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Classification of Minerals

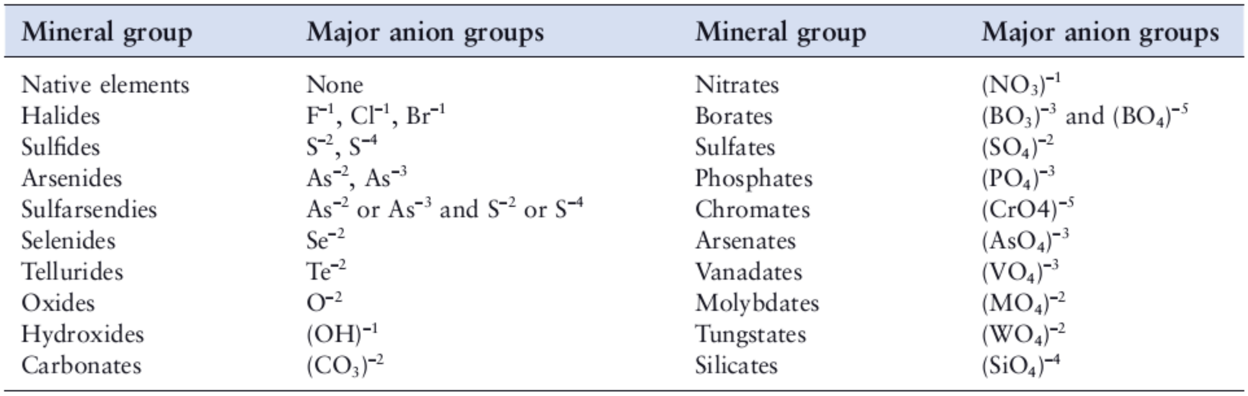
Approximately 3,000 mineral species are now known. The number increases continually because additional species are discovered, currently at the rate of about 50 minerals per year.

Classification of Mineral Species

To deal systematically with minerals, it is necessary to have classification scheme. The purpose of classification is to bring like things together and to separate them from unlike things—to give order to arrays of data, thus increasing utility.

It is useful to visualize minerals in terms of major anions and anion groups and/or radicals bonded to various cations that effectively neutralize their charge during the formation and growth of minerals. One common way to group or classify minerals is to do so in terms of the *major anion group* in the mineral structure. Those that contain (SiO 4) $^{-4}$ silica tetrahedra are silicate minerals, by far the most common minerals in Earth's crust and upper mantle. Those that do not contain silica tetrahedra are non-silicate minerals and are further subdivided on the basis of their major anions. Table 1 summarizes the common mineral groups according to this major anion group classification system. This system, groups the *mineral species* into major divisions, or *classes*, according the nature of anionic group present, was originally devised by Swedish chemist Berzelius. The **classes** are further subdivided into ***groups***, the fundamental division of which is a single mineral ***species***.

Table 1: Mineral classification based on the major anion groups.



Mineral group	Major anion groups	Mineral group	Major anion groups
Native elements	None	Nitrates	$(NO_3)^{-1}$
Halides	F^{-1}, Cl^{-1}, Br^{-1}	Borates	$(BO_3)^{-3}$ and $(BO_4)^{-5}$
Sulfides	S^{-2}, S^{-4}	Sulfates	$(SO_4)^{-2}$
Arsenides	As^{-2}, As^{-3}	Phosphates	$(PO_4)^{-3}$
Sulfarsendies	As^{-2} or As^{-3} and S^{-2} or S^{-4}	Chromates	$(CrO4)^{-5}$
Selenides	Se^{-2}	Arsenates	$(AsO_4)^{-3}$
Tellurides	Te^{-2}	Vanadates	$(VO_4)^{-3}$
Oxides	O^{-2}	Molybdates	$(MO_4)^{-2}$
Hydroxides	$(OH)^{-1}$	Tungstates	$(WO_4)^{-2}$
Carbonates	$(CO_3)^{-2}$	Silicates	$(SiO_4)^{-4}$

In this lecture, we are going to follow the classification scheme of Berry and Mason that they adapted in their book Mineralogy, which divides the minerals into the following classes:

I. Native elements
II. Sulfides (including sulfosalts)
III. Oxides and hydroxides
IV. Halides
V. Carbonates, nitrates, borates, iodates

VI. Sulfates, chromates, molybdates, tungstates
VII. Phosphates, arsenates, vanadates
VIII. Silicates

Native elements

The important native elements can be classified as follows:

- Metals
  - Gold Group
    - Gold, Au
    - Silver, Ag
    - Copper, Cu
  - Platinum group
    - Platinum, Pt
    - Palladium, Pd
    - Platiniridium, (Pt, Ir)
  - Iron Group
    - Iron, Fe
    - Nickel-iron (Ni, Fe)
- Semi-Metals and Nonmetals
  - Arsenic Group
    - Arsenic, As
    - Antimony, Sb
    - Bismuth, Bi
  - Sulfur Group
    - Sulfur, S
  - Carbon Group
    - Diamond, C
    - Graphite, C

Sulfides and Sulfosalts

The sulfides include a large group of minerals, predominantly metallic in character, with general formula A_mX_p, in which X, the larger atom is predominantly sulfur, and the smaller atom is one or more of the metals.

The sulfosalts have general formula $A_mB_nX_p$. The common elements in these sulfosalts are: Ag, Cu, and Pb as A; As, Sb, Bi, ans Sn as B; and S as X.

Many of these minerals are opaque or nearly so and, in many cases, transmit red light only. They range in hardness from 1 to 6.

Examples of minerals of this group are: Chalcocite (Cu_2S), Bornite (Cu_5FeS_4), Galena (PbS), Sphalerite [(Zn, Fe)S], Chalcopyrite ($CuFeS_2$), Covellite (CuS0, Cinnabar (HgS), Oyrite (FeS_2), Molybdenite (MoS), Bournonite ($PbCuSbS_3$) etc.

This class consists of the groups are: Nickeline Group, Pyrite Group, and Krennerite Group.

Oxides and Hydroxides

The oxides and hydroxides include compounds in which atoms or cations, typically of one or more metals, are combined with oxygen.

Spinel Group, Hematite Group, and Rutile Group consist of most of the minerals among the minerals of the oxide class. Gibbsite [$Al(OH)_3$], Goethite [FeO(OH)], etc. are the minerals termed as hydroxides.

The oxide minerals are very common and usually occur as accessory minerals in all kinds of rocks. The most common oxide minerals are the following:

Corundum- Al_2O_3

Corundum is hexagonal and optically negative. It occurs in Al-rich igneous and metamorphic rocks. If transparent blue, it is the gemstone sapphire, if transparent red, it is the gemstone ruby. When it occurs as an accessory mineral it usually shows its hexagon shaped outline. It has high refractive indices. Commonly shows lamellar twinning.

Spinel- $MgAl_2O_4$

Spinel is an isometric mineral that occurs in ultrabasic rocks like peridotite, and in many low silica ignoeous rocks like basalts, where it contains high concentrations of Cr. It is also found in Al-rich contact metamorphic rocks. It shows a wide variety of colors depending on trace amounts of other ions substituting for both Mg and Al. Because of the isometric nature, Spinel is difficult to distinguish from garnet, although spinel tends to occur as much smaller crystals.

Chromite- $Fe^{+2}Cr_2O_4$

Chromite is a major ore of Cr. It is found in low silica, Mg-rich igneous rocks, usually associated with Olivine. Often it is seen as small inclusions in Olivine, indicating that it is an early crystallizing phase in basaltic and gabbroic magmas. Chromite is isometric and usually opaque in thin section. Electron Microprobe analysis is usually necessary to distinguish it from other opaque oxide minerals.

Magnetite- Fe_3O_4

Magnetite is one of the most common oxide minerals. It is a major ore of Fe, and is found as an accessory mineral in all rock types. It is isometric and commonly crystallizes with an octahedral habit. In hand specimen it is most easily identified by its strongly magnetic nature, black color, and hardness of 6. In thin section it is opaque and thus difficult to distinguish from the other opaque oxide minerals.

Ilmenite- $FeTiO_3$

Ilmenite is a major ore of Ti. It is found as a common accessory mineral in a wide range of igneous volcanic and plutonic rocks, as well as metamorphic and clastic sedimentary rocks. It forms a solid solution series with Hematite, as will be discussed below, and commonly occurs along with Magnetite. Ilmenite is hexagonal, but is usually opaque which makes its distinction from other oxide minerals difficult. Ilmenite, however, often shows an elongated or acicular habit, whereas Magnetite usually crystallizes as more equant crystals with an octahedral habit.

Hematite- Fe_2O_3

Hematite is one of the most important ores of Fe. It is more oxidized than Magnetite, and thus forms as an alteration product of magnetite as well as other Fe bearing minerals. In most unaltered igneous rocks, hematite occurs as a component of Ilmenite in solid solution. Hematite is hexagonal, but rarelyoccurs in crystals where its symmetry can be determined. It is found in a variety of forms, ranging from oolitic spherules, to massive fine grained aggregates, to botryoidal masses. It is most easily distinguished by its black to dark red color and reddish brown streak. In thin section it is not easily distinguished from other opaque oxide minerals.

Halides

The halides comprise those elements in which a halogen element—F, Cl, Br, I—is the sole or principal anion. Chlorine, fluorine, and bromine have notable concentration in the ocean waters (130, 625, and 65 parts per million (ppm) respectively).

Fluorine is of strikingly different geological occurrence from the other halogens. It occurs almost exclusively in minerals of igneous rocks, pegmatites, hydrothermal veins, or rocks altered by pyrometasomatic action. On the other hand, the great bulk of the chlorine is of the earth’s crust is dissolved in sea water or occurs in solid stratiform deposits of soluble salts that were formed by the evaporation of sea water at various periods of geological time, whereas it occurs as only a minor element in a few minerals of igneous or metamorphic origin—for example, apatite, sodalite etc.

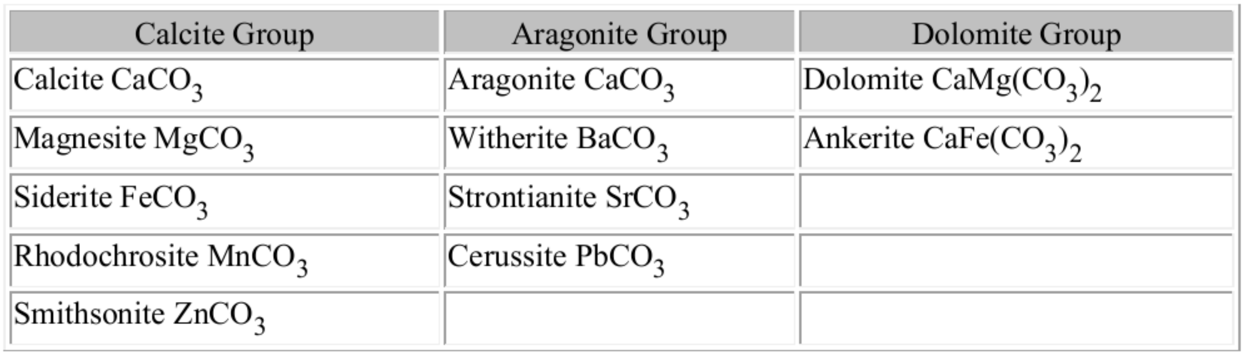
The important halide minerals are:

Halite	NaCl
Sylvite	KCl
Fluorite	CaF_2
Carnallite	$KMgCl_3.6H_2O$
Cryolite	Na_3AlF_6

Carbonates, Nitrates, Borates

The carbonates are an important group of minerals near the Earth's surface. Carbonate minerals make up the bulk of limestones and dolostones. Are found as cementing agents in clastic sedimentary rocks, and make up the shells of many organisms. The carbonates are based on the CO_3^{-2} structural unit, which has carbon surrounded by 3 oxygens in triangular coordination. Thus each Oxygen has a residual charge of -2/3. In the carbonate structure, no two triangles share the corner oxygens and the C-O bonds are highly covalent.

There are three structural types of carbonates:



Calcite Group	Aragonite Group	Dolomite Group
Calcite $CaCO_3$	Aragonite $CaCO_3$	Dolomite $CaMg(CO_3)_2$
Magnesite $MgCO_3$	Witherite $BaCO_3$	Ankerite $CaFe(CO_3)_2$
Siderite $FeCO_3$	Strontianite $SrCO_3$	
Rhodochrosite $MnCO_3$	Cerussite $PbCO_3$	
Smithsonite $ZnCO_3$		

In addition, there are the hydroxyl Cu carbonates - Malachite, $Cu_2CO_3(OH)_2$ and Azurite $Cu_3(CO_3)_2(OH)_2$.

The Calcite Group

The calcite group minerals are all hexagonal. They have Ca, Mg, Fe, Mn, or Zn divalent cations in coordination with the $CO3^{-2}$ groups, in a structure that is similar to that of NaCl.

Calcite $CaCO_3$ - The most common carbonate mineral is calcite. It is the principal constituent of limestone and its metamorphic equivalent - marble. Deposits of fine grained calcite in powder form are referred to as chalk. It forms the cementing agent in many sandstones, and is one of the more common minerals precipitated by living organisms to form their skeletal structures.

Calcite is also precipitated from groundwater where it form veins, or in open cavities like caves and caverns can form the cave decorations - like stalactites and stalagmites, and encrustations. It is also precipitated from hot springs where it is called travertine.

Calcite does occur in rare igneous rocks called carbonatites. These form from carbonate magmas. Calcite is also precipitated from hydrothermal fluids toform veins associated with sulfide bearing ores.

Properties

In hand specimen, calcite is distinguished by its rhombohedral cleavage, its hardness of 3, and by its effervescence in dilute HCl. It can range in color from white, to slightly pink, to clear, but dark colored crystals can also occur. Calcite canbe distinguished from Aragonite by the lack of rhombohedral cleavage and biaxial nature of Aragonite.

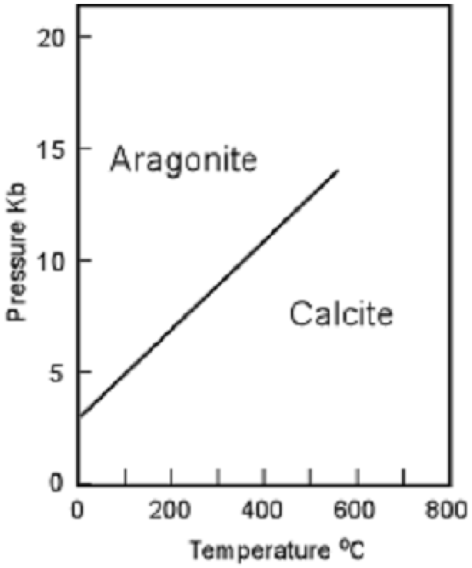
Magnesite $MgCO_3$

Magnesite is a common alteration product of Mg-rich minerals on altered igneous and metamorphic rocks. Like calcite, it shows perfect rhombohedral cleavage, but unlike calcite, it does not readily effervesce in dilute HCl. Itdoes, however, effervesce in hot HCl. These properties and its association with Mg-rich minerals and rocks make it distinguishable from Calcite.

The Aragonite Group

The Aragonite group of minerals are all orthorhombic, and can thus be distinguished from minerals of the calcite group by their lack of rhombohedral cleavage. Aragonite (CaCO3) is the most common mineral in this group.

Aragonite is the higher pressure form of $CaCO_3$ but, nevertheless occurs and forms at surface temperatures and pressures. When found in metamorphic rocks it is a good indicator of the low temperature, high pressure conditions of metamorphism, and is thus commonly found in Blueschist Facies metamorphic rocks. Water containing high concentrationsof Ca and carbonate can precipitate Aragonite. Warm water favors Aragonite, while cold water favors calcite, thusAragonite is commonly found as a deposit of hot springs. Aragonite can also form by biological precipitation, and the pearly shells of many organisms are composed of Aragonite.



Fine needle-like crystals of Aragonite are produced by carbonate secreting algae.

Properties

In hand specimen, Aragonite, like calcite effervesces in cold HCl. But, unlike Calcite, Aragonite does not show a rhombohedral cleavage. It is usually transparent to white in color and forms in long bladed crystals.

The Dolomite Group

Dolomite - $CaMg(CO_3)_2$and Ankerite - $CaFe(CO_3)_2$ form a complete solid solution series, although because Mg-rich environments are much more common than Fe-rich environments, Mg-rich dolomites are much more common than Ankerites. Ankerite is common mineral in Pre-Cambrian iron formations. Dolomite is a common constituent of older limestones, probably the result of secondary replacement of original calcite. It is also found as dolomitic marbles, and in hydrothermal veins.

Properties

Dolomite, and therefore rocks containing large amounts of dolomite, like dolostones, is easily distinguished by the fact that dolomite only fizzes in cold dilute HCl if broken down to a fine powder. Also, dolostones tend to weather to a brownish color rock, whereas limestones tend to weather to a white or gray colored rock. The brown color of dolostones is due to the fact that Fe occurs in small amounts replacing some of the Mg in dolomite.

The Phosphate Group

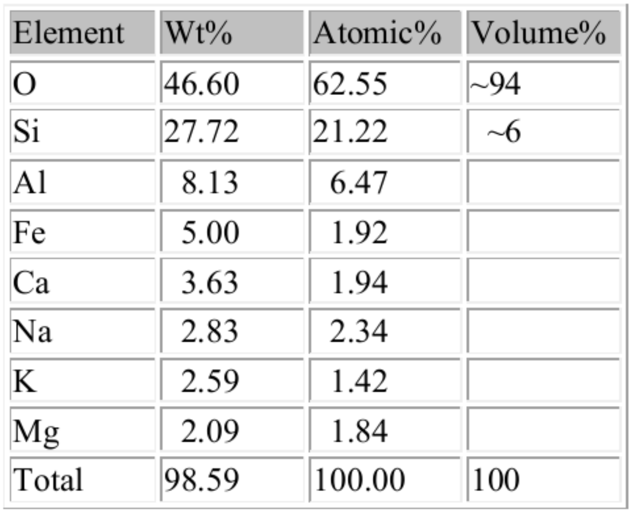
Apatite $Ca_5(PO4)_3(OH,F)$

Apatite is very common and almost ubiquitous (always present) accessory mineral in igneous rocks and many metamorphic rocks. If the rock contains any phosphorous it is usually found in apatite. Apatite forms as hexagonal crystals.

Nitrates, being very soluble minerals, occur only in arid, virtually rainless, regions of the earth. Borates occur for the most part in dry lake basins in mountainous regions and lacustrine formations of the Tertiary age.

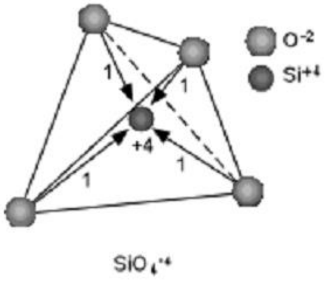
Silicates

The relative abundance of elements in the Earth's crust determines what minerals will form and what minerals will be common. Because Oxygen and Silicon are the most abundant elements, the silicate minerals are the most common. The silicates include about a third of all mineral species. The earth's crust has been estimated to consist of about 95 percent silicate minerals, of which some 60 percent is feldspar and 12 percent is quartz.



Element	Wt%	Atomic%	Volume%
O	46.60	62.55	~94
Si	27.72	21.22	~6
Al	8.13	6.47	
Fe	5.00	1.92	
Ca	3.63	1.94	
Na	2.83	2.34	
K	2.59	1.42	
Mg	2.09	1.84	
Total	98.59	100.00	100

The radius ratio of Si^{+4} to O^{-2} requires that Si^{+4} be coordinated by $4O^{-2}$ ions in tetrahedral coordination. In order to neutralize the +4 charge on the Si cation, one negative charge from each of the Oxygen ions will reach the Si cation. Thus, each Oxygen will be left with a net charge of 1, resulting in a SiO_4^{-4} tetrahedral group that can be bonded to other cations. It is this SiO_4^{-4} tetrahedron that forms the basis of the silicate minerals.

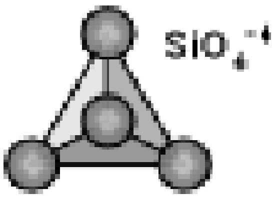


When these SiO_4^{-4} tetrahedrons are linked together, only corner oxygens will be shared with other SiO_4^{-4} groups. Several possibilities exist and give rise to the different silicate groups. Silicate classification for most silicate minerals is based on the types of linkages of the SiO_4^{-4} tetrahedron is as follows:

1. Nesosilicates/orthosilicates (independent tetrahedral group)
2. Sorosilicates (double tetrahedral structures)
3. Cyclosilicates (ring structures)
4. Inosilicates (chain structures)
5. Phyllosilicates (sheet structures)
6. Tektosilicates (three-dimensional network)

Nesosilicates

Nesosilicates, also known as orthosilicates, are silicate minerals characterized by isolated silica tetrahedra that are not linked through shared oxygen ions to other silica tetrahedra in the structure. The ratio of silicon (Si^{+4}) ions to oxygen (O^{-2}) ions in the tetrahedral sites of such minerals is 1:4. This ratio is reflected in the formulas of nesosilicate



minerals, which always contain an $(SiO_4)^{-4}$ component, and implies isolated tetrahedra.

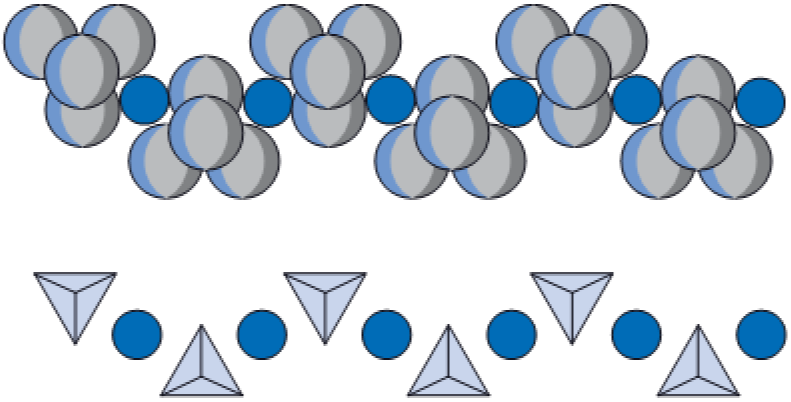


Figure 1: Basic nesosilicate (orthosilicate) structure with isolated tetrahedra linked to other polyhedral elements in the structure.

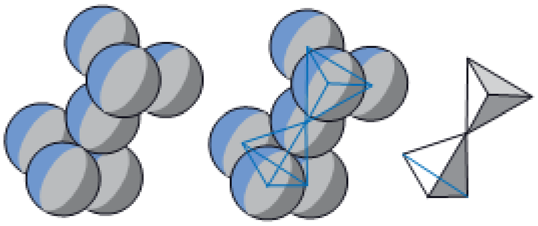
For example the **olivine group**, the most abundant mineral group in the upper mantle, has the formula $(Mg,Fe)_2SiO_4$. The olivines are orthorhombic and usually green colored in hand specimen. Zircon ($Zr SiO_4$) and thorite ($Th SiO_4$) are also of this kind.

A second important mineral group, the **garnet group**, is widespread and abundant in metamorphic rocks; it also occurs in igneous rocks and the mantle. Examples are: almandine $Fe_3Al_2(SiO_4)$, grossularite $Ca_3Al_2(SiO_4)$ etc.

A third important nesosilicate group is the aluminum silicate group. This group comprises three polymorphs that are common in metamorphic rocks, especially in pelitic assemblages produced by the metamorphism of shales and mudrocks. The three polymorphs of aluminum silicate (Al_2SiO_5) are the low pressure polymorph **andalusite**, the high pressure polymorph **kyanite** and the high temperature polymorph **sillimanite**.

Zircon ($ZrSiO_4$) and thorite ($ThSiO_4$) etc. are also of this kind.

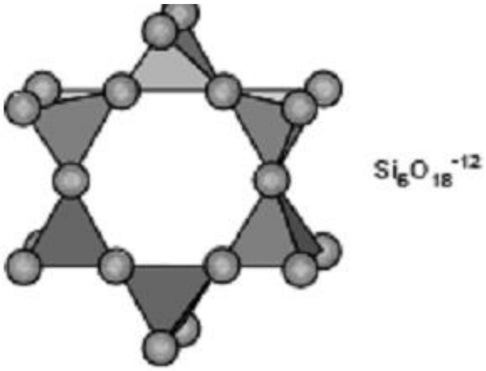
Sorosilicates



Two silicon-oxygen tetrehedra are linked by the sharing of one oxygen between them; the resulting composition is Si_2O_7, with an Si:O ratio of 2:7. For example, the mineral hemimorphite has the formula $Zn_4(Si_2O_7)(OH)_2.H_2O$.

The most important group of sorosilicate minerals is the **epidote group**. The epidote group consists of five species; several of the monoclinic varieties display extensive substitution solid solution. These include epidote, clinozoisite and allanite.

Clycosilicates



The cyclosilicates are based on rings of SiO_4 tetrahedra, with a Si:O ratio of 1:3 The most common minerals based on this structure are beryl, cordierite , and tourmaline.

Beryl is a common constituent of coarse grained granitic rocks and pegmatites and is found in aluminous mica schists. Cordierite is a common constituent of aluminous metamorphic rocks. It is common in contact metamorphic rocks where it is commonly associated with sillimanite or andalusite, feldspars and micas. Tourmaline is a common mineral in pegmatites (SiO_2-rich igneous rocks with large grain size), where it is associated with quartz and alkali feldspar. It is also found in metasomatized rocks of all types, where it is precipitated from a Boron and Silica- rich fluid phase.

Inosilicates

In chain structures, tetrahedral are joined together to produce chains of indefinite extent. There are two principal modifications of this structure yielding somewhat different compositions: (a) single chains in which the Si:O ratio is 1:3 as characterized **pyroxenes** and **pyroxenoids**; and (b) double chains, in which alternate tetrahedral in two parallel single chains are cross-linked and the Si:O ratio is 4:11, as characterized by **amphiboles**.

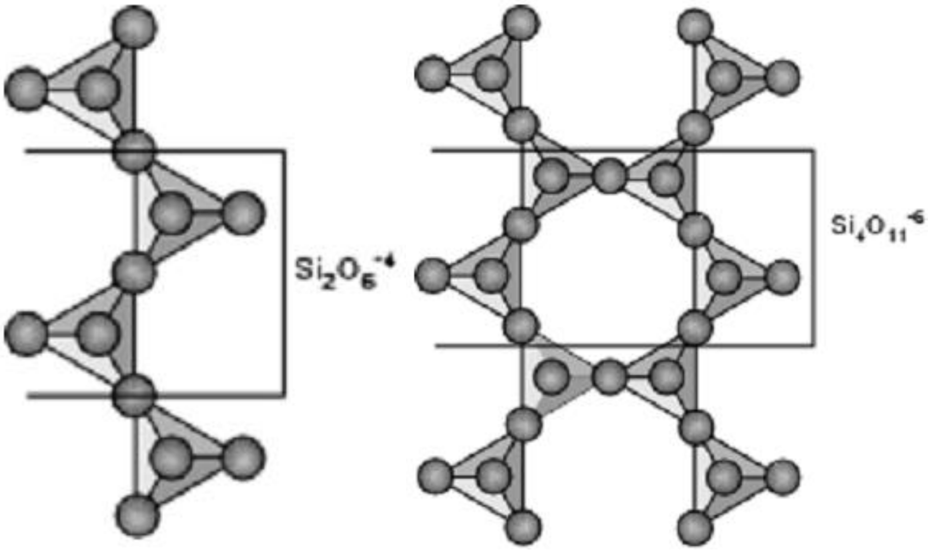
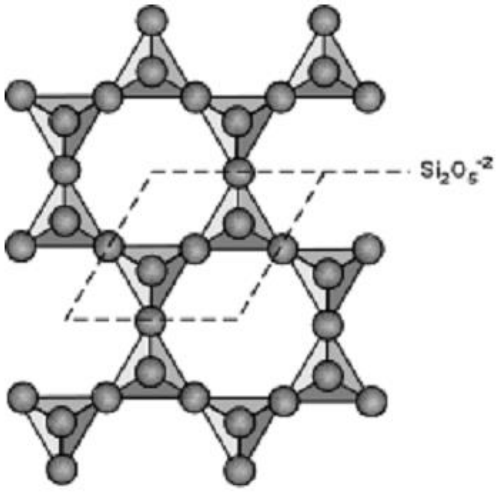


Figure 2: single chain inosilicate structure (at the left) and double chain inosilicate structure (at the right)

Phyllosilicates



The phyllosilicates, or sheet silicates, are an important group of minerals that includes the micas, chlorite, serpentine, talc, and the clay minerals. The basic structure of the phyllosilicates is based on interconnected six member rings of SiO_4^{-4} tetrahedra that extend outward in infinite sheets. Three out of the 4 oxygens from each tetrahedra are shared with other tetrahedra. This leads to a basic structural unit of $Si_2O_5^{-2}$. Minerals in this group commonly have a Si/O ratio of 2:5 or 4:10.

Their chemical formulas are often complicated by the fact that aluminum (Al^{+3}) cation substitutes in limited, and often variable, amounts for silicon (Si^{+4}) cation in the "silica" tetrahedra to form a limited number of aluminum tetrahedra.

Because one out of every four oxygen ions is not linked to another silica tetrahedron, one out of every four oxygen ions must bond to other cations in order to be electrically neutralized. Typically these cations occur in octahedral sites that alternate in some way with the tetrahedral layers to which they are linked. The two most common are those that contain magnesium (Mg^{+2}) bonded to oxygen (O^{-2}) and hydroxyl (OH^{-1}) ions and those that contain aluminum (Al^{+3}), also bonded to oxygen and hydroxyl ions. The magnesium sites are called **brucite** sites (b) after the mineral brucite [Mg(OH) 2], and the aluminum sites are called **gibbsite** sites (g) after the mineral gibbsite [Al(OH) 3]. Iron frequently substitutes partially for the magnesium in brucite sites.

Common rock - forming phyllosilicate mineral groups include (1) serpentines, (2) talc, (3) chlorites, (4) micas, and (5) clays. Other moderately common phyllosilicate minerals include apophyllite, prehnite and stilpnomelane.

Mica group

Widespread and nearly ubiquitous in their occurrence are the members of the mica group. These minerals are significant rock-forming minerals in both igneous and meta-morphic rocks and are not uncommon in sedimentary rocks. Micas are three - layer phyllosilicates with two tetrahedral layers in which one out of every four silica tetrahedra has an aluminum (Al^{+3}) cation substituting for the silicon (Si^{+4}) cation as reflected in the ($AlSi_3O_{10}$) component of their formulas. Biotite [$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$], phlogopite [$K(Mg)_3(AlSi_3O_{10})(OH)_2$], Muscovite [$(KAl_3AlSi_3O_{10}(OH)_2)$], and lepidolite [$(K(Li,Al)_3AlSi_3O_{10}(OH,F)_2)$], glauconite [$(K,Na)(Fe,Al,Mg)_2(Si,Al)_4)O_{10})(OH)_2$] are some minerals of this group.

Clay group

Clay group minerals commonly occur as microscopic crystals (<4 μm or 0.004 mm) in soils, sedimentary rocks and low temperature hydrothermal and metamorphic rocks, where they form by the low temperature alteration of aluminum silicate minerals, such as feldspars, micas and amphiboles. The term *clay* implies an earthy, fine grained material that develops plasticity when mixed with a limited amount of water. Chemical analysis of clays show that they are made up of hydrous aluminosilicates, commonly with appr3eciable amount of iron, magnesium, calcium, sodium, and potassium. All are very fine grained, frequently forming colloidal solutions. Genetically, most clays are the product of sedimentation, diagenesis, or weathering, but they can also formed by hydrothermal activity.

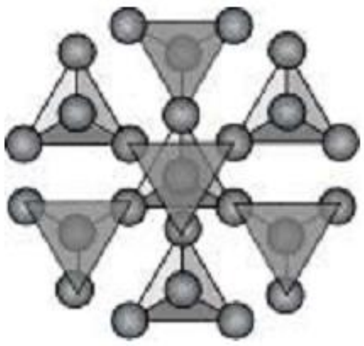
Clay minerals are the main constituents of the fine grained sedimentary rocks called mudrocks (including mudstones, claystones, and shales). In fact clay minerals make up about 40% of the minerals in sedimentary rocks. In addition, clay minerals are the main constituent of soils. Understanding of clay minerals is also important from an engineering point of view, as some minerals expand significantly when exposed to water. Clay minerals are used extensively in the ceramics industry and are thus important economic minerals.

Clay minerals are: kaolinite, montmorillonite or smectite, illite, vermiculite, serpentine, pyrophillite, and talc.

Smectites are called expansive clays due to their ability to absorb and release large amounts of water held in interlayer sites and thus to change volume significantly. These expansive clays are hazardous for use in foundation construction due to their shrink and swell properties. Clay minerals are widely used in industry as absorbents and fillers.

Tectosilicates

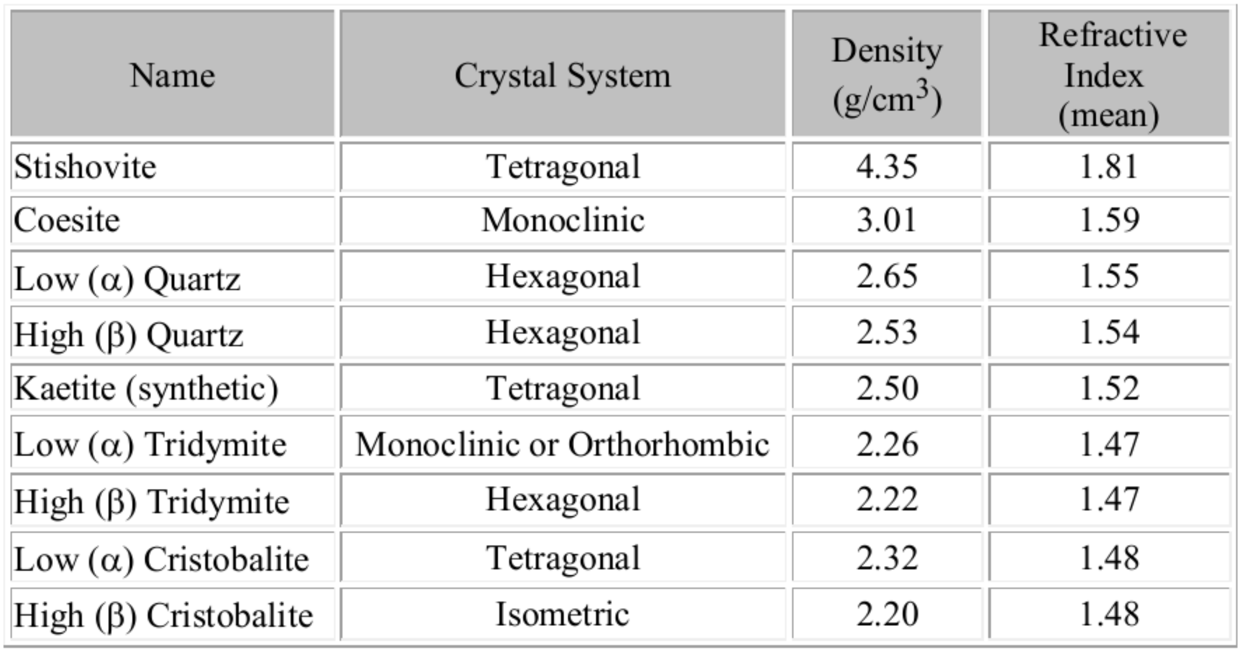
Tectosilicate minerals are composed principally of silica tetrahedra linked through all their oxygen anions to adjacent silica tetrahe-dra to form three -dimensional framework structures. These silicates, often called framework silicates, have a Si/O ratio of 1:2, unless aluminum substitutes for some of the silicon ions in the tetrahedral sites, in which case the (Si + Al)/O ratio is 1:2. This is because all four oxygen (O^{-2}) anions are shared with adjoining silica tetrahedra so that each silica tetrahedron possesses one-half of each of the four oxygen anions, making the Si/O ratio 1:4 × 0.5 = 1:2. Tectosilicates constitute an extremely important group of rock-forming minerals, comprising nearly 75% of the minerals in Earth’s crust, and occur widely in igneous, metamorphic and sedimentary rocks.



The two most abundant groups of tectosilicate minerals are the pure SiO_2 **silica group** and the aluminum silicate **feldspar group**; the latter is the most abundant group of minerals in Earth's crust. Other important tectosilicate mineral groups include (1) the silica-poor, aluminum-rich **feldspathoid** group, (2) the aluminum-rich, hydrated zeolite group, and (3) the scapolite group.

Silica group (SiO_2 minerals)

There are nine known polymorphs of SiO_2, one of which does not occur naturally. These are:



Name	Crystal System	Density (g/cm^3)	Refractive Index (mean)
Stishovite	Tetragonal	4.35	1.81
Coesite	Monoclinic	3.01	1.59
Low (α) Quartz	Hexagonal	2.65	1.55
High (β) Quartz	Hexagonal	2.53	1.54
Kaetite (synthetic)	Tetragonal	2.50	1.52
Low (α) Tridymite	Monoclinic or Orthorhombic	2.26	1.47
High (β) Tridymite	Hexagonal	2.22	1.47
Low (α) Cristobalite	Tetragonal	2.32	1.48
High (β) Cristobalite	Isometric	2.20	1.48

Stishovite and Coesite are high pressure forms of SiO_2, and thus have much higher densities and refractive indices than the other polymorphs. Stishovite is the only polymorph where the Si occurs in 6 fold (octahedral) coordination with Oxygen, and this occurs due to the high pressure under which the mineral forms. Both Stishovite and Coesite have been found associated with meteorite impact structures.

At low pressure with decreasing temperature, SiO_2 polymorphs change from high Cristobalite - Low Cristobalite - High Tridymite - Low Tridymite - High Quartz - Low Quartz. The high to low transformations are all displacive transformations. Since displacive transformations require little rearrangement of the crystal structure and no change in energy, the high (α) polymorphs do not exist at the surface of the earth, as they will invert to the low (β) polymorphs as temperature is lowered.

Transformations between α Cristobalite, α Tridymite, and α Quartz, however, as well as between the high pressure polymorphs and Quartz, are reconstructive transformations. Since reconstructive transformations require significant structural rearrangement and significant changes in energy, they occur slowly, and the high temperature and high pressure polymorphs can occur as metastable minerals at the Earth's surface.

Quartz

Quartz is hexagonal and commonly occurs as crystals ranging in size from microscopic to crystals weighing several tons. Where it crystallizes unhindered by other crystals, such as in cavities in rock or in a liquid containing few other crystals, it shows well-developed hexagonal prisms and sometimes showing apparent hexagonal pyramids or dipyramid. When it crystallizes in an environment where growth is inhibited by the surroundings, it rarely show crystal faces. It is also found as microcrystalline masses, such as in the rock chert, and as fibrous masses, such as in chalcedony.

As visible crystals, Quartz is one of the more common rock forming minerals. It occurs in siliceous igneous rocks such as volcanic rhyolite and plutonic granitic rocks. It is common in metamorphic rocks at all grades of metamorphism, and is the chief constituent of sand. Because it is highly resistant to chemical weathering, it is found in a wide variety of sedimentary rocks.

Several varieties of Quartz can be found, but these are usually only distinguishable in hand specimen.

> Rock Crystal - clear Quartz in distinct crystals - usually found growing in open cavities in rock.
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> Amethyst - violet colored Quartz, with the color resulting from trace amounts of Fe in the crystal.
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> Rose Quartz - a pink colored variety that usually does not show crystal faces, the color resulting from trace amounts of Ti^{+4}.
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> Smokey Quartz - a dark colored variety that may bealmost black, usually forming well-formed crystals. The color appears to result from trace amounts of Al^{+3} in the structure.
>
> Citrine - a yellow colored variety.
>
> Milky Quartz - a white colored variety with the color being due to fluid inclusions. Milky Quartz is common in hydrothermal veins and pegmatites.

A fibrous variety of Quartz is called Chalcedony. It is usually brown to gray to translucent with a waxy luster. It is found lining or filling cavities in rock where it was apparently precipitated from an aqueous solution.

Very fined grained aggregates of cryptocrystalline quartz make up rock like Flint and Chert. Flint occurs as nodules in limestone, whereas chert is a layered rock deposited on the ocean floor. The red variety of flint is called Jasper, where the color results from inclusions of hematite.

Tridymite

Tridymite is the high temperature polymorph of SiO2. Thus, it is only commonly found in igneous rocks that have been cooled rapidly to surface temperatures, preventing the slow transformation to quartz, the stable form of SiO_2 at surface temperatures. Because of this, we only expect to find Tridymite in siliceous volcanic rocks like rhyolites, where it commonly occurs as wedge shaped crystals in cavities in the rock. In volcanic rocks, Tridymite is commonly associated with Cristobalite and Sanidine.

Cristobalite

Cristobalite is also a high temperature SiO_2polymorph, and thus has a similar occurrence to Tridymite. It also occurs in thermally metamorphosed sandstones. In volcanic rocks it can occur both as a lining in open cavities, and as fine grained crystals in the groundmass of the rock.

Opal

Opal is amorphous, and thus a mineraloid, with a formula - $SiO_2.nH_2O$.

Feldspars

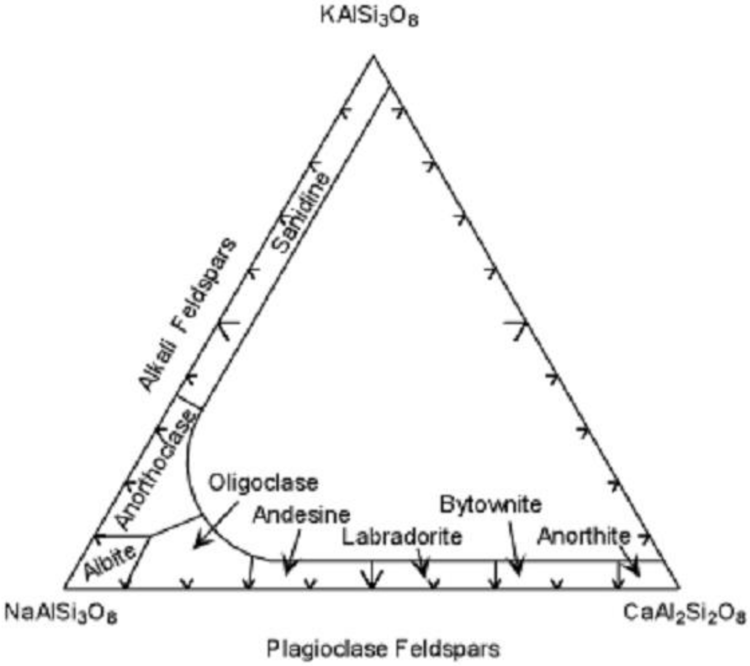
The feldspars are the most common minerals in the Earth's crust. They consist of three end-members:

$KAlSi_3O_8$ - Orthoclase (or), $NaAlSi_3O_8$ - Albite (ab), and $CaAl_2Si_2O_8$ -Anorthite (an)

$KAlSi_3O_8$ and $NaAlSi_3O_8$ form a complete solid solution series, known as the **alkali feldspars** and $NaAlSi_3O_8$ and $CaAl_2Si_2O_8$ form a complete solid solution series known as the **plagioclase feldspars**.

The feldspars have a framework structure, consisting of SiO_4 tetrahedra sharing all of the corner oxygens. However, in the alkali feldspars 1/4 of the Si^{+4}ions are replaced by $Al^{+3}$and in the plagioclase feldspars 1/4 to 1/2 of the Si^{+4} ions are replaced by Al^{+3}. This allows for the cations K^+, Na^+, and $Ca^{+2}$to be substituted into void spaces to maintain charge balance.

Compositions of natural feldspars are shown inthe diagram below based on the 3 components – $NaAlSi_3O_8$ - Albite (ab), $KAlSi_3O_8$ - Orthoclase (or), and $CaAl_2Si_2O_8$ -Anorthite (an). The Alkali Feldspars form a complete solid solution between ab and or, with up to 5% of the an component. The high temperature more K-rich variety is called Sanidine and the more Na-rich variety is called anorthoclase.



The plagioclase feldspars are a complete solid solution series between ab and an, and can contain small amounts of the or component. Names are given to the various ranges of composition, as shown here in the diagram are:

Albite - ab_{90} to ab_{100}

Oligoclase - ab_{70} to ab_{90}

Andesine - ab_{50} to ab_{70}

Labradorite - ab_{30} to ab_{50}

Bytownite - ab_{10} to ab_{30}

Anorthite - ab_{0} to an_{10}

Plagioclase Feldspars

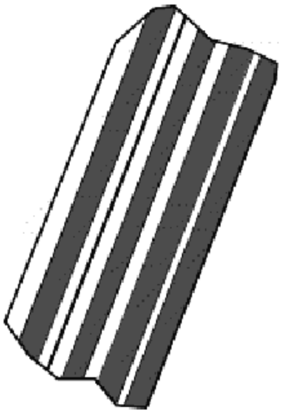
Plagioclase is the most common feldspar. It forms initially by crystallization from magma. The plagioclase solid solution series is coupled solid solution where the substitution is:

$Na^{+1}Si^{+4} <=> Ca^{+2}Al^{+3}$

Plagioclase occurs in basalts, andesites, dacites, rhyolites, gabbros, diorites, granodiorites, and granites. In most of these igneous rocks, it always shows the characteristic albite twinning. Plagioclase also occurs in a wide variety of metamorphic rocks, where it is usually not twinned. In such rocks where the plagioclase is not twinned, it is difficult to distinguish from the alkali feldspars. Plagioclase can be a component of clastic sedimentary rocks, although it is less stable near the Earth's surface than alkali feldspar and quartz, and usually breaks down to clay minerals during weathering.

In hand specimen, plagioclase is most commonly white colored and shows perfect and good cleavage. It is most easily identified and distinguished from quartz, sanidine, orthoclase, and microcline, by its common polysynthetic twinning. If this twinning is not present, plagioclase can still be distinguished from quartz by its cleavage, but cannot easily be distinguished from the alkali feldspars. If both plagioclase and alkali feldspar occur in the same rock, the two can usually be distinguished by differences in color or differences in the extent of weathering.

In thin section, plagioclase commonly shows the characteristic albite polysynthetic twinning. This twinning is the most characteristic identifying feature of plagioclase, and makes its identification easy when present. Although some cross-hatched twinning may also occur in plagioclase, it is always very simple with only one or two cross twins per grain. Thus, be careful not to identify plagioclase as microcline. The cross-hatched twinning in microcline is always much more complex.



Alkali Feldspars

As an alkali feldspar cools from high temperature to lower temperature, the crystal structure changes from that of sanidine, which is monoclinic, through orthoclase, also monoclinic, but with a different crystal structure than sanidine, to microcline, which is triclinic. These transformations are order-disorder transformations, and thus require large amounts of time. Furthermore, if the feldspar is allowed to cool very slowly, then exsolution will occur, and the solid solution will separate into a Na-rich phaseand a K-rich phase. Thus, one expects to find sanidine in rocks that were cooled very rapidly from high temperature, i.e. volcanic rocks. Orthoclase and microcline will be found in plutonic igneous rocks (cooled slowly at depth in the earth) and in metamorphic rocks. In addition, in the plutonic rock types if the cooling takes place slowly enough, then perthitic exsolution lamellae may also form.

Sanidine

Sanidine generally occurs with an equant habit (almost square) and shows perfect and cleavages, which readily distinguish it from quartz. Rarely does sanidine show twinning, but when it does, it is usually simple twinning.

Orthoclase

Orthoclase is a common alkali feldspar in granitic rocks and K - Al rich metamorphic rocks. It often shows perfect and cleavages which will distinguish it from quartz. Also, quartz usually shows a smooth surface texture, while orthoclase appears much rougher.

Microcline

Microcline is the lowest temperature form of alkali feldspar. Upon cooling, orthoclase must rearrange its structure from monoclinic to triclinic. When this happens, twinning usually results. The twinning characteristic of microcline is a combination of albite twinning and pericline twinning. This results in a cross-hatched pattern (often called tartan twinning) that is the most distinguishing characteristic of microcline.

Anorthoclase

Anorthoclase is a Na - rich feldspar with approximately equal amounts of the Anorthite (Ca) and orthoclase (K) components. Generally anorthoclase occurs in Na - rich volcanic rocks. Like the other alkali feldspars, it has perfect cleavages.

Feldspathoids

The feldspathoid group of minerals are SiO2 poor, alkali rich minerals that occur in low SiO_2, high Na_2O - K_2O igneous rocks. In general, these minerals are not compatible with quartz, and therefore, are rarely, if ever, seen in rocks that contain quartz. They do, however, often occur with feldspars.

The main feldspathoids are Nepheline $(Na,K)AlSiO_4$, Kalsilite KAlSi2O6, and Leucite $KAlSi_2O_6$. At high temperature there is completesolid solution between Nepheline and Kalsilite, but at low temperature Nepheline can contain only about 12 wt% K_2O.

Nepheline occurs in both volcanic and plutonic alkaline igneous rocks. Nepheline has a yellowish colored alteration product, called cancrinite. Nepheline is hexagonal.

Sodalite occurs predominantly in alkali-rich plutonic igneous rocks, like syenites, but can also be found in volcanic rocks. It is essentially3 nepheline molecules with an added NaCl molecule.

Leucite is found in alkalic volcanic rocks, and is rarely found in plutonic rocks. It is a tetragonal mineral.