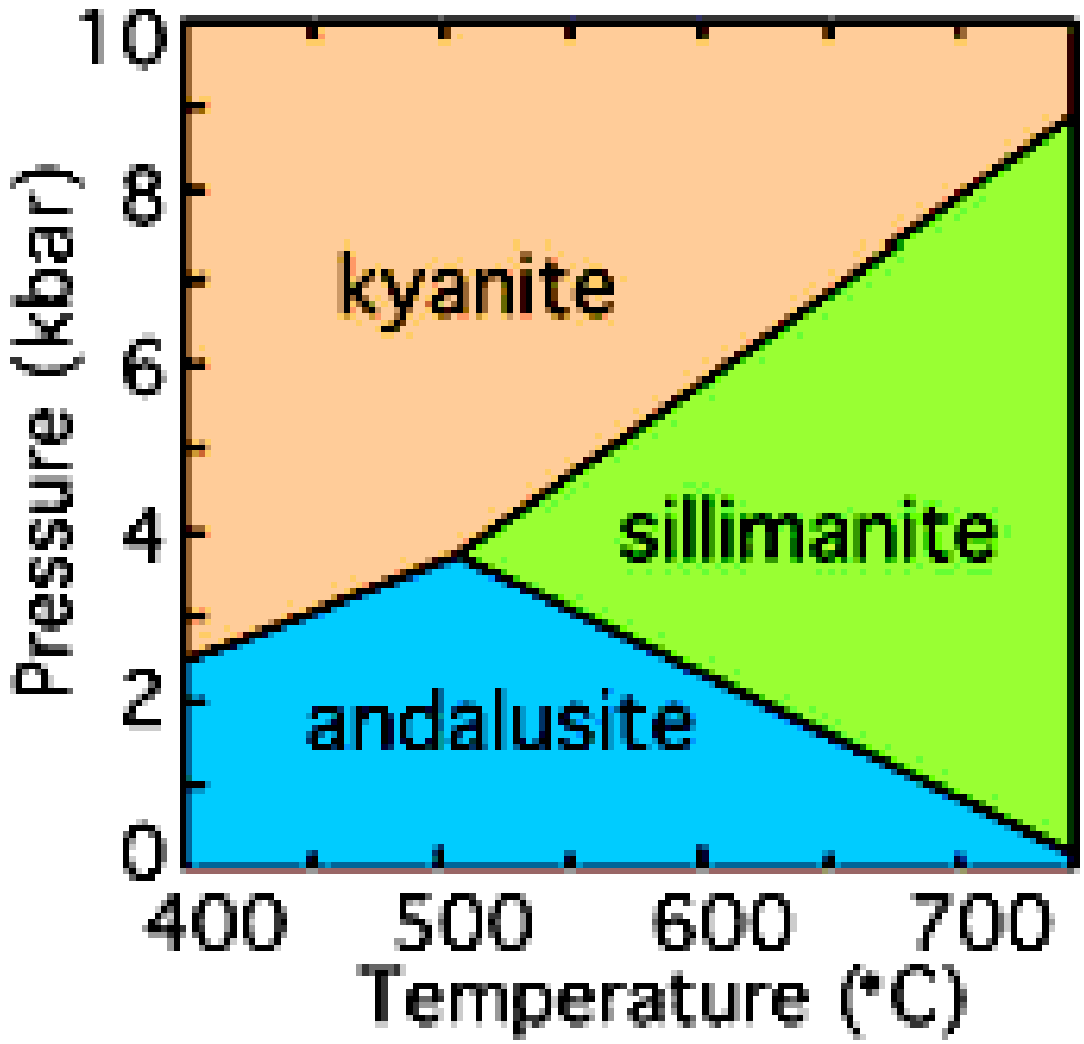
Environments of Mineral Formation

Unary, Binary, and Ternary Mineral Stability Diagrams

Minerals of differing composition (or polymorphs of the same mineral) that coexist at a set of pressure (P) temperature (T) or composition (X) can be represented by their equilibrium conditions

In any rock (igneous, metamorphic, or sedimentary) is composed of a series of minerals that can be represented in PT or X space as MINERAL STABILITY DIAGRAMS

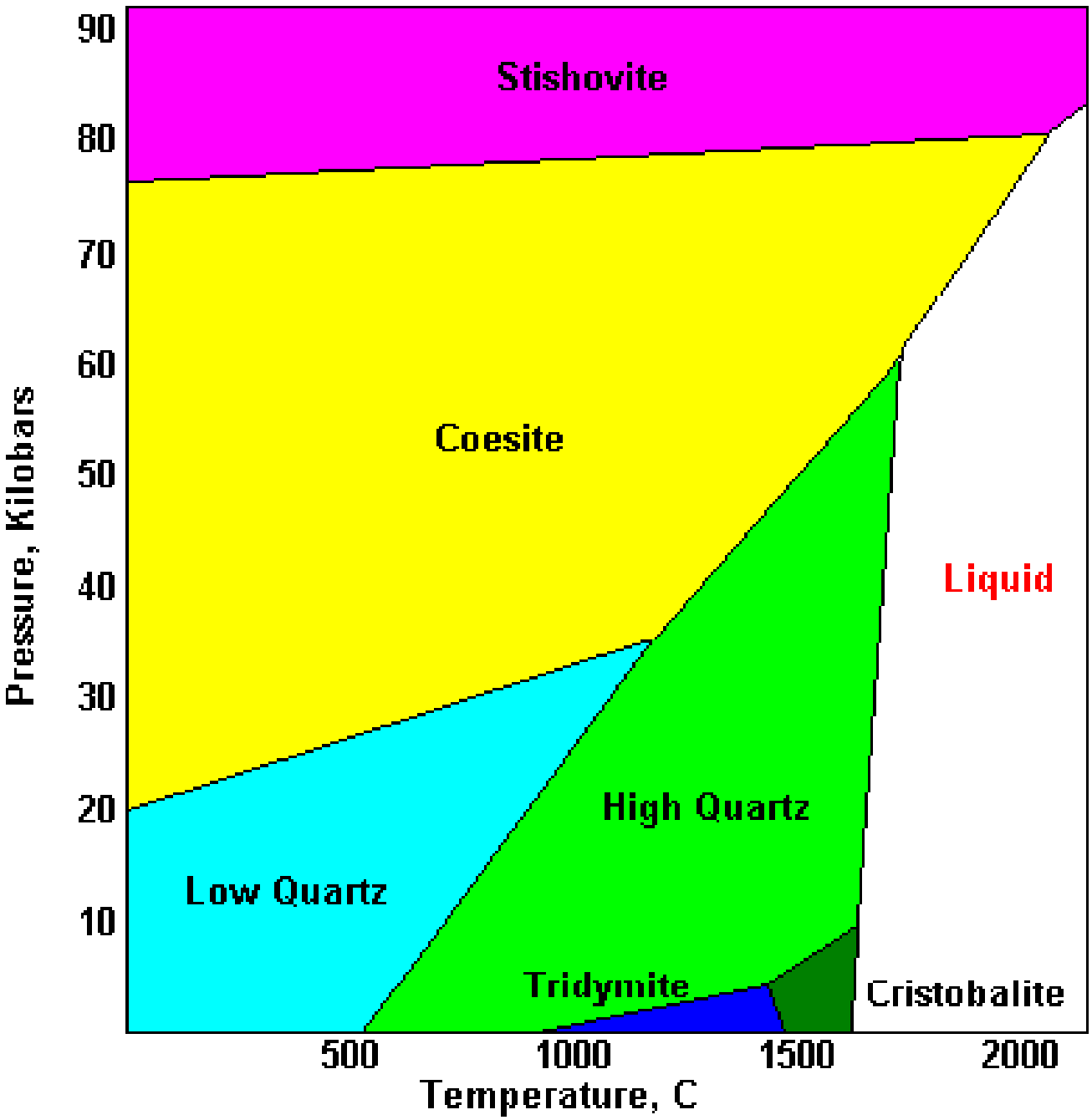
Diagrams can be set-up to represent different P, T, or X spaces where phases may or may not coexist to represent the conditions under which a set of minerals might form



In the Al_2SiO_5 phase diagram, lines represent **univariant curves** (divisions between PT stability field along which both minerals can coexist).

The three phases can all coexist where the univariant curves intersect, a fixed position called the **invariant point**.

The relationships of these phases in PT space can also be used to understand the **chemical equilibrium** for a system (the lowest possible energy configuration for any specific composition).



Likewise, the quartz polymorphs represent a set of equilibrium structural conditions for any given PT configuration.

Each polymorph is a unique phase that exists as the most stable form for a specific set of conditions.

The concept of the phase diagram is based on the **Phase Rule,** which must be defined in terms of a few concepts:

System: some arbitrary yet specific part of the universe we want to investigate

isolated: no mass or energy exchange between the system of interest and the environment that surrounds it

closed: no mass exchange between the system of interest and the environment, but energy transfer is permitted

open: free transfer of mass and energy between the system and the surrounding environment

Component (C): any chemical constituent that is part of the system

Phase (*P*): any mechanically separable part of the system with distinct chemical and physical properties

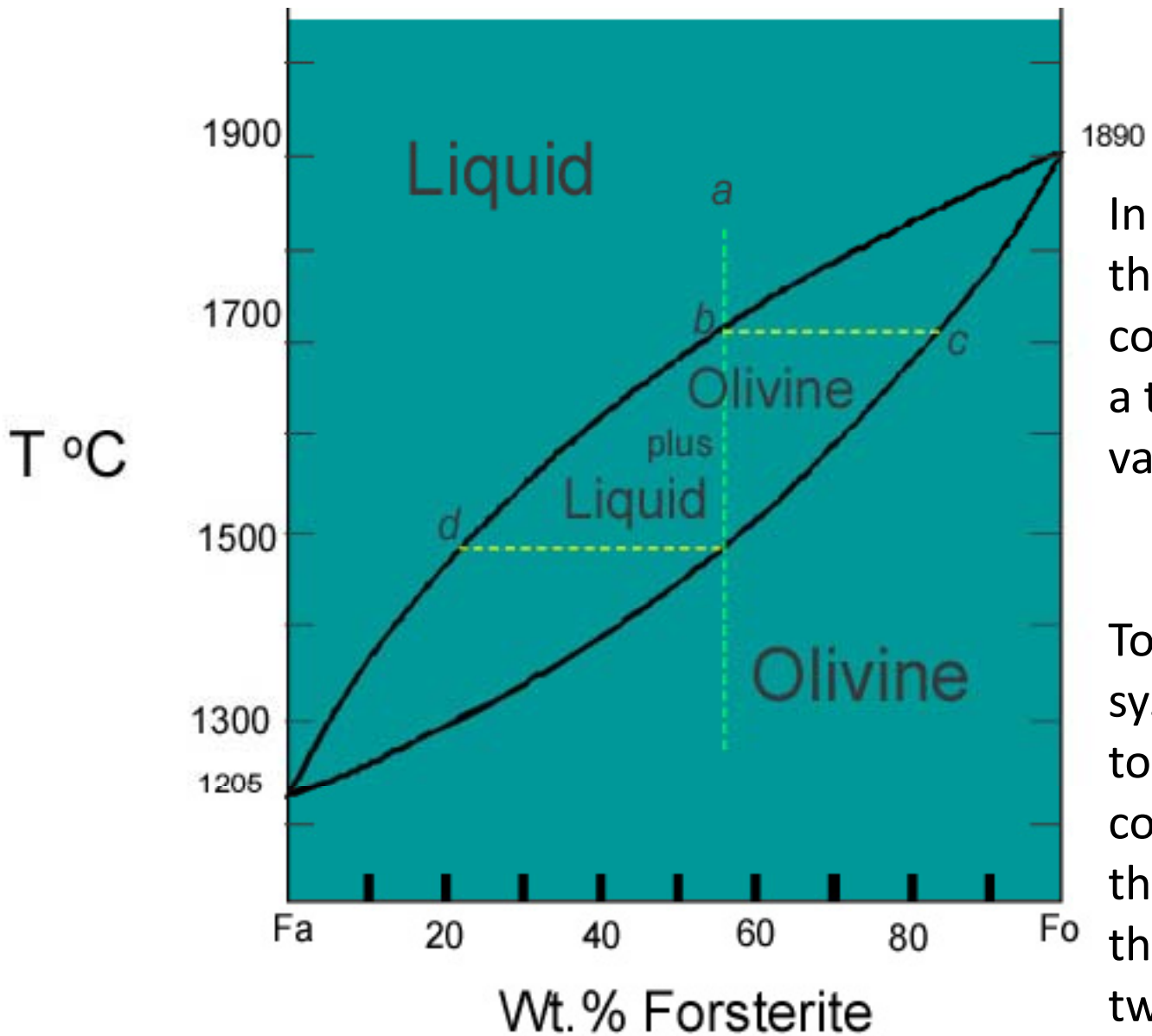
The **Phase Rule** (after Gibbs, 1876) is a way of describing any system in equilibrium in terms of quantified differences in the thermodynamic variables in a system (and the constraints on those variables)

For the most part (at least in geologic systems), the first order variables of greatest concern are P, T, and X.

These factors can be quantified as the **Degrees of Freedom**:

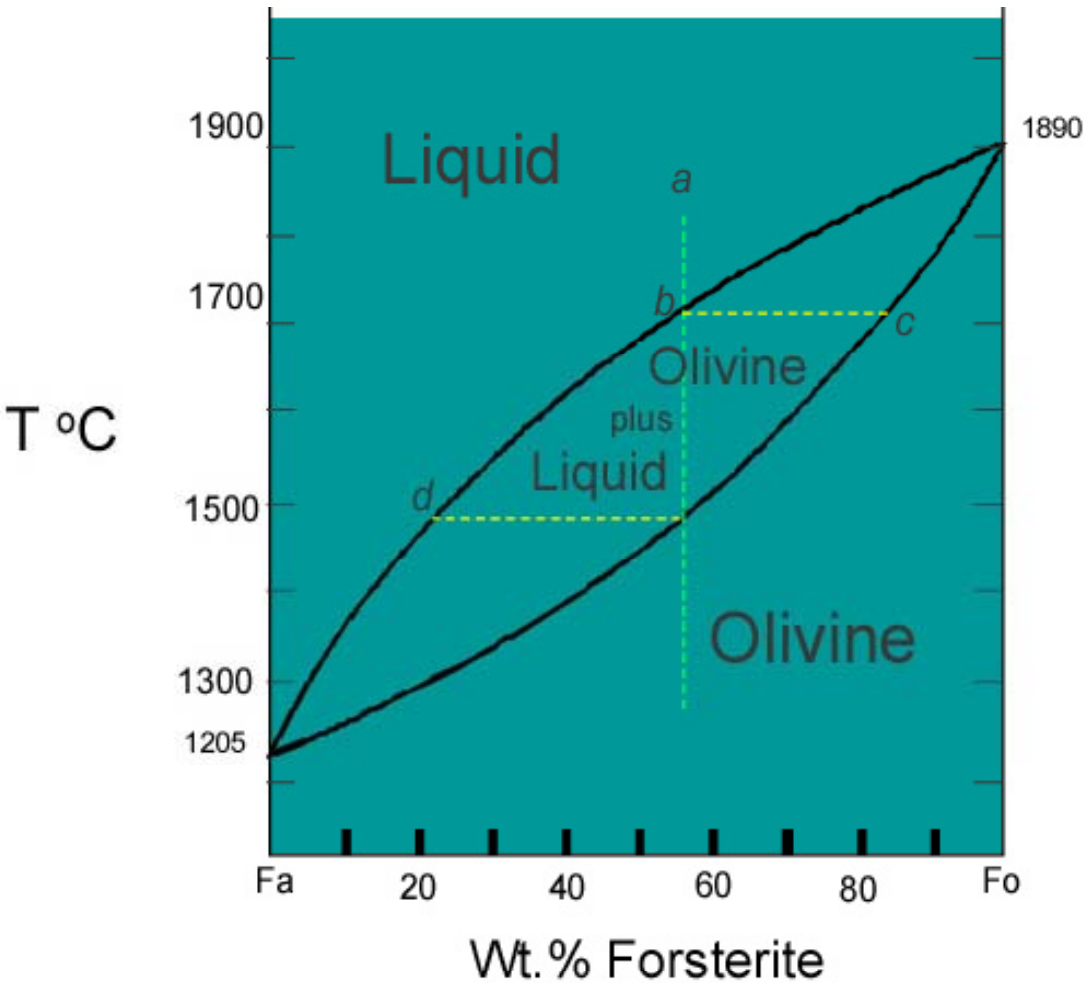
$$\mathbf{F = C - \mathit{P} + 2}$$

Phase diagrams are based on this principle as any point can be represented by a unique P, T, X condition that can be constrained based on our knowledge of other variables in the system



In a binary system, there are two components leading to a total of three variables.

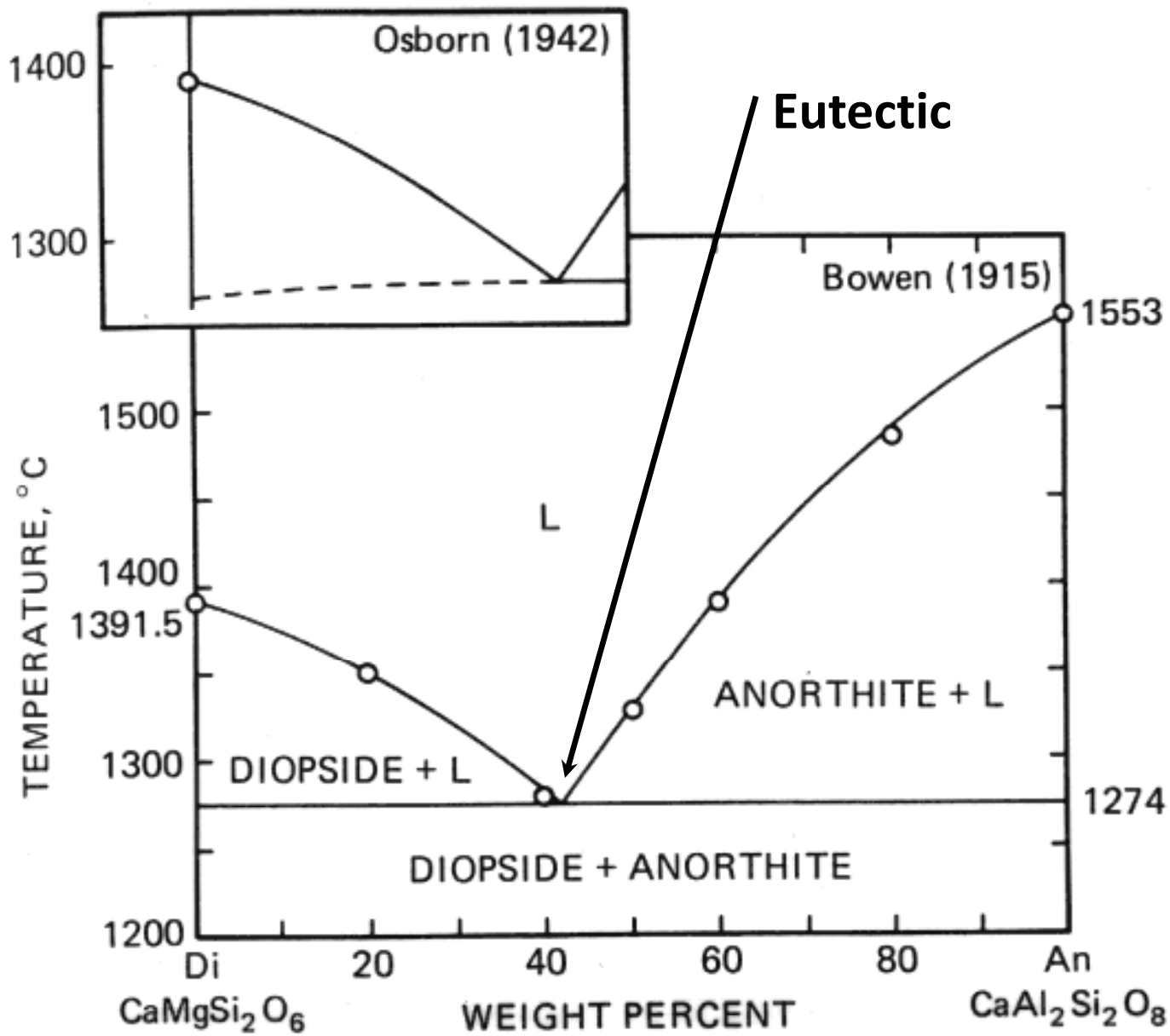
To study these systems, it is possible to hold on variable constant to simplify the system to study the interaction of only two variables.



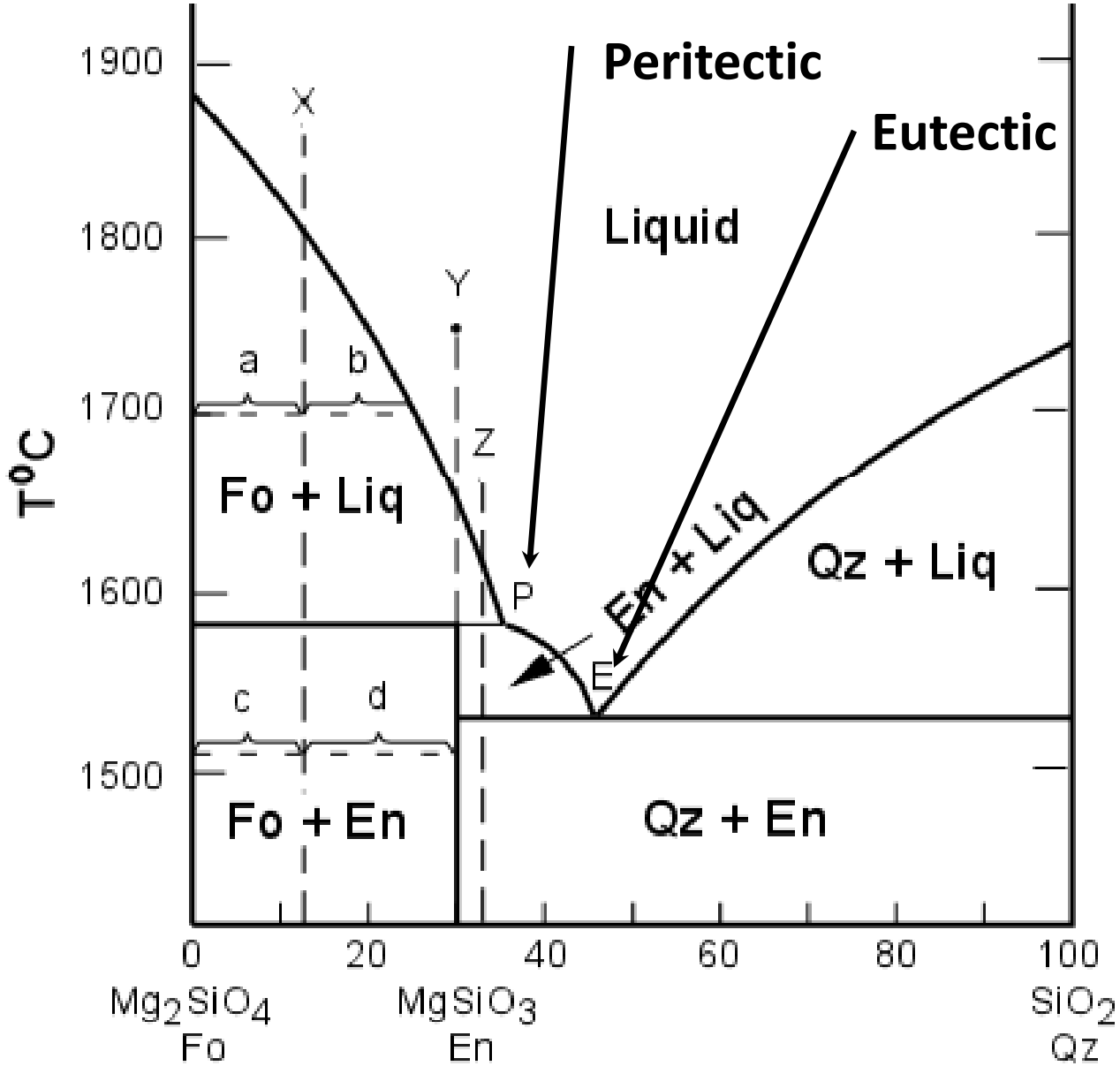
In the case of Olivine composition vs. temperature (relationship of T with the SSS between Fayalite (Fe_2SiO_4) and Forsterite (Mg_2SiO_4)) there are three fields: Liquid, Olivine, and Olivine+Liquid.

Liquidus: the line that divides the liquid *only* field from the liquid + crystals field (along this line crystal form as temperature drops)

Solidus: the line that divides the liquid + crystal field from the solid field

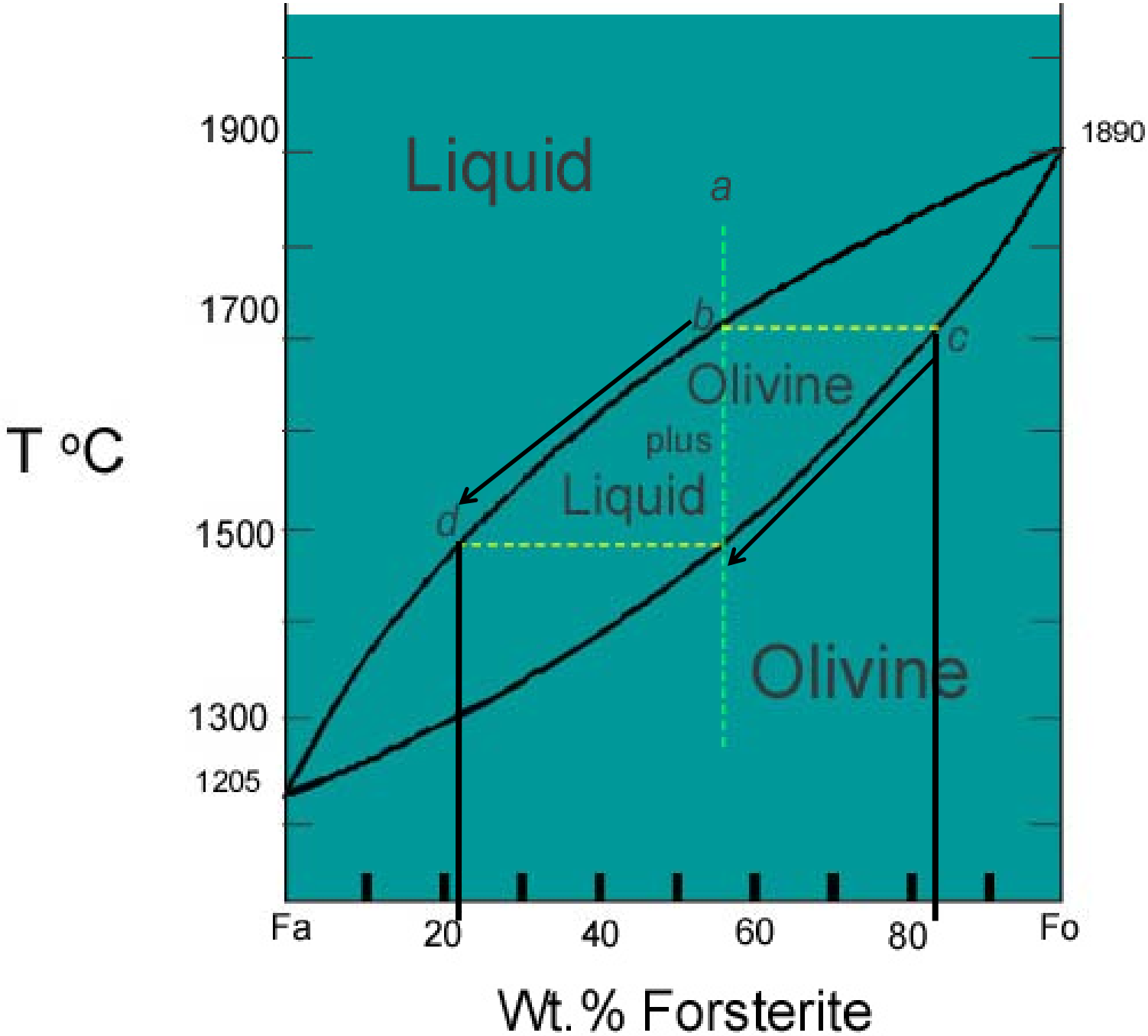


Eutectic point: intersection between the line representing the liquidus and the solidus. At this single unique location, the liquid is in equilibrium with all solid phases stable in the system



Peritectic point: reaction point between two previously precipitated phases (with liquid present) that results in the formation of a new solid phase.

As with a eutectic position, the temperature must remain stable until the reaction goes to completion and one of the reactants is exhausted in making the new phase.

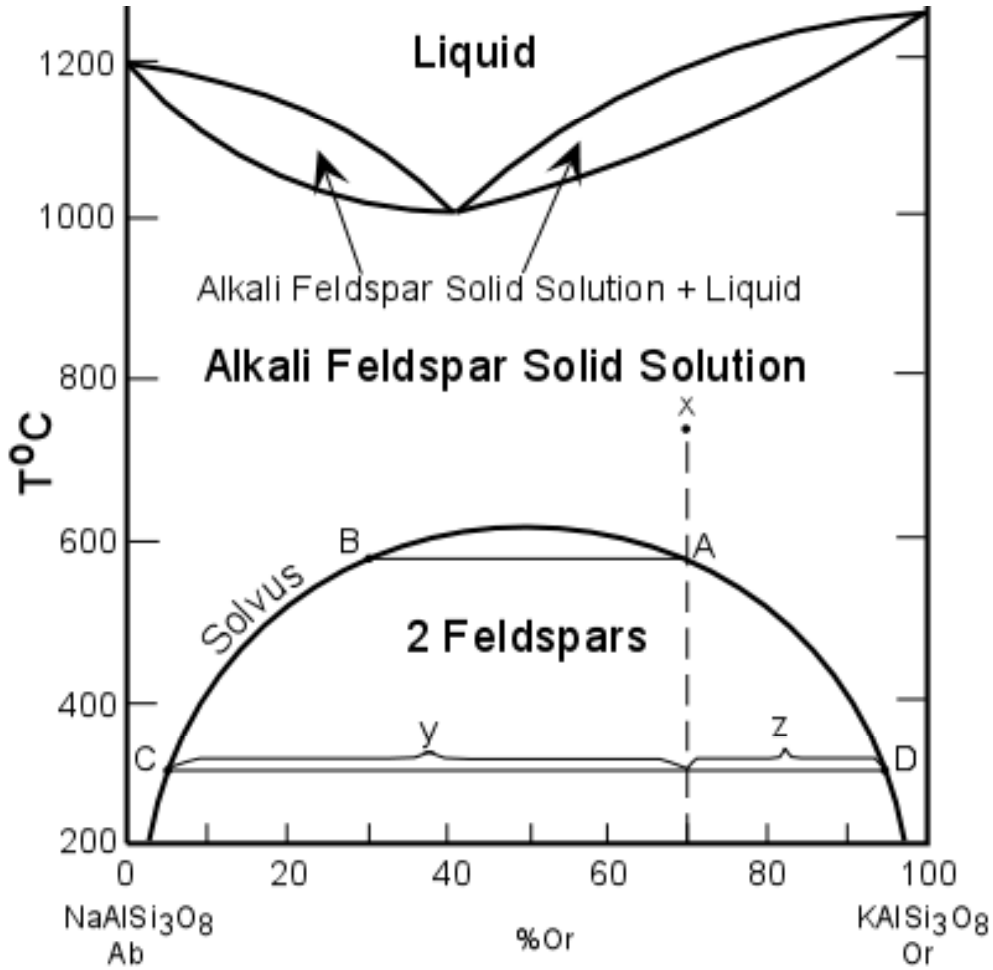

Liquid
a
b
c
d
Olivine
plus
Liquid
Olivine
1900
1700
1500
1300
1205
1890
T °C
Fa
20
40
60
80
Fo
Wt.% Forsterite

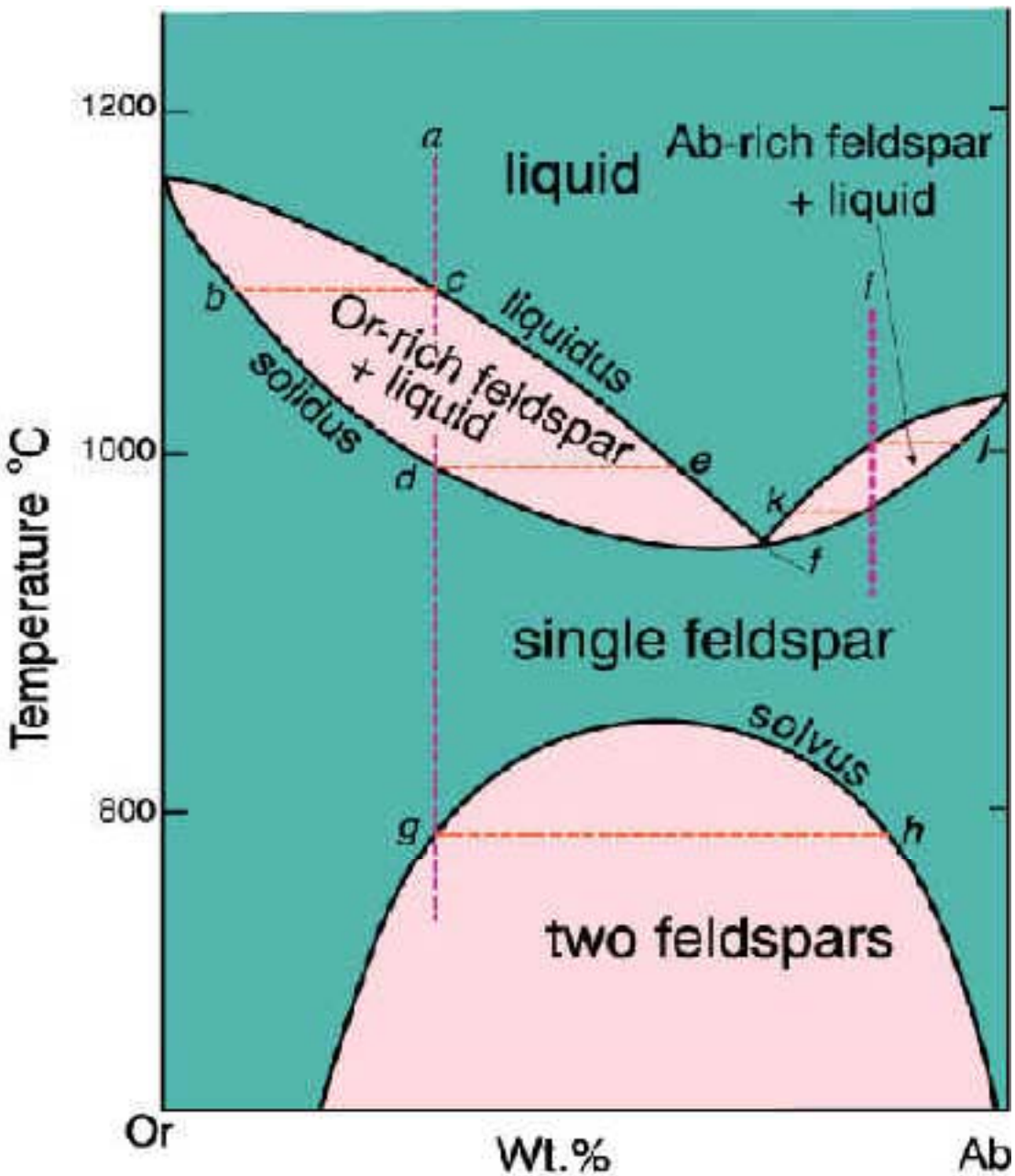
Composition of Alkali Feldspars

The alkali feldspars, consist of two end-members, $NaAlSi_3O_8$ – $KAlSi_3O_8$. However complete solid solution only occurs at high temperatures.

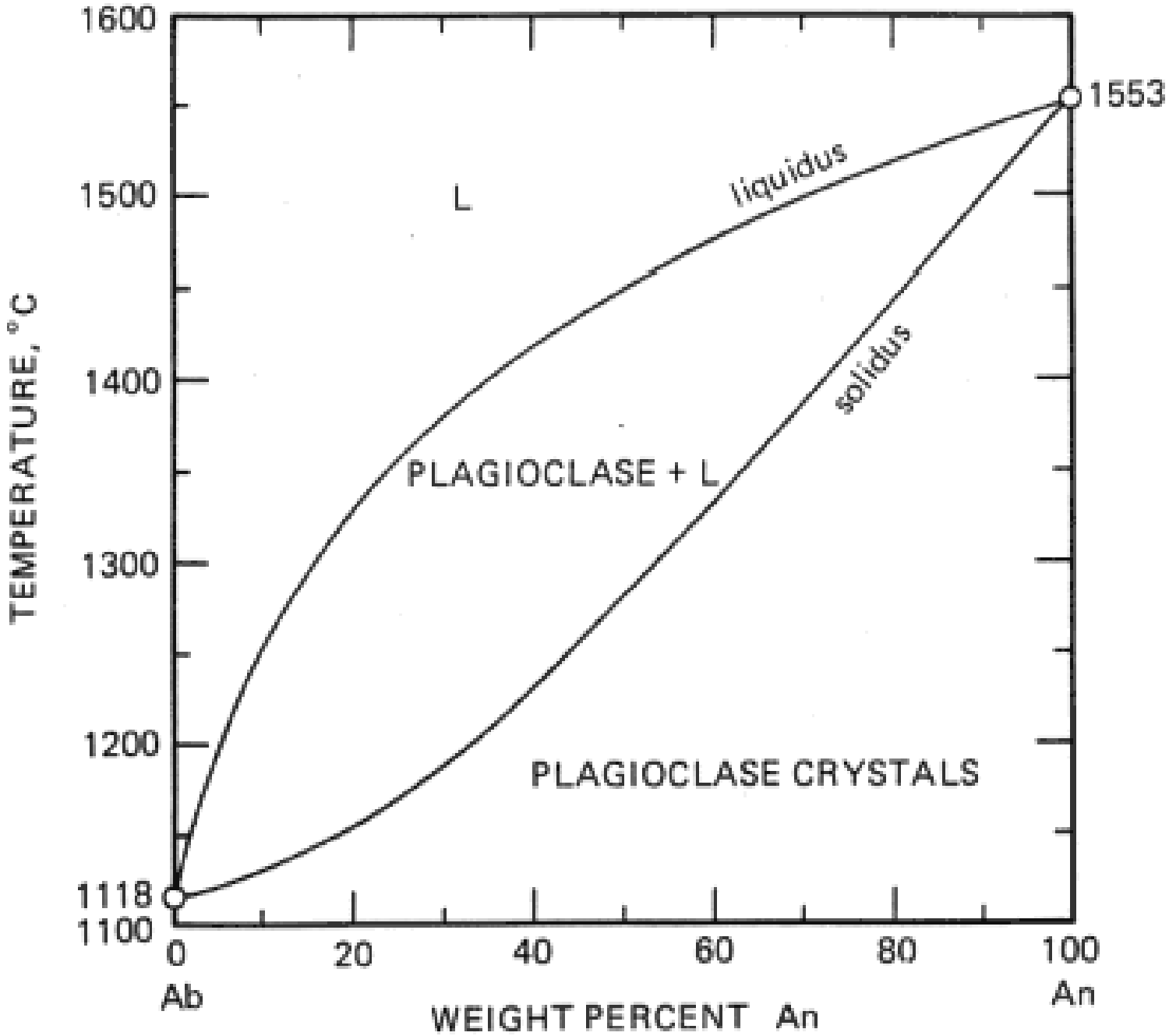
Areas of importance on this diagram include:

1)The Liquid Field
2)Liquid + Solid
3)Single Solid Phase
4)Miscibility Gap (immiscibility)
5)Unmixed Phases





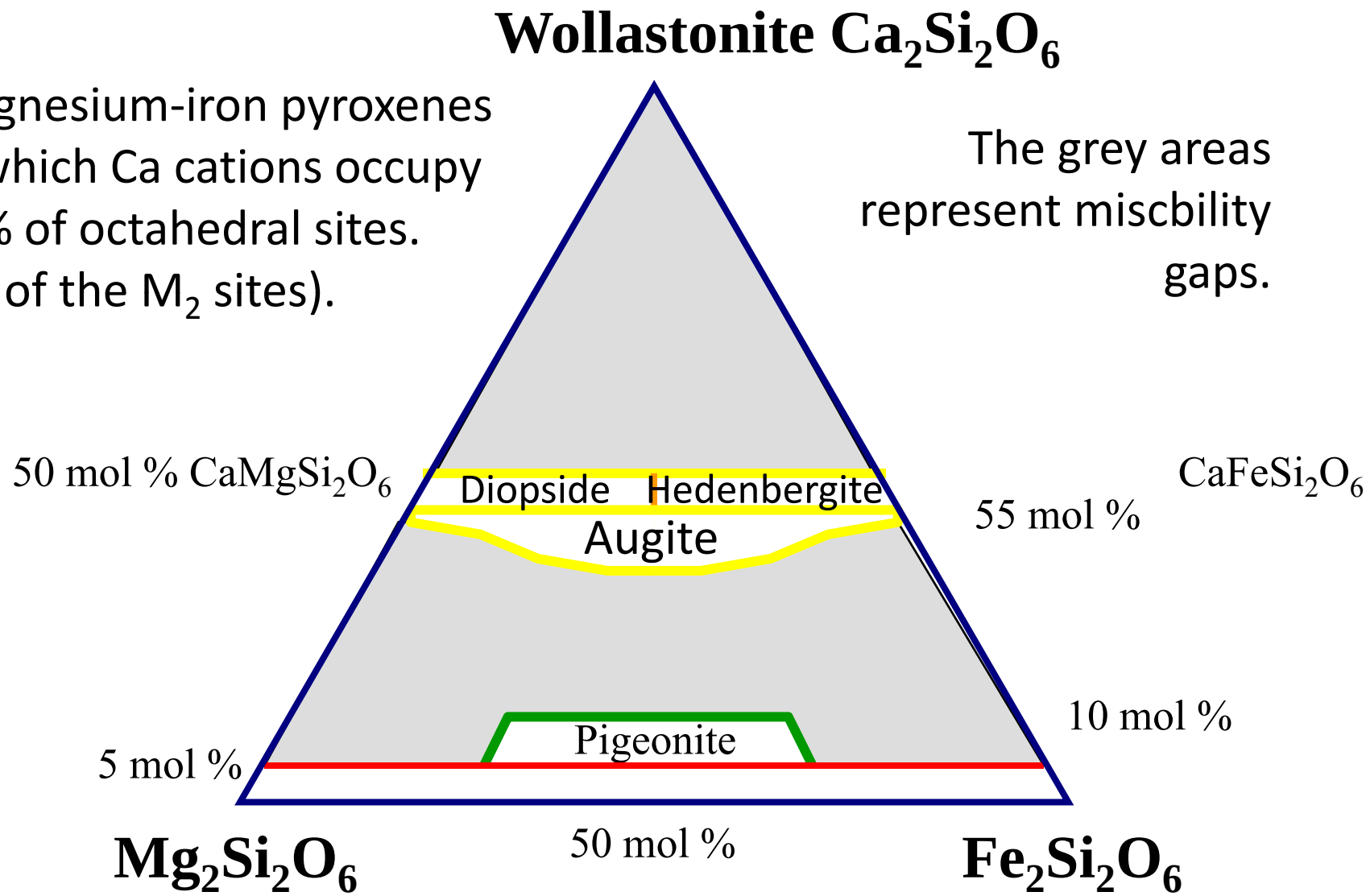
a: initial composition
b: composition of first crystals to form
c: equivalent thermal position on the liquidus
d: composition of last crystals from initial composition **a**
e: equivalent liquid composition for last crystals to form
g: single crystal feldspar begins to exsolve into 2 feldspars of distinct compositions


1600
1500
1400
1300
1200
1118
1100
TEMPERATURE, °C
1553
L
liquidus
solidus
PLAGIOCLASE + L
PLAGIOCLASE CRYSTALS
0
20
40
60
80
100
Ab
An
WEIGHT PERCENT An

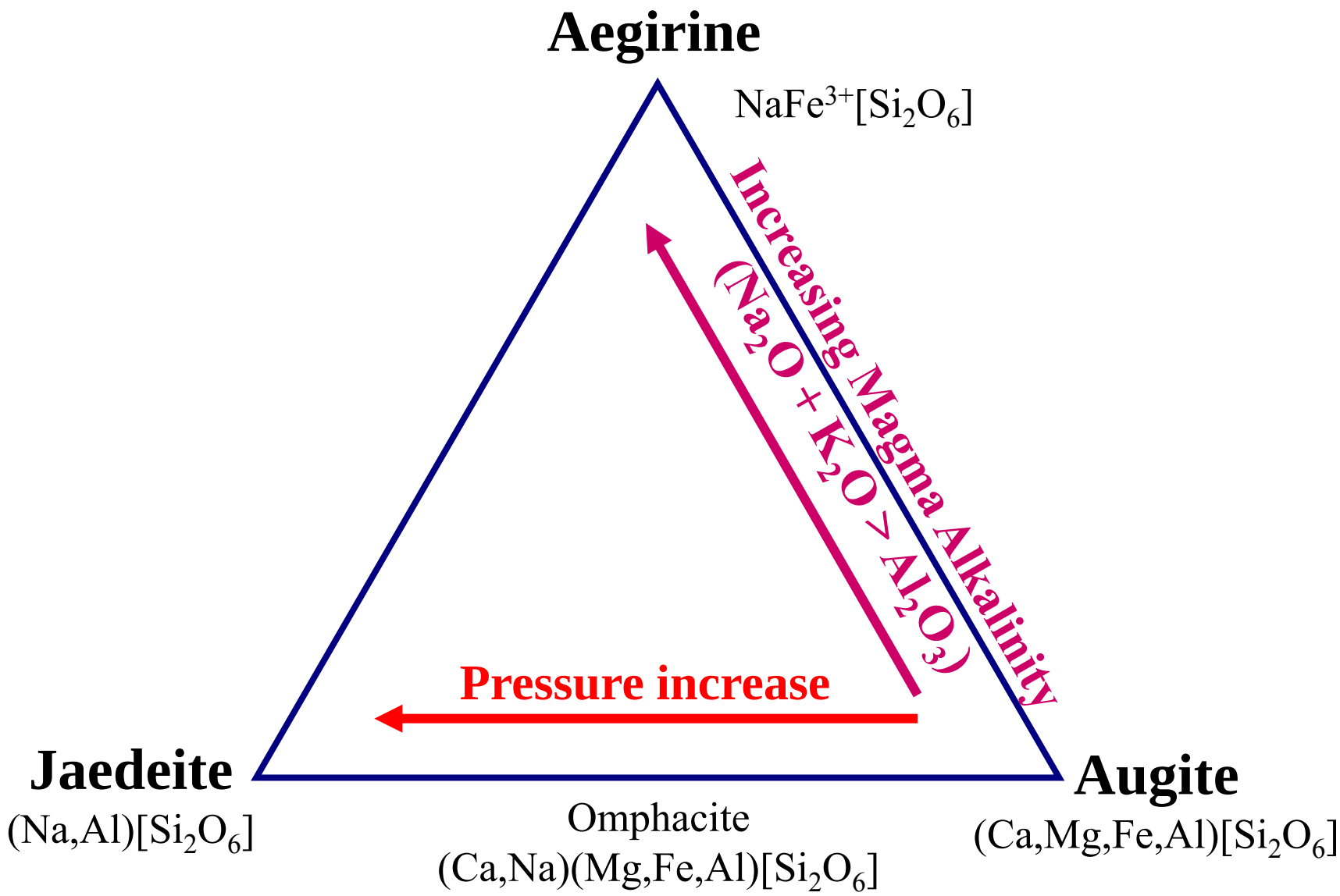
Clinopyroxenes

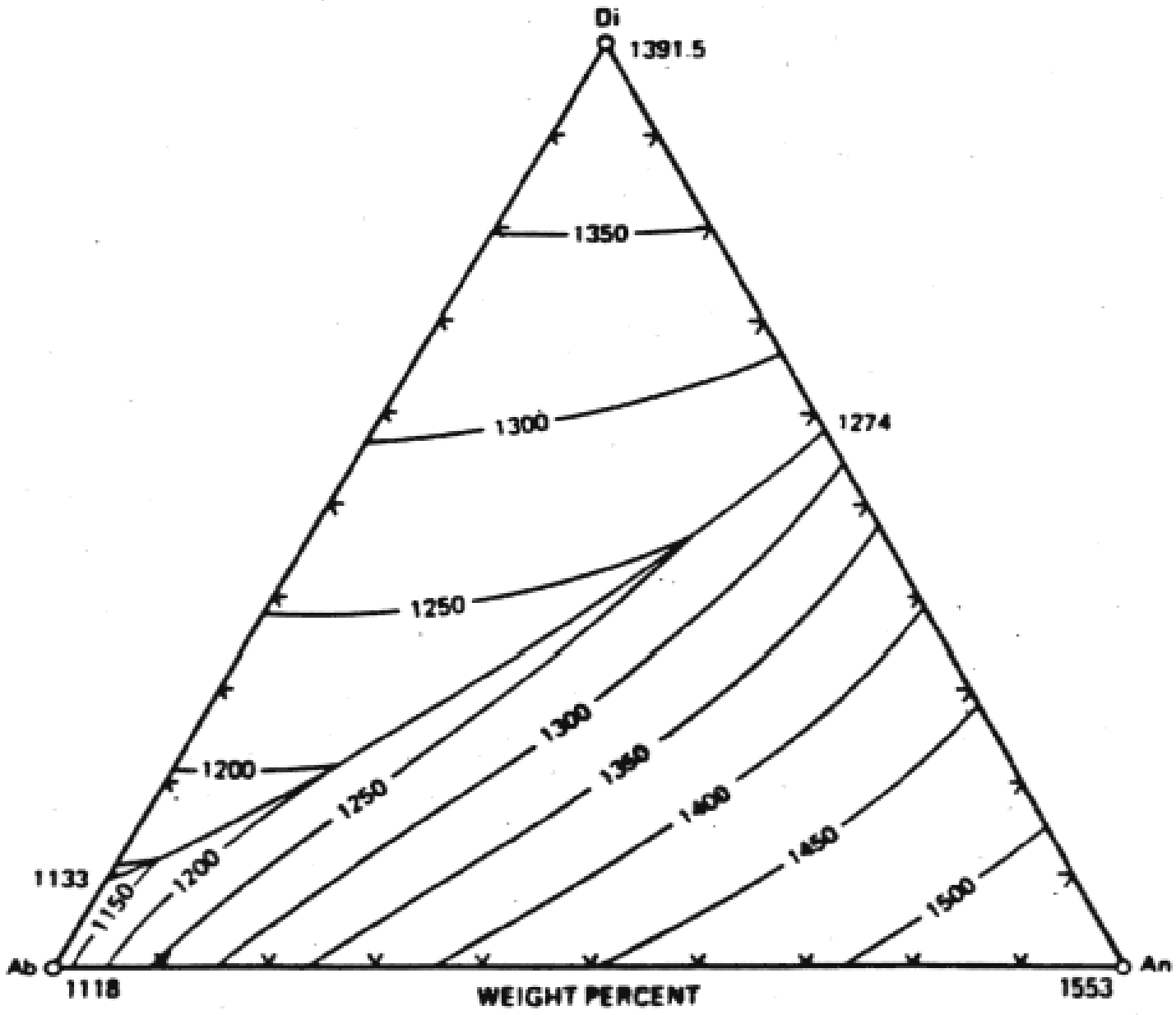
Magnesium-iron pyroxenes in which Ca cations occupy 50% of octahedral sites. (All of the M_2 sites).

The grey areas represent miscbility gaps.

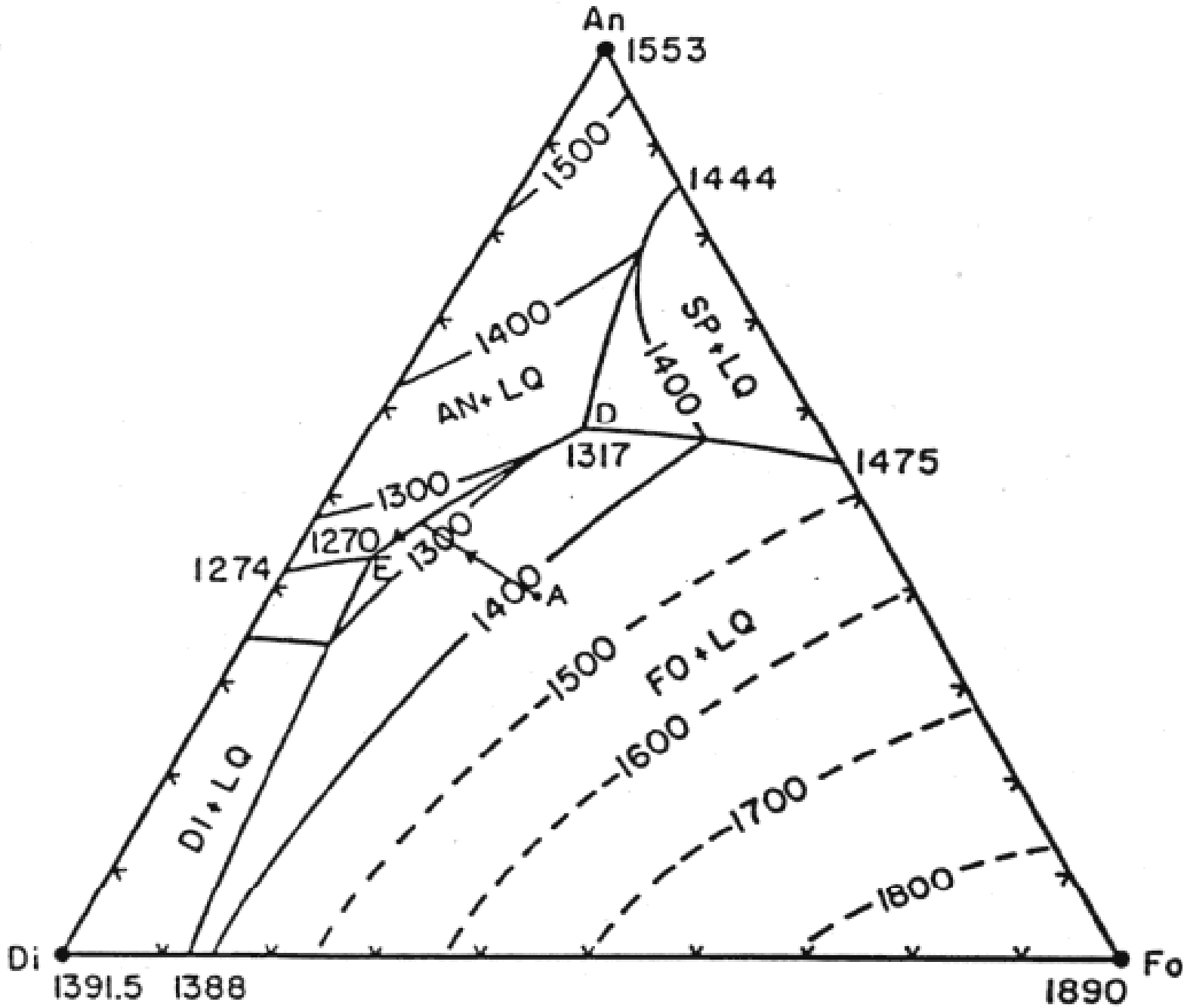


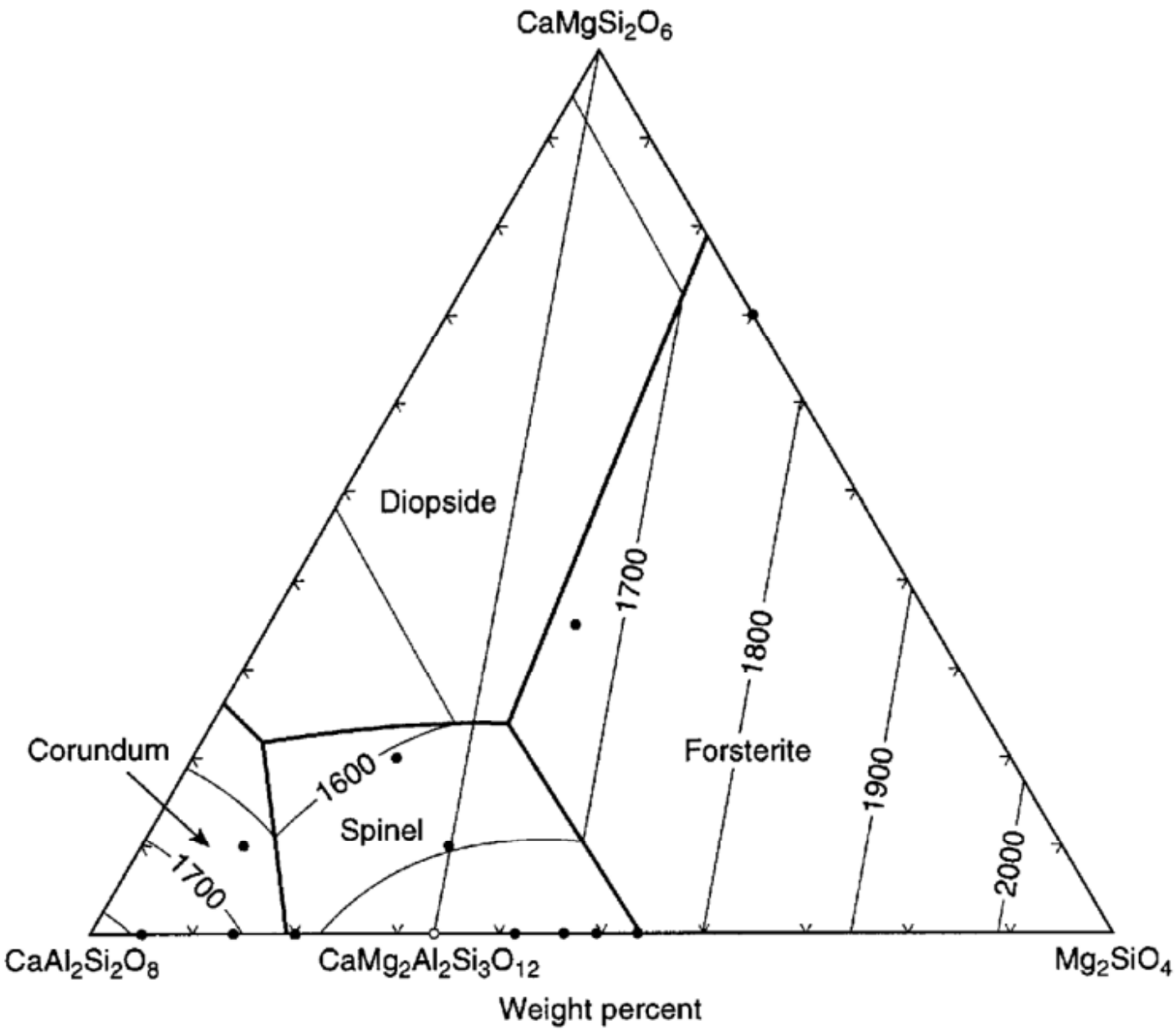
In special circumstances a complex coupled substitution involving both of the M-sites will occur.





Anorthite ($CaAl_2Si_2O_8$)-Wollastonite($Ca_2Si_2O_6$)-Titanite($CaTiSiO_5$)

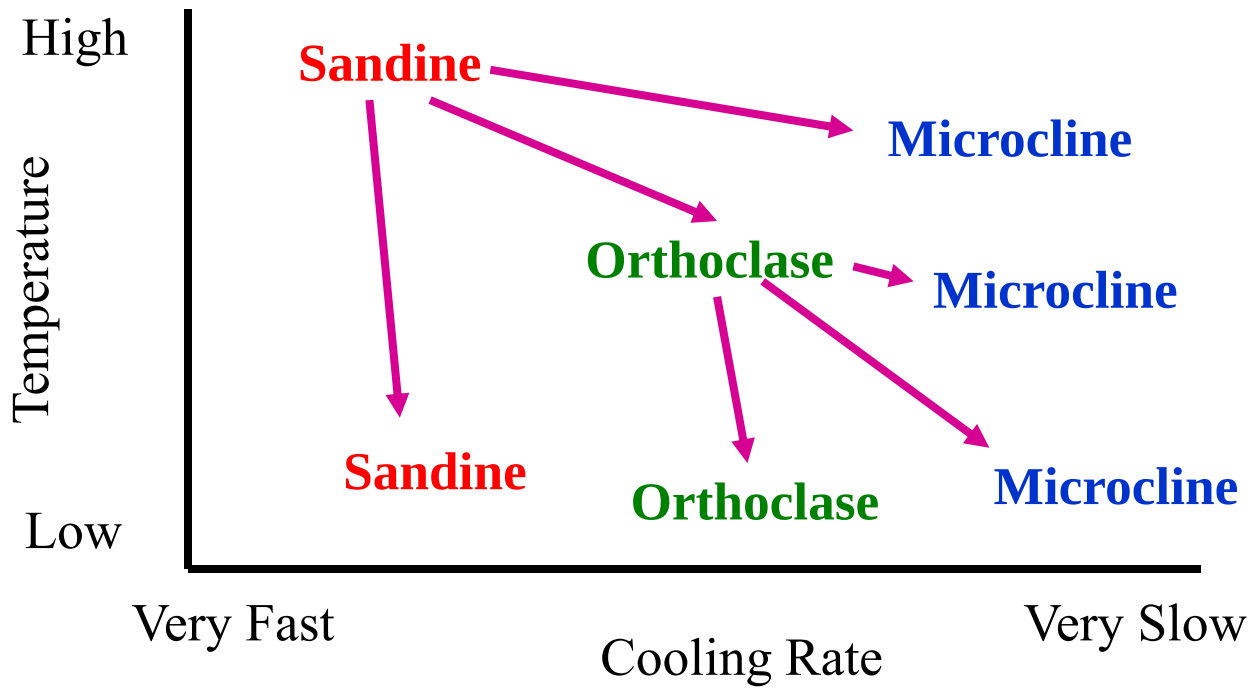

An
1553
1500
1444
1400
AN+LQ
SP+LQ
1400
D
1317
1475
1300
1270
1300
1274
E
1400
A
1500
FO+LQ
1600
1700
1800
DI+LQ
Di
1391.5
1388
Fo
1890



Anorthite ($CaAl_2Si_2O_8$)-Diopside($CaMgSi_2O_6$)-Forsterite(Mg_2SiO_4)

Feldspars are a classic example of the Al avoidance principle.

Which, itself, is measure of order in the lattice.



How does ordering vary in this diagram?

How does crystallographic structure vary with ordering?

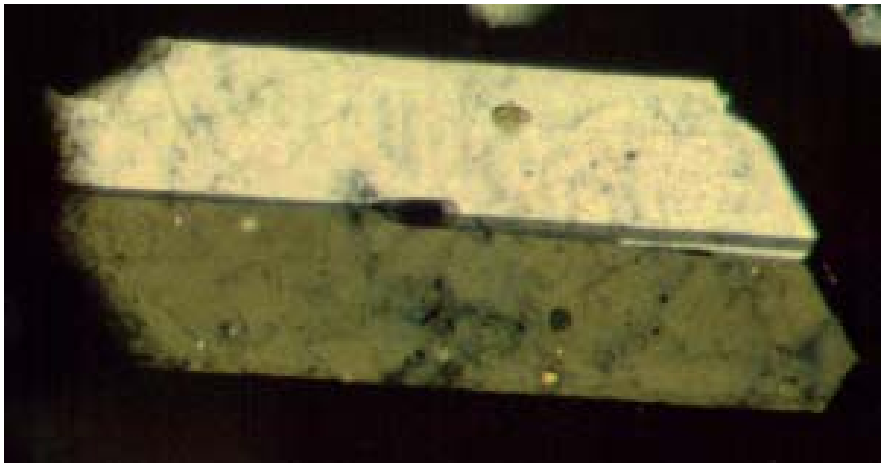
What induces change in the structural symmetry?

Twinning

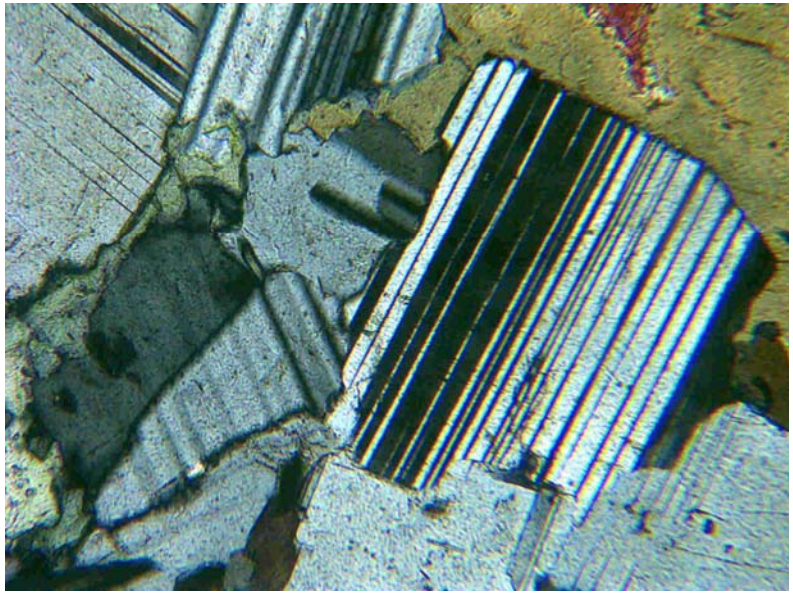
Twins result when different domains of a single crystal have different atomic orientations. The domains share atoms along a common surface. They are observed in cross polarised light only.

Twins are NOT intergrowths – twin planes are continuous.

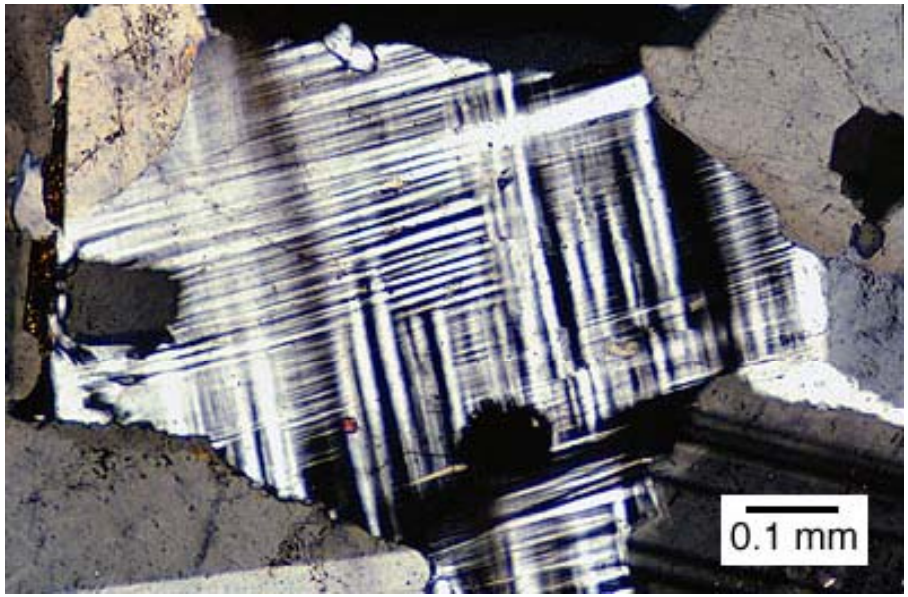
Simple Twins
2 domains with a
common plane of atoms.



Complex Twins
>2 individual domains
(polysynthetic twinning)



A more complex polysynthetic twinning is observed in the triclinic forms of K-feldspar – so called "tartan twinning".

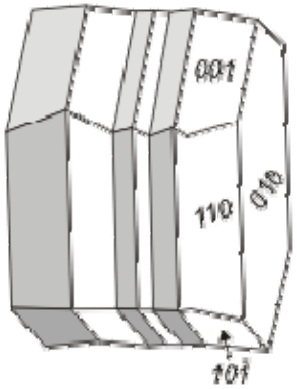


The different types of twins observed in different minerals are known by their various twin laws.

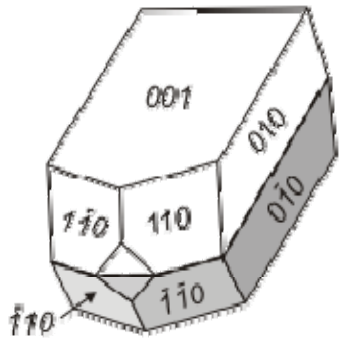
K-Fsp contain simple twins related by Carlsbad, Baveno, albite or pericline laws, which are defined by orientation to crystallographic lattice.

Combining albite and pericline, results in tartan.

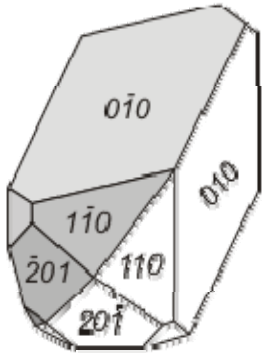
Twinning is not restricted to the feldspars. It is also seen in some pyroxenes, calcite, and the feldspathoids, leucite and nepheline.



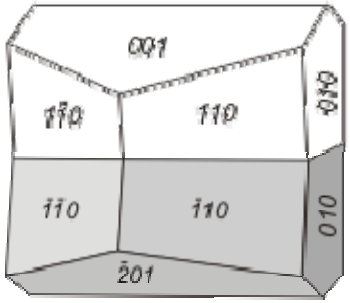
Albite



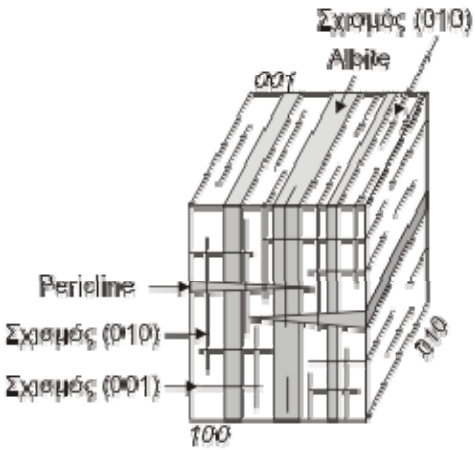
Manebach



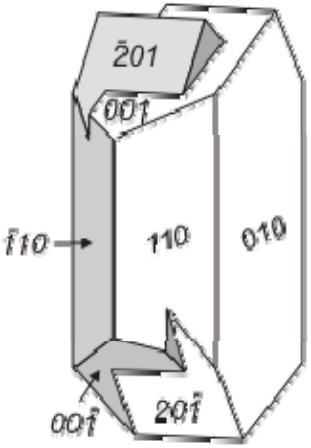
Baveno



Pericline



Albite-Pericline



Carlsbad

Leucite and Nepheline

The feldspathoid group minerals are also anhydrous tectosilicates.

Chemically, they are similar to feldspars, but contain less SiO_2. Subsequently the tend to form from melts rich in alkalis (Na and K), and poor is SiO_2.

Leucite ($KAlSi_2O_6$) is tetragonal, with K^+ accommodated in large 12 coordinated cavities in the structure.

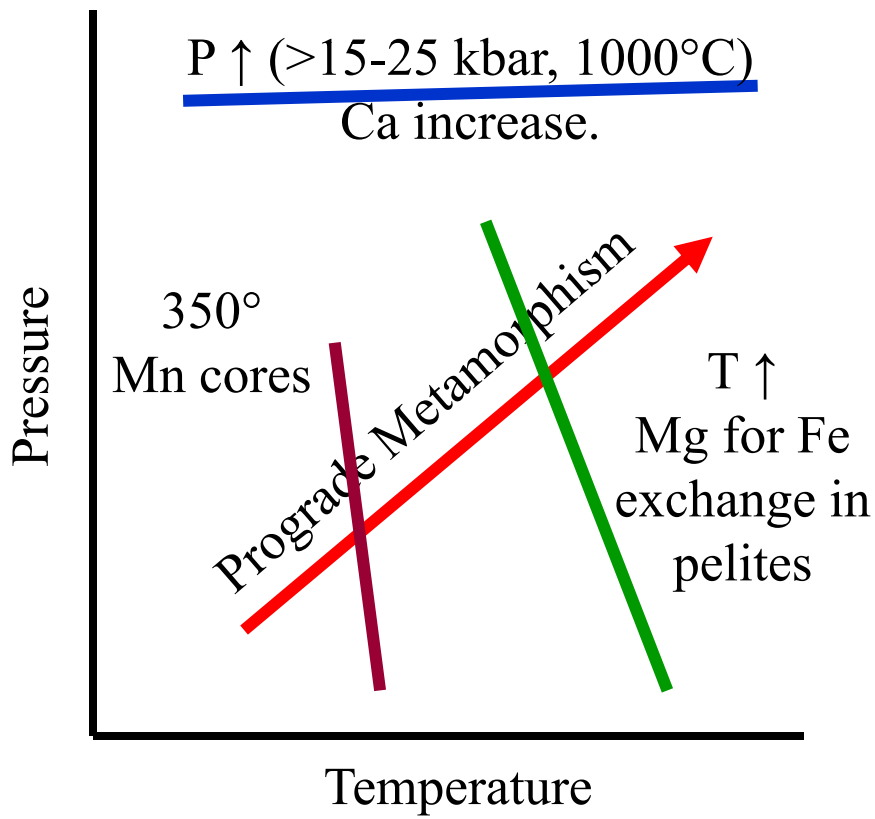
Nepheline (Na,K)AlSiO4) is hexagonal.

While leucite is not particularly common, nepheline is found in many alkaline rocks. Care must be taken because its optical properties are similar to those of quartz – the one exception is that it is optically negative!

N.B. Neither mineral is ever found in the presence of quartz.

Paragenesis and Composition, ex. GARNET

Pure end-member compositions of garnet are rare. The majority are some intermediate composition, which is determined by a combination of factors.



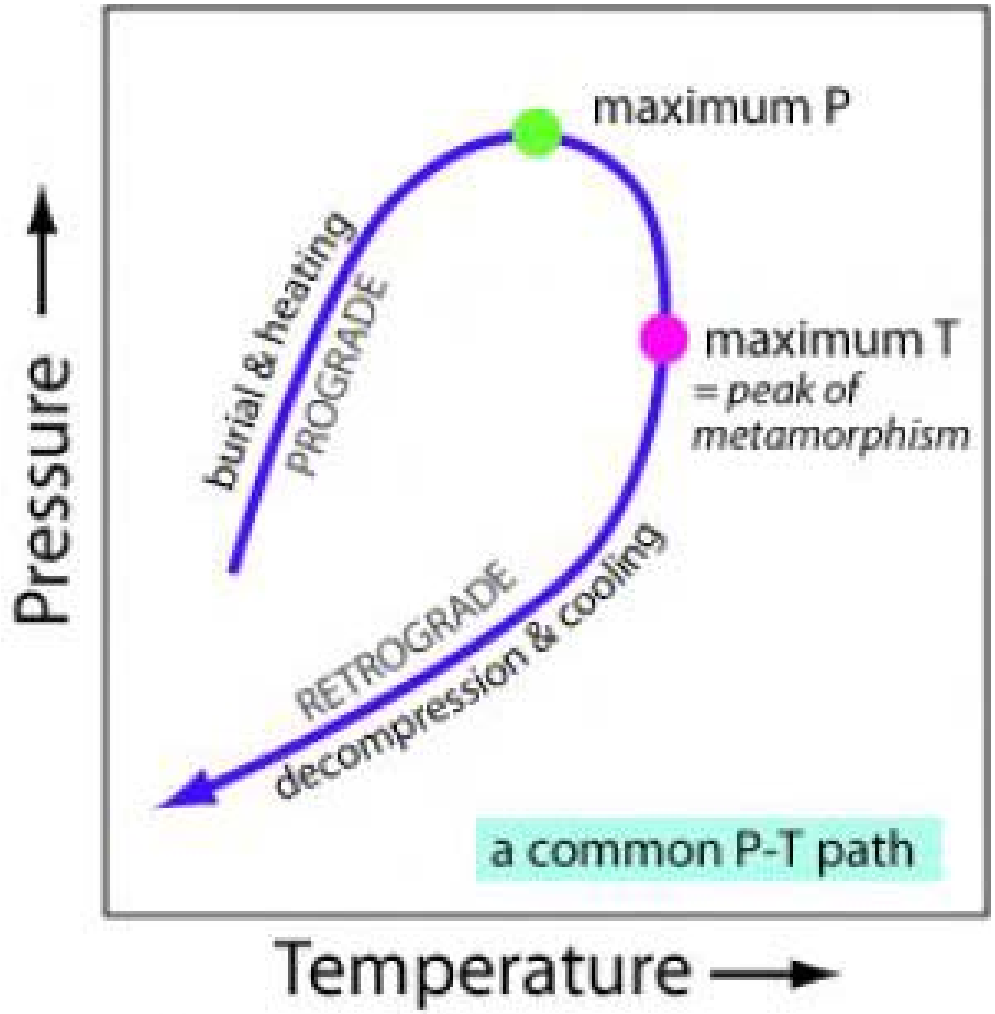
$Fe_3Al_2Si_3O_{12} + KMg_3AlSi_3O_{10}(OH)_2$

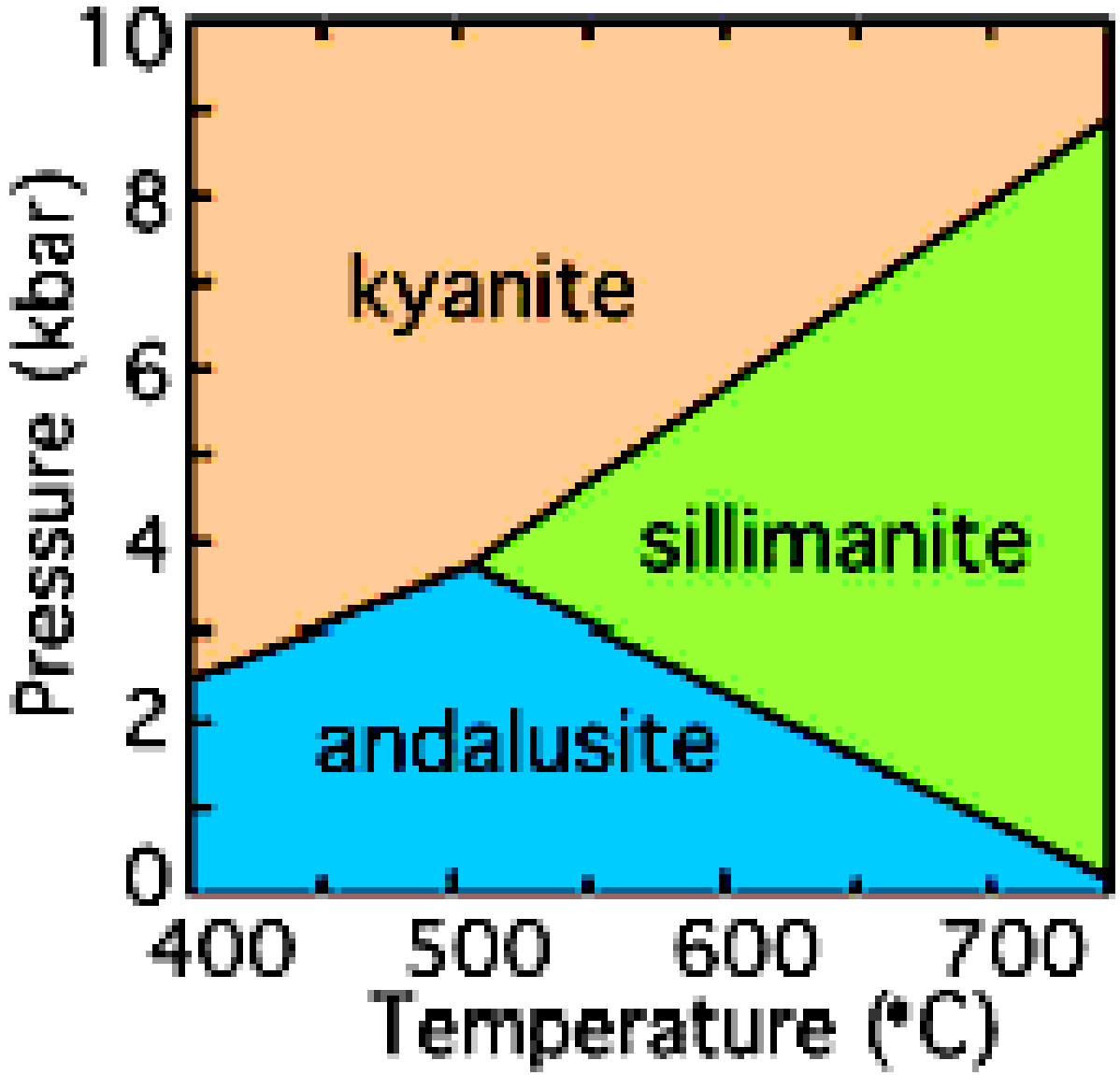
$\Updownarrow$

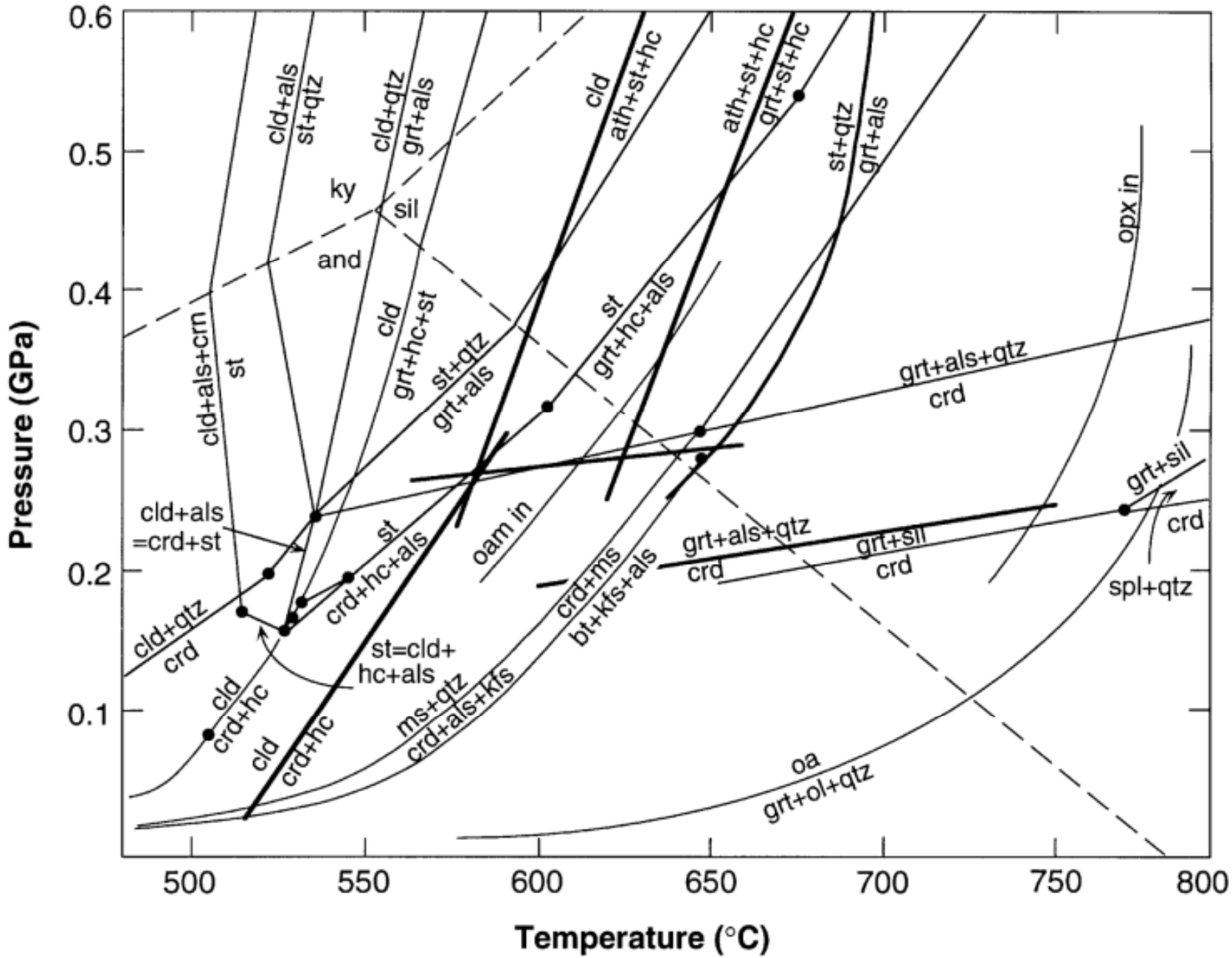
$Mg_3Al_2Si_3O_{12} + KFe_3AlSi_3O_{10}(OH)_2$

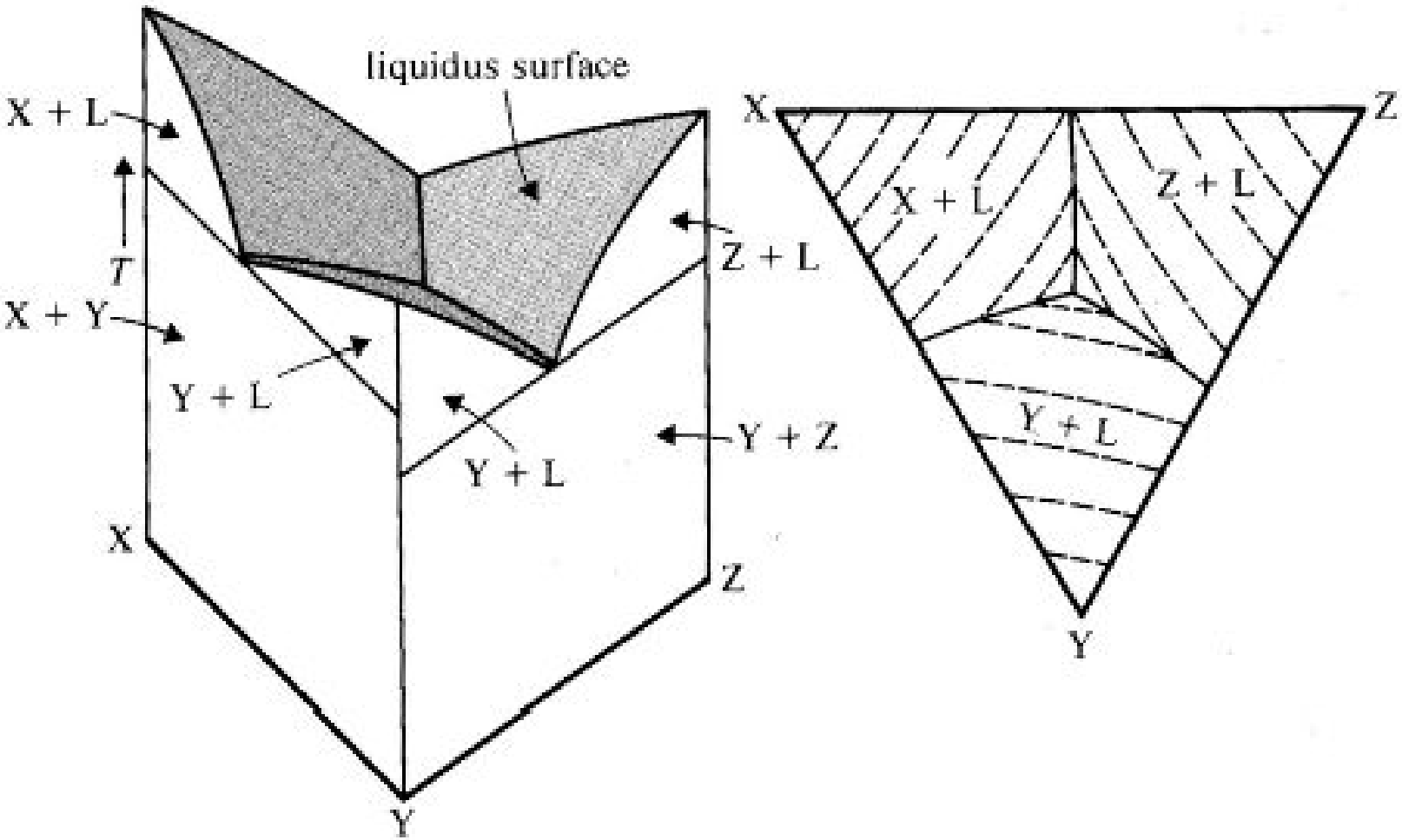
This reaction is a classic thermometer.

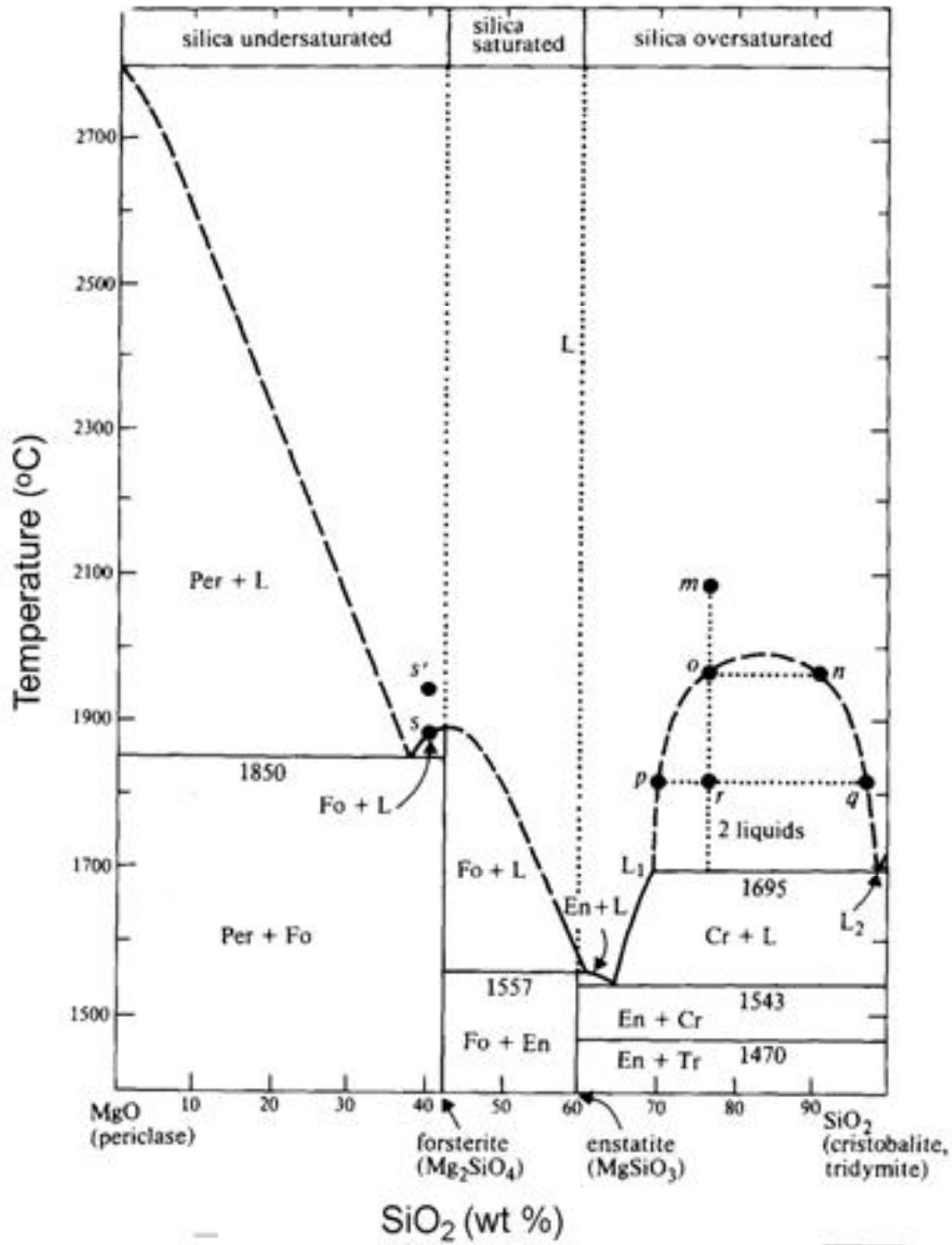
Exchange between Mg, Fe, Ca and Mn is favourable because of similarities in ionic radii and same charge.

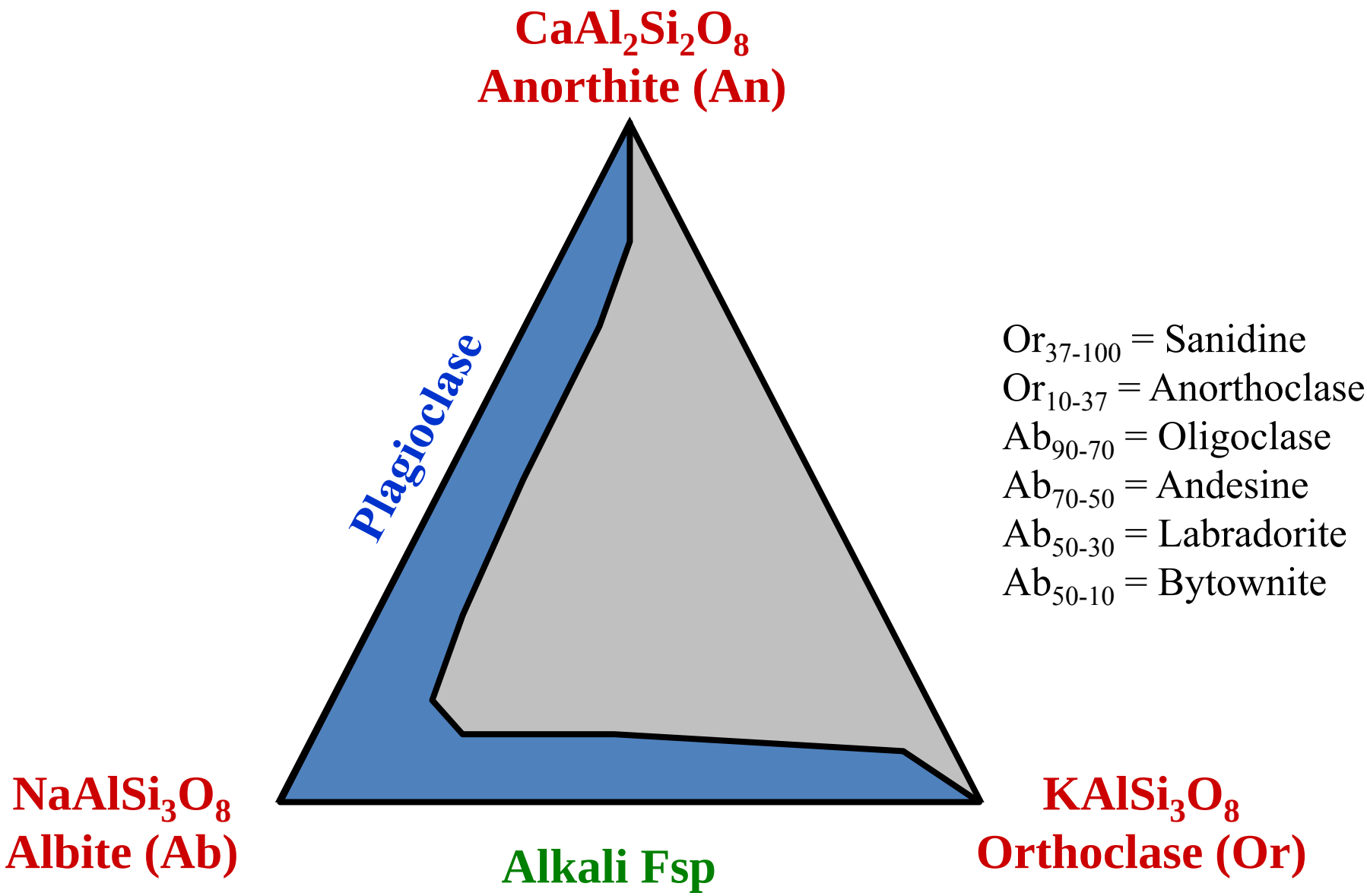

maximum P
burial & heating
PROGRADE
maximum T
= peak of
metamorphism
RETROGRADE
decompression & cooling
a common P-T path
Pressure
Temperature

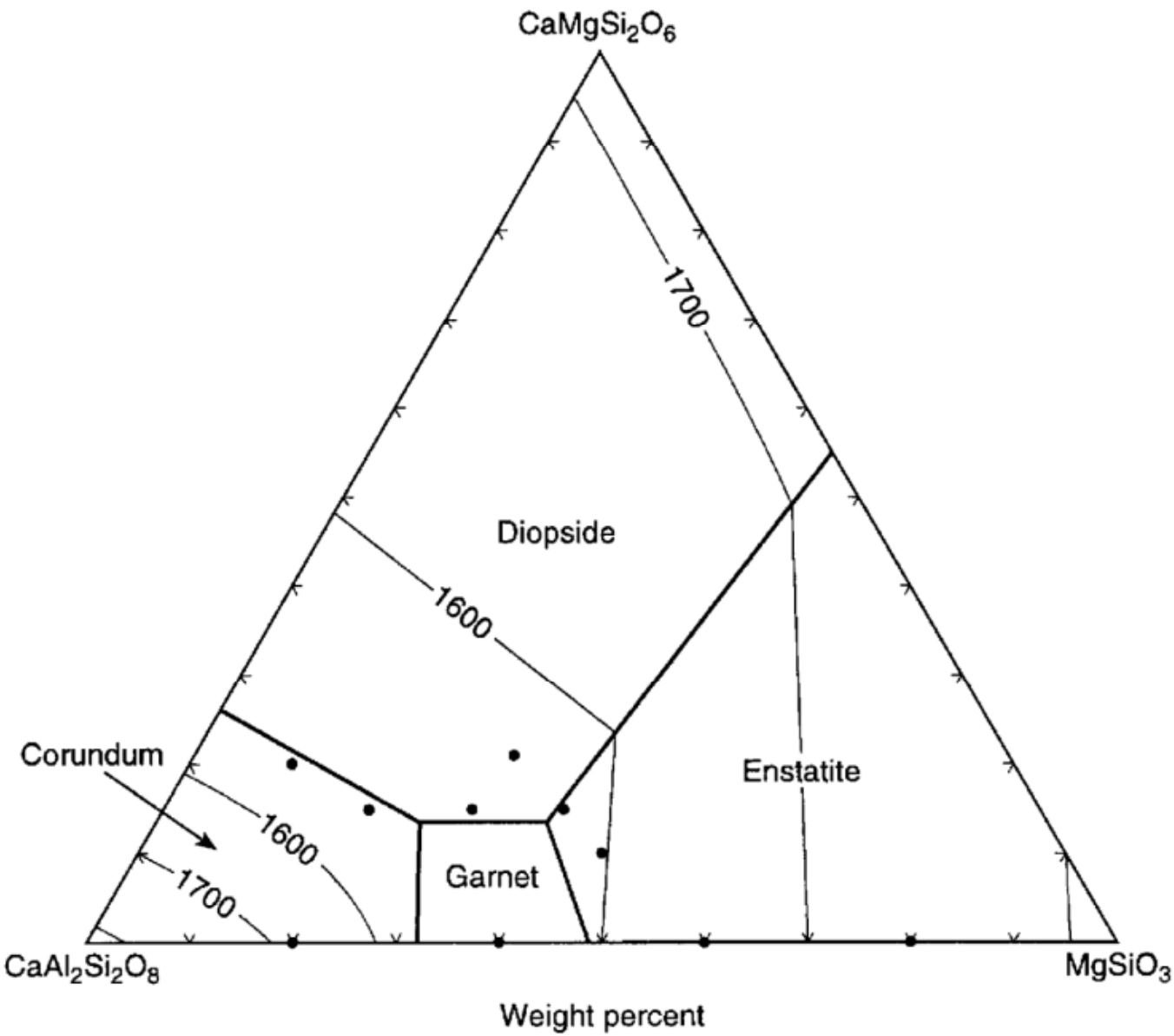

kyanite
sillimanite
andalusite
Pressure (kbar)
0
2
4
6
8
10
400
500
600
700
Temperature (°C)


Pressure (GPa)
Temperature (°C)
0.6
0.5
0.4
0.3
0.2
0.1
500
550
600
650
700
750
800
cld+als
st+qtz
cld+qtz
grt+als
cld
ath+st+hc
ath+st+hc
grt+st+hc
st+qtz
grt+als
opx in
ky
sil
and
cld+als+crn
st
cld
grt+hc+st
st+qtz
grt+als
st
grt+hc+als
grt+als+qtz
crd
grt+sil
cld+als
=crd+st
st
crd+hc+als
oam in
grt+als+qtz
crd
grt+sil
crd
crd
spl+qtz
cld+qtz
crd
st=cld+
hc+als
cld
crd+hc
cld
crd+hc
ms+qtz
crd+als+kfs
crd+ms
bt+kfs+als
oa
grt+ol+qtz


liquidus surface
X + L
T
X + Y
Y + L
Y + L
Z + L
Y + Z
X
Z
Y
X
Z
X + L
Z + L
Y + L
Y


silica undersaturated
silica saturated
silica oversaturated
Temperature (°C)
2700
2500
2300
2100
1900
1700
1500
L
Per + L
s'
s
1850
Fo + L
Fo + L
Per + Fo
1557
Fo + En
En + L
m
o
n
p
r
q
2 liquids
L1
L2
1695
Cr + L
1543
En + Cr
En + Tr
1470
MgO
(periclase)
10
20
30
40
50
60
70
80
90
SiO2
(cristobalite,
tridymite)
forsterite
(Mg2SiO4)
enstatite
(MgSiO3)
SiO2 (wt %)


$CaAl_2Si_2O_8$
Anorthite (An)
Plagioclase
Or_{37-100} = Sanidine
Or_{10-37} = Anorthoclase
Ab_{90-70} = Oligoclase
Ab_{70-50} = Andesine
Ab_{50-30} = Labradorite
Ab_{50-10} = Bytownite
$NaAlSi_3O_8$
Albite (Ab)
Alkali Fsp
$KAlSi_3O_8$
Orthoclase (Or)


$CaMgSi_2O_6$
1700
Diopside
1600
Corundum
1600
1700
Garnet
Enstatite
$CaAl_2Si_2O_8$
$MgSiO_3$
Weight percent