

Tutorial Earth History 6: Minerals and Mineralogy

Rocks are part of our lives, and in some cases form a basis for life. We build houses with them, some attribute a healing effect to them, for others they are just good enough to throw with. In this article we look at the basics of mineralogy.

Elements of the Earth's Crust

For a better understanding, it is advisable to learn about the basics of the structure of atoms. For this there is also a contribution from my side, which you can have a look at.¹

There are over 100 elements in the periodic table, but most of them are extremely rare in geological environments. It turns out that there are only eight elements in the Earth's crust that make up over 99% of all rocks on Earth. These are oxygen, silicon, aluminum, iron, calcium, sodium, potassium and magnesium. These are the "Big Eight" (Fig. 1).

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Element	Symbol	Percentage of Crust	
		By Weight	By Atoms
Oxygen	O	46.6%	62.6%
Silicon	Si	27.7%	21.2%
Aluminum	Al	8.1%	6.5%
Iron	Fe	5.0%	1.9%
Calcium	Ca	3.6%	1.9%
Sodium	Na	2.8%	2.6%
Potassium	K	2.6%	1.4%
Magnesium	Mg	2.1%	1.8%
All others		1.5%	0.1%

Abb. 1: Elements of the Earth's Crust

An average rock contains 46 percent of oxygen by weight, but 94 percent by volume! Why is this so? Not only is oxygen a light element, but its ion has a large radius. Why is oxygen by far the most abundant? If we look at the other common elements in the Earth's crust, we find that oxygen is the only one that forms an anion (Fig. 2); and something has to balance all the positive charges of the remaining seven cations.

¹ <https://internet-evoluzzer.de/molekularbiologie-der-zelle-teil-2-atome-periodensystem-und-atombindung/>

Oxygen is very abundant in air and water, and therefore combines with almost every cation.



Fig. 2 Ion radii of some anions and cations.

Next in abundance is silicon, which (like carbon) is an element that readily combines into long chains and forms complex three-dimensional structures. This is important in the production of common rock-forming minerals, which are usually combinations of silicon and oxygen, or silicates.

In third place is aluminum, which is also an element that readily combines with silicon to form complex three-dimensional arrangements, so that many silicate minerals are rich in aluminum. These three elements happened to be the most common rock-forming elements during Earth's formation.

The remaining five common elements occur much less frequently than the "Big Three," and each make up only 5% or less of the Earth's crust. All five are metallic cations that combine with oxygen or with complex silicate structures to form the wide variety of minerals. Note that they have different charges: Sodium and potassium are both cations with a +1 charge, and they can sometimes substitute for each other in a mineral because they have the same charge. Similarly, calcium and magnesium and iron (Fe²⁺) are common +2 cations and can substitute for each other in many minerals. About 1.5% of the Earth's crust is made up of elements that are not part of these "Big Eight".

Even more surprising is which elements are not included in the "Big Eight". Hydrogen and helium are the most abundant elements in much of the solar system, especially the Sun and the outer planets (Jupiter, Saturn, Uranus, Neptune). But they are rare on Earth, except where hydrogen combines with oxygen to form water.

Why? When the Earth formed, it was not large enough to have strong gravity to hold these elements, and they floated off into space. Giant planets like Jupiter and Saturn have much more mass and thus more gravity, and they have hydrogen and helium in them. Phosphorus and sulfur are also relatively rare and concentrated only in special environments. Perhaps most surprising is how rare carbon is in crustal rocks. Carbon is, after all, the building block of all life! There are some minerals and rocks that contain carbon, but they are rare compared to silicates.

Minerals

Now that we have the basis of the elements available in the earth's crust, let's see how they combine to form more complex molecules known as minerals. The word "mineral" has all sorts of casual and inconsistent meanings in popular culture, but to geologists and chemists it has a very strict and clear definition. A mineral occurs naturally, is inorganic, has a certain crystalline structure, has a certain chemical composition, and has characteristic physical properties.

Let's discuss these properties individually.

Naturally occurring: there are many complex compounds in the world, but if they are not naturally produced, they are not minerals. So a synthetic diamond produced in a laboratory has all the properties of a diamond extracted from the earth, but technically it is not a mineral. Ice formed as ice crystals or snowflakes is mineral, but not the ice in our ice cubes in a Coke glass. Most things sold in a health food store that are called "minerals" have been synthetically produced and therefore are not a mineral, as a scientist uses the word.

Inorganic: Organic substances are made of the element carbon, so minerals are not usually made of carbon. However, there are a handful of important minerals with carbon (such as the mineral calcite or CaCO_3), so in this context we use "organic" to refer to substances with carbon-hydrogen bonds, as we do with nutrients such as sugars, amino acids, and fats. Sugar forms beautiful crystals, but because of its hydrocarbon bonds, it is organic and therefore not mineral.

Unique crystalline structure: like the word "mineral," the word "crystal" has a different meaning to a scientist than it does in popular culture. Usually, people use the word "crystal" to describe anything that sparkles. By scientific definition, a crystal must have a regular three-dimensional arrangement of atoms in its internal structure that is repeated over and over again. This three-dimensional arrangement is called a lattice. It is analogous to the regularly repeating pattern in wallpaper. For example, the atoms of salt crystal (sodium chloride or NaCl , Fig. 3) are arranged in a cubic pattern, with each sodium or chlorine atom forming a 90° angle with the others. The same lattice is found in the mineral galena, which is equal parts lead and sulfur (lead sulfide or PbS). All minerals have a regular three-dimensional lattice, often very complex and with many other angles between atoms besides the 90° seen in the simple cubic lattice.

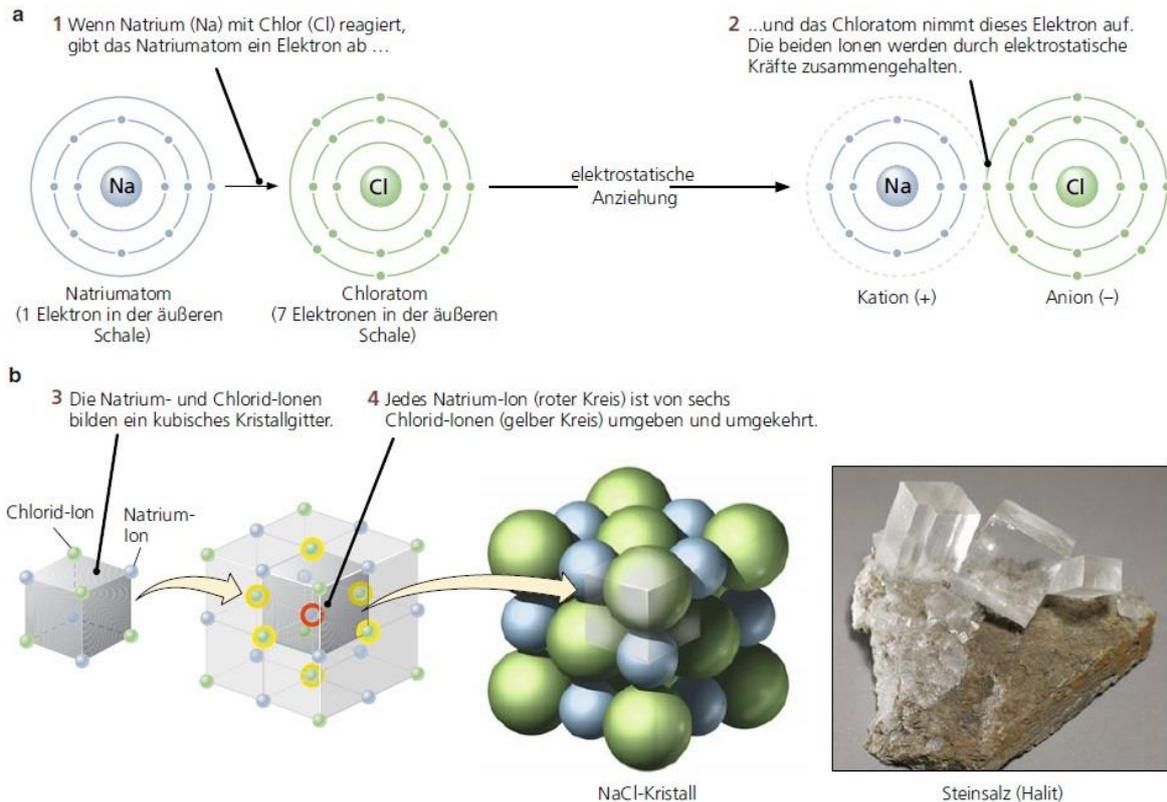


Fig. 3: Crystal structure of NaCl

Some things in nature can have a three-dimensional arrangement of atoms, but they are not regular and do not repeat. Take volcanic glass or obsidian, for example. At the molecular level, the atoms are not in a repeating pattern, but in a random ball of long chains, like a bowl of spaghetti. Technically, a glass is not actually a solid at all, but a supercooled liquid. Over very long periods of time, the glass flows slowly and changes shape. This will be clear if you ever see a piece of window glass in a very old house. When it has been in its window frame for a century or so, the glass becomes thicker at the bottom because it has flowed slowly downhill over the decades. Thus, by definition, a glass is not a crystal. A popular item in many souvenir stores are drinking goblets and chandeliers made of "cut crystal," but this is not the definition of "crystal" that scientists use.

Certain chemical composition: most minerals have a simple chemical formula. A bit of substitution, that is, an exchange of one ion for another, is allowed. For example, the mineral calcite (calcium carbonate or CaCO_3) may have a certain percentage of magnesium replacing calcium sites in its lattice and still be calcite. However, if it becomes 50:50 Ca/Mg, then it is no longer calcite, but another mineral, dolomite.

Characteristic Physical Properties: Most of the mineral properties we have discussed occur at the atomic level. However, to identify the mineral, one must know what physical properties are typical of a small piece of the mineral. These include its color, its hardness (from soft minerals such as gypsum to the hardest mineral, diamond), whether it breaks with an irregular surface or exhibits cleavage and breaks into many parallel planes (Fig. 4), and less commonly used properties such as density (lead sulfide or galena, for example, is unusually dense because it contains lead), reaction

to acid (the mineral calcite bubbles in dilute hydrochloric acid), and magnetism (the mineral magnetite is naturally magnetic). Many of these properties of minerals can be understood by knowing the crystal lattice.

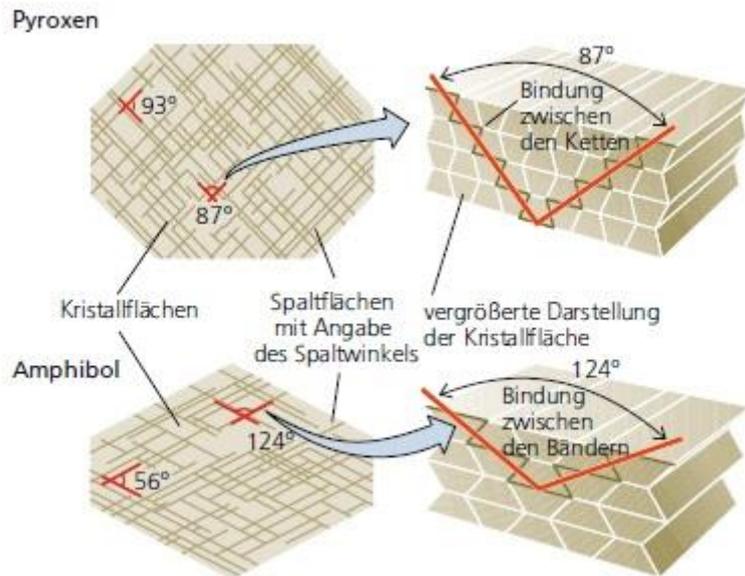


Fig. 4: Fissility of minerals.

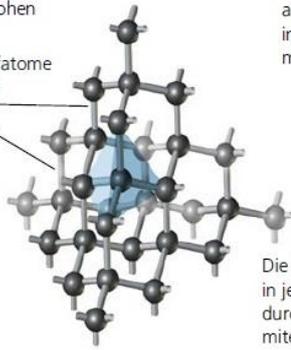
The atomic properties and crystal lattice can strongly influence the behavior of a mineral at the macroscopic level. Let us take as an example the two common minerals made of pure carbon: diamond and graphite (Fig. 5). One is the hardest substance in nature and the other the softest, yet they are chemically identical. Why are they so different? Diamond has a crystal lattice in which all the carbon atoms are tightly bound together and have very short, strong chemical bonds. This structure withstands great stress, and an experienced diamond cutter must know exactly how to divide a large stone into several smaller ones. Graphite (which is in our pencil), on the other hand, has all its carbon atoms arranged in layers, with very long, very weak molecular bonds between the layers. It is enough to slide the graphite tip of a pencil across the paper to break these weak bonds, leaving tiny graphite flakes as pencil marks on the paper.

Natürlicher **Diamant** entsteht im Erdmantel bei hohem Druck und hohen Temperaturen.

Die dicht gepackten Kohlenstoffatome werden durch starke Bindungen zusammengehalten und bilden ein Tetraeder.

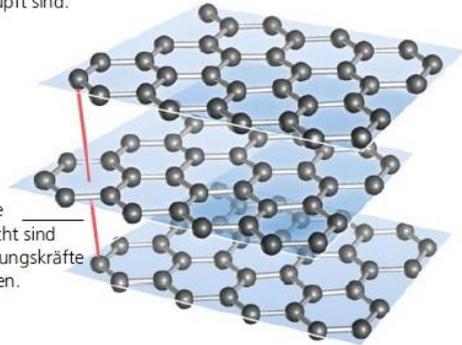


Diamant



Graphit entsteht unter niedrigeren Druck- und Temperaturbedingungen als Diamant. Seine Kohlenstoffatome sind in Schichten angeordnet, in denen die Kohlenstoffatome durch starke kovalente Bindungen miteinander verknüpft sind.

Die Kohlenstoffatome in jeder zweiten Schicht sind durch schwache Bindungskräfte miteinander verbunden.



Graphit

Fig. 5: Diamond and graphite

Another example is calcium carbonate or CaCO_3 in two different mineral lattices: calcite (the most common mineral in limestones and marble) and aragonite (Fig. 6). They have the same chemistry, but their lattices are very different and result in very different properties. The most obvious of these is that aragonite is much more soluble than calcite, so aragonite dissolves under weakly acidic conditions, but calcite does not.

Eigenschaften	Calcit	Aragonit
	 <p>Calcitkristalle sind tendenziell eher dick oder rund, wie bei diesem Kanonenspat aus Zacatecas.</p>	 <p>Aragonitkristalle sind häufig nadelig spitz. Bei dieser Stufe aus Mexiko wächst Aragonit auf Calcit.</p>
Wachstumsbedingungen	Beim Ausgasen von CO_2 aus der wässrigen Calciumhydrogencarbonat-Lösung bildet sich Calcit.	Magnesium-Ionen in der Kristallisations-Lösung verhindern das Calcit-Wachstum und begünstigen das Wachsen des Aragonits.
Zusammensetzung	Calciumcarbonat (CaCO_3) Oft Manganerhalte, aber auch Mischreihen mit anderen Carbonaten, häufig Spuren von Blei, Eisen, Zink, Barium, Strontium oder Cobalt	Calciumcarbonat (CaCO_3) Es sind nur sehr geringe Verunreinigungen anderer Elemente vorhanden.
Löslichkeit in Säuren	In Säuren wie Salzsäure unter Aufbrausen und Entwicklung von Kohlenstoffdioxid CO_2 : 	Bildet ebenfalls mit Säuren Kohlenstoffdioxid; löst sich in kohlesäurehaltigem Wasser aber besser als Calcit. Die bessere Löslichkeit des Aragonits ermöglicht einen chemischen Nachweis.

Fig. 6: Calcite and Aragonite

So for some minerals, it is not enough to know the chemical composition; the crystal lattice also makes a big difference in the properties of the mineral.

Mineral Classes

There are literally thousands of different types of minerals, but most can be divided into only a few classes based on their chemical composition. There is no room to discuss them all in a short introduction like this, but their main characteristics should be discussed. The mineral classes are: Oxides, halides, sulfides, sulfates, carbonates, and silicates (Fig. 7).

Klasse	Kennzeichnende Anionen	Beispiel
Elemente	Keine Ionen	Kupfer (Cu)
Sulfide, Arsenide und komplexe Sulfide	Sulfid-Ion (S^{2-}) Arsen- und Arsen-Schwefel- Verbindungen mit Metallen	Bleiglanz (PbS) Safflorit ($CoAs_2$) Enargit (Cu_3AsS_4)
Oxide und Hydroxide	Sauerstoff-Ion (O^{2-}) Hydroxid-Ion (OH^-)	Hämatit (Fe_2O_3) Bricit ($Mg(OH)_2$)
Halogenide	Cl^- , F^- , Br^- , I^-	Halit (Steinsalz) (NaCl)
Carbonate	Carbonat-Ion (CO_3^{2-})	Calcit ($CaCO_3$)
Sulfate und Wolframverbindungen	Sulfat-Ion (SO_4^{2-}) Wolframat-Ion (WO_4^{2-})	Anhydrit ($CaSO_4$) Scheelit ($CaWO_4$)
Phosphate	Phosphat-Ion (PO_4^{3-})	Apatit ($Ca_5[(F, Cl, OH)(PO_4)_3]$)
Silicate	Silicat-Ion (SiO_4^{4-})	Olivin (Forsterit) (Mg_2SiO_4)

Fig. 7: Mineral Classes

Oxides consist of a cation and oxygen, as is the case with various iron oxides.

Halogenides consist of a cation and a halogen, such as chlorine. Common salt (NaCl) would be an example of this.

Sulfides are a combination of cations with sulfur, as is the case with pyrite (FeS_2).

Sulfates, on the other hand, consist of a cation and sulfuric acid, as is the case with gypsum.

Carbonates consist of a cation with carbonic acid, as we know it from calcite and aragonite.

Silicates, on the other hand, are compounds of silicon, oxygen and a cation and form the most common minerals in the earth's crust.

In addition, there are the pure elements such as copper, gold, silver and diamonds, which consist of only one element.

All silicates have the same basic building block: the silicon-oxygen tetrahedron or SiO_4 unit (Fig. 8). Each class of silicate minerals uses these basic building blocks over and over again, linking them together to form increasingly complex structures.

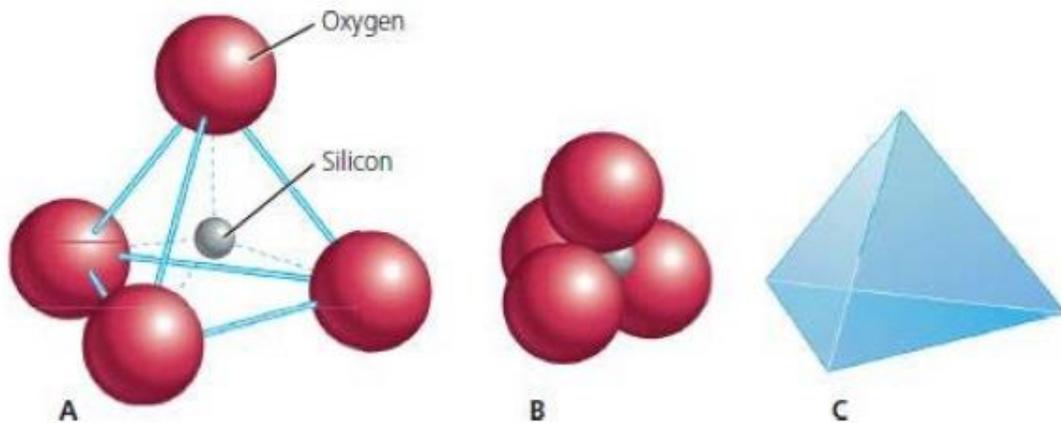


Fig. 7: Silicon-oxygen tetrahedron

The simplest silicate mineral structures (Fig. 8a) are made up of isolated tetrahedra, where the silicon-oxygen building blocks (SiO_4) do not bond directly to each other, but through the electrostatic charges of the cations (especially magnesium and iron) between them in the lattice. Common single tetrahedral minerals are the green mineral olivine, $[(\text{Mg}, \text{Fe})\text{SiO}_4]$, and garnet, which is composed of SiO_4 tetrahedra with a variety of cations to make the six major types of garnets (from reddish brown almandine to green grossular and several others).

The next most complex arrangement is found in pyroxenes (Fig. 8b), which have the SiO_4 tetrahedra linked into long single chains. Common pyroxenes include the dull greenish-black mineral augite (MgSiO_3) as well as jadeite, one of the two minerals that make up the beautiful gemstone jade. The cleavage angles for pyroxenes are 90 degrees.

The next step in silicate complexity is to connect two single chains side by side to create a double-chain silicate structure, much like the rails of a railroad track are connected. Double-chain silicates are known as amphiboles (Fig. 8c), and their lattice structure gives hand specimens their most diagnostic property through cleavage angles of about 60° or 120° (technically 56° and 124°). The most common amphibole is the lustrous pitch-black prismatic mineral known as hornblende, which occurs in many igneous and metamorphic rocks.

Mineral	Formel	Anzahl der Spaltflächen und Spaltwinkel	Silicatstruktur	Beispiel
a Olivin	$(\text{Mg,Fe})_2\text{SiO}_4$	1 Spaltfläche	Inselsilicat	
b Pyroxen	$(\text{Mg,Fe})\text{SiO}_3$	2 Spaltflächen; 87° und 93°	Kettensilicat	
c Amphibol	$\text{Ca}_2(\text{Mg,Fe})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	2 Spaltflächen; 124° und 56°	Bandsilicat	
d Glimmer	Muskovit: $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ Biotit: $\text{K}(\text{Mg,Fe})_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	1 Spaltfläche	Schichtsilicat	
e Feldspat	Orthoklas: KAlSi_3O_8 Plagioklas: $(\text{Ca,Na})\text{AlSi}_3\text{O}_8$	2 Spaltflächen; nahe 90°	Gerüstsilicat	

Fig. 8: Silicate mineral structures

Once we have a double chain structure, the next most complex arrangement is to connect the double chains side by side to form layered silicates. Layered silicates consist of two layers of silicon-oxygen tetrahedra ("t") enclosing a layer of aluminum-oxygen octahedra ("o"). This "t-o-t" structure can be compared to an Oreo cookie, with the "t" layers represented by the chocolate cookie layers and the "o" layer representing the creamy filling. Most phyllosilicates consist of stacks of "t-o-t" structures with other materials (various types of cations, water molecules) trapped between the "t-o-t" layers. The best known phyllosilicates are a class of minerals known as mica (Fig. 8d), characterized by splitting into large, flat, thin layers. The silvery white mica is known as muscovite, and before it was possible to make stained glass windows, large slabs of muscovite (called "singlass") were used as windows and curtains. There is also a common black mica known as biotite, a green mica known as chlorite, and a lithium-rich lavender-colored mica known as lepidolite, which we can see in many different types of rocks. In addition to mica, all of the clay minerals that make up the world's muds are phyllosilicates; for this reason, they are the most abundant minerals on Earth.

We have looked at silicates from isolated tetrahedra to single chains to double chains to layers, each structure becoming more complex. The final step is to combine the silicon-oxygen tetrahedron into a complex three-dimensional framework structure. Some of the most common and important minerals are framework silicates. The most important of these is quartz made from pure silicon dioxide (SiO_2), one of the most abundant sedimentary minerals on Earth. The other important class of framework silicates includes the aluminum-rich feldspars (Fig. 8e), the most abundant minerals in igneous rocks. Two types of feldspars are particularly important: the pink potassium feldspars (KAlSi_3O_8), which occur in three mineral forms (orthoclase, microcline, and sanidine), and the plagioclase feldspars. They continuously transform from pure calcium-rich plagioclase, known as anorthite, to intermediate plagioclase with a mixture of calcium and sodium to pure sodium-rich plagioclase, known as albite. Plagioclase crystals typically show many fine parallel lines known as striations on their cleavage surfaces. Plagioclase is typically the most abundant mineral in most igneous rocks.

These are a lot of mineral names to master, especially for beginning students, but this is the minimum number of minerals required to understand the rocks that occur on the Earth's surface and within its interior. When given the opportunity to study hand samples of each of these minerals, test their properties, and compare them with each other, the names make more sense and become easy to remember with experience and practice. Almost every geology student masters these minerals after the first few lessons, so it's not that hard to learn. It just takes practice! Once we know your minerals, we can understand the rocks that form them.

We will take a closer look at the rocks that form minerals in the next post.

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