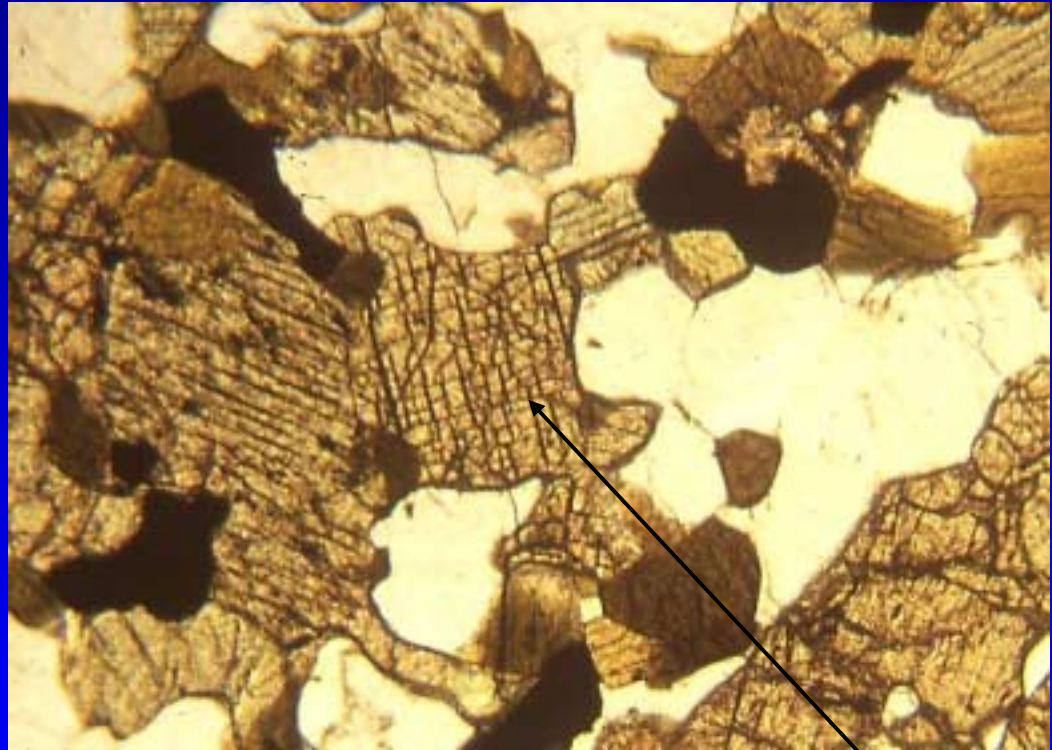
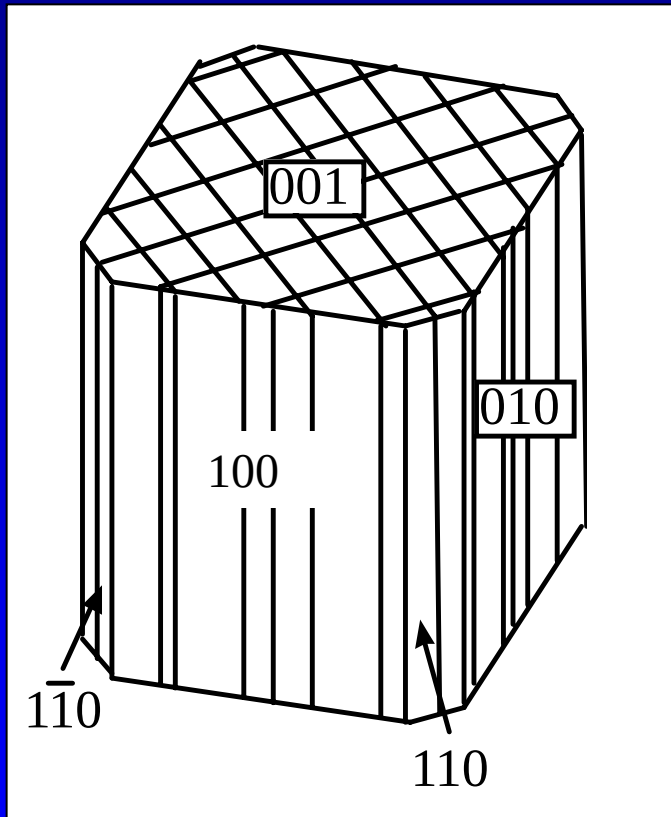


Phase transitions and exsolution phenomena in pyroxenes

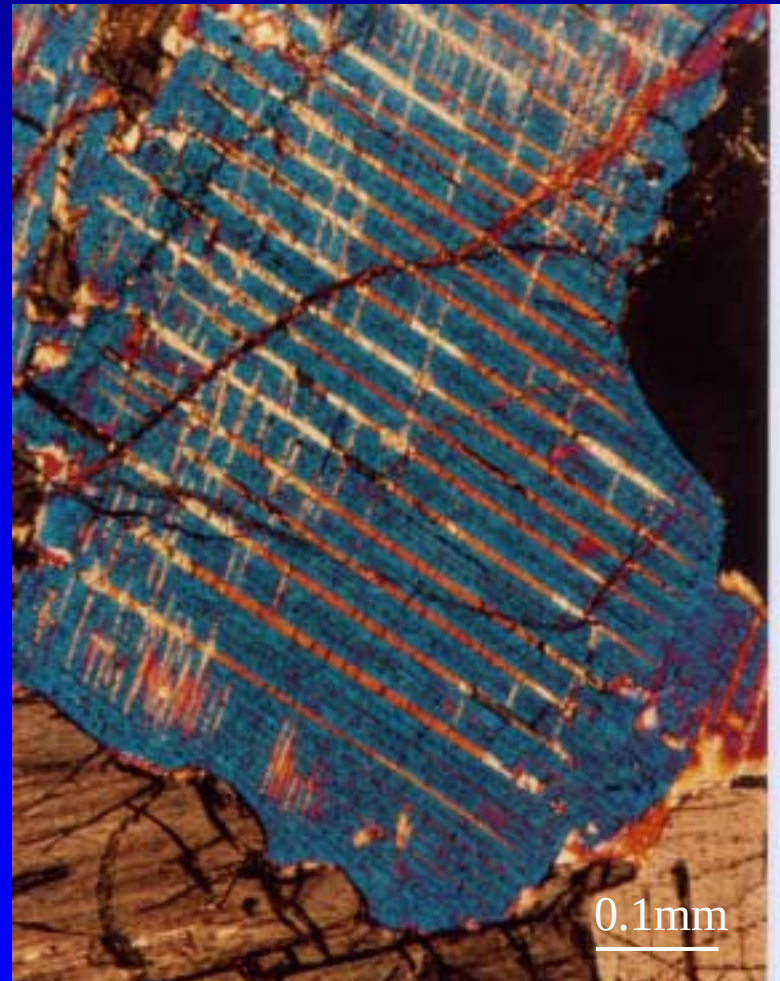
Cleavage in the pyroxenes



Optical micrograph showing two cleavages at 90°

Exsolution lamellae in pyroxenes

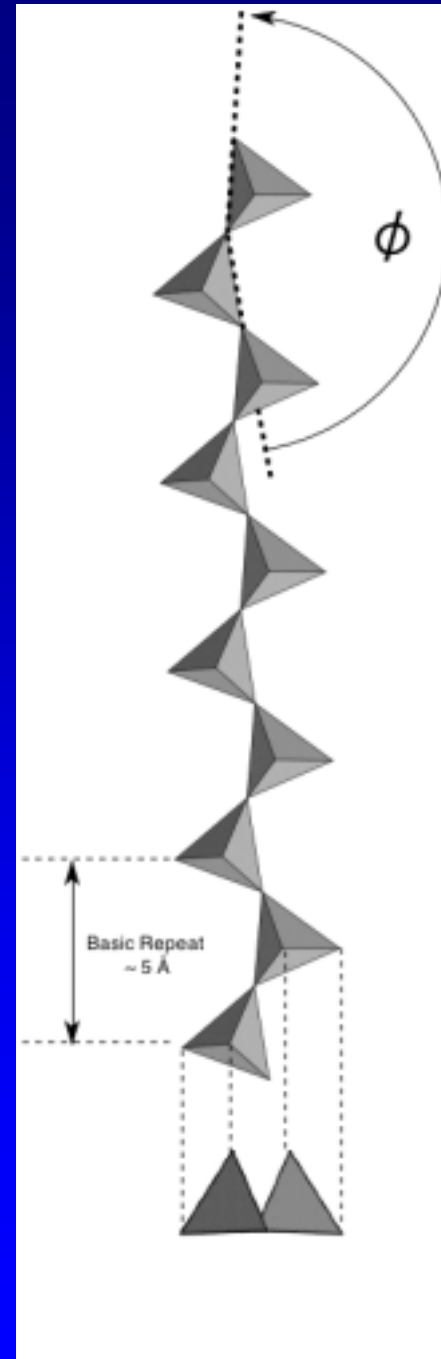
Because exsolution takes place by the *solid state diffusion* of ions through the structure, it is very slow and so the two phases generally exist on a microscopic scale



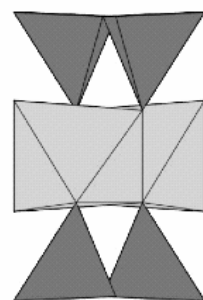
Basic structure and chemistry of pyroxenes XYZ_2O_6

Pyroxene endmembers :

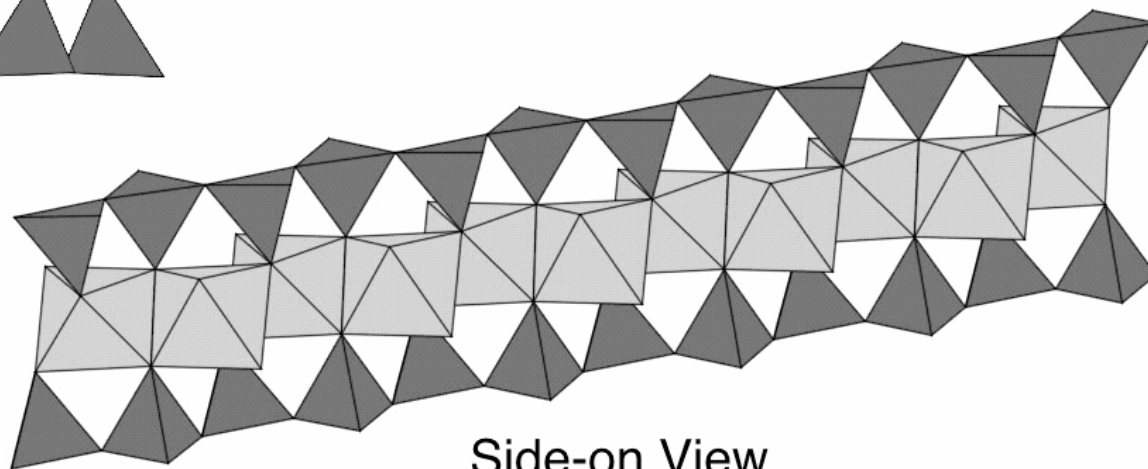
- i) **enstatite** $Mg_2Si_2O_6$ (or simply $MgSiO_3$)
- ii) **ferrosilite** $Fe_2Si_2O_6$ (or simply $FeSiO_3$)
- iii) **diopside** $CaMgSi_2O_6$
- iv) **hedenbergite** $CaFeSi_2O_6$
- v) **jadeite** $NaAlSi_2O_6$
- vi) **Ca-Tschermak**
 $CaAl(AlSi)O_6$



Pyroxene chain - 'I-beams'



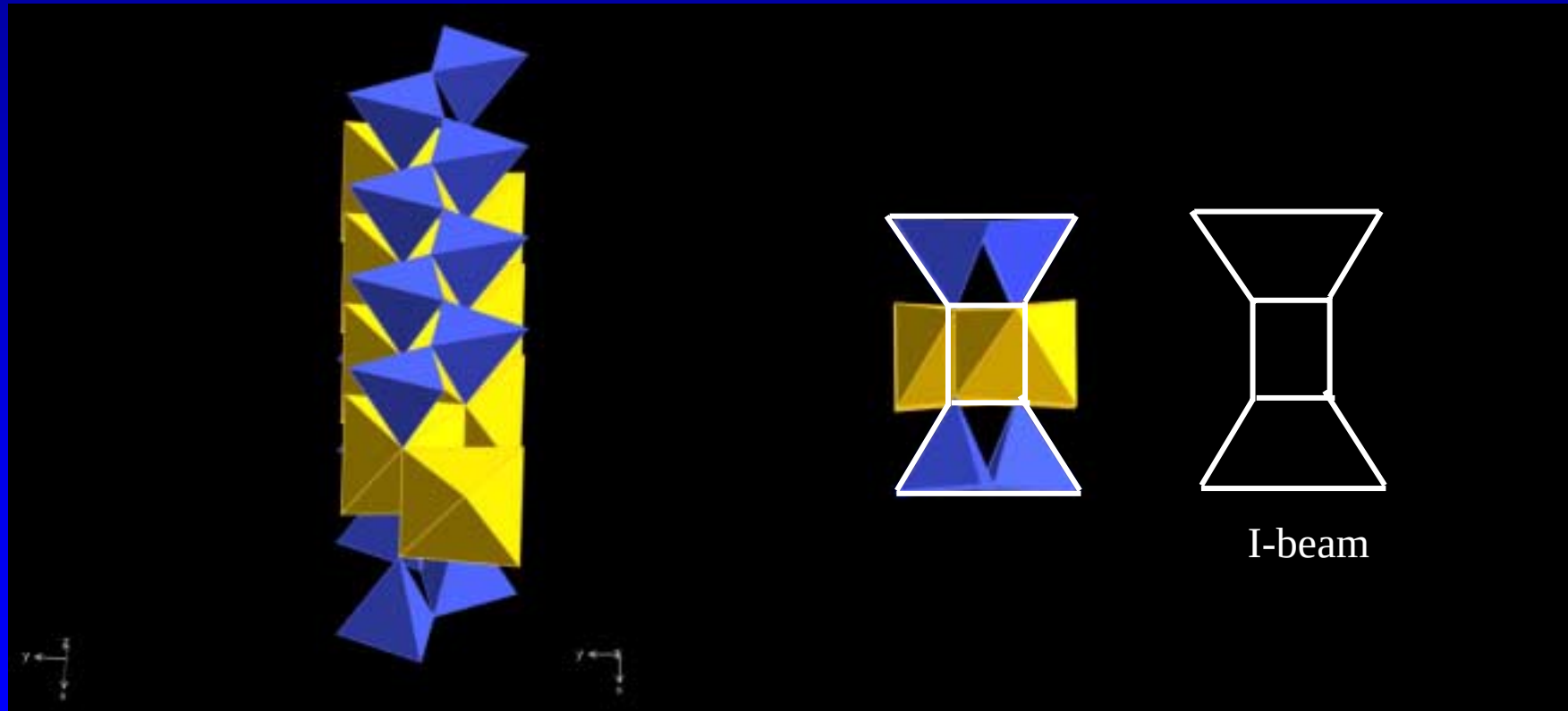
End-on View



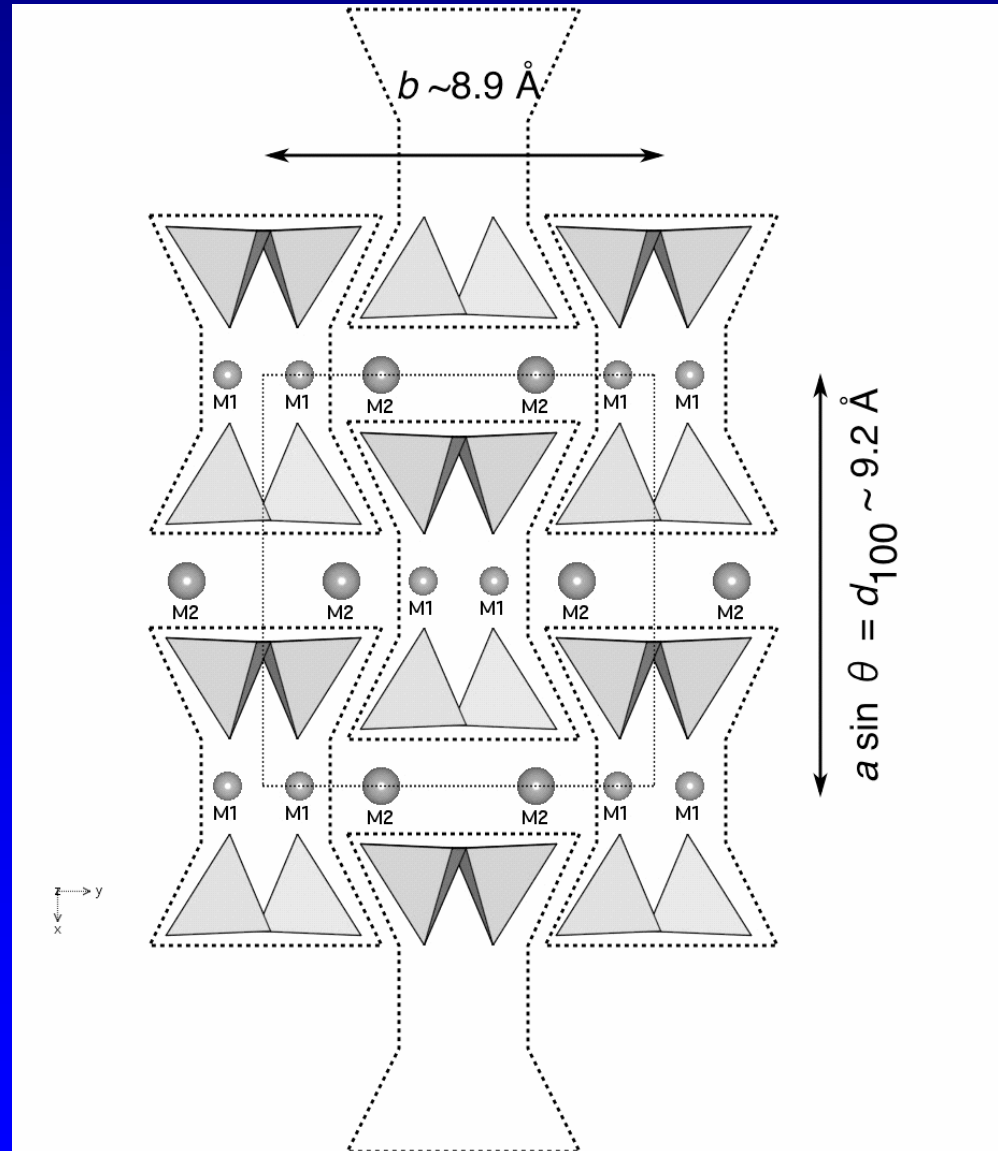
Side-on View

The structure of pyroxenes :

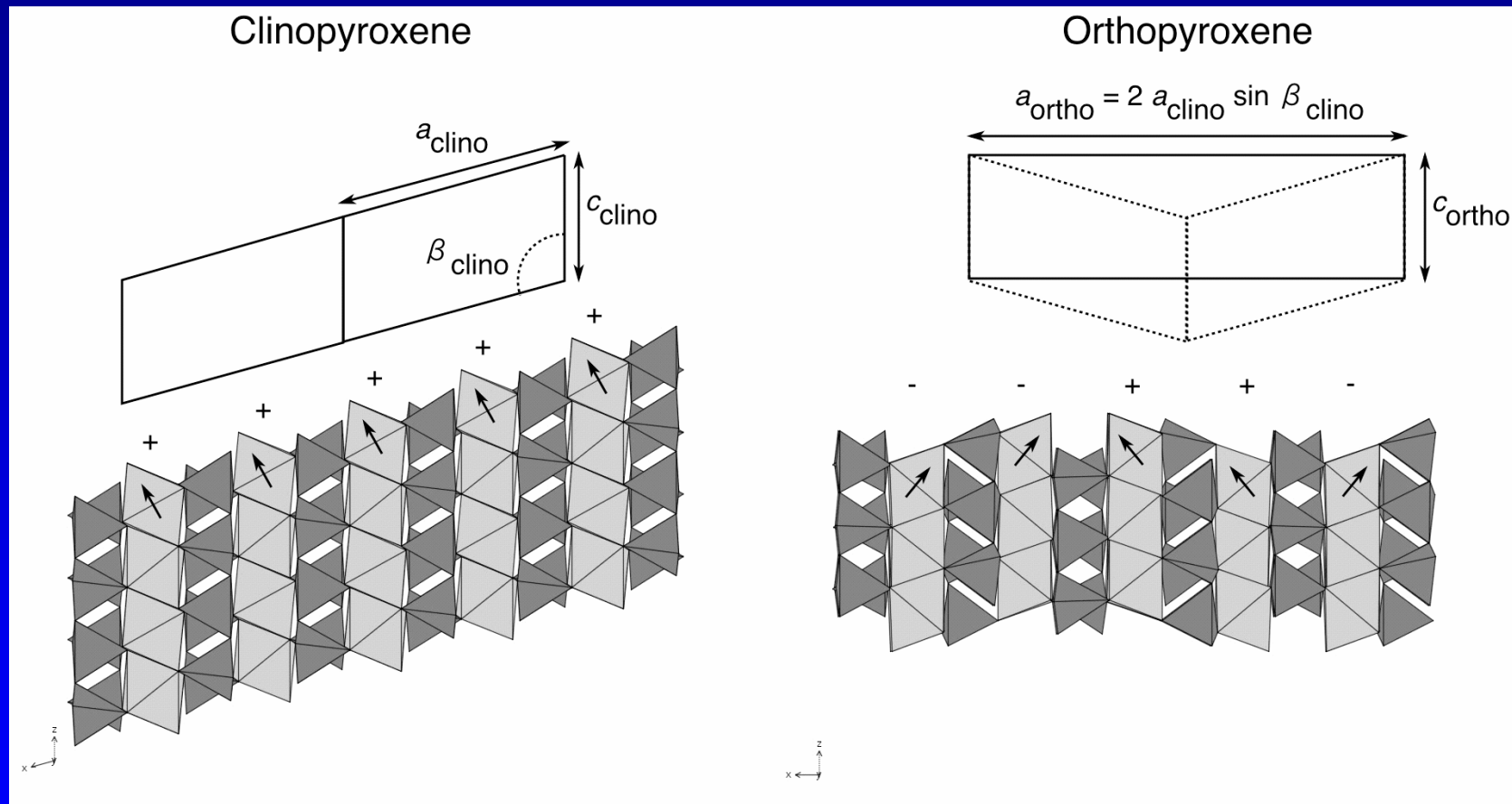
Two opposing chains connected by a chain of octahedra : I-beam



Pyroxene structure from 'I-beams'



Clinopyroxene and orthopyroxene structures



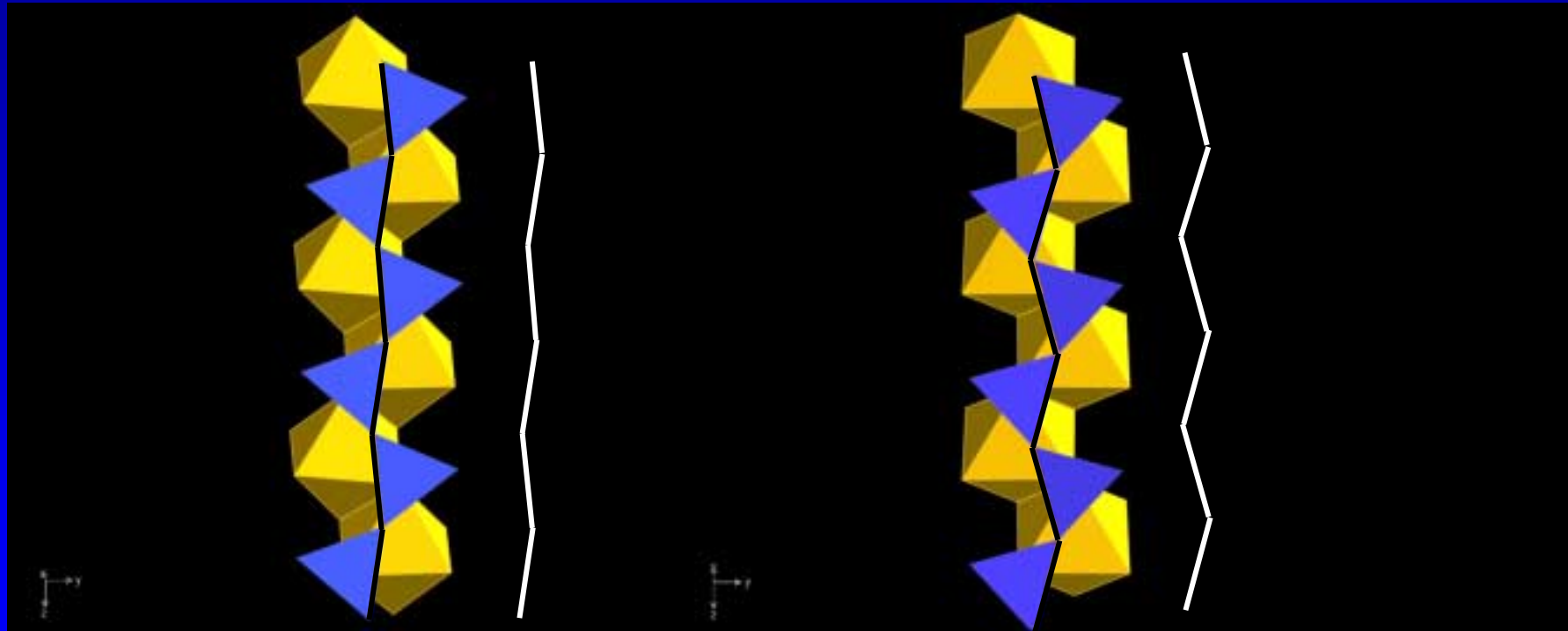
How does the silicate chain fit to the octahedral chain?

QuickTime™ and a
Graphics decompressor
are needed to see this picture.

How can the silicate chain fit to the octahedral chain?

Diopside chain

Pigeonite chain



High - low pigeonite

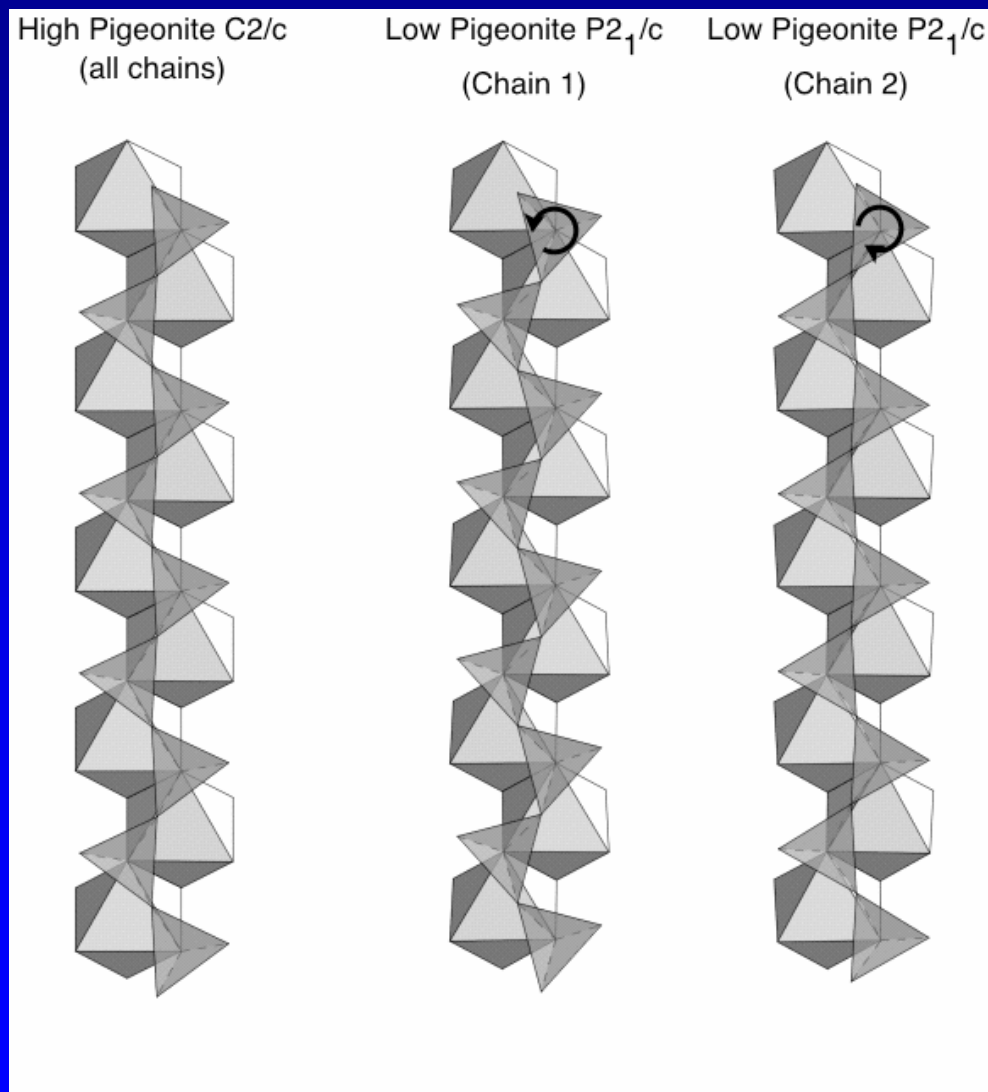
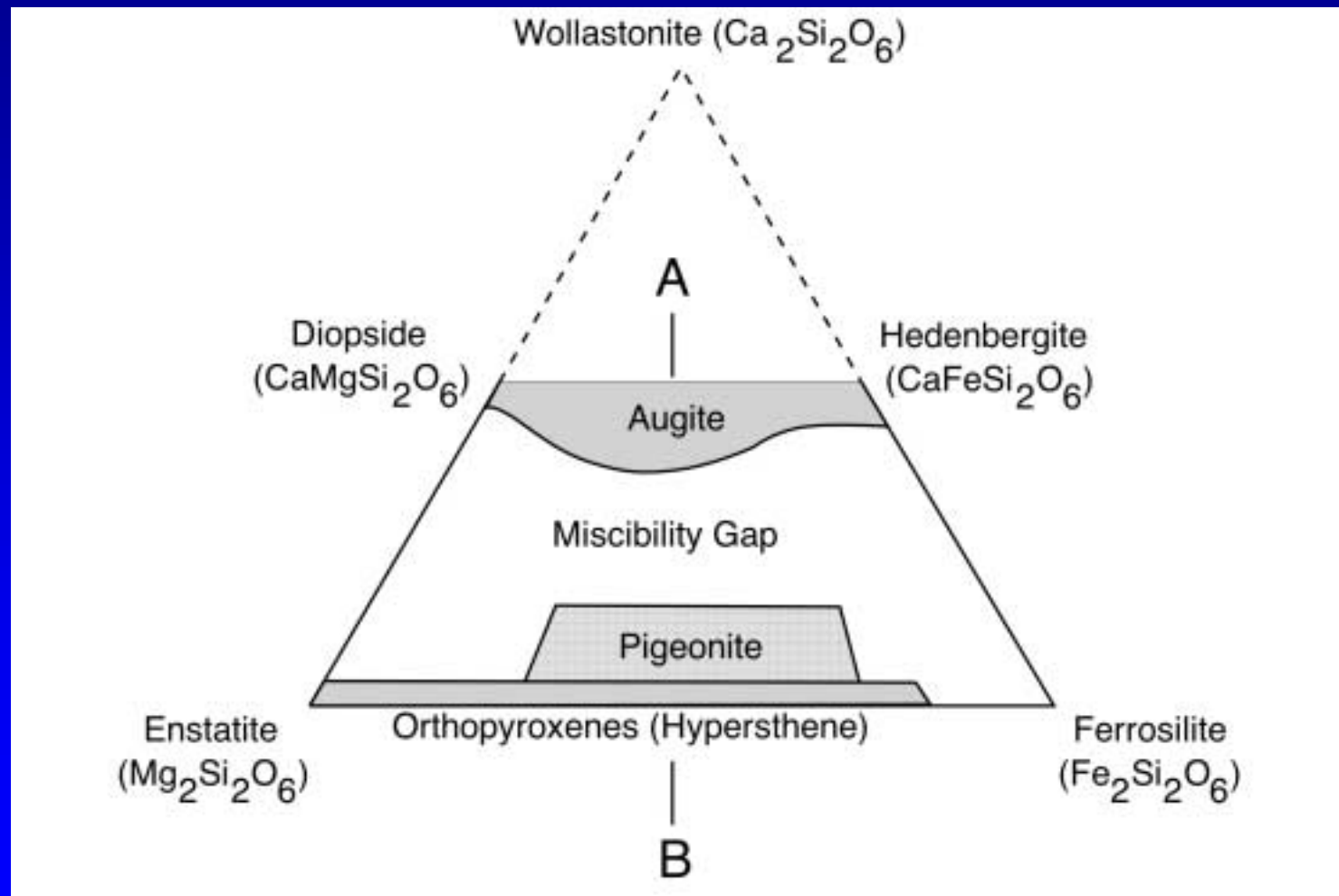
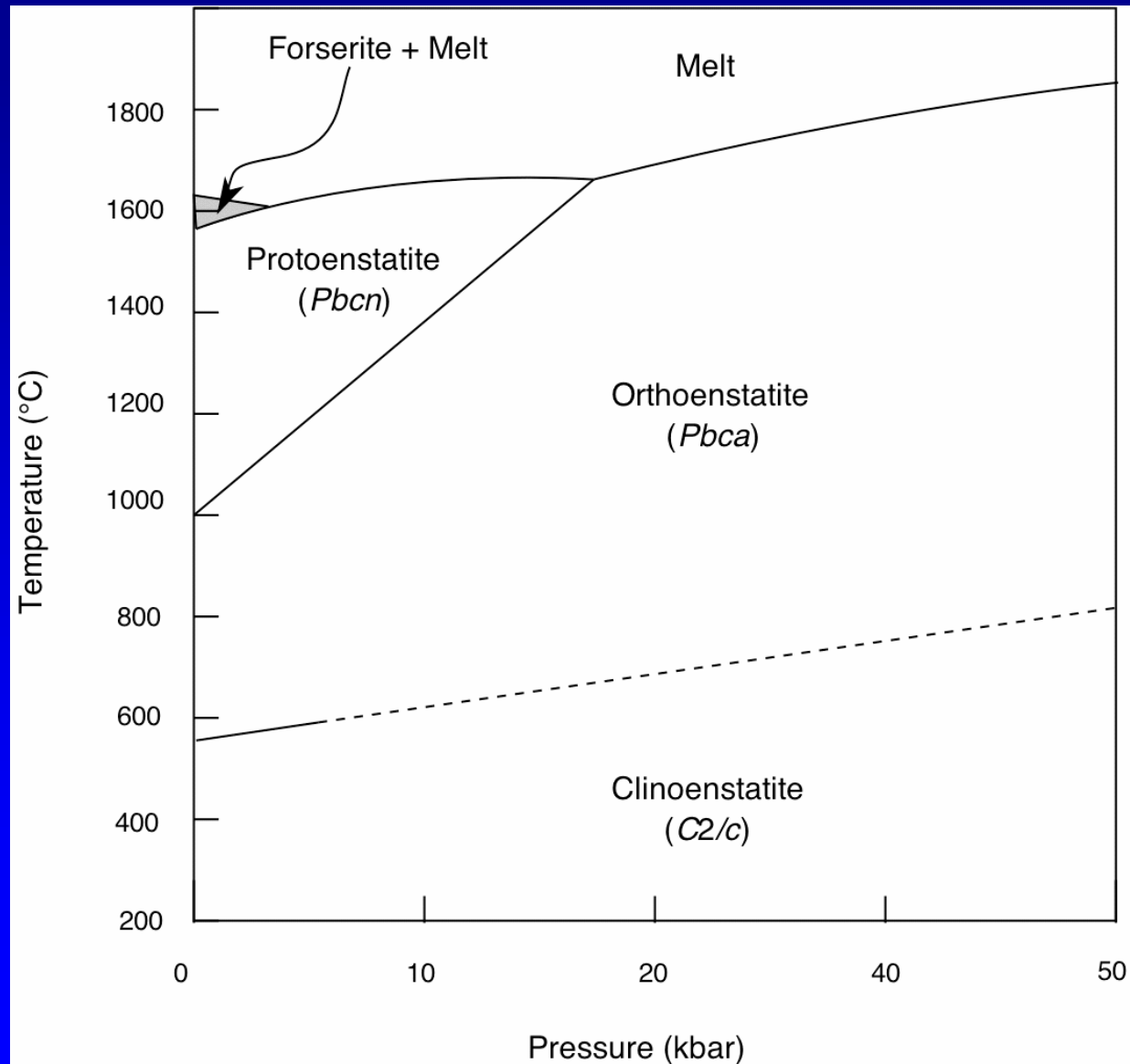


Table 1		$C2/c$	$Pbca$	$P2_1/c$
M 1	Size and coordination	Small [6]	Small [6]	Small [6]
	Shape	Regular	Regular	Regular
	Cations	Small cations such as Mg, Fe ²⁺ , Al	Small cations such as Mg, Fe ²⁺ , Al	Small cations such as Mg, Fe ²⁺ , Al
M 2	Size	Large [8]	Small [6]-[7]	Small [7]
	Shape	Irregular	Irregular	Irregular
	Cations	Large cations such as Na, Ca	Only small cations such as Mg and Fe ²⁺ Very little Ca!	Small amount of Ca is tolerated. Mainly Mg and Fe ²⁺

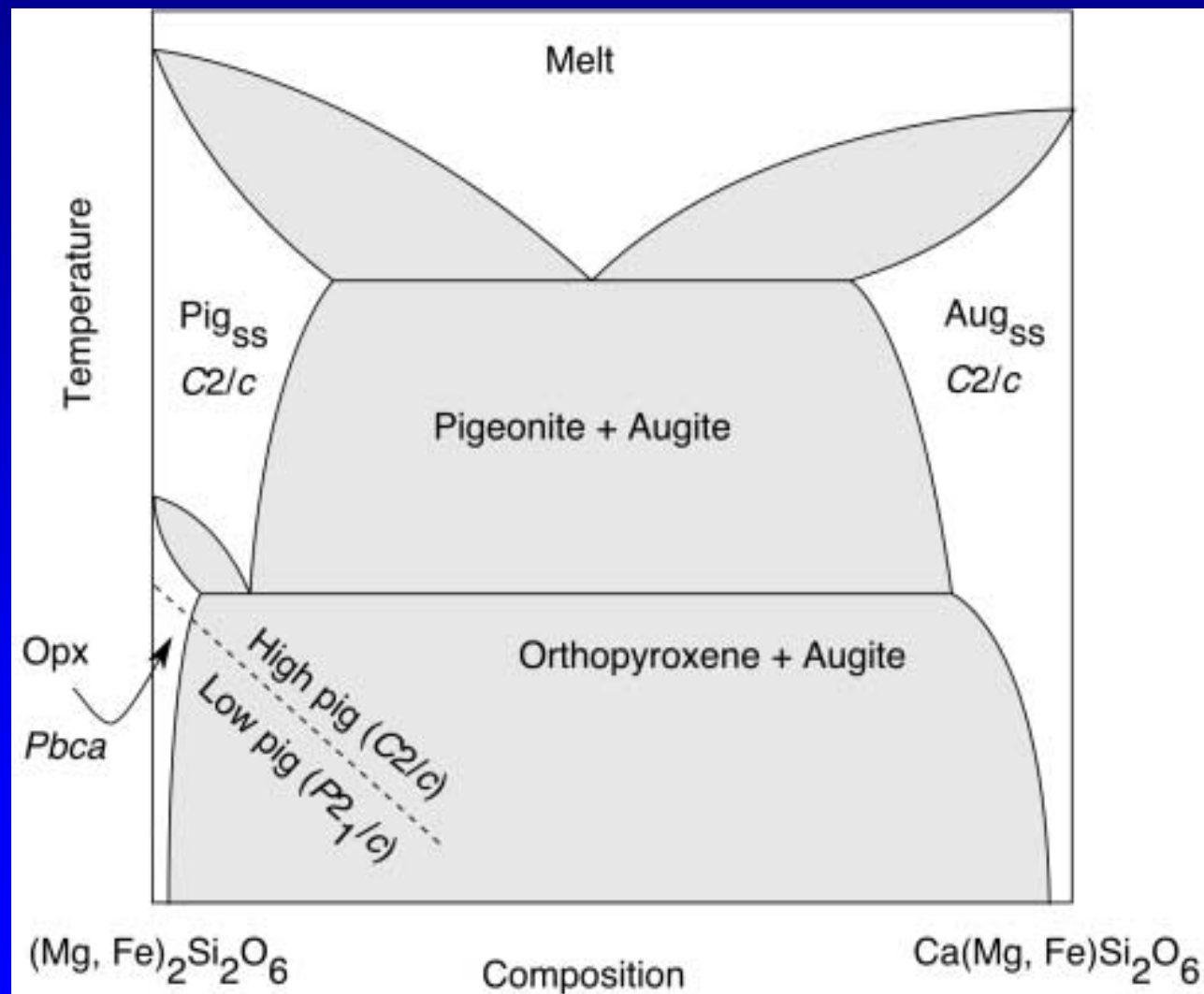
Pyroxene solid solutions



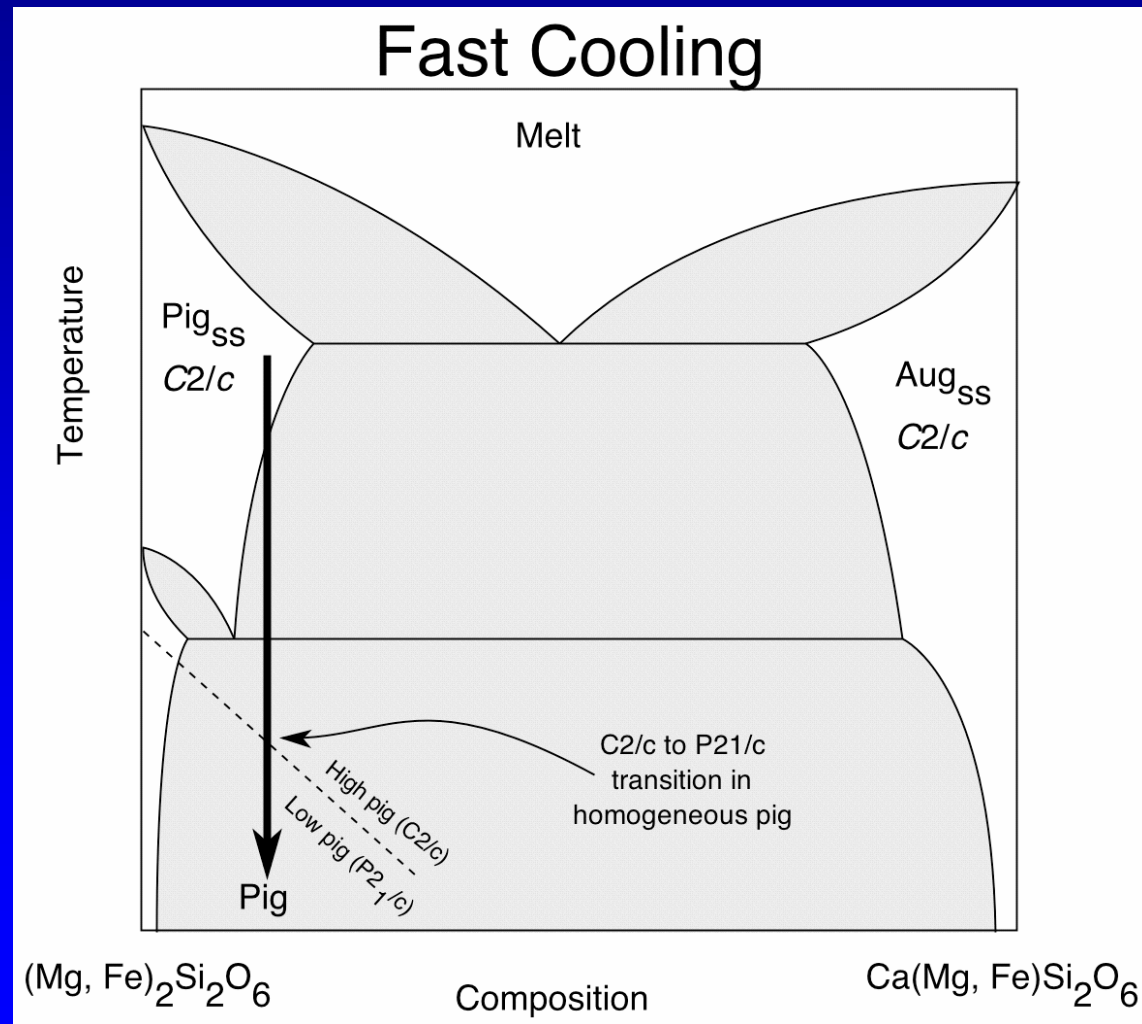
P-T relations of enstatite MgSiO_3



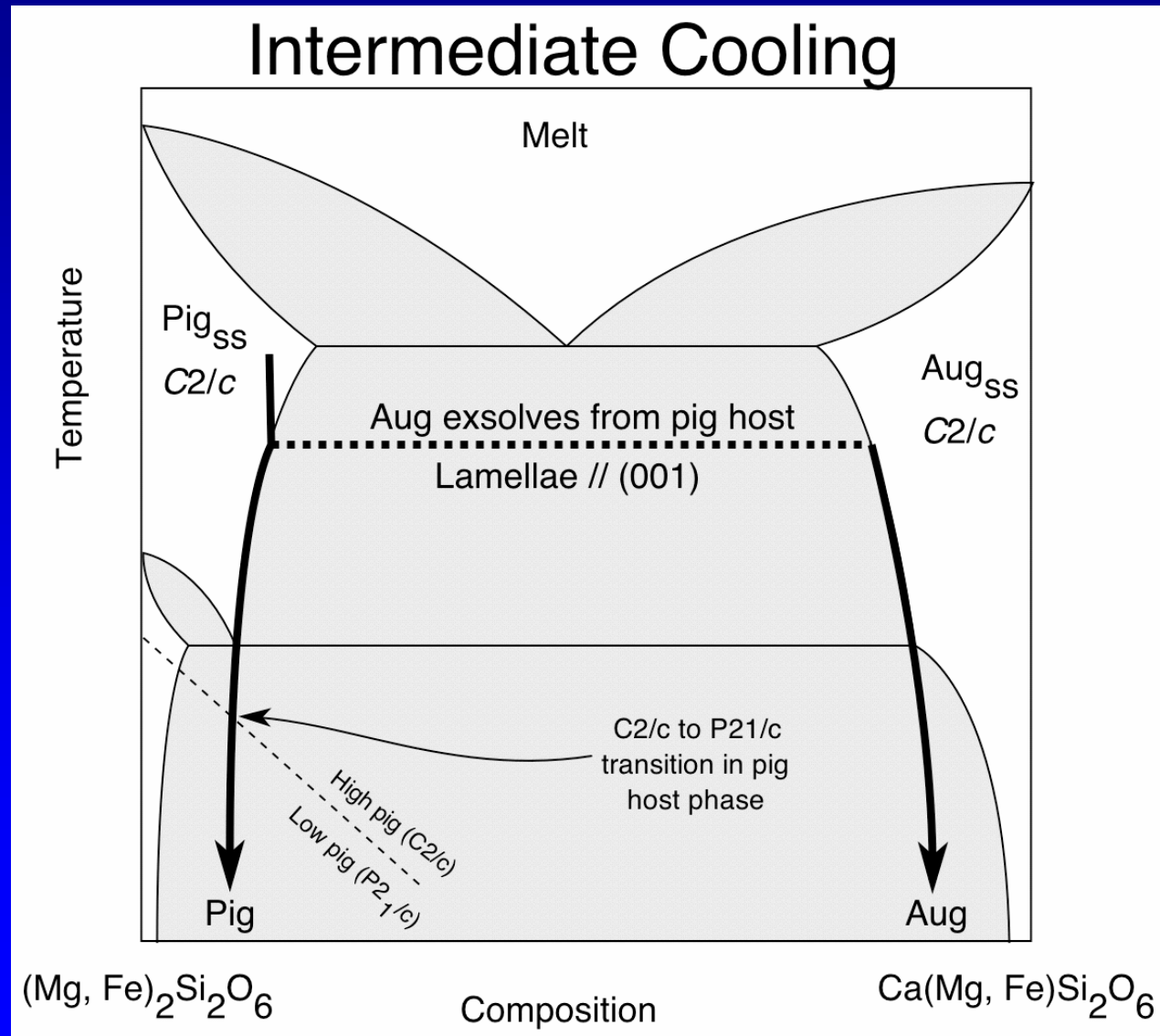
Augite- pigeonite phase diagram (pseudo-binary)



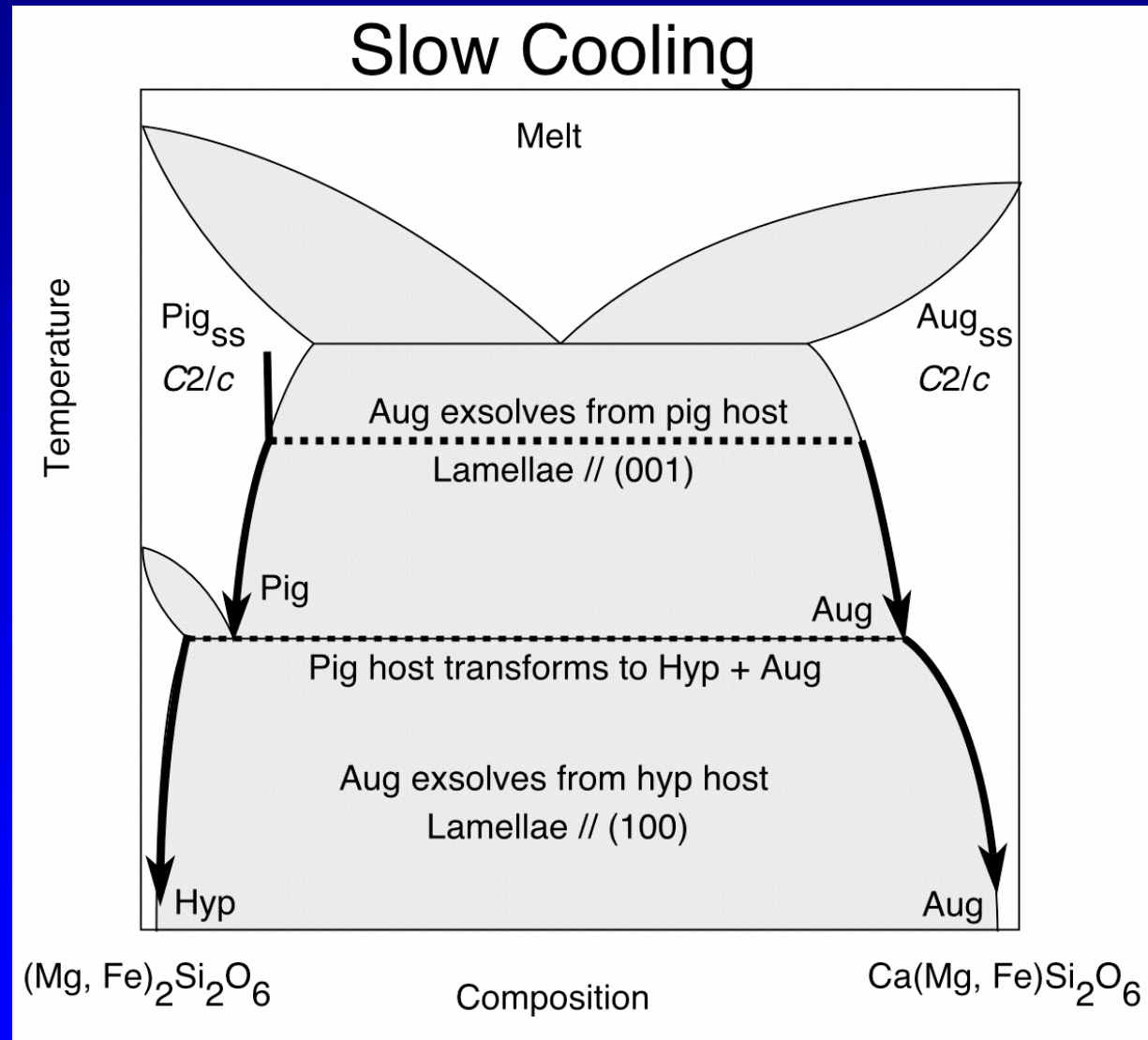
Behaviour of pyroxenes during cooling



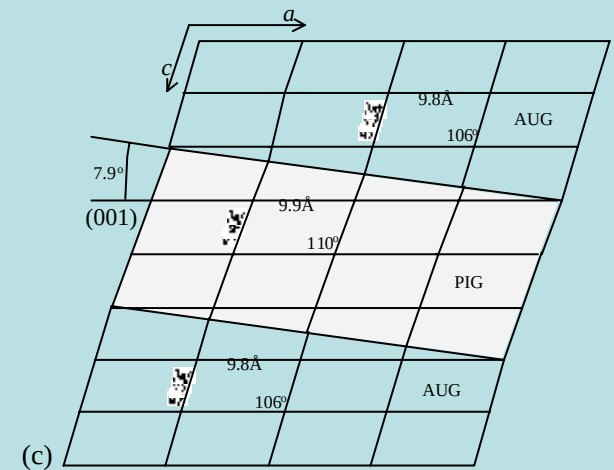
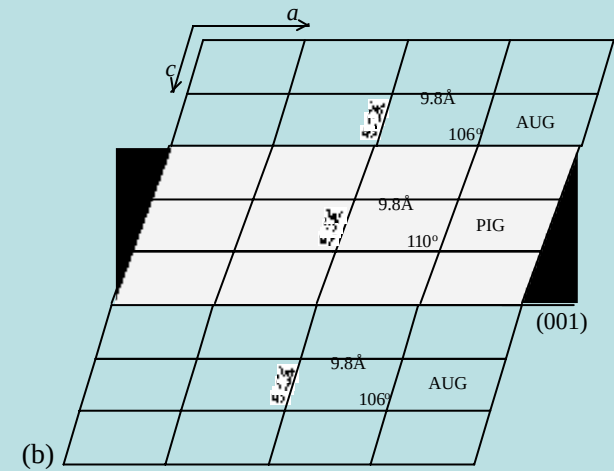
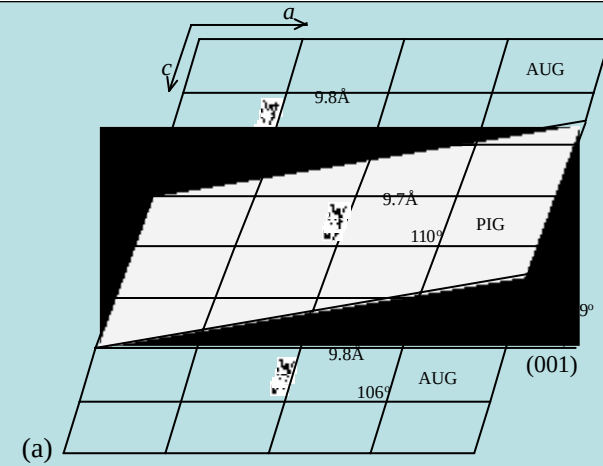
Behaviour of pyroxenes during cooling



Behaviour of pyroxenes during cooling

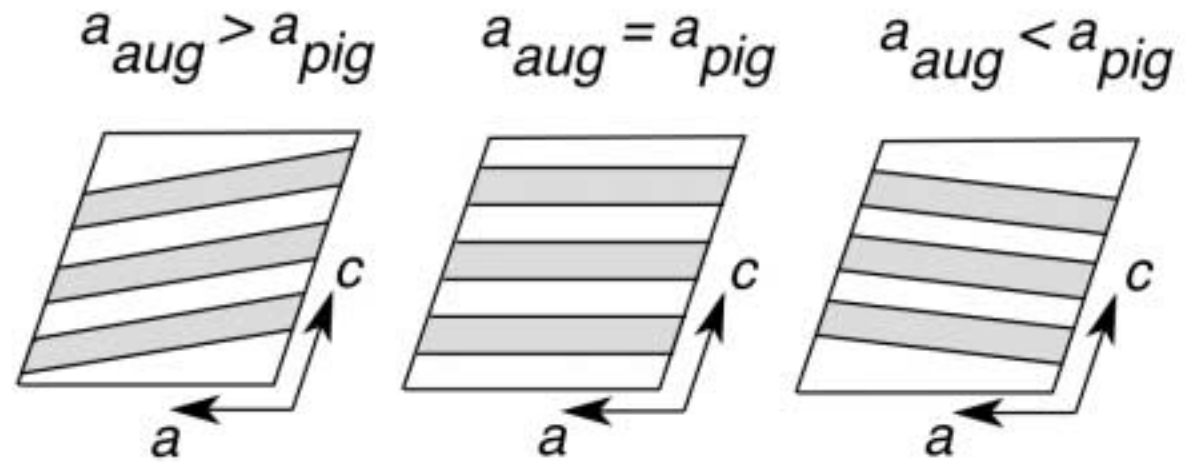


Accommodation of strain within exsolution lamellae

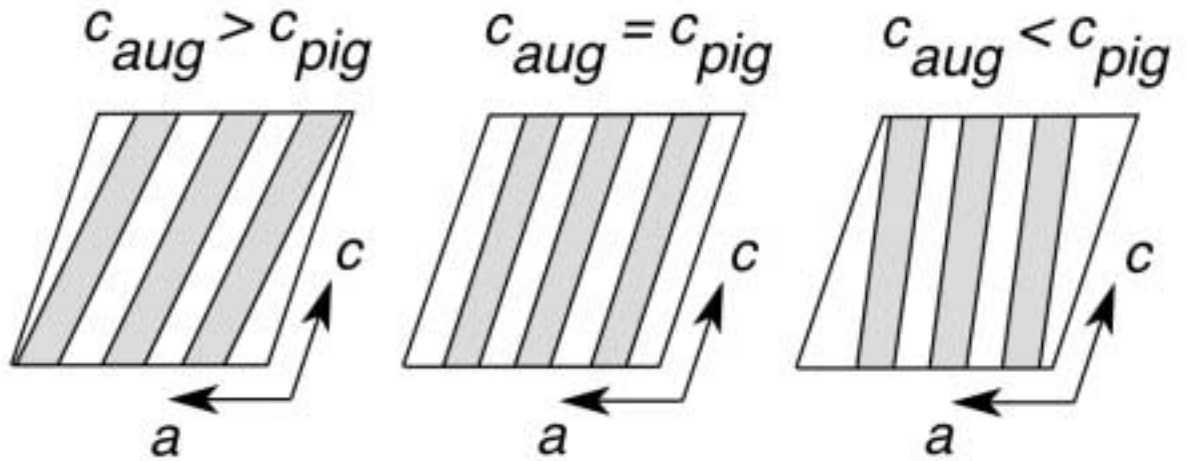


Accommodation of strain in exsolution lamellae

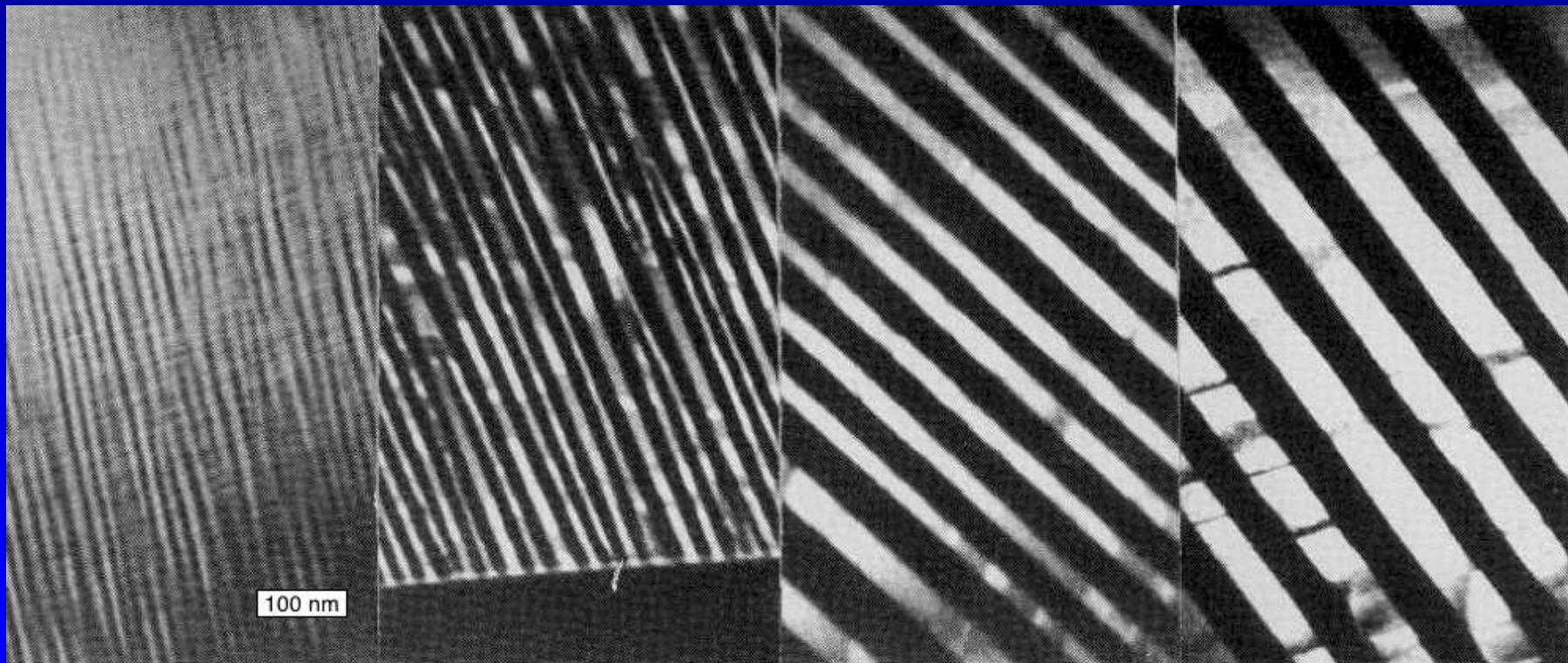
"001" Lamellae



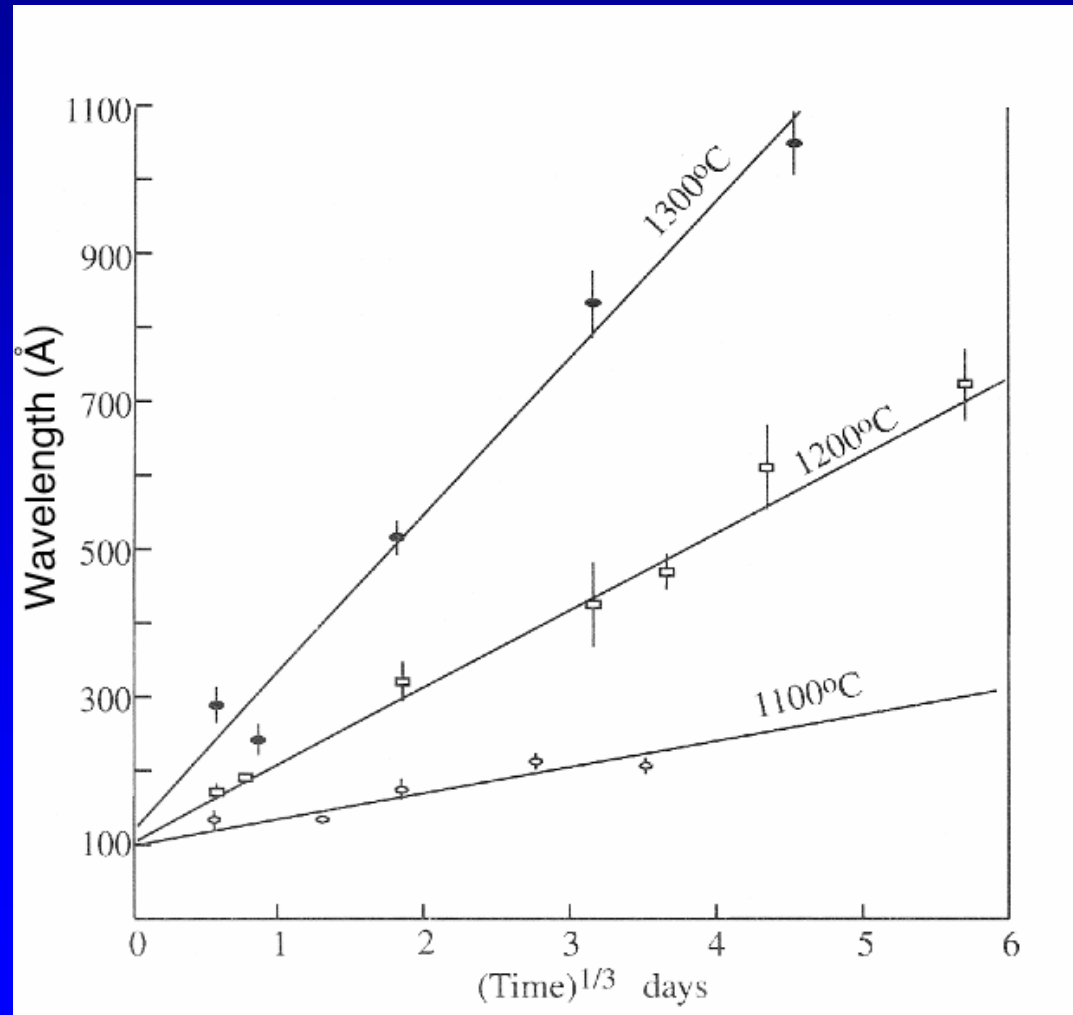
"100" Lamellae



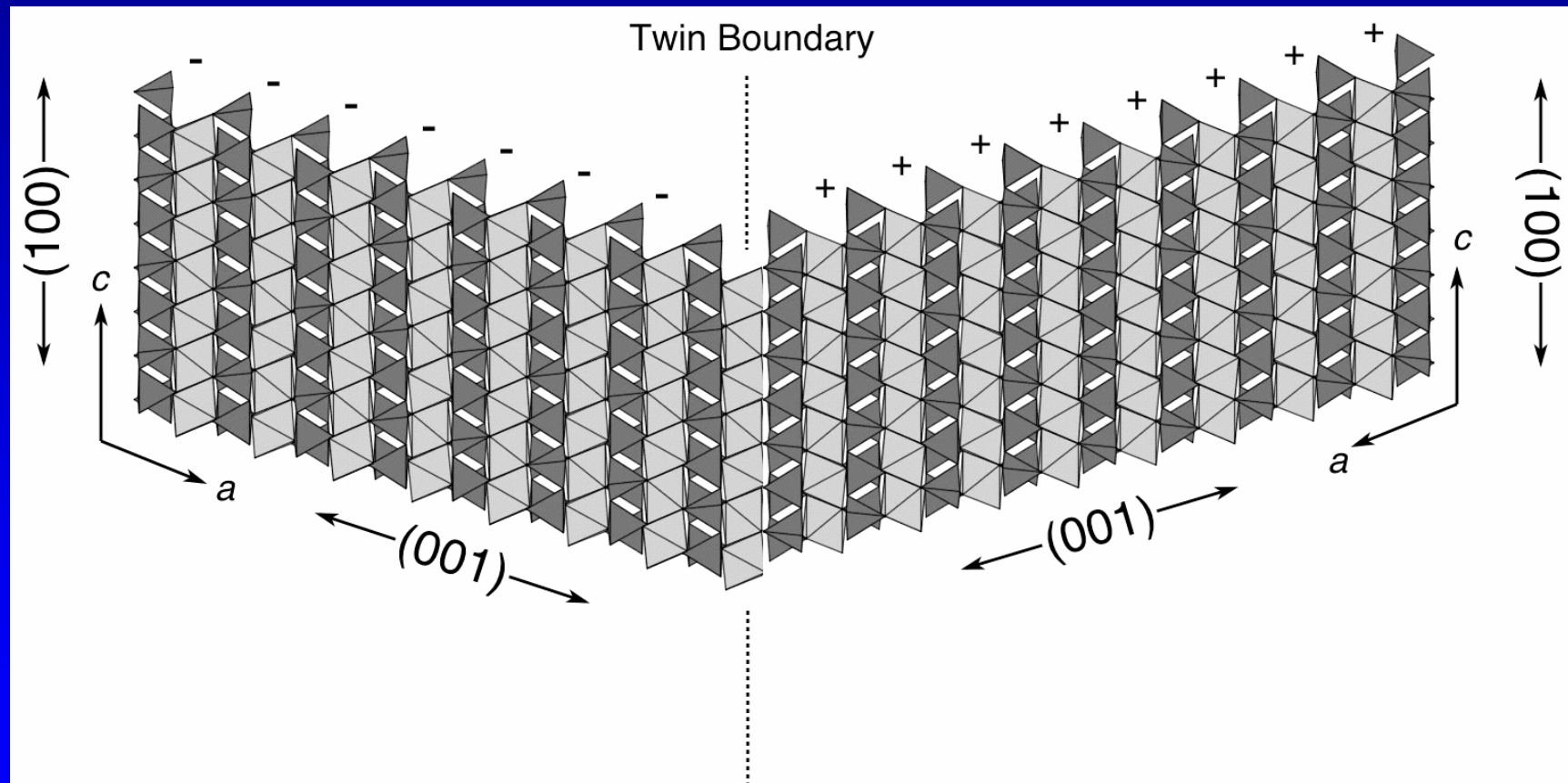
The growth of exsolution lamellae



The growth of exsolution lamellae : experiments

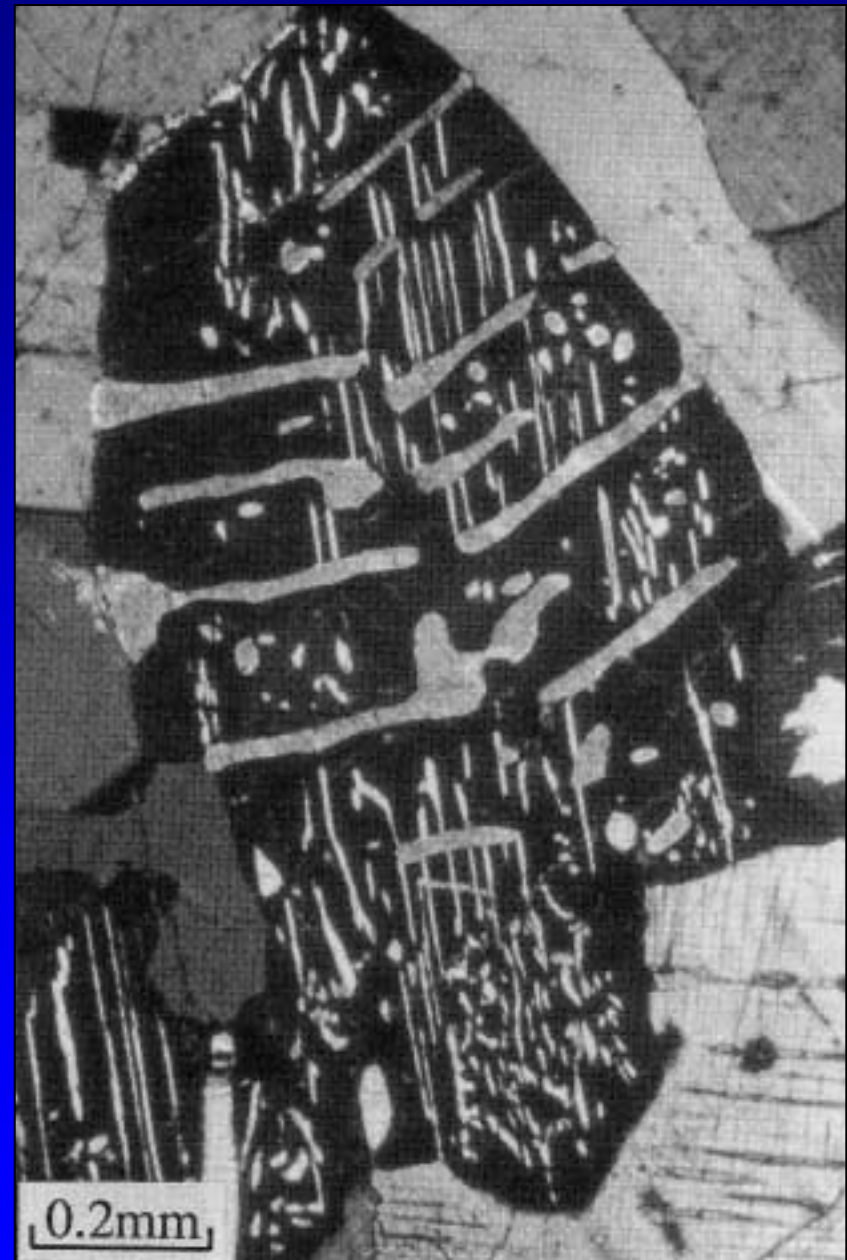


Twinning in clinopyroxene



Pigeonite to orthopyroxene transformation

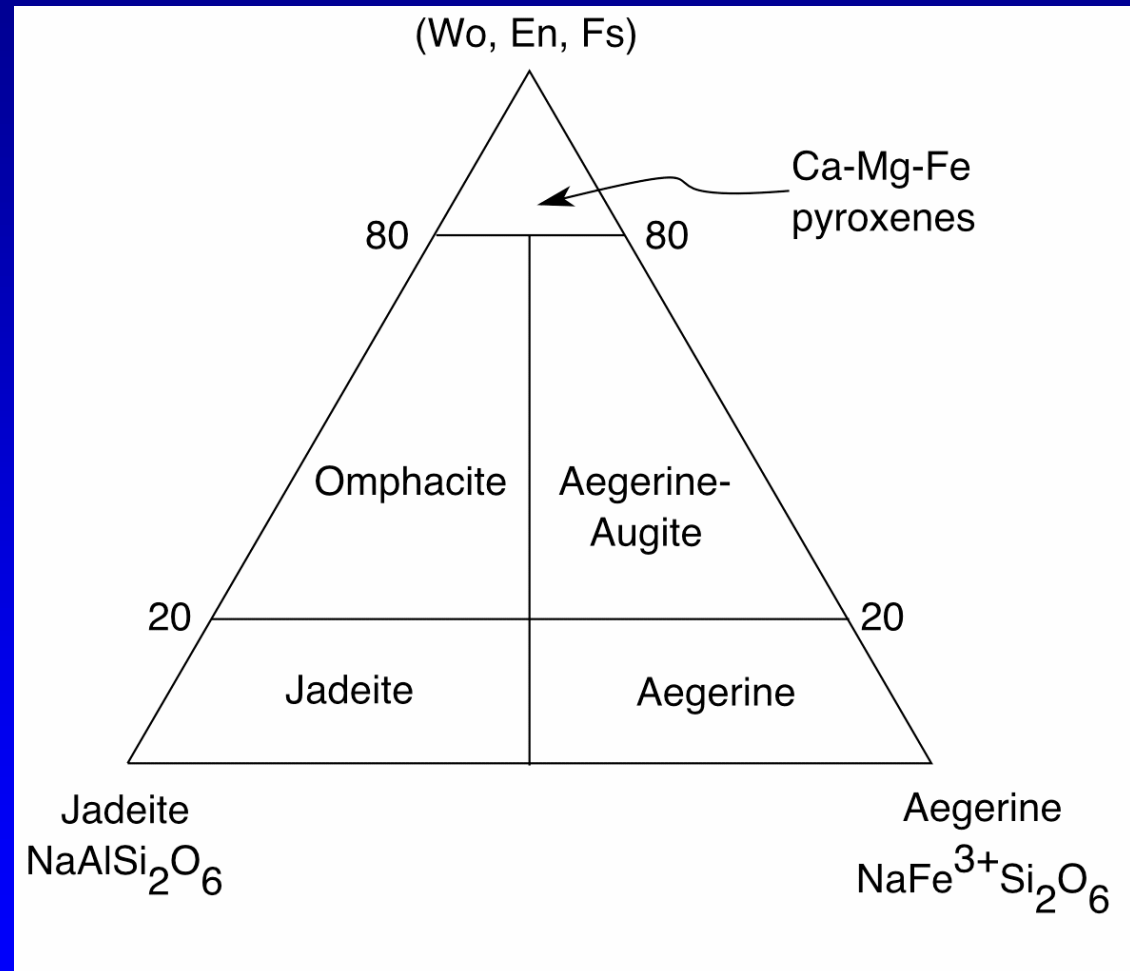
1. Formation of a twinned crystal of clinopyroxene (pigeonite)
2. Exsolution of augite from pigeonite
3. Transformation of pigeonite to orthopyroxene
4. Exsolution of augite from orthopyroxene



Na-bearing pyroxenes

Jadeite : $\text{NaAlSi}_2\text{O}_6$

Aegerine : $\text{NaFe}^{3+}\text{Si}_2\text{O}_6$



The solid solution : Jadeite - Diopside

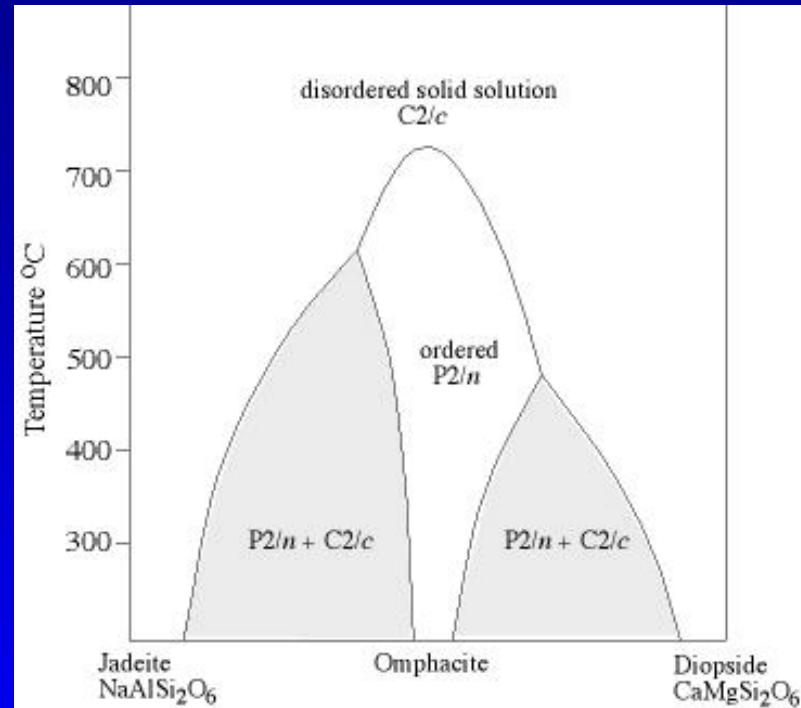
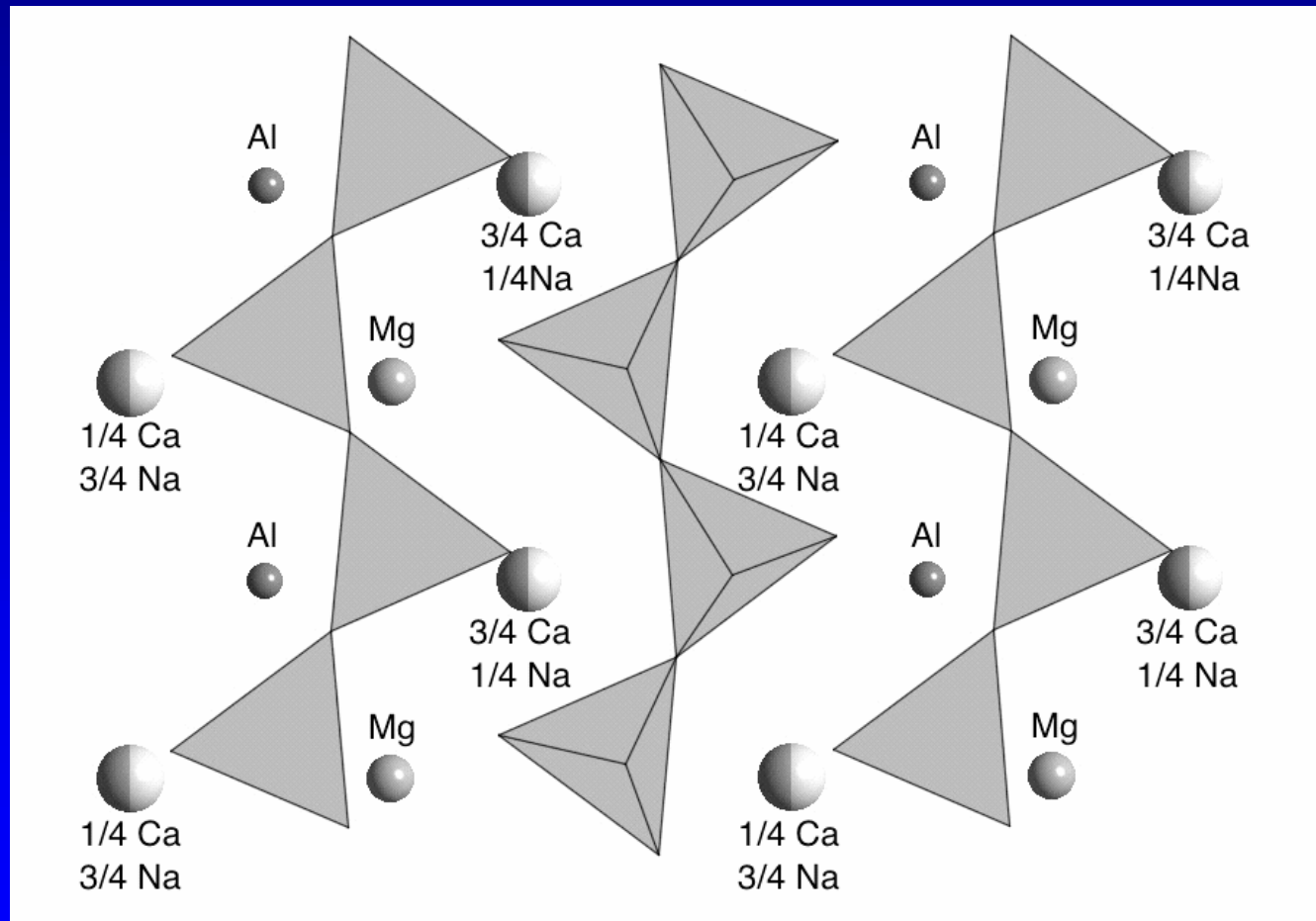
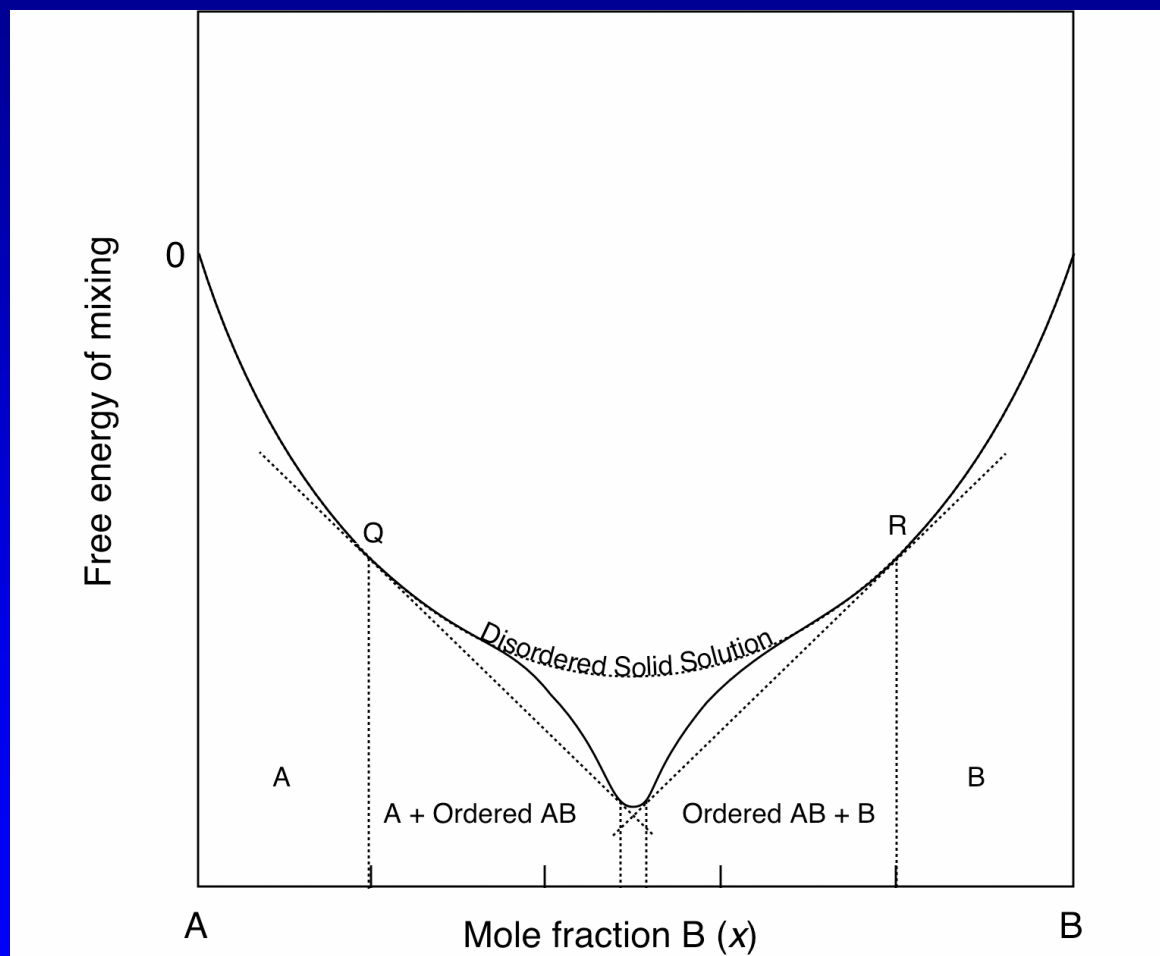


Figure 9.23

Cation ordering in omphacite



Cation ordering in omphacite



Phase transitions and exsolution in the alkali feldspars

Phase transitions in the feldspars

There are three types of behaviour which take place in the feldspar structure on cooling:

At high temperatures:

(i) at high temperatures the feldspar structure is expanded and can contain Na, K and Ca in the large M-sites.

(ii) at high temperatures the Al and Si are randomly distributed in the T-sites

(iii) at high temperatures there are extensive solid solutions in the alkali feldspars and in the plagioclase feldspars.

In this ideal high-T state, feldspars are monoclinic.

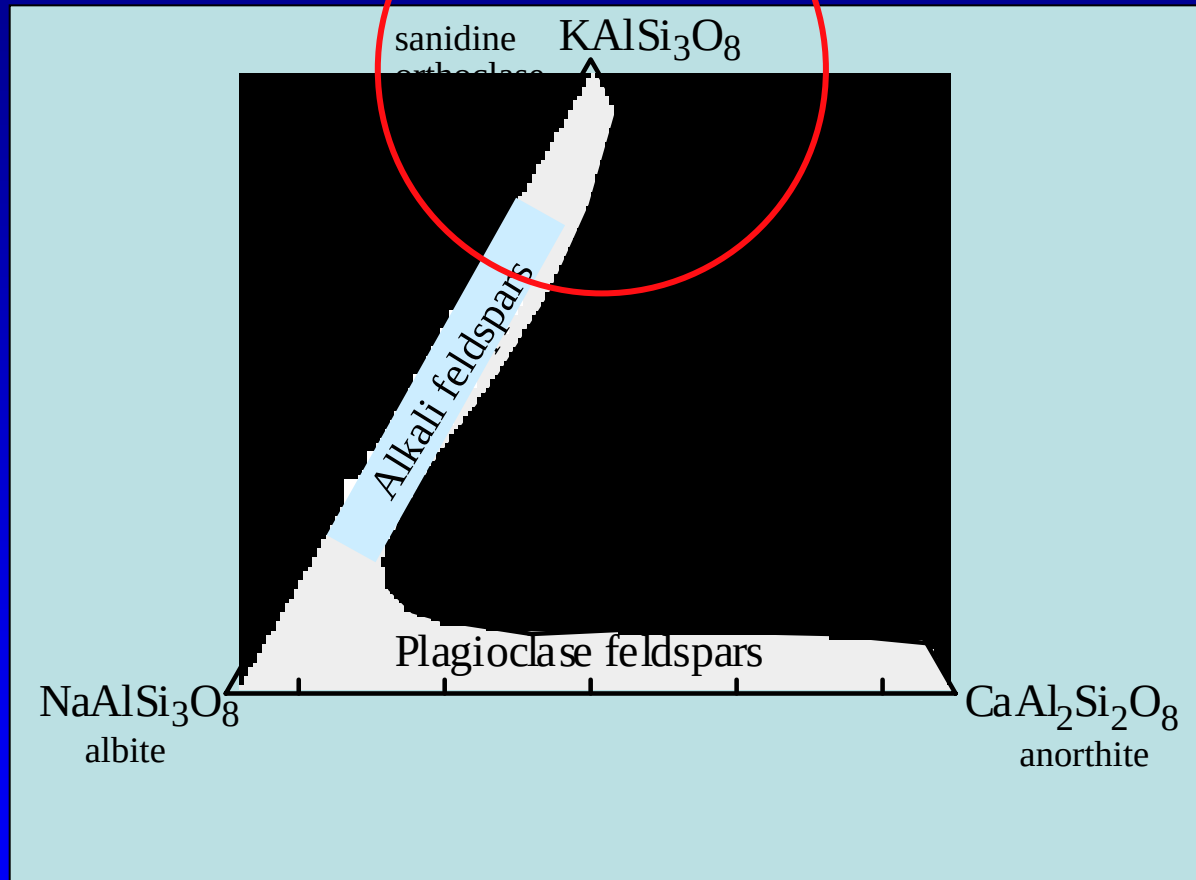
Phase transitions in the feldspars

(iv) at **lower temperatures** there is a tendency for the structure to distort by a displacive transition. This tendency depends on the size of the cation in the M-site. K is large and prevents the distortion, Na and Ca are smaller and so the structure distorts to triclinic.

(v) there is also a strong tendency for Al and Si to become *ordered* as the temperature is reduced. This is to avoid Al in adjacent tetrahedra (*the aluminium avoidance rule* or *Loewenstein's Rule*).

(vi) at lower temperatures the extent of solid solution decreases i.e. exsolution processes

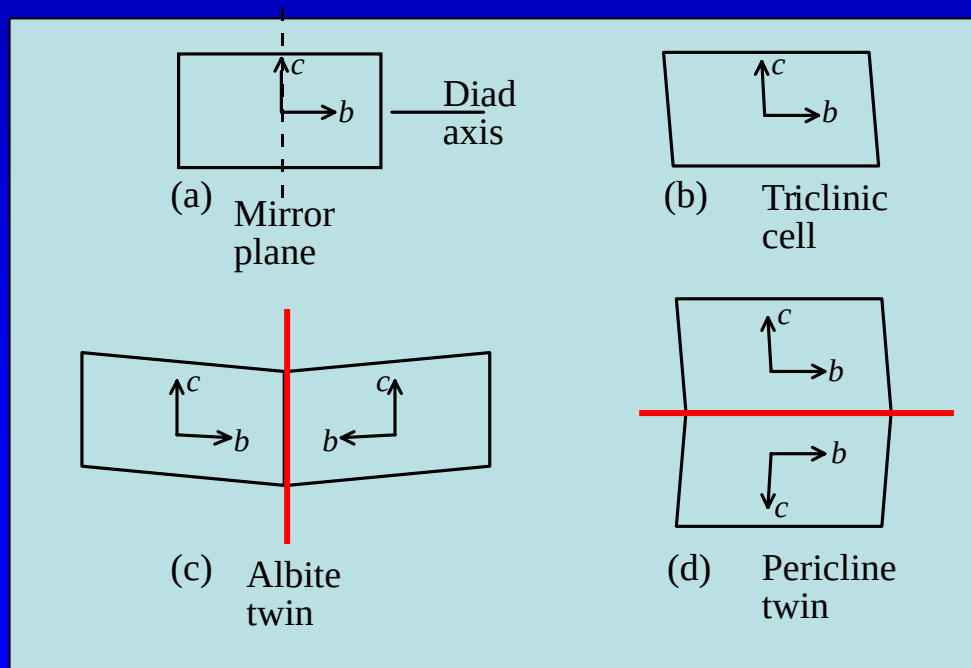
K - Feldspars



Phase transitions in K-feldspar, KAlSi_3O_8

1. At high temperature the structure is monoclinic with Al,Si *disordered*. This is called **sanidine**.
2. As the temperature decreases Al tends to go into one of the T_1 sites. This reduces the symmetry to triclinic.

This has an important consequence :



Transformation twinning

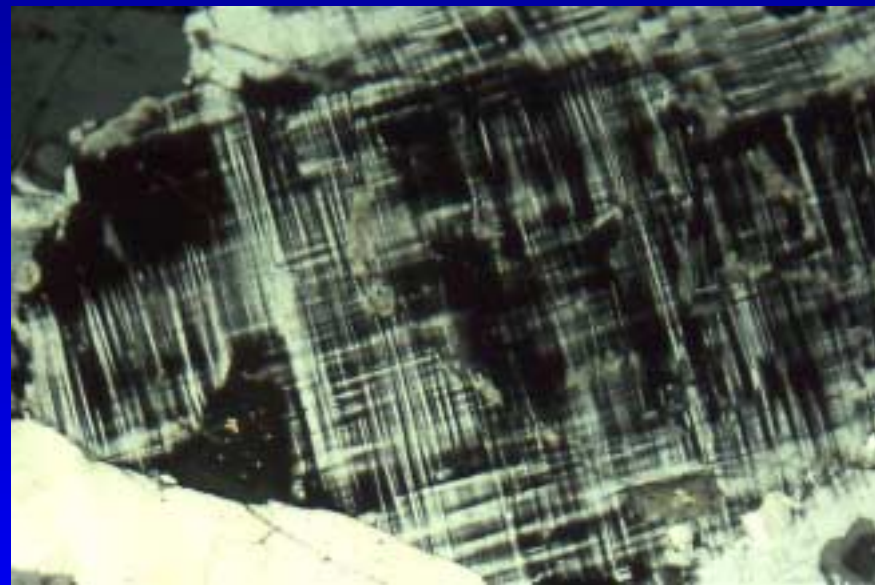
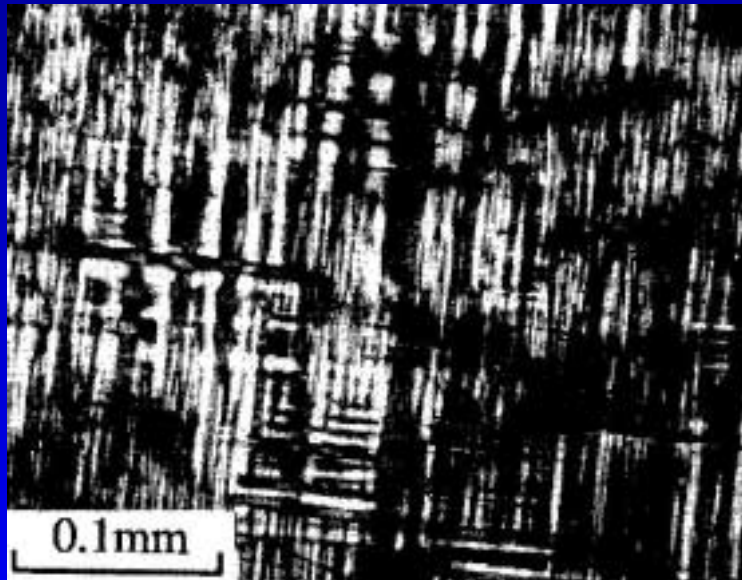
The 2 equivalent orientations of the triclinic unit cell can form twin domains, either related by a mirror plane (albite twin) or by a diad axis (pericline twin).

When both possibilities exist in a single crystal then there are two twin planes at right angles

Phase transitions in K-feldspar, KAlSi_3O_8

Fully Al,Si ordered K-feldspar is called *microcline*.

Microcline has characteristic cross-hatched twinning, seen in a polarizing microscope :



This characteristic microstructure is due to the existence of both albite and pericline twinning in the crystal which has transformed from the high temperature disordered monoclinic structure.



Sanidine

Monoclinic

Al,Si disordered

Found in volcanic
(fast cooled)
rocks

Orthoclase : an intermediate stage between sanidine and microcline. It is monoclinic on average, but in an electron microscope it looks like microcline i.e. very fine twins

Found in rocks with intermediate cooling rate

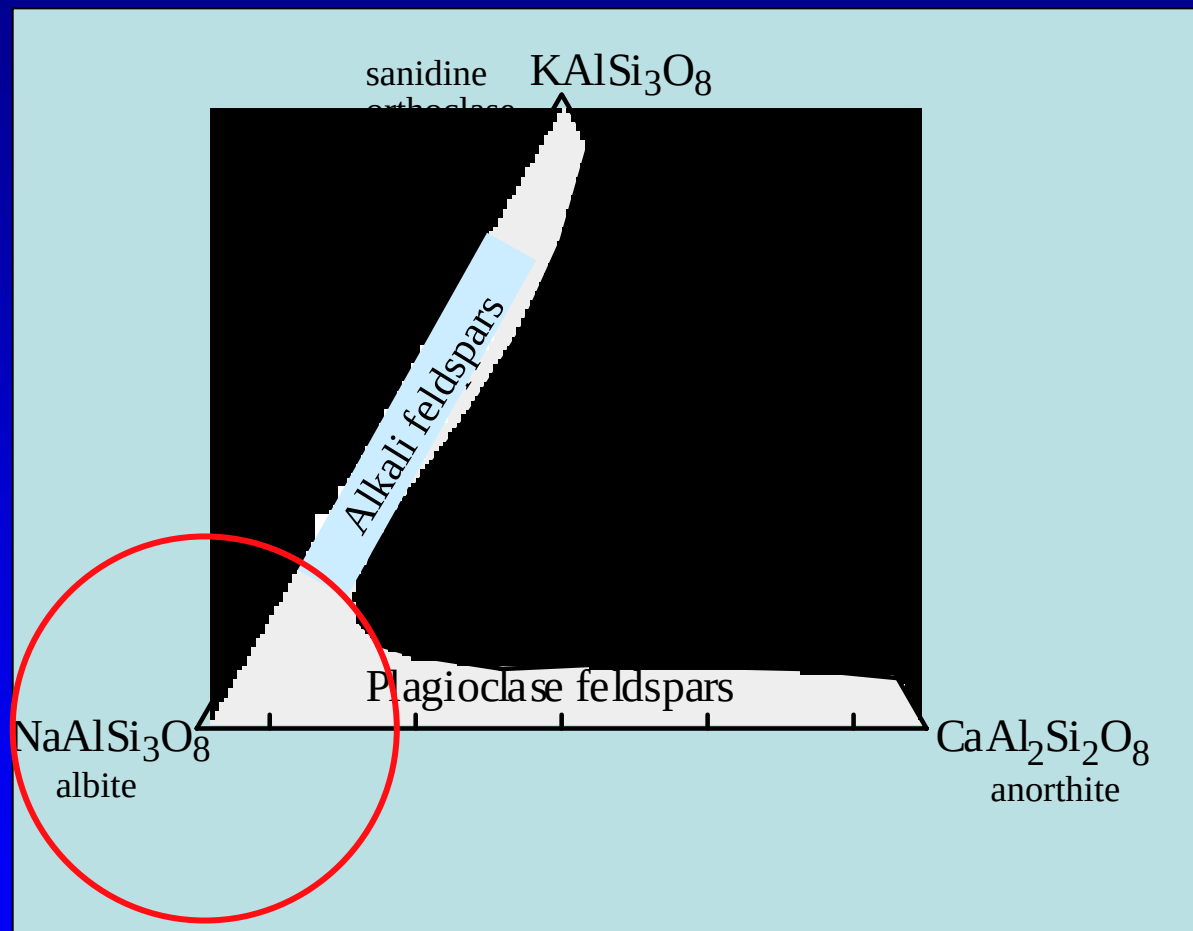
Microcline

Triclinic

Al,Si ordered

Found in plutonic
(slowly cooled)
rocks

Na - Feldspars



Phase transitions in Na-feldspar, $\text{NaAlSi}_3\text{O}_8$

1. At very high temperature the structure is monoclinic with Al,Si disordered. This is called **monalbite**.

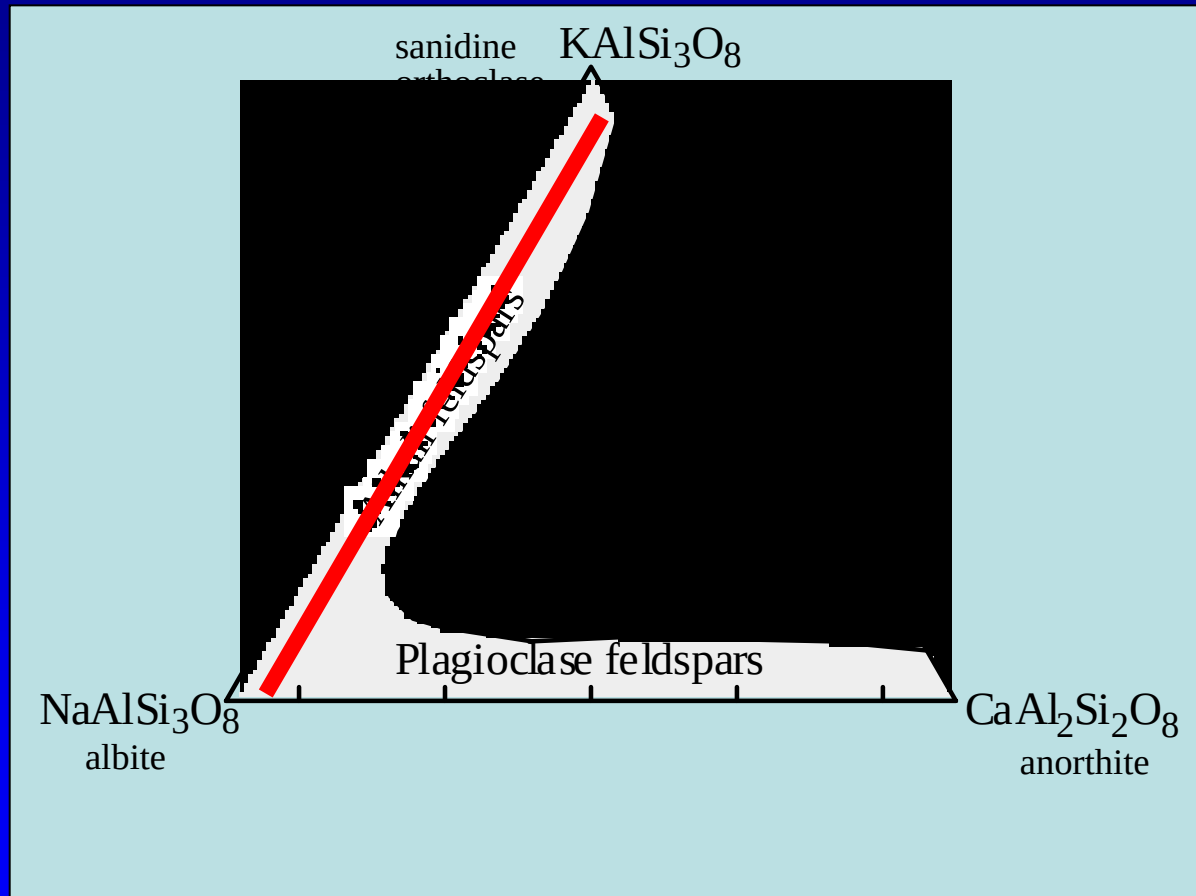
But on cooling below about 1000°C monalbite undergoes a displacive transition to triclinic symmetry because the Na is too small to stop the structure from distorting. This triclinic albite is called **high albite**.

In most rocks albite grows as high albite because the temperature is below that where albite is monoclinic.

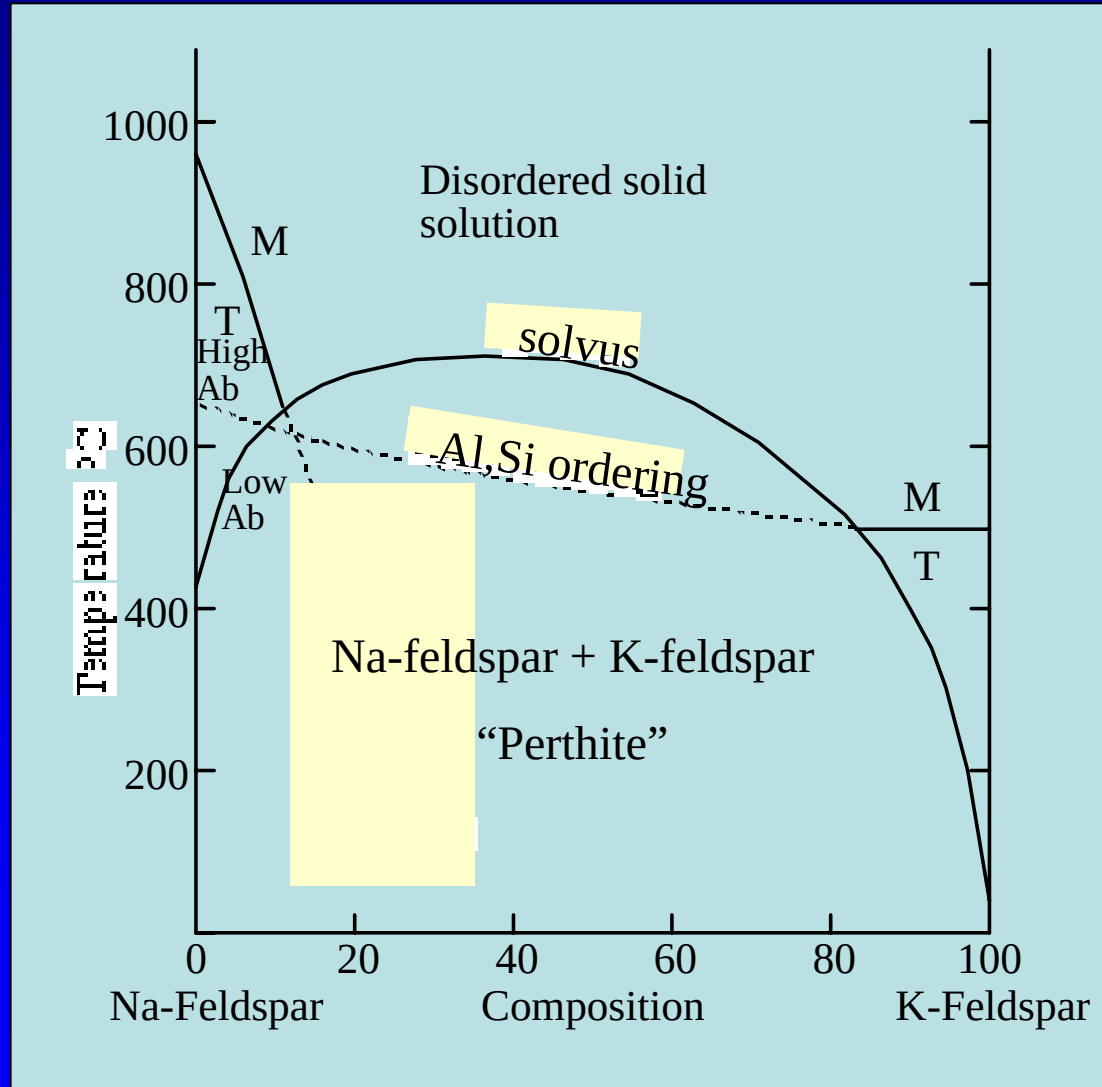
2. As the temperature decreases Al, Si begin to order. There is no twinning associated with this because high albite is already triclinic and cannot reduce its symmetry further.

Albite with ordered Al,Si is called **low albite**. It has no transformation twinning.

Alkali - Feldspars



The alkali feldspar phase diagram

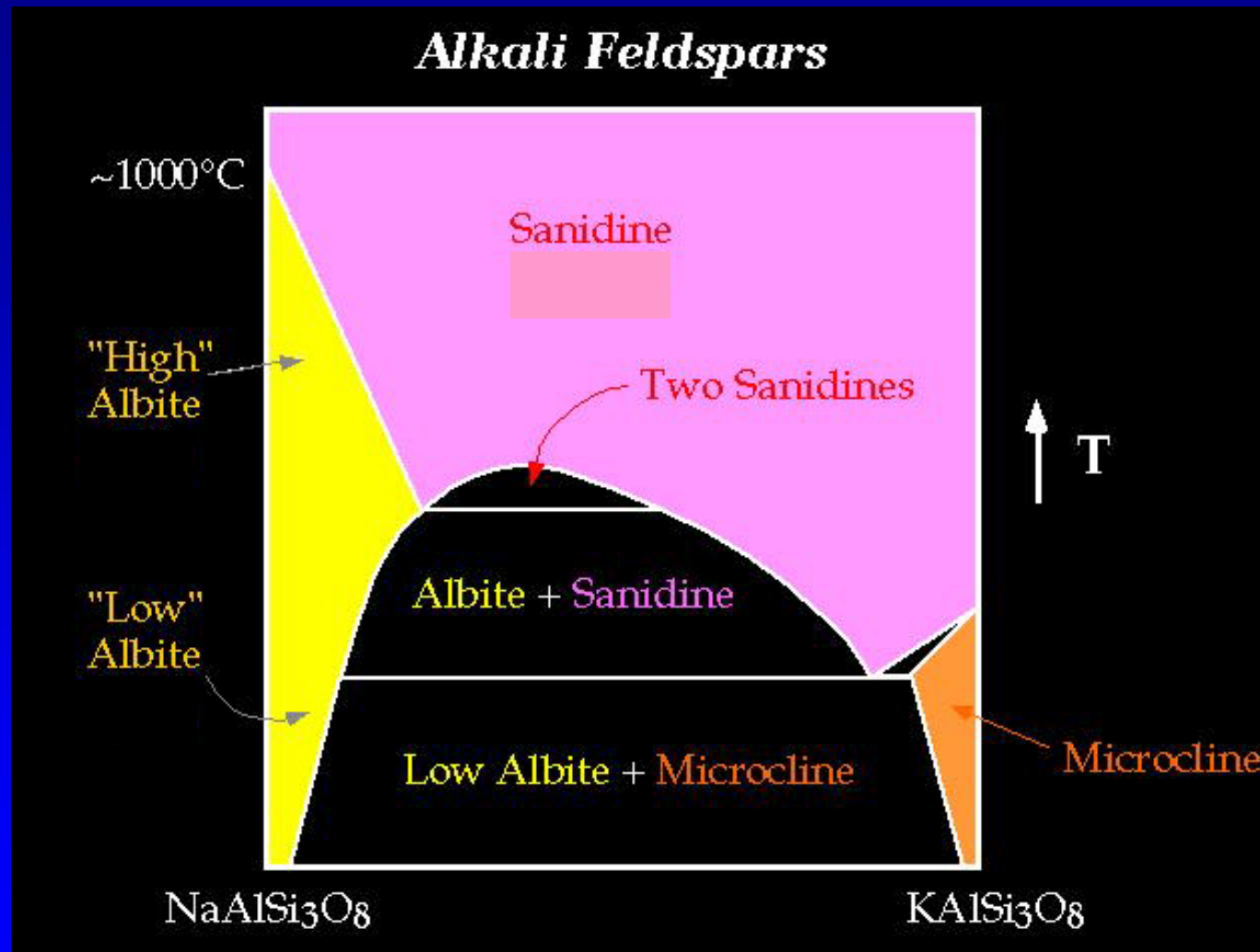


The disordered solid solution can only exist at high temperatures.

Below the solvus the solid solution breaks down to 2 phases - one Na-rich, the other K-rich.

This *exsolution* process results in a 2-phase intergrowth, called *perthite*

The alkali feldspar phase diagram



Perthite microstructure - an intergrowth of Na-feldspar and K-feldspar

Na-feldspar

white

