# Unit 2: Minerals and Rocks

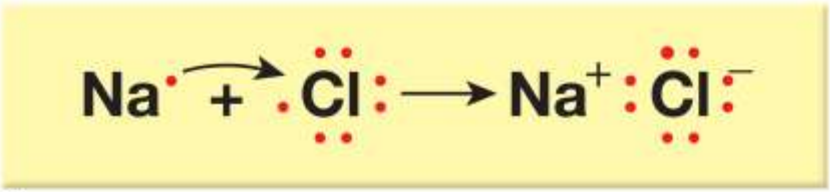
## 1.0 Minerals

**Mineral:** a naturally occurring, inorganic, solid element or compound with a definite composition and regular internal structure.

Naturally occurring minerals are those that occur in nature and have not been invented by humans (i.e. synthetics such as silicon carbide). Minerals that are inorganic are those that have not been produced solely by living organisms or biological processes (i.e. pearls). That minerals must be solid means that ice of a glacier is a mineral but liquid water is not.

Compositionally, minerals chemically consist of either one element or several. A diamond is an example of a mineral consisting of a single element – pure carbon. Mineral compositions can be very complex and contain up to 10 or more elements. However, simple or complex, each mineral has a definite chemical composition or at least a define range in composition.

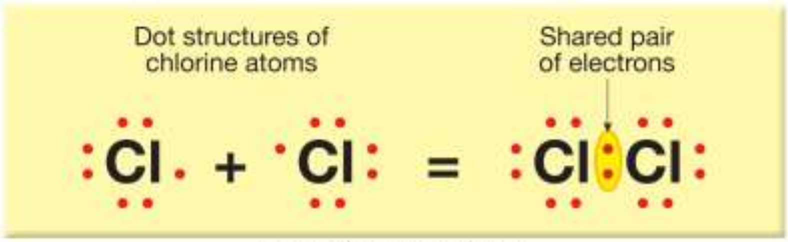
Most minerals form by atom bonding such as ionic, covalent and metallic. In the process of ionic bonding, atoms gain or lose the outermost (valence) electrons to form ions. As a result, minerals form ionic compounds that consist of an orderly arrangement of oppositely charged ions.



A.

*Example of ionic bonding of halite (table salt).*

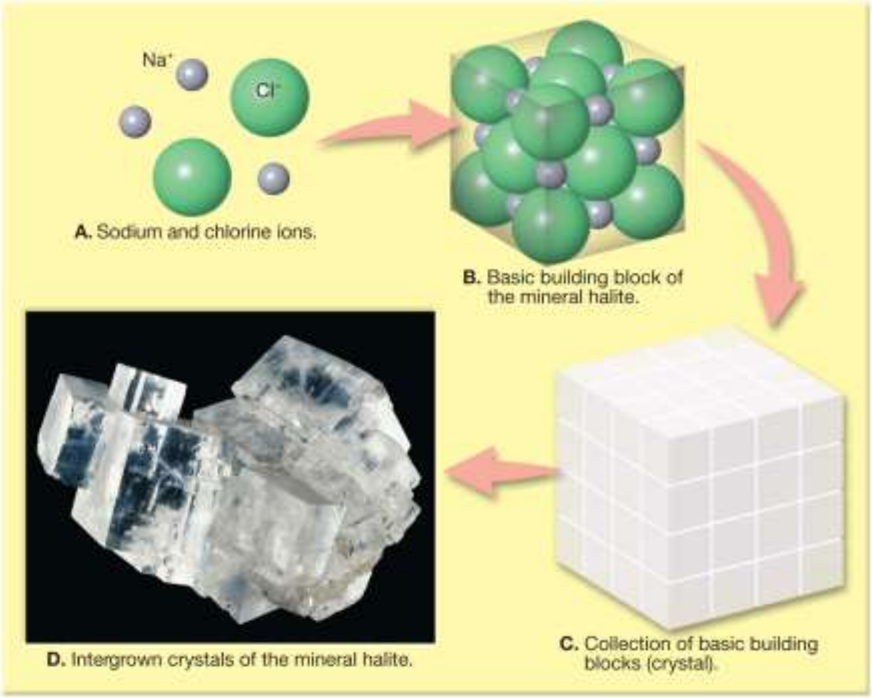
In covalent bonding minerals, atoms share an electron to achieve electrical neutrality. These bonds are generally stronger than ionic bonds. Both ionic and covalent bonds typically occur in the same compound.



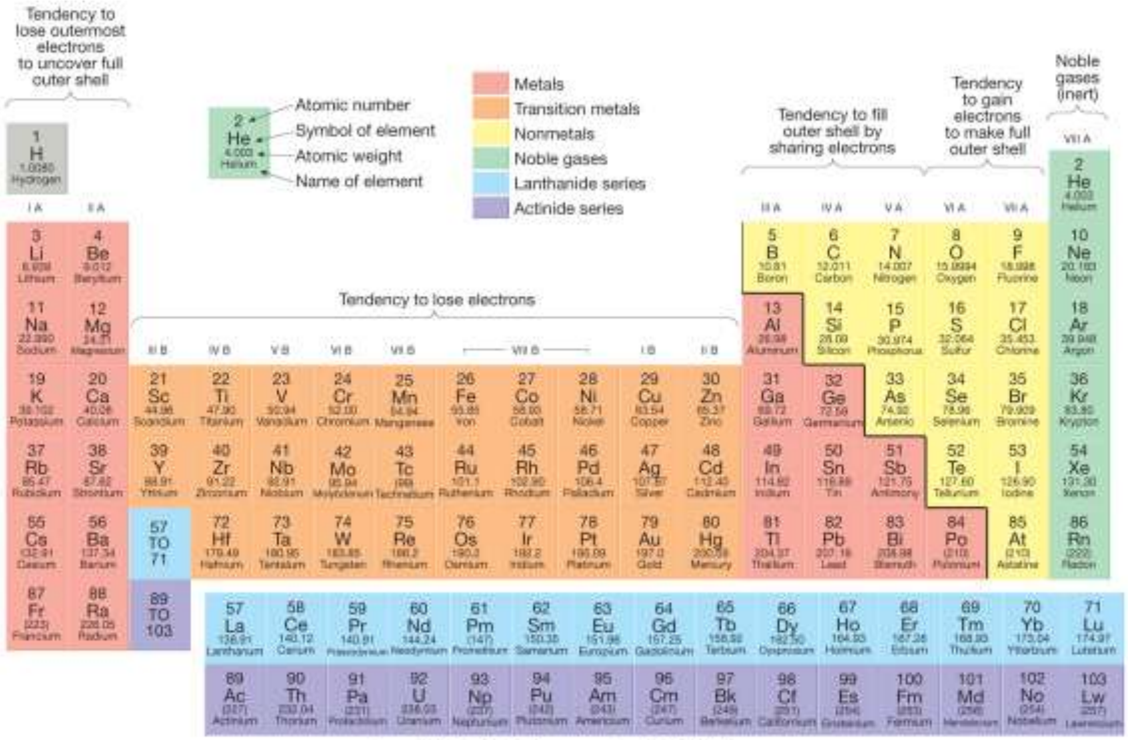
*Example of covalent bonding.*

When metallic bonding occurs valence electrons are free to migrate among the atoms. As a result these bonds are weaker and less common.

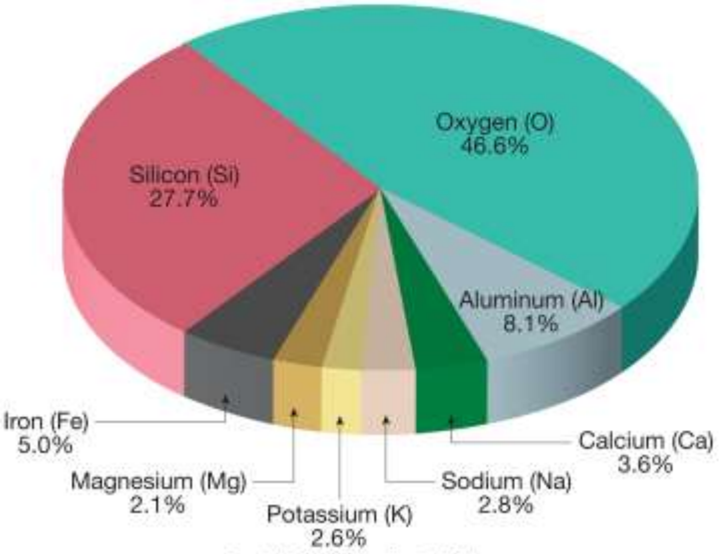
Minerals consist of an orderly array of atoms chemically bonded to form a particular crystalline structure. Internal atomic arrangement in ionic compounds is determined by ionic size.



The elements present and the proportions of the elements present control the defining characteristics of a mineral. It is important to know that minerals can contain any element that is listed in the periodic table.

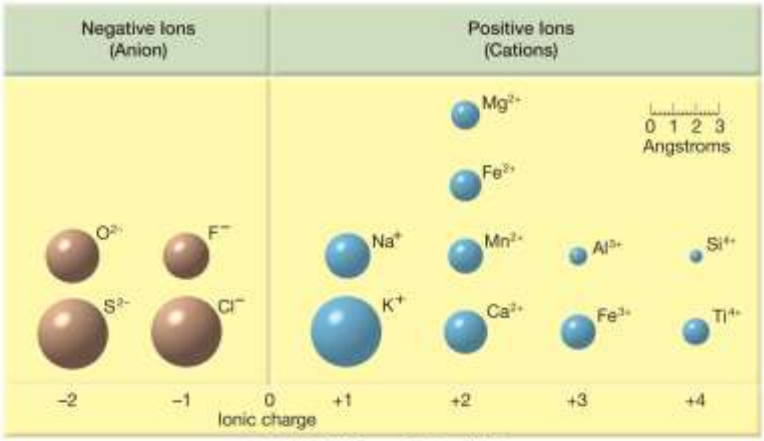


Some elements are more abundant within the earth than others and therefore are more commonly found in minerals.



Oxygen is the most abundant element found on earth followed by silicon, aluminum and iron. These most abundant elements are found in the majority of minerals. It is also the reason why quartz ($SiO_2$) is one on the most abundant minerals.

**Solid Solution:** a phenomena observed in minerals, in which two or more ions of similar size and charge may be substituted more or less interchangeably for each other in the same mineral structure. Ionic substitutions are controlled by size and charge.



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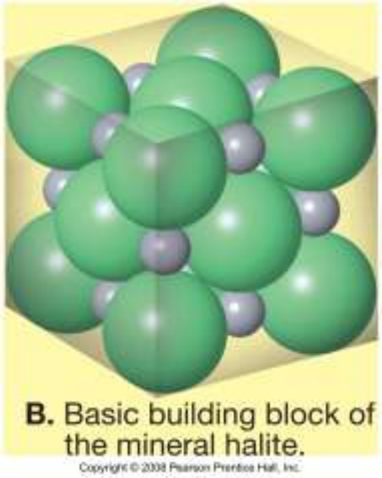
*Note that Mg, Fe, Mn and Ca are of similar size and charge. These ions commonly substitute for one another in many minerals. The same principle applies to the other cations and anions.*

Because a mineral is considered a solid solution, ionic substitution can occur in a mineral structure. For example iron ($Fe^{2+}$) and magnesium ($Mg^{2+}$) ions have the same charge and are nearly the same size. In many cases, when a mineral contains one of these ions, it can also contain the other with varying proportion. This is why in many minerals there is a range in composition. The effects of this solid solution substitution on mineral characteristics are dealt with later in this unit.

*Example*: Olivine (#28 in your rock and mineral kit)
*Chemical Formula*: $(Fe,Mg)_2SiO_4$
*Compositional Range*: $Fe_2SiO_4$ to $Mg_2SiO_4$

It is important to understand that minerals are solid and therefore on a microscope scale are considered crystalline. *Crystalline* materials are solids in which the atoms are arranged in regular, repeating patterns. Geoscientists have developed an x-ray analytical technique (X-ray Diffraction) that can determine crystal structure and subsequently identify the mineral. Another analytical device is the Electron Microprobe which can determine the exact chemical composition of a mineral. These tools are particularly useful for identifying an unknown specimen or determining how much of a specific element is present within a specific mineral.

Crystal structures of minerals form because they are the most stable arrangement of atoms in a solid. The crystal form of a mineral is the external expression of its internal structure. In most cases, the crystal form is interrupted due to competition for space and rapid heat loss. Minerals can contain various cations and anions. As one knows, opposite charges attract and like charges repel. In order to minimize the repulsion charges, negative and positive charges are symmetrically distributed through the solid. Think of a crystal structure as a single structural and compositional unit that is repeated over and over in three dimensions. The more complex the mineral, the larger and more complex the repeating unit.



*This picture represents the crystal structure of the mineral halite (commonly known as table salt). The large green balls represent* $Cl^-$ *and the grey balls represent* $Na^+$.

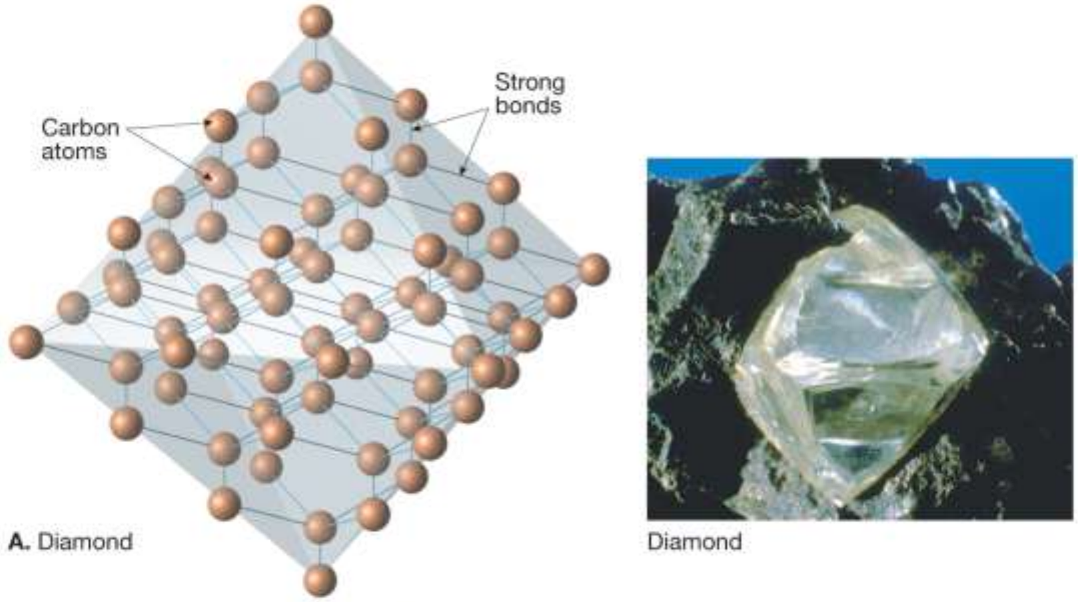
In order for crystals in a given minerals to form, there must be enough of the requisite elements present. There also must be enough time for the atoms to arrange themselves in the proper regular pattern. If there aren't enough elements or not enough time to arrange the atoms, then the resulting structure is disordered. For example, minerals can form from volcanic lava. If the lava cools too quickly, minerals cannot form their arranged atoms symmetrically before the structure freezes. The resulting solid, in which atoms are randomly arranged are considered a noncrystalline *glass*.

*Volcanic glass does not contain any crystal structure and therefore appears smooth and uniform in colour.*

## 1.1 Characteristics and Properties of a Mineral

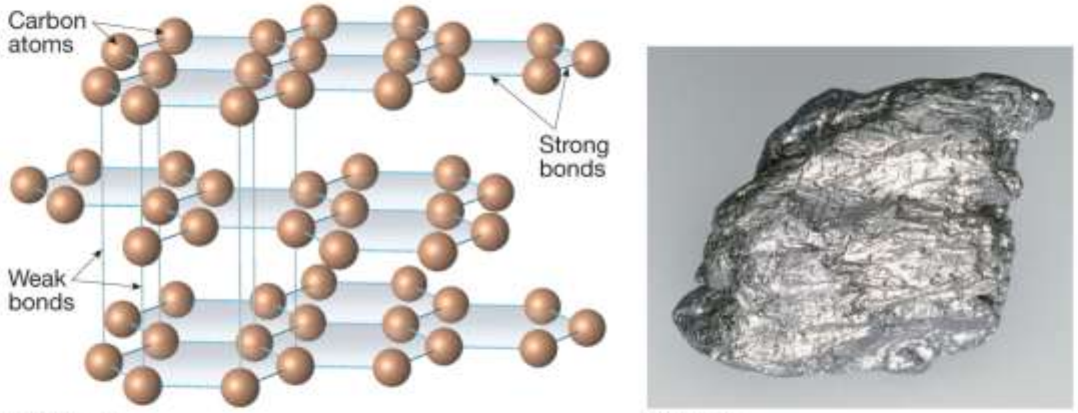
The two fundamental characteristics of a mineral that together distinguish it from all other minerals are: chemical composition and its crystal structure. Each individual mineral is defined by a unique composition and structure. No two minerals are identical in both respects. For example, diamond and graphite are chemically the same: both are made up of pure carbon. Their crystal structure and physical properties however are completely different because of their internal crystalline structures. In a diamond, each carbon atom is firmly bonded to every adjacent carbon atom in three dimensions. This gives a diamond its properties of being: clear or transparent, colourless and very hard. Graphite on the other hand has carbon atoms that are strongly bonded in two dimensions, into sheets, but the sheets are weakly held together in the third dimension. The properties of graphite are: black, opaque and soft. These properties are the reason why diamonds can be used on a saw blade (cut hard materials) and graphite can be used in the lead of a pencil (so soft it leaves residue behind).

**Polymorphism:** minerals that have the same chemical composition but distinctly different crystal structures (i.e. diamond versus graphite). There may be two or more polymorphs of a single composition. Under a given set of conditions one polymorph will be stable and under other conditions, other atomic arrangements may be stable. For example, diamond is stable under high pressures conditions however, at low pressures, graphite is the stable form.



**A.** Diamond

Diamond



**B.** Graphite

Graphite

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Mineral compositions and crystal structure can typically only be determined using sophisticated laboratory equipment. It is not possible to look at a lump of a mineral and know its chemical composition without first identifying what mineral it is. Therefore if scientific instruments are not on hand or not feasible, other physical properties can be used for mineral identification.

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*This picture shows quartz exhibiting a variety of colours.*

There are several physical characteristics or properties that a mineral can display. Many properties are not necessarily unique for one mineral. For example several minerals can be green in colour. Colour of a mineral can also change due to the presence of impurities. Therefore colour is not a good way of identifying a mineral.

A *diagnostic property* is a physical property that can be used to identify a specific mineral. These diagnostic properties include: streak, hardness, crystal form, cleavage, fracture, lustre and specific gravity.

*Streak* is the colour of a powdered mineral. It is tested by scraping a mineral across the face of a porcelain or unglazed tile and analyzing the colour of the powder left behind as a mark or streak. There are two main limitations to the usefulness of streak as a diagnostic property. Many different minerals leave a white, grey or brown streak. Also minerals harder than ceramic simply gouge the test surface and do not leave a streak. Streak is useful when used in conjunction with another diagnostic property. Streak is particularly useful in identifying metallic ores.

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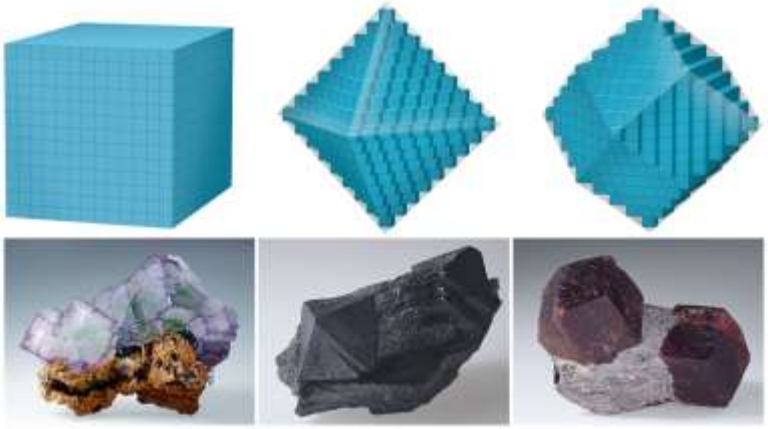
*Some minerals leave behind a streak with a distinct colour (as shown left) however not all minerals streak. Minerals that are harder than a porcelain plate only scratch it and leave no residue behind.*

*Hardness* is the ability of a mineral to resist scratching. This diagnostic property is related to the strength of the internal bonds holding the mineral together. Classically, hardness is measured using *Mohs hardness scale*, on which ten minerals are arranged in order of hardness, from talc (1 - the softest) to diamond (10- the hardest). An unknown mineral is assigned a hardness on the basis of which mineral it can scratch and which mineral can scratch it. For example a mineral that can scratch and in turn be scratched by quartz is assigned a hardness of 7. Because diamond is the hardest mineral known and corundum is the second-hardest they might be identified by their hardness. Some minerals however have different hardness depending on impurities etc.

*Crystal form* is the shape of well-developed crystals of a mineral. This reflects the internal symmetry of the crystal structure. All crystals however, do not always look alike in form. Some minerals show a readily apparent relationship such as halite. Halite tends to crystallize in cubes. Calcite may form in a dogtooth form that reflects the rhombohedral atomic units from which they are built. Well-developed crystal forms are relatively uncommon. Different minerals may also show the same crystal form.



**A.** Cube (fluorite) **B.** Octahedron (magnetite) **C.** Dodecahedron (garnet)

*Example of a few crystal forms.*

A. Bladed B. Prismatic C. Banded D. Botryoidal

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*These beautiful crystal forms are hard to find. The bladed and prismatic relate to crystalline structure during mineral growth. The banded and botryoidal are irregular growths.*

*Cleavage* is another property that is controlled by internal crystal structure and represents the tendency of minerals to break preferentially in certain directions. These breaks correspond to zones of weakness in the bonds of a crystal structure. To test the cleavage plane produced by a mineral one only has to strike the mineral with a hammer and break it. There are cases where the cleavage is the same as the crystal form; such as halite. Halite grows well-developed cubes and will also break into cubic faces. When a mineral displays cleavage the mineral breaks into consistent and repeating geometric planes. Biotite for example has a basal or two dimensional cleavage where the mineral will break into sheets. This is an example of basal cleavage.

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*This is an example of basal cleavage of biotite and muscovite minerals. The bonds in each layer are relatively strong but the bonds connecting each layer to one another are very weak and break easily.*

Many minerals do not display cleavage but instead break into random, not well-defined planes. These minerals therefore exhibit more of an irregular *fracture* than cleavage. One distinctive fracture type is a *conchoidal* or shell-like fracture displayed by quartz or volcanic glass.

*This is an example of a mineral that breaks into conchoidal fractures. Note the concave appearance of the fracture. If struck with a hammer, this mineral will break into in random concave features.*

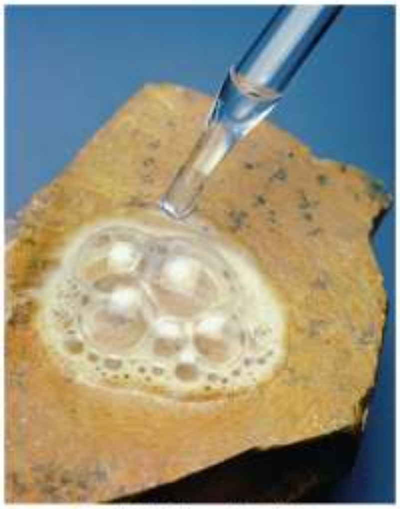
*Lustre* is a diagnostic property that describes the surface sheen of a mineral. There are several terms used to describe lustre including: *metallic* (bright and shine like metal), *pearly* (soft, iridescent like a pearl), *vitreous* (glassy) and *earthy* (dull).

**C.** Dodecahedron (garnet)

*The cubic yellow mineral (pyrite) shows metallic luster whereas the purple garnets show vitreous lustre. Other examples of luster are found in your lab 2 help sheets.*

*Specific gravity* of a mineral is related to its density. Specific gravity is the ratio of the mass of a mineral to the mass of an equal volume of water. By definition, a mineral having the same density as liquid water has a specific gravity of 1. The higher the specific gravity, the denser the mineral. Specific gravity is related to the atomic weights of the elements in the mineral. Gold for example is one of the heaviest elements.

There are other properties that are useful in identifying minerals. The iron mineral magnetite for example is strongly magnetic; very rare among minerals. Sodium chloride is salty or bitter to taste. A few minerals effervesce (fizz) when acid is dripped on them such as carbonate minerals. Uranium minerals are radioactive and can be detected by a Geiger counter. Some minerals fluoresce (glow) in ultraviolet light such as calcite and fluorite.



*This is an example of a mineral that effervesces (fizzes) in the presence of an acid.*

It is important to know the properties and diagnostic properties of minerals to help with immediate identification. Many times a geologist that is working in the field and away from any laboratory equipment will employ some of the simple tests listed above to make a quick and temporary mineral identification. There are many times that a geologist is looking for one specific mineral. For example if one is exploring for a deposit such as uranium, a portable Geiger counter can be used on rock outcrops to determine if uranium is present or not.

## 1.2 Types of Minerals

There are mainly two types of minerals that are present on the earth. These are *silicates* and *non-silicates*. These two types can be further separated into more detailed classes based on their crystal structures. The table below lists the major mineral classes.

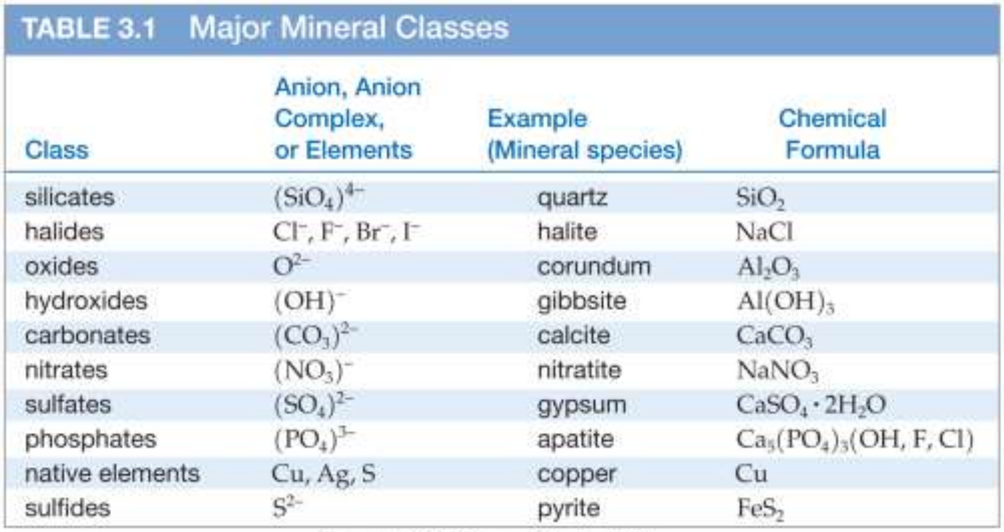


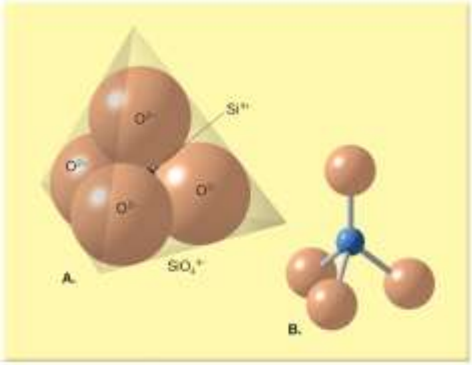
**TABLE 3.1 Major Mineral Classes**

| Class | Anion, Anion Complex, or Elements | Example (Mineral species) | Chemical Formula |
|---|---|---|---|
| silicates | $(SiO_4)^{4-}$ | quartz | $SiO_2$ |
| halides | $Cl^-, F^-, Br^-, I^-$ | halite | $NaCl$ |
| oxides | $O^{2-}$ | corundum | $Al_2O_3$ |
| hydroxides | $(OH)^-$ | gibbsite | $Al(OH)_3$ |
| carbonates | $(CO_3)^{2-}$ | calcite | $CaCO_3$ |
| nitrates | $(NO_3)^-$ | nitratite | $NaNO_3$ |
| sulfates | $(SO_4)^{2-}$ | gypsum | $CaSO_4 \cdot 2H_2O$ |
| phosphates | $(PO_4)^{3-}$ | apatite | $Ca_5(PO_4)_3(OH, F, Cl)$ |
| native elements | Cu, Ag, S | copper | Cu |
| sulfides | $S^{2-}$ | pyrite | $FeS_2$ |

### *1.2.1 Silicates*

The two most common elements in the earth's crust are silicon and oxygen, which together make up over 70% of the crust. The largest class of minerals is therefore the **silicate** class, all of which contain silicon and oxygen. Because the class is so large, it is subdivided into smaller groups based on crystal structure, or in other words, by the ways in which silicon and oxygen atoms are linked. These smaller groups include chain silicates, (pyroxenes, amphiboles), sheet silicates and framework silicates.

The basic structural unit for all silicate minerals is the silica tetrahedron. This unit is comprised of a silica cation $(4^+)$ surrounded by four oxygen anions $(O^{2-})$. It is the different ways in which these tetrahedral assembled that distinguish the different silica groups. The tetrahedron is expressed as $SiO_4$ and therefore has a net charge of - 4. The simplest way to organize the tetrahedron is to have isolated units that are linked by different cations that balance the - 4 charge. For example the most common single tetrahedron silicate mineral is olivine. The net charge is balanced by either the $Fe^{2+}$ or $Mg^{2+}$ cations. This why the chemical formula for olivine is $(Fe,Mg)_2SiO_4$. It takes two of these $2^+$ cations to balance the - 4 charge of the silica tetrahedon. Another common silicate of this type is garnet with the formula $(Ca,Mg,Fe)_3(Al,Fe)_2Si_3O_{12}$.



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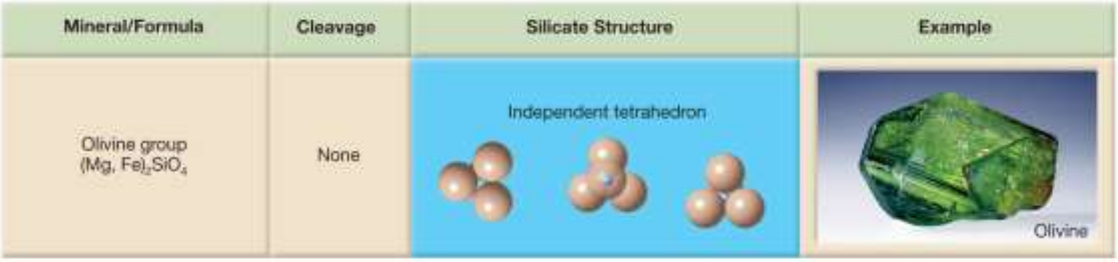
*Because silicon and oxygen are the most abundant elements on earth, the most common crystal structure is the silica tetrahedron. This tetrahedron is the most common "building block" for other more complex mineral structures.*

*Olivine is # 28 in your rock and mineral kit.*



| Mineral/Formula | Cleavage | Silicate Structure | Example |
|---|---|---|---|
| Olivine group<br>$(Mg, Fe)_2SiO_4$ | None | Independent tetrahedron | Olivine |

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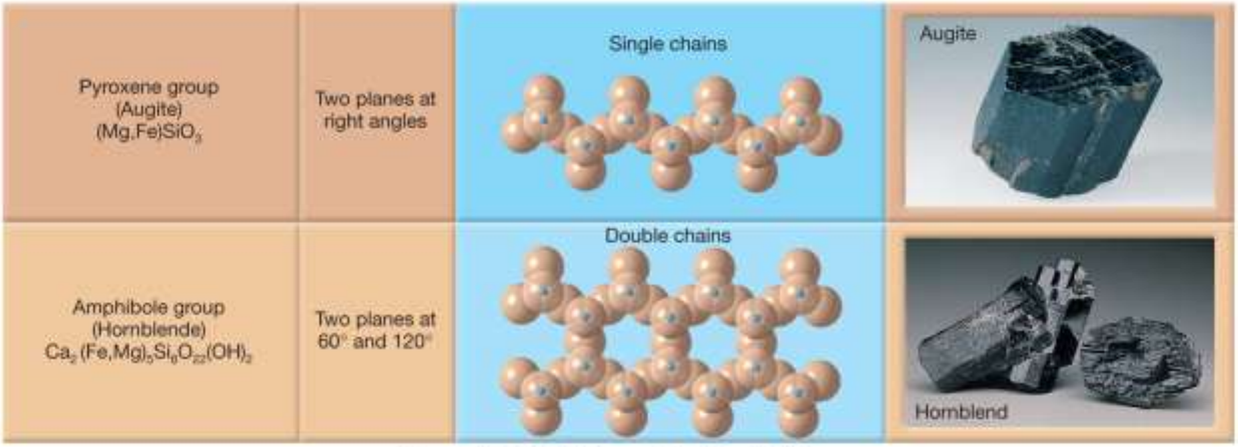
### *1.2.2 Chain Silicates*

As the name implies, these silicates arrange the silica tetrahedron into long chains that are linked by sharing an oxygen atom between each tetrahedron in one dimension. The most common are single chain silicates. An example is the pyroxene group and comprises many different minerals. An example of a simple pyroxene is $(Fe,Mg)_2Si_2O_6$ or orthopyroxene. Other minerals use different cations such as $Ca^{2+}$, $Al^{3+}$, and $Na^+$ to balance the chain structure.

Double chain silicates are more complex. Amphiboles are an example of double chain silicates and have water in their crystal structure in the form of hydroxyl ions $(OH^-)$ that substitute for some of the oxygen in the structure. An example of a double chain silicate amphibole is hornblende with the formula:
$(Ca,Na)_3(Mg,Fe,Al,Ti)_4(Si,Al)_8O_{22}(OH,F)_2$



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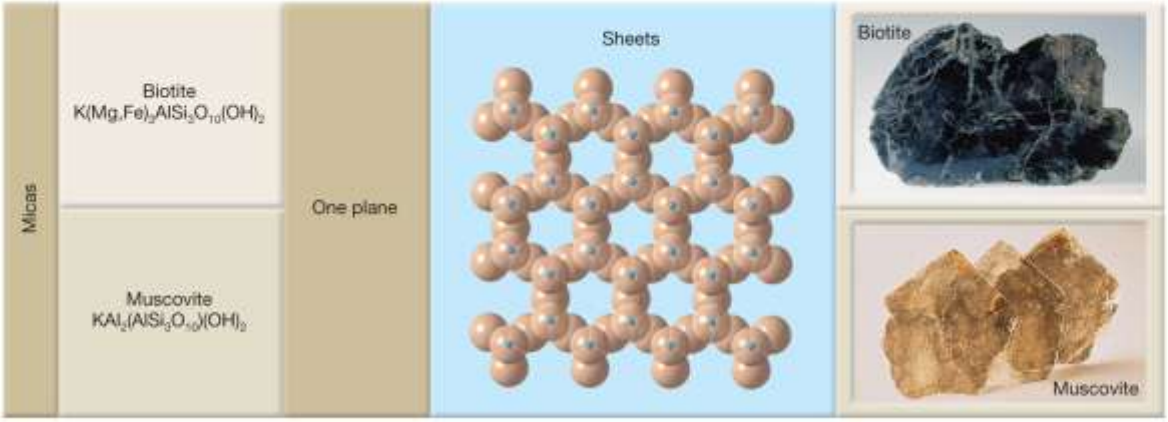
### *1.2.3 Sheet Silicates*

Sheet silicates are minerals that are linked by sharing the tetrahedron oxygen in two dimensions. Therefore the net charge of each tetrahedron is -1 so fewer cations are required. Similar to amphiboles, many sheet silicates contain water ($OH^-$ hydroxyl) substituting for oxygen reducing the need for charge-balancing cations. These cations typically fit between the stacked sheets and bond the sheets together. For many sheet silicates there are not enough cations to hold the layered sheets and the cation layers are weak and break easily. That is why many sheet silicates have cleavage that is parallel to the weakly bonded sheets. This cleavage is called basal cleavage. Examples of common sheet silicates are micas minerals such as muscovite and biotite. Clay minerals are also sheet silicates.



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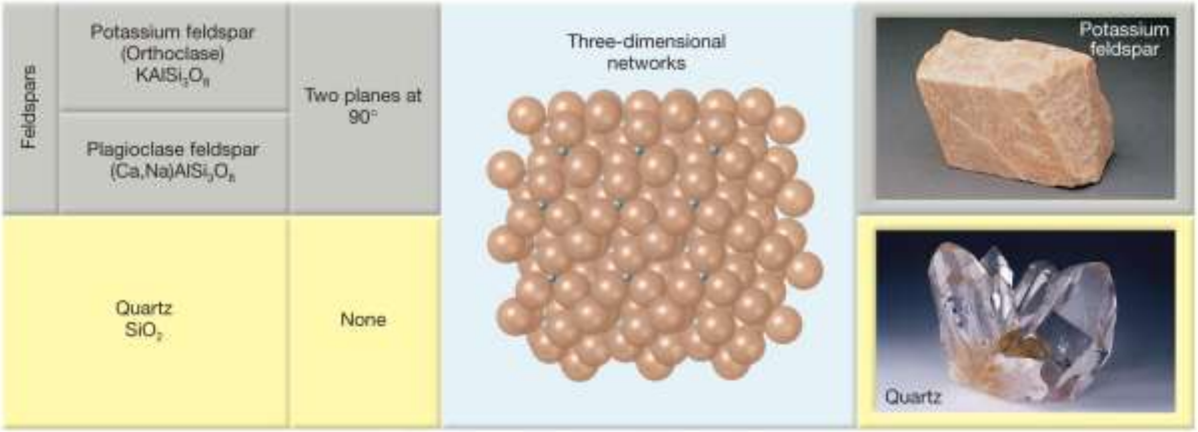
### *1.2.4 Framework Silicates*

When the silica tetrahedrons are linked in all three dimensions they are called framework silicates. These minerals share the oxygen atom in three directions. This means that the mineral is entirely comprised of $SiO_2$ where the net charge is $[1(+4) + 4(\frac{1}{2})(-2)] = 0$. Quartz is an example of such as minerals. There are no planes of weakness and therefore no cleavage planes. There are other framework silicates because aluminum ($Al^{3+}$) often times substitutes for silica ($Si^{+4}$) along with other cations [i.e. sodium ($Na^{+}$), potassium ($K^{+}$) and calcium ($Ca^{2+}$)]. The most abundant framework silicate in the crust are the feldspar minerals. There are also other variant silicates that form ring structures etc but are less common.



| | | | | |
|---|---|---|---|---|
| Feldspars | Potassium feldspar (Orthoclase) $KAlSi_3O_8$ | Two planes at 90° | Three-dimensional networks | Potassium feldspar |
| | Plagioclase feldspar $(Ca,Na)AlSi_3O_8$ | | | |
| | Quartz $SiO_2$ | None | | Quartz |

### *1.2.5 Non-silicates*

Just as silicates by definition all contain silicon and oxygen as part of their chemical composition, each non-silicate mineral class is defined by some chemical constituent or characteristic that all members of the group have in common. Non-silicate classes include carbonates, sulphates, sulphides, halides, oxides and native elements. For example carbonates contain carbon and oxygen. These minerals dissolve relatively easily particularly in acids. The most abundant carbonate mineral is calcite ($CaCO_3$). Another common carbonate mineral is dolomite $CaMg(CO_3)_2$. Carbonates may also contain elements such as iron, manganese or lead. Sulphates are another type of non-silicate. These minerals contain sulphur and oxygen. Gypsum is a calcium sulphate that is most abundant and used commercially in building materials such as drywall. Barium, lead and strontium can also substitute in the sulphate structure.

Sulphides are the most common non-silicate ore mineral. The common constituent that they have in common is the element sulphur, but these minerals lack oxygen. For example chalcopyrite is a sulphide mineral that contains sulphur as its base constituent and Cu as the positive cation ($CuFeS_2$). Chalcopyrite is a mineral that would be mined as a resource for copper. Other sulphide minerals may not appear to be economic in their most basic form but contain metals as impurities. For example arsenopyrite has the chemical formula FeAsS but can commonly contain quantities of Au in its crystal structure.

*Pyrite is a common sulphide mineral*

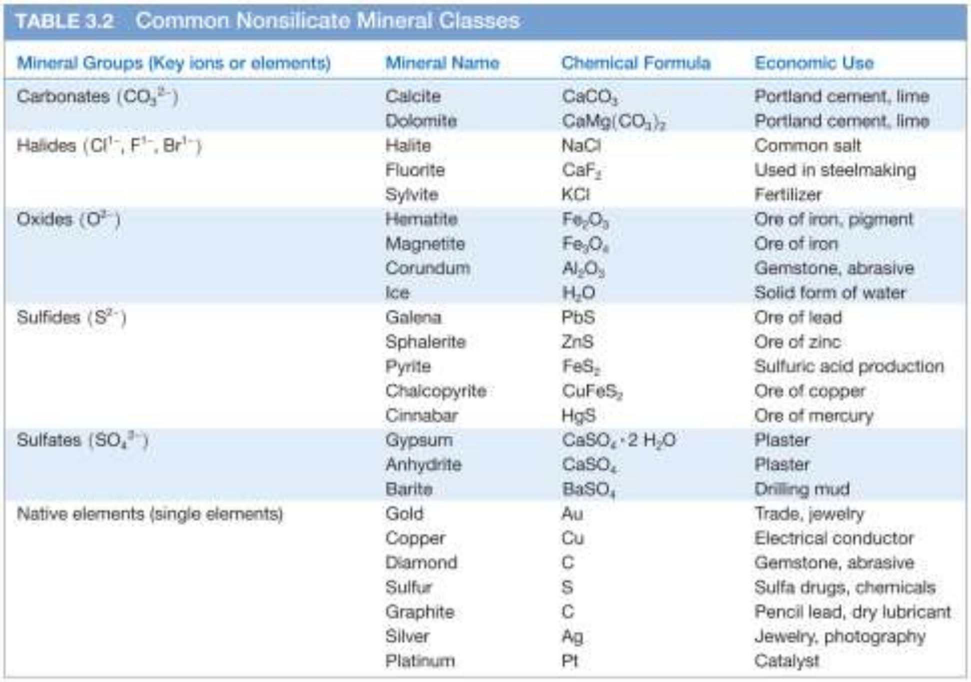


**TABLE 3.2 Common Nonsilicate Mineral Classes**

| Mineral Groups (Key ions or elements) | Mineral Name | Chemical Formula | Economic Use |
|---|---|---|---|
| Carbonates ($CO_3^{2-}$) | Calcite | $CaCO_3$ | Portland cement, lime |
| | Dolomite | $CaMg(CO_3)_2$ | Portland cement, lime |
| Halides ($Cl^{1-}$, $F^{1-}$, $Br^{1-}$) | Halite | $NaCl$ | Common salt |
| | Fluorite | $CaF_2$ | Used in steelmaking |
| | Sylvite | $KCl$ | Fertilizer |
| Oxides ($O^{2-}$) | Hematite | $Fe_2O_3$ | Ore of iron, pigment |
| | Magnetite | $Fe_3O_4$ | Ore of iron |
| | Corundum | $Al_2O_3$ | Gemstone, abrasive |
| | Ice | $H_2O$ | Solid form of water |
| Sulfides ($S^{2-}$) | Galena | $PbS$ | Ore of lead |
| | Sphalerite | $ZnS$ | Ore of zinc |
| | Pyrite | $FeS_2$ | Sulfuric acid production |
| | Chalcopyrite | $CuFeS_2$ | Ore of copper |
| | Cinnabar | $HgS$ | Ore of mercury |
| Sulfates ($SO_4^{2-}$) | Gypsum | $CaSO_4 \cdot 2\,H_2O$ | Plaster |
| | Anhydrite | $CaSO_4$ | Plaster |
| | Barite | $BaSO_4$ | Drilling mud |
| Native elements (single elements) | Gold | $Au$ | Trade, jewelry |
| | Copper | $Cu$ | Electrical conductor |
| | Diamond | $C$ | Gemstone, abrasive |
| | Sulfur | $S$ | Sulfa drugs, chemicals |
| | Graphite | $C$ | Pencil lead, dry lubricant |
| | Silver | $Ag$ | Jewelry, photography |
| | Platinum | $Pt$ | Catalyst |

### *1.2.6 Gemstones*

**Table 3.A Important Gemstones**

| Gem | Mineral Name | Prized Hues |
|---|---|---|
| **Precious** | | |
| Diamond | Diamond | Colorless, yellows |
| Emerald | Beryl | Greens |
| Opal | Opal | Brilliant hues |
| Ruby | Corundum | Reds |
| Sapphire | Corundum | Blues |
| **Semiprecious** | | |
| Alexandrite | Chrysoberyl | Variable |
| Amethyst | Quartz | Purples |
| Cat's-eye | Chrysoberyl | Yellows |
| Chalcedony | Quartz (agate) | Banded |
| Citrine | Quartz | Yellows |
| Garnet | Garnet | Reds, greens |
| Jade | Jadeite or nephrite | Greens |
| Moonstone | Feldspar | Transparent blues |
| Peridot | Olivine | Olive greens |
| Smoky quartz | Quartz | Browns |
| Spinel | Spinel | Reds |
| Topaz | Topaz | Purples, reds |
| Tourmaline | Tourmaline | Reds, blue-greens |
| Turquoise | Turquoise | Blues |
| Zircon | Zircon | Reds |

Precious stones or gemstones are not grouped by mineral chemistry or crystal structure. Instead, gemstones are minerals that have been grouped by colour. This inaccuracy comes from historical practices of our ancestors by identifying precious stones by colour such as rubies, sapphires, emeralds etc. What actual constitutes a gemstone are minerals that contain chemical impurities. For example the mineral corundum is a common gemstone or can be a nonprecious mineral. When corundum is of gem quality and has vivid colours such as yellow, purple or blue, it is called a *sapphire*. However, when corundum is a vivid red colour it is called a *ruby*.  If it is not of gem quality, it is simply called corundum.  A precious stone of gem quality is generally cut and polished by a professional to achieve the beautiful faceted stones one typically sees in jewelry.

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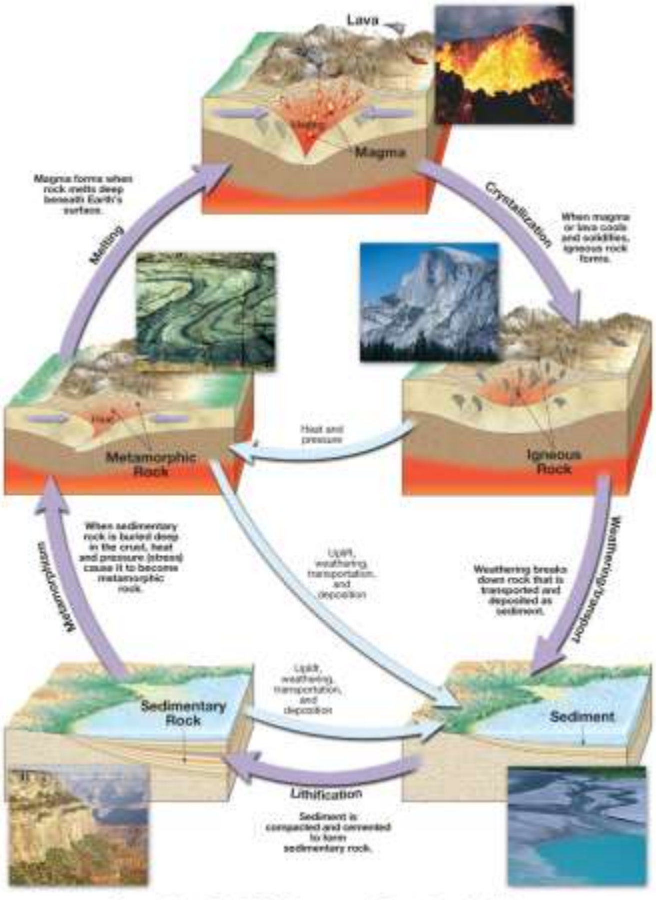
## 1.3 Rocks and the Rock Cycle

A rock is a solid or cohesive aggregate of one or more minerals.  This means that a rock consists of many individual mineral grains of not necessarily the same mineral. These minerals are held together in a solid mass.  Rocks are divided into three classes depending on the process that formed them. The categories: igneous, sedimentary or metamorphic represent the rock cycle that are responsible for forming all rock types on earth.  Igneous rocks form by crystallizing from a hot, typically silicate melt.  They occur in the deep crust and make up the whole mantle of the earth.  Processes such as volcanoes bring these rocks to the surface. Sedimentary rocks form at or near the earth's surface at very low temperatures.  These rocks are usually the weathered products of preexisting rocks.  Metamorphic rocks are those that have been formed by the application of heat or pressure.  Preexisting rocks are altered or transformed by metamorphism to form new metamorphic rocks.  Pressures and temperatures increase with depth within the earth.

The idea that rocks are continuously subjected to change through time constitutes the concept of the *rock cycle*.



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For example an igneous rock may be erupted out of a volcano as a lava, cool and harden. This hardened igneous rock is now exposed at the earth surface to weathering processes. This rock is broken up into tiny fragments by erosion and is carried away by streams or rivers and is deposited as a loose sediment. As this sediment is buried by more sediments being deposited on top, the lower sediment hardens and becomes a sedimentary rock. Sedimentary and igneous rocks can both be subject to pressure and temperature if they are buried deeply or hot fluids rise from the mantle and heat the rock. Buried rock re-melts and can form once again as an igneous rock. And so the cycle continues.

Each class of the rock cycle will be discussed in detail in subsequent units. We will look at igneous, sedimentary and metamorphic processes. We will also look at the different types or ore and ore deposits that can be associated with each rock type and process.