# INSIDE MINERALS – Tutorial Script

Rocks are the books that we read to learn the history of our Earth. Minerals, fossils, glass, and other components that make up rocks are the words that tell the story within the book. In this video tutorial we will review minerals – how they form and why, so that later when we see minerals in rocks, we can use them as clues to the formation history of the rock and its place in the larger geologic history of our planet. Note: this video tutorial assumes an understanding of basic rock types and basic chemistry, as described in the Rock Cycle and Water Molecule Shape video tutorials.

Technically, to be called a mineral, a substance must meet these five requirements: be naturally occurring, be solid, have a crystal structure, be defined by a chemical formula, and be inorganic. The first of these, naturally occurring, means that human-made substances, like silicon wafers, plastics, and lab-made diamonds are not technically considered minerals. Because they are human made, we won't see them in rocks (although future geologists might!). The second of these, solid, means that water at room temperature is not a mineral, but below its freezing point, as solid ice, it is. The third of these means that there must be a particular arrangement of atoms that is a regular, repeating pattern. For example, ice at the atomic level looks like six water molecules connected in a ring, each ring connected to another ring like a chain link fence that is 3-dimensional. The pattern is repeating and consistent and ultimately determines the form the crystals will take when they grow. Glass, on the other hand, forms as a liquid solidifies too quickly for atoms to bond in any kind of crystalline pattern. All glass, including glass that forms when lava is thrown through the air in a volcanic eruption, is natural and solid, but not crystalline and thus not a mineral. The fourth of these, a chemical formula, means that all instances of a particular mineral will have the same relative ratios of each atom in its crystal structure. Ice, for example, will always be two hydrogens for every one oxygen: $H_2O$. Quartz will always be one silicon for every two oxygens: $SiO_2$. The last of the mineral requirements, inorganic, has many different definitions depending upon who is using the word, but for the purposes of defining minerals, inorganic means that the chemical formula can't contain Oxygen, Carbon, and Hydrogen (all three together).

Sometimes a mineral might have very small amounts of impurities, substitutions of a particular ion in the crystal structure with another ion of a similar size or charge. In such cases, the crystal structure is modified slightly in the area of the substitution to accommodate the different size, shape, or charge of the substituting ion. Certain chemical and physical characteristics of the mineral can change as a result. For example, light will no longer interact with the mineral in the same way it did before. The impurities will absorb certain colors and reflect others. Corundum is a good example of ionic substitution changing color. The chemical formula for corundum is $Al_2O_3$. With a little titanium and iron substitution for aluminum corundum will turn blue (and is called sapphire); with a little chromium substitution for aluminum, corundum turns red (and is called ruby). Note: If the substitution is significant enough to change the chemical formula, it's a new mineral.

Sometimes two minerals will have the same chemical formula, but different crystalline structures. These minerals are called **polymorphs** (a single chemical formula with many (poly) forms (morph)). How is this possible? Because they formed under different geologic conditions – different pressures and temperatures. This one difference, crystalline structure, is enough to radically change the physical and chemical characteristics of the mineral. Recognizing different minerals in rocks helps us to learn more about the temperatures and pressures to which a rock was subjected. For example, a mineral with the simple chemical formula, Carbon (100% carbon), is graphite at surface temperatures and pressures, but when pressures get high enough, like those found at the base of the continental crust, becomes diamond. Another set of polymorphs that are used commonly to identify metamorphic settings is $Al_2SiO_5$. At high pressures and low temperatures, this mineral is kyanite; at high pressures and high temperatures, the atoms have a different crystal structure, and the mineral is sillimanite. At lower pressures (low to moderate temperatures), again a different crystal structure, and the mineral is andalusite. All three of these minerals have the same chemical formula, but different crystal structures.

Minerals come in all shapes, sizes, and compositions. Common families of minerals include oxides, such as iron oxides (iron + oxygen) or rust minerals; sulfides, such as Galena, a mineral made only of lead and sulfur; sulfates, where the sulfur is combined with oxygen into a sulfate ion and then bonded to an electron donor like Calcium – example: gypsum; carbonates, like calcite, which is formed from calcium bonded to a carbonate ion (carbon plus oxygen); salts, like halite (table salt, NaCl); and native element minerals, those made of only a single element, like pure carbon graphite or diamond. Silver, Copper, Gold, and Sulfur are also found as native elements.

The most common mineral family on the planet are silicates made up of the two most abundant atoms in earth's crust: oxygen and silicon. The building block of all silicates is the **silicon-oxygen tetrahedron**. The silicon atom has 14 protons. Its neutral form will also have 14 electrons – 2 in the first shell, 8 in the next, leaving 4 electrons in the outermost shell or orbitals. As all atoms will bond in ways that fill their outermost shells, that means that silicon is looking for 4 bonding electrons. Oxygen has 8 protons and in its neutral form 8 electrons – 2 in the first shell, 6 in the next. That means that oxygen is looking for 2 more electrons to fill its outer shell. Silicon and oxygen form covalent bonds in a tetrahedral arrangement. Silicon shares one of its electrons with each oxygen and vice versa. As a result, silicon gets 4 extra electrons and becomes satisfied, the oxygens however are only partially satisfied: they are each still looking for one more electron each. How these oxygens find their additional electron is what makes up the diversity within the silicate family of minerals.

The simplest way for the oxygen in the silicon-oxygen tetrahedrons to get their additional electrons is to form ionic bonds with atoms that have one or two extra electrons they want to get rid of. When they give these electrons to the oxygen, they become positively charged and the oxygens become negatively charged, and the two are attracted in an ionic bond. **Olivine** has the chemical formula, $(Fe,Mg)_2SiO_4$. Notice the beginning of the chemical formula shows that there are two electron-giving ions for every silicon-oxygen tetrahedron in the mineral, and those two ions are either iron ($Fe^{2+}$) or magnesium ($Mg^{2+}$). The ratio of this iron to magnesium will vary depending on formation. Each ion, whether iron or magnesium, will give one electron to one oxygen and another to an adjacent tetrahedron's oxygen. In this way, they glue or bond the tetrahedrons together into a crystalline pattern. Because at the molecular level these bonds do not ever line up along a plane, when we break the mineral it will also never break along a plane (when minerals break along planes we call it **cleavage**). Breaks that are not along a plane are called **fracture**. So Olivine has no cleavage. It only fractures. Olivine also has the lowest silicon:oxygen ratio of all major rock-forming silicates (1:4). It crystallizes from molten rock (magmas) underground at the highest temperatures from magmas with the lowest silicon composition. It is one of the first minerals to form when magmas produced by melting the mantle rise through the crust and begin to cool.

As magmas crystallize, the silicon content of the remaining melt will increase relative to the other ingredients. Similarly the minerals that form will have increasing silicon:oxygen ratios. How so? The oxygens partially satisfy their electron needs by covalently bonding with another silicon on another silicon:oxygen tetrahedron. They share electrons with and covalently bond with two silicon atoms, connecting two tetrahedra. At the lower silicon:oxygen ratios in a cooling magma, tetrahedra will first combine in single chains, which happens with the mineral **pyroxene**. When all the tetrahedra share two of their oxygens with their neighbors in a single chain, the resulting silicon: oxygen ratio is 1:3. Two of the oxygens are satisfied, but two are still looking for extra electrons. Where do they find these? From the same characters that helped with olivine: iron and magnesium and other elements such as calcium that will provide electrons and turn themselves in the process into positive ions. So each single chain in a pyroxene is bonded to a nearby chain with a line of ionic bonds. The chemical formula for pyroxene is Iron, Magnesium, or Calcium $SiO_3$. Each iron or magnesium or calcium shares two electrons, one each with an oxygen on adjacent chains. In this way, they glue or bond the chains together. When these minerals break, they will break most easily along the ionic bonds, which line up nicely between chains. As such, pyroxenes will cleave in square columns (two planes at 90°).

As the silicon content of the magma increases, the tetrahedra start to bond with each other even more. The next step is double chains. One of the unsatisfied oxygens in each tetrahedron in a chain shares an electron with tetrahedra in another chain, so the two chains are glued together with covalent bonds. You now have a double chain. The unsatisfied oxygens will create ionic bonds with atoms that want to give away electrons, and we see a crystal structure very similar to single chain tetrahedron, including cleaving in square-like columns, only in this case the angles of the column sides are 60 and 120°. The ratio of silicon or aluminum to oxygen is 1:2.75. An example is the mineral **hornblende**, part of the amphibole family. Hornblende has a chemical formula of Calcium, Magnesium or Iron, 4 of them, Silicon or Aluminum, 8 of them, 22 oxygens and some water $(OH)_2$. As you can see from the chemical formula, water (OH) is incorporated into this mineral, and aluminum starts to substitute for silicon in the tetrahedra. Calcium, Magnesium, and Iron are all the electron donors that surround and glue together the double chains.

The next stage of silica increase leads to bonding of many chains into a single sheet. 3 oxygen in each tetrahedra are covalently bonded to silicon atoms in another tetrahedra. Each sheet connects to a sheet above and below by ionic bonds. These minerals are easily identifiable because they cleave between sheets along those ionic bonds. Good examples are in the **mica** family: **muscovite** and **biotite**. The silicon or aluminum to oxygen ratio is now 1:2.5. The chemical formula of biotite is Potassium, (Magnesium, Iron)3, Aluminum, Silicon$_{3,}$ 10 oxygens, and again 2 waters. Again, as silica content is rising in cooling and evolving magmas, so too is water and aluminum and hence these begin to appear in the minerals that are forming.

The last arrangement of silicon-oxygen tetrahedra, which occurs with the largest concentration of silica in the most evolved magmas is the three-dimensional framework. In this arrangement, every oxygen in every tetrahedron is sharing itself with another silicon in an adjacent tetrahedron. The ratio of silicon to oxygen is 1:2, and in its pure form, its chemical formula is $SiO_2$, and the mineral is **quartz**. There are no ionic bonds. All oxygens are satisfied through covalent bonds with silicon. And none of these bonds align in a plane in the crystal structure, so there is no cleavage. Quartz only fractures, and this is one of its main distinguishing characteristics.

If in this last arrangement of the 3-dimensional framework, there is some aluminum substituting for silicon, then ionic bonds are required to fully satisfy the aluminum, which has a higher charge than silicon. Aluminum has only three electrons in its outer shell and thus needs five more to be satisfied as opposed to the 4 of silicon. Potassium, Calcium, and Sodium can act as electron donors, and the ionic bonds formed with these will align in two different planes that meet at 90°. This is what we see in the **Feldspar** family. The chemical formula for this family is, generally, (Potassium, Calcium, or Sodium), Aluminum, 3 Silicon, and 8 Oxygens. Feldspars, because of the way the ionic bonds are aligned, cleave at right angles.

So to review that sequence, silicate minerals, the most common rock-forming minerals on Earth's surface, have the basic silicon-oxygen tetrahedron as their building block. As silicon content increases in the magma from which these minerals crystallize, the ratio of silicon to oxygen will increase in the minerals. This increase is accomplished through tetrahedra covalently bonding to each other in increasing numbers of directions, starting from single tetrahedra in a sea of ionic bonds, olivine, to covalently bonded single chains bonded to each other with ionic bonds as in pyroxene, to covalently bonded double chains that bond to themselves with ionic bonds, as in hornblende, to covalently bonded sheets that bond one sheet to the next with ionic bonds, as in the mica minerals, muscovite and biotite, to a three dimensional framework of covalently bonded tetrahedra in 3 directions in quartz and feldspars. So what? How is this information useful to us? Ultimately, when we can identify a particular silicate mineral in a rock, and through that identification know whether it's a high- or low-silica silica mineral, we learn something about its formation environment, the composition, temperature, and evolution of the magma from which it crystallized, and even things about the eruption style of the volcanic center from which it was produced including the potential hazards associated with that volcanic center. We will learn more about that as we study rocks in the weeks to come.

Pause now.

For more information and more detail, continue on to the next video in this series.

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Minerals Series:
Part I: The Rock Cycle
Part II: Water Molecule Shape
Part III: Inside Minerals
Part IV: Identifying Minerals
Part V: Minerals Addendum

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