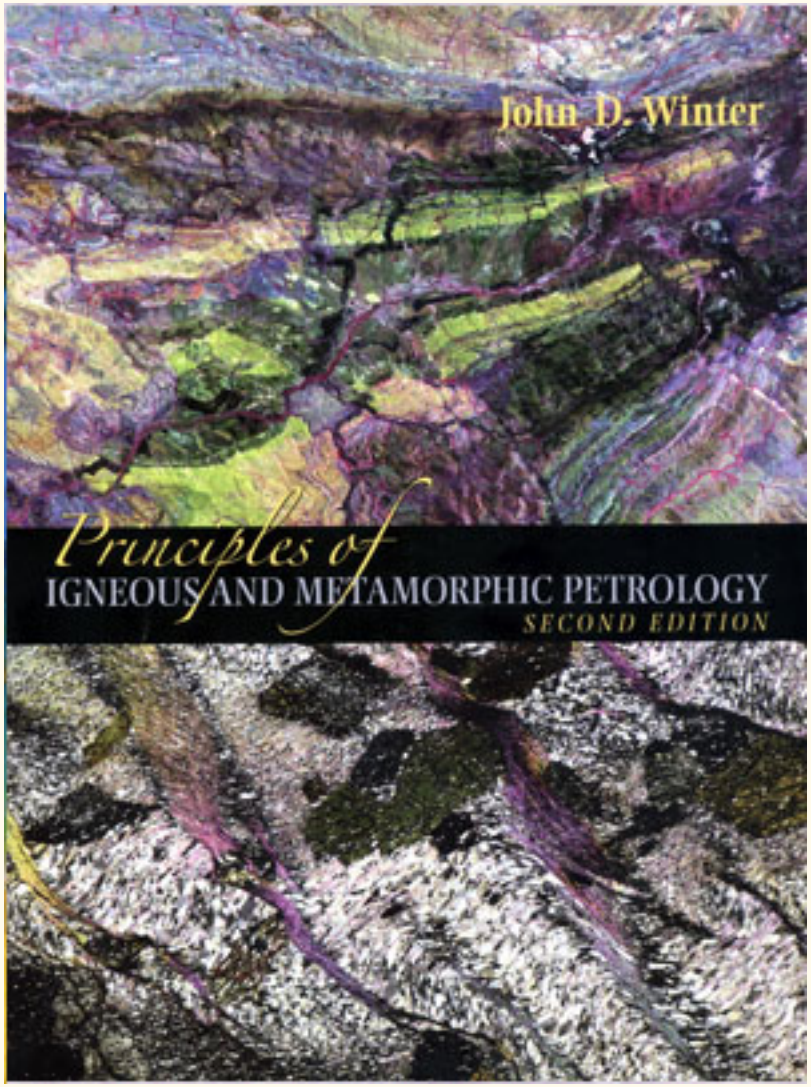
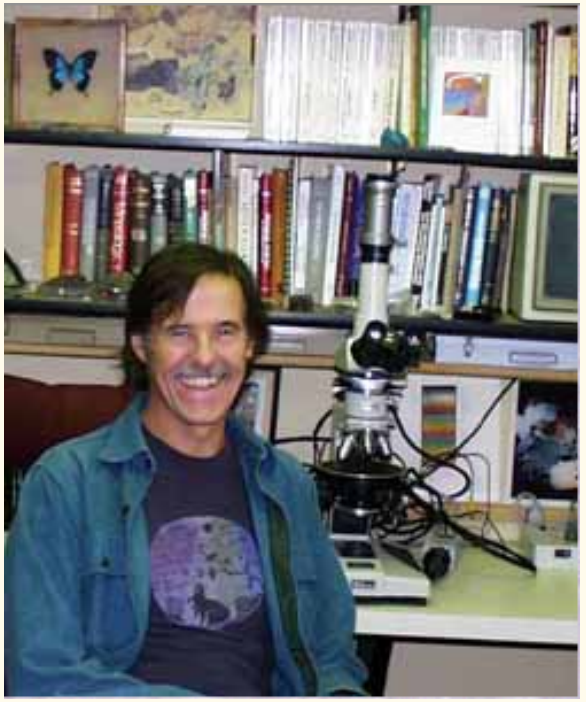
This and future lectures will draw *heavily* from:

http://www.whitman.edu/geology/winter/





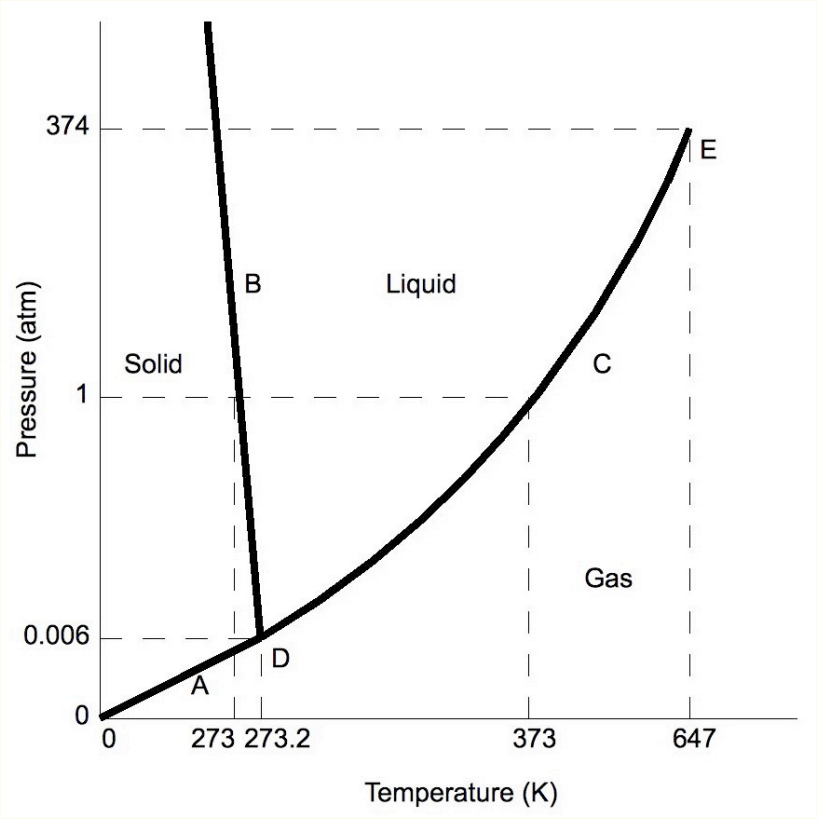
Petrology

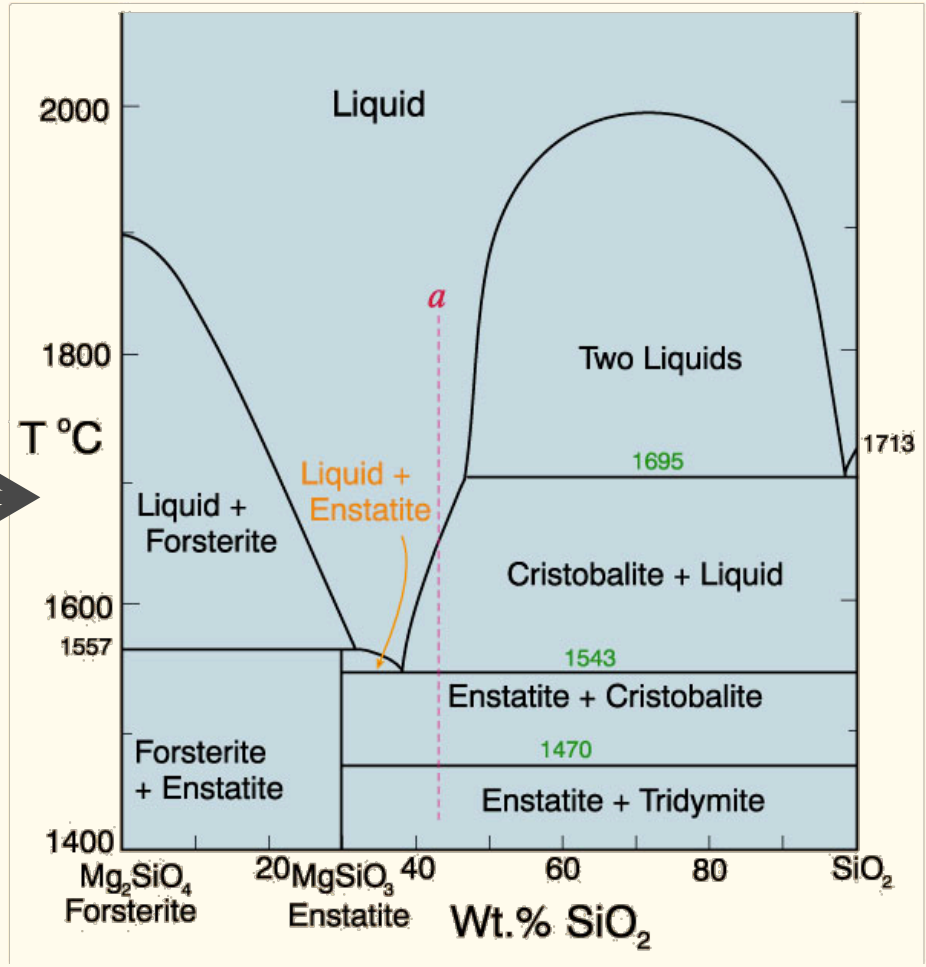
Igneous – formed by solidification of melt

Metamorphic – changed by T, P different from those at which original rock formed

Sedimentary – formed by settling of detrital grains + chemical precipitates

Phase Equilibrium





Petrology

Igneous – formed by solidification of melt

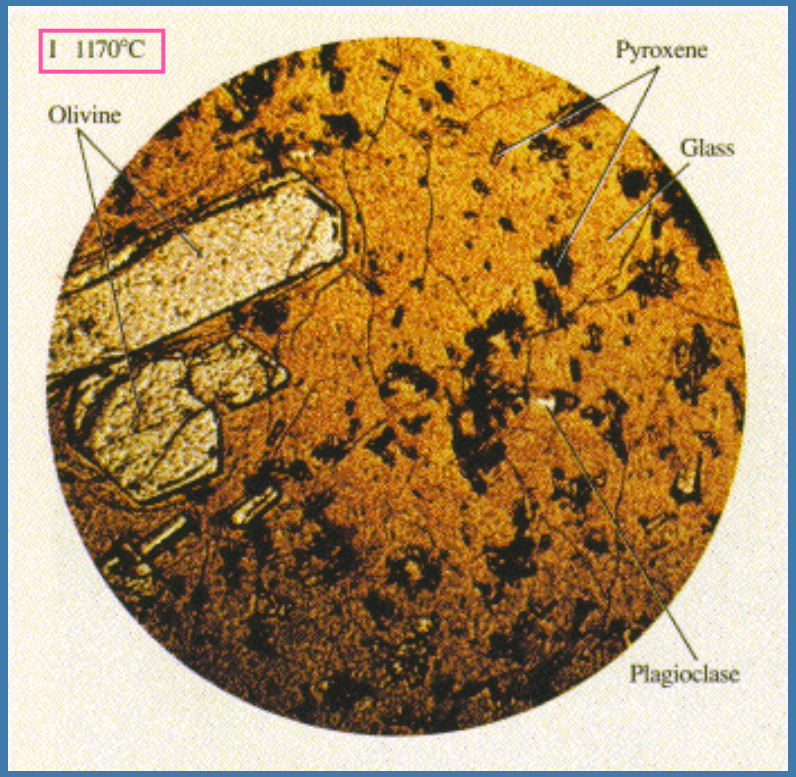
Metamorphic – changed by T, P different from those at which original rock formed

LATER

Sedimentary – formed by settling of detrital grains + chemical precipitates

Makaopuhi Lava Lake

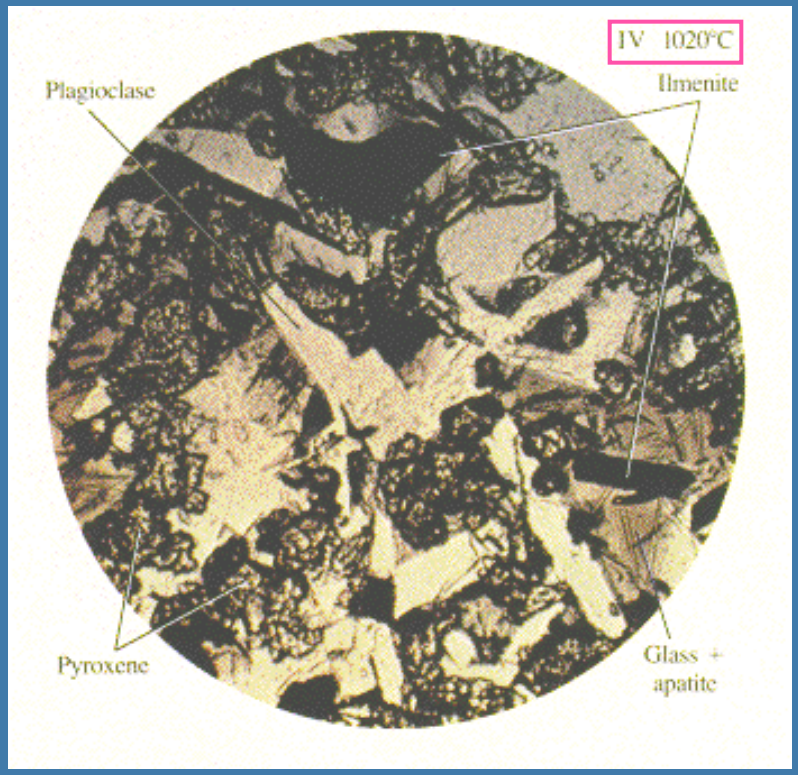
Magma samples recovered from various depths beneath solid crust



From Wright and Okamura, (1977) *USGS Prof. Paper*, **1004**.

Makaopuhi Lava Lake

Thermocouple attached to sampler to determine temperature



From Wright and Okamura, (1977) *USGS Prof. Paper*, **1004**.

Makaopuhi Lava Lake

- Temperature of sample vs. Percent Glass

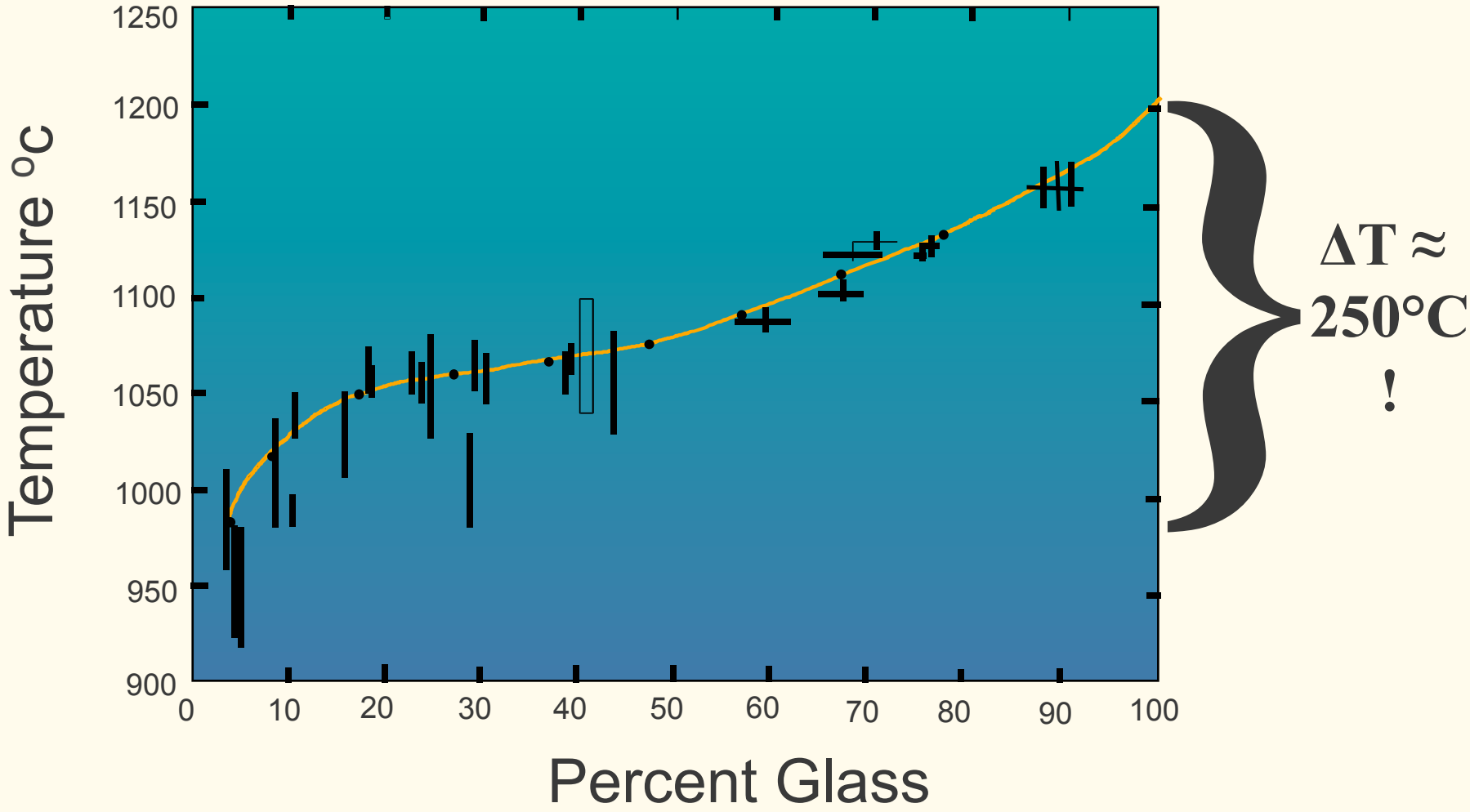


Fig. 6.1. From Wright and Okamura, (1977) *USGS Prof. Paper*, **1004**.

Makaopuhi Lava Lake

Minerals that form during crystallization

olivine decreases below 1175°C

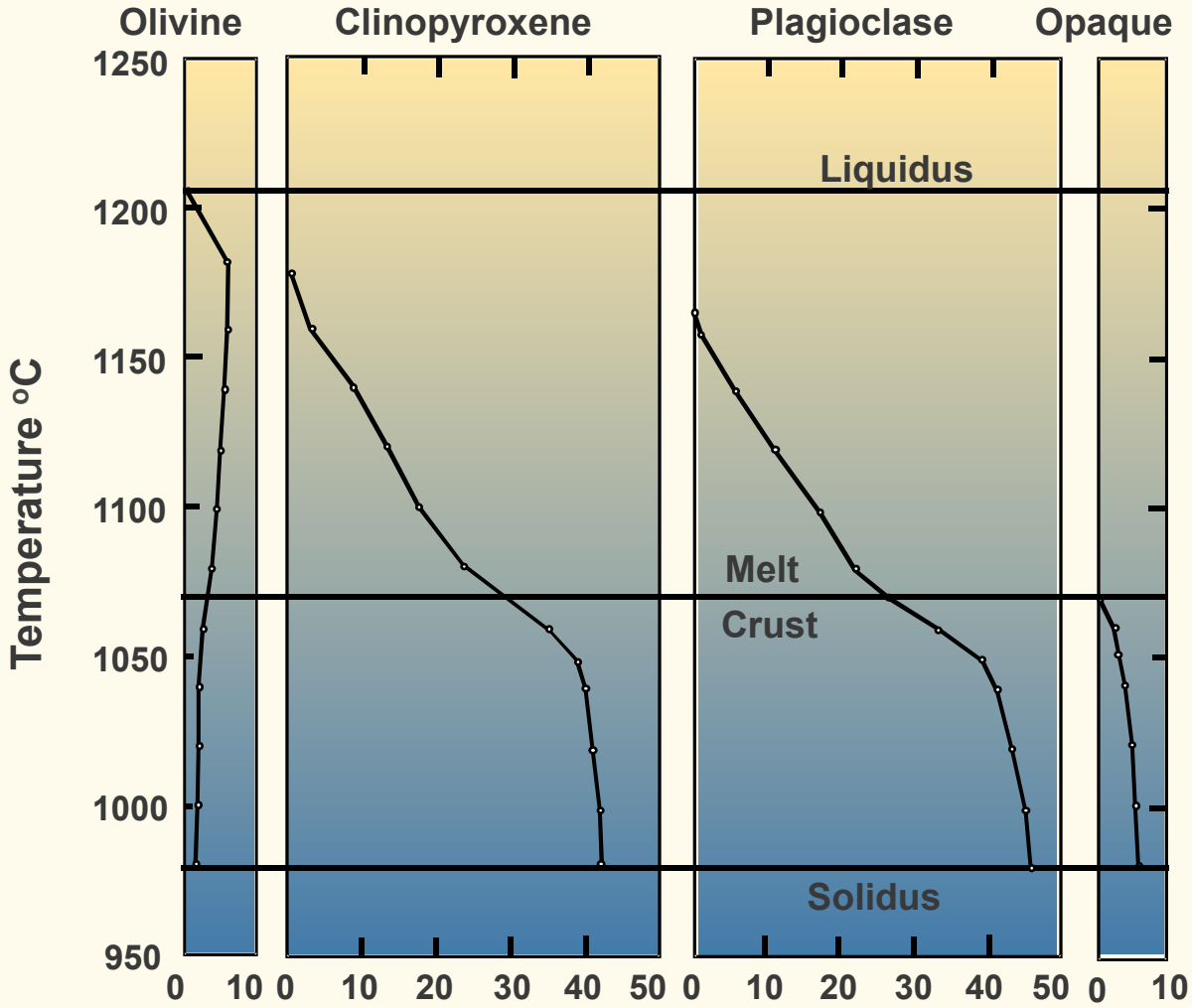


Fig. 6.2. From Wright and Okamura, (1977) *USGS Prof. Paper*, **1004**.

Makaopuhi Lava Lake

Mineral composition during crystallization

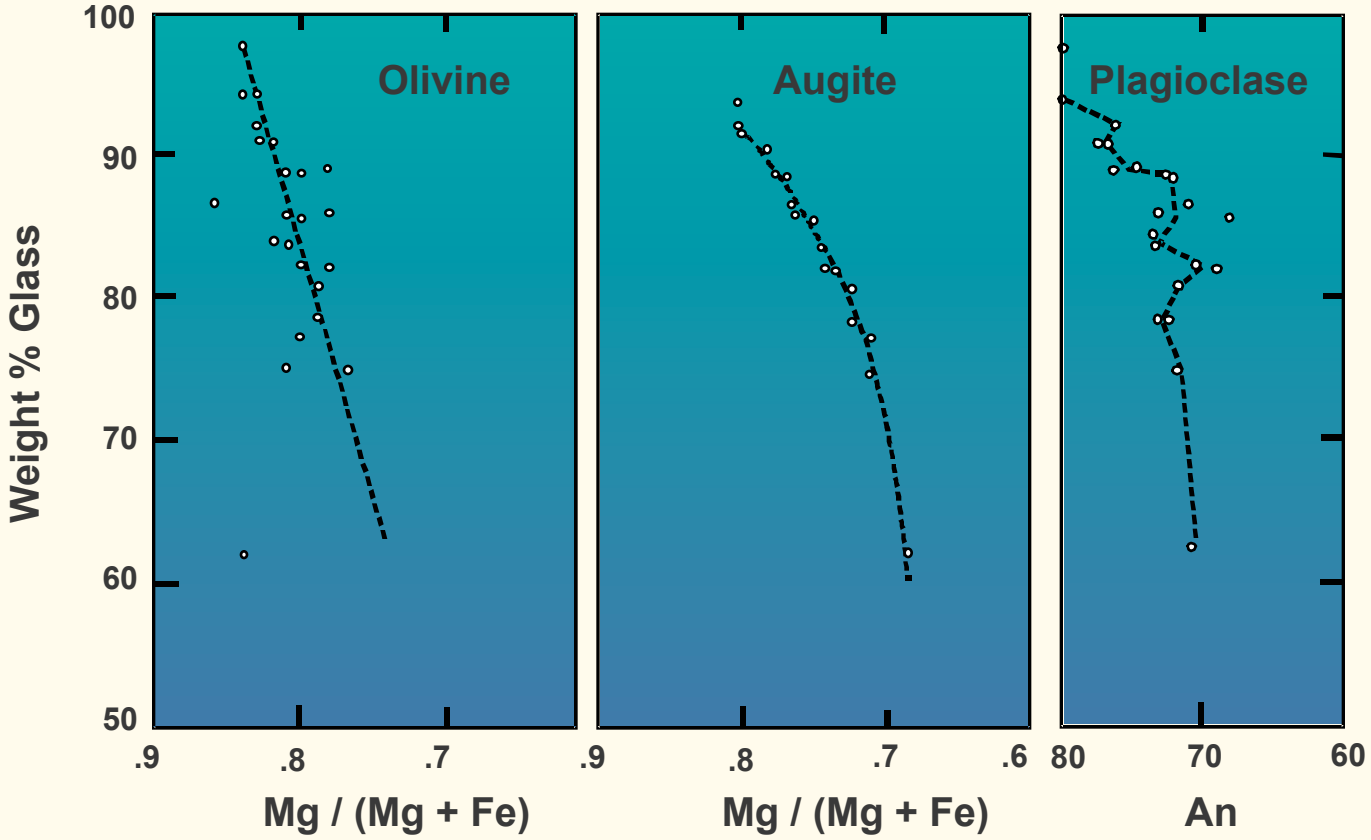


Fig. 6.3. From Wright and Okamura, (1977) *USGS Prof. Paper*, **1004**.

Crystallization Behavior of Melts

1. Cooling melts crystallize from a liquid to a solid over a range of temperatures (and pressures)
2. Several minerals crystallize over this T range, and the number of minerals generally increases as T decreases
3. Minerals that form do so sequentially, with considerable overlap
4. Minerals that involve solid solution change composition as cooling progresses
5. The melt composition also changes during crystallization
6. The minerals that crystallize (as well as the sequence) depend on T and X of the melt
7. Pressure can affect the types of minerals that form and the sequence
8. The nature and pressure of the volatiles can also affect the minerals and their sequence

Winter Chapter 6:

The Phase Rule and One- and Two-Component Systems

The Phase Rule

$$\mathbf{F} = C - \phi + 2$$

F = # degrees of freedom

The number of intensive parameters that must be specified in order to completely determine the system

The Phase Rule

$$F = C - \phi + 2$$

F = # degrees of freedom

The number of intensive parameters that must be specified in order to completely determine the system

ϕ = # of phases

phases are mechanically separable constituents

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ϕ = # of phases

phases are mechanically separable constituents

C = minimum # of components (chemical constituents that must be specified in order to define all phases)

The Phase Rule

$$F = C - \phi + 2$$

F = # degrees of freedom

The number of intensive parameters that must be specified in order to completely determine the system

ϕ = # of phases

phases are mechanically separable constituents

C = minimum # of components (chemical constituents that must be specified in order to define all phases)

2 = 2 intensive parameters

Usually = temperature and pressure for us geologists

High Pressure Experimental Furnace

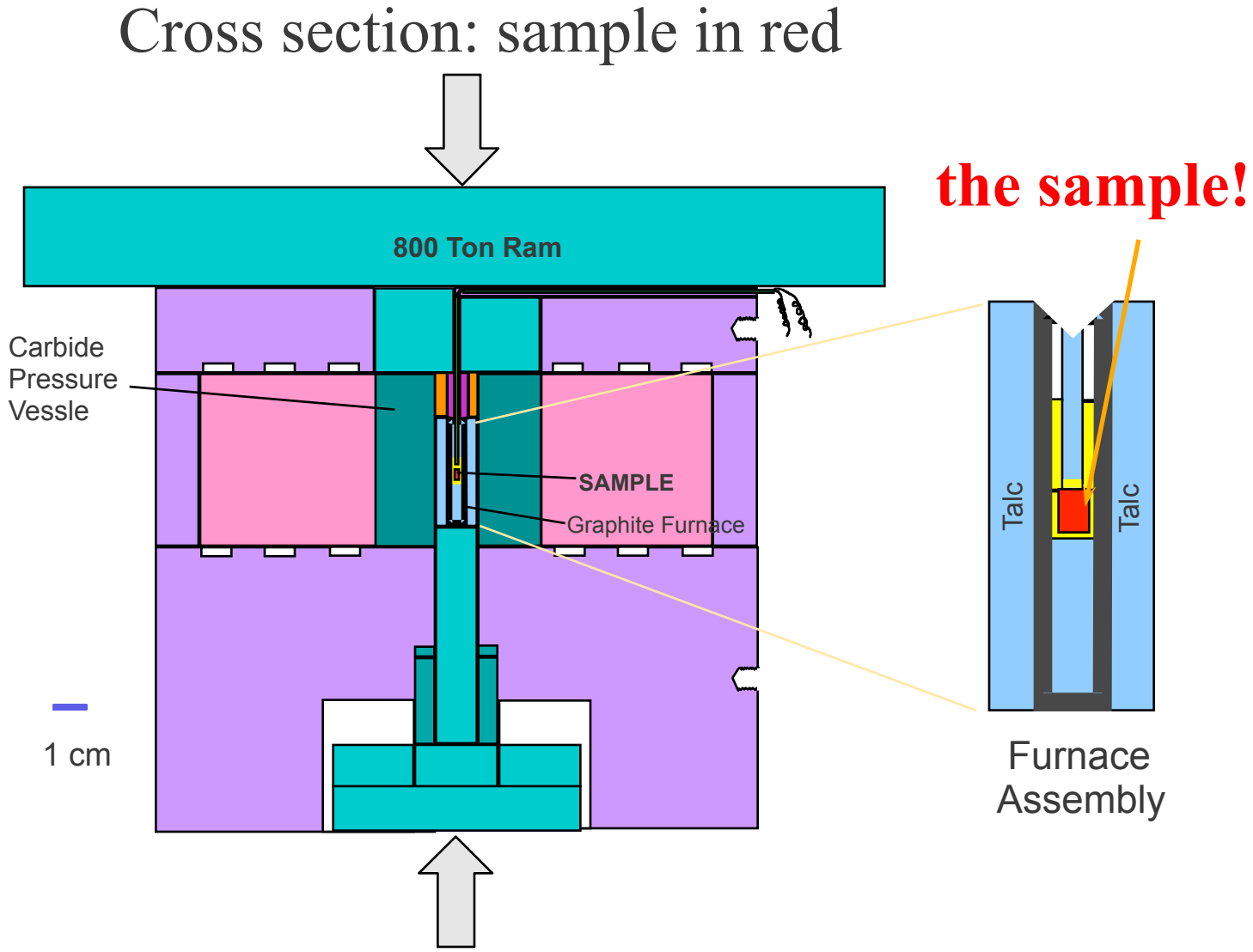


Fig. 6.5. After Boyd and England (1960), J. Geophys. Res., **65**, 741-748. AGU

1 - C Systems

1. The system SiO_2

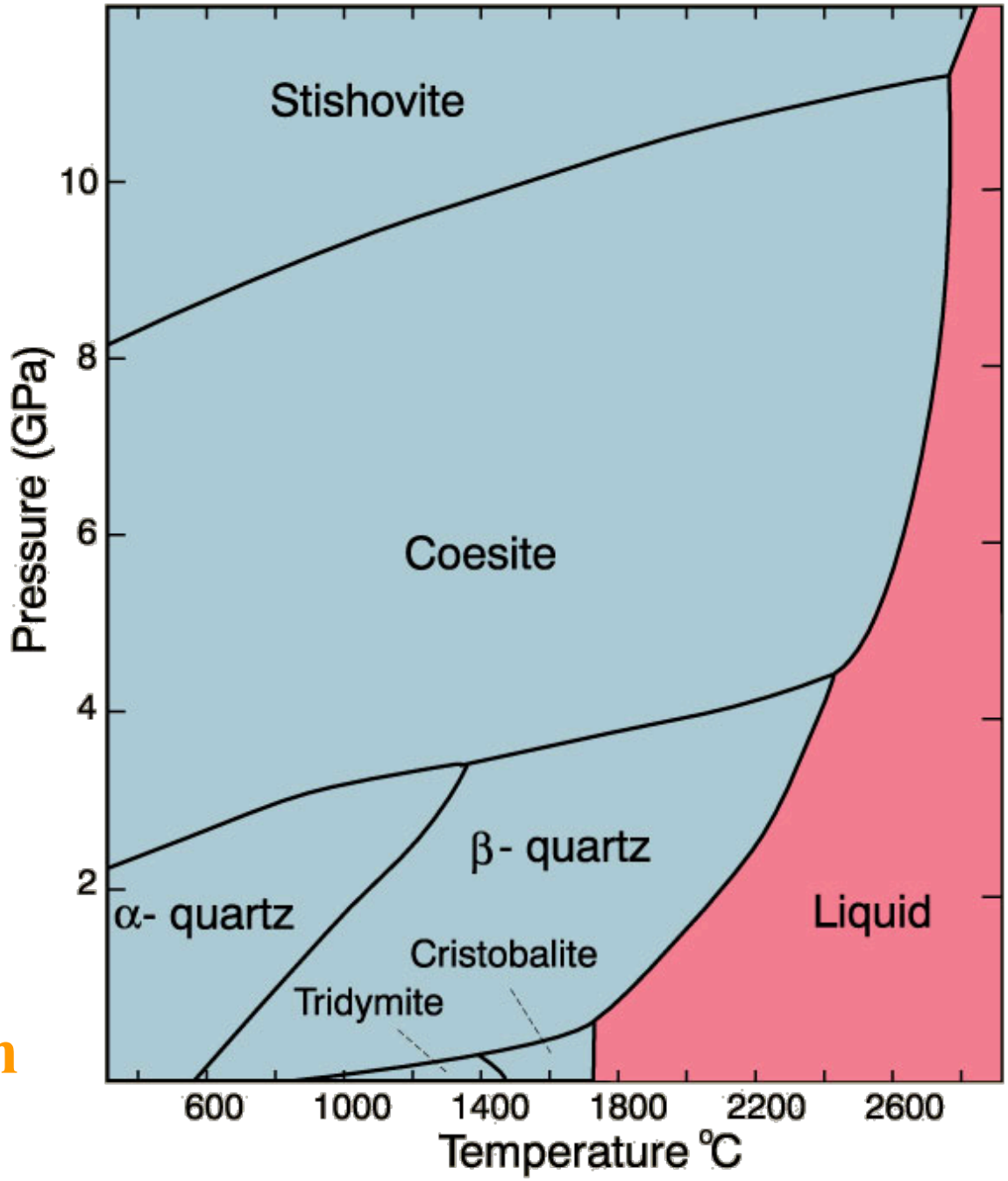


Fig. 6.6. After Swamy and Saxena (1994), J. Geophys. Res., 99, 11,787-11,794. AGU

Planetary note: Stishovite/coesite from meteorite impacts

1 - C Systems

2. The system H_2O

Isobaric phase rule:

$$F = C - \phi + \mathbf{1}$$

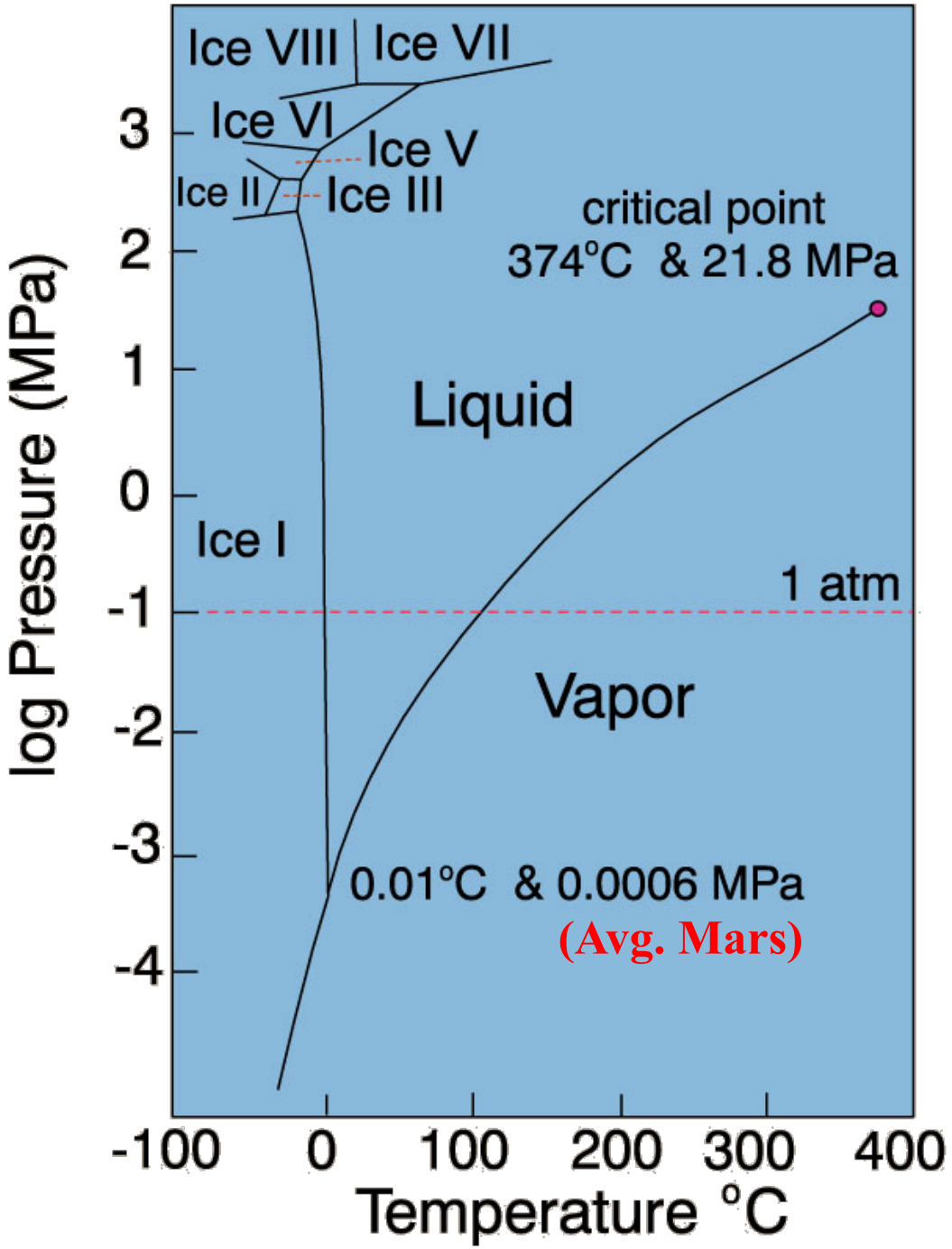
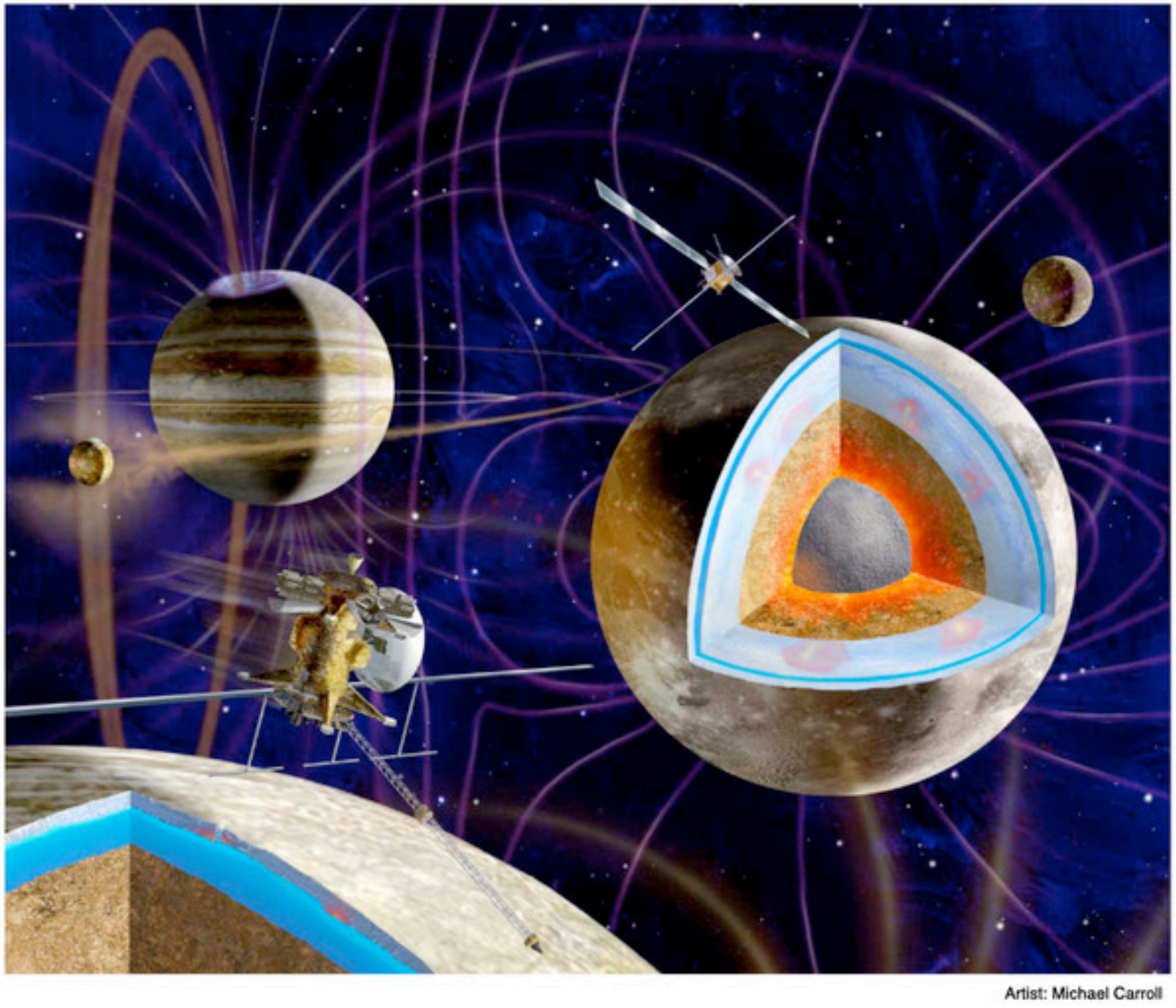


Fig. 6.7. After Bridgman (1911) Proc. Amer. Acad. Arts and Sci., 5, 441-513; (1936) J. Chem. Phys., 3, 597-605; (1937) J. Chem. Phys., 5, 964-966.

High-pressure ices ➔ icy moon “ocean sandwiches”



Artist: Michael Carroll

2 - C Systems

A. Systems with Complete Solid Solution

1. Plagioclase (Ab-An, $NaAlSi_3O_8$ - $CaAl_2Si_2O_8$)

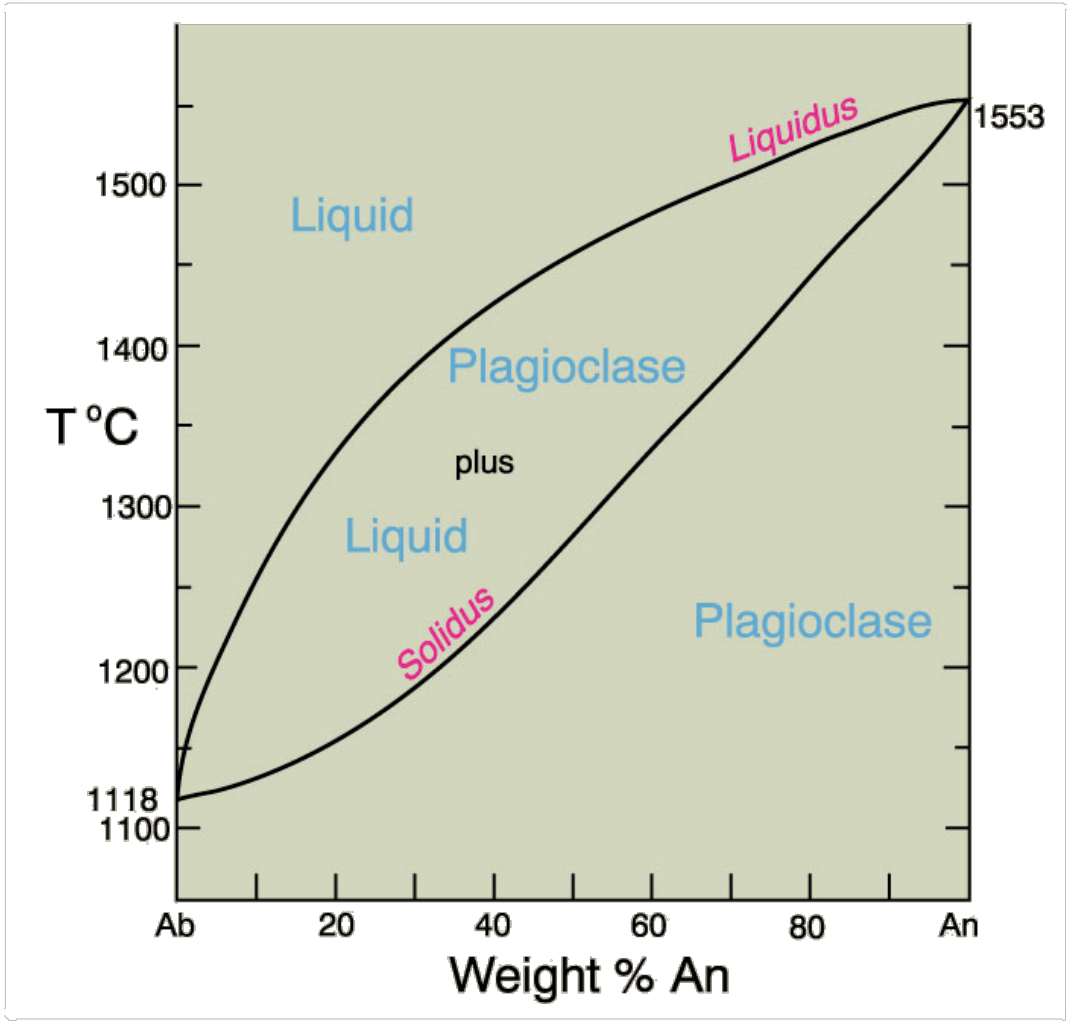
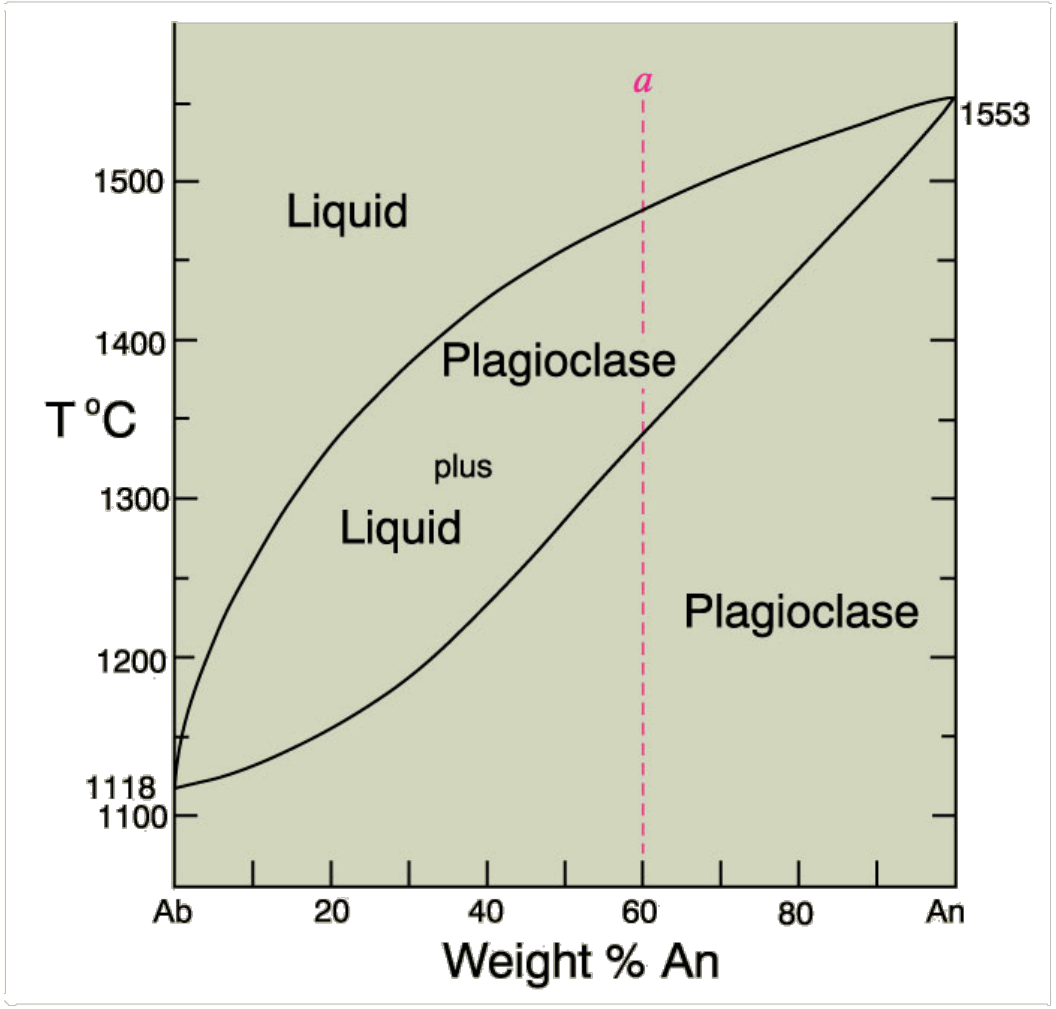


Fig. 6.8. Isobaric T-X phase diagram at atmospheric pressure. After Bowen (1913) Amer. J. Sci., 35, 577-599.

Bulk composition *a* = An_{60}

= 60 g An + 40 g Ab

X_{An} = 60/(60+40) = 0.60



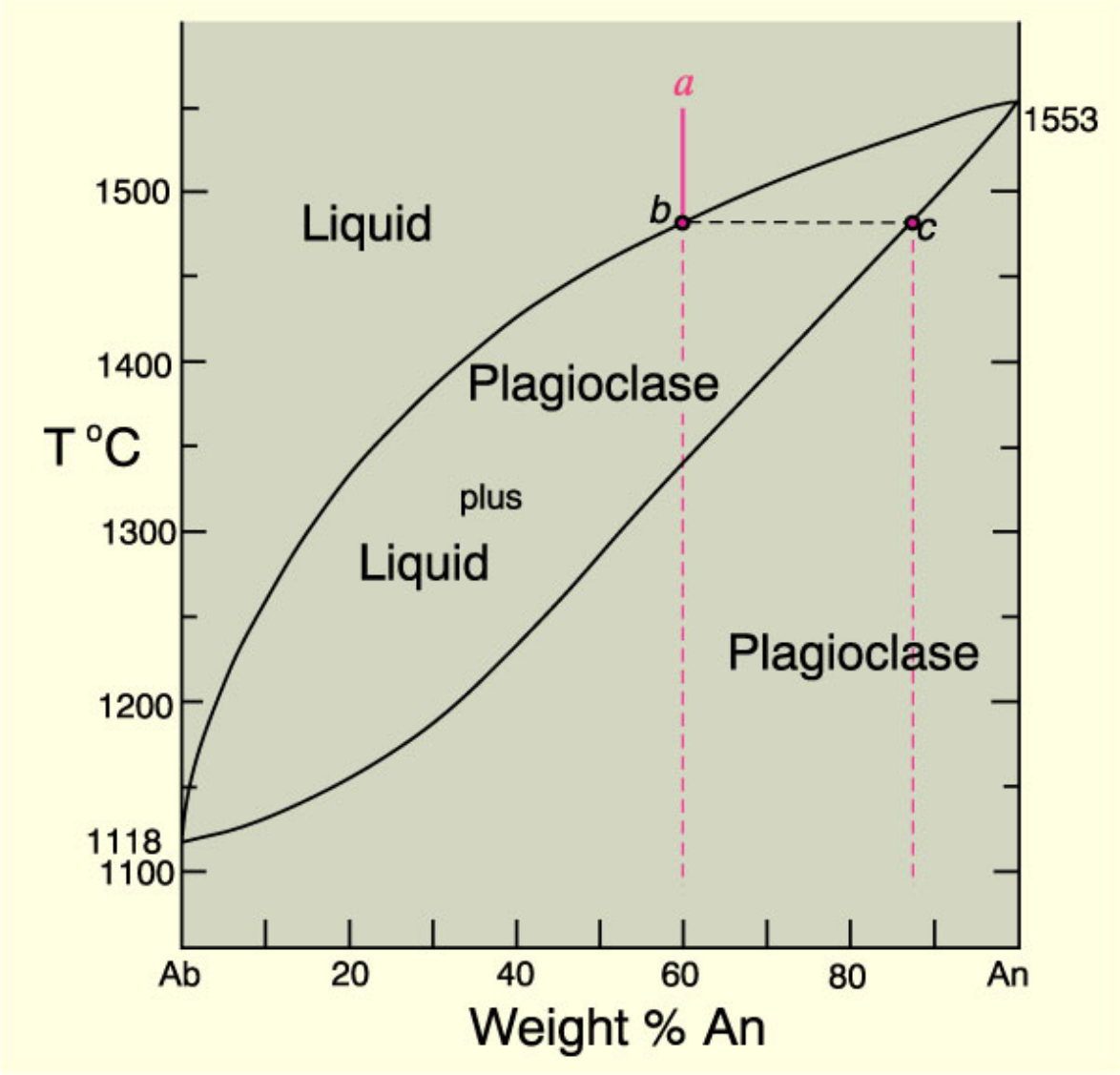
F = 2

1. Must specify 2 independent intensive variables in order to completely determine the system
   = a divariant situation

same as:

2. Can vary 2 intensive variables independently without changing ϕ, the number of phases

Must specify T and X_{An}^{liq} or can vary these without changing the number of phases



F = 2 - 2 + 1 = 1 ("univariant")

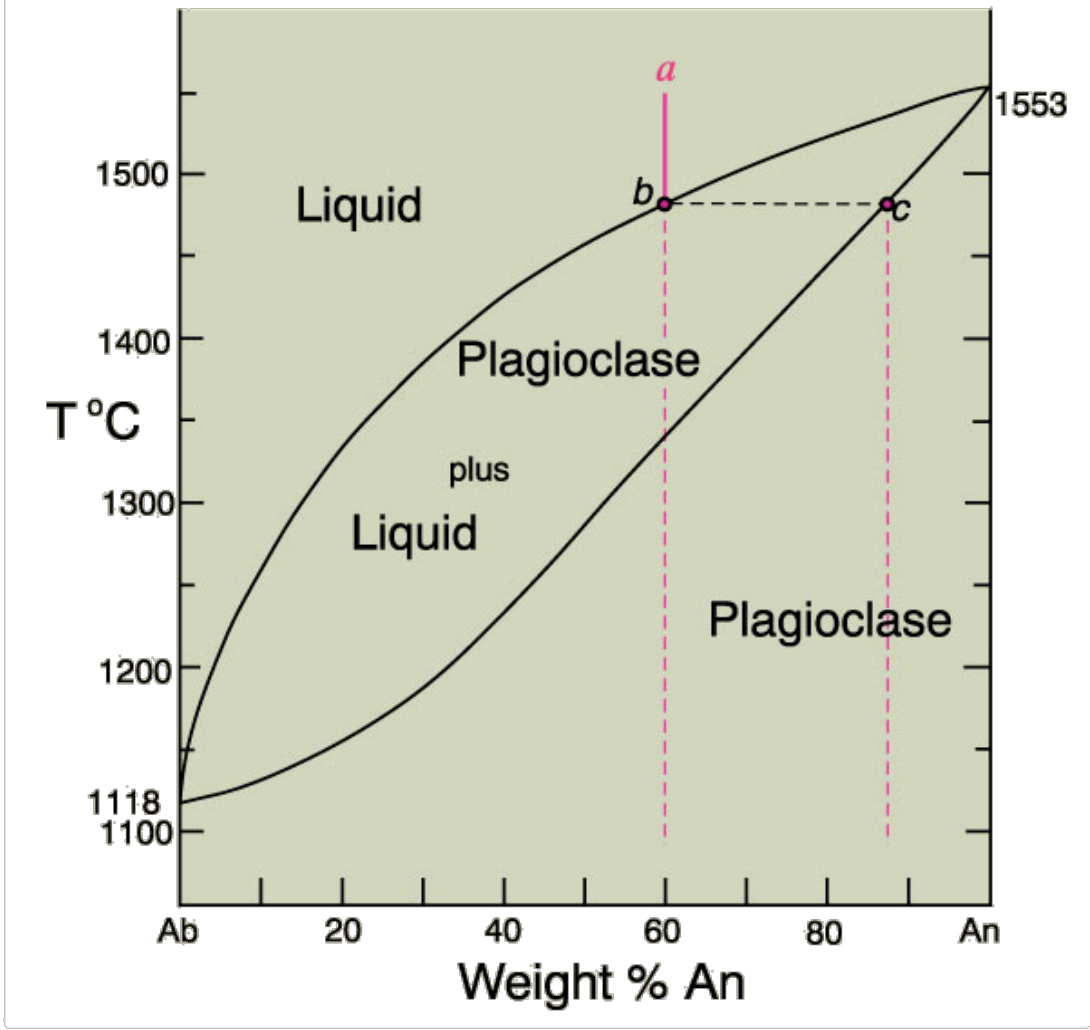
Must specify only one variable from among:

T X^{liq}_{An} X^{liq}_{Ab} X^{plag}_{An} X^{plag}_{Ab} **(P constant)**

Considering an isobarically cooling magma,

X^{liq}_{An} and X^{plag}_{An} are dependent upon T

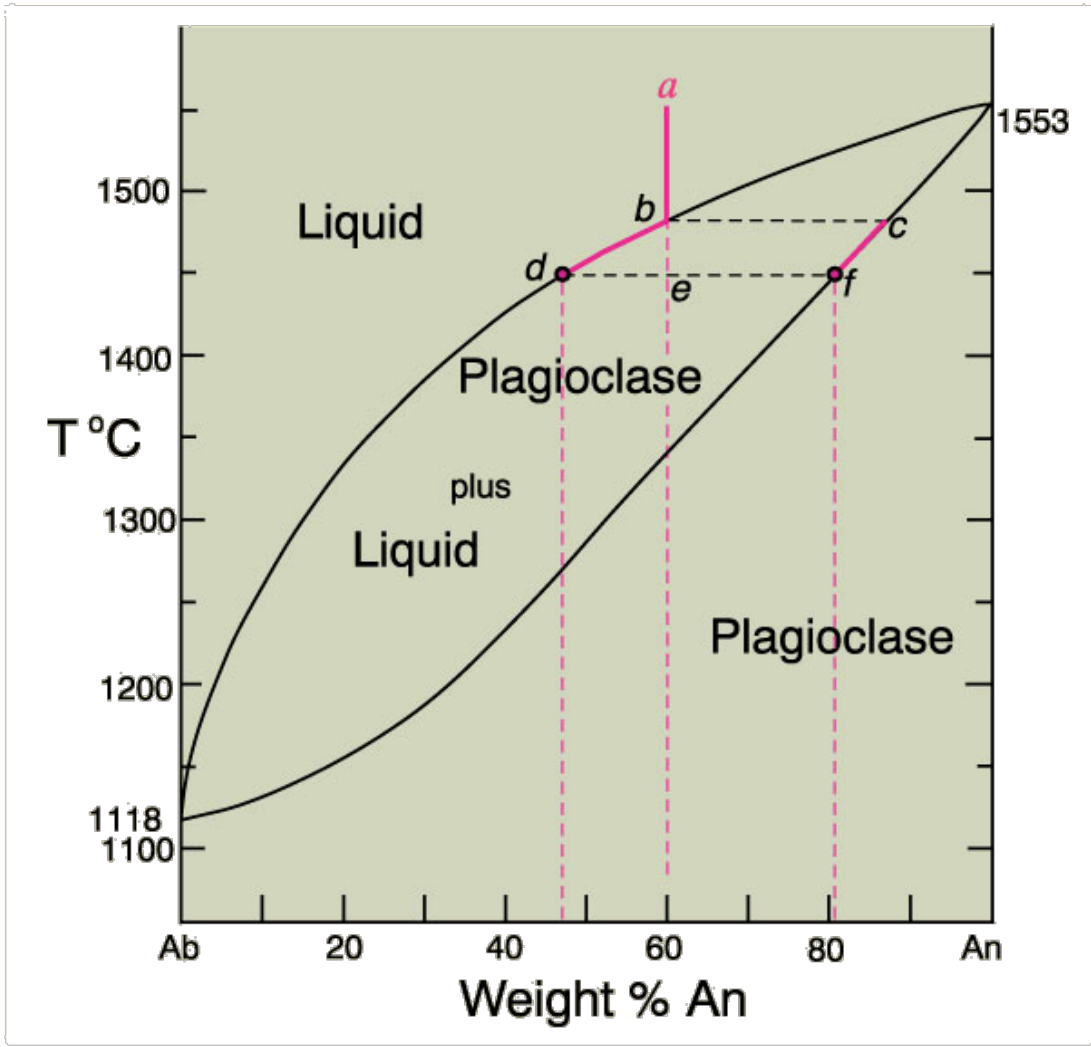
The **slope** of the solidus and liquidus are the expressions of this relationship



At 1450°C, liquid ***d*** and plagioclase ***f*** coexist at equilibrium

A continuous reaction of the type:

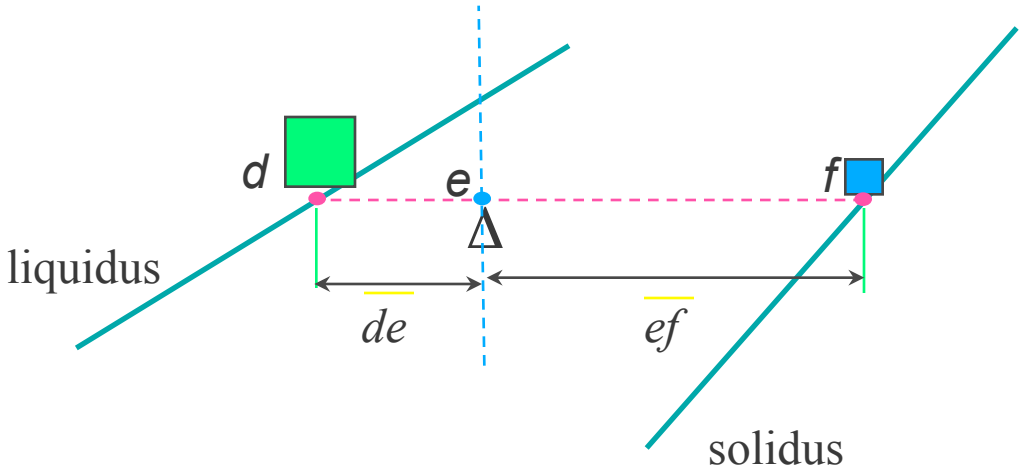
$liquid_B + solid_C = liquid_D + solid_F$



The lever principle:

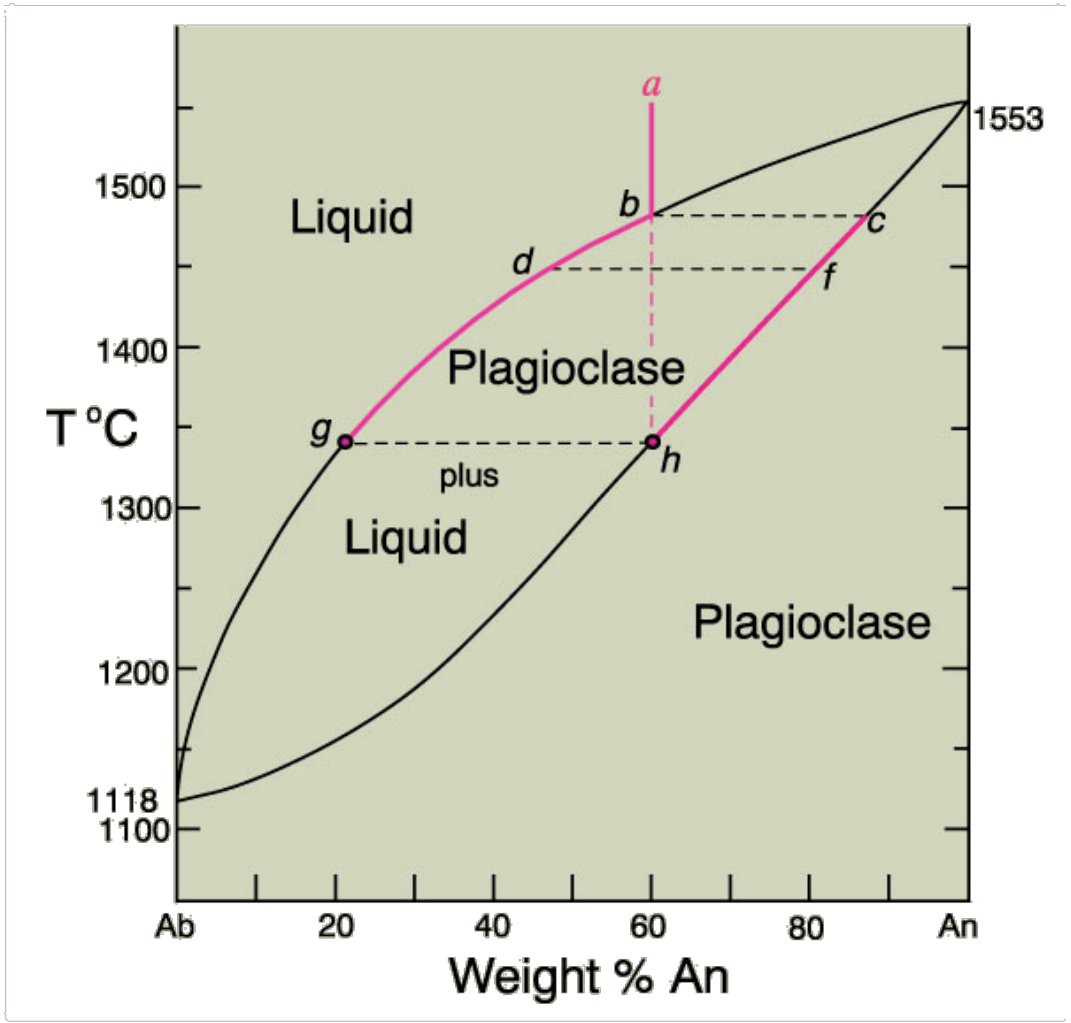
$$\frac{\text{Amount of liquid}}{\text{Amount of solid}} = \frac{\overline{ef}}{\overline{de}}$$

where d = the liquid composition, f = the solid composition and e = the bulk composition



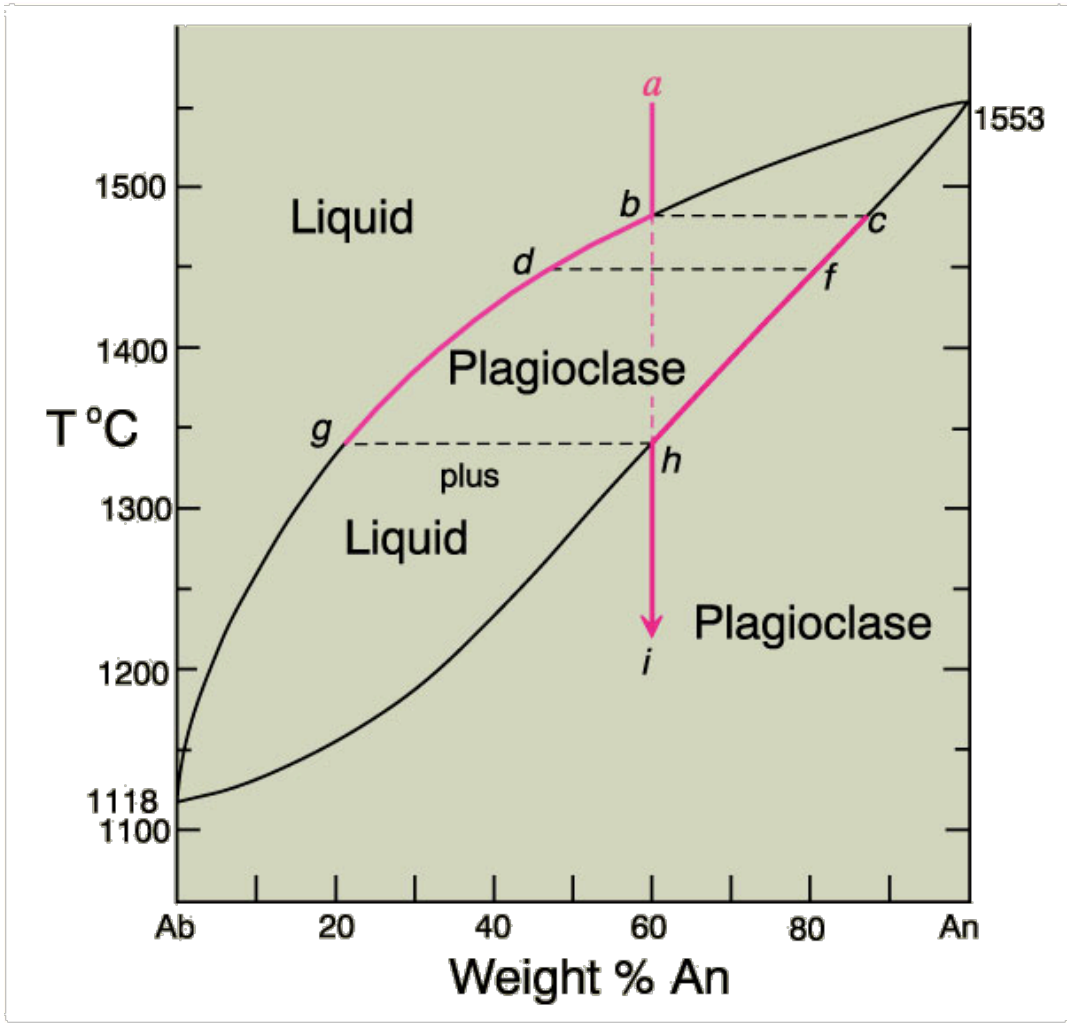
When $X_{plag} \rightarrow$ h, then $X_{plag} = X_{bulk}$ and, according to the lever principle, the amount of liquid $\rightarrow 0$

Thus g is the composition of the last liquid to crystallize at 1340°C for bulk X = 0.60



Final plagioclase to form is i when $X_{An}^{plag} = 0.60$

Now $\phi = 1$ so F = 2 - 1 + 1 = 2

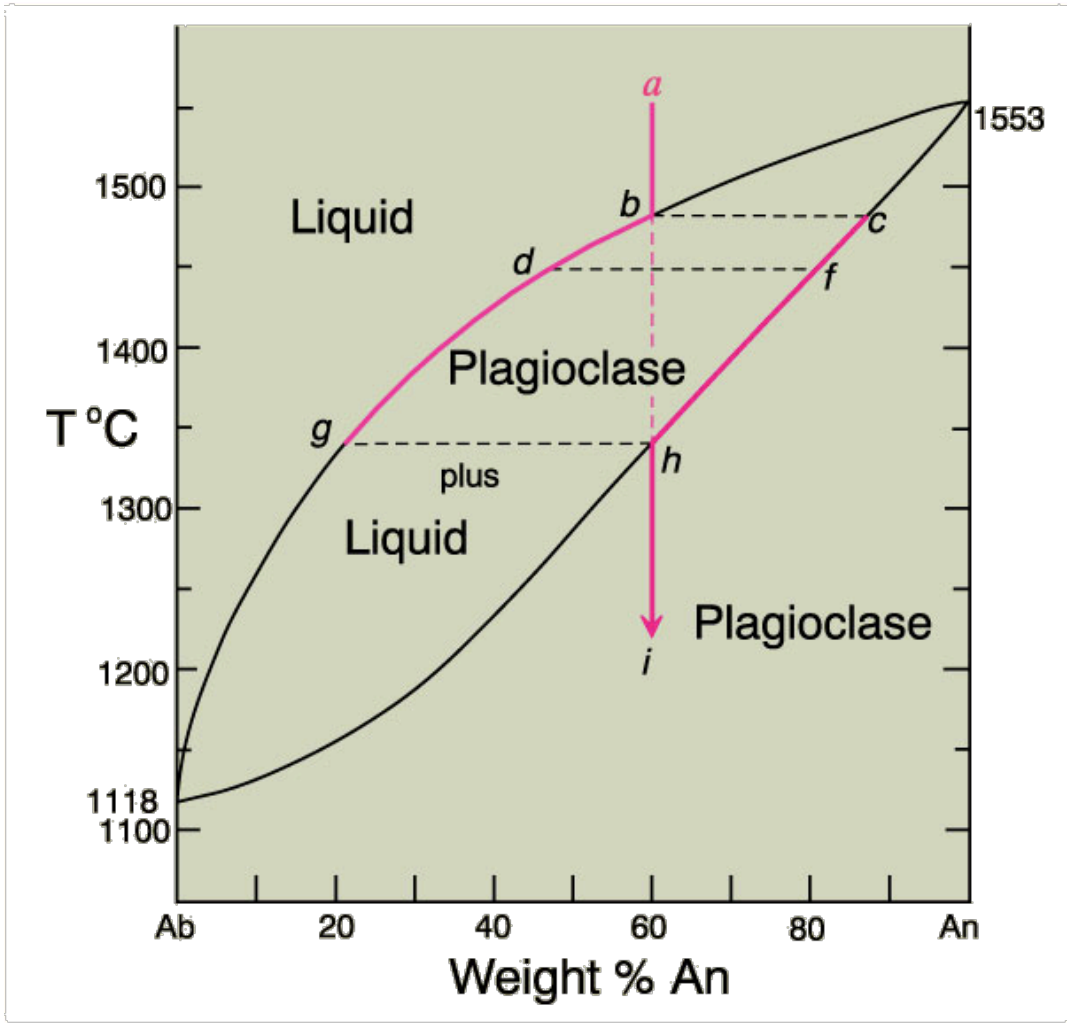


Note the following:

1. The melt crystallized over a T range of 135°C *
4. The composition of the liquid changed from b to g
5. The composition of the solid changed from c to h

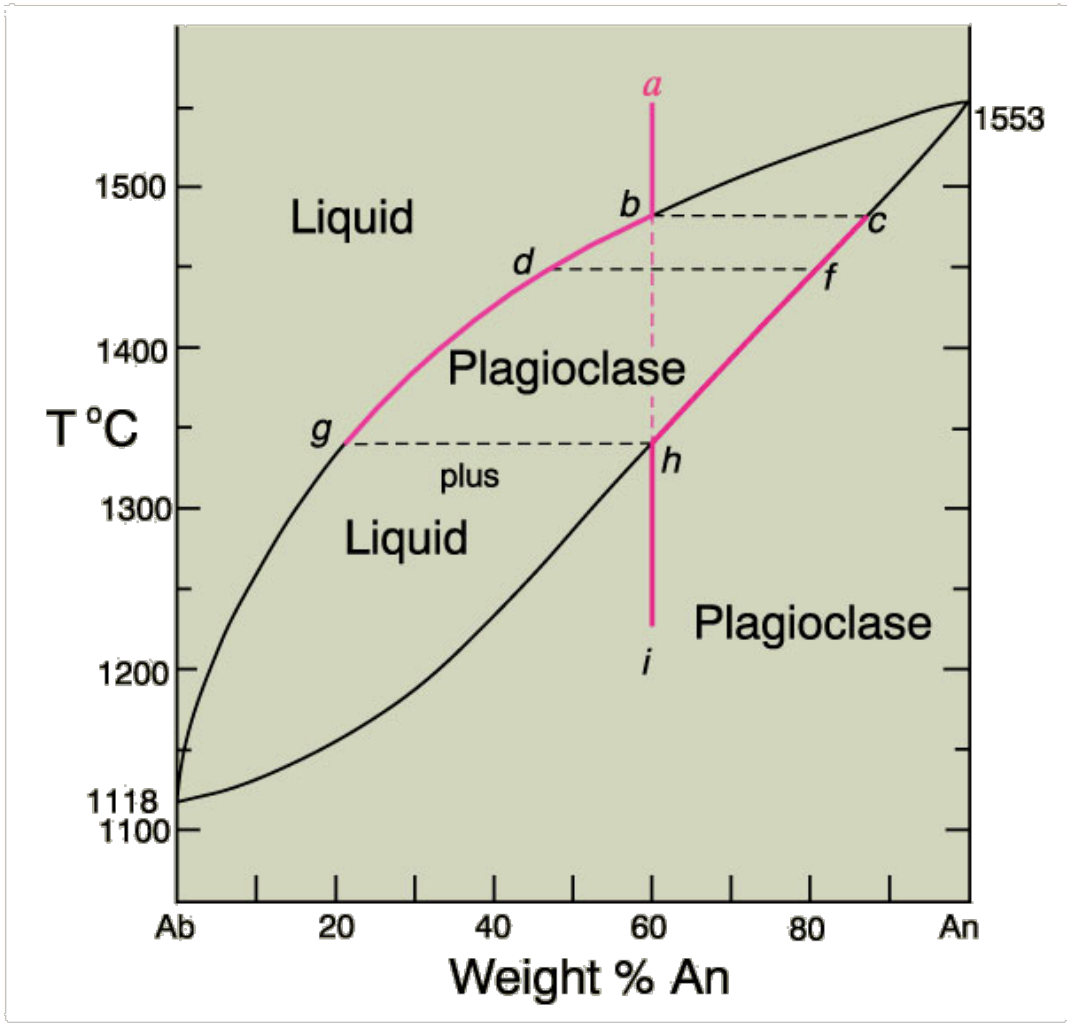
Numbers refer to the "behavior of melts" observations

* The actual temperatures and the range depend on the bulk composition



Equilibrium melting is exactly the opposite

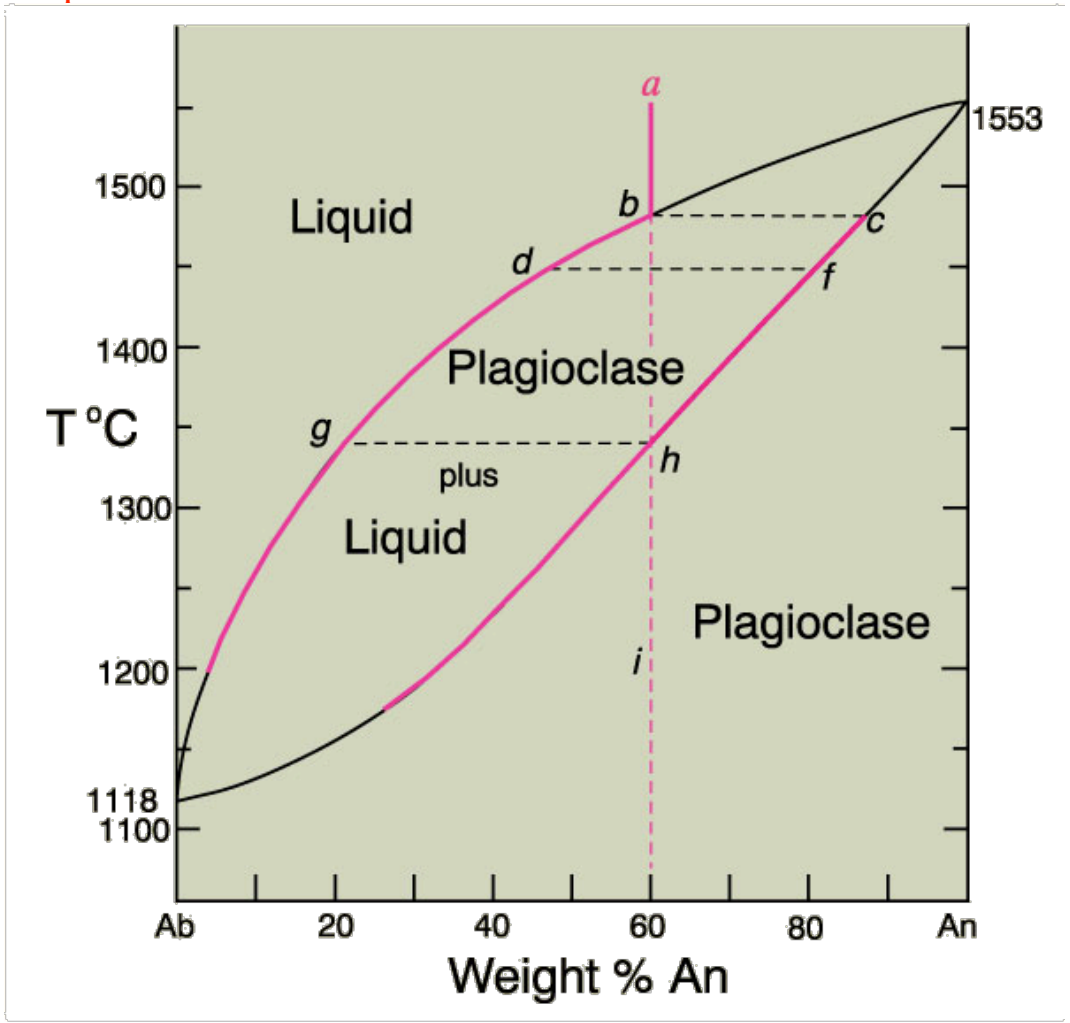
- Heat An_{60} and the first melt is g at An_{20} and 1340°C
- Continue heating: both melt and plagioclase change X
- Last plagioclase to melt is c (An_{87}) at 1475°C



Fractional crystallization:

Remove crystals as they form so they can't undergo a continuous reaction with the melt

At any T $X_{bulk} = X_{liq}$ due to the removal of the crystals

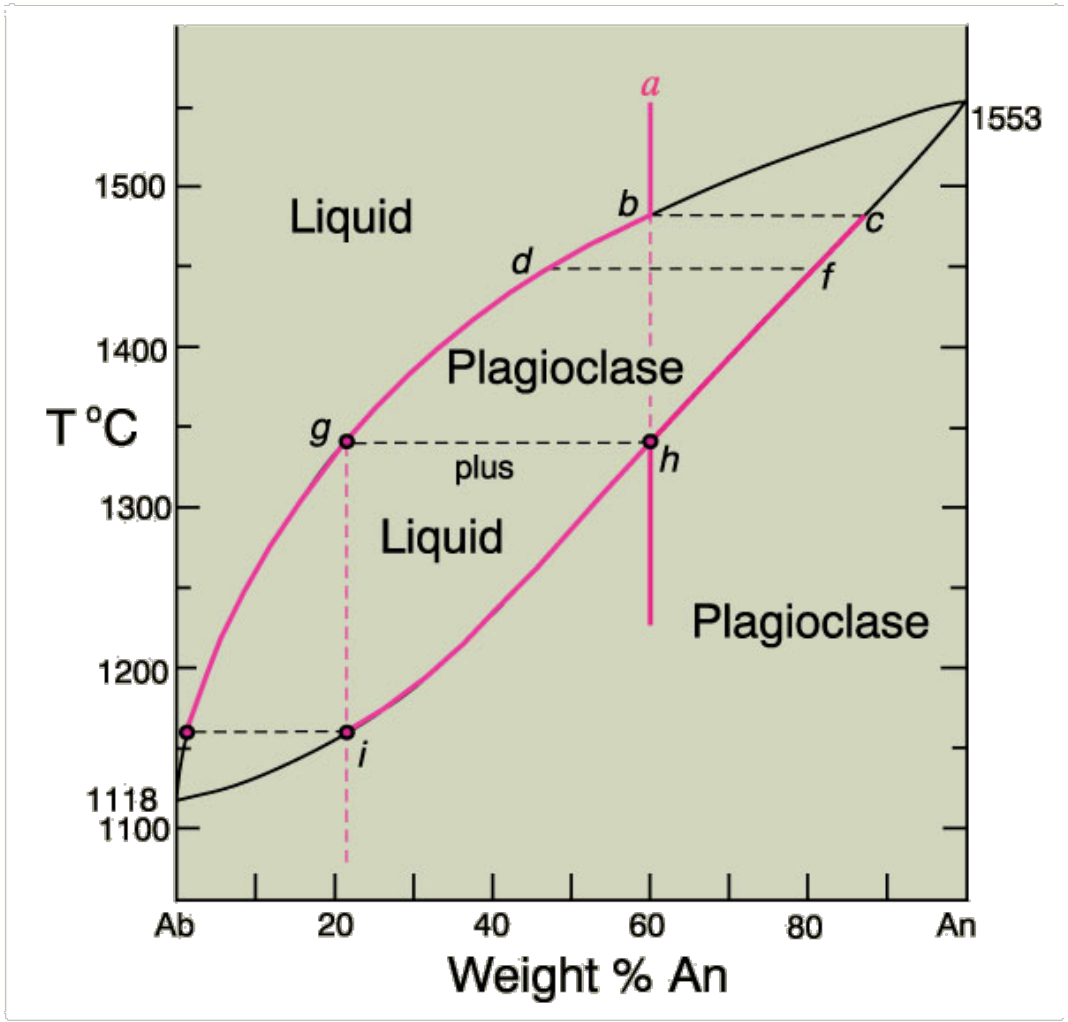


Partial Melting:

Remove first melt as forms

Melt X_{bulk} = 0.60 first liquid = ***g***

remove and cool bulk = g → final plagioclase = ***i***



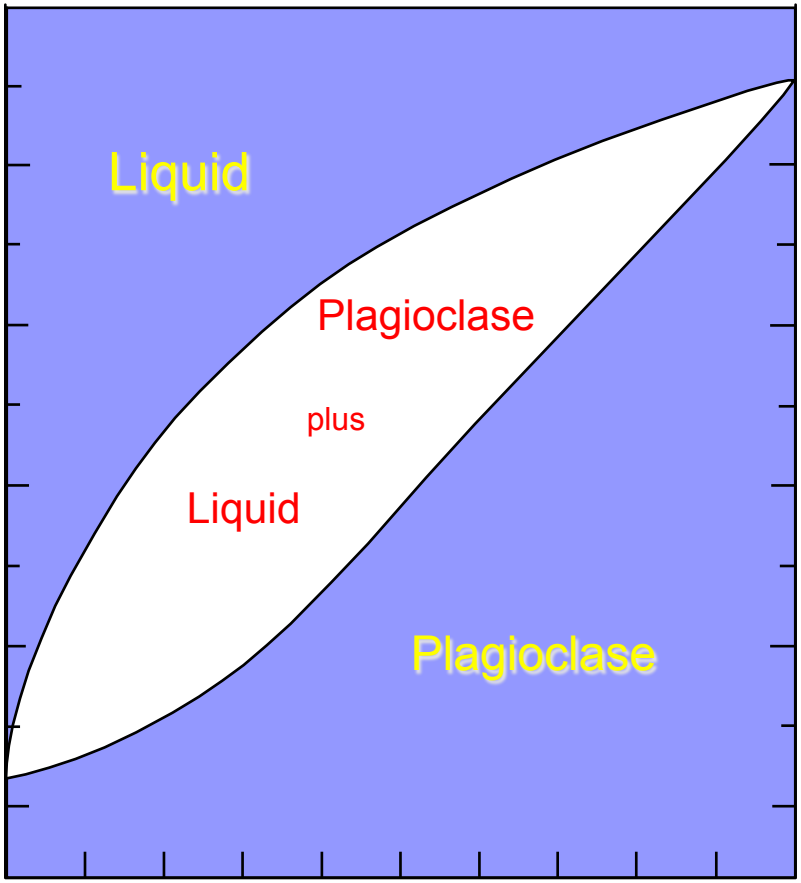
Note the difference between the two types of fields

The blue fields are one phase fields

Any point in these fields represents a true phase composition

The blank field is a two phase field

Any point in this field represents a bulk composition composed of two phases at the edge of the blue fields and connected by a horizontal tie-line



2. The Olivine System

Fo - Fa (Mg_2SiO_4 - Fe_2SiO_4)

also a solid-solution series

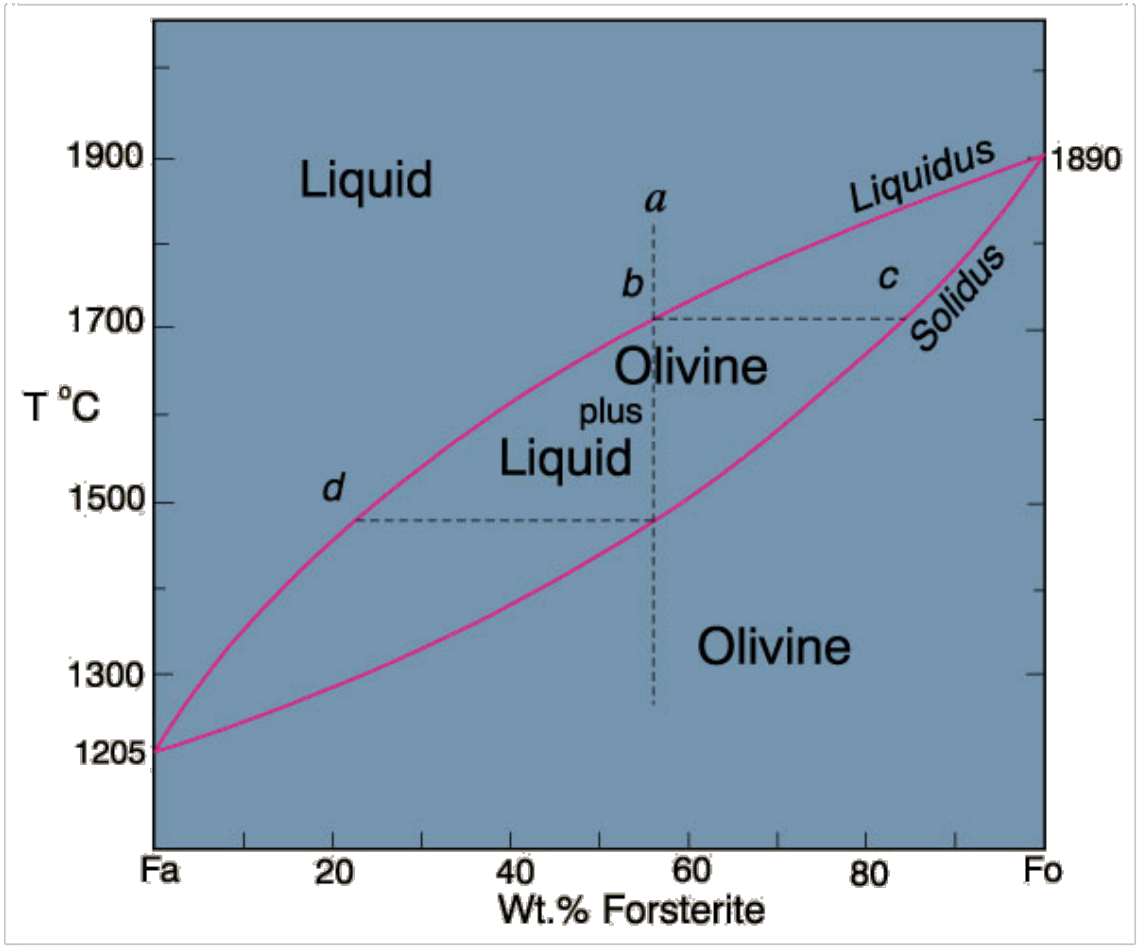


Fig. 6.10. Isobaric T-X phase diagram at atmospheric pressure After Bowen and Shairer (1932), Amer. J. Sci. 5th Ser., 24, 177-213.

2-C Eutectic Systems

Example: Diopside - Anorthite

No solid solution

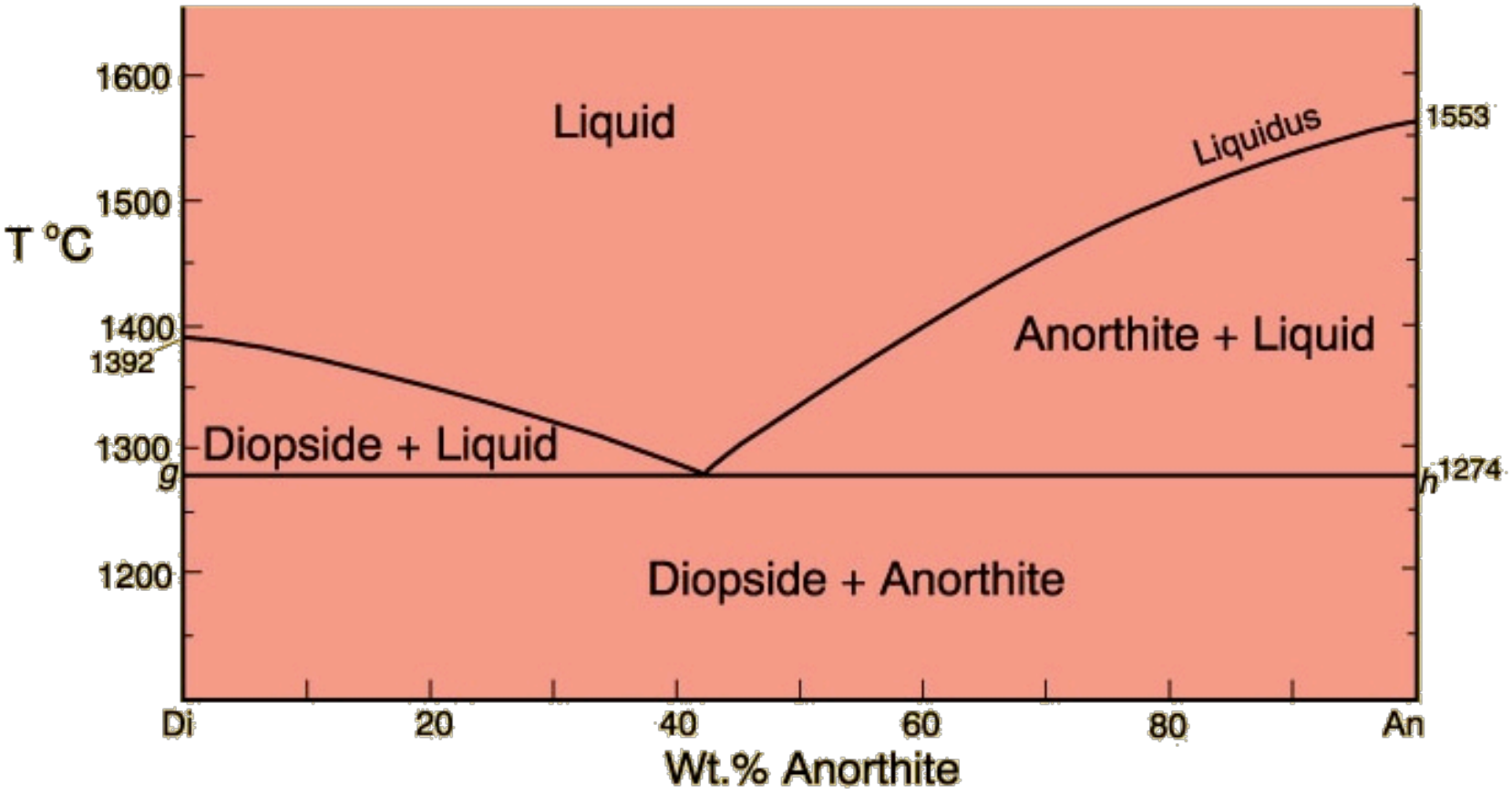


Fig. 6.11. Isobaric T-X phase diagram at atmospheric pressure. After Bowen (1915), Amer. J. Sci. 40, 161-185.

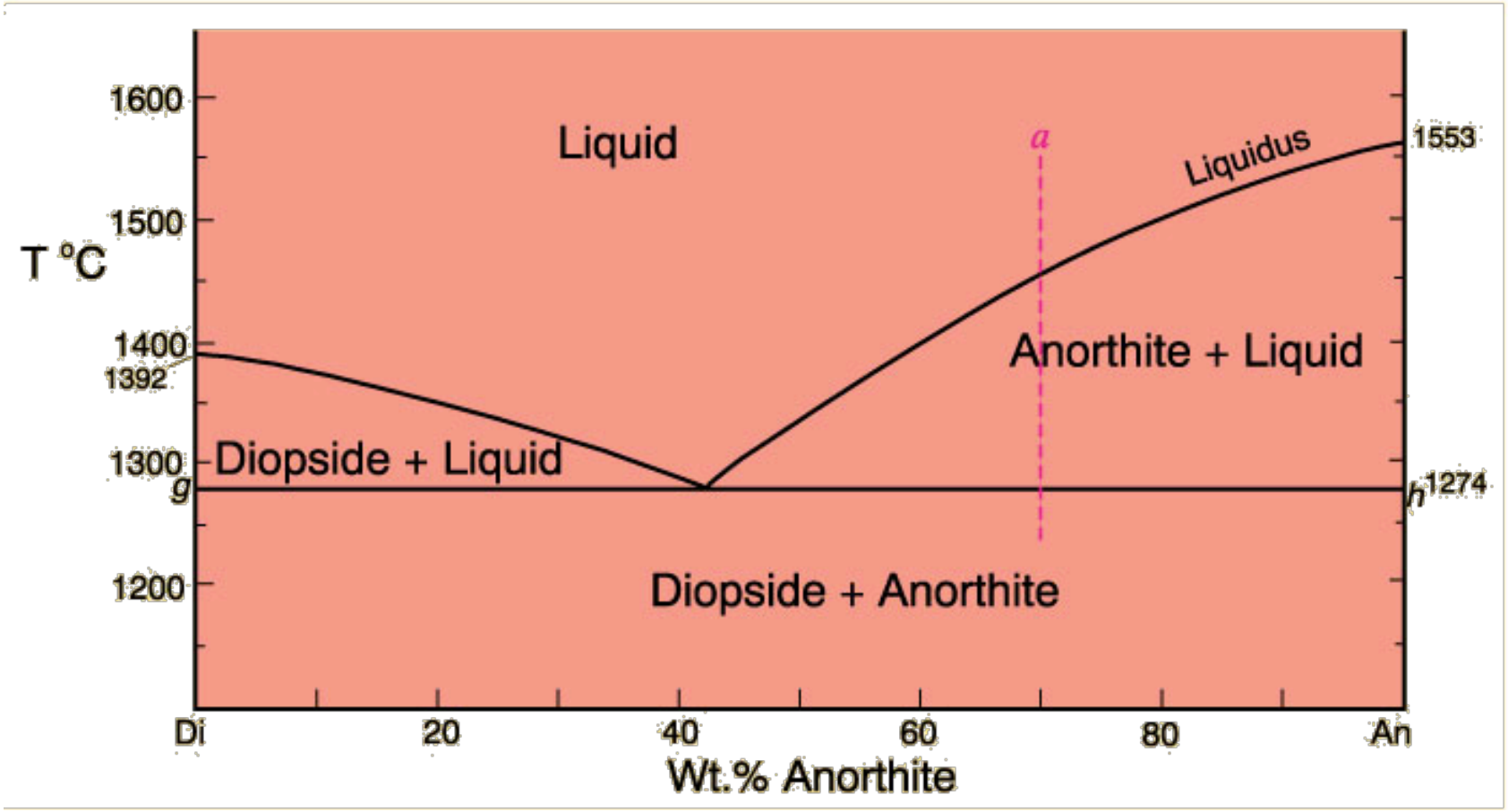
Diopside-anorthite a simplistic model for basalt …on Earth and Mars

Table 1. Crystalline components (amorphous-free) of the Rocknest scoop 5 soil.

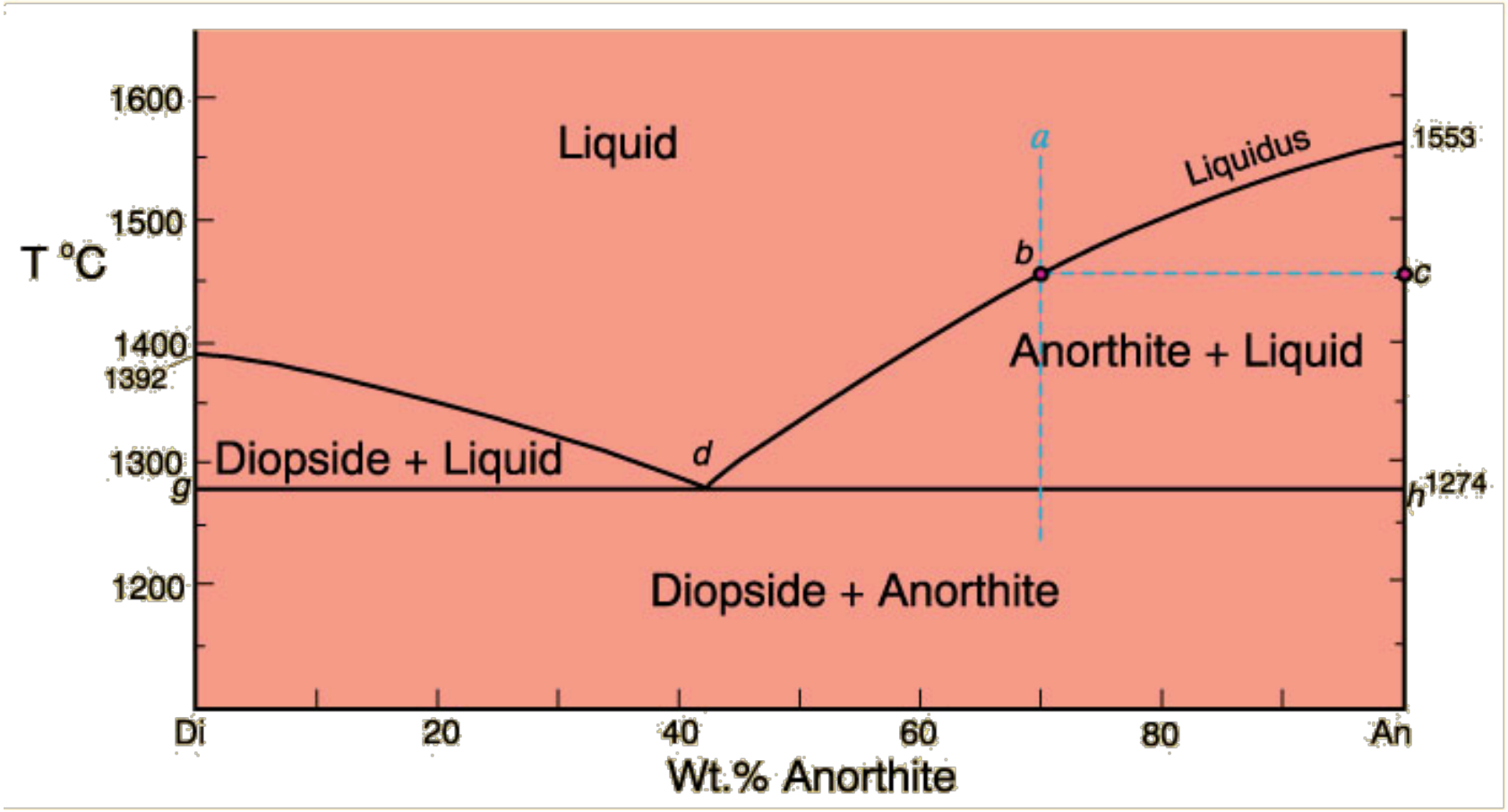
Mineral	Wt.%	2σ
Andesine (~An50)	42.9%	3.4%
Forsterite (~Fo58)	20.5%	2.6%
Augite	16.7%	3.5%
Pigeonite	11.4%	3.9%
Sanidine	2.1%	1.9%
Magnetite	1.8%	1.1%
Quartz	1.7%	0.7%
Anhydrite	1.4%	0.9%
Hematite	0.8%	1.1%
Ilmenite	0.7%	1.2%

Cool composition a:

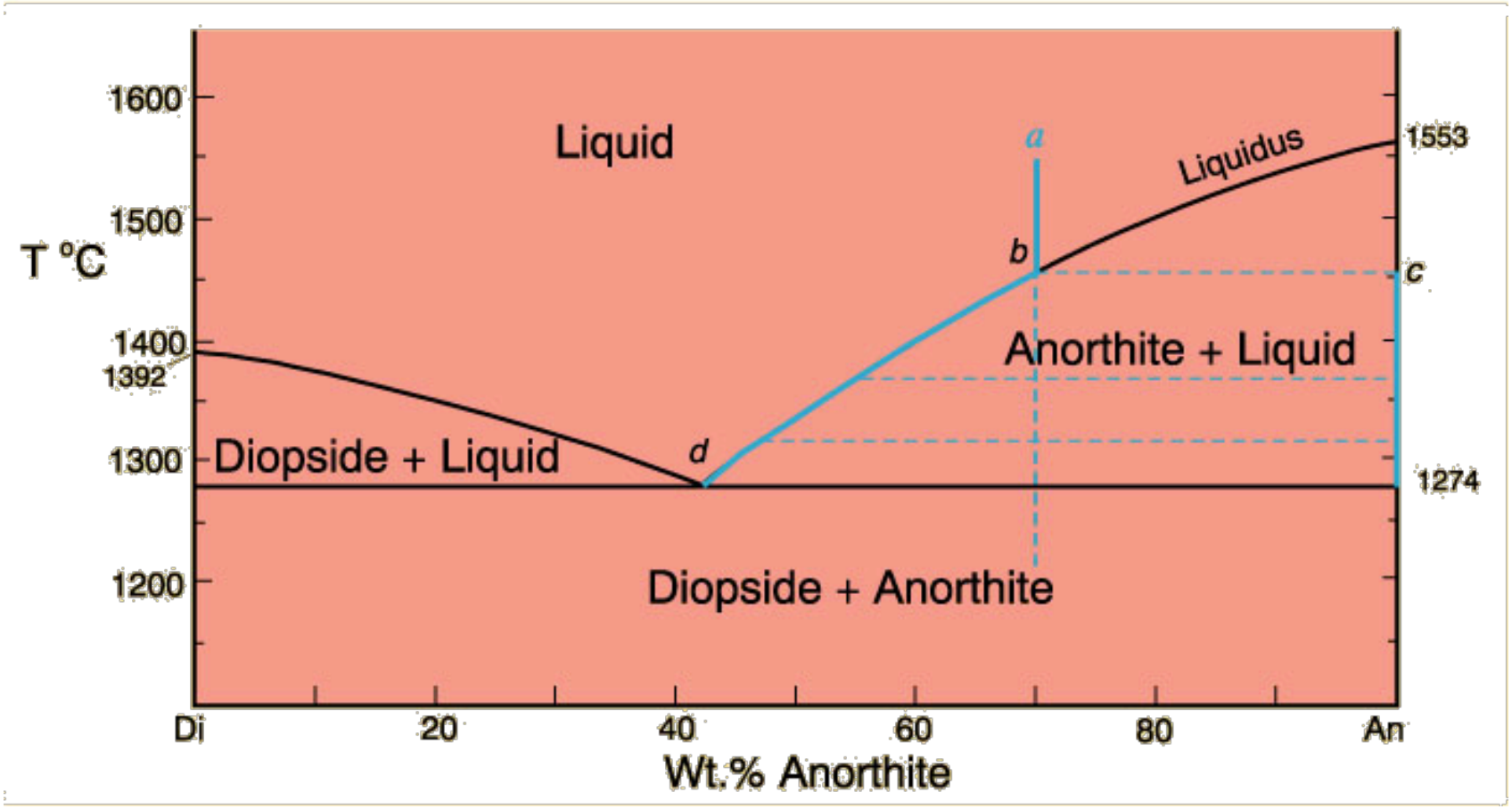
bulk composition = An_{70}



Cool to 1455°C (point b)

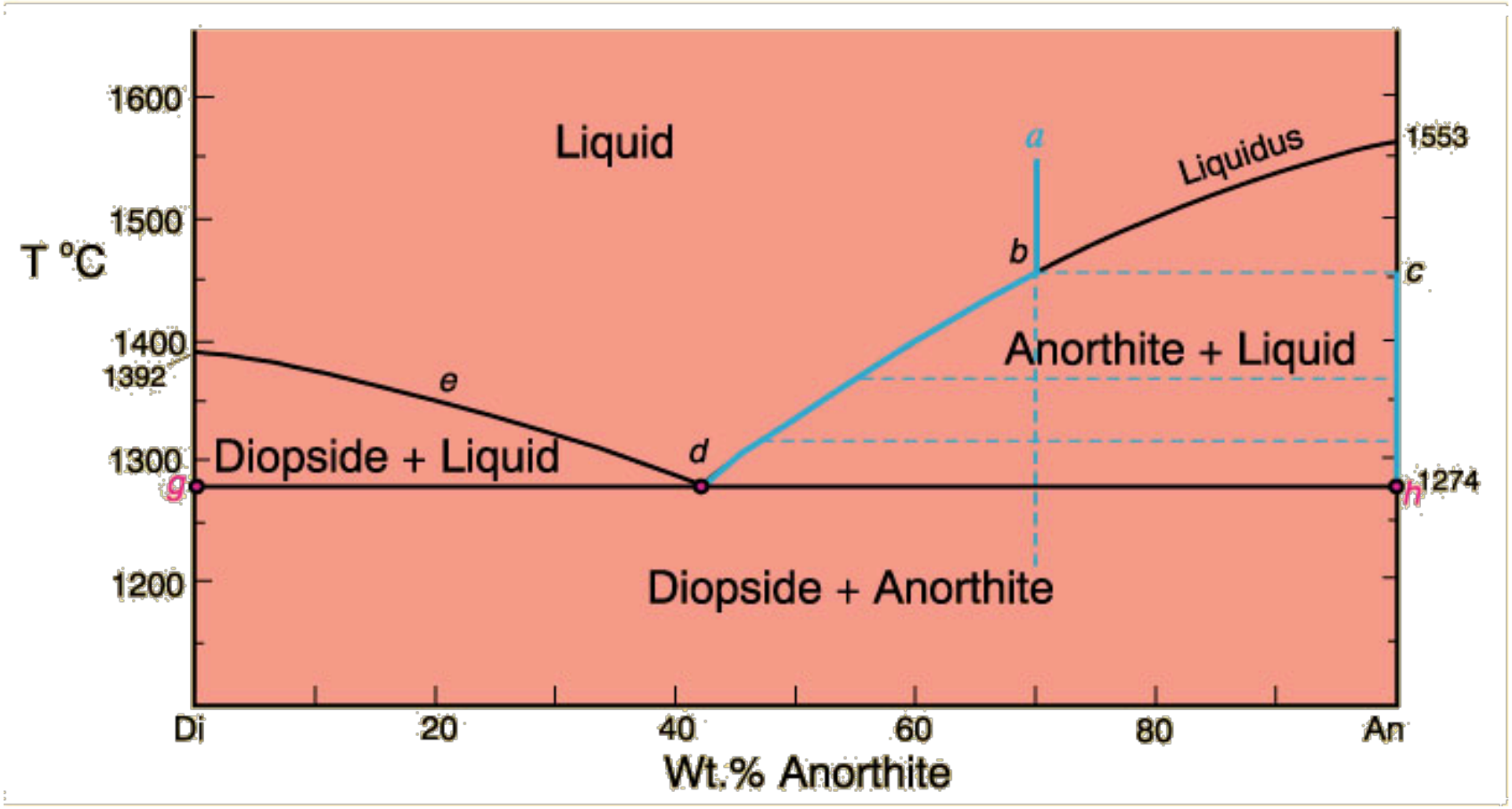


- Continue cooling as X_{liq} varies along the liquidus
- **Continuous reaction**: $liq_A \rightarrow$ anorthite + liq_B



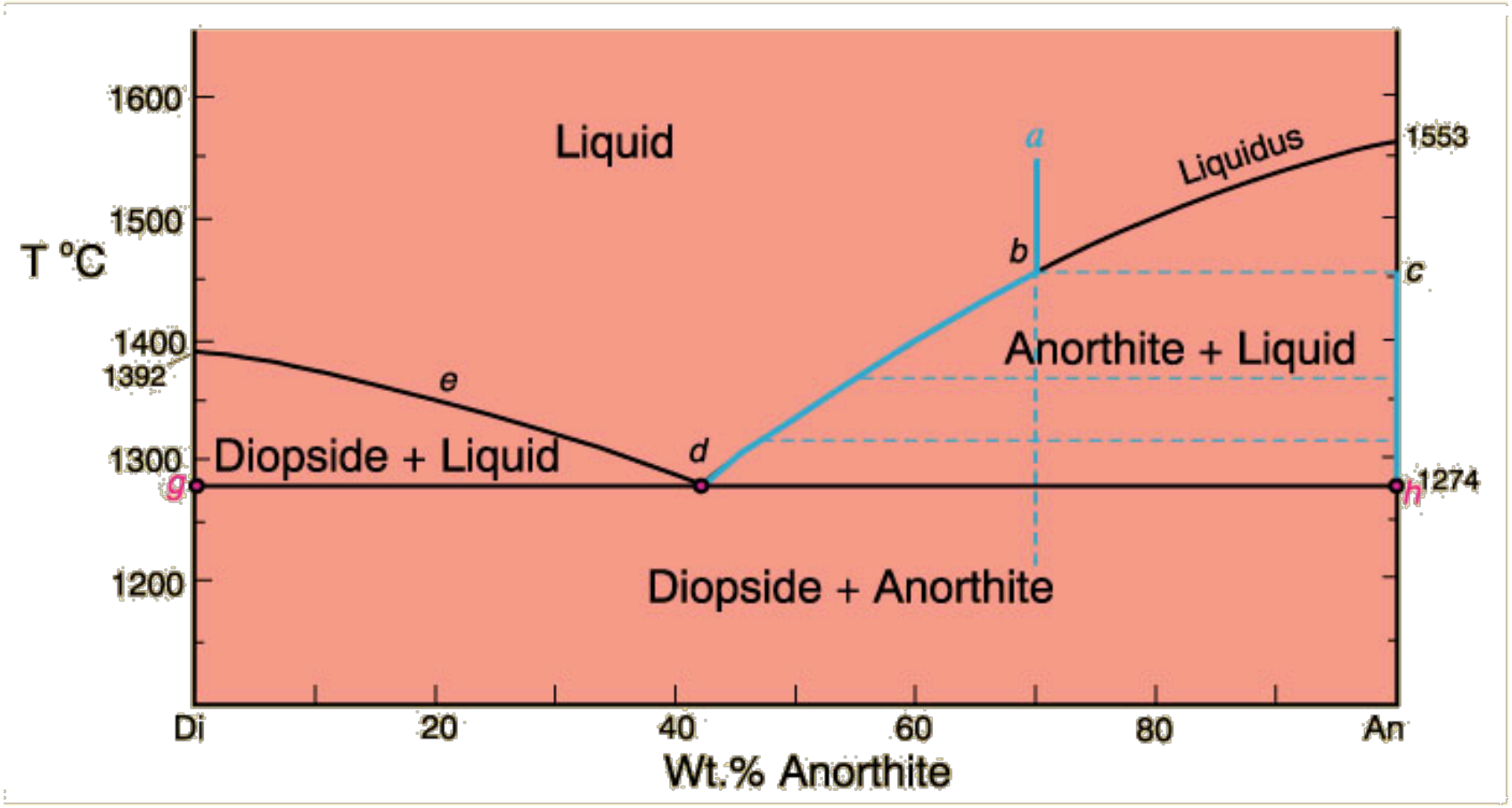
at 1274°C $\phi = 3$ so $F = 2 - 3 + 1 = 0$ invariant

- (P) T and the composition of all phases is fixed
- Must remain at 1274°C as a discontinuous reaction proceeds until a phase is lost

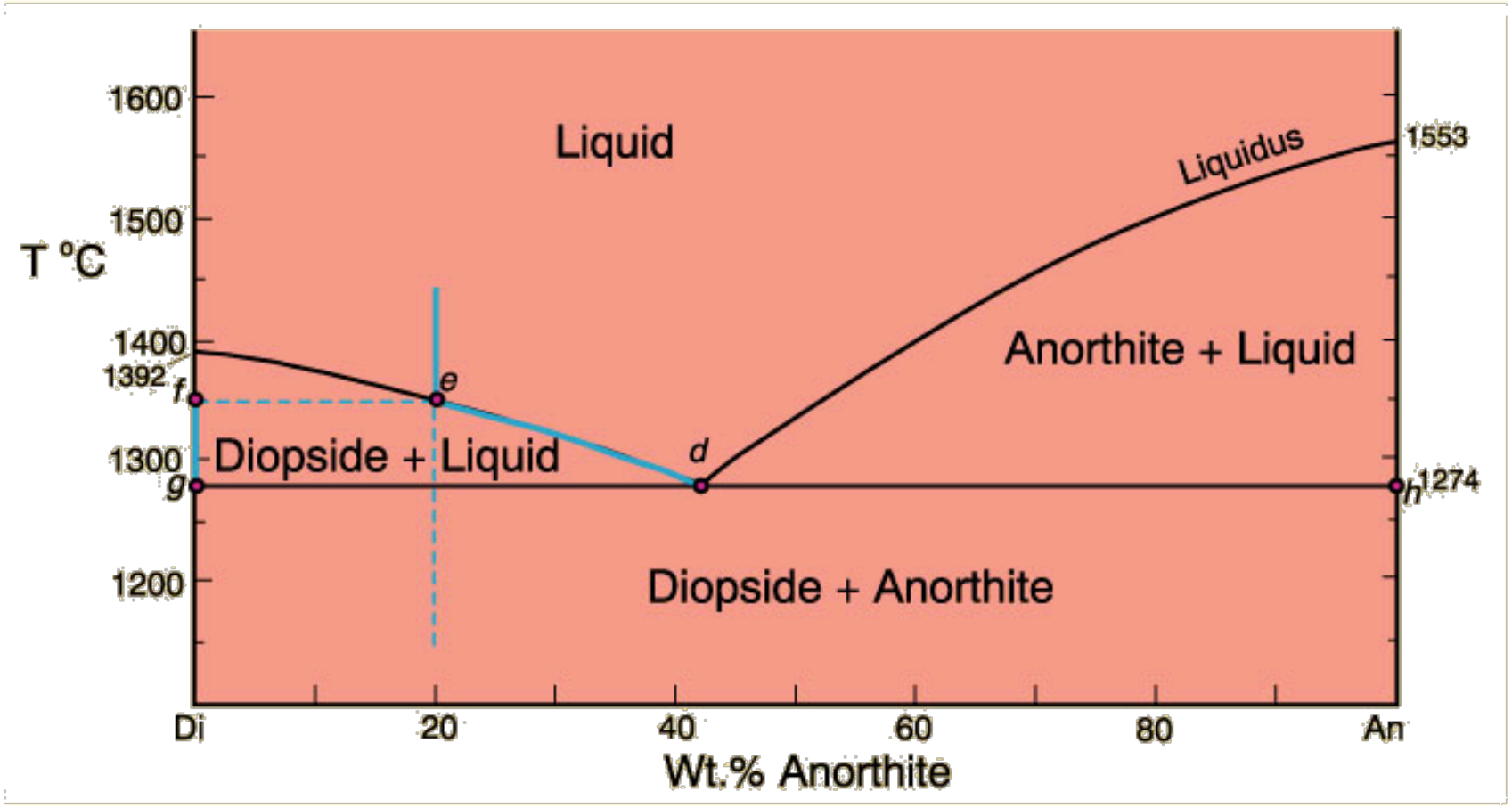


Discontinuous Reaction: all at a single T

- Use geometry to determine



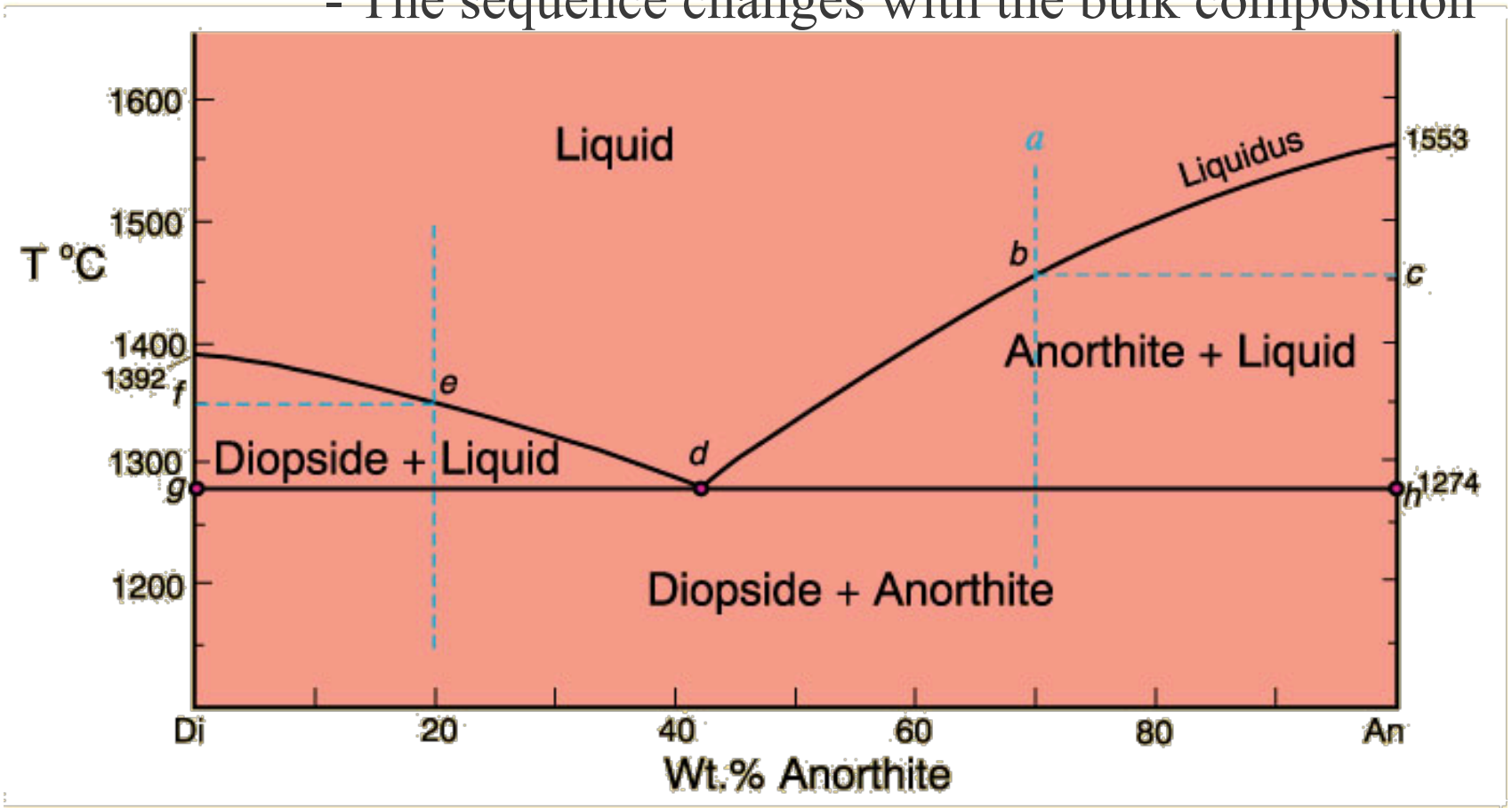
Left of the eutectic get a similar situation



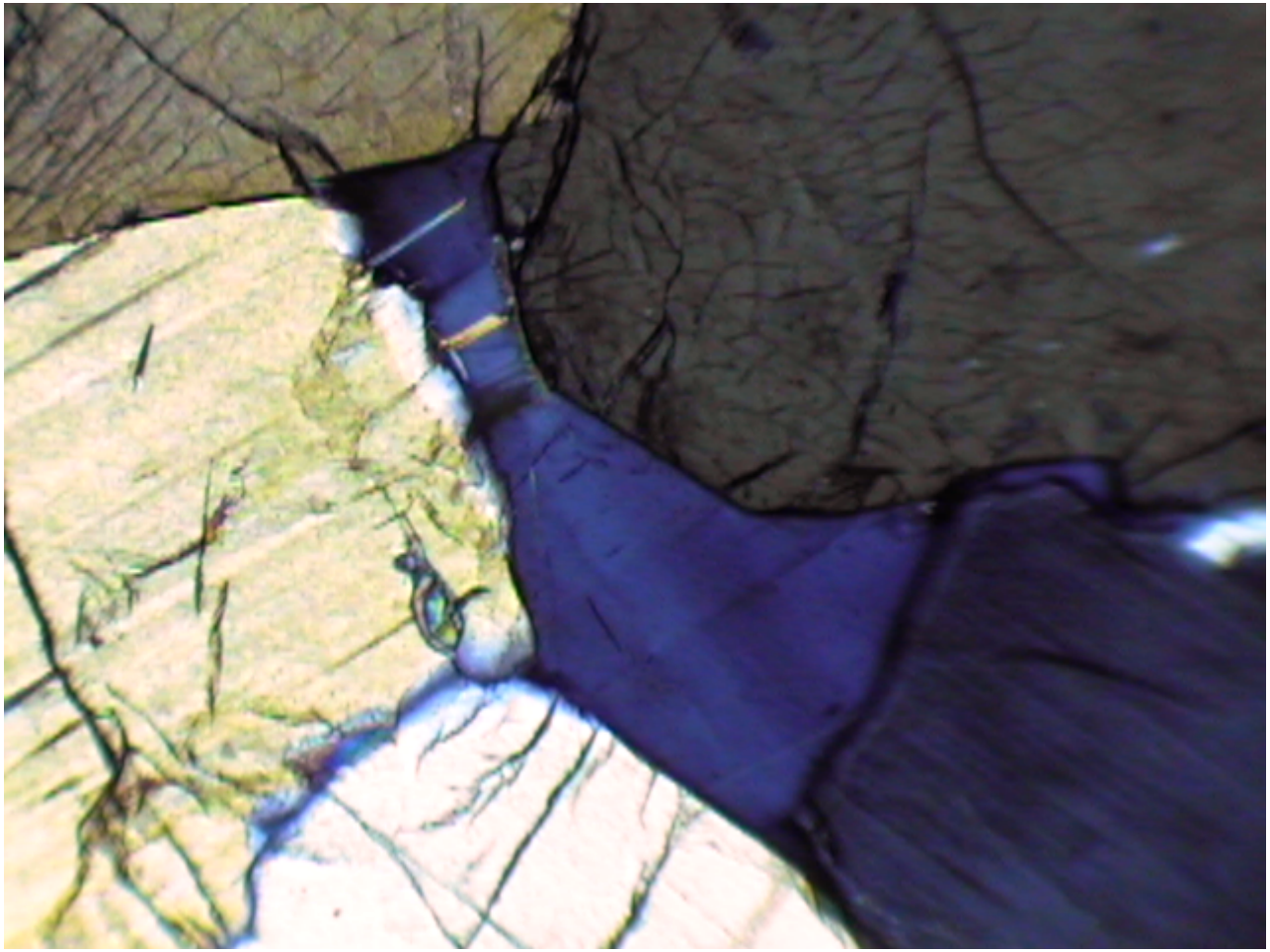
Note the following:

1. The melt crystallizes over a T range up to ~280°C
2. A sequence of minerals forms over this interval
   - And the number of minerals increases as T drops
6. The minerals that crystallize depend upon T
   - The sequence changes with the bulk composition

#s are listed points in text



Augite forms before plagioclase

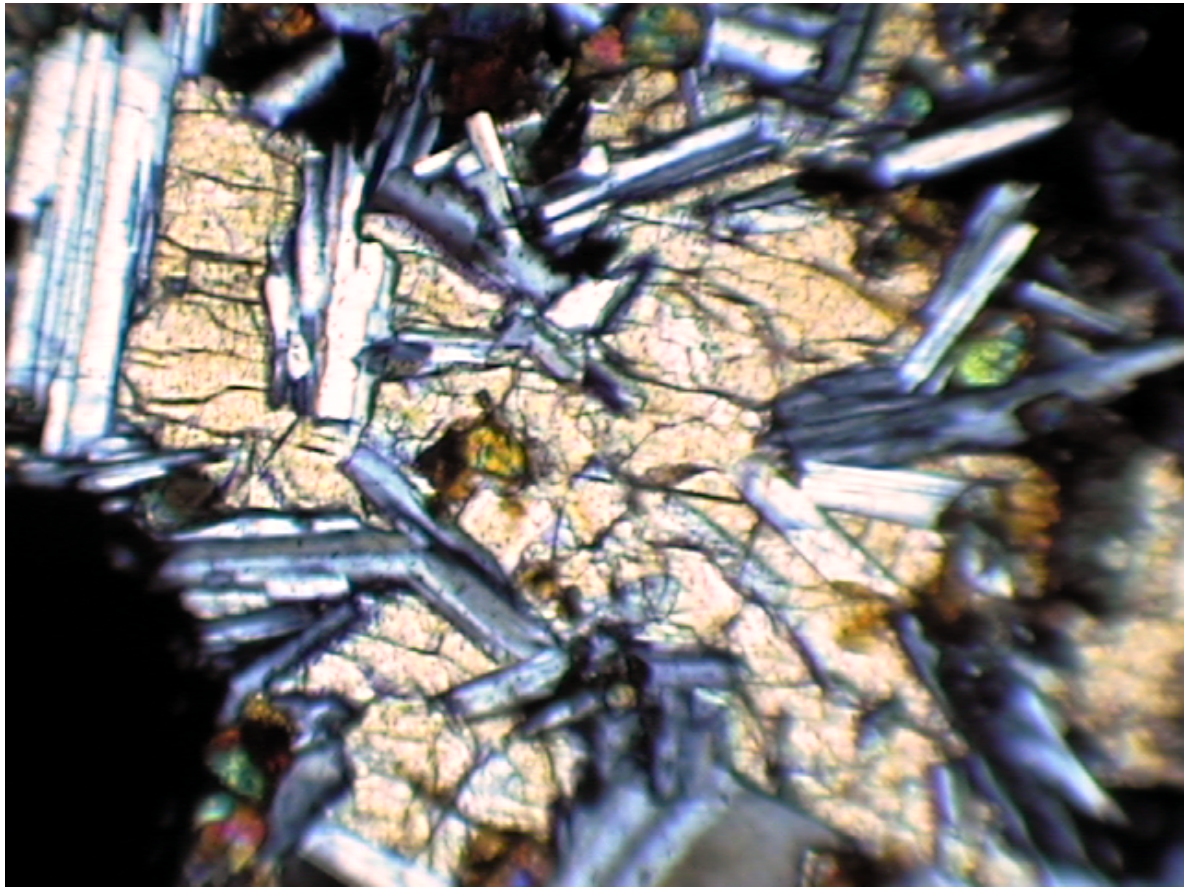


Gabbro of the Stillwater Complex, Montana

This forms on the left side of the eutectic

Plagioclase forms before augite

Ophitic texture



Diabase dike

This forms on the right side of the eutectic