

## LECTURE 5

### THE CHEMISTRY OF MINERALS

#### 5.1 LECTURE OUTLINE

Welcome to lecture 5. Having learned about the physical properties of minerals and their optical properties, we are now ready to learn more on the chemistry of minerals. For your information, the subject on mineral chemistry has evolved in partnership with petrology to become one of the branch of the geological sciences widely referred to as geochemistry. The subject of mineral chemistry embraces other related topics such as thermodynamics, phase equilibrium investigations, mineral synthesis, and the chemical analysis and description of minerals. Coordinated and correlated with crystallographic and physical investigations has lead to the study of what is currently characterized as crystal chemistry.

In this lecture, we are going to learn some selected topics in mineral chemistry. In particular, we shall learn about chemical analyses of minerals and how they can be interpreted and used to determine the mineral formula and content of unit cells; the chemical bonding of atoms and ions; the chemical classification of minerals; isostructuralism and isotypism; polymorphism, pseudomorphism and polytypism. The topic on phase equilibrium investigations will be covered in the following lecture 6.



#### OBJECTIVES

By the end of this lecture, you should be able to:

- To describe the possibilities and limitations of chemical analyses of minerals.
- Determine the chemical mineral formula and unit cell content from a given chemical analysis.
- Distinguish various chemical bonds: ionic, covalent, metallic and van der Waals bonds.
- Outline the chemical classification of minerals.
- Define the usage of the terms: isostructuralism, isotypism, polymorphism and polytypism as used in minerals.
- Differentiate between displacive and reconstructive polymorphism.
- List possible scientific evidences that can be deduced from the study of pseudomorphs.

## 5.2 CHEMICAL ANALYSIS

The science of mineral chemistry is based on a good understanding of the composition of minerals. For this reason, it is important to understand the possibilities and limitations of chemical analyses of minerals. Quantitative chemical analysis aims to identify the elements present and to determine their relative amounts. In the statement of an analysis, the amounts of elements present are expressed in percentages by weight. Ideally, the complete analysis of a mineral should total 100 percent. In practice however, due to limitations on accuracy, a summation of between 99.5 and 100.5 is considered a good analysis.



The mere fact that an analysis shows a total that lies between the 99.5 and 100.5 does not necessarily indicate that it is accurate. A good total may result from the balancing of plus and minus errors, even including such things as overlooking or misidentifying one or more elements. For example, the mineral bavenite, discovered in 1901, was described as a hydrated calcium aluminum silicate on the basis of an analysis with the good total of 99.72, whereas reexamination, 30 years later, showed that bavenite also contains beryllium, which was overlooked and apparently precipitated and weighed together with aluminum in the original analysis (Berry et al., 1982).

## 5.3 INTERPRETATION OF ANALYSIS

Recall that in our definition of a mineral in lecture 1, we implied that a mineral has a characteristic chemical composition. A characteristic chemical composition can be expressed by a formula that indicates the elements that constitute the mineral and the proportions in which they are combined. For example, the characteristic formula of *halite* is expressed by the formula NaCl, which indicates that there are equal numbers of sodium ions and chlorine ions in halite. Similarly, the composition of *brucite* is expressed by the formula Mg(OH)<sub>2</sub>, which means that it is a compound consisting of one magnesium for each two hydroxyls; the composition of a certain tourmaline mineral is: (Ca,Na)(Mg,Fe)<sub>3</sub>Al<sub>5</sub>Mg(BO<sub>3</sub>)<sub>3</sub>Si<sub>6</sub>O<sub>18</sub>(OH,F)<sub>4</sub>.

From the aforementioned examples, it can be appreciated that formulas may be simple or complex, depending on the number of elements present and the way they are combined.

The basic data for assigning the correct chemical formula to a mineral are provided by its chemical analysis. The chemical analysis shows what elements are present, and how much of each, but not how they are combined in the structure of the mineral. As mentioned earlier, the results of chemical analyses are expressed in weight percentages. In order to determine the formula of a mineral, the weight percentages must be converted to atomic proportions. Dividing the weight percentage of each element in the analysis by the atomic weight of that element does this. To give a simple illustration, consider example 1 for the analysis of a specimen of *marcasite* from Mwingi, Kenya shown in Table 5.1.

### Example 1

Table 5.1 Chemical analysis of marcasite.

Element	Weight percent	Atomic weight	Atomic proportions
Fe	46.55	55.85	0.833 = 1
S	<u>53.05</u>	32.07	1.654 = 1.986
Total	99.60		

Within the experimental error of the analysis, the formula of marcasite becomes FeS<sub>2</sub> since the ration of Fe to S is approximately 1:2.

### Example 2

As noted in example 1 above, marcasite has a fixed chemical composition. However, marcasite is rather exceptional among minerals in that most minerals are *not fixed* in composition although each does have a *characteristic* composition that can be expressed by a formula. This phenomenon is best illustrated by example 2 for the analyses of sphalerite indicated in Table 5.2 (a).

Table 5.2 (a). Chemical analysis of sphalerite

Analysis	1	2	3
Fe	0.15	7.99	18.25
Mn	-	-	2.66
Cd	-	1.23	0.28
Zn	66.98	57.38	44.67
S	32.78	32.99	33.57
Total	99.91	99.59	99.43

The analyses shown in Table 5.2 (a) show that sphalerite may be nearly pure zinc sulfide, or it may contain considerable quantities of iron and minor amounts of manganese and cadmium. This observation is made clear when the analyses are recalculated in atomic proportions as indicated below in Table 5.2 (b).

Table 5.2 (b). Analyses of sphalerite recalculated in atomic proportions.

Element	Atomic weight	Analysis 1	Analysis 2	Analysis 3
Fe	55.85	0.003	?	0.327
Mn	54.94	-	?	0.048
Cd	112.41	-	?	0.002
Zn	65.38	1.024	?	0.683
		<u>1.027</u>	?	<u>1.060</u>
S	32.07	1.022	?	1.047

With respect to analyses 1 and 3 above, the atomic proportions of total metals to sulfur is  $\approx$  1:1, corresponding to the formula ZnS, but with some zinc replaced by Fe, Mn, and Cd. Therefore, the formula ZnS is an oversimplification for the composition of sphalerite. Sphalerite can be pure ZnS (analysis 1- Table 5.2 (a)), but it can also have one-third or more of the zinc being replaced by iron. This phenomenon is common in minerals and, in this example, it can be indicated by writing the formula as (Zn,Fe)S, which shows that the total of Zn + Fe is 1 with respect to S = 1, but the actual amounts of Zn and Fe are variable.



Using analyses 1 and 3 in Tables 5.2 (a) & (b) as reference examples, calculate the atomic proportions of the elements and the chemical composition formula of the mineral analysis 2 in Table 5.2 (b).

When you want to express the composition corresponding to a particular analysis as a formula, you first reduce the atomic proportions of the mutually replacing elements to decimal fractions of unity. Thus analysis 3 can be mathematically reduced and expressed as a formula (omitting the very small amount of cadmium) in the following manner as shown in Table 5.3.

Table 5.3. Conversion of atomic proportions to decimal fractions for sphalerite analyses

Element	Atomic Proportions	Decimal Fractions
Fe	0.327	$\frac{0.327}{1.060} = 0.31$
Mn	0.048	$\frac{0.048}{1.060} = 0.05$
Cd	0.002	-
Zn	0.683	$\frac{0.683}{1.060} = 0.64$
S	1.047	$\frac{1.047}{1.047} = 1$
Formula:		$(\text{Zn}_{0.64}\text{Mn}_{0.05}\text{Fe}_{0.31})\text{S}$

Therefore, the formula  $(\text{Zn}_{0.64}\text{Fe}_{0.31}\text{Mn}_{0.05})\text{S}$  is a special case of the general formula  $(\text{Zn,Fe})\text{S}$ , and it expresses the composition of a specific analyzed sample of sphalerite.

### Example 3.

Lets consider another example of atomic/chemical substitution exemplified by the mineral olivine. Typical olivine analyses are shown in Table 5.4 (a).

Table 5.4 (a). Chemical analyses of olivine.

Element	Analysis 1	Analysis 2
FeO	8.58	47.91
MnO	0.20	0.41
MgO	50.00	18.07
SiO <sub>2</sub>	40.99	33.72
Total	99.77	100.11

The above olivine analyses illustrate an especially significant limitation of the analytical technique when it is applied to oxygen-containing compounds. In reality, there is no analytical procedure for determining the total amount of oxygen in a compound. As a result, the analyses of such compounds are expressed in terms of the oxides of the individual elements, instead of in terms of the elements themselves. And instead of the weight percentages of the oxides being converted to atomic proportions, they are converted to molecular proportions by dividing the analytical figures by the formula weight of each oxide [e.g., formula weight of SiO<sub>2</sub> = 28.09 + (2 X 16.00) = 60.09].

The preceding two analyses of olivine in Table 6.4 differ so much from one another that you might well think they represent different minerals. Conversion into molecular proportions (see Table 5.4 (b)), however, shows that they are all variants of the same basic formula.

Table 5.4 (b). Molecular proportions of olivine analyses.

Element	Formula weight	Analysis 1	Analysis 2
FeO	71.85	0.119	0.667
MnO	70.94	0.003	0.006
MgO	40.31	<u>1.240</u>	<u>0.448</u>
		1.362	1.121
SiO <sub>2</sub>	60.09	0.682	0.561

Despite the wide variation in the amounts of MgO and FeO, the ratio of molecular proportions of FeO + MnO + MgO to SiO<sub>2</sub> is always approximately 2:1, corresponding to the formula (Mg,Fe)<sub>2</sub>SiO<sub>4</sub>. If the minor quantity of manganese is neglected, you can express each analysis precisely in the form (Mg<sub>x</sub>Fe<sub>1-x</sub>)<sub>2</sub>SiO<sub>4</sub> by merely normalizing the molecular

proportions (e.g., in column 1 by dividing the 1.240 of MgO by 1.362 = 0.91) as follows: 1: ( $\text{Mg}_{0.91}\text{Fe}_{0.09}$ ); 2: ( $\text{Mg}_{0.40}\text{Fe}_{0.60}$ ).

## 5.4 THE CHEMICAL BOND

The basic unit in crystal structures is the *atom* or *ion*, the ion being an atom carrying electric charge. An atom that has given up one or more electrons is said to be a *cation* and is indicated by a positive superscript, such as  $\text{Zn}^{2+}$ ; an atom that has received one or more electrons is said to be an *anion* and is indicated by a negative superscript, such as  $\text{S}^{2-}$ . An atom or an ion may act individually or be closely associated with other atoms or ions to form groups that behave as units. Such groups, such as  $(\text{CO})_3^{2-}$  are generally called *radicals*.

An atom is made up of a very small, positively charged nucleus surrounded by one or more shells of electrons, the whole entity acting as a sphere whose effective radius is of the order of 1Å. The radius depends not only on the nature of the element, but also on its state of ionization and the manner in which it is linked to adjacent atoms or ions. The different kinds of linkage are generally referred to as *chemical bonding*.

There are four kinds of bonds that are typically common in crystal structures. These are the *metallic* bond, the *covalent* (or *homopolar*) bond, the *ionic* (or *heteropolar* or *polar*) bond, and *vander Waals* bond. A brief description for each of these bonds is discussed here below:

\*

### 5.4.1 The Metallic Bond

The metallic bond is formed by valence electrons released by a metallic atom (1-2 electrons per atom) and moving freely through the metal lattice. This type of bond is responsible for the cohesion of a metal. Metals consist of elements whose atoms readily lose their outer electrons. The crystal structure of a metal is determined by the packing of the positively charged atoms, the detached electrons being dispersed among the atoms and freely mobile. This electron mobility is responsible for the color, luster, and good electrical and thermal conductivity of metals. In minerals, metallic bonding is present in native metals. The atoms in metals are typically arranged according to one of the two different arrays: one termed

*cubic closest packing* [CCP(=FCC)], and the other is called *hexagonal closest packing* (HCP) (see Figure 5.1).

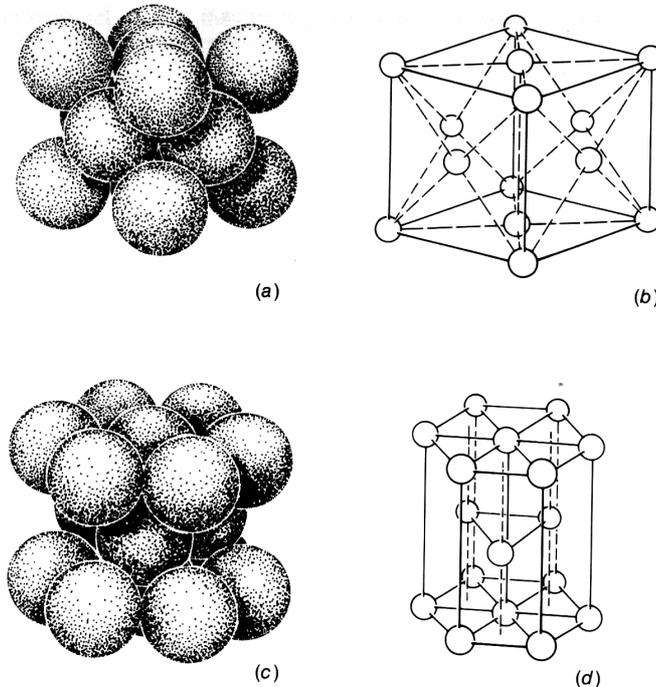
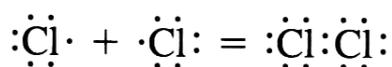


Figure 5.1 Packing arrangements. (a) FCC lattice with atoms drawn to scale of cube edge; (b) FCC lattice, unit cube indicated by solid lines; (c) HCP lattice, unit cell indicated by heavy solid lines.

As illustrated in Figure 5.1, cubic closest packing is a periodic structure that can be described with a face-centered cubic unit cell, and hexagonal closest packing is based on a primitive hexagonal cell with two atoms per unit cell.

#### 5.4.2 The Covalent Bond

The covalent bond is formed by atoms sharing a pair of electrons of equivalent energies and opposite spins (one from each atom) in their outer shells. For example, the atoms in chlorine gas,  $\text{Cl}_2$ , are always linked in diatomic molecules. Each chlorine atom has seven outer shell electrons, and the stable condition of eight electrons in the outer shell is reached by each atom sharing one electron with one another:



Covalent bonds are involved in the formation of most radicals, are common in organic compounds, and are rare in minerals. The best mineralogical example of the covalent bond in minerals occurs in diamond, where every carbon atom is surrounded by four other carbon atoms, each sharing one electron with the central atom. This pattern is repeated throughout the structure, and thus each crystal is in essence one giant molecule (see Figure 5.2).

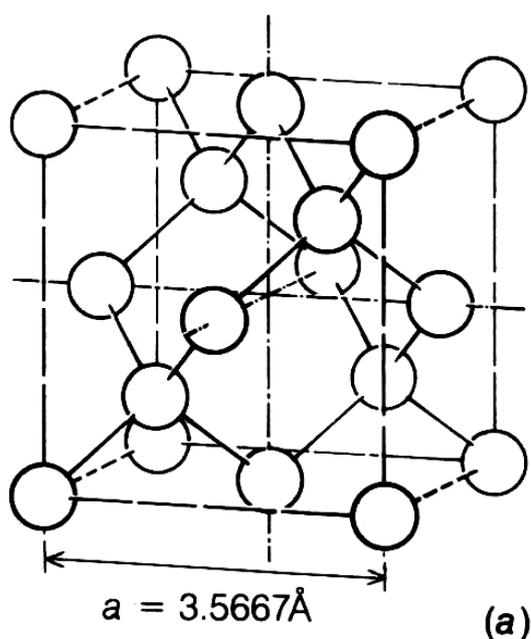


Figure 5.2 Diamond structure. Atoms in the face-centered cubic unit cell and the tetrahedral bonds from each atom to its four closest neighbors.

### 5.4.3 The Ionic Bond

The ionic bond is formed by electron transfer from one atom to another, resulting in oppositely charged ions that attract each other (e.g.  $\text{Na}^+\text{Cl}^-$ ). Sodium and chlorine combine readily to give a structure of oppositely charged ions bonded by electrostatic attraction. There is, however no pairing of individual positive and negative ions to give discrete molecules

such as those we have distinguished in covalent bonds. Instead, in ionic bond, each ion is surrounded with ions of opposite charge, the number being determined by the relative sizes of the ions. Ionic bonding is common in inorganic compounds and is therefore extremely important in the structure of minerals.

#### 5.4.4 The van der Waals Bond

This type of bonding, sometimes referred to as residual bonding, is typically present in crystalline solids of frozen inert gases (helium, neon, argon, etc.). One consequence of these elements having completely filled outer electron shells is their inability to form bonds of the metallic, covalent, or ionic type. The force that does exist between such atoms is what is generally termed the van der Waals bond, force, or attraction. The van der Waals force is a result of electrical imbalances that exist because of an off-centering of positively charged atomic nuclei within their negatively charged cloud of surrounding electrons. Consequently, the attraction forces are weak, a condition that is reflected in the very low temperatures and high pressures required to condense the inert gases to liquids and solids. The bond is apparently of little significance in minerals, other than perhaps accounting for certain weaknesses within certain minerals (e.g. graphite).



Explain the main characteristics of the four types of chemical bonds?

### 5.5 CHEMICAL CLASSIFICATION OF MINERALS

Presently, there are approximately 3500 mineral species known. In order to deal systematically with minerals, it is necessary to have a classification scheme. Basically, as you might know, the purpose of classification is to bring like things together and to separate them from unlike things – in other words, to give order to arrays of data, and thus increasing their utility.



Recall that in lecture 1 of this unit (section 1.3), it was shown that in the early years of the development of mineralogy as a science, many systems of classification were proposed. One of those systems of classification, proposed by the Swedish chemist Berzelius (1779-1848), was based on chemical criteria. Since then, that chemical classification has gradually become accepted.

This system of classification groups the mineral species into major divisions, or classes, according to the nature of the anionic group present. The chemical classification is as outlined here below.

1. Native elements
2. Sulfides (including sulfosalts)
3. Oxides and hydroxides
4. Halides
5. Carbonates, nitrates, borates, iodates.
6. Sulfates, chromates, molybdates, tungstates
7. Phosphates, arsenates, vanadates
8. Silicates.

This classification, although originally was purely based on chemical principles, it has a definite significance in terms of crystal structure as exemplified in Table 5.5 here below.



To have a better understanding of the chemical classification of minerals, you are advised to make a quick comparative review of the topic “Structure and classification of silicate and non-silicate minerals” found in the first year study unit SGL 101, section 4.3 to 4.4.

Table 5.5. The general classification of minerals

BASIS		
Chemical Composition	Crystal Structure	
	Bond Type	Geometry
Native elements: metals semi-metals nonmetals	Metallic Covalent Covalent	} Cubic or Hexagonal Close-packed
Sulfides (etc.) (and sulfosalts)	Metallic, covalent, and ionic	
Oxides (and hydroxides)	Ionic	Simple packing of spheres
Halides	Ionic	Simple packing of spheres
Carbonates (and nitrates, borates and iodates)	Ionic	Packing involving complex ions: $(XO_3)^-$
Sulfates (and chromates, molybdates, tungstates, etc.)	Ionic	$(XO_4)^-$
Phosphates (and arsenates, vanadates, etc.)	Ionic	$(XO_4)^-$
Silicates	Ionic	Complex groups

## 5.6 ISOSTRUCTURALISM AND ISOTYPISM

These terms, which are often used in their adjectival terms (Isostructural and isotypic) when applied to minerals, are defined and used as follows:

### 5.6.1 Isostructural Minerals

This feature is shown by two or more minerals, or other crystalline substances that have the same structure but different chemical composition. In other words, isostructural minerals have a one-to-one equivalence in the structural arrangement of their constituent atoms. Examples of isostructural pairs of minerals are halite (NaCl) and galena (PbS), berlinite ( $AlPO_4$ ) and quartz ( $SiO_2 = SiSiO_4$ ), and tantalite ( $FeTa_2O_6$ ) and brookite ( $TiO_2 = TiTi_2O_6$ ).

### 5.6.2 Isotypic Minerals

This feature is said to occur between two or more minerals that have analogous structures. That is to say, Isotypic minerals have closely related structures but do not exhibit a one-to-

one equivalence of site occupancy. There are no implications with regard to chemistry. An example of an Isotypic pair of minerals is halite (NaCl) and calcite (CaCO<sub>3</sub>).

## 5.7 POLYMORPHISM AND POLYTYPISM

### 5.7.1 Polymorphism

Polymorphism is exhibited by an element or compound that can exist in more than one crystallographic structure. Each polymorph has its own physical properties and a distinct internal arrangement of its atoms and/or ions. Polymorphism is an expression of the fact that crystal structure is not determined exclusively by chemical composition. In other words, for some substances, the same atoms and/or ions in the same proportions may assume more than one structure.

A polymorphic substance can be described as dimorphic, trimorphic, etc., according to the number of distinct crystalline forms it can have. A good illustration of dimorphism is the relationship between diamond and graphite (Figure 5.3). In diamond, each carbon atom is linked to four other carbon atoms by homopolar bonds, all the linkages being of equal strength, so that each crystal, as a whole, is a giant molecule. In graphite, each carbon atom is linked to three other carbon atoms by homopolar bonds, thus forming planar sheets, which, are joined by weak van der Waals forces.

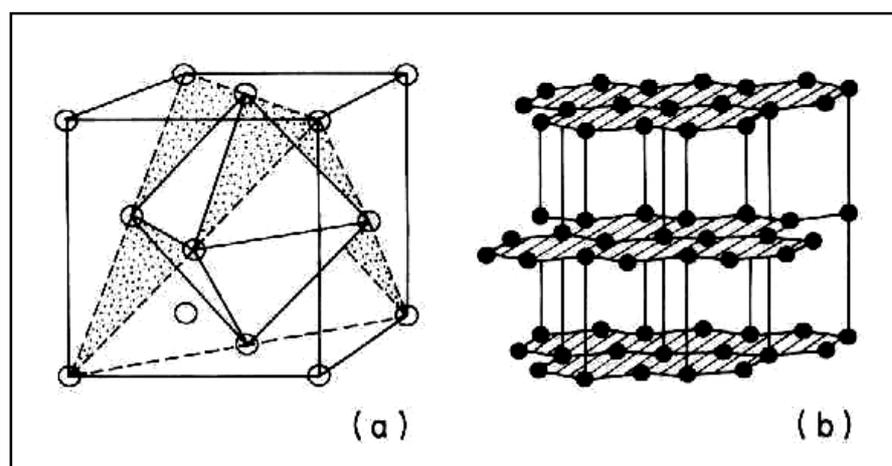


Figure 5.3. The atomic structure of diamond (a) and graphite (b).

Different polymorphs of the same substance are formed under different conditions of pressure, temperature, and/or chemical environment. Hence the presence of a given polymorph in a rock will often tell us something about the conditions under which the rock was formed. For instance, the natural occurrence of diamond in igneous rocks implies an origin at considerable depths in the earth (Figure 5.4) where the combination of temperature and pressure is within the diamond stability field. Thus, it can be seen that diamond is actually unstable under the physical conditions in which it is found. The fact that it has not changed spontaneously into graphite is due to the infinitesimal rate of reaction that the energy relations favor.

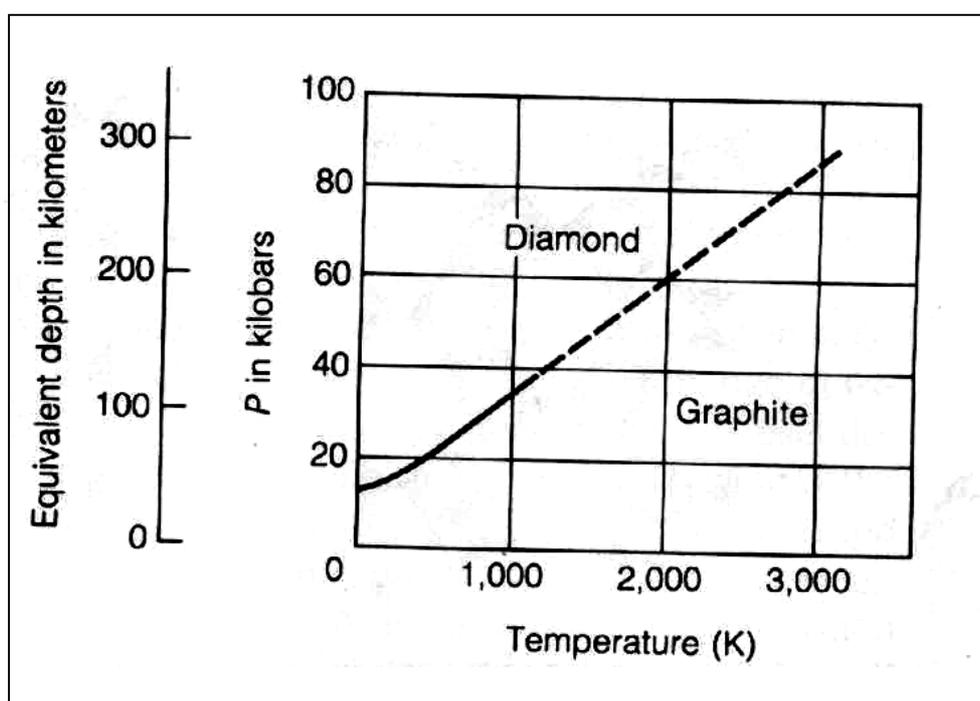


Figure 5.4. Diamond-graphite equilibrium curve, calculated to 1200 K, extrapolated beyond.

The change from one polymorph to another is generally termed as *inversion* or *transformation*. The rate of change can be essentially instantaneous or extremely slow, depending largely on the degree of reconstitution of the structure that is required. Two kinds of inversion, termed *displacive* and *reconstructive*, are recognized (Figure 5.5).

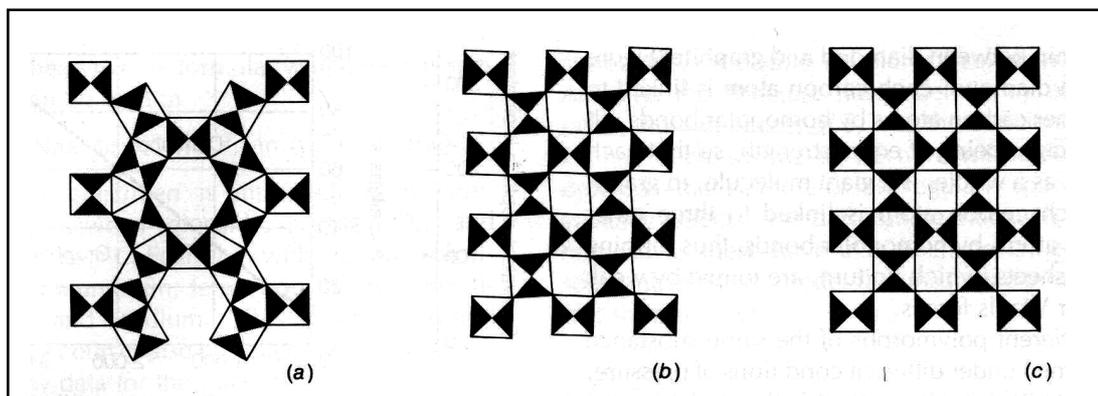


Figure 5.5 Inversions between polymorphic forms. (a), (b), and (c) represent three different crystal structures that involve identical building blocks. Reconstructive inversions occur between (a) and (b) [or between (a) and (c)] which involve rearrangements, breaking of original bonds, and formation of new bonds; hence they are sluggish. Displacive inversions [such as between (b) and (c)] generally involve slight relative positional change; hence they are essentially instantaneous.

***Displacive inversions*** are immediate and reversible at the transition temperature and pressure. In such inversions, metastability is precluded (i.e., high temperature form can not be preserved). Often such changes do not involve the breaking of bonds between neighboring atoms or ions, but simply their bending, for example, low-quartz $\leftrightarrow$  high-quartz and low-leucite $\leftrightarrow$  high-leucite. High-low polymorphs are characterized by the fact that the high temperature form has higher symmetry than the corresponding low-temperature form.

***Reconstructive inversions*** are sluggish. Consequently, some high-temperature polymorphs are quenchable as metastable phases because these transformations require the breaking of bonds in the structure and the rearrangement of the atomic or ionic linkages. Reconstructed transformations are exemplified by the quartz $\leftrightarrow$ tridymite $\leftrightarrow$  cristobalite inversions. In general, the high-temperature polymorph of a substance has a more open structure, and thus a lower density, than a low-temperature form. The open character of the structure is dynamically maintained at high temperatures by thermal agitations. It can also be statically maintained by the incorporation of foreign ions into the interstices of the structure. These foreign ions often buttress the structure and prevent its transformation to a different polymorph when the temperature is lowered.



Distinguish *displacive* and *reconstructive* inversions in polymorphic forms.

### 5.7.2 Polytypism

Polytypism is another phenomenon that can be considered as a variety of polymorphism. It involves the stacking of identical layers in different sequences within a structure. As a result, polytypes have the same unit cell lengths in two dimensions but commonly have a different cell length in the third dimension, the one essentially perpendicular to the layers. Some of the best-known examples of polytypism among minerals are sphalerite-wurtzite, the micas, and some of the clay minerals. Polytypes are readily distinguished on the basis of their X-ray patterns.

## 5.8 PSEUDOMORPHISM

When a mineral is replaced by another mineral without any change in the external form, such a replacement is referred to as a *pseudomorph*. The phenomenon of replacement is one referred to as pseudomorphism. There are two types of pseudomorphism: one in which no change of substance occurs; and the other in which there is addition of some element or elements and removal of others.

The first type of pseudomorphism is observed when one polymorph changes to another without change in external form. This specific type of pseudomorphism is known as *paramorphism*, and the replacing form is a *paramorph* of the replaced form (e.g., a paramorph of calcite after aragonite).

The second type of pseudomorphism – in which the later pseudomorph mineral has been formed from the original mineral by a process of chemical change - may originate in the following ways:

- the loss of a constituent (e.g., native copper after cuprite or azurite)
- the gain of a constituent (e.g., gypsum after anhydrite and malachite after cuprite)
- a partial exchange of constituents (e.g., goethite (limonite) after pyrite), or

- a complete exchange of constituents (e.g., quartz after fluorite).

The formation of pseudomorph implies that the original mineral was no longer stable under changed physical and chemical conditions and thus was replaced by another mineral suited to those conditions. The study of pseudomorphs can therefore provide valuable evidence or information toward deciphering the geological history of the rock containing them. They may, for example, indicate the nature and composition of circulating solutions that added or subtracted certain elements. Alternatively, if the stability fields of the original mineral and of the pseudomorph are known, it may be possible to estimate the temperature and pressure conditions under which the change took place.



List possible scientific evidences that can be deduced from the study of pseudomorphs.



## 5.9 SUMMARY

In lecture 5 you learned the possibilities and limitations of chemical analyses of minerals. Given the chemical analysis of a mineral, we learned how to determine its chemical mineral formula. In order to determine the formula of a mineral, the weight percentages of the individual elemental analysis must be converted to atomic proportions. The atomic proportions are obtained by dividing the weight percentage of each element in the analysis by the atomic weight of that element. In chemical bonding, we learnt that there are four kinds of bonds that are typically common in crystal structures. These are the *metallic* bond, the *covalent* bond, the *ionic* bond, and *vander Waals* bond.

The system of chemical classification of minerals groups the mineral species into major divisions, or classes, according to the nature of the anionic group present. We defined isostructural and isotypic minerals, and learnt that isostructural minerals are those that have the same structure but different chemical composition; and that isotypism is a feature said to occur between two or more minerals that have analogous or similar structures.

We learnt that *polymorphism* is a phenomenon exhibited by an element or compound that can exist in more than one crystallographic structure. Each polymorph has its own physical properties and a distinct internal arrangement of its atoms and/or ions. We noted that different polymorphs of the same substance are formed under different conditions of pressure, temperature, and/or chemical environment. It therefore follows that the presence of a given polymorph in a rock will often tell us something about the conditions under which the rock was formed. Two types of inversion or transformation, namely *displacive* and *reconstructive*, accompany the change from one polymorph to another. Displacive inversions are immediate and *reversible* and *reconstructive* inversions are sluggish.

We finally learnt that when a mineral is replaced by another mineral without any change in the external form, such a replacement is referred to as a *pseudomorph*. Since the formation of pseudomorph implies that the original mineral was no longer stable under the changed physical and chemical conditions, their study can provide valuable evidence or information toward deciphering the geological history of the rock containing them.



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