

**Minerals and Rocks, Geosciences 301**

**Chapter 7**

**THE ROCK FORMING SILICATE MINERALS**

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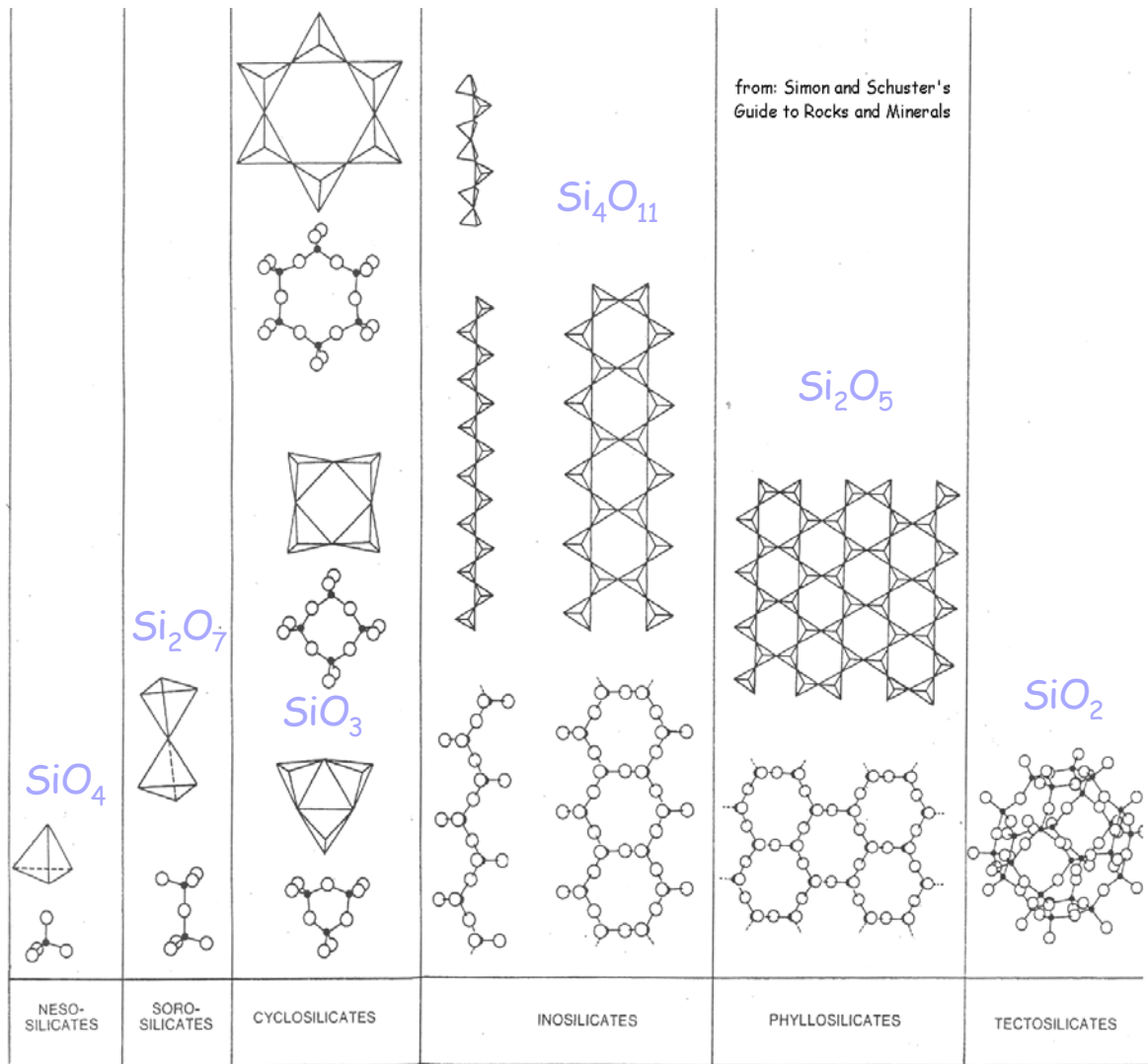
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Edited by Dave Barnes

## The Rock Forming Silicate Minerals

The silicates are the most abundant minerals in the earth's crust and frequently referred to as the rock forming minerals. They are structurally a very complicated group and it would be worth your while to study pages 56 and 57 in your field guide (also, see Figure 1, below), in order to understand the structural classification of silicate minerals that is universally recognized. We will briefly discuss the salient features of each structural group.

**Figure 1**



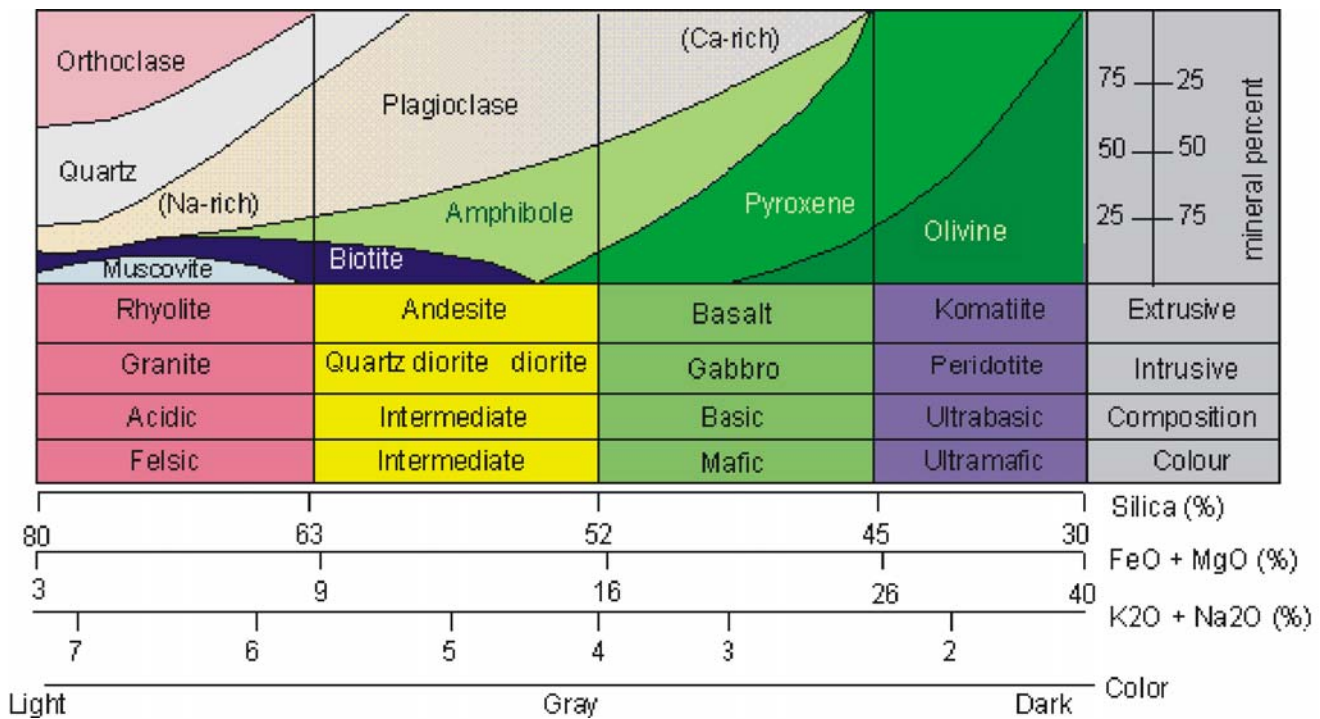
**Table 1: The Silicate Minerals**

<u>Silicate Group</u>	<u>Igneous</u>	<u>Pegmatite</u>	<u>Metamorphic</u>	<u>Sedimentary (low temp)</u>
Single Tetrahedra {Nesosilicates } (SiO <sub>4</sub> );(R&M: 157-172)	<b>Olivine Series;</b> (Accessory Minerals: Topaz, Sphene, Zircon)		<b>Garnet Series,</b> Alum-Silicate: Andalusite, Kyanite, Sillmanite; Staurolite	
Double Tetrahedra {Sorosilicates} (Si <sub>2</sub> O <sub>7</sub> ); (R&M: 181)				<b>Epidote, Zoisite</b>
Single Chain {Inosilicates} (SiO <sub>3</sub> );(R&M: 193-202; 213-5)	<b>Pyroxenes (Fe-Mg)</b>  <b>Augite - Enstatite</b>	<b>Spodumene</b>	<b>Pyroxenes: (Ca,Na) Jadeite, Diopside,</b>  Wollastonite,  Pyroxinoids	
Ring {Cyclosilicates} (SiO <sub>3</sub> ); (R&M: 188-190)		<b>Tourmaline,</b>  <b>Beryl</b>	<b>Tourmaline</b>	
Double Chain {Inosilicates} (Si <sub>4</sub> O <sub>11</sub> )(OH) <sub>2</sub> ; (R&M: 203-212)	<b>Hornblende Series</b>		<b>Tremolite-Actinolite, Cummingtonite</b>	
Sheet {Phyllosilicates} (Si <sub>4</sub> O <sub>10</sub> )(OH) <sub>2</sub> ; (R&M: 219-243)	<b>Biotite-Muscovite</b>	<b>Muscovite</b>  Lepidolite	<b>Muscovite, Biotite, Chlorite,</b>  <b>Serpentine, Talc</b>	<b>Clays, Glauconite</b>
Network {Tektosilicates} (SiO <sub>2</sub> , AlSi <sub>3</sub> O <sub>8</sub> ); (R&M: 244-274)	<b>Quartz, K-feldspar, Plagioclase</b>  <b>Series; feldspathoids</b>	Quartz, K-spar	Quartz, K-spar, Plagioclase, Zeolite	Quartz (all kinds!), K-spar,  Zeolite

### Primary Silicate Minerals in Igneous Rocks

The composition of essential (predominant) minerals define the igneous rock types from felsic thru ultramafic

<p>The essential felsic (silicic) minerals are:</p> <ul style="list-style-type: none"> <li>• Quartz,</li> <li>• Plagioclase,</li> <li>• K-feldspar</li> </ul>	<p>The essential Mafic/ultramafic minerals are:</p> <ul style="list-style-type: none"> <li>• Olivine,</li> <li>• Ortho-, and Clinopyroxene</li> <li>• Amphiboles (hornblende),</li> <li>• Biotite</li> </ul>
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**Figure 1** from: UBC Petrology WWW site: <http://www.eos.ubc.ca/courses/eosc221/petrology/rock.html>

### Structural Formulas and Silicate Group Minerals

The structural formulas concept describes the structural and chemical relationship between related minerals (mineral groups) through a generalized description of the chemical formula on the basis of similar cation characteristics in the silicate minerals.

#### Symbology

W = large cations, C.N. >6 (with oxygen) Ca, Na, K

X = medium-sized, bi-valent cations, C.N. =6 (with oxygen) Mg, Fe<sup>+2</sup>, & Ca (sort of)

Y = medium-sized, trivalent cation, C.N. = 6 (with oxygen) Typically Al and sometimes Fe<sup>+3</sup>

Z = small cations, C.N. = 4 (with oxygen) Mainly Si, but also Al

## NESOSILICATES

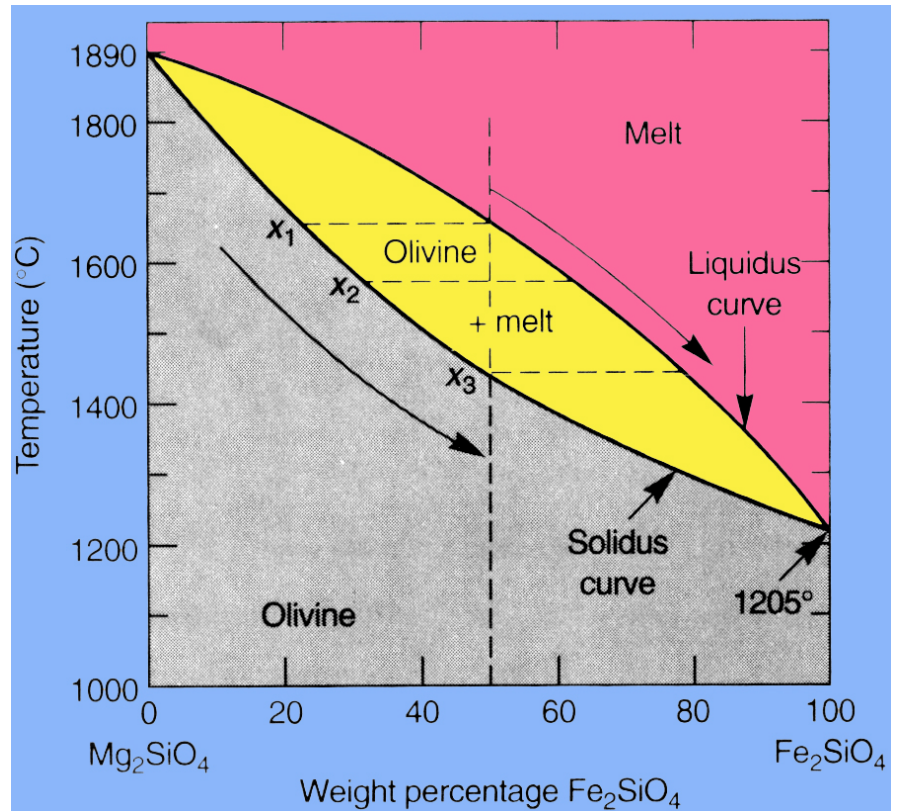
### Olivine Series

Olivine is a common silicate mineral and one of the earlier crystals formed from igneous melts as demonstrated by the experiments of N. L. Bowen. The olivine mineral group is actually a complete solid series that ranges in composition from magnesium rich fosterite ( $\text{Mg}_2\text{SiO}_4$ ) to iron rich fayalite ( $\text{Fe}_2\text{SiO}_4$ ). Since  $\text{Mg}^{+2}$  and  $\text{Fe}^{+2}$  are very similar in size and identical in charge they form a complete solid solution series with one structural state (phase) existing in the solid form. This is demonstrated in the phase diagram (Fig 2). The two end numbers are Fosterite and Fayalite, and in the literature you will often find that the abbreviations Fo and Fa are used. The structural formula for the Olivine group is  $\text{X}_2\text{SiO}_4$

Olivine is very common in mafic igneous rocks like basalt, gabbro and peridotite and is an important constituent of the mantle. It is important for geophysicists to understand olivine properties in order to understand seismic wave propagation in the mantle. The olivine we typically see in hand specimens is relatively rich in magnesium hence a light green (olivine is olive green) in color and occurs as massive granular crystal aggregates with no distinct shape observable.

**Figure 2**

T-X (temperature/composition) phase diagram for the olivine group solid solution series. The vertical dashed line is a cooling/heating trajectory line for an olivine crystal with composition  $\text{FA}_{50}$ . The horizontal dashed lines intersect the solidus and liquidus curves at the composition of crystals and melt (respectively) at the corresponding temperatures during equilibrium cooling or melting. The trends in crystal and melt compositions during cooling are indicated by the heavy (solidus) and light (liquidus) curved arrows. Note that early formed crystals (during cooling) are more magnesian than the original melt and that the melt becomes more iron rich during equilibrium crystallization.



## INOSILICATES

### Pyroxenes (single chain) and Amphiboles (double chain)

These two ferro-magnesium mineral groups are very common in all types of igneous and metamorphic rocks and have delightfully complex structures and chemistries. They usually range from green to black in color and in habit from prismatic to fibrous. The amphiboles in metamorphic rocks tend to be acicular to fibrous and some varieties are used as asbestos.

Figure 3

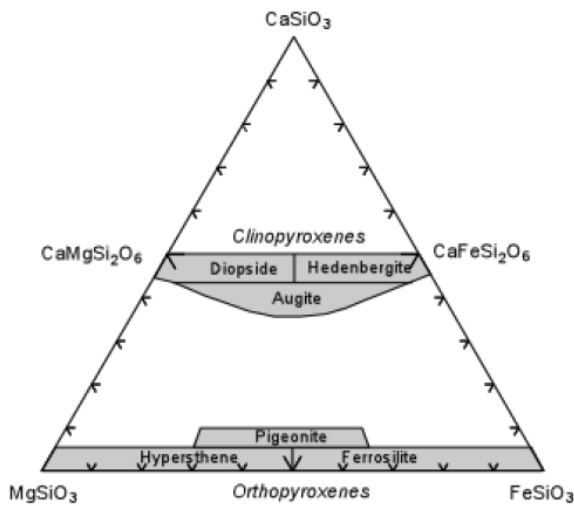
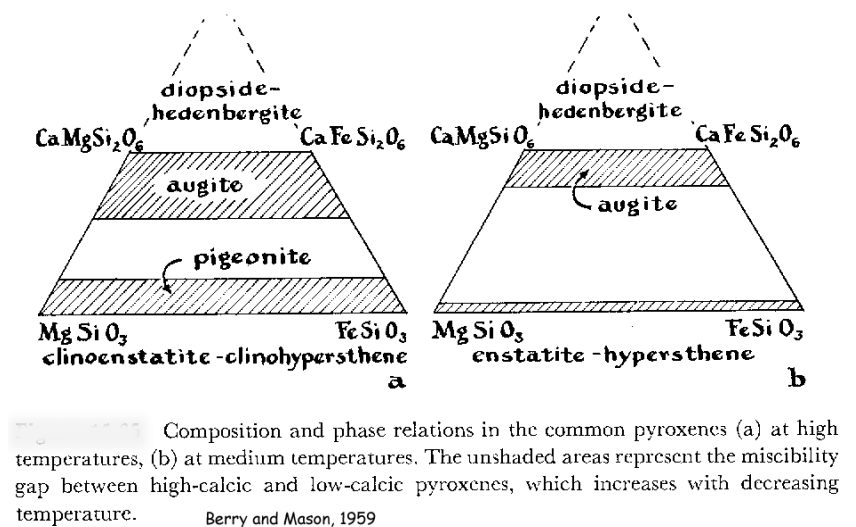


Figure 4



An example of the chemical variation in the pyroxene minerals is shown in figures 3. This plot shows the three component system Enstatite (En) -  $\text{MgSiO}_3$ , Wollastonite (Wo) -  $\text{CaSiO}_3$ , Ferrosilite (Fs) -  $\text{FeSiO}_3$ . Wo does not have a pyroxene structure. Complete solid solution exists between Diopside, Di, ( $\text{CaMgSi}_2\text{O}_6$ ) and Hedenbergite, Hd, ( $\text{CaFeSi}_2\text{O}_6$ ). These pyroxenes are monoclinic and are thus called the clinopyroxenes. Augite is also a clinopyroxene, but note that it is depleted in the Wo component relative to the Di - Hd series. En - Fs also forms a complete solid solution series. These minerals are orthorhombic, so the series is often referred to the orthopyroxenes. Pigeonite is a monoclinic pyroxene that has slightly more of the Wo component than the orthopyroxenes. Temperature of formation (Figure 4) determines the degree of incompatible atomic substitution possible in the pyroxenes in a similar way that we discussed in the carbonate minerals.

Pyroxenes are single chain silicates and therefore always have an  $\text{SiO}_3$  (or  $\text{Si}_2\text{O}_6$ ) anionic molecule. The structural formula for the pyroxene group minerals is  $\text{X}_2\text{Si}_2\text{O}_6$  or the more general formula:  $(\text{WXY})_2\text{Z}_2\text{O}_6$  through coupled atomic substitution (see below)

Amphiboles on the other hand are double chain silicates and have an  $\text{Si}_4\text{O}_{11}(\text{OH})$  group in their formula. The following list is arranged to demonstrate the similar chemical characteristics between some of the common species in these two groups.

**Table 2**

<u>Chemistry</u>	<u>Pyroxenes</u>	<u>Amphiboles</u>
Mg	Enstatite (Opx)	Anthophyllite
CaMg	Diopside (Cpx)	Tremolite-Actinolite (Fe)
Ca(MgFe)	Augite (Cpx)	Hornblende (+Na)
CaFe	Hedenbergite (Cpx)	

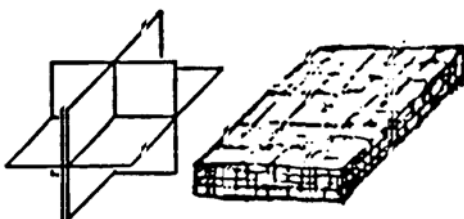
Opx= Orthopyroxene (orthorhombic crystalline structure) Cpx= Clinopyroxene (monoclinic, with high Ca with or without Al and the alkalis).

Some Sodium Rich Varieties

NaFe	Aegirine	Riebeckite (Crocidolite)
NaAl	Jadeite	Glaucophane
LiAl	Spodumene	

The difficulty in distinguishing these mineral groups can be overcome if one is careful in determining the exact nature of the prismatic cleavage displayed. Pyroxene has two directions at  $90^\circ$  angles while amphiboles have to directions which are at  $60^\circ$  and  $120^\circ$  from each other. The following figure (Fig 5) might help in visualizing the difference.

Pyroxene (001) basal section



Amphibole (001) basal section



## ***CYCLOSILICATES (ring silicates)***

### **Tourmaline & Beryl**

The cyclosilicates have a formula similar to the chain silicates ( $\text{SiO}_3$ ) but the structure is different in that the chain of Tetrahedra are attached to themselves in a ring like fashion; typically a six membered ring with hexagonal symmetry. There are only two common members of this group that we need to consider here; Tourmaline and Beryl. Both minerals are typically found in pegmatites and have rather exotic chemistry as is typical of pegmatite minerals and include such elements as boron and beryllium.

Both beryl and tourmaline contain rather exotic elemental components, such as beryllium, boron, uranium, etc because these elements are generally *incompatible* in other more common rock forming minerals. Incompatible, in this case, refers to the lithophile elements (those elements which tend to form oxygen compounds) that do not readily substitute for the major elements in the common rock forming minerals. As a result these incompatible lithophile elements are enriched (concentrated) in residual magmatic fluids after other minerals crystallize along with silica, aluminum, alkalis (periodic table group 1A and 2A; Na, K, etc), water, and other volatiles. {This would be like a group of adults accompanying their small children to a playground with a really fun area of the playground accessible only through a piece of small diameter conduit. The adults would be left out and have to hang around outside the cool play area.} The result of this *fractionation* can produce highly pressurized fluids that can be injected into the country rock and crystallize the exotic (relatively rare) minerals found in pegmatites, the late stage mineralization found in some intrusive igneous rock bodies.

## ***TECTOSILICATES (framework silicates)***

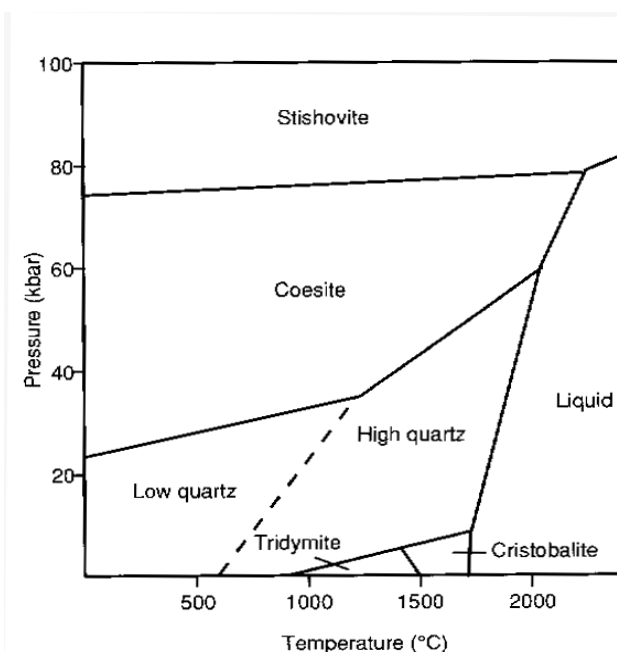
### **Quartz**

Quartz is one of the most common minerals in the earth's continental crust and is relatively abundant in all rock types. A thorough knowledge of its occurrence and properties is essential in all aspects of geology, particularly petrology, sedimentology, and environmental geology. Quartz is also a very useful mineral and it is sought after for many commercial purposes.

We should first consider some of silica's more obvious physical properties that are so frequently found useful. It is a very hard and refractory mineral and thus it is often used as an abrasive in sandpaper and as a foundry casting sand. Large amounts are used to make glass and various ceramic products. Quartz is also the basic raw material for silicon which is the basis for computer chips, solar cells and other products. Optical quality quartz is frequently used in scientific instruments such as spectrometers. The piezoelectric properties of quartz have found many uses in the electronics industry and in manufacture of quartz watches.

There is a surprising number of structural variations for silica as shown in the following phase diagram.

**Fig. 6 Phase Diagram for Silica**



It should be noted that the high temperature, polymorphs, Beta Quartz (high quartz), Tridymite and Cristobalite are all less dense than low quartz while the high pressure polymorphs are denser. The high pressure phases were first produced in laboratory experiments and subsequently found in nature.

Good crystalline quartz can have some trace impurities that may produce a color in the crystals. Amethyst (purple) Citrine (yellow) and Rose quartz are some well known examples. Smoky quartz has a dark gray to black color which has been attributed to crystal lattice damage caused by radioactivity. There are countless names given to the many varieties of amorphous silicon. The following tables list some of the better known examples.

**TABLE 3**

<i>Chert</i>	tan-brown - often in layers or nodules in marine sediments
<i>Flint</i>	usually dark gray - black
<i>Jasper</i>	reddish color due to Fe <sub>2</sub> O <sub>3</sub> -associated with banded iron ores
<i>Carnelian</i>	red to orange-red chalcedony
<i>Chrysoprase</i>	greenish semi-translucent chalcedony
<i>Agate</i>	a variety of colors usually in curved bands. Agates from Brazil are particularly prized
<i>Bloodstone</i>	green with red spots. Also called heliotrope
<i>Opal</i>	often has some water included. Opal with a play of colors is called precious opal.

Most types of amorphous (having no crystalline structure) silica are as hard as quartz (opal is slightly softer) and they have the characteristic conchoidal fracture.

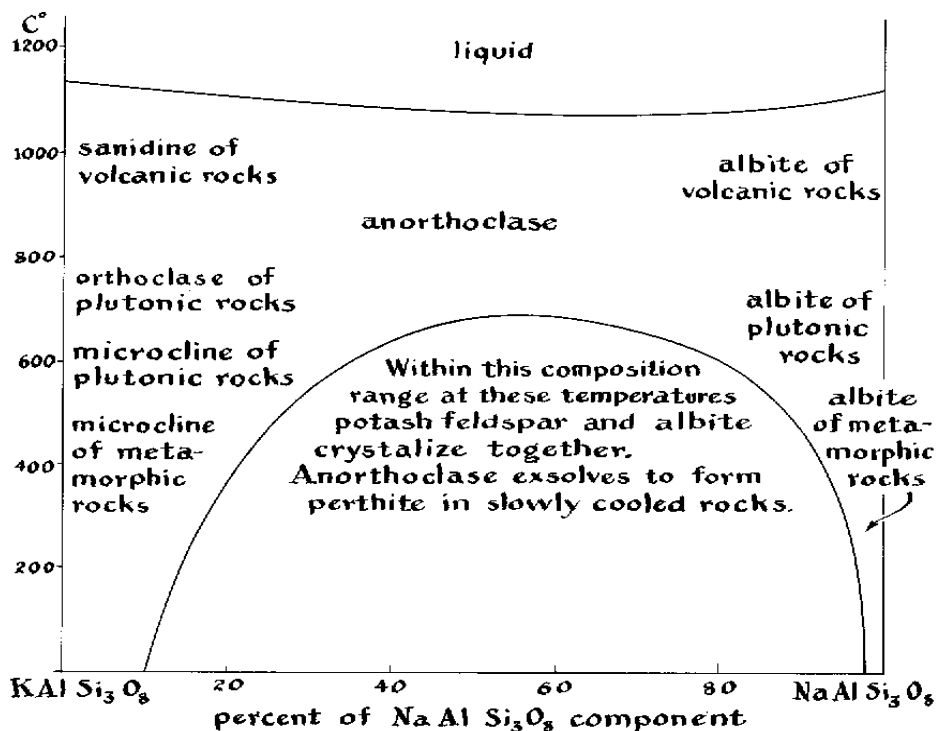
## Feldspars

### Potassium Feldspar (Sanidine, Orthoclase, Microcline); Plagioclase Feldspar (Albite - Anorthite)

Feldspars are the most abundant group of minerals in the earth's crust and may appear to be rather drab, however they display an amazingly complex structure that has been the object of many research papers and even books.\*

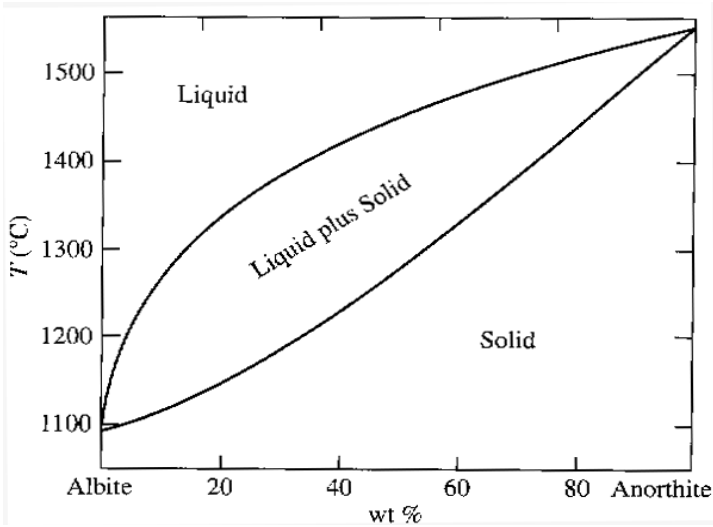
The so called alkali feldspars ( $\text{Na}^{+1}$  and  $\text{K}^{+1}$  rich) form one of the two major series of feldspars and because of their chemistry they are frequently found in felsic rocks such as granite and diorite. The  $\text{K}^{+1}$  ion is much larger than the  $\text{Na}^{+1}$  ion and therefore the structure between the two end members is not compatible and there is an exsolution into two separate phases which produces a perthitic (banded) texture which is often seen in these feldspars. The T-X phase diagram for the alkali feldspars is shown in Fig. 7 and you should know and understand what this diagram is trying to depict.

*Figure 7 Phase diagram for the alkali feldspars*

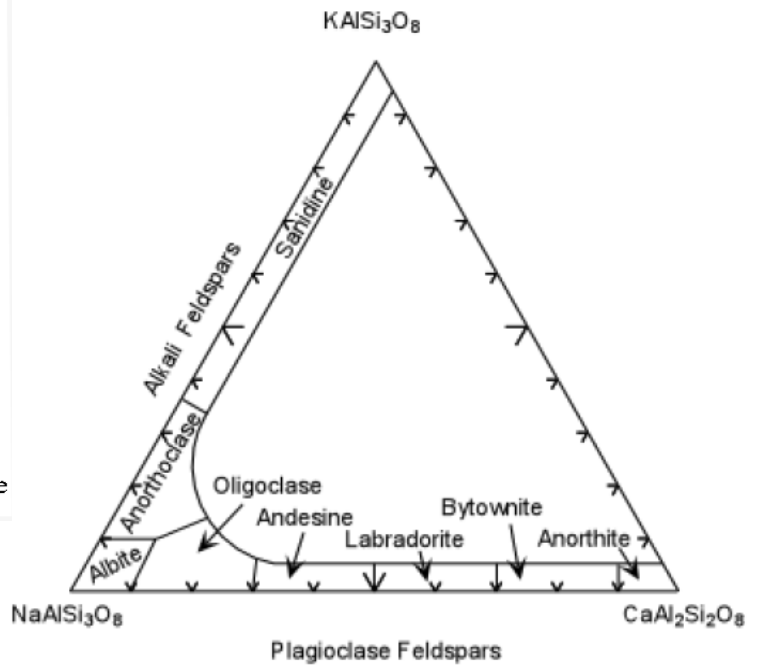


The plagioclase series behave differently, however, because of the similarity in size between the  $\text{Na}^{+1}$  (0.95 Å) and  $\text{Ca}^{+2}$  (0.99 Å) there is a complete solid solution between the ends numbers as we have previously seen in the olivine series. The T-X and ternary composition phase diagrams for this pair of minerals is shown below in Figure 8a-c.

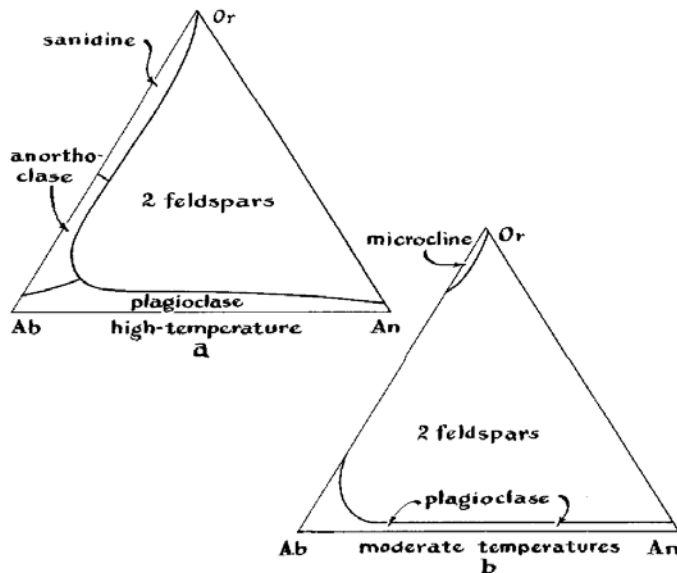
**Figure 8a Plagioclase T-X Phase diagram**



**Figure 8b Ternary composition diagram for the**



**Figure 8c Ternary Composition Diagram for AN-AB-OR at high and low temperature**



Phase relations in the Or-Ab-An system (a) at high temperatures, (b) at moderate temperatures.

The feldspars can be looked at in terms of the three components Albite (Ab) -  $\text{NaAlSi}_3\text{O}_8$ , Orthoclase (Or) -  $\text{KAlSi}_3\text{O}_8$ , and Anorthite (An) -  $\text{CaAl}_2\text{Si}_2\text{O}_8$ . At high temperature, complete solid solution exists between Ab and Or, to form the alkali feldspar solid solution series. But, as shown in the diagram, the alkali feldspar solid solutions can contain up to 5% of the An component. Similarly a complete solid solution series exists between Ab and An, to form the plagioclase solid solution series. Plagioclase can contain up to about 5% of the Or component. Some of the intermediate varieties of plagioclase do have a

submicroscopic structural distortion that produces a play of colors often referred to as a labradorescence.

It is important to know and understand the difference between perthitic texture in the alkali feldspars and polysynthetic twinning (repeated twinning of three or more individuals according to the same twin law and on parallel composition planes) in the plagioclase series as this is all the information available in hand specimen to distinguishing these two minerals. The ability to tell them apart becomes very important in identifying different rock types.

### **Coupled Atomic Substitution**

Variations in the composition of several of the rock forming silicate mineral groups occurs as a result of the coupled substitution of metal cations due to the transitional nature of  $Al^{+3}$ . Divalent/trivalent substitutions in tetrahedral (CN 4 [4]) and octahedral (CN 6 [6]) sites of many rock forming silica minerals result in order to maintain electrical neutrality, for example:

$Al^{+3}$  (IR .51) can occur in either CN 6[6] or CN 4[4] and a range of compositions for Mg-Al pyroxene exist:  
 $Mg_2Si_2O_6 \rightarrow (MgAl)_2(SiAl)_2O_6 \rightarrow Al_4O_6$

$Al_4O_6$  is not a real mineral; it is the hypothetical Tschermak's molecule. The range of pyroxene compositions is  $[6](Mg_{1-x}Al_x)_2[4](Si_{1-x}Al_x)_2$ ; in nature  $x < 1$

### **Coupled Substitution in the Plagioclase Feldspars**

Coupled substitution also applies to the variation in composition in the feldspar group, especially between albite and anorthite in the plagioclase feldspar solid solution series:

Structural formula for the feldspar group:  $WZ_4O_8$ ;  $(Ca,Na,K)(Al,Si)_4O_8$

*Plagioclase Series:*  $(Ca,Na)(Al,Si)_4O_8$ ; from Albite ( $NaAlSi_3O_8$ ) to Anorthite ( $CaAl_2Si_2O_8$ )

*Alkali Feldspars:*  $(Na,K)(Al,Si)_4O_8$

Note that the variation in Na/Ca ratio in the [6] site is coupled with the variation in Si/Al ratio in the [4] site as follows:

$(Ca_xNa_{1-x})(Al_{1+x}Si_{3-x})O_8$

e.g.  $Ca_{.20}Na_{.80}(Al_{1.2}Si_{2.8})O_8$

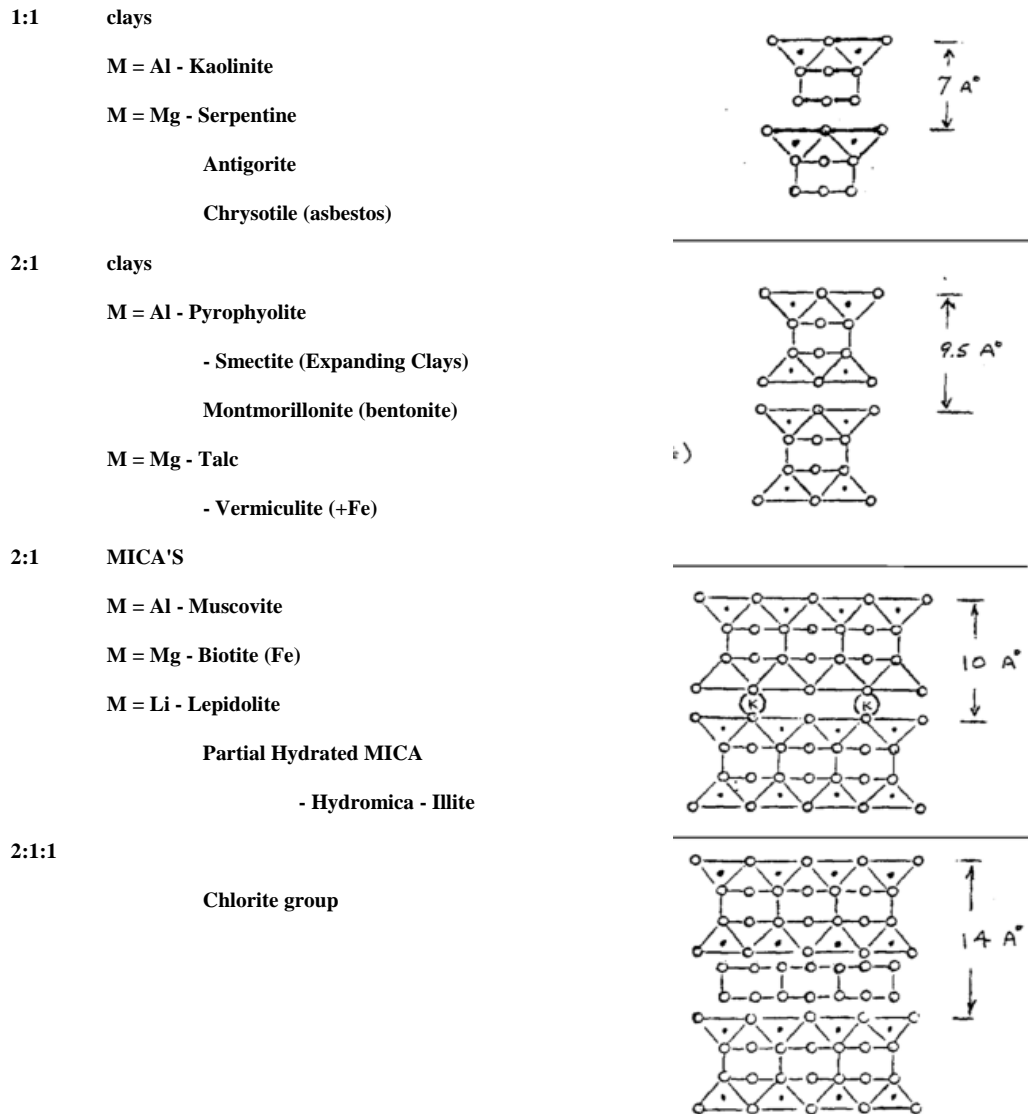
Oligoclase (see Figure 8b)

**PHYLLOSILICATES** (*sheet silicates*)

**Mica's and the clays**

The micas and clays are Phyllosilicates; sheet or layered silicates. A two dimensional polymerization of silica tetrahedra forms a layered ( $Si_2O_5$ ) structure and is one of the basic building blocks of this group. Another layer of octahedrally coordinated magnesium (brucite layer) or aluminum (gibbsite layer) makes up the other basic structural unit associated with the pyllsilicate minerals. The layered silicates are hydrous with hydroxyl molecule(s) associated with the octahedral layer, the brucite (Mg) or Gibbsite (Al) layer. A simple classification scheme based on the number of tetrahedral and octahedral layers is shown in Figure 8. Since micas and clays have different properties and different modes of origin we will discuss each group separately.

**Figure 9 Phyllosilicates (layer silicates) classification on the basis of tetrahedral/octahedral layering**



## Micas

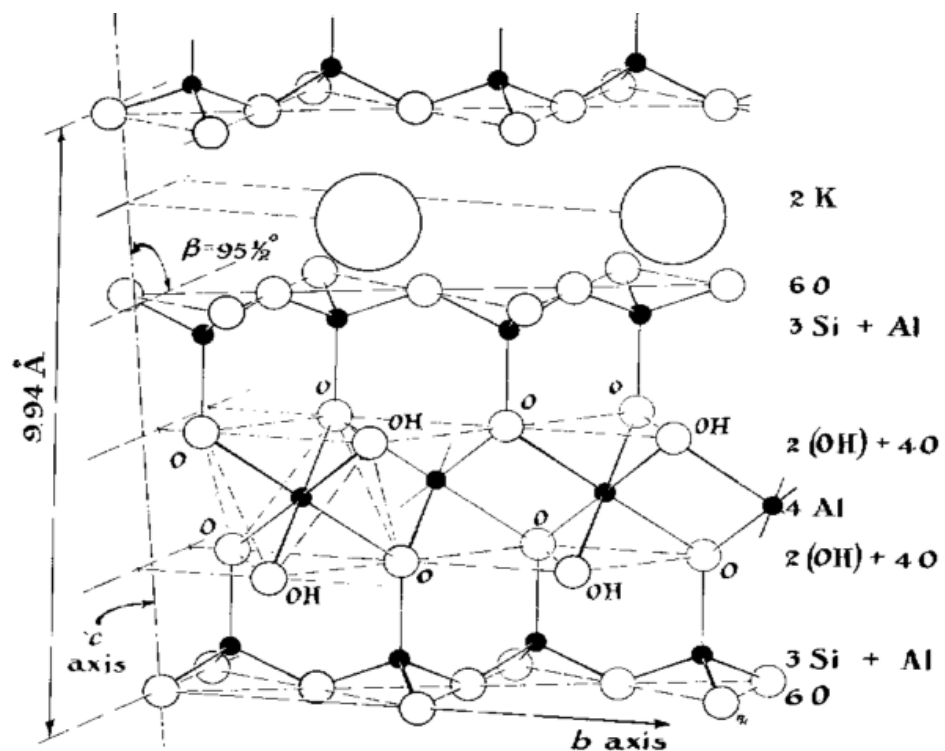
The two common micas are 1) Muscovite the clear mica (Figure 10) and 2) biotite the black, iron rich mica. The micas have some aluminum substituting for silicon in the tetrahedral layers which leaves a charge imbalance that is compensated for by large potassium atoms between the layers. This produces a bond between layers and hence micas can form quite large crystals compared to clays.

The Lithium mica, Lepidolite is found exclusively in pegmatites and is readily distinguished by its lilac color. It is often associated with the Lithium bearing tourmaline.

Muscovite is a common mineral in Igneous and Metamorphic rocks and the large "books" of this mica found in pegmatites are valued as good heat and electrical insulators. It has been used as windows in stoves and as such it is frequently called isinglass. Biotite is also very common mineral in Igneous and Metamorphic rocks and except for its black color is similar to Muscovite.

A layered silicate mineral similar to the micas but typically only associated with marine sediments is the mineral Glauconite. It is found in green grains or pellets and apparently forms authigenically (at the same time or later then the rock of which they constitute a part) in reducing environments which in turn are the result of decaying organic matter, particularly fecal pellets.

Figure 10



Structure of muscovite,  $K_2Al_4(Si_3Al)O_{20}(OH)_4$ . Pyrophyllite layers with one aluminum substituted for one out of four silicons in each tetrahedral layer, linked together by potassium atoms in twelvefold coordination with oxygen.

Part 1; Basic facts (Knowledge and Comprehension) from Chapter 7

1. What are the six silicate mineral subclasses and how are they distinguished?
2. What are the seven essential minerals in primary igneous rocks.
3. Understand the concept of “structural formulas” for the rock forming silicate minerals and use the concept to describe olivine, pyroxene, and feldspar group minerals.
4. What are “incompatible elements”?
5. What is meant by “amorphous” and “microcrystalline”

Part 2; Higher level Thinking (Application, Analysis, Synthesis, and Evaluation) from Chapter 7.

1. How do the rules for atomic substitution explain the compositional relationships among the clino- and orthopyroxenes?
2. Explain how one might establish the volcanic origin of a pyroxene. What compositional range(es) would establish this volcanic origin?
3. What is the origin of “perthite” and “antiperthite”
4. What property of all minerals requires the “coupled substitution” relationship?
5. How might you distinguish “volcanic” feldspar from “plutonic feldspar”?