



## 4. Minerals: rock's elementary building block

### 4.1. What is a mineral?

A **mineral** is a naturally occurring solid inorganic substance composed of a regular 3D arrangement of atoms repeating in all directions (**crystal structure**). Each mineral can be identified with a chemical formula. A mineral growing freely form **crystals** whose external geometrical shape reflects the internal regular arrangement of atoms. The crystal structure of a mineral depends on its chemical composition. It also depends on the temperature and pressure at which it formed. For example, graphite and diamond have the same chemical composition (carbon) but they formed in very different conditions of pressure and temperature and therefore are characterized by very different crystal structures. Since diamond forms at very high pressure deep inside the Earth's crust, the atoms of carbon in diamond are more densely packed than in graphite. Minerals with the same chemical composition but different crystal structures like diamond and graphite are called **polymorphs**.

Examples of minerals and their chemical formula:

Quartz:  $\text{SiO}_2$ , Olivine:  $(\text{Fe, Mg})_2\text{SiO}_4$ , Halite:  $\text{NaCl}$ , Calcite:  $\text{CaCO}_3$ , Pyrite:  $\text{FeS}_2$ , Hematite :  $\text{Fe}_2\text{O}_3$

### 4.2. Structure of matter and chemical bonds

Minerals are made of atoms. The simplest way to represent an **atom** is a nucleus composed of protons and neutrons surrounded by electrons occupying different orbits or shells. There is a specific number of electrons that can occupy each shells. Since atoms are electrically neutral, the number of protons in the nucleus is equal to the number of electrons. Each element is characterized by a specific number of proton(s)/electron(s) called the **atomic number**: H (1), C (6), N (7), O (8). Atoms of a given element characterized by different numbers of neutrons are different **isotopes** of that element. For example, the notation for an isotope of carbon that has 6 protons and 6 neutrons is carbon-12 or  $^{12}\text{C}$ . Two other isotopes of carbon are  $^{13}\text{C}$  (6 protons and 7 neutrons) and  $^{14}\text{C}$  (6 protons and 8 neutrons). There are two types of isotopes: **stable isotopes** and **radioactive isotopes** (or radioisotopes). The latter decay into stable or radioactive isotopes over time while emitting radiations. For example,  $^{14}\text{C}$  is radioactive and decays into the stable isotope  $^{14}\text{N}$ .

Since a neutron has a certain mass, different isotopes of a same element have a different mass. The mass of an atom can be approximated to the sum of masses of the protons and neutrons in the nucleus. By convention, the mass of the isotope of carbon  $^{12}\text{C}$  (6 protons and 6 neutrons) is 12 atomic mass units. The **atomic mass** of an isotope is the sum of the number of protons and neutrons in the nucleus. The atomic mass of an element depends on the relative abundances of its isotopes (e.g. the atomic mass of carbon is 12.011 because  $^{12}\text{C}$  is by far the most abundant isotope of carbon, i.e. 98.9% of all carbon).



The electrons participating in chemical bonds are usually those of the outermost shell. Chemical bonds allow the atoms to achieve a more stable electronic configuration. There is an optimal number of electrons on the outermost shell which can be achieved through chemical bonds. For example, the optimal configuration for C, N and O is to have 8 electrons occupying the outermost shell. In minerals, three types of chemical bonds exist: the **covalent bond**, the **ionic bond** and the **metallic bond**.

In **Covalent bonds**, an atom shares one or more electrons with another atom. The electrons of one atom are attracted by the positively charged nucleus of the other atom and vice versa. This configuration results in very strong chemical bonds.

*Example:* diamond in which each atom of carbon is surrounded by 4 atoms and each atom shares 4 electrons with its neighbors. Note that another mineral has the same chemical composition: graphite. However, graphite has a very different crystal structure. In graphite, the atoms of carbon are arranged in sheets in which atoms are held together by covalent bonds but the sheets are held together by a much weaker type of chemical bond (similar to the metallic bond described below). This makes graphite much less hard than diamond. The softness of graphite can be observed every time one uses a pencil to write or to draw. Pencil cores are made of graphite.

In **ionic bonds**, an atom gains one or more electrons from another atom (transfer of electron(s)). An atom that has lost one or more electrons is called a **cation** (positively charged ion). An atom that has gained one or more electrons is called an **anion** (negatively charged ion). The ionic bond results from the attraction between ions of opposite charges.

*Example:* halite NaCl (table salt) in which each atom of chlorine “takes” one electron from an atom of sodium. The atom of chlorine that has gained one electron is negatively charged (anion) and attracted by the positively charged sodium (cation).

In **Metallic bonds**, atoms which have a strong tendency to lose electrons (cations) are surrounded by free-moving electrons (delocalized electrons). The cations are held together by their attraction to the surrounding electrons.

*Example:* copper which has one electron on the outermost shell that is only weakly attracted by the nucleus. In the metal copper, these outer electrons are not bounded to the nuclei and move freely. The cations  $\text{Cu}^+$  are held together by their attraction to the free electrons surrounding them.

The most common mineral family on Earth is the family of **silicate minerals**. Silicate minerals are often characterized by a combination of covalent and ionic bonds. The basic structural unit of silicate minerals is the silicon-oxygen tetrahedron or  $[\text{SiO}_4]^{4-}$  (silicate anion) in which one atom of silicon is surrounded by 4 atoms of oxygen and shares one electron with each oxygen. Each atom of oxygen can share one electron with another atom of silicon (covalent bond) or bind with positively charged ions (ionic bonds).

Examples:

(1) Quartz ( $\text{SiO}_2$ ) is one of the most common silicate minerals of the continental crust. Quartz is composed of a juxtaposition of silicon-oxygen tetrahedra. Each atom of oxygen is linked to 2



silicon atoms by electron sharing. There is only one type of chemical bond in this mineral: covalent bonds.

(2) Olivine is a silicate rich in Mg and/or Fe ( $(\text{Fe, Mg})_2\text{SiO}_4$ ) very abundant in the upper mantle and common in the oceanic crust. In olivine, the silicon-oxygen tetrahedra are linked to the metallic cations  $\text{Fe}^{2+}$  or  $\text{Mg}^{2+}$  by ionic bonds. The -4 charge of each silicate anions is balanced by the +2 charge of two metallic cations. There are two types of chemical bond in this mineral: covalent and ionic bonds.

There are many other combinations of silicate anions and other elements which produce a broad variety of crystal structures in the family of silicate minerals (e.g. single-chain silicates, double-chain silicates, sheet silicates...).

### 4.3. Crystallization processes

**Crystallization** is the process by which atoms in a gas or a liquid assemble in an orderly 3D pattern (crystal lattice) to form a solid substance (mineral crystal).

Crystallization occurs typically in the following three contexts:

(1) **Saturation**: When dissolved anions and cations in an aqueous solution reach a certain concentration, they become saturated and if water is removed by evaporation or if more ions are added to the solution the anions and cations combine to form crystals. One example is the precipitation of salt ( $\text{NaCl}$  = halite = table salt) when seawater evaporates in a pond, lake or embayment. The rock produced by accumulation of minerals precipitated from saturated brines is called **evaporite** (see chapter on sedimentary rocks).

(2) **Phase change** (*liquid-solid, gas-solid*): Crystals can form when the temperature of a liquid drops and the liquid solidifies into a solid — **solidification**. This happens when water freezes to form ice. It also happens when **magma** (molten rock) cools and minerals crystallize to form a solid rock, i.e. igneous rock (see chapter on igneous rocks). The transformation of a gas into a solid without transiting by the liquid phase is called **deposition**.

(3) **Biomineralization**: Many organisms are capable of precipitating minerals to form a skeleton or shell. Our bones and teeth are mineralized structures. In the marine world, the most common biomineral is calcium carbonate ( $\text{CaCO}_3$ ). It is produced by diverse organisms such as reef corals, coralline algae, mollusks, urchins, sea stars, and foraminifera (one kind of large single-celled organism). Another common biomineral is silica ( $\text{SiO}_2$ ) and is produced by several groups of marine microorganisms such as radiolarians and diatoms.

### 4.4. Common families (or classes) of minerals

The most common minerals are the **silicate minerals**. They form most of the Earth's mantle and crust. I already provided some details about their structure.



Another class of minerals comprises the **carbonates**. The most common carbonate mineral is  $\text{CaCO}_3$  already mentioned above in relation with biological mineralization. The basic structural unit of carbonates is the carbonate anion  $(\text{CO}_3)^{2-}$ . In carbonate minerals, carbonate anions are arranged in sheets and are bound to cations located between the sheets. In the case of  $\text{CaCO}_3$ , the cations are  $\text{Ca}^{2+}$ . Calcium carbonate can also precipitate abiologically in seawater saturated in  $\text{Ca}^{2+}$  and  $(\text{CO}_3)^{2-}$  or even (in relatively rare cases) crystallize out of a cooling magma.

Other minerals that can form in the context of saturated brines leading to the formation of evaporites include the **halides** and **sulfates**. The most common halide mineral is halite ( $\text{NaCl}$ ). Another common mineral that can form during evaporation of seawater is gypsum, a calcium sulfate. The basic structural unit of sulfates is the sulfur-oxygen tetrahedron, i.e. an atom of sulfur surrounded by four atoms of oxygen ( $\text{SO}_4^{2-}$ ). In the case of gypsum, water is also present in the crystal lattice and the chemical formula of gypsum is  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ . When gypsum is buried under younger layers of sedimentary rocks, the increasing pressure and temperature squeeze out the water molecules and gypsum becomes anhydrite ( $\text{CaSO}_4$ ).

Another common class of minerals includes the **sulfides**. In sulfides, the sulfide anion ( $\text{S}^{2-}$ ) is bonded to metallic cations (e.g.  $\text{Fe}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cu}^{2+}$ ). An example of sulfide is pyrite ( $\text{FeS}_2$ ). Sulfides are important because they represent a major source of metals for the industry (metal **ores**). A geological setting in which sulfides commonly form is the ocean floor near mid-ocean ridges. Seawater percolates through cracks in the ocean crust where it is heated near spreading centers. The hot seawater reacts with the rock of the ocean crust (basalt) and dissolves iron, zinc, copper and sulfur. When this hot water returns to the ocean and meets the cold seawater, the sudden drop of temperature triggers the precipitation of sulfides which accumulate around the hot spring and builds a chimney called a **black smoker**. Black smokers are of huge interest not only because they are formed of metal sulfides but also because they shelter a diverse ecosystem whose primary source of energy is not sunlight (photosynthesis) but chemical reactions (chemosynthesis, e.g.  $\text{CO}_2 + 4\text{H}_2\text{S} + \text{O}_2 \rightarrow \text{CH}_2\text{O} + 4\text{S} + 3\text{H}_2\text{O}$ ). Chemosynthesis can be performed by specialized bacteria and can sustain a diverse ecosystem in the deep ocean without any sunlight.

Another common class of minerals is called **oxide**. In oxides the oxygen is bound to other atoms, usually metallic cations, through ionic bonds. One very common oxide and major source of iron for the industry (iron ore) is the iron oxide called hematite ( $\text{Fe}_2\text{O}_3$ ). If the anion is not  $\text{O}^{2-}$  but  $\text{OH}^-$ , the mineral is called a hydroxide. Another iron ore is the iron hydroxide goethite ( $\text{FeO}(\text{OH})$ ). Among the most famous rocks rich in iron oxide are the **banded iron formations** which are composed of thin layers of sediments rich in iron oxide. These rocks are usually Precambrian in age (older than  $500 \times 10^6$  years) and they probably formed when the oxygen produced by photosynthesis reacted with the dissolved iron in the ocean. Their study is important to understand the history of the atmospheric oxygen of our planet (see the chapter on the evolution of life for further explanations).



**Native elements** are minerals composed of a single element. Sometimes they can be combined in alloys like the iron-nickel alloy of metallic meteorites. Other examples of native element minerals are native gold, native copper, graphite and diamond.

#### 4.5. Physical properties of minerals

Minerals can be characterized by their physical properties. Some of the properties that can be used to characterize and identify minerals are listed below.

**Hardness:** harder minerals are able to scratch softer minerals. The hardest mineral is diamond which is able to scratch all the others. On the **Mohs scale** of hardness, diamond has a hardness of 10. The softest mineral is talc and has a hardness of 1. The hardness of a mineral depends on its structure and chemical bonds.

**Cleavage:** it is the tendency of minerals to split along specific planes. Chemical bonds along these cleavage planes tend to be weaker and thus break more easily.

**Fracture:** a mineral may be broken along surfaces that are not cleavage planes. These surfaces are called fractures. The quality (shape and texture) of the broken surface is one criteria used to identify minerals (e.g. the conchoidal fracture of quartz, the splintery fracture of fibrous minerals like asbestos).

**Luster:** it is the way the surface of a mineral reflects light. Different terms are used to qualify mineral luster (e.g. metallic, vitreous...).

**Color:** the color of a mineral is not always a good identification criterion because it may depend on the presence of tiny amounts of particular elements. For instance, quartz is colorless but amethyst, a variety of quartz with trace amounts of  $\text{Fe}^{3+}$ , is violet. Citrine, another variety of quartz, is yellow and can be obtain by heating amethyst. **Streak** refers to the color of the mark left by a mineral when it is scratched on an abrasive surface such as a plate of unglazed porcelain (e.g. the reddish brown streak of hematite).

**Density:** the density of a mineral ( $\text{g/cm}^3$ ) depends on the way atoms are packed and on the mass of individual atoms. Diamond and graphite are both composed of carbon but diamond is denser because the atoms of carbon in diamond are packed more closely. Fe-olivine ( $\text{Fe}_2\text{SiO}_4$ ) and Mg-olivine ( $\text{Mg}_2\text{SiO}_4$ ) have a similar structure but Fe-olivine is denser than Mg-olivine because the atomic mass of iron is much greater than that of magnesium. The density of minerals is commonly expressed in terms of **specific gravity** which is the ratio of the weight of a volume of a mineral to the weight of an equal volume of water at a temperature and pressure of reference. The specific gravity of water is 1. The specific gravity of halite is 2.16 and that of pyrite is 5.

**Crystal habit:** it is the shape of an individual crystal or an aggregate of crystals of a given mineral. The crystal habit of a mineral reflects the internal arrangement of atoms as well as the speed and direction of crystal growth.