Structure of Silicate minerals
Mineral description

The silicate mineral class is of great importance because about 27% of the known minerals and nearly 40% of the common minerals are silicates.

With few exceptions all the igneous rock-forming minerals are silicates, and they constitute well over 90% of the Earth's crust (Fig. 18.1).

In addition, most metamorphic rocks are composed primarily of silicate minerals.

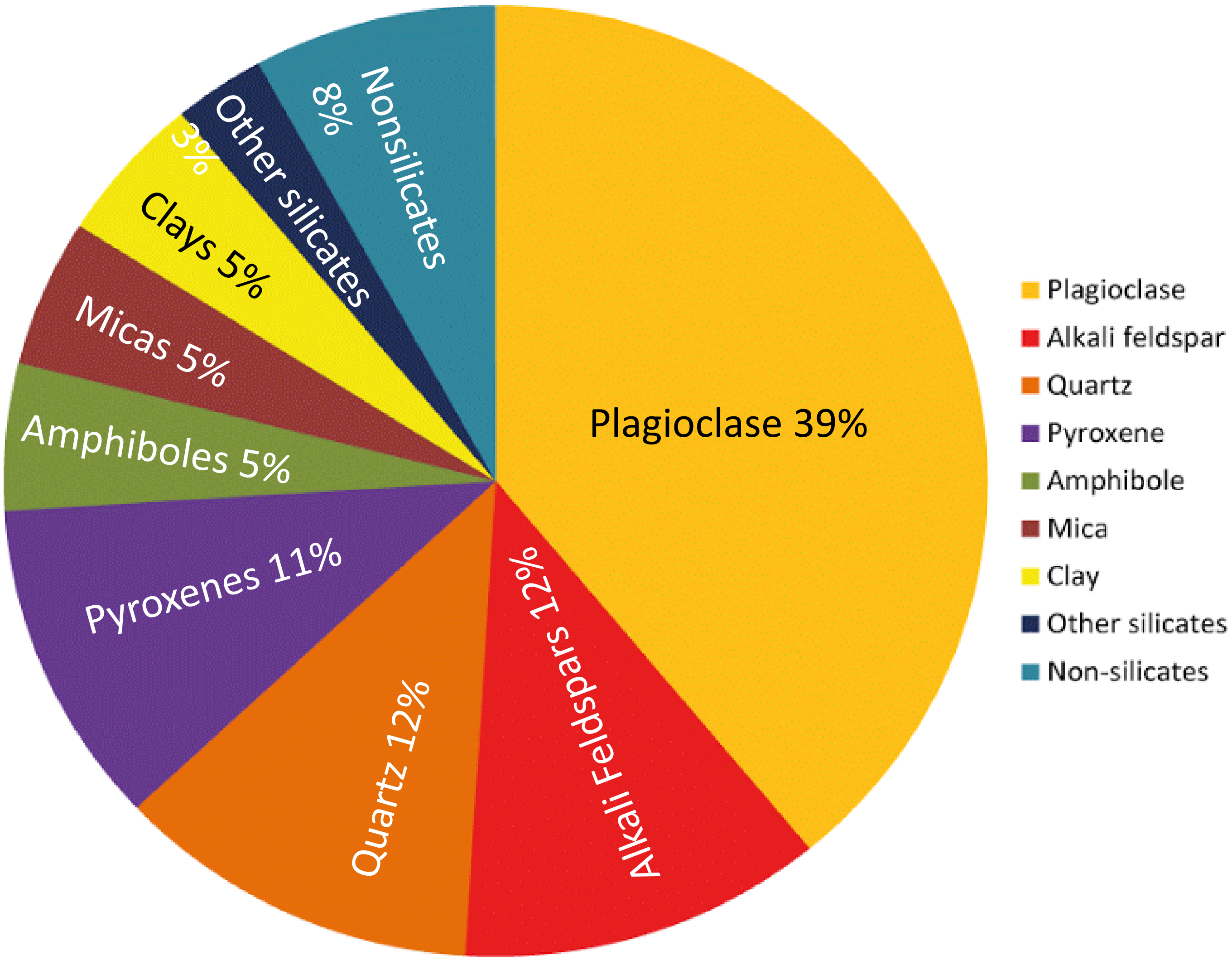


Fig. 18.1: Estimated volume percentages for the common minerals in the Earth's crust, inclusive of continental and oceanic crust. Ninety-two percent are silicates. (from Ronov, A.B. and A.A. Yaroshevsky, 1969. Chemical composition of the Earth's crust. Americal Geophysical Union Monograph No. 13,50)

Rock-forming minerals are those minerals that make up the major components of a rock, and they are used in the classification of rock types.

The more important rock-forming silicate minerals include:

1. Olivine,
2. Garnet,
3. Pyroxenes,
4. Amphiboles,
5. Micas,
6. Clay minerals,
7. Feldspars,
8. Quartz.

Other rock-forming minerals are calcite and dolomite dominant in sedimentary rocks.

When the average weight percentages of the eight most common elements in the Earth's crust are recalculated on the basis of atomic percent (Fig. 5.2), out of every 100 atoms, 62.5 are O, 21.2 are Si, and 6.5 are Al.

Fe, Mg, Ca, Na, and K each account for about 2 to 3 more atoms.

With the possible exception of Ti, all other elements are present in insignificant amounts in the Earth's crust (Fig. 5.2).

When the atomic percentages of the 8 most abundant elements are recalculated in terms of volume percentages (Fig. 5.2, last column) ,

the Earth's crust can be regarded as a packing of oxygen ions, with interstitial metal ions, such as Si^{4+}, Al^{3+}, Fe^{2+} Ca^{2+}, Na^{+}, K^{+}, and so forth.

The dominant minerals of the crust are silicates, with oxides and other oxygen compounds, such as carbonates, in subordinate amounts.

Of the different assemblages of silicate minerals that characterize igneous, sedimentary, and metamorphic rocks, ore veins, pegmatites, weathered rocks, and soils, each has the potential to yield information about the environment in which the rock was formed.

The soil from which our food is ultimately extracted is made up, in large part, of silicates.

The brick, stone, concrete, and glass used in the construction of our buildings either are silicates or are largely derived from silicates.

The moon and the four terrestrial planets of our solar system have rocky crusts made of silicates and oxides like those of Earth.

The fundamental structural unit of all silicates consists of four O^{2-} at the apices of a regular tetrahedron surrounding and coordinated by one Si^{4+} at the center (Figs. 17.Id and 18.2).

The powerful bond that unites the oxygen and silicon ions is the cement that holds the Earth's crust together.

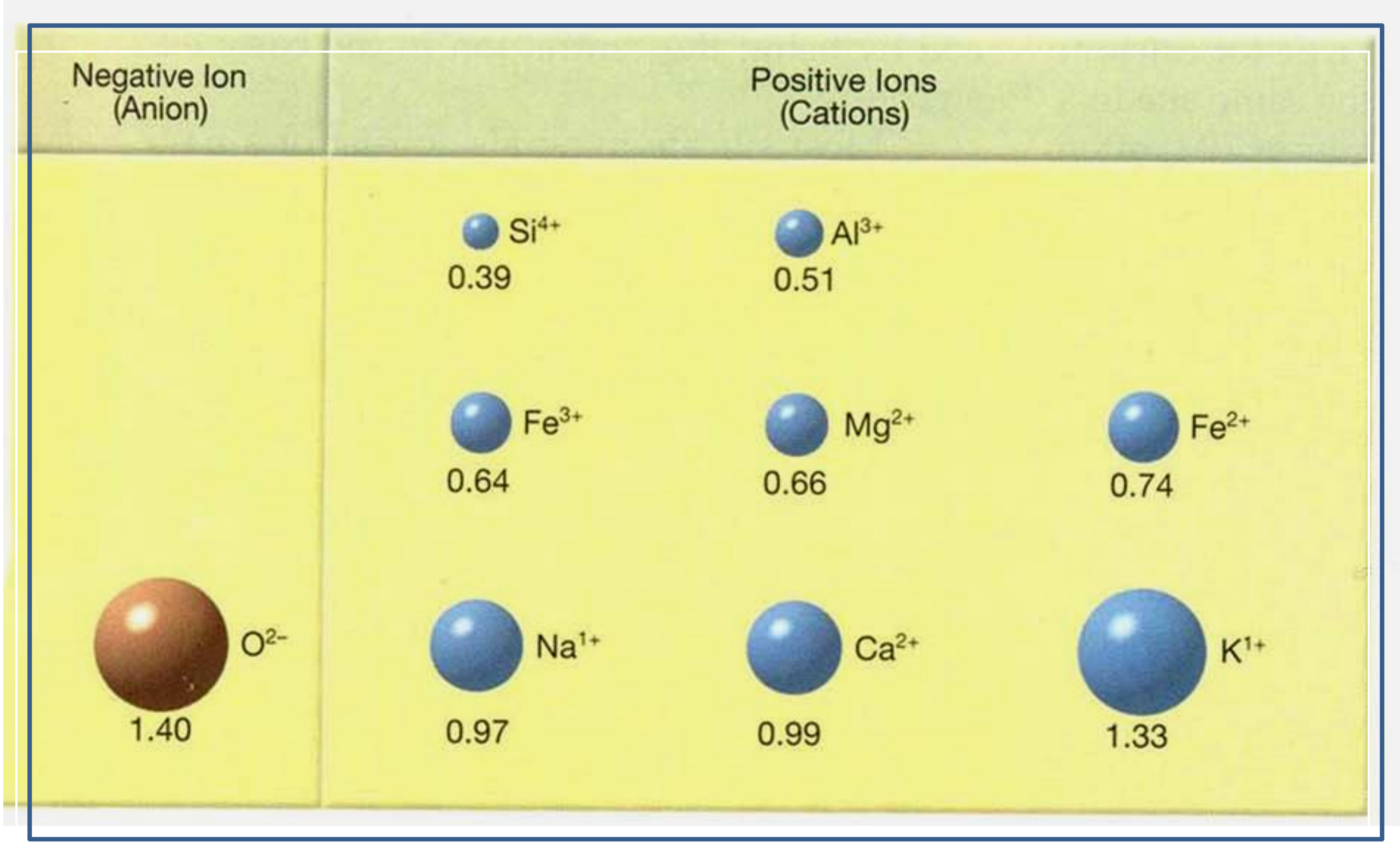


Fig. 3.20: Relative sizes and electrical charges of ions of the eight most common elements in Earth’s crust. These are the most common ions in rock-forming minerals. Ionic radii are expressed in angstroms I1 angstrom equals 10^{-8} cm)

This bond may be estimated by use of Pauling's electronegativity concept (Fig. 3.21) as 50% ionic and 50% covalent.

Although the bond arises in part from the attraction of oppositely charged ions, it also involves sharing of electrons and interpenetration of the electronic clouds of the ions involved.

The bond is strongly localized in the vicinity of these shared electrons.

Although electron sharing is present in the Si-O bond, the total bonding energy of Si^{4+} is distributed equally among its four closest oxygen neighbors.

Hence, the strength of any single Si-O bond is equal to one-half the total bonding energy available in the oxygen ion.

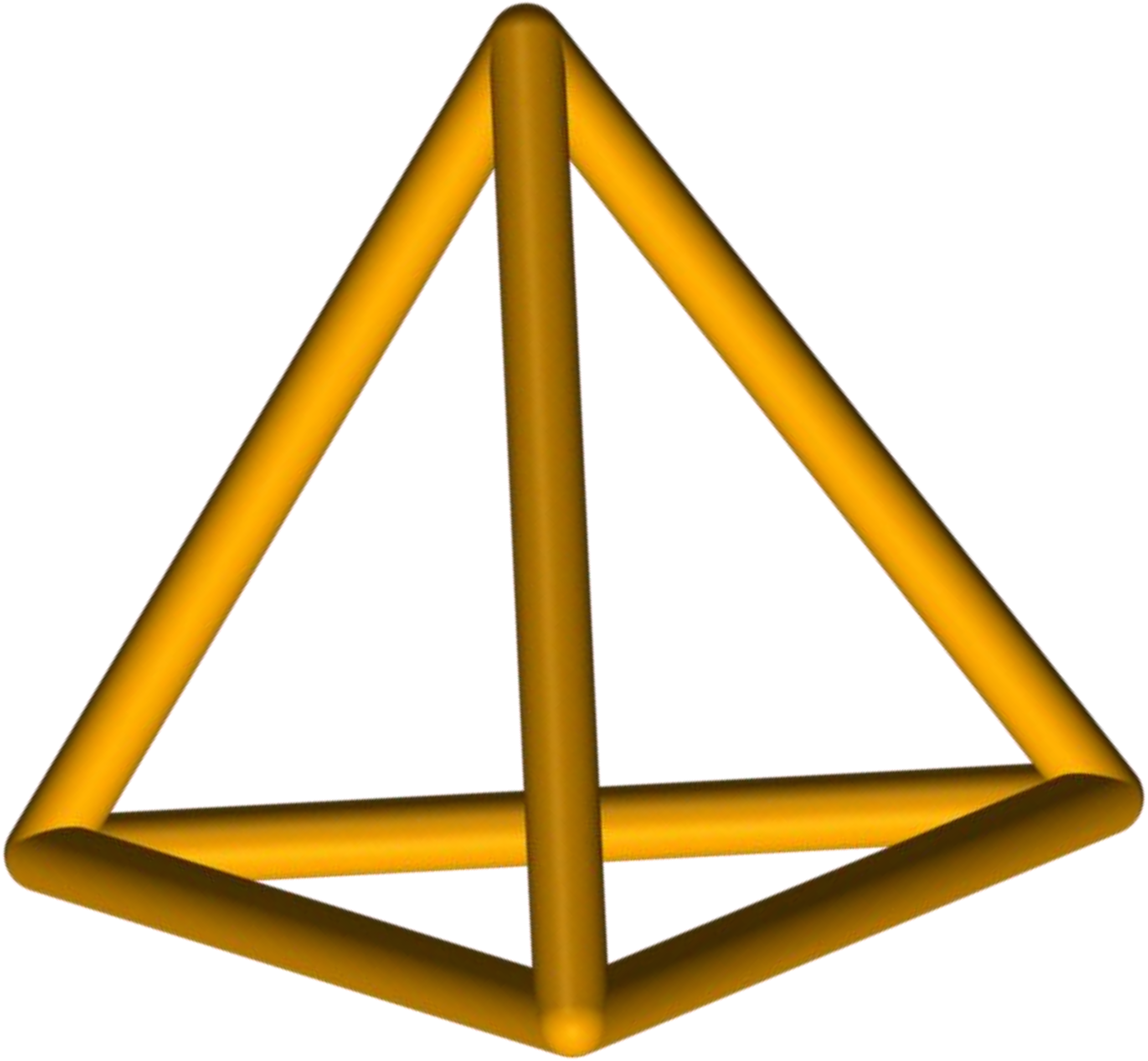
Each O^{2-} has, therefore, the potential of bonding to another silicon ion and entering into another tetrahedral group, thus, uniting the tetrahedral groups through the shared (or bridging) oxygen.

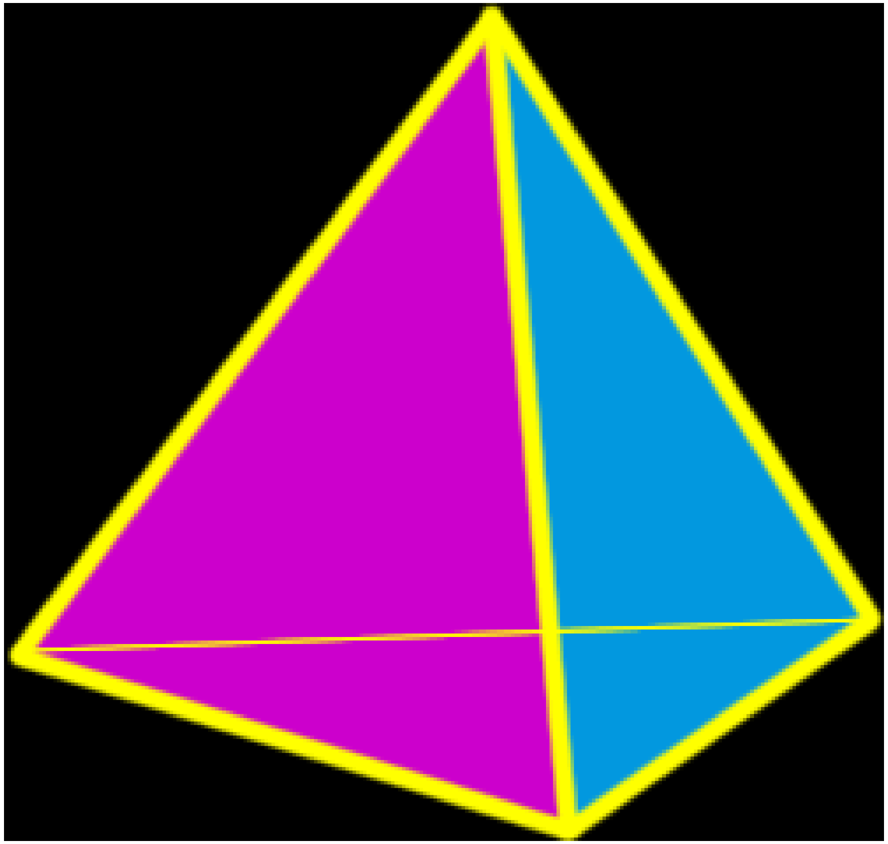
Such linking of tetrahedra is often referred to as polymerization, and the capacity for polymerization is the origin of the great variety of silicate structures.

In no case, however, are three or even two oxygens shared between two adjacent tetrahedra in nature.

Such sharing would place two highly charged Si^{4+} ions close together, and the repulsion between them would destabilize the structure.

The sharing of oxygens may involve one, two, three, or all four of the oxygen ions in the tetrahedron, giving rise to a diversity of structural configurations.

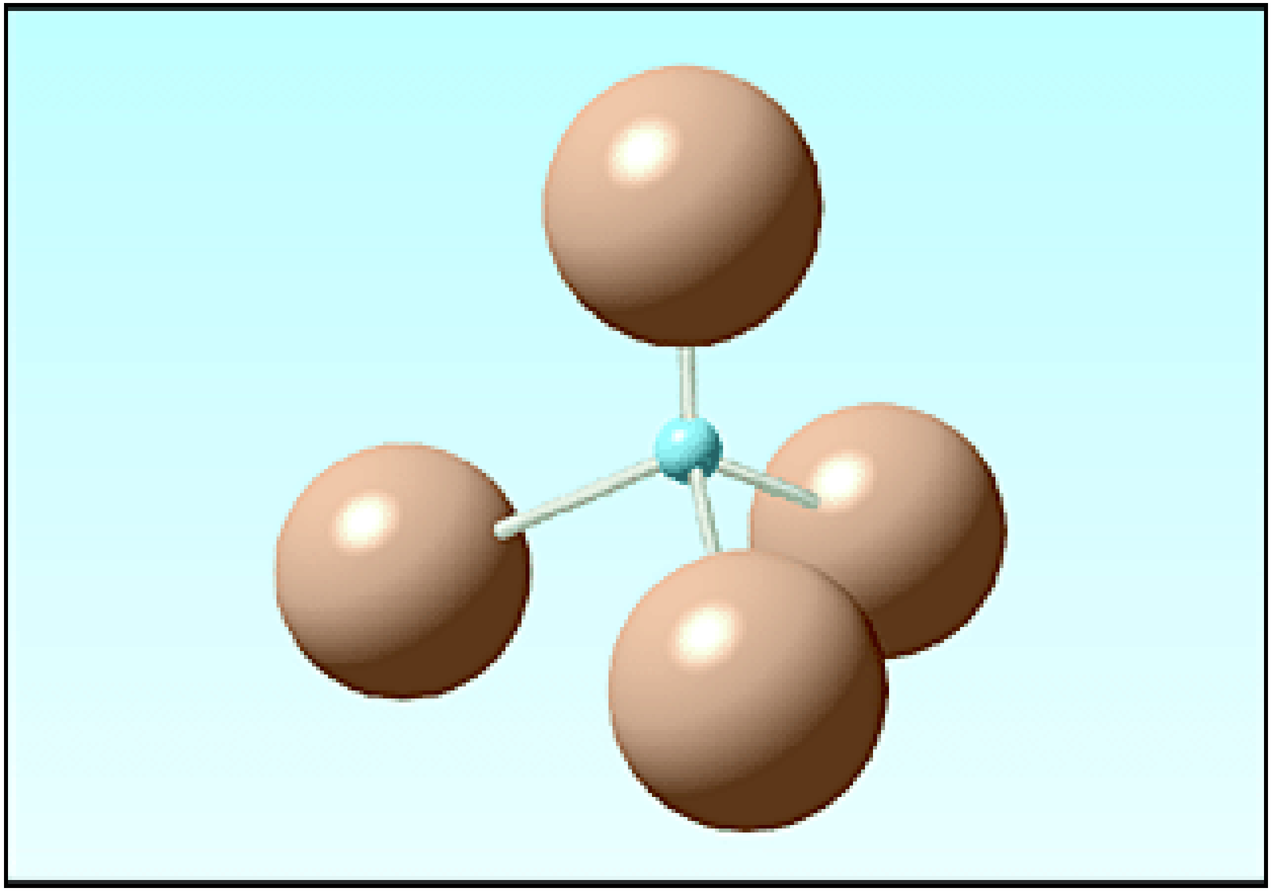




4 faces: equilateral triangles
4 vertices
6 edges
Dihedral angles: 70 degrees, 32 minutes

The tetrahedron is one kind of pyramid, which is a polyhedron with a flat polygon base and triangular faces connecting the base to a common point. In the case of a tetrahedron the base is a triangle (any of the four faces can be considered the base), so a tetrahedron is also known as a "triangular pyramid".

THE SILICA TETRAHEDRON



Silicate Minerals

Each of the silicate minerals contains oxygen and silicon atoms. Except for a few silicate minerals such as quartz, most silicate minerals also contain one or more additional elements in their crystalline structure.

These elements give rise to the great variety of silicate minerals and their varied properties.

All silicates have the same fundamental building block, the silicon-oxygen tetrahedron (tetra = four, hedra = abase).

This structure consists of four oxygen atoms surrounding a much smaller silicon atom, as shown in Figure 2.22.

In some minerals, the tetrahedra are joined into chains, sheets, or three-dimensional networks by sharing oxygen atoms (Fig. 2.23).

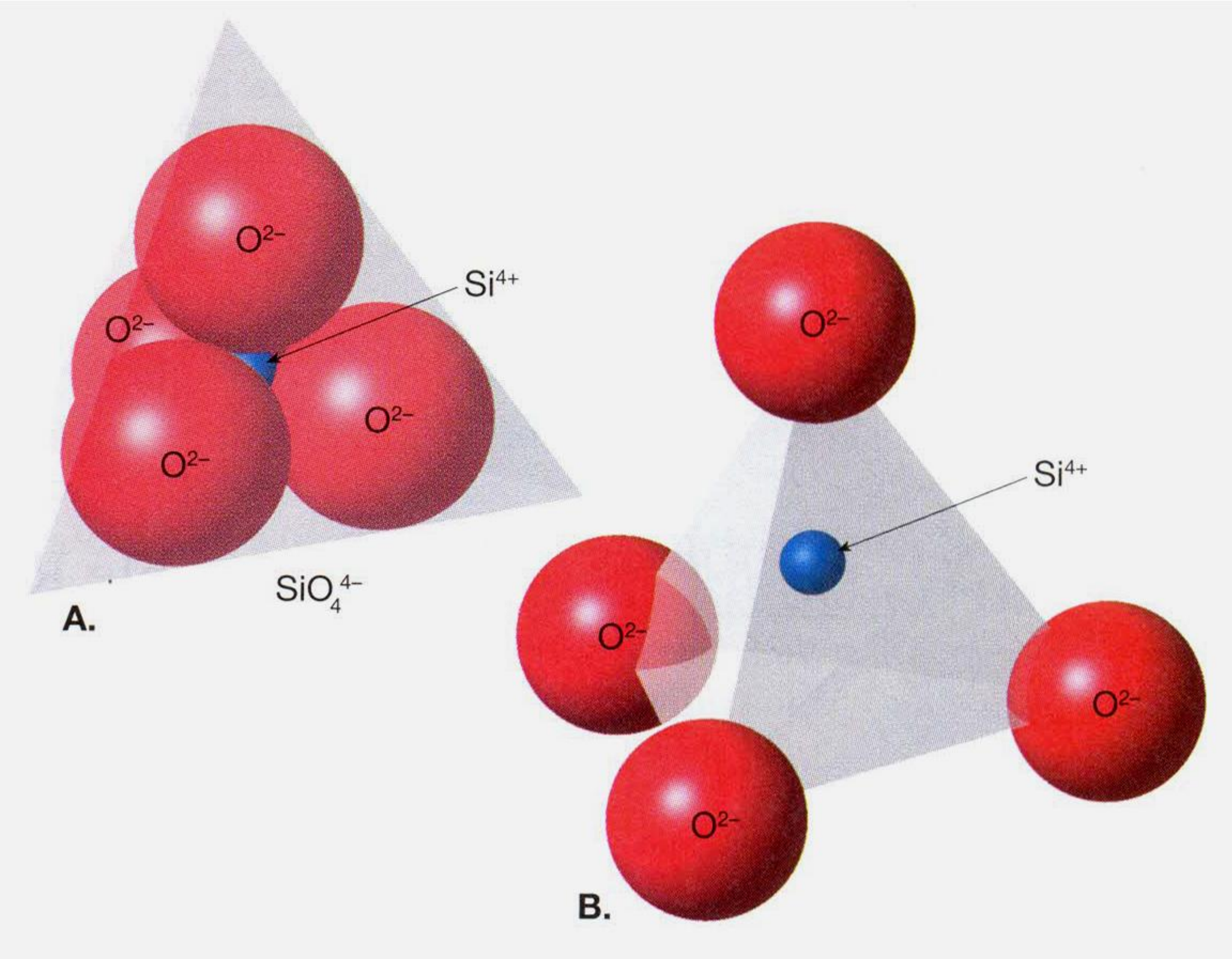
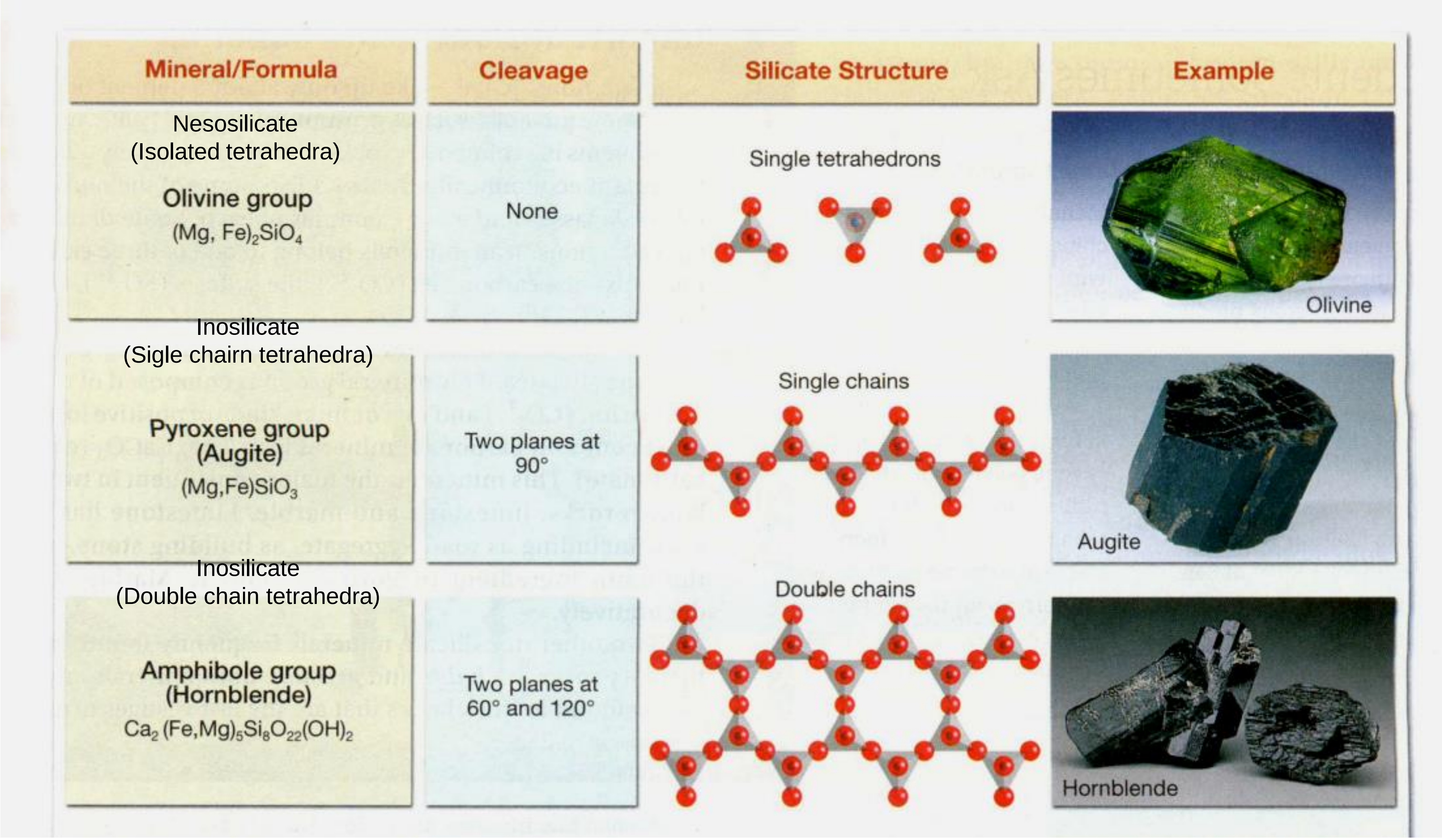


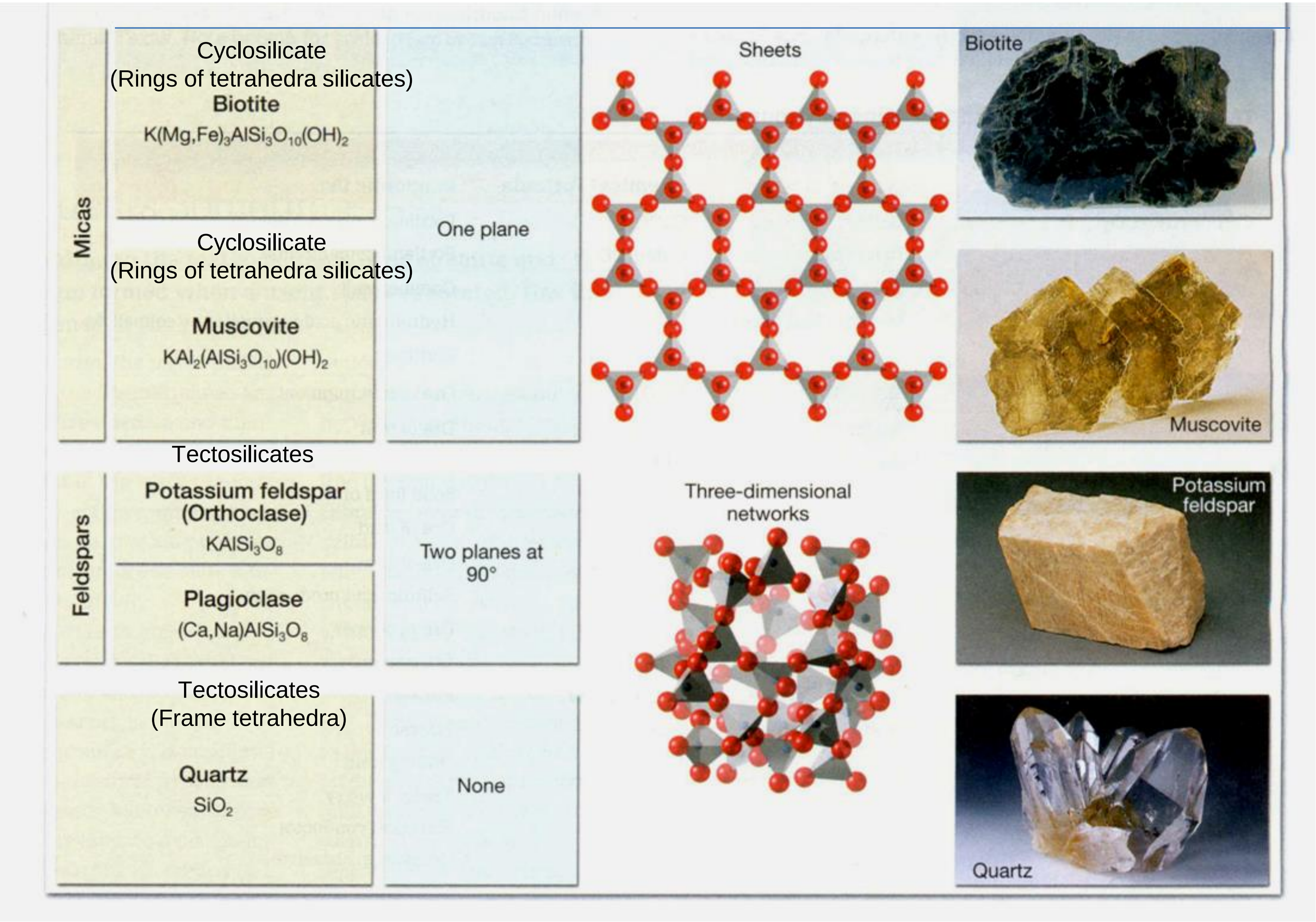
FIGURE 2.22 Two representations of the silicon–oxygen tetrahedron. **A.** The four large spheres represent oxygen ions, and the blue sphere represents a silicon ion. The spheres are drawn in proportion to the radii of the ions. **B.** An expanded view of the tetrahedron that has an oxygen ion at each of the four corners.

Summary



Mineral/Formula	Cleavage	Silicate Structure	Example
Nesosilicate (Isolated tetrahedra) **Olivine group** $(Mg, Fe)_2SiO_4$	None	Single tetrahedrons	Olivine
Inosilicate (Sigle chairn tetrahedra) **Pyroxene group (Augite)** $(Mg,Fe)SiO_3$	Two planes at 90°	Single chains	Augite
Inosilicate (Double chain tetrahedra) **Amphibole group (Hornblende)** $Ca_2 (Fe,Mg)_5Si_8O_{22}(OH)_2$	Two planes at 60° and 120°	Double chains	Hornblende

Figure 2.23: Common silicate minerals. Note that the complexity of the silicate structure increases from top to bottom (photo by Dennis Tasa and E.J. Tarbuck)



Micas	Cyclosilicate (Rings of tetrahedra silicates) **Biotite** $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	One plane	Sheets	Biotite
	Cyclosilicate (Rings of tetrahedra silicates) **Muscovite** $KAl_2(AlSi_3O_{10})(OH)_2$			Muscovite
Feldspars	Tectosilicates **Potassium feldspar (Orthoclase)** $KAlSi_3O_8$	Two planes at 90°	Three-dimensional networks	Potassium feldspar
	Plagioclase $(Ca,Na)AlSi_3O_8$			
	Tectosilicates (Frame tetrahedra) **Quartz** SiO_2	None		Quartz

Figure 2.23: Common silicate minerals. Note that the complexity of the silicate structure increases from top to bottom (photo by Dennis Tasa and E.J. Tarbuck)

These larger silicate structures are then connected to one another by other elements.

The primary elements that join silicate structures are iron (Fe), magnesium (Mg), potassium (K), sodium (Na), and calcium (Ca).

Major groups of silicate minerals and common examples are given in Figure 2.23.

The feldspars are by far the most plentiful group, comprising over 50 percent of Earth's crust.

Quartz, the second most abundant mineral in the continental crust, is the only common mineral made completely of silicon and oxygen.

Notice in Figure 2.23 that each mineral group has a particular silicate structure. A relationship exists between this internal structure of a mineral and the cleavage it exhibits.

Because the silicon-oxygen bonds are strong, silicate minerals tend to cleave between the silicon-oxygen structures rather than across them.

For example, the micas have a sheet structure and thus tend to cleave into flat plates (see muscovite in Figure 2.16).

Quartz, which has equally strong silicon-oxygen bonds in all directions, has no cleavage but fractures instead.

How do silicate minerals form?

Most crystallize from molten rock as it cools. This cooling can occur at or near Earth's surface (low temperature and pressure) or at great depths (high temperature and pressure).

The environment during crystallization and the chemical composition of the molten rock mainly determine which minerals are produced.

For example, the silicate mineral olivine crystallizes at high temperatures (about 1200°C, whereas quartz crystallizes at much lower temperatures (about 700°C).

In addition, some silicate minerals form at Earth's surface from the weathered products of other silicate minerals. Clay minerals are an example.

Still other silicate minerals are formed under the extreme pressures associated with mountain building.

Each silicate mineral, therefore, has a structure and a chemical composition that indicate the conditions under which it formed.

Thus, by carefully examining the mineral makeup of rocks, geologists can often determine the circumstances under which the rocks formed.

Classification of silicate minerals based on their tetrahedra structures

Figure 18.3 illustrates the various ways in which $Si0_4$ tetrahedra can be combined Which gives rise to the following types of silicates:

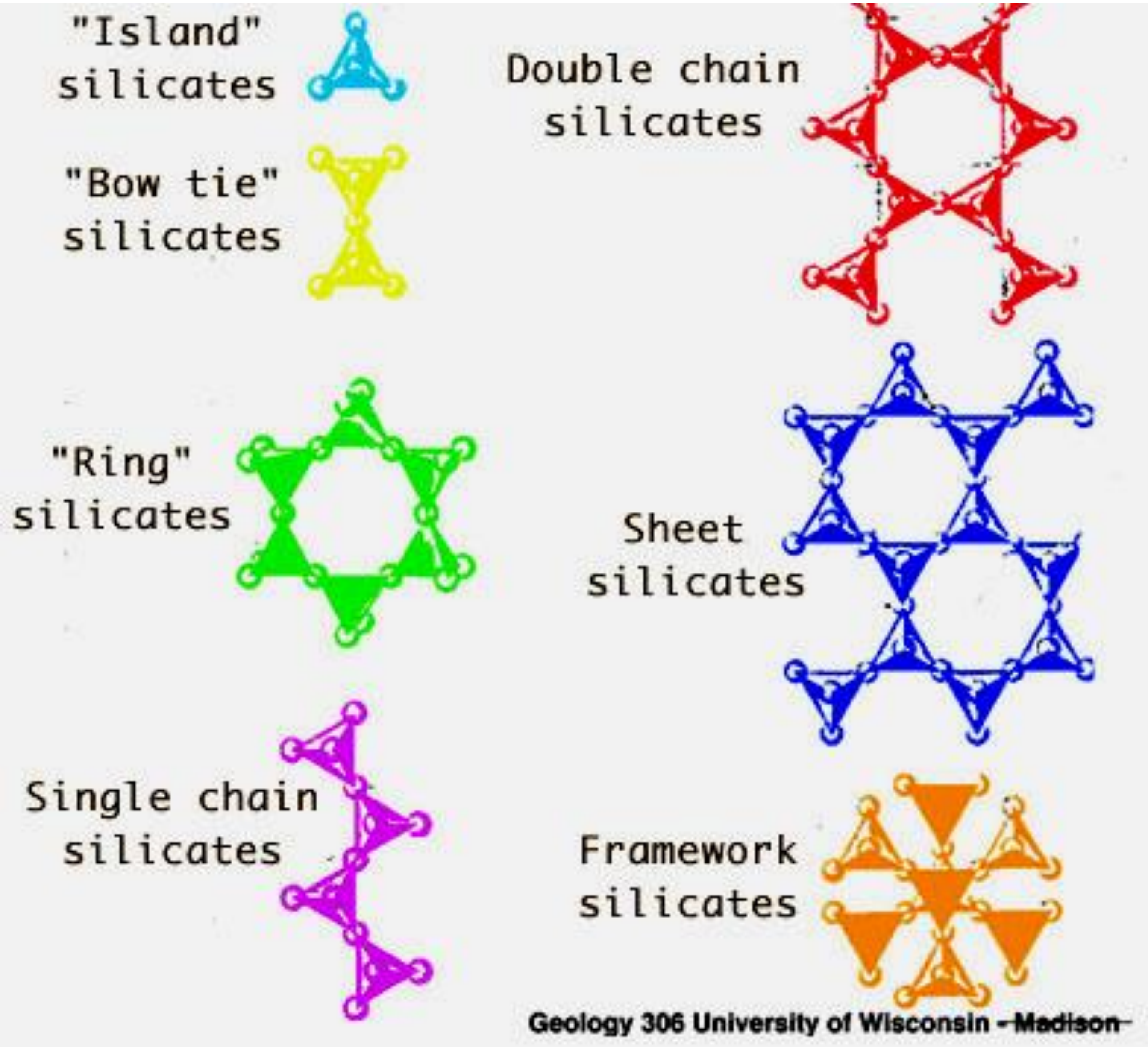
(1) Nesosilicates (or Orthosilicates or Isolated/single tetrahedra silicates, e.g. olivine, garnet)
(2) Sorosilicates (Double tetrahedral silicate groups)
(3) Cyclosilicates (Rings of tetrahedra silicates, e.g. Beryl, tourmaline)

Types of silicates: contd…

(4) **Inosilicates** (single and double chians of tetrahedra silicates, e.g., Amphoboles and pyroxenes)

(5) **Phyllosilicates** (Sheet or Layers of tetrahedra silicates, e.g., muscovite)

(6) **Tectosilicates** (Framework of tetrahedra silicates, e. g., quatz, feldspars)



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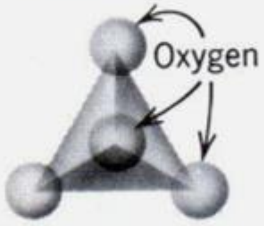
Class	Arrangement of SiO_4 tetrahedra (central Si^{4+} not shown)	Unit composition	Mineral example
Nesosilicates		$(SiO_4)^{4-}$	Olivine, $(Mg, Fe)_2SiO_4$
Sorosilicates		$(Si_2O_7)^{6-}$	Hemimorphite, $Zn_4Si_2O_7(OH)\cdot H_2O$

Fig. 18.3: Silicate classification

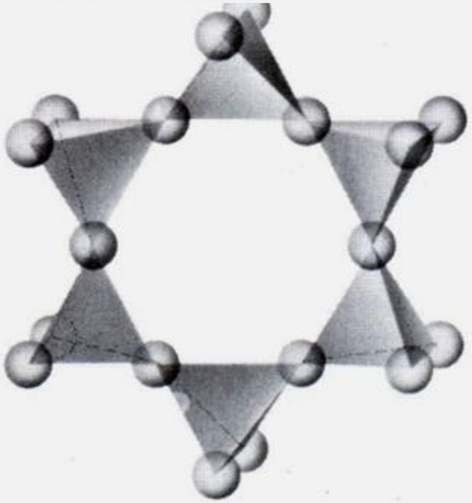
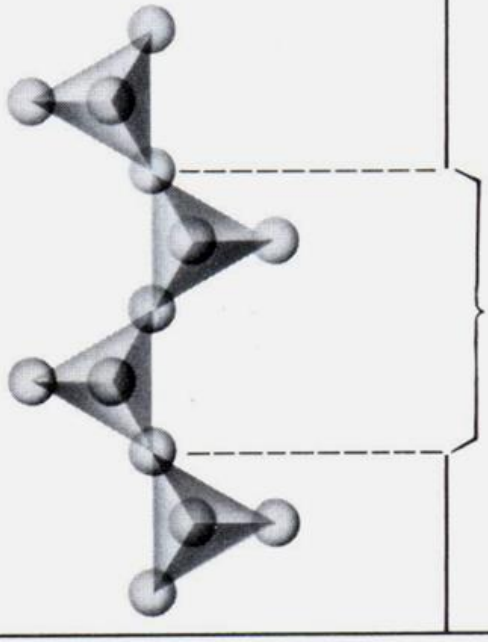
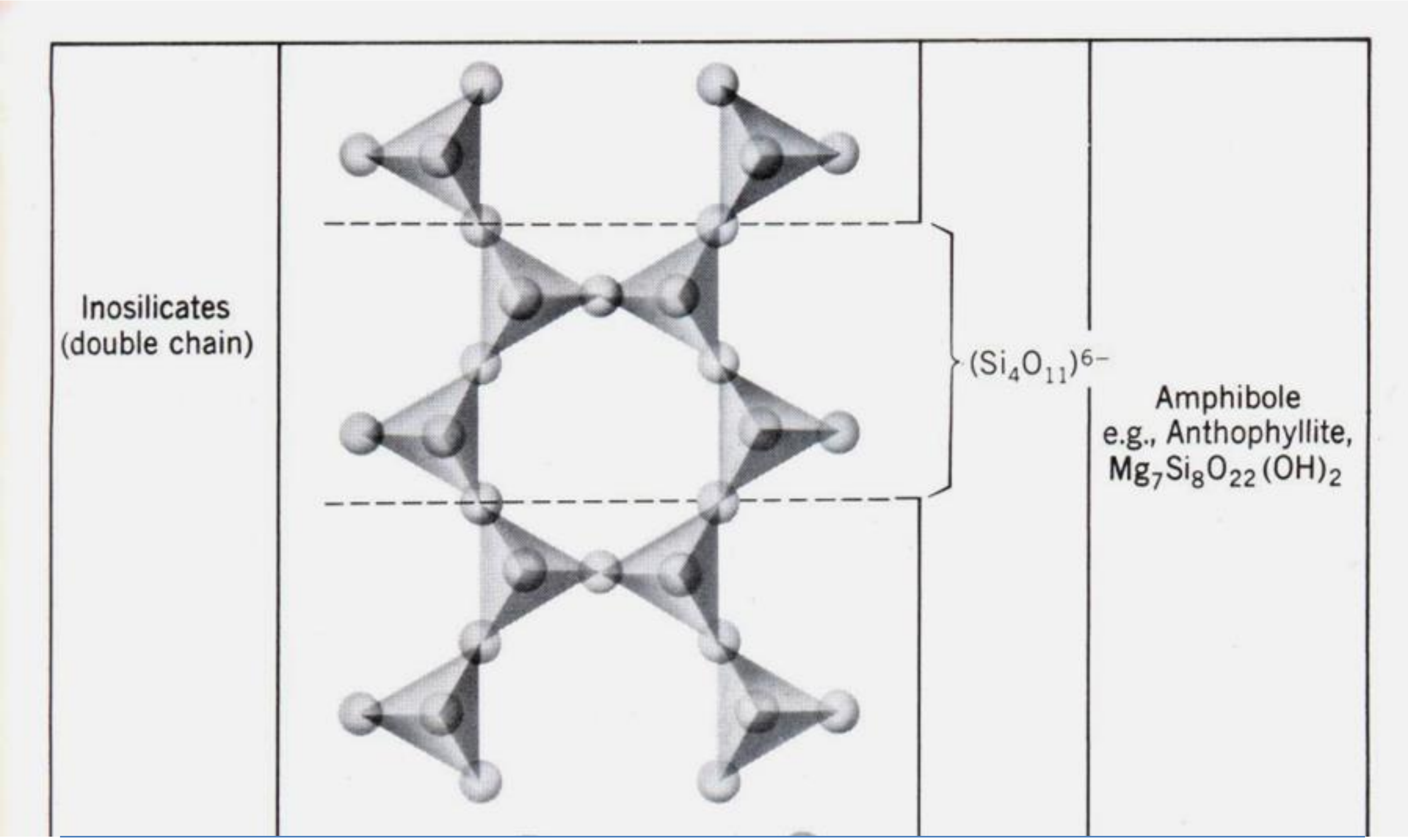
Class	Arrangement of SiO_4 tetrahedra (central Si^{4+} not shown)	Unit composition	Mineral example
Cyclosilicates		$(Si_6O_{18})^{12-}$	Beryl, $Be_3Al_2Si_6O_{18}$
Inosilicates (single chain)		$(Si_2O_6)^{4-}$	Pyroxene e.g., Enstatite, $MgSiO_3$

Fig. 18.3: Silicate classification



Inosilicates (double chain)

$(Si_4O_{11})^{6-}$

Amphibole
e.g., Anthophyllite,
$Mg_7Si_8O_{22}(OH)_2$

Fig. 18.3: Silicate classification contd..

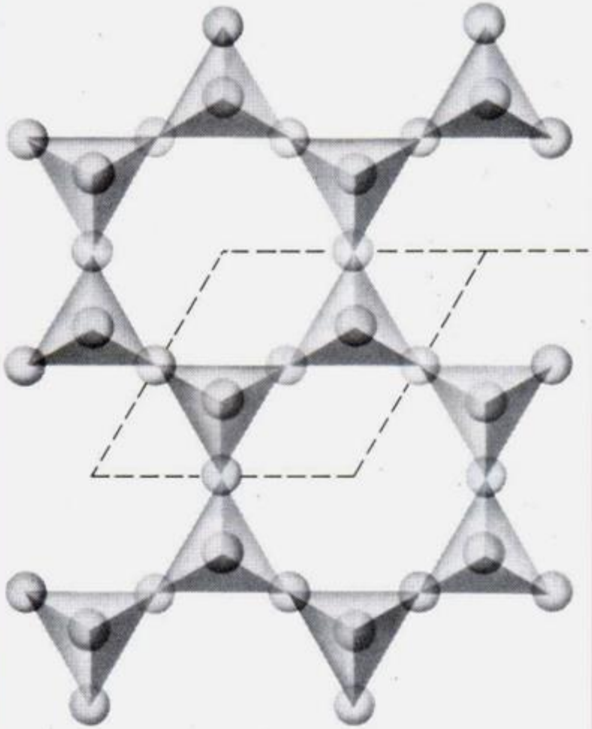
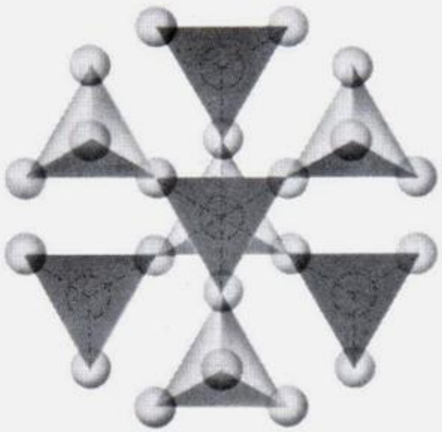
Phyllosilicates		$(Si_2O_5)^{2-}$	Mica e.g., Phlogopite, $KMg_3(AlSi_3O_{10})(OH)_2$
Tectosilicates		$(SiO_2)^0$	High cristobalite, SiO_2

Fig. 18.3: Silicate classification contd..

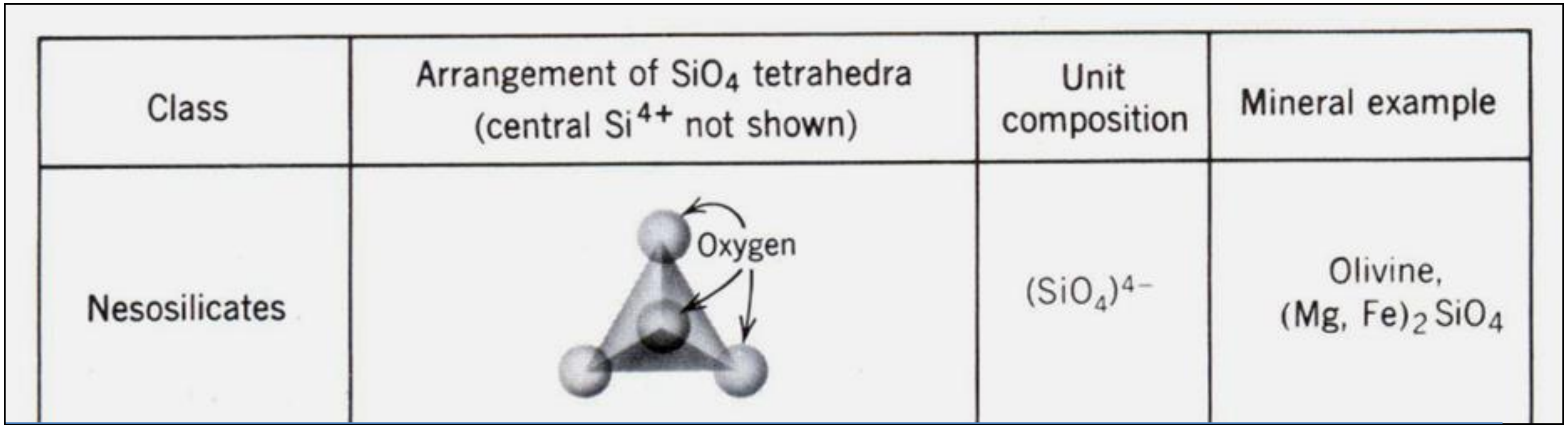
1. Nesosilicates

(Isolated Tetrahedra silicates)

Silicates with independent tetrahedral $Si0_4$ groups (in which the tetrahedra are not linked to each other) are known as nesosilicates (from the Greek word nesos, meaning island) or orthosilicates (from the Greek word orthos, meaning normal).

In nesosilicates the $Si0_4$ tetrahedra are isolated (Fig. 18.3). These are bound to each other by ionic bonds from interstitial cations. Their structures depend primarily on the size and charge of the interstitial cations.

The atomic packing of the nesosilicate structure is generally dense, causing the minerals of this group to have relatively high specific gravity and hardness.

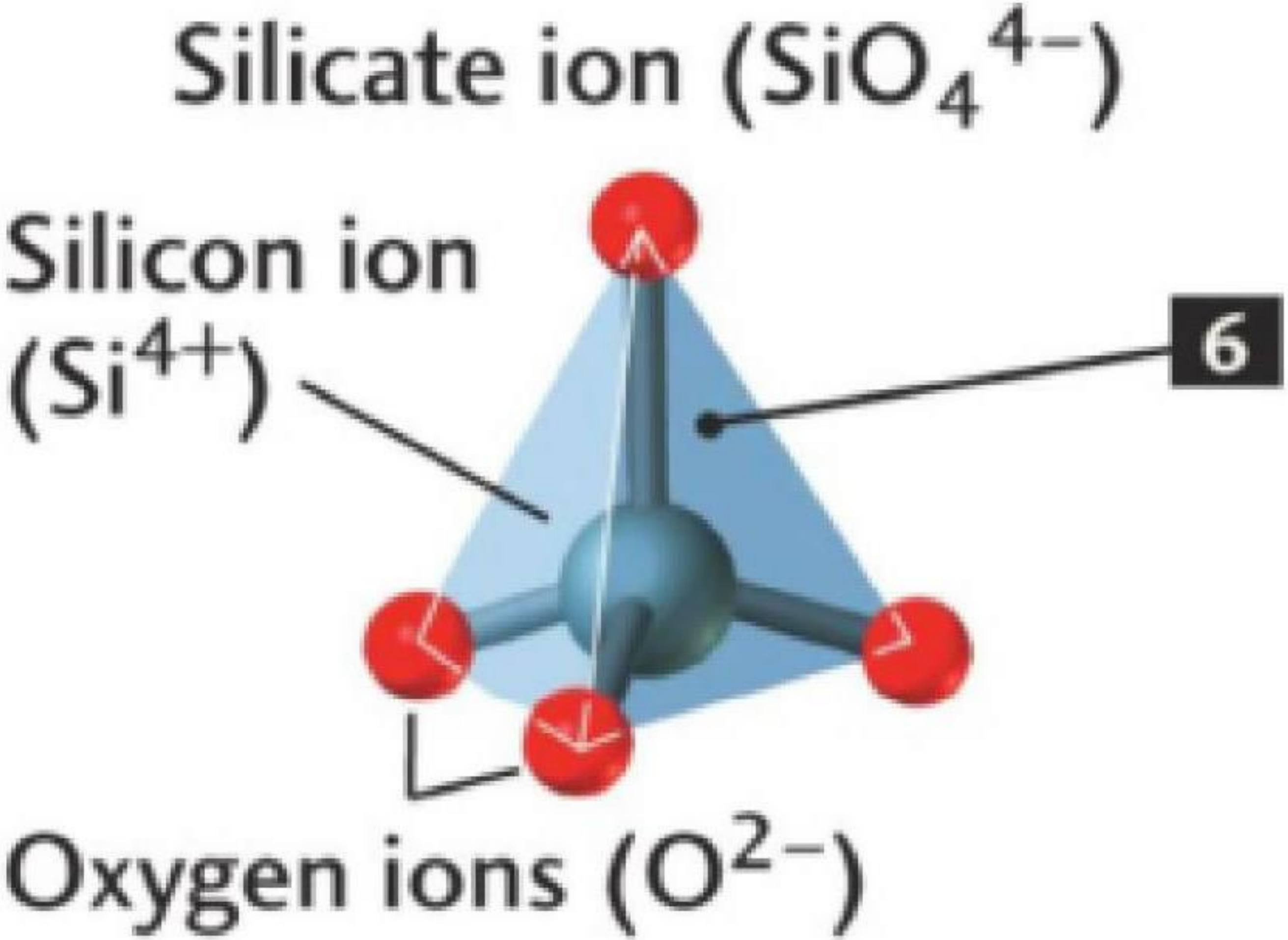


Class	Arrangement of SiO_4 tetrahedra (central Si^{4+} not shown)	Unit composition	Mineral example
Nesosilicates		$(SiO_4)^{4-}$	Olivine, $(Mg, Fe)_2SiO_4$

Fig. 18.3: Silicate classification

Isolated Tetrahedra silicates

- Tetrahedra DO NOT SHARE any of their oxygens; Tetrahedra linked via a cation e.g. Fe^{2+}
- Mineral Example is Olivine $(Mg,Fe)_2SiO_4$



Isolated tetrahedra

Because the $Si0_4$ tetrahedra are independent, bond strengths are about equal in all directions.

Therefore, the crystal habit of the nesosilicates is generally equidimensional and pronounced cleavage directions are absent.

Although Al^{3+} substitutes commonly for Si in silicates, the amount of Al substitution in $Si0_4$ tetrahedra in nesosilicates is generally low.

Common members, in high-temperature igneous rocks, of the nesosilicate group are forsterite, Mg2Si04, and fayalite, Fe_2Si0_4, end-members of the $(Mg,Fe)_2Si0_4$ olivine series.

Garnets are another group of common nesosilicate minerals, especially in metamorphic rocks. The aluminosilicates of the nesosilicate group, kyanite, sillimanite, and andalusite, are commonly found in medium- to high-grade metamorphic rocks of Al-rich bulk composition.

2. Sorosilicates

(Double tetrahedral silicate groups)

Silicates in which two $Si0_4$ groups are linked, giving rise to Si_20_7 groups are classed as sorosilicates (from the Greek word soros, meaning heap) or disilicates (in reference to the double tetrahedral groupings).

The **sorosilicates** are characterized by isolated, double tetrahedral groups formed by two $Si0_4$ tetrahedra sharing a single apical oxygen (**Fig. 18.8**).

The resulting ratio of silicon to oxygen is 2:7. More than 70 minerals are known in this group, but most of them are rare.

Epidote group and **vesuvianite** are most important minerals crystallizing in this group.

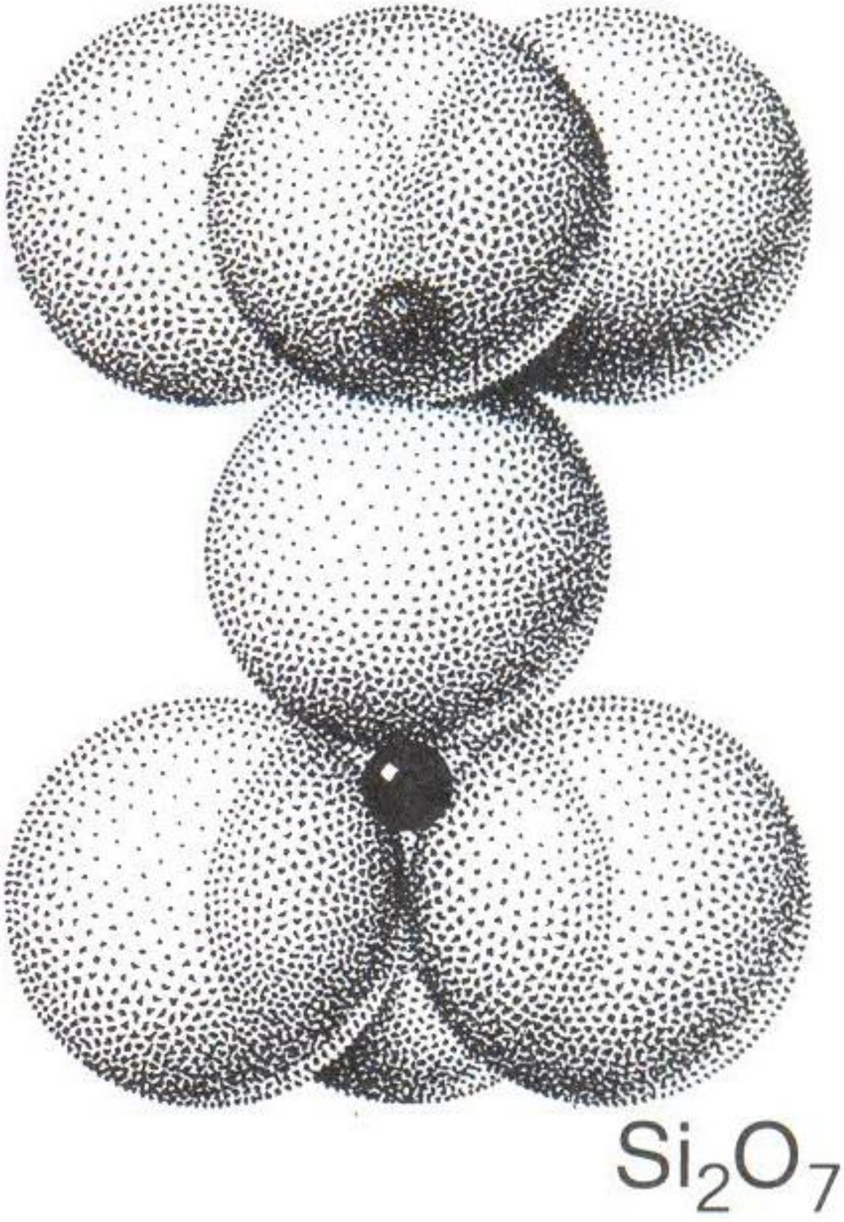


Fig. 18.8: Close-packed representation of an Si2O7 group

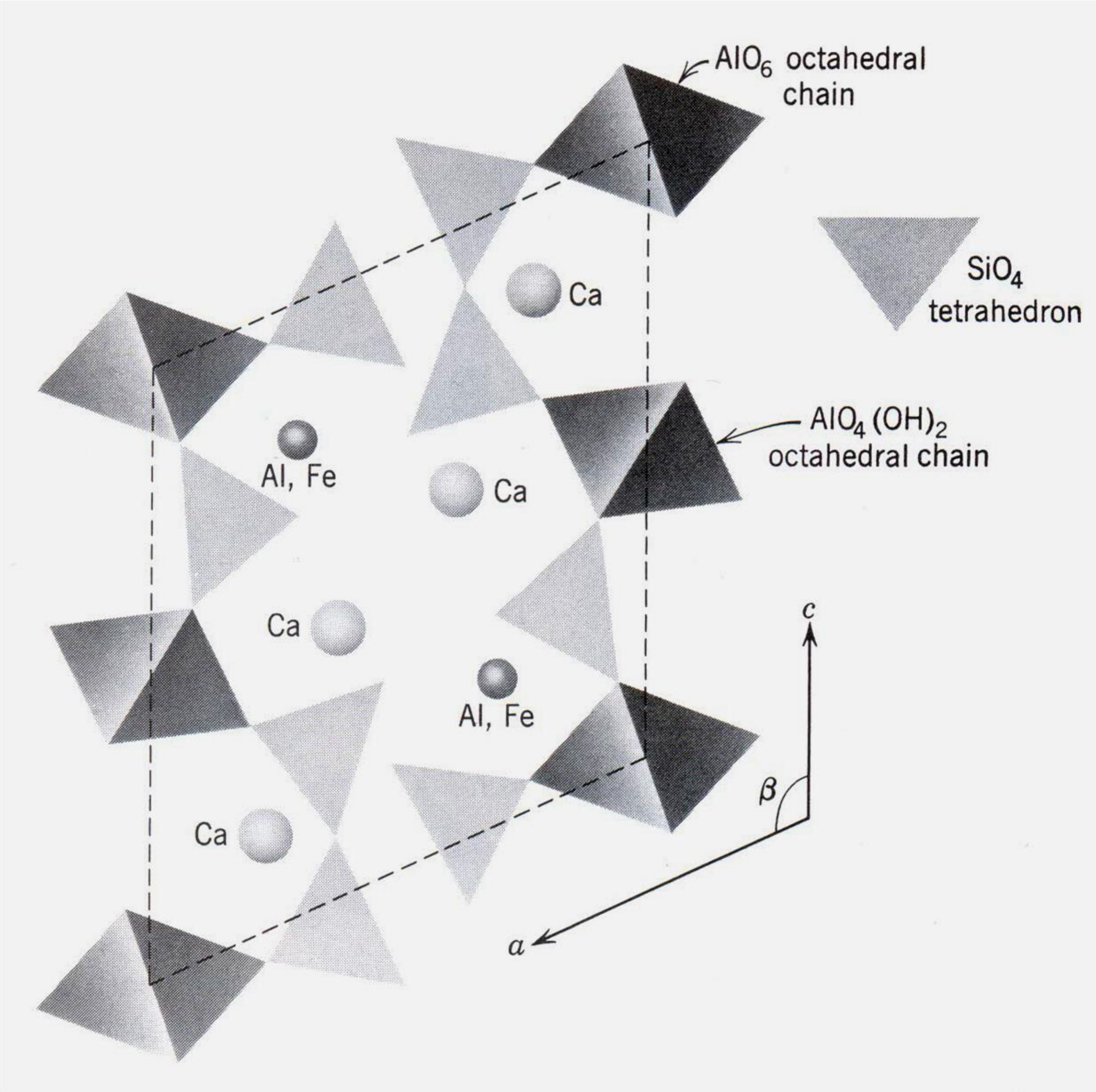


Fig. 18.9: Schematic representation of the structure of epidote, projected on (010). Dashed lines outline unit cell

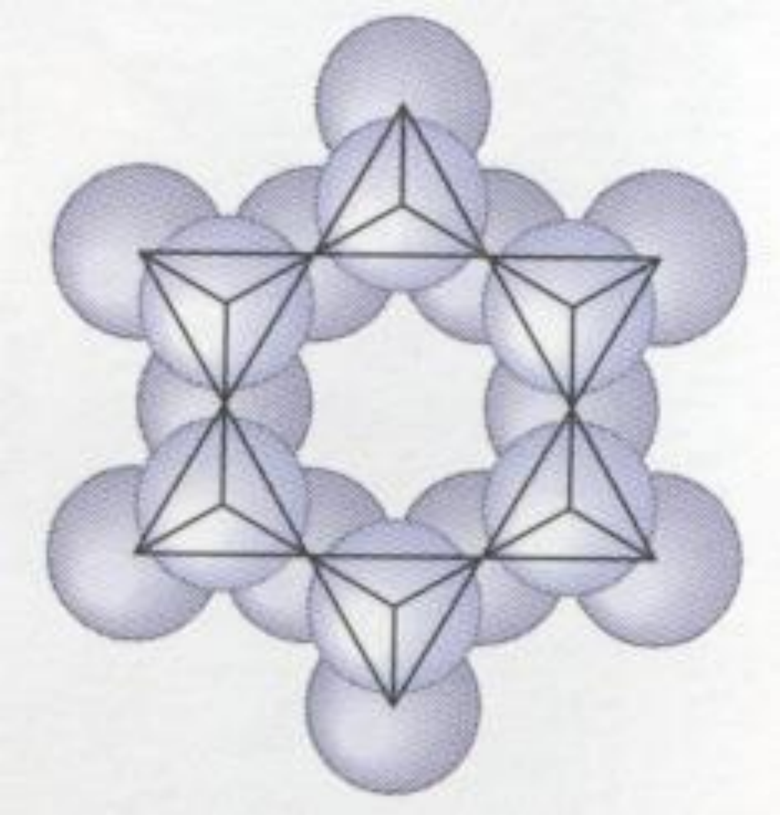
Cyclosilicates

(Rings of tetrahedra silicates)

The cyclosilicates contain rings of linked $Si0_4$ tetrahedra having a ratio of Si:O = 1:3.

Three possible closed cyclic configurations of this kind may exist, as shown in Fig. 18.11. The simplest is the Si_30_9 ring, represented among minerals only by the rare titanosilicates *benitotite* ($BaTiSi_3O_9$)

Ring Silicate



- Joined by shared oxygens in 3, 4 or 6 membered rings
- Mineral Example is Beryl (emerald & aquamarine) $Be_3Al_2\{Si_6O_{18}\}$

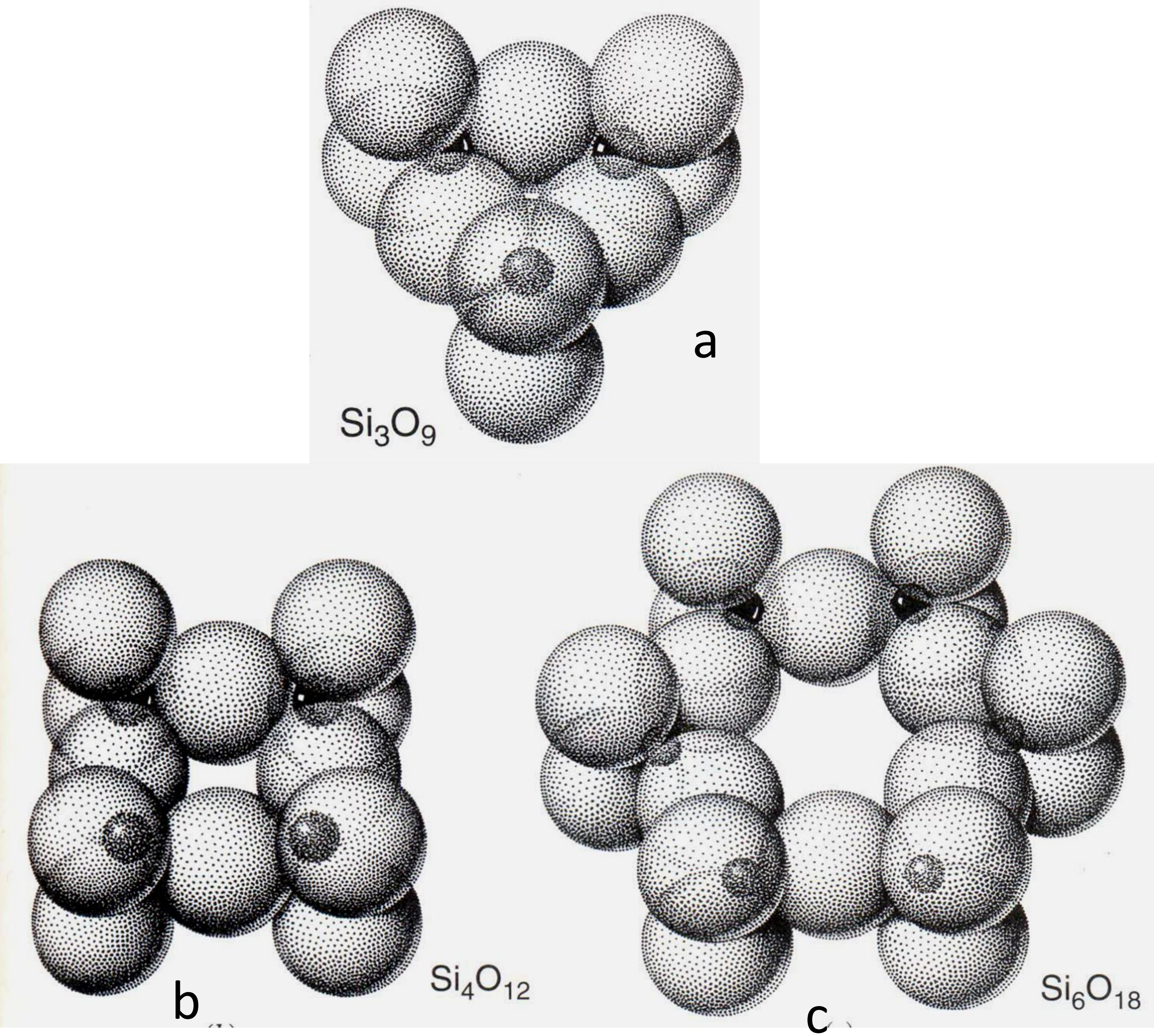


Fig. 18.11: Close-packed representation of ring structures in cyclosilicates

The Si_6O_{18} ring is the basic framework of the common and important minerals, beryl, $Be_3Al_2Si_60_{18}$, and tourmaline.

In the structure of beryl, Si_60_{18} rings are arranged in layers parallel to {0001}.

If more than two tetrahedra are linked, closed ringlike structures are formed of a general composition $Sij.0_{3r}$. Four-fold tetrahedral rings have composition $Si_{4}O_{12}$. This group is known as the ring silicates, or the cyclosilicates (from the Greek word kyklos, meaning circle).

Tetrahedra may also be joined to form infinite single chains with a unit composition $Si_{2}0_{6}$ (or $Si0_{3}$).

$Si0_4$ tetrahedra may link into chains by sharing oxygens (Fig. 18.3). Simple chains may be joined side-by-side by further sharing of oxygens in alternate tetrahedra to form bands or double chains (Fig. 18.3).

In the simple chain structure, two of the four oxygens in each $Si0_4$ tetrahedron are shared, giving a ratio of Si:O = 1:3. In the band structure, half of the tetrahedra share three oxygens and the other half share two oxygens, yielding a ratio of Si:O = 4:11.

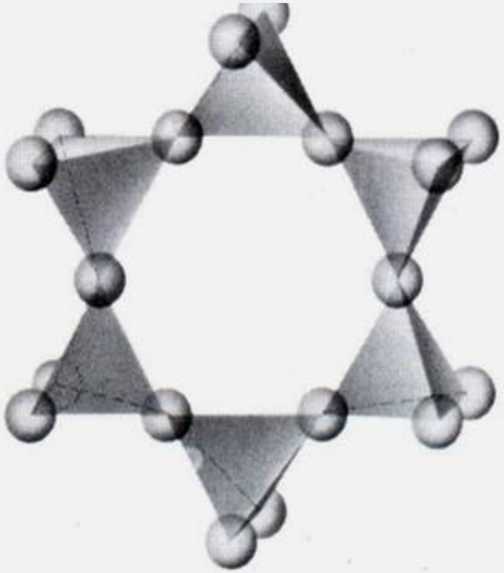
Class	Arrangement of SiO_4 tetrahedra (central Si^{4+} not shown)	Unit composition	Mineral example
Cyclosilicates		$(Si_6O_{18})^{12-}$	Beryl, $Be_3Al_2Si_6O_{18}$

Fig. 18.3: Silicate classification

Inosilicates

(Single and double chains of tetrahedra)

Included in the inosilicates are two important rock-forming groups of minerals:

(a) The pyroxenes as single chain members and,
(b) The amphiboles as double chain members.

Many similarities exist between the two groups in crystallographic, physical, and chemical properties.

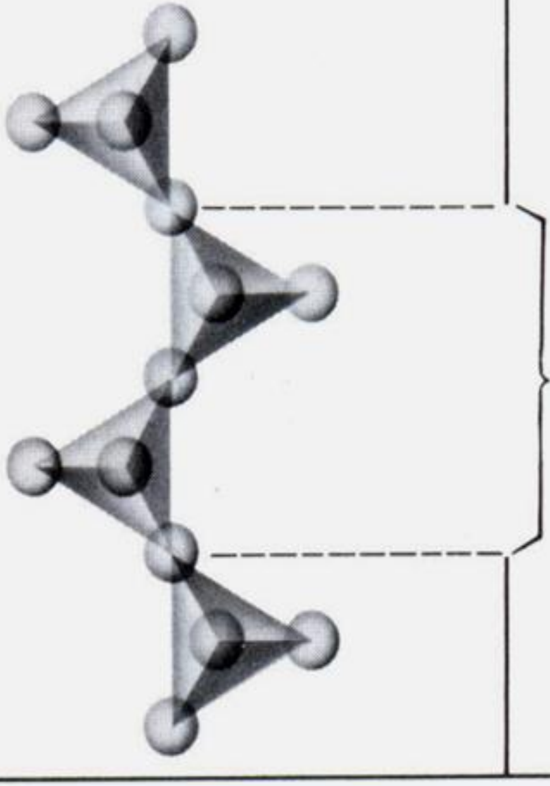
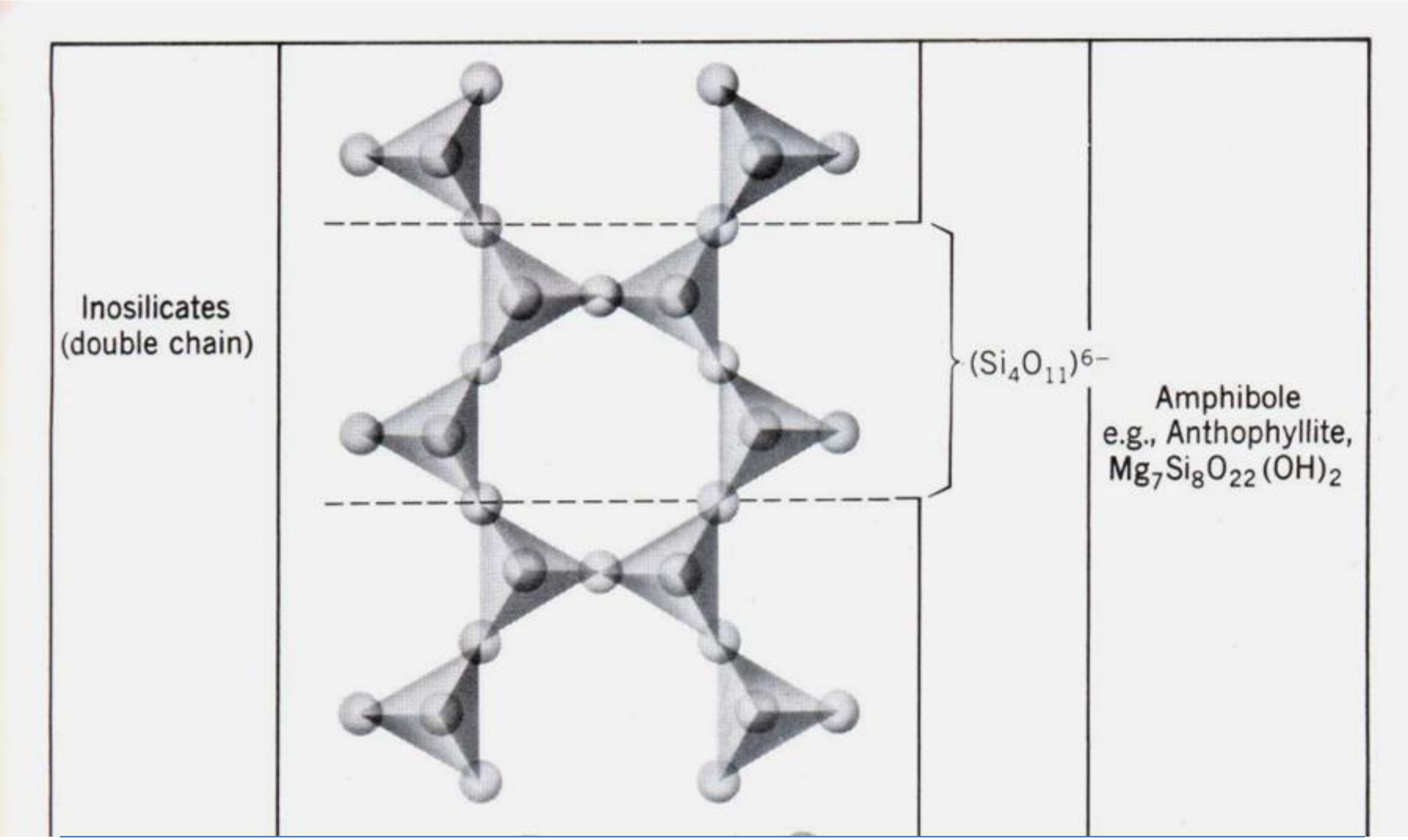
Class	Arrangement of SiO_4 tetrahedra (central Si^{4+} not shown)	Unit composition	Mineral example
Inosilicates (single chain)		$(Si_2O_6)^{4-}$	Pyroxene e.g., Enstatite, $MgSiO_3$

Fig. 18.3: Silicate classification



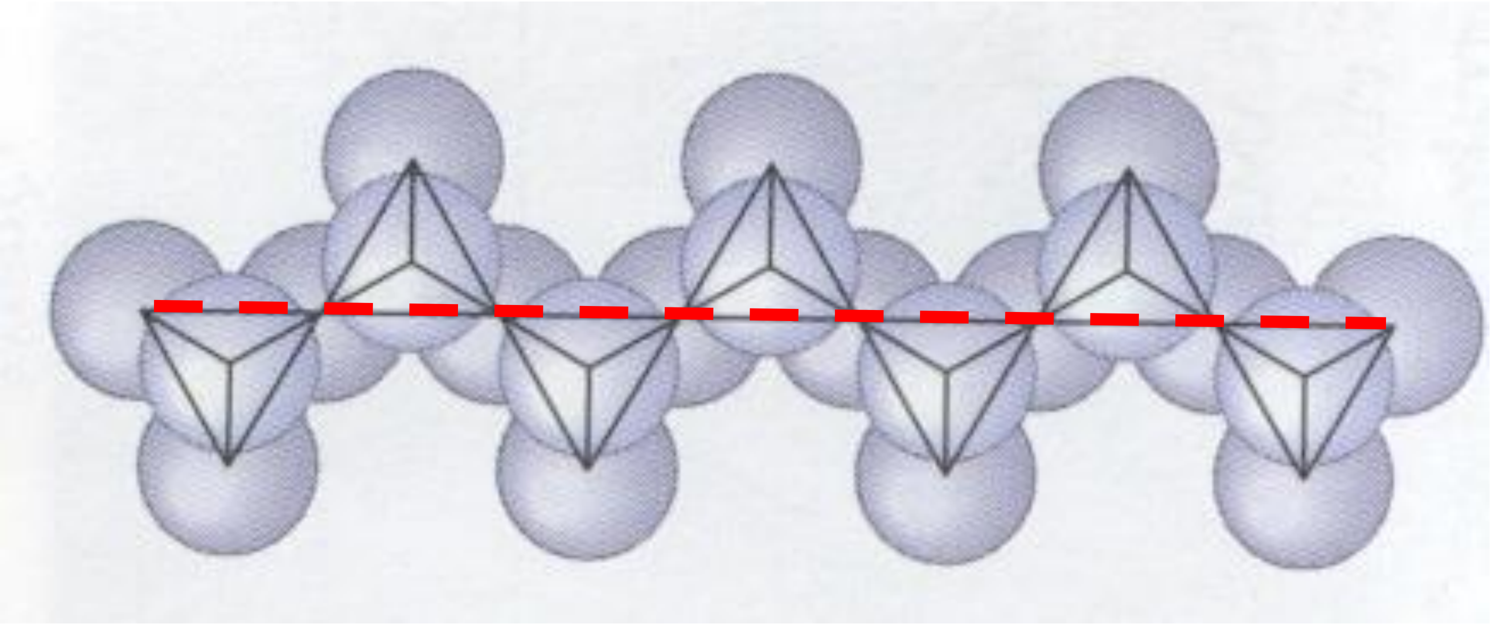
Inosilicates (double chain)		$(Si_4O_{11})^{6-}$	Amphibole e.g., Anthophyllite, $Mg_7Si_8O_{22}(OH)_2$

Fig. 18.3: Silicate classification contd..

Infinite double chains give a ratio of Si:0 = 4:11, resulting in Si4On (or Si_80_{22}).

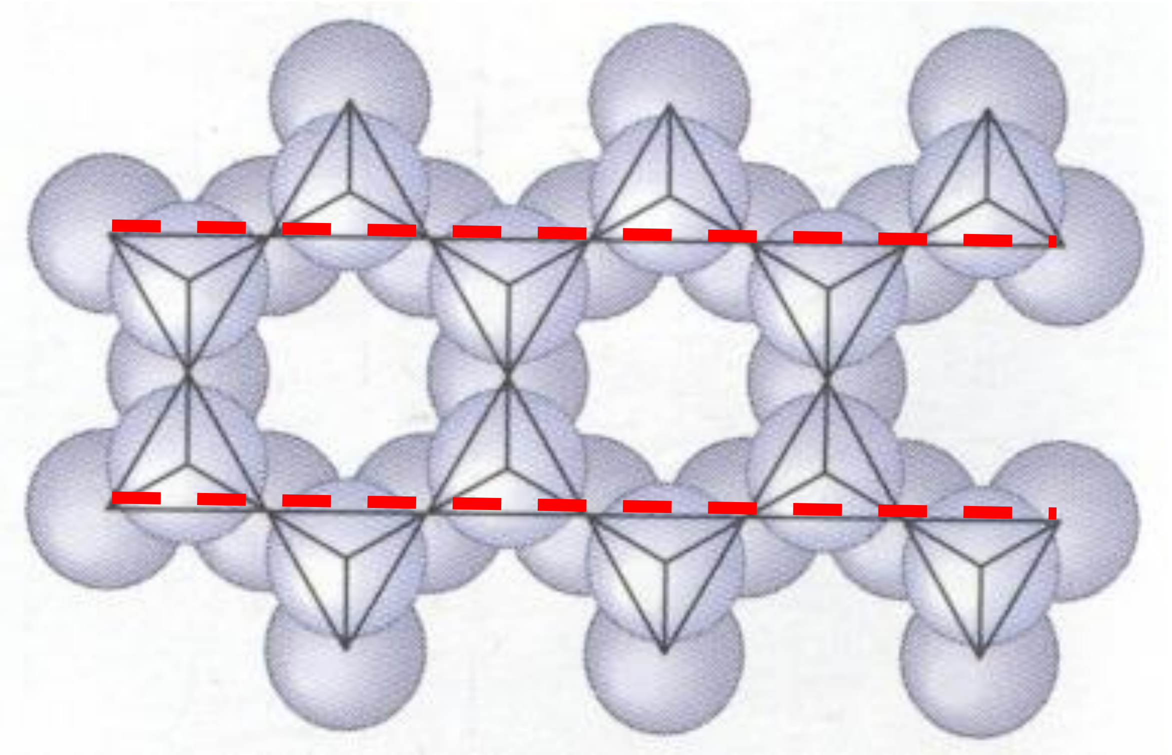
Both of these types of chain silicates are also known as inosilicates (from the Greek word inos, meaning thread).

Single chain silicates



- **Each tetrahedron linked to 2 others by shared oxygens; chains linked by cations e.g. Mg $^{2+}$**
- **Mineral Example is a pyroxene such as enstatite (Fe,Mg)SiO_3**

Double chain silicates



- 2 parallel chains joined by shared oxygens between every other tetrahedra pair; chains linked by cations
- Mineral Example is an amphibole such as hornblende $Ca(Mg,Fe)_4Al(Si_7Al)O_{22}(OH,F)$

Phyllosilicates

(Sheet or Layers of tetrahedra silicates)

When three of the oxygens of a tetrahedron are shared between adjoining tetrahedra, infinitely extending flat sheets are formed of unit composition Si_2O_5.

Such sheet silicates are referred to as phyllosilicates.

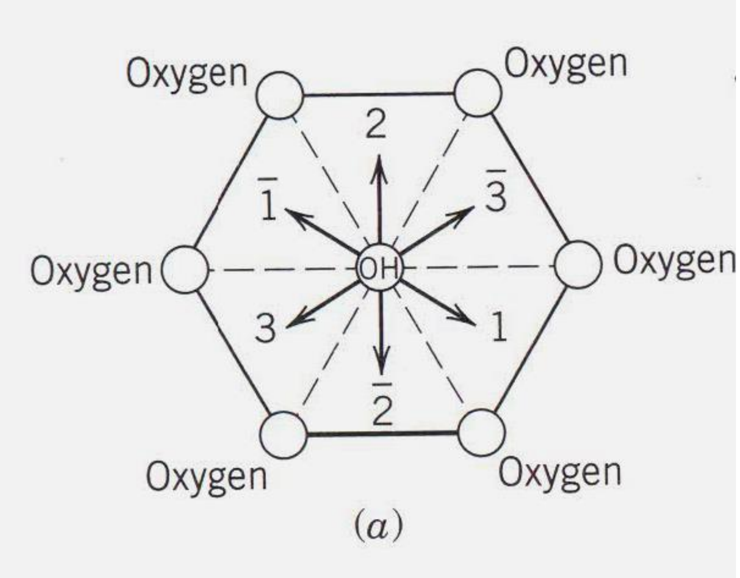
The derivation of the name of this important group implies (from the Greek word *phyllon* meaning *leaf*), most of its many members have a platy or flaky habit and one prominent cleavage.

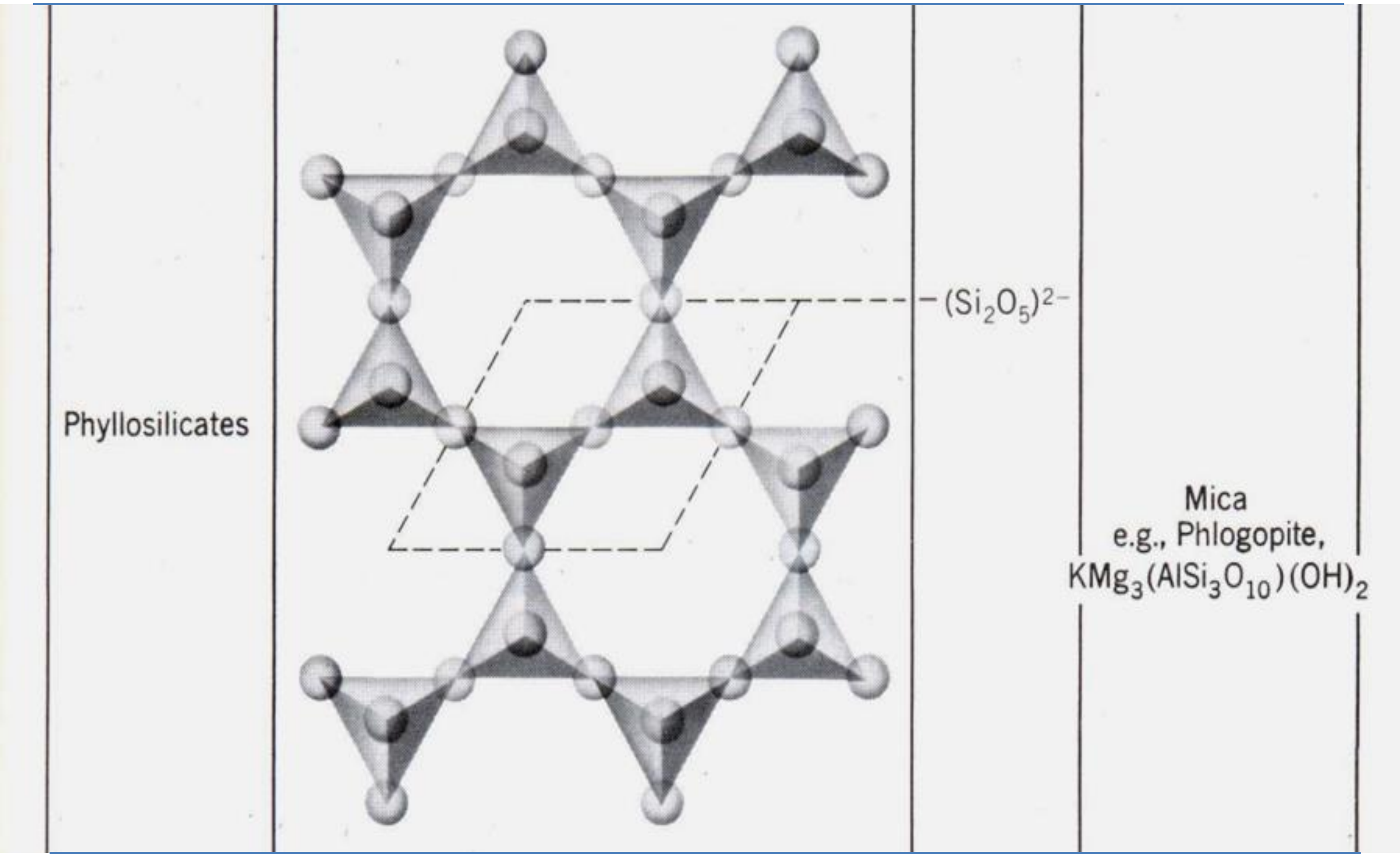
They are generally soft, of relatively low specific gravity, and may show flexibility or even elasticity of the cleavage lamellae.

All these characterizing peculiarities arise from the dominance in the structure of the infinitely extended sheet of Si04 tetrahedra.

In this sheet (see Fig. 18.3), three of the four oxygens in each Si04 tetrahedron are shared with neighboring tetrahedra, leading to a ratio of Si: O = 2:5. Each sheet, if undistorted, has sixfold symmetry.

Most of the members of the phyllosilicates are hydroxyl bearing, with the (OH) group located in the center of the six-fold rings of tetrahedra, at the same height as the unshared apical oxygens in the $Si0_4$ tetrahedra (see Fig. 18.29).





Phyllosilicates		$(Si_2O_5)^{2-}$	Mica e.g., Phlogopite, $KMg_3(AlSi_3O_{10})(OH)_2$

Fig. 18.3: Silicate classification contd..

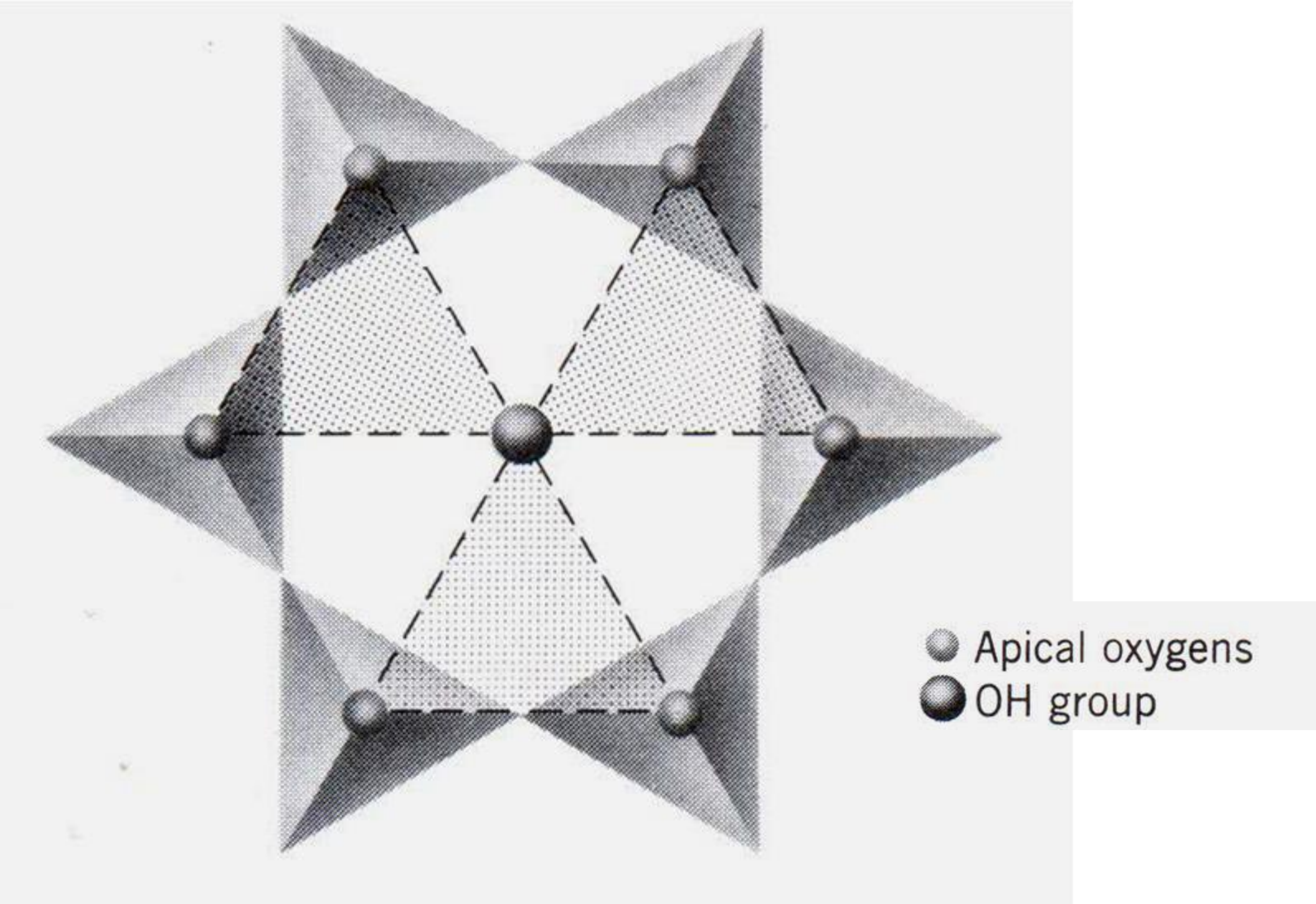
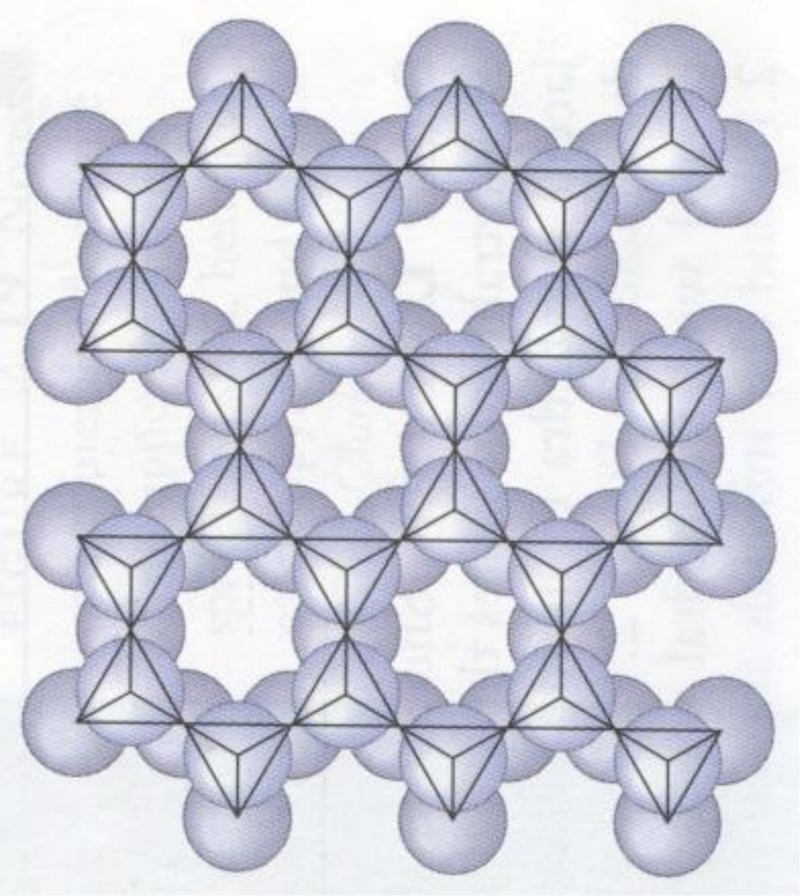


Fig.18.29: Undistorted, hexagonal ring in an Si_2O_5 sheet showing the location of apical oxygens and (OH) group. In an ideal sheet structure the size of the triangles (outlined by shading) is the same as the size of traiangular faces of XO6 octahedra.

Sheet (Layer) Silicates



- Each tetrahedron linked to 3 others by shared oxygens; sheet bonded by cations e.g. K^+
- Mineral Example is mica such as muscovite $KAl_3Si_3O_{10}(OH)_2$

Geologically, the phyllosilicates are of great significance. The micas are the primary minerals of schists and are widespread in igneous rocks.

They form at lower temperatures than amphiboles or pyroxenes and frequently are formed as replacements of earlier minerals as a result of hydrothermal alteration.

Tectosilicates

(Framework of tetrahedra silicates)

Approximately 64% of the rocky crust of the Earth is made up of minerals built about a three-dimensional framework of linked SiO4 tetrahedra (Fig. 18.1).

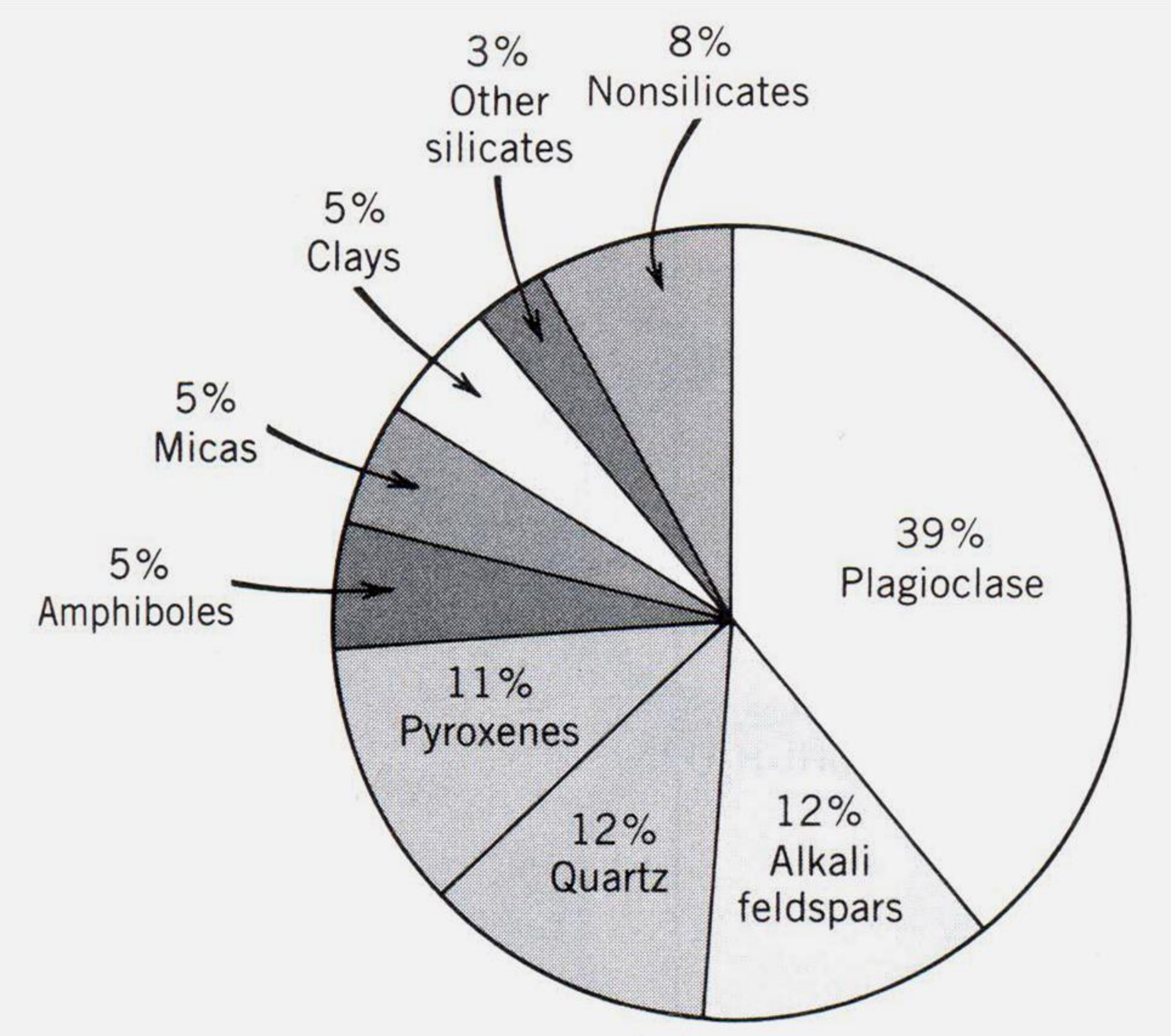


Fig. 18.1: Estimated volume percentages for the common minerals in the Earth's crust, inclusive of continental and oceanic crust. Ninety-two percent are silicates. (from Ronov, A.B. and A.A. Yaroshevsky, 1969. Chemical composition of the Earth's crust. Americal Geophysical Union Monograph No. 13,50)

When all four oxygens of a $Si0_4$ tetrahedron are shared by adjoining tetrahedra, a three-dimensional network of unit composition SiO_2 results.

These framework silicates are also known as tectosilicates (from the Greek word tecton, meaning builder).

Most common minerals belonging to this class are quartz and feldspars.

In other words, here all the oxygen ions in each SiO4 tetrahedron are bridging oxygens that are shared with neighboring tetrahedra.

This results in a stable, strongly bonded structure in which the ratio of Si:O is 1:2 (Fig. 18.3).

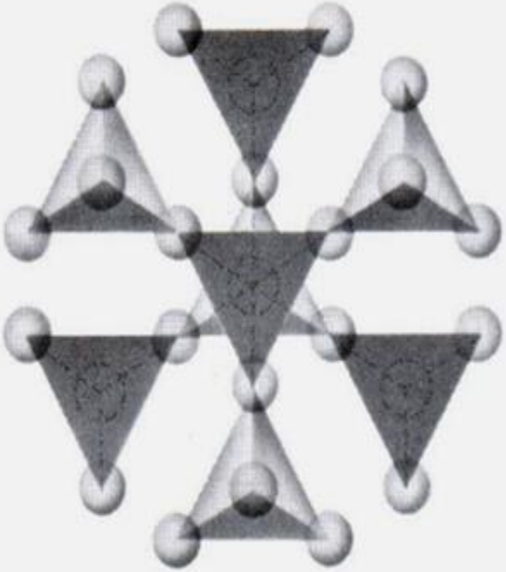
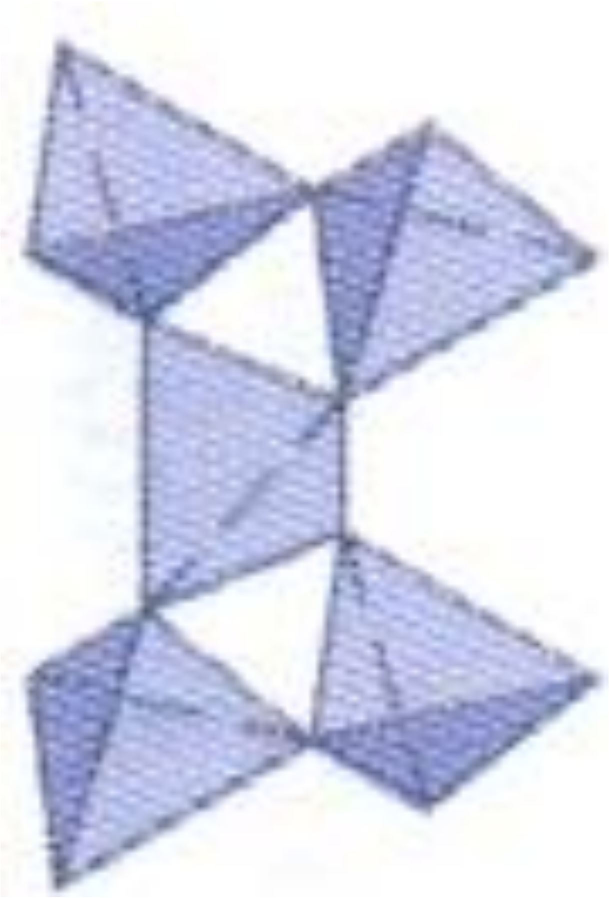
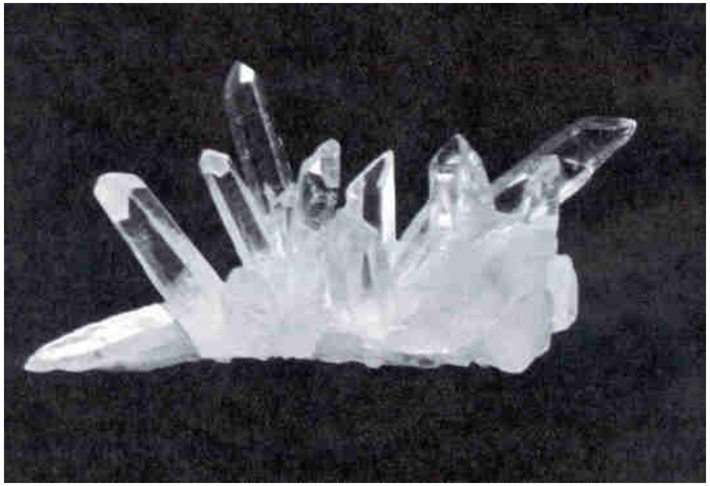
Tectosilicates		$(SiO_2)^0$	High cristobalite, SiO_2

Fig. 18.3: Silicate classification contd..

Framework Silicates





Quartz

- Each tetrahedron shares all its oxygens with other tetrahedra or AlO^{4-} tetrahedra
- Mineral Example is a feldspar such as orthoclase $KAlSi_3O_8$; quartz (SiO_2)

SiO_2 GROUP

An SiO_2 framework that does not contain other cations is electrically neutral.

There are at least nine different ways in which such a framework can be built. These modes of geometrical arrangement correspond to nine known polymorphs of Si02, one of which is synthetic (Table 18.3).

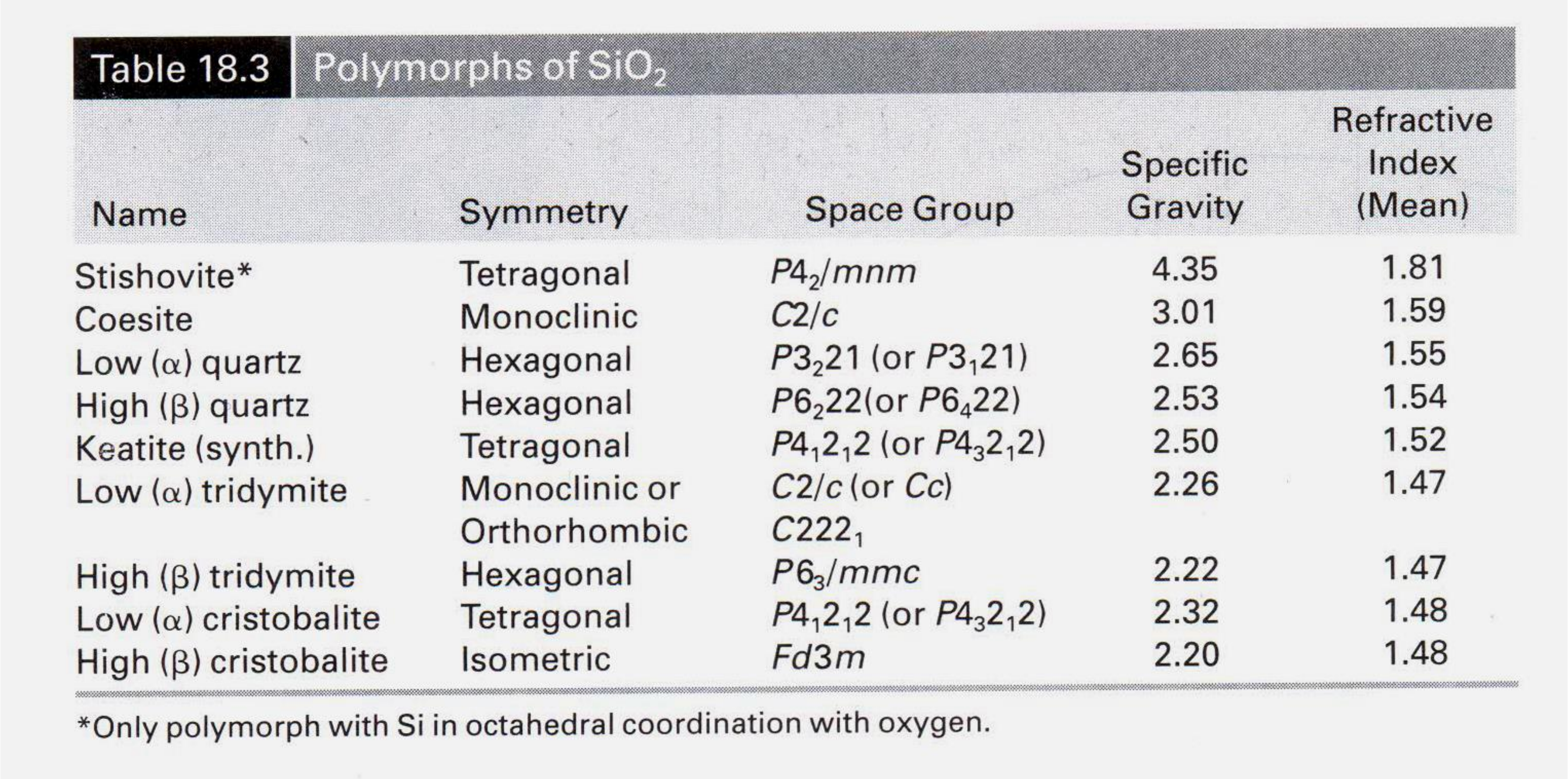


Table 18.3 Polymorphs of SiO_2

Name	Symmetry	Space Group	Specific Gravity	Refractive Index (Mean)
Stishovite*	Tetragonal	$P4_2/mnm$	4.35	1.81
Coesite	Monoclinic	$C2/c$	3.01	1.59
Low (α) quartz	Hexagonal	$P3_221$ (or $P3_121$)	2.65	1.55
High (β) quartz	Hexagonal	$P6_222$(or $P6_422$)	2.53	1.54
Keatite (synth.)	Tetragonal	$P4_12_12$ (or $P4_32_12$)	2.50	1.52
Low (α) tridymite	Monoclinic or Orthorhombic	$C2/c$ (or Cc) $C222_1$	2.26	1.47
High (β) tridymite	Hexagonal	$P6_3/mmc$	2.22	1.47
Low (α) cristobalite	Tetragonal	$P4_12_12$ (or $P4_32_12$)	2.32	1.48
High (β) cristobalite	Isometric	$Fd3m$	2.20	1.48

*Only polymorph with Si in octahedral coordination with oxygen.

Polymorphs (Many forms)

Minerals with different crystal structure but same composition are called polymorphic mienrals. Examples- quartz varieties and diamond and graphite (Diamond density: 3.5 g/cm3)] where as graphite has 2.1 g/cm3). Both have the same chemical composition but have different structures)

Each of these polymorphs has its own space group, cell dimensions, characteristic morphology, and lattice energy.

Which polymorph is stable is determined primarily by energy considerations; the higher-temperature forms with great lattice energy possess the more expanded structures that are reflected in lower specific gravity and refractive index.

In addition to the nine polymorphs of SiO_2 there are two related and essentially amorphous substances, **lechatelierite**, a high silica glass of variable composition, and **opal**, **$SiO_2.nH_2O$,** with a locally ordered structure of silica spheres and highly variable H20 content.

The principal, naturally occurring Si02 polymorphs fall into three structural categories:

- **low quartz,** with the lowest symmetry and the most compact structure;
- **low tridymite,** with higher symmetry and a more open structure; and
- **low cristobalite,** with the highest symmetry and the most expanded structure of the three polymorphs.

Feldspar Group

When Al3+ substitutes for Si4+ in the framework structure, a coupled substitution is required to maintain charge balance.

Consequently, large monovalent or divalent cation can enter the SiO_2 framework to produce feldspar.

The compositions of the majority of common feldspars can be expressed in terms of the system:

KAlSi308 (orthoclase; Or)-NaAlSi308 (albite; Ab)-$CaAl,Si_20_8$ (anorthite; An).

The members of the series between KAlSi3O8 and NaAlSi308 are known as the alkali feldspars and the members in the series between $NaAlSi_30_8$ and $CaAl_2Si_2O_8$ as the plagioclase feldspars.

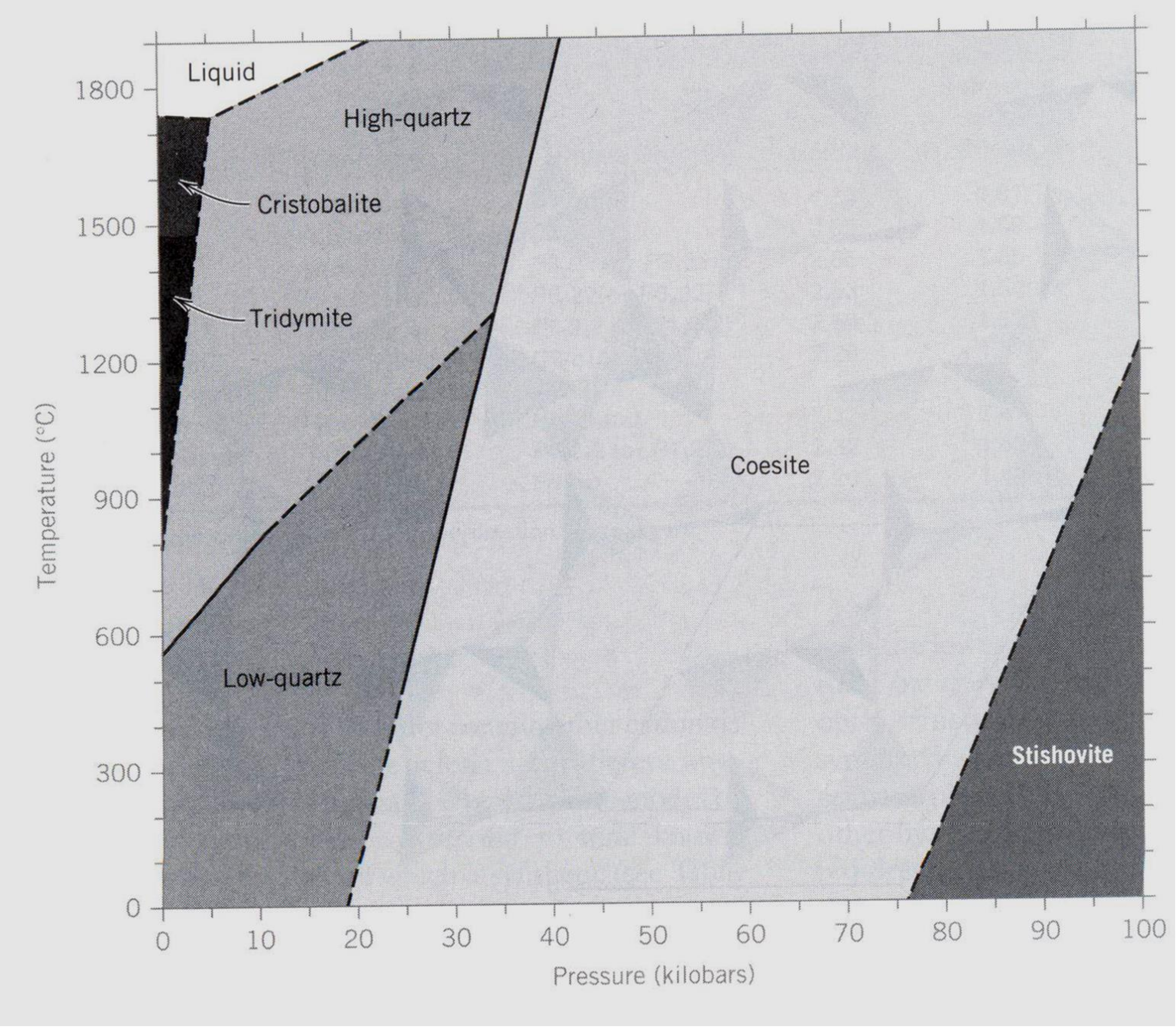
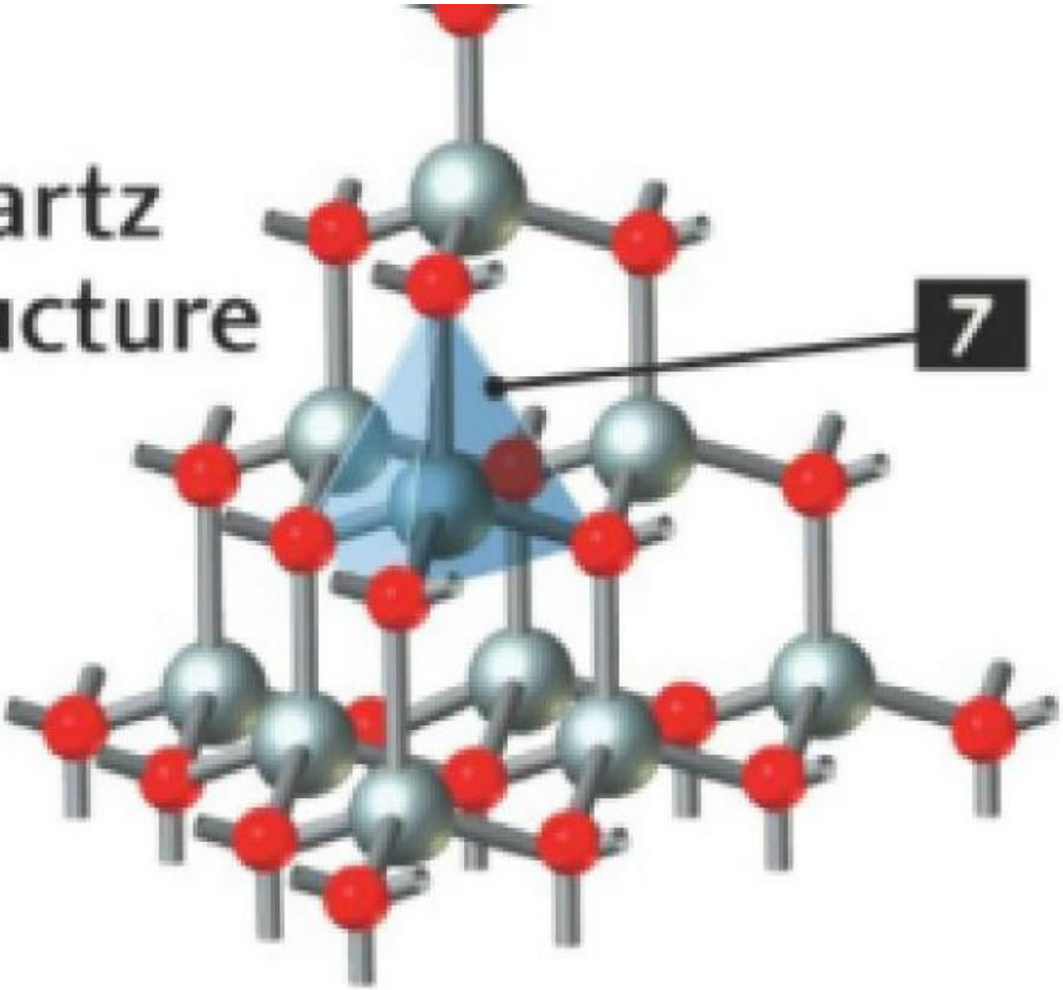


Fig. 18.46: Stability relations of the SiO2 polymorphs



Quartz structure

Thank you

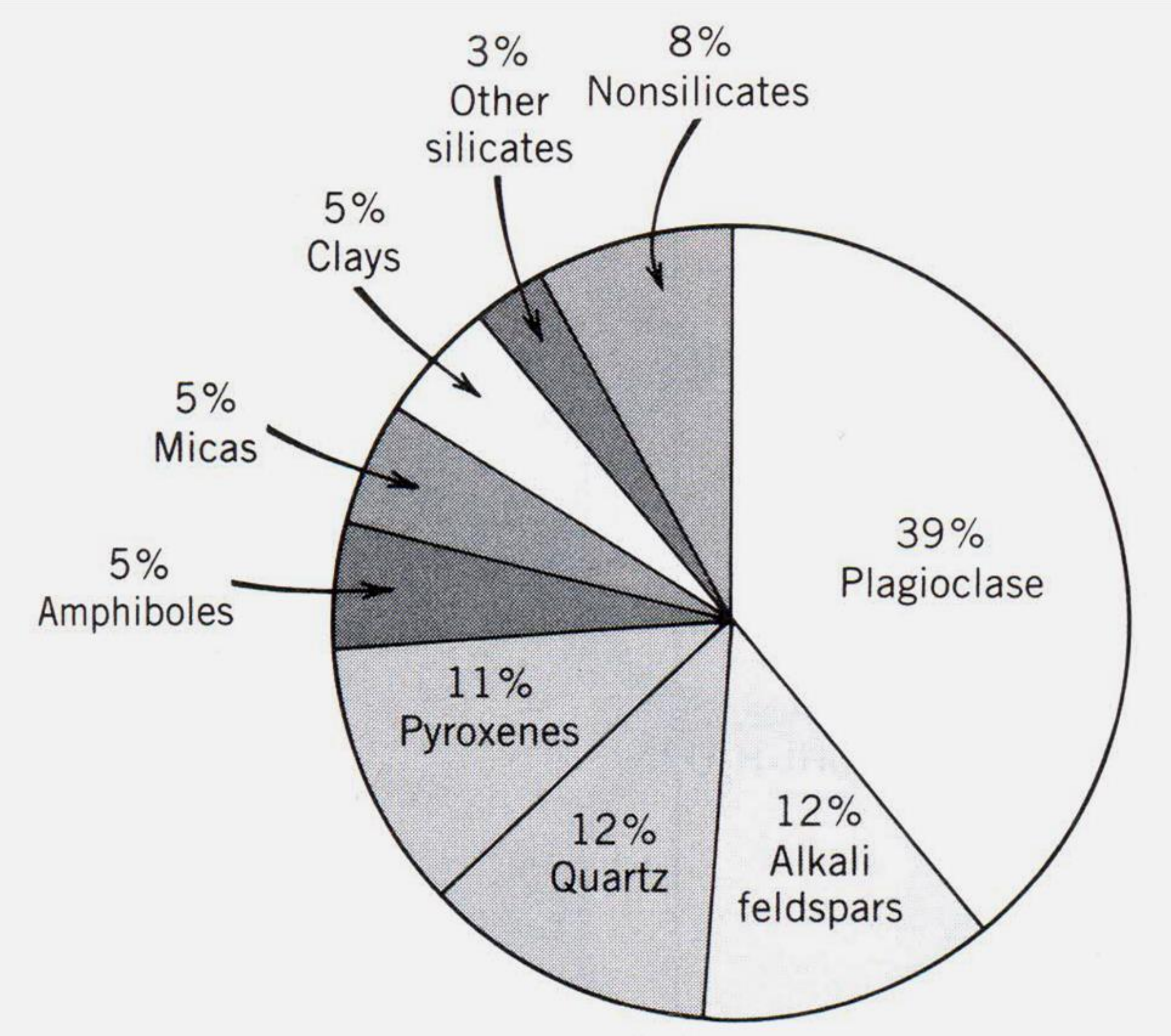


Fig. 18.1: Estimated volume percentages for the common minerals in the Earth's crust, inclusive of continental and oceanic crust. Ninety-two percent are silicates. (from Ronov, A.B. and A.A. Yaroshevsky, 1969. Chemical composition of the Earth's crust. Americal Geophysical Union Monograph No. 13,50)

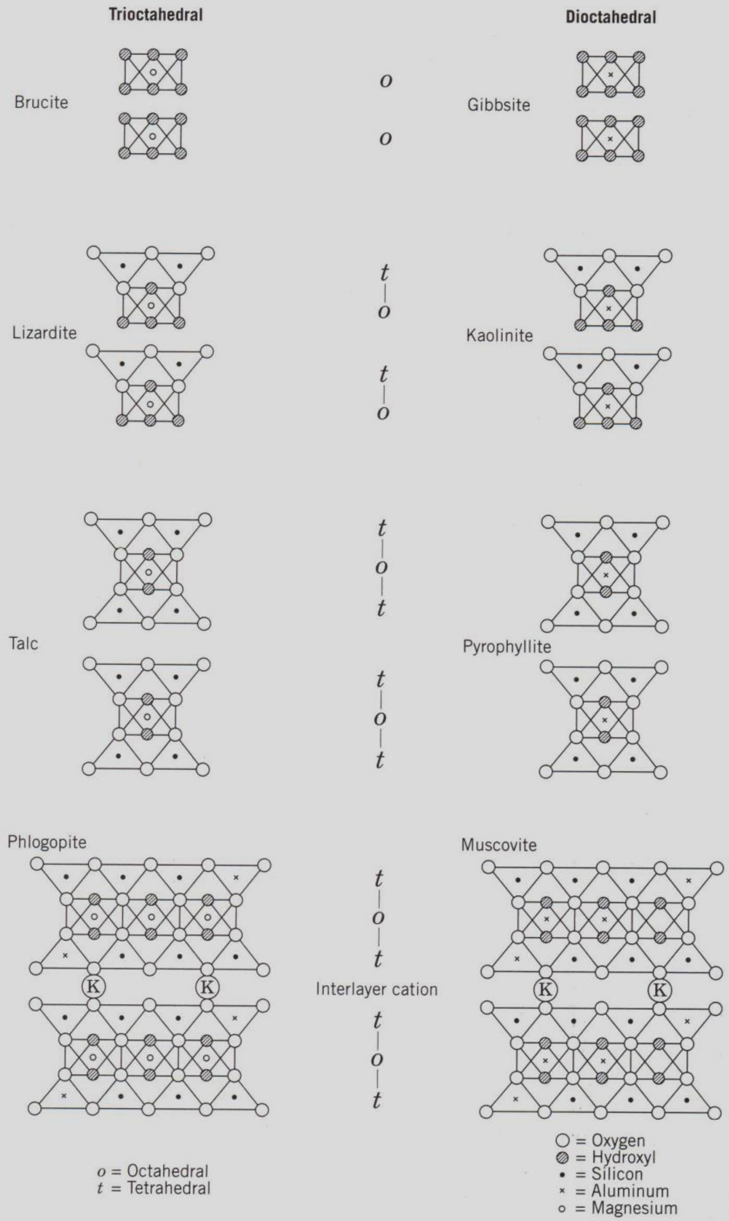


FIG. 18.34 Schematic development of some of the phyllosilicate structures (compare with Fig. 19.65).