

arrangement is only systematic on the scale of a few tetrahedra. So a glass is ordered only on a local scale. In order to be a mineral, a material must be made up of an orderly arrangement of atoms on scales of tens of units put together.

Before we continue, there are two important points to be made about number 4 and 5 above. In many ways these two descriptions of a mineral form the basis for understanding minerals. The chemical formula portion of the mineral description forms the field of crystal chemistry, while the atomic arrangement characteristic forms the field of crystallography. In fact, an earlier book on the subject of mineralogy was titled *Crystallography and Crystal Chemistry: An Introduction* (Bloss, 1994). The importance of the concepts of crystallography and crystal chemistry and their interrelationships cannot be overstressed. We can view crystal chemistry as the materials that nature has provided (i.e., the elements) and crystallography as the way nature has put these elements together to form minerals. Our goal will be to describe the basic rules that are followed in selecting which elements to use to build which minerals, and in turn how those elements are arranged in these minerals. The criteria that nature has chosen to make these selections will be based upon certain physical characteristics (e.g., pressure and temperature) present at the time of formation of the mineral. We can in turn determine the physical conditions at the time when the mineral was formed, perhaps tens of millions of years ago. This is really the foundation of the field of petrology, which is based on the study of formation conditions of rocks using characteristics we can learn from their minerals and mineral assemblages.

Given these descriptions for defining a mineral, we can now proceed to thinking about what's really important to learn about minerals. In this chapter, our goal is to present the concepts and vocabulary that we feel every geologist should know about mineralogy. These terms are part of the daily language of geology, and thus are worthy of memorization. As noted in the Preface, they form four groups that are the basic building blocks for this textbook: **chemical elements**, **crystal systems**, **optical systems**, and the **Big Ten minerals**. Each of these topics will be revisited with its own chapter in the next section of this book, and with several chapters in the advanced latter portion of the text. Our goal here is to let you know, right at the beginning, what's really important about mineralogy and to get you used to some of its terminology. That's why we have called this chapter "The Essence of Mineralogy."

Chemical Elements

As stated above, the elements are the basic building blocks for minerals, and for that matter, all materials. There are about 90 known naturally occurring elements. The good news is that only eight of these—oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium—compose over 98% of the Earth's crust by weight (Figure 1.3). If you haven't yet had a chemistry course, or you've forgotten these, you'll want to become familiar with the chemical symbols for these elements, which are shown in Table 1.1 and will be used throughout this book.

Because this group of eight elements forms the majority of the crust, these elements, in turn, make up the building blocks for the vast majority of rock-forming minerals. Let's consider the information in Table 1.1 and see what conclusions can be drawn from it.

Notice that each of the elements in the list has a number in the column to the right of it to indicate the amount and type of charge on that ion. Atoms like oxygen, which have a negative charge, are called **anions** (think of it as "a negative ion"). These atoms have an overall negative charge because they have more electrons (which are negatively charged) around the nucleus than they have protons (with positive charges) in the nucleus. On the other hand, some atoms have lost electrons relative to the normal stable element, and they are called **cations**. Such atoms have a positive charge because the number of protons in the nucleus is greater than the number of electrons around the nucleus (Figure 1.4).

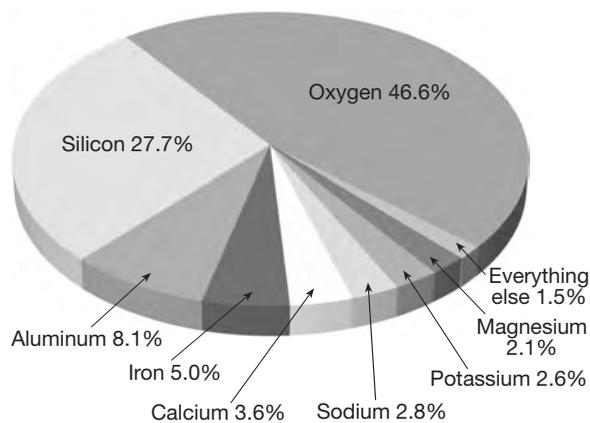


Figure 1.3. A pie chart showing the weight percents of the eight most abundant elements in the Earth's crust. Silicon and oxygen are by far the most abundant elements in the Earth's crust, so it is no surprise that combinations of Si and O are the fundamental building blocks of most common minerals.

Name	Chemical symbol	Charge (usually superscripted)	Common coordination number with oxygen
oxygen	O	2-	—
silicon	Si	4+	4
aluminum	Al	3+	4-6
iron	Fe	3+ or 2+	4-6
magnesium	Mg	2+	6
calcium	Ca	2+	6-8
sodium	Na	1+	6-8
potassium	K	1+	8-12

Because oxygen is so abundant in the Earth, it is the most important anion, or possibly element, in mineralogy. Most of this class will be concerned with minerals in which oxygen bonds with an assortment of cations. For the time being, memorize these eight elements and their charges. Later, we'll show you systematic methods for recalling them without having to resort to memorization.

By the way, these abundances are probably very similar on other terrestrial planets in our own solar system and on extrasolar planets as well. The crustal abundances of elements on a body depend on two factors: (1) the distance away from the sun of the body when the planets are condensing from the solar nebula, and (2) the amount of radioactive elements that are present to provide heat to drive the post-formation evolution of the planetary interior. The Earth's Moon, for example, has a crust composed prima-

rily of feldspar that may have floated to the top of an immense magma ocean when the Moon melted. Thus, the most common elements in its crust are those in feldspar: O, Si, Al, and Ca, along with heavier elements found in basalts, such as Fe and Mg. See Dreibus and Wänke (1987) and Haskin and Warren (1991) for more information on planetary compositions. Mars is more like the Earth.

Returning to Table 1.1, the next column is titled "Common Coordination Number with Oxygen." This number tells you how many oxygen atoms (or other anions or ions) will surround the cation. In other words, negatively-charged anions will bond to positively-charged cations. For example, Si^{4+} will almost always be located inside a tetrahedron of four oxygen atoms (Figure 1.5); this is called 4-fold coordination. Only under situations of great pressure will Si^{4+} bond with six oxygens in what is called an octahedral coordination polyhedron. Al^{3+} , on the other hand, will surround itself with four, five, or six oxygens depending on pressure, temperature, and the other cations that are its neighbors in the structure.

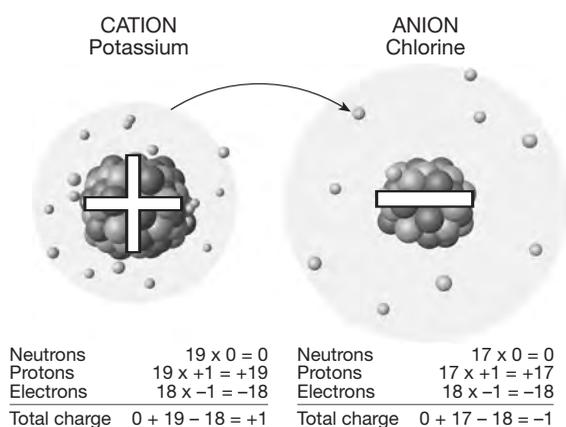


Figure 1.4. Naturally-occurring potassium chloride is the mineral species sylvite, which is used as a salt substitute (though it has a rather bitter taste!). The K atom has lost one of its electrons, so it has an overall positive (+) charge. The Cl atom has gained an electron, which makes it a negative ion, or anion. The two ions bond together in the mineral structure because their opposite charges attract.

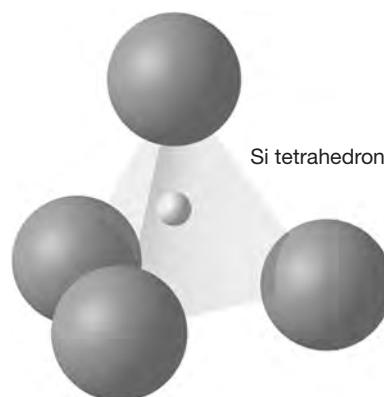


Figure 1.5. Si tetrahedra like this one are the fundamental building blocks of silicate minerals.

Iron is a special case because it commonly occurs in two different valence states, Fe^{2+} and Fe^{3+} . The Fe^{3+} cation, which is smaller and more highly charged, prefers 4-coordinated sites (Fe^{3+} surrounded by four oxygen atoms) when they are available. The larger Fe^{2+} cation favors 6-coordinated sites because they have more room (Figure 1.6).

Mg is almost always found surrounded by six oxygens. Na and Ca are happiest with six–eight oxygens around them, and K prefers large sites with eight–twelve oxygens. For the time being, you should memorize the coordination numbers.

Why do these differences exist? For now, we can answer this question by using some simple logic. Note that as we go from Si^{4+} to Al^{3+} to Mg^{2+} to K^{1+} , the coordination number gets bigger. This implies that cations themselves are getting bigger, because they need larger sites (i.e., more oxygens around them) to fit into. So, as the charge *decreases*, the size *increases*. Size is controlled to some extent by the relationship between the number of electrons and the number of protons. In neutral atoms (e.g., Si^0), the number of negatively-charged electrons equals the number of positively-charged protons. Cations have an overall positive charge because they have lost electrons. The more that the number of protons exceeds the number of electrons, the smaller the size of the cation overall, because the charge imbalance allows the protons to “pull in” the electron cloud

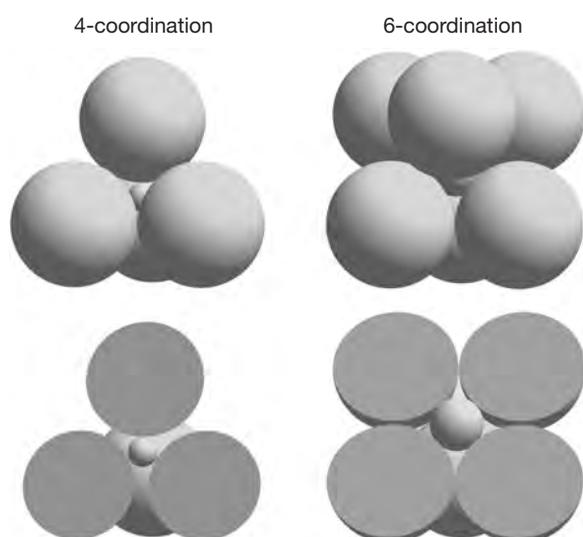


Figure 1.6. The amount of space inside a tetrahedron of four oxygens is significantly smaller than the space inside an octahedron of six oxygens. This difference governs the size of the cation that can fit in the sites. Small, highly-charged cations like Si and Al like the tetrahedral site, while larger cations such as Fe^{2+} and Mg prefer the octahedral, 6-coordinated site.

closer to the nucleus. Thanks to angular momentum, the electrons do not go crashing into the nucleus, but remain circulating around it.

From these examples, you might think that charge is the primary factor in determining the number of anions necessary to satisfy the charge on any cation. Although this is more-or-less true, charge is *not* the only factor. Cation coordination numbers vary for reasons we will discuss in more detail throughout the book. Many mineralogical peculiarities are explained by these variations in coordination number. In the Earth’s mantle, for example, at depths of >670 km, the increased pressure is high enough to force many elements into larger coordination environments because the difference in size between the cations and the surrounding oxygens gets smaller as everything compresses (i.e., coordination number increases as pressure increases). In fact, olivine does not exist in the lower mantle, but is replaced by a mineral called silicate perovskite in which the Si atoms are in 6-fold coordination. We can even observe this behavior in the laboratory by putting olivine and garnet together in a huge press and watching them change into perovskite.

Another good example of this dependence on formation conditions is found in the aluminosilicate minerals, which have the basic formula Al_2SiO_5 . Three different minerals have this same composition, but the coordination of oxygens around the Al in the structure is dependent upon the pressure and temperature conditions during formation. In fact, this change in crystal structure makes a very useful indicator of geologic conditions! **Kyanite** is only found in rocks from high pressure, low temperature environments, so all the Al is most comfortable in 6-fold coordination. **Andalusite** forms at very low temperatures and pressures, so half its Al atoms assume 5-fold coordination geometries. Finally, **sillimanite** is a relatively low pressure but high temperature mineral; at high temperatures, the oxygen atoms are slightly bigger, so half of the Al in the structure takes on 4-fold coordination (Figure 1.7).

The elements and their coordinations, as listed in Table 1.1, will form a “leaping-off point” from which to tackle the chemistry of all minerals. Once you have a feeling for which elements occupy which types of sites in which types of geologic conditions, then you’re really empowered to start looking at a mineral formula and imagine what type of structure it might have, and in turn what its physical properties might be! Furthermore, knowing the charges assumed by various common cations will help immensely when it comes time to memorize mineral formulas for this class. In fact, you are not *memorizing*

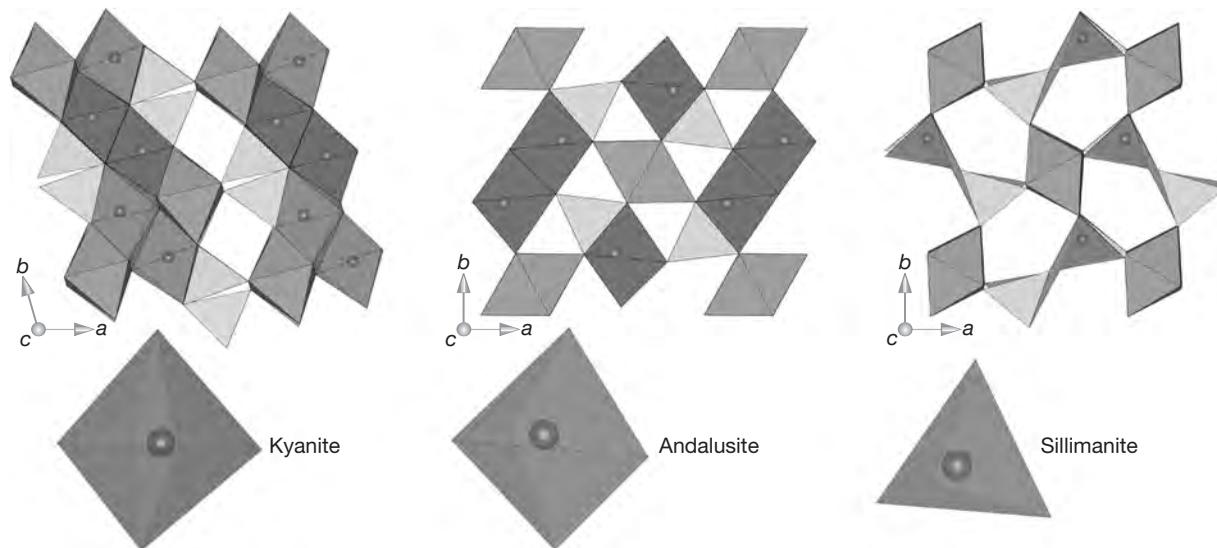


Figure 1.7. The minerals kyanite, andalusite, and sillimanite all have the same formula, Al_2SiO_5 . The difference between them is the number of oxygen atoms that surround one of the Al sites, shown here as the polyhedron that is somewhat transparent. There are oxygen atoms at the corners off all the polyhedra shown; see the DVD-ROM for a clearer depiction of these structures. In kyanite, there are six oxygens around each Al^{3+} . In andalusite, the Al^{3+} atoms are 5-coordinated, and in sillimanite, each Al^{3+} is surrounded by only four oxygens. These differences reflect the pressure and temperature conditions under which each mineral forms.

the chemical formulas when you understand coordination numbers and charges, you are *figuring them out* based on the first principles of crystal chemistry. So, we think you will find that the charges and coordination numbers given in Table 1.1 are well worth memorization. In future chapters, we will show a method whereby you can figure out the charges and coordination numbers rather than relying on simple memorization. Eventually, you will work with them enough that they become part of your background knowledge in this field.

Crystal Systems

How do atoms fit together to make crystals with different shapes? The answers to this question lie in the field of crystallography, which is the study of crystal systems. Crystal systems describe the organization of atoms in a mineral, which often can be observed in the external morphology of the mineral. An understanding of crystallography will allow us to explain the nearly infinite long-range order that is characteristic of minerals. Crystal systems are the underlying basis for crystallography. In this book we will use the non-British system that includes exactly six distinctive crystal classes that are given in Table 1.2 (in England there are seven, but we won't worry about that here).

The rationale for these classifications is fairly simple. From the preceding section, we know that one important aspect of mineralogy is going to be describing where the atoms are located within a crystal structure. It is not enough to say that all the Si atoms are in tetrahedral coordination (i.e., have coordination number of 4) with oxygen; we also need to say *where* that Si tetrahedron is located in the structure: in the center? On the corners? To do this, we need to develop a terminology that permits us to say where atoms are located.

You are probably already familiar with one way to do this: using Cartesian coordinates, which are sets of x , y , and z axes in 3-D. We could specify the location of each atom in a mineral in terms of coordinates relative to a set of x , y , and z coordinates, and then plot the results to see how the structure looks. The Cartesian system is a way of defining atomic positions in three dimensions

Table 1.2. The Six Crystal Systems, the Three Optical Classes, and Their Relationships

Crystal systems	Optical classes
isometric ($a=b=c$)	isotropic
tetragonal ($a=b \neq c$)	uniaxial
hexagonal ($a=b \neq c$)	
orthorhombic ($a \neq b \neq c$)	biaxial
monoclinic ($a \neq b \neq c$)	
triclinic ($a \neq b \neq c$)	