to illustrate the potential interaction between rock types. As sedimentary rocks are buried to increasing depths they are subjected to increasing temperature and

pressure and are converted to metamorphic rocks. With continued burial, increasing temperatures cause melting to form magma. The magma cools on or below the earth's surface to form igneous rocks. Igneous rocks on the surface are broken down into sediments to form sedimentary rocks.

24. What is the concentration factor?
A rock containing economic concentrations (reserves) of metallic minerals is known as an ore. Metals are uneconomical to produce in their natural concentrations in the crust. The concentration factor is the degree of concentration necessary to for economic mining. The degree of concentration is dependent upon the quality and quantity of the ore body, mining costs, and the market price of the mineral. Metals such as copper are concentrated between 50 to 200 times normal levels in commercial mines. Rare, expensive minerals (e.g., gold) have concentration factors measured in the thousands.

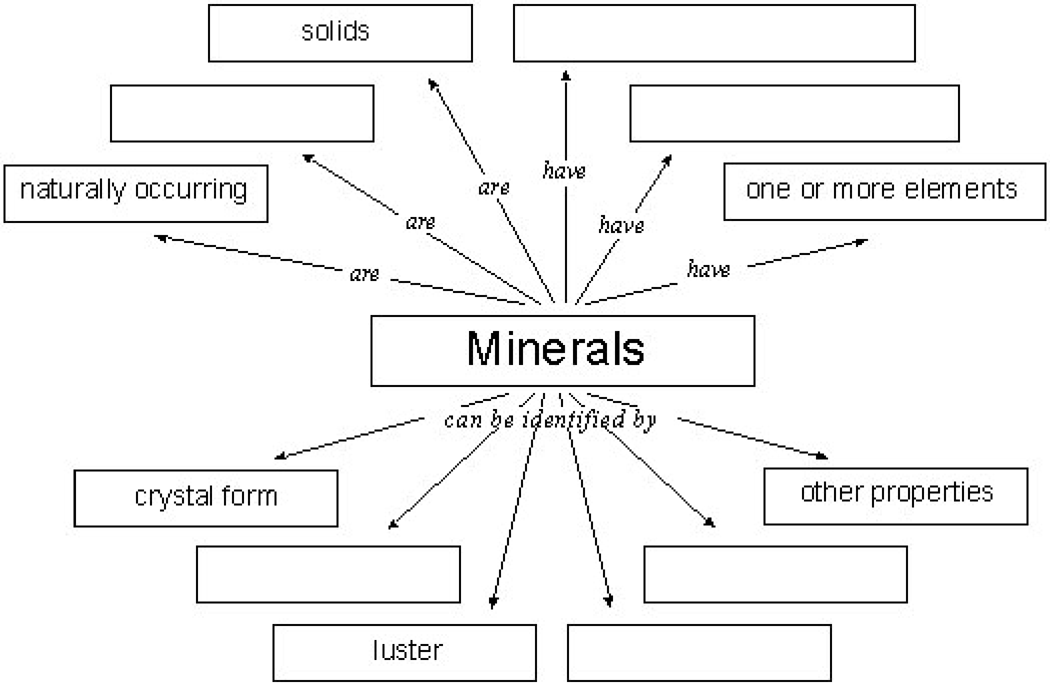
25. How do minerals become concentrated in the crust?
Minerals become concentrated through geologic processes associated with the formation of sedimentary and igneous rocks.

26. What igneous processes result in the formation of mineral resources?
Igneous processes that concentrate metals involve the interaction of water with hot rocks (near magma sources) or the formation of minerals from magmatic fluids. Hot waters dissolve out metal-rich minerals around magma chambers and then deposit the minerals (hydrothermal deposits) in cooler environments. Specific minerals may be segregated as magma solidifies. Igneous processes may cause metal-rich minerals to settle to the bottom of a magma chamber (crystal settling) or to become concentrated in veins around the magma chamber.

27. What sedimentary processes concentrate mineral resources?
Processes such as chemical weathering, deposition in flowing water, and evaporation can all result in the concentration of minerals. Few precious metals are formed directly during the formation of sedimentary rocks but common metals such as iron and aluminum are typically the result of sedimentary processes. The majority of nonmetallic industrial minerals (e.g., sand and gravel, clays, gypsum) are formed by sedimentary processes.

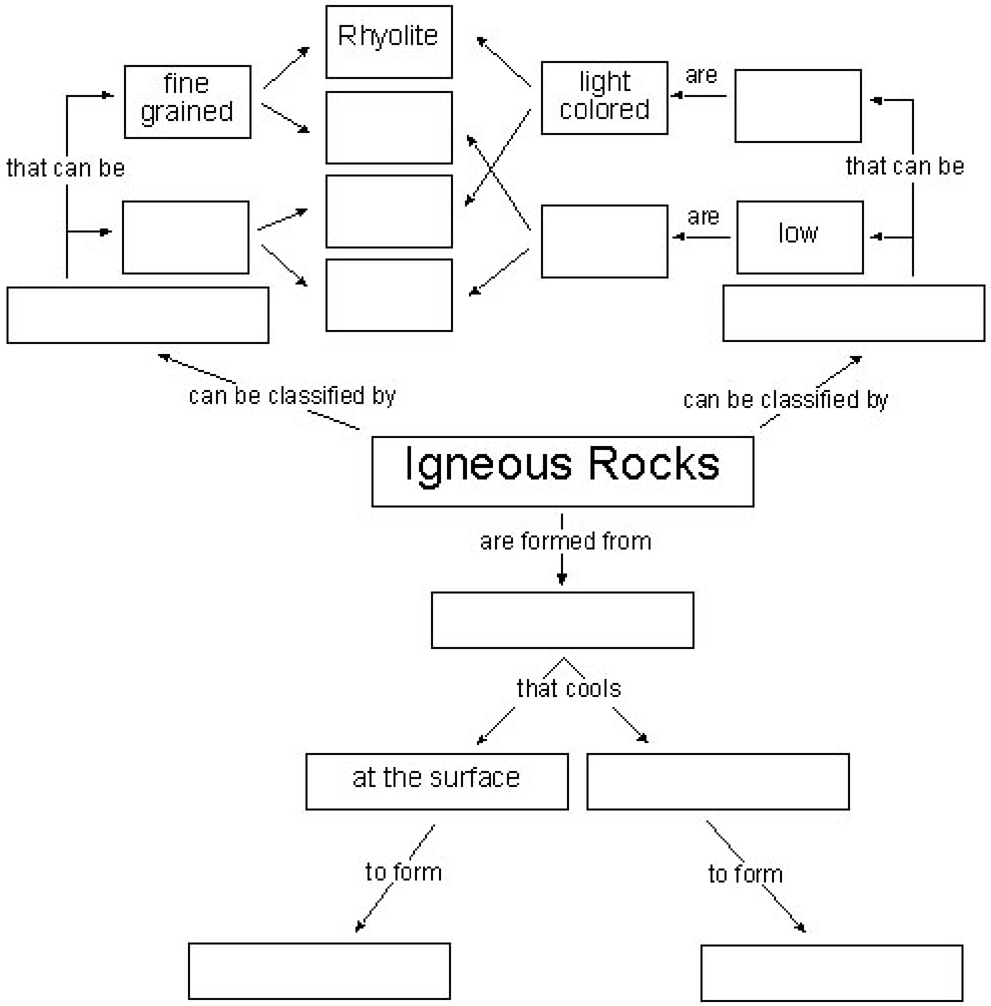
28. What are the most valuable mineral resources in the U.S.? Annual production of crushed stone, cement, and sand and gravel ($5.1 to 8.6 billion) are all worth more than the annual value of precious metals such as gold ($4 billion). Copper and gold are the most valuable metallic resources.

Concept map for Minerals



Finish the partially completed concept map for minerals shown above. Print the page and fill in the blanks with appropriate terms. Try to complete the map after reading the section on minerals in the online text or following a lecture or lab exercise on minerals. How could you add additional levels to the concept map?

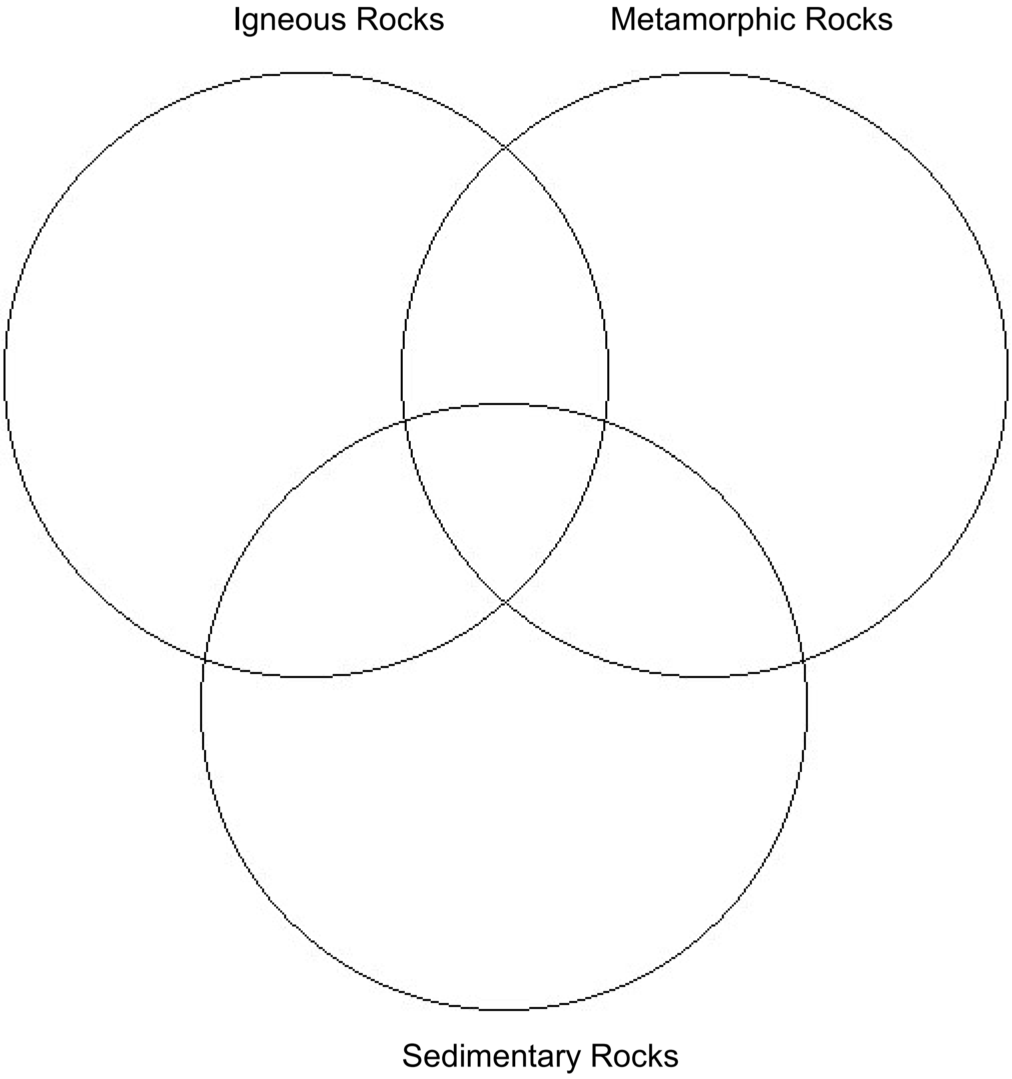
Concept map for Igneous Rocks



Finish the partially completed concept map for igneous rocks shown above. Fill in the blanks with appropriate terms. Try to complete the map after reading the section on igneous rocks without looking at the text.

Venn Diagram: A Comparison of Rock Types

Use the Venn diagram below to compare and contrast the similarities and differences between igneous, sedimentary, and metamorphic rocks.



Rock Cycle Diagram

The following diagram illustrates the rock cycle. Match the letters below to the blank ovals on the diagram (note: some letters are used more than once). Example: If you believe that metamorphic rock is converted to magma by cementation and compaction then enter "a" in the top left oval.

a. Cementation and compaction (lithification)
b. Heat and Pressure
c. Weathering, transportation, deposition
d. Cooling and solidification
e. Melting