

C = 3: Ternary Systems: Example 1: Ternary Eutectic Di - An - Fo

Note three binary eutectics

No solid solution

Ternary eutectic = M

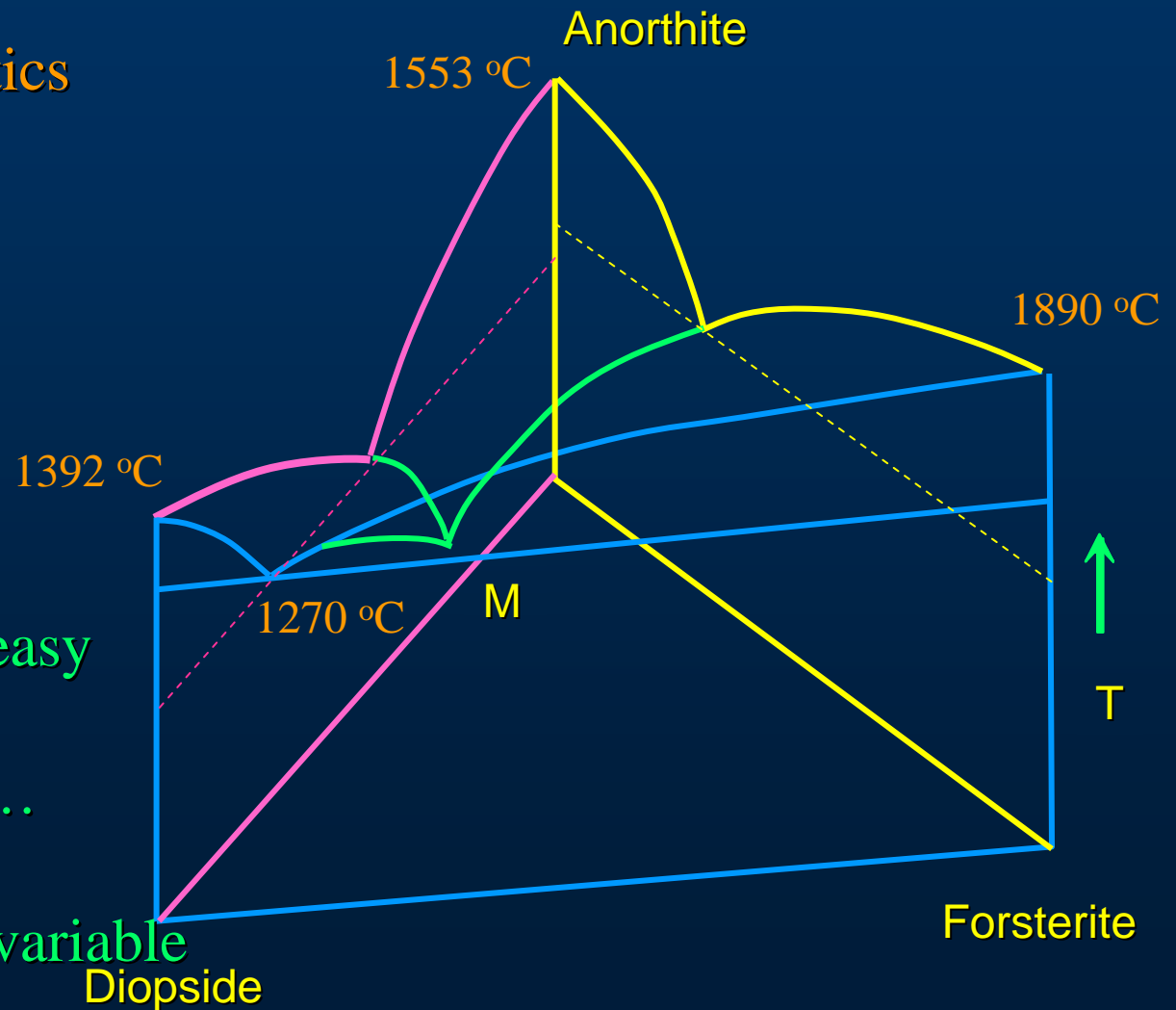
As add components,
becomes increasingly
difficult to depict.

1-C: P - T diagrams easy

2-C: isobaric T-X,
isothermal P-X...

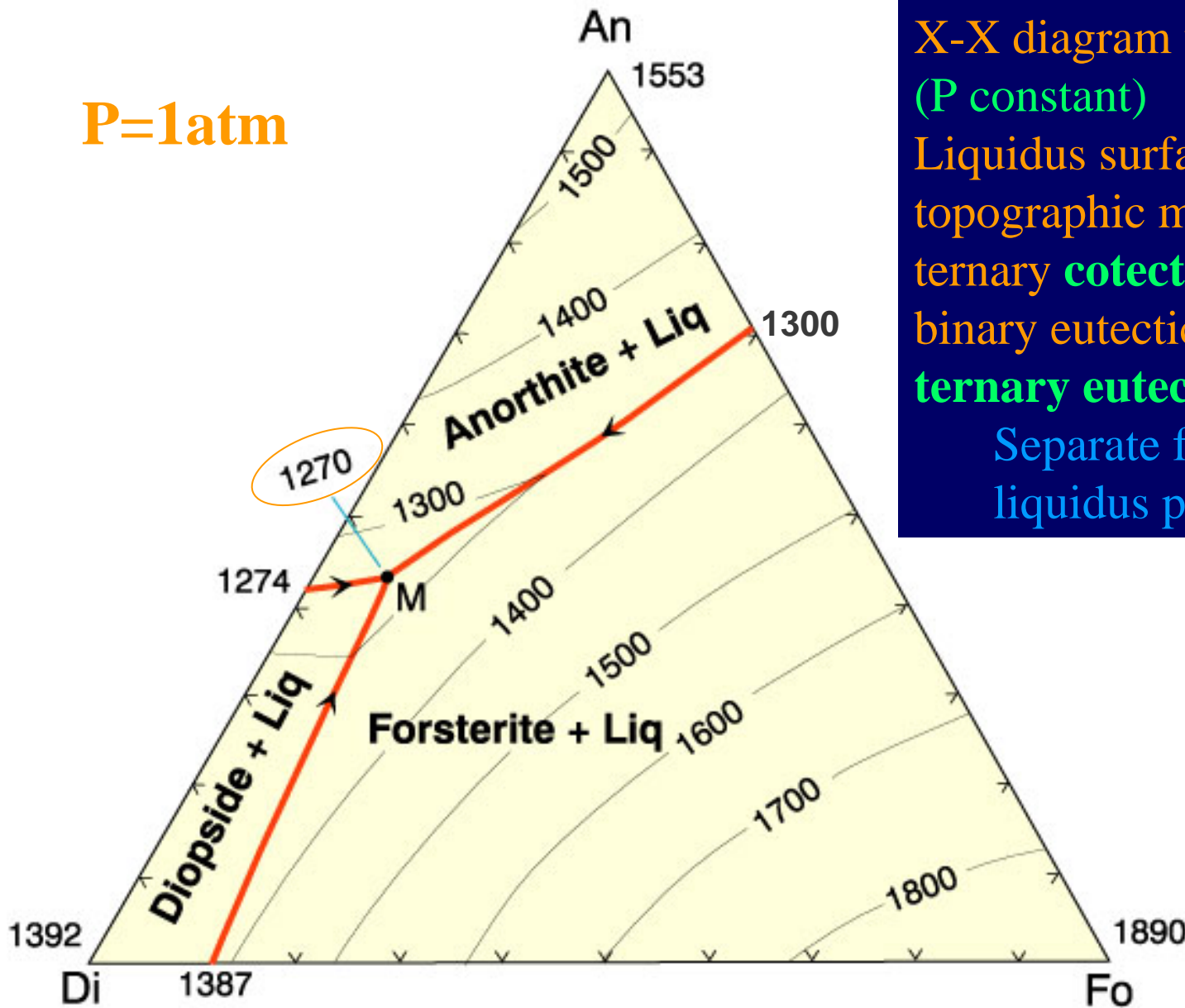
3-C: ??

Still need T or P variable



T - X Projection of Di - An - Fo

P=1atm



X-X diagram with T contours
(P constant)

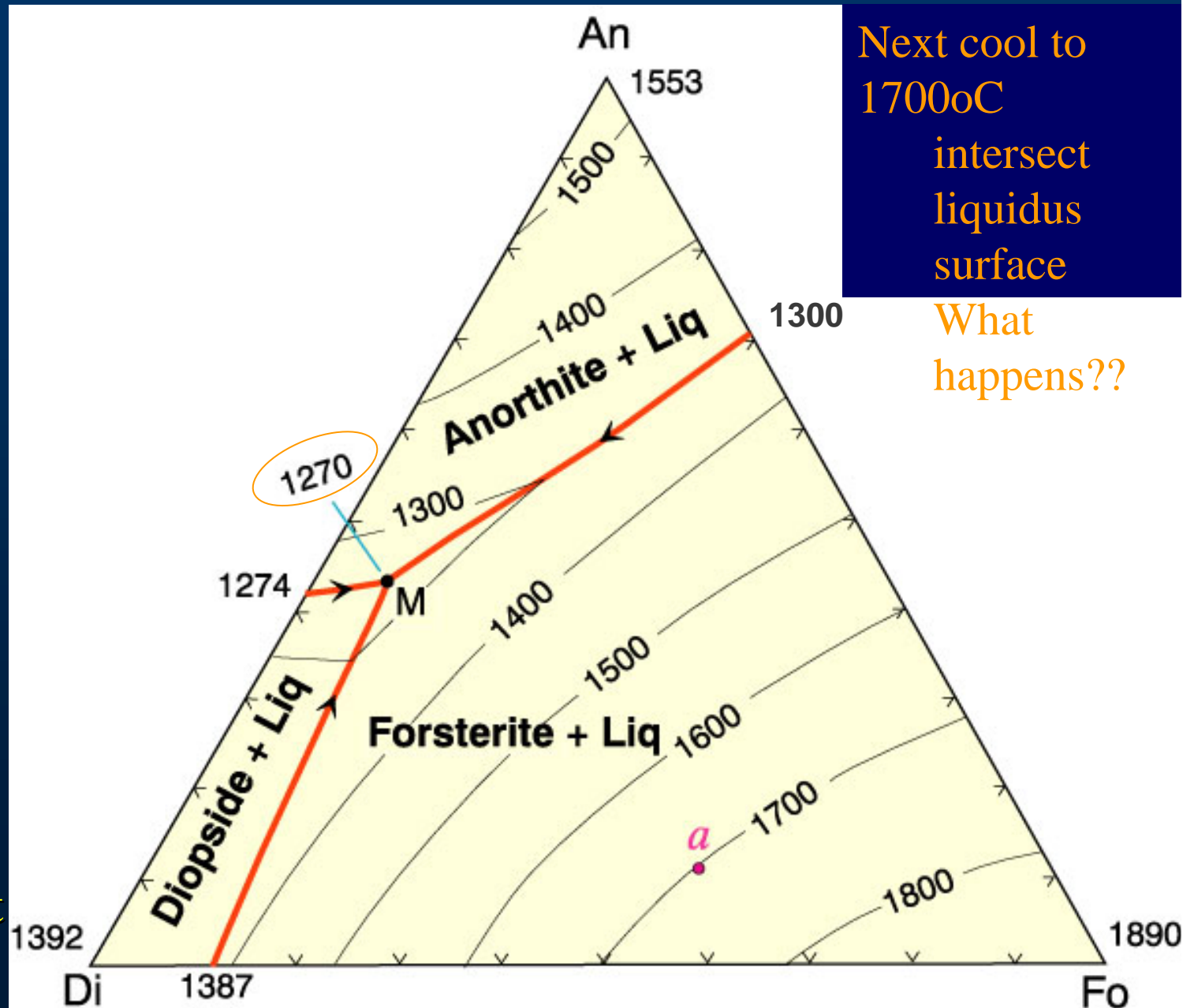
Liquidus surface works like
topographic map red lines are
ternary **cotectic** troughs run from
binary eutectics down T to
ternary eutectic M

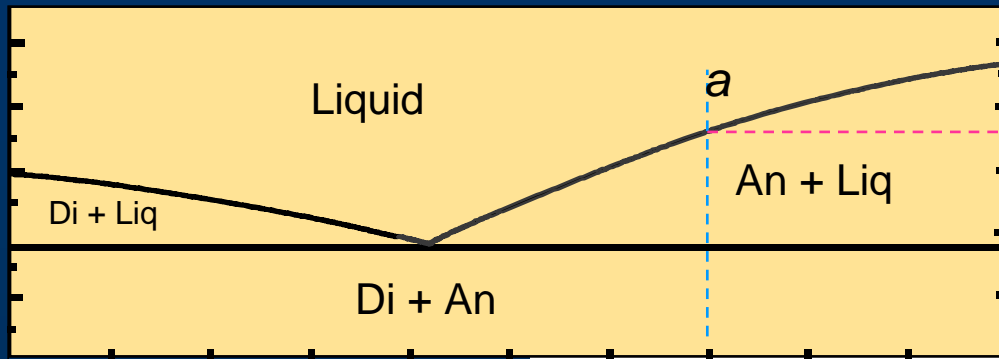
Separate fields labeled for
liquidus phase in that field

diagram illustrating
the liquidus
temperatures in the
Di-An-Fo system at
atmospheric pressure
(0.1 MPa). After
Bowen (1915), A. J.
Sci., and Morse
(1994), Basalts and
Phase Diagrams.
Krieger Publishers.

Crystallization Relationships

Cool
composition
a from 2000oC
At 2000oC:
phi = ? (1
(liquid)
F = ?
F = C - f + 1
= 3 - 1 + 1 = 3
= T,
X(An)Liq,
X(Di)Liq,
and X(Fo)Liq
only 2 of 3 X's
are independent



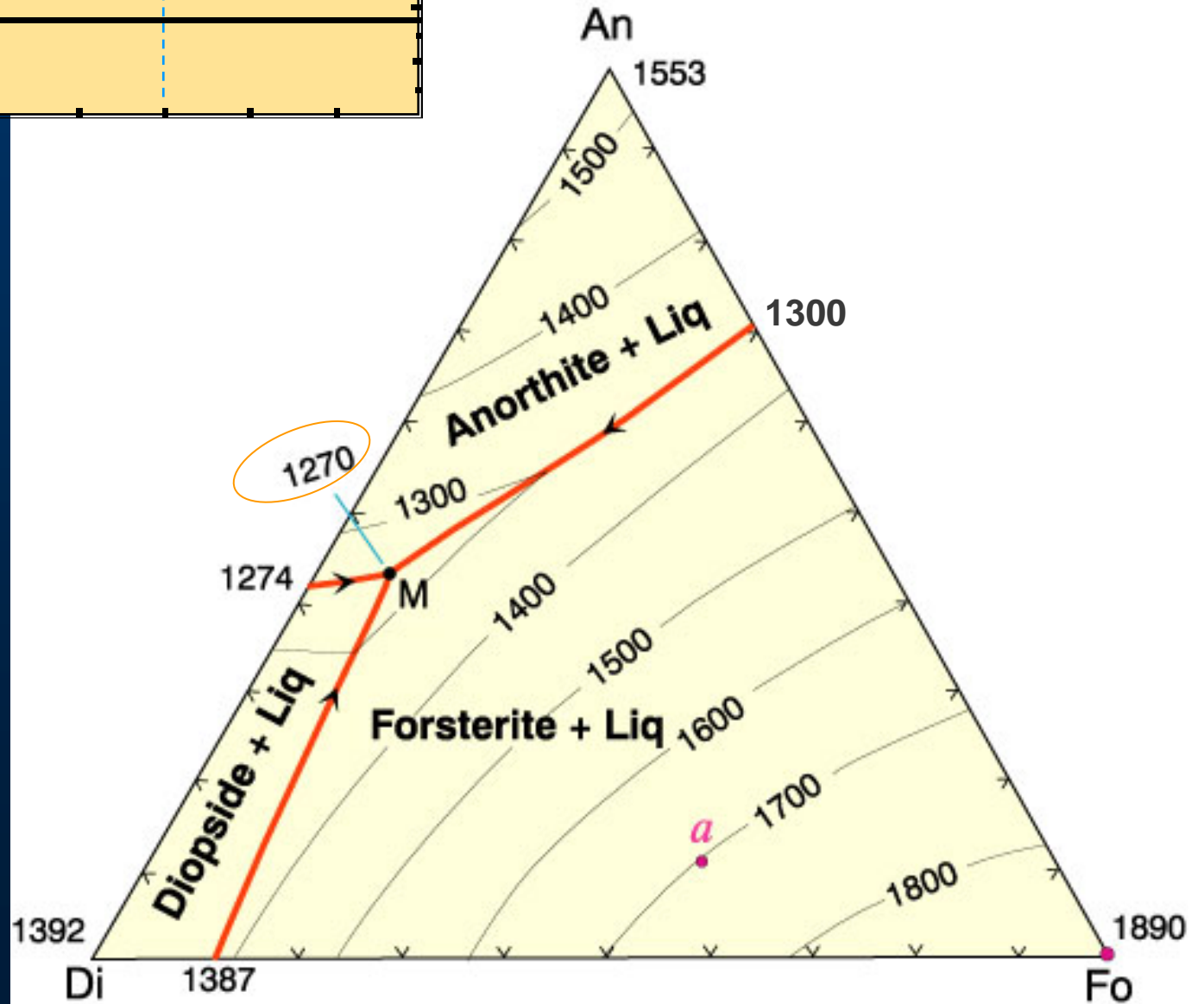


An

Pure Fo forms
just as in binary

$\phi = ?$

$F = ?$



☞ $\phi = 2$ (Fo + Liq)

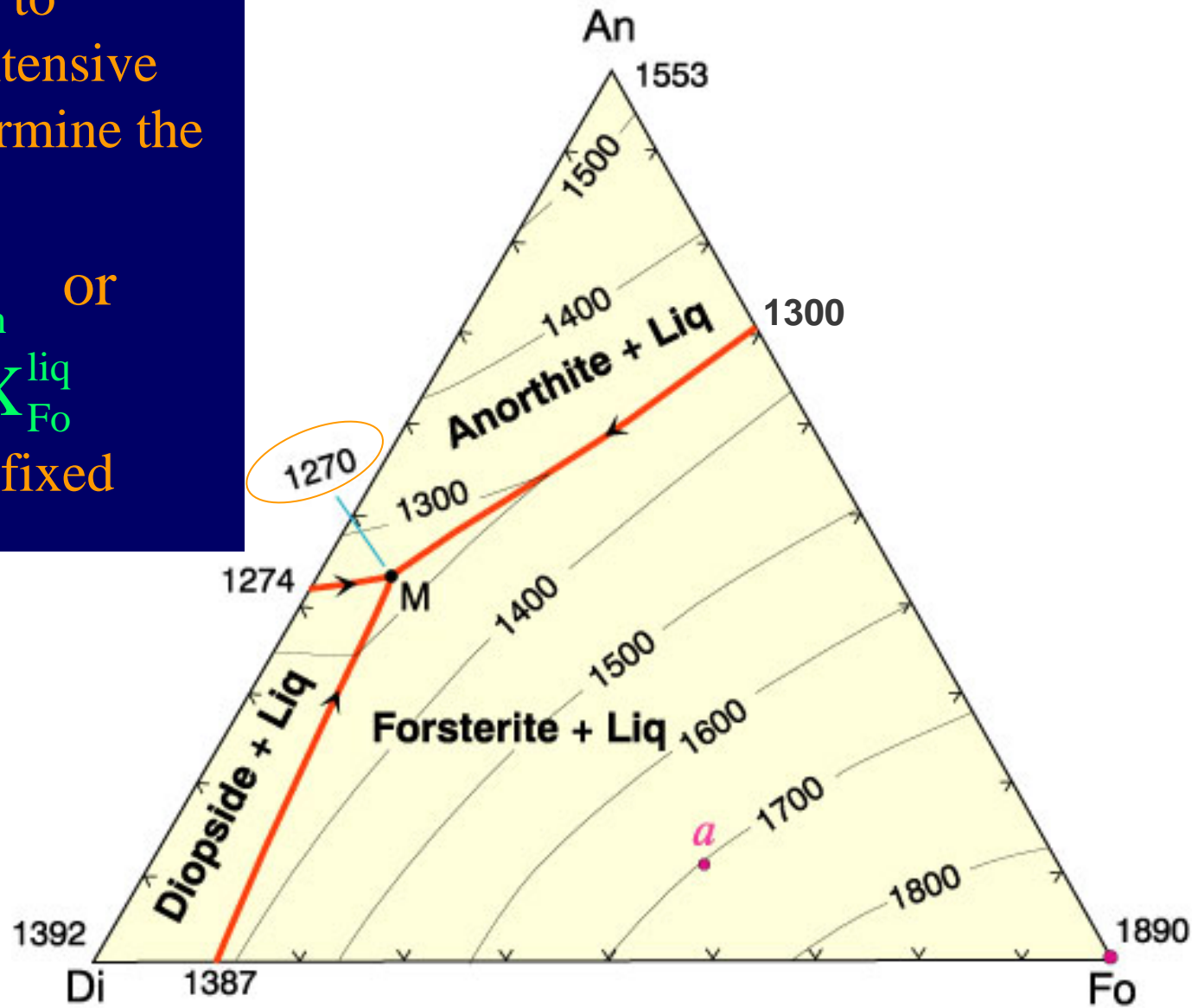
☞ $F = 3 - 2 + 1 = 2$

If on liquidus, need to specify only 2 intensive variables to determine the system

☞ T and $X_{\text{An}}^{\text{liq}}$ or

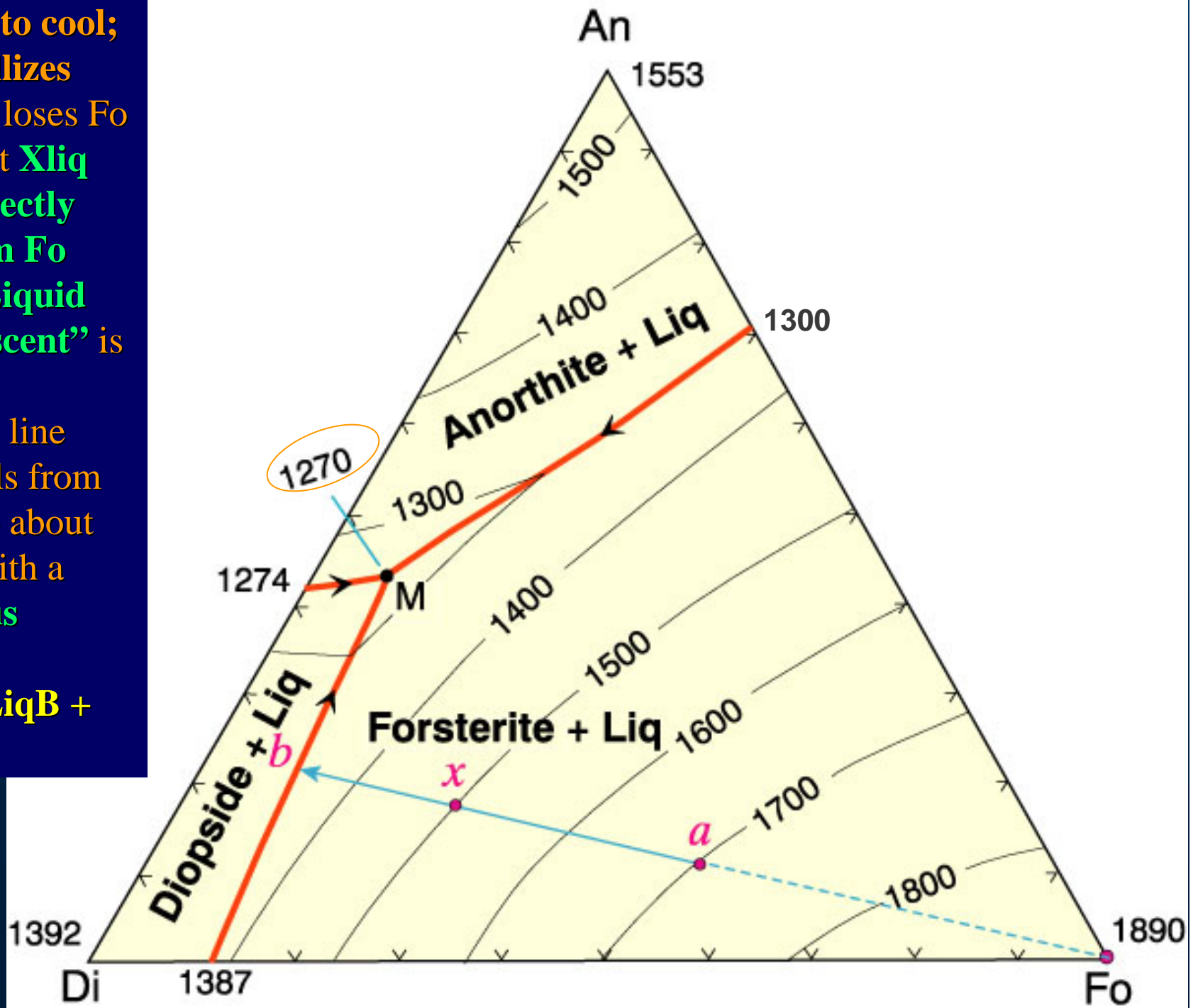
☞ $X_{\text{Di}}^{\text{liq}}$ and $X_{\text{Fo}}^{\text{liq}}$

X of pure Fo is fixed



Continue to cool;
Fo crystallizes
and liquid loses Fo
component X_{liq}
moves directly
away from Fo
corner “Liquid
line of descent” is
a -> b

Along this line
liquid cools from
1700oC to about
1350oC with a
continuous
reaction:
 $LiqA \rightarrow LiqB +$
 Fo



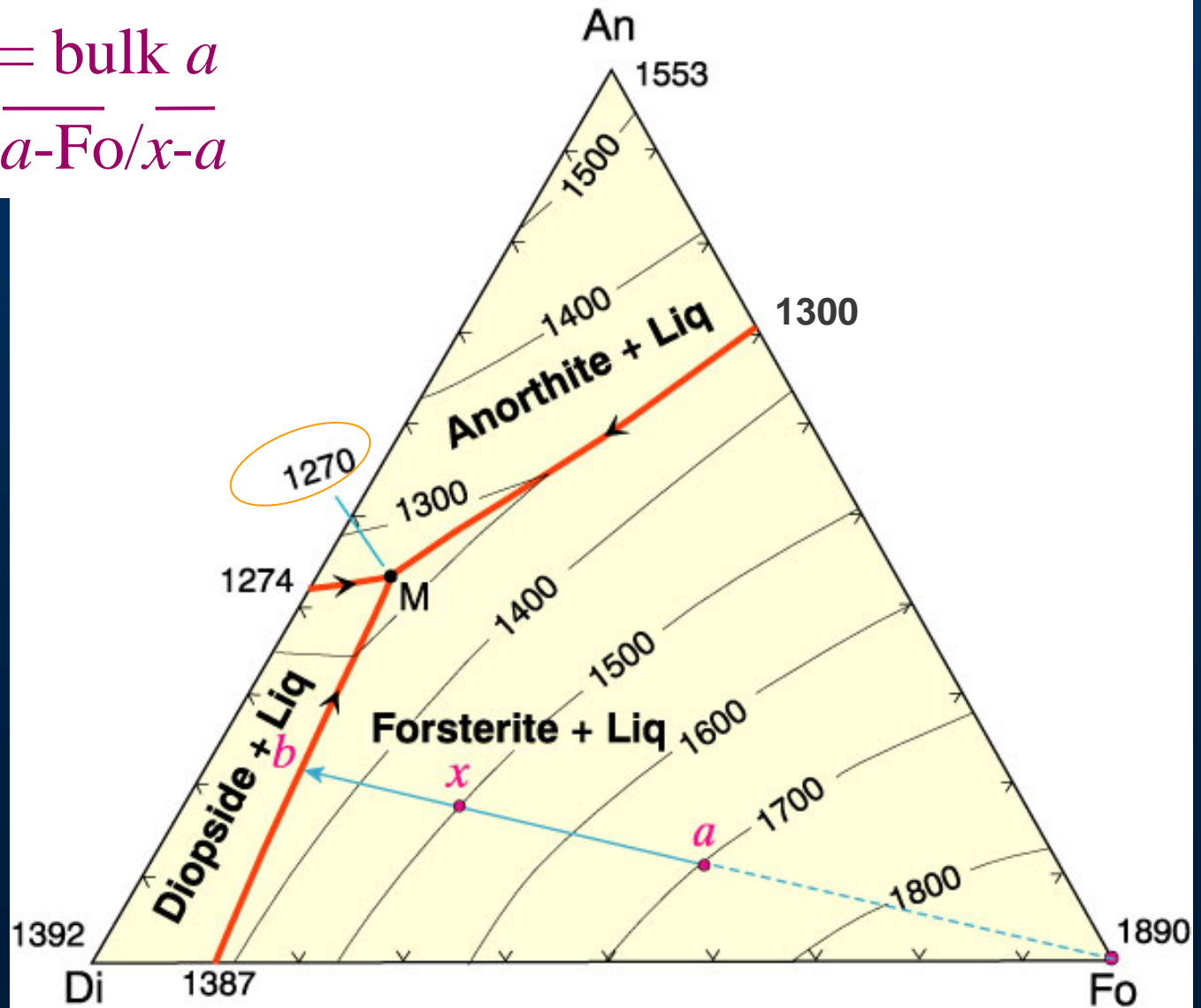
Lever principle → relative proportions of liquid & Fo

- At 1500°C

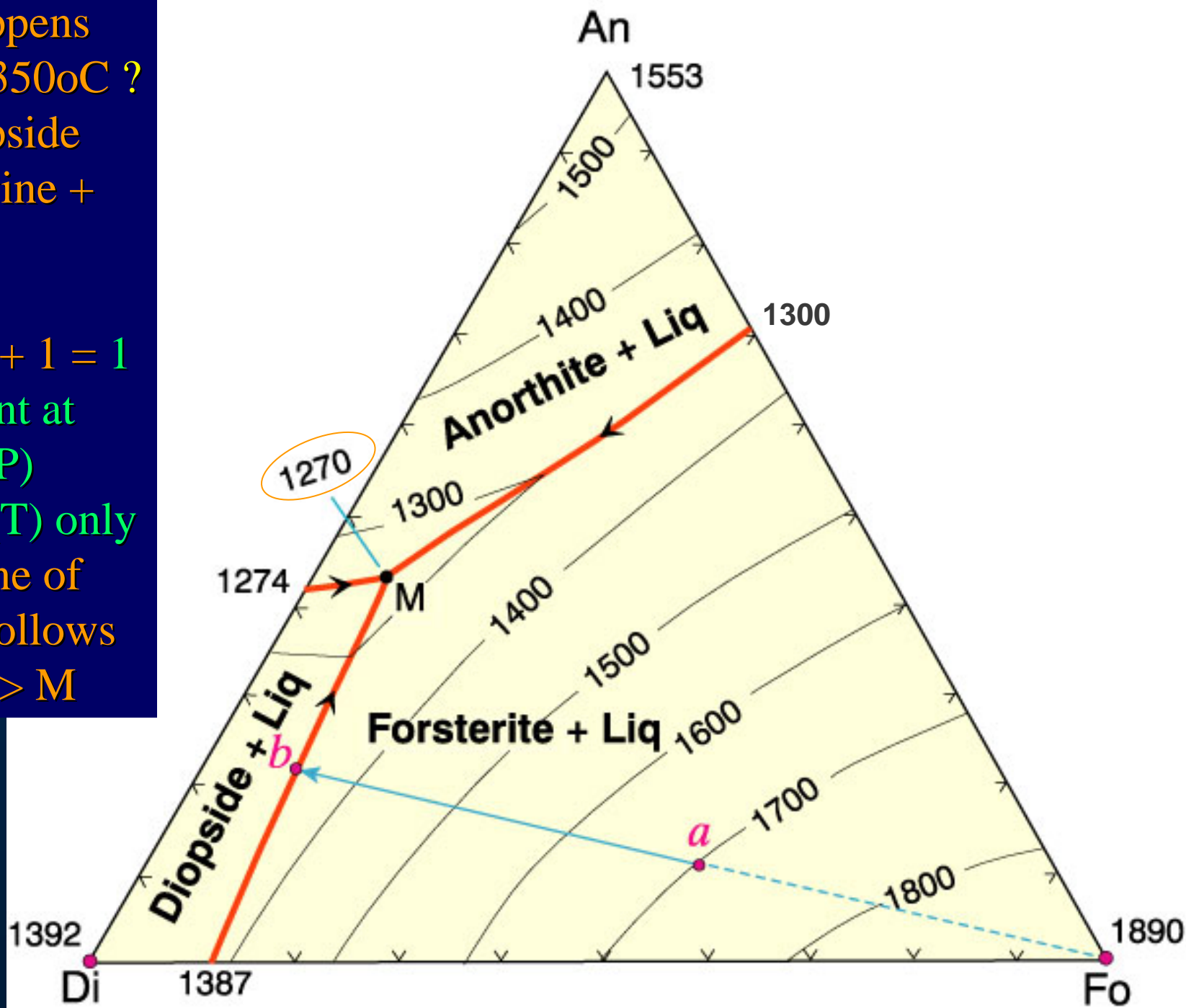
☞ $\text{Liq } x + \text{Fo} = \text{bulk } a$

☞ $\text{Liq } x/\text{Fo} = \frac{a - \text{Fo}}{x - a}$

At any point
can use the
lever
principle to
determine the
relative
proportions of
liquid and Fo



What happens next at 1350oC ?
Pure diopside joins olivine + liquid
 $\phi = 3$
 $F = 3 - 3 + 1 = 1$
(univariant at constant P)
 $X_{liq} = F(T)$ only
Liquid line of descent follows cotectic \rightarrow M



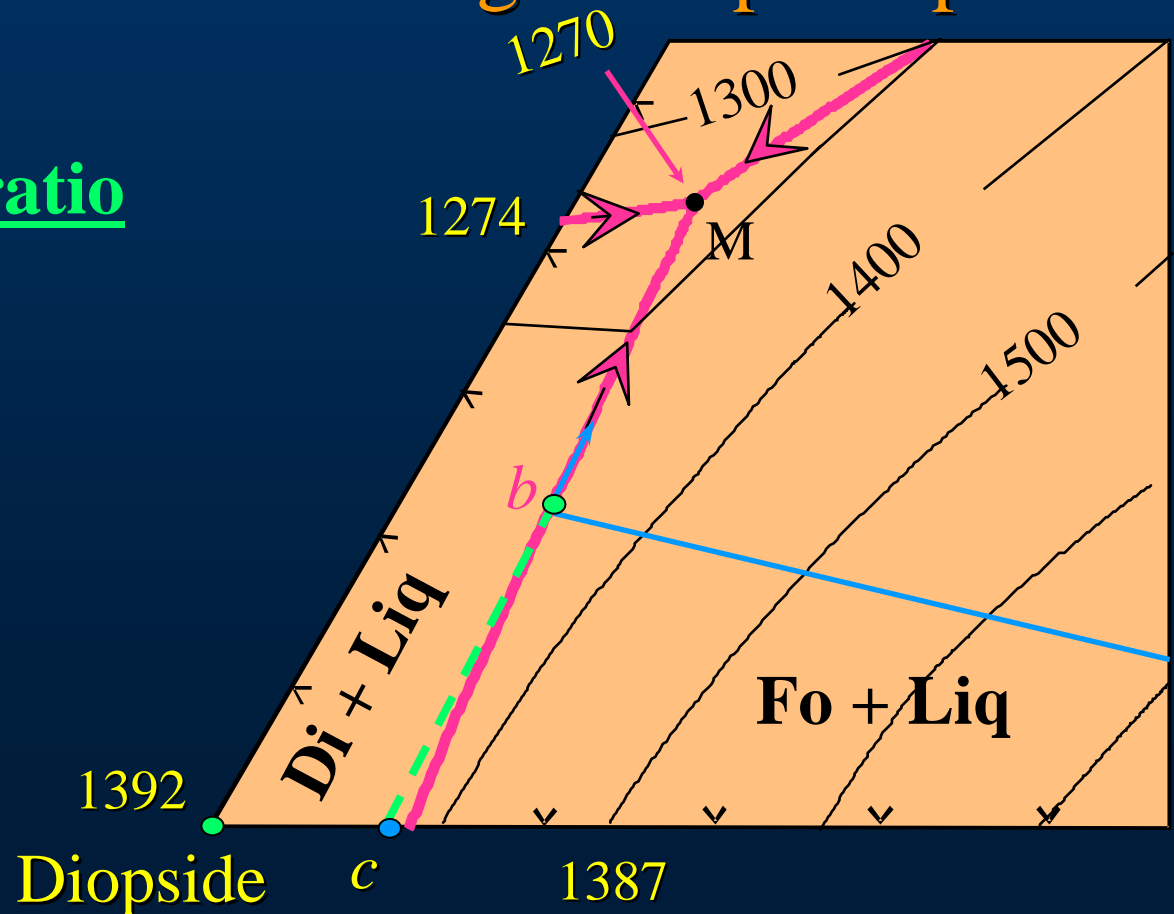
- New continuous reaction as liquid follows cotectic:



- Bulk solid extract
- Di/Fo in bulk solid extract using lever principle

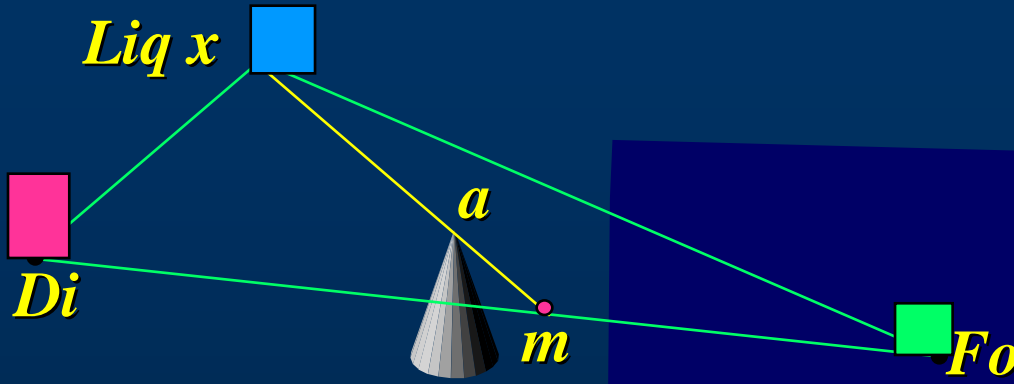
instantaneous ratio

$$\frac{\text{Fo}-c}{\text{Di}-c}$$



At 1300°C liquid = X

Imagine triangular plane X - Di - Fo balanced on bulk *a*

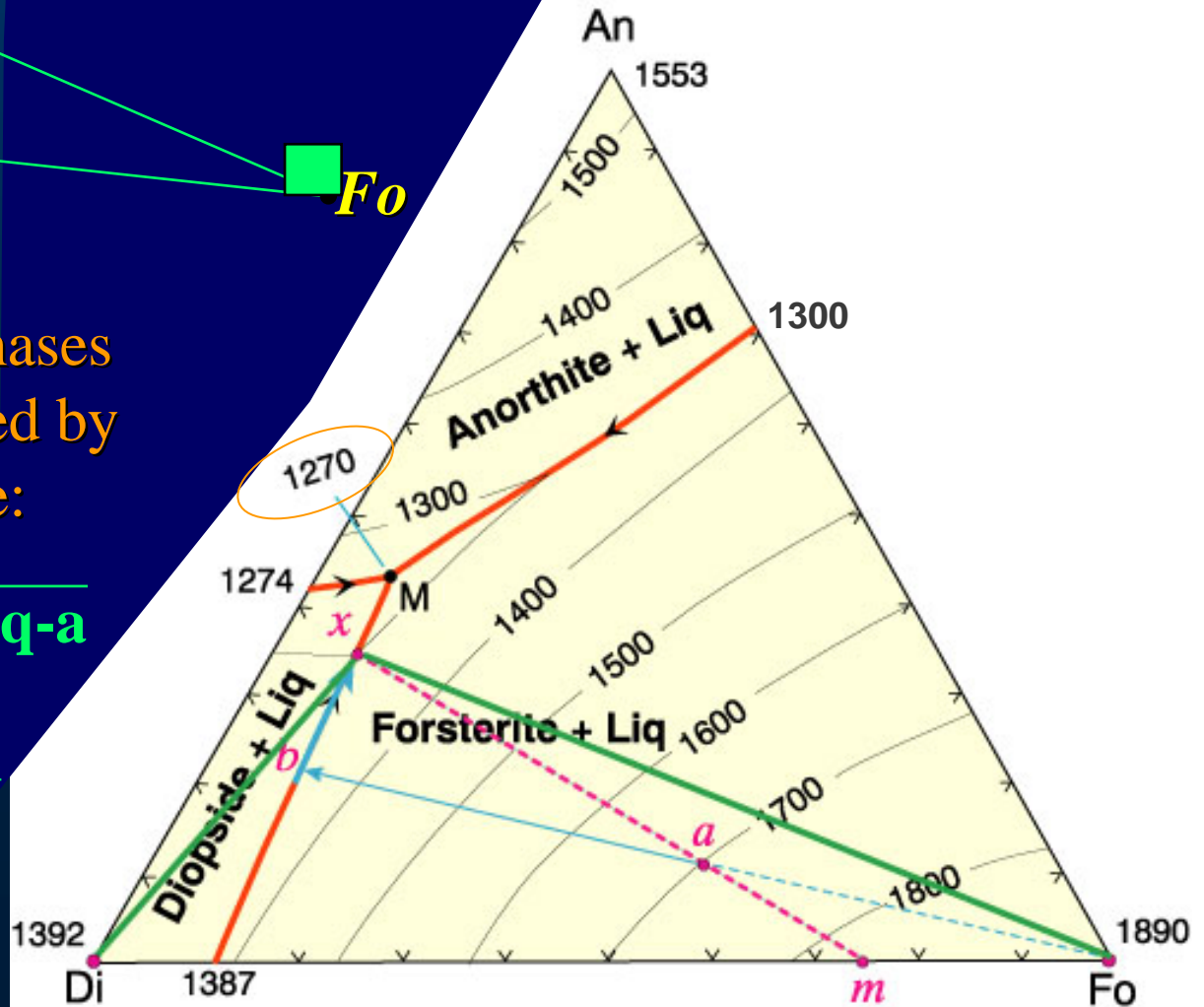


Total amounts of three phases at any T can be determined by a modified lever principle:

$$\text{Liq/total solids} = \frac{a-m}{\text{Liq}-a}$$

$$\text{total Di/Fo} = \frac{m-\text{Fo}}{\text{Di}-m}$$

cumulative amount



At 1270 °C reach **M** the **ternary eutectic** anorthite joins liquid + forsterite + diopside

$$\phi = 4, F = 3 - 4 + 1 = 0$$

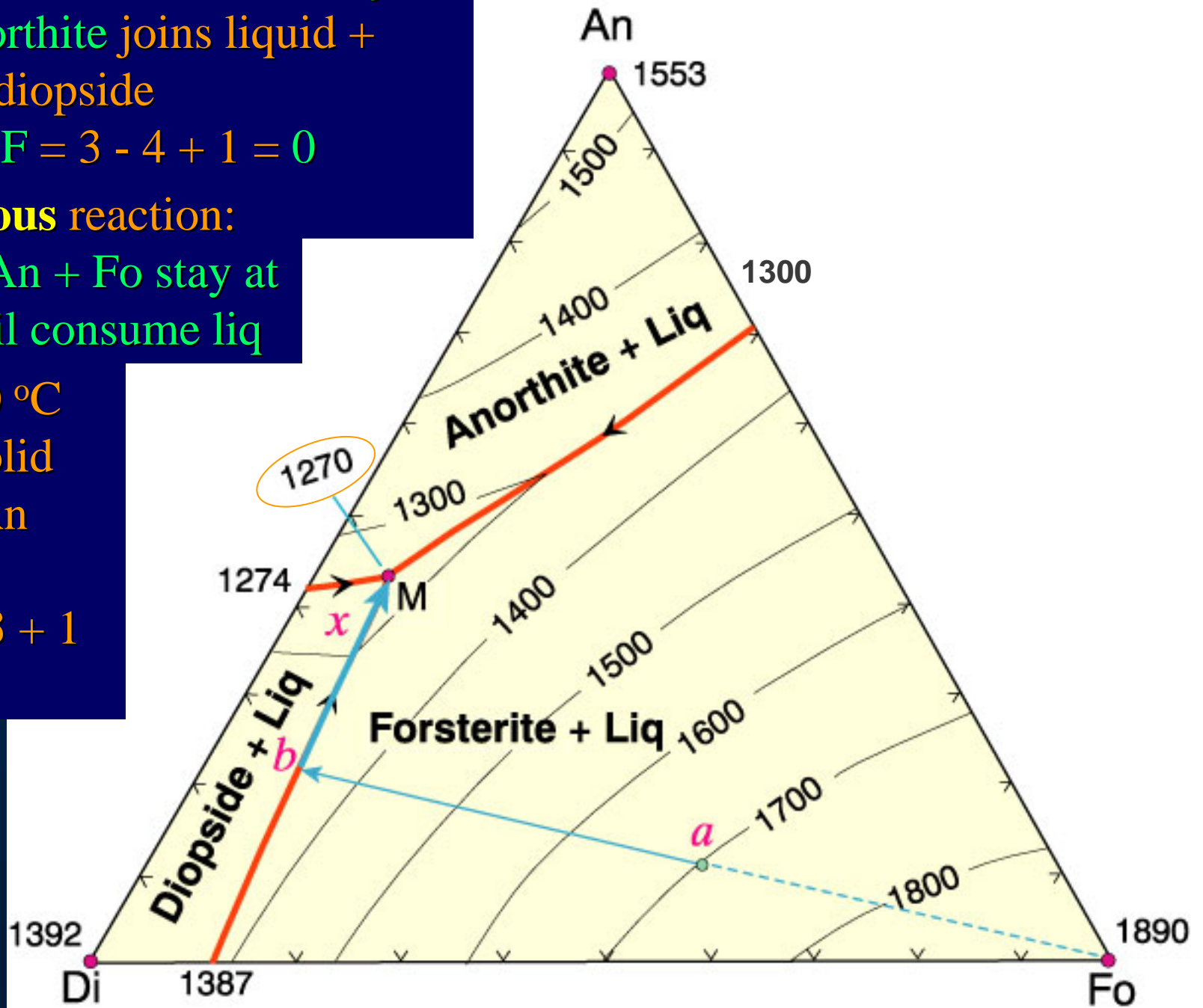
Discontinuous reaction:

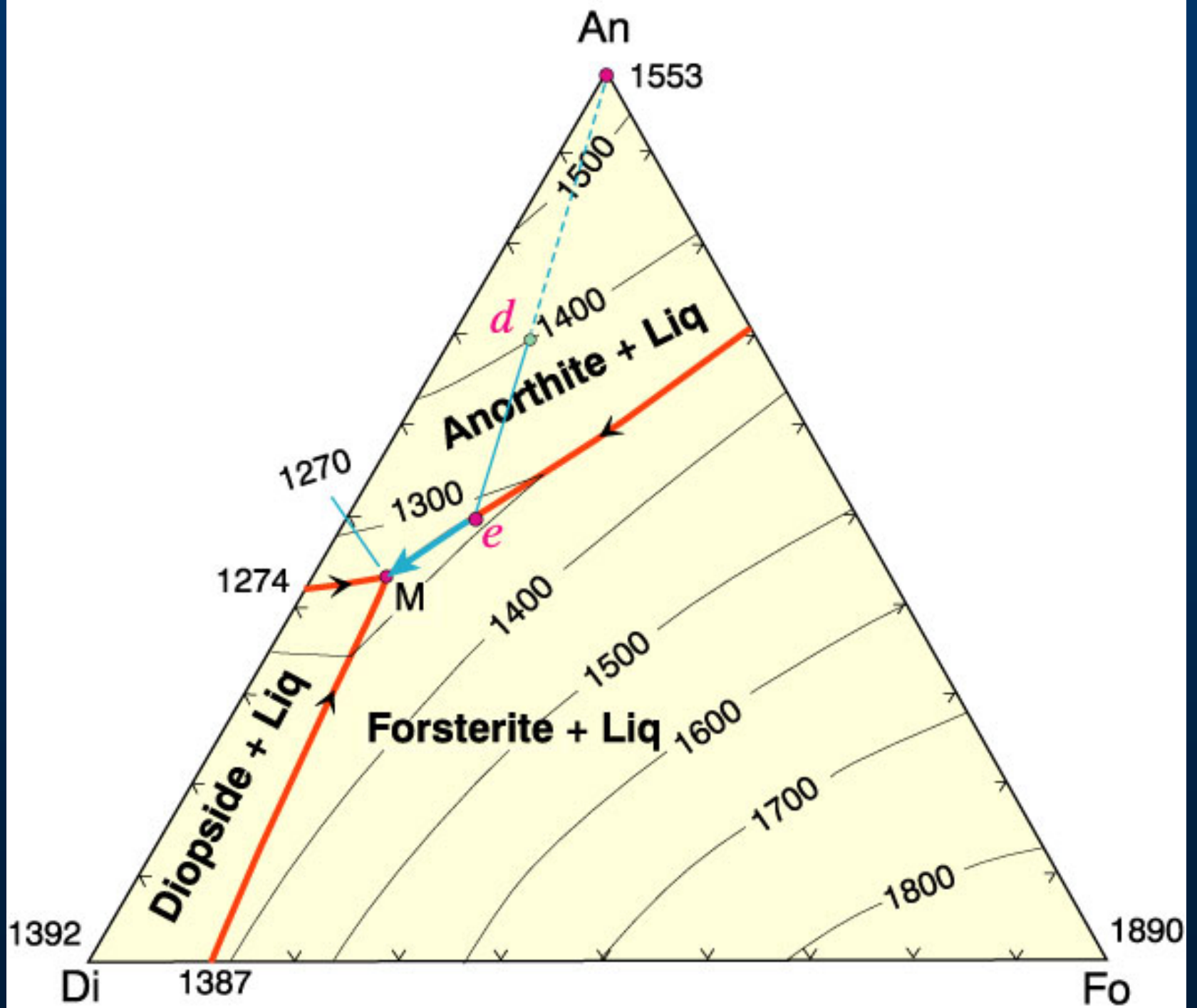
Liq = Di + An + Fo stay at 1270°C until consume liq

Below 1270 °C
have also solid
Fo + Di + An

$$\phi = 3$$

$$F = 3 - 3 + 1 = 1$$

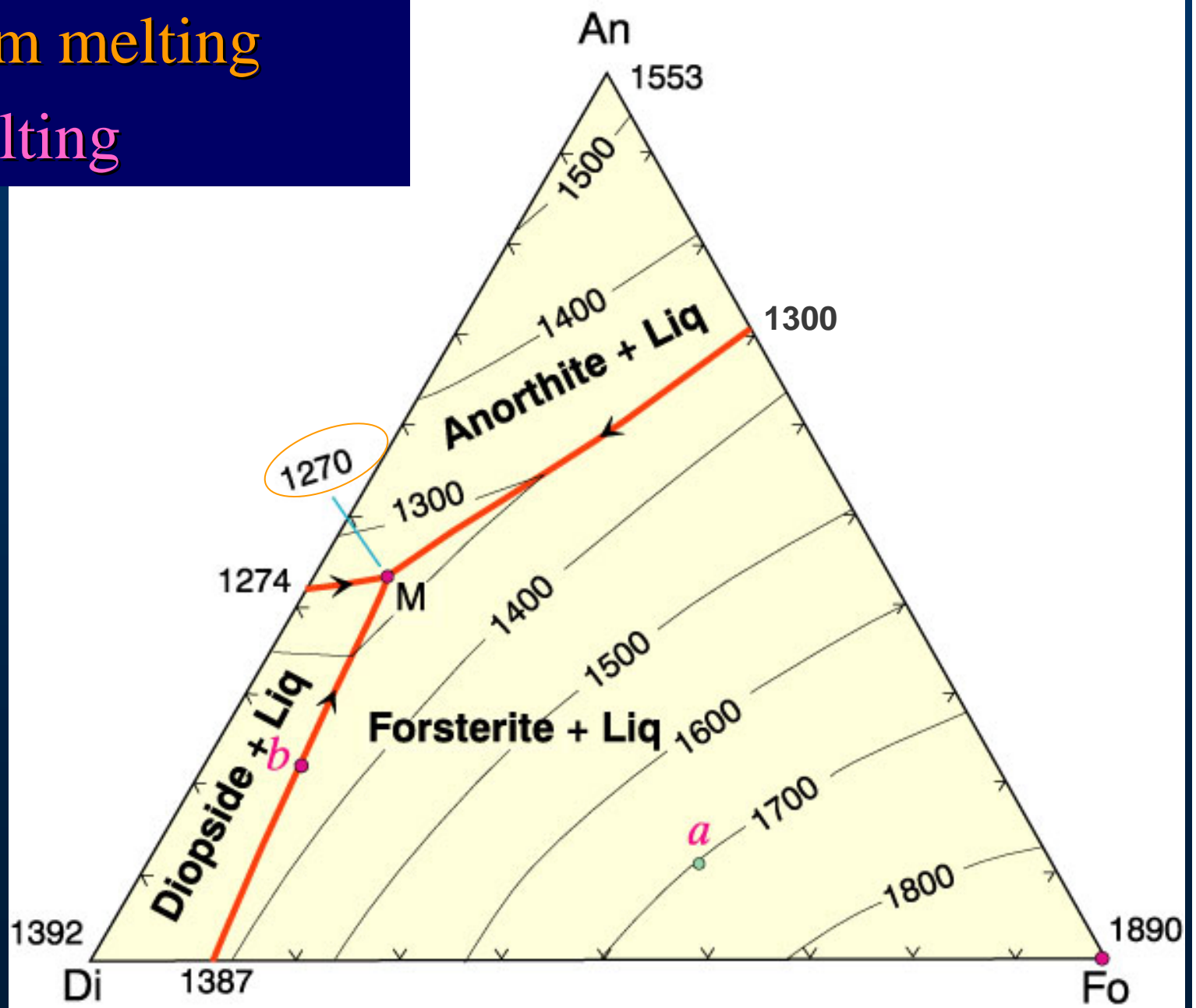




Fractional crystallization

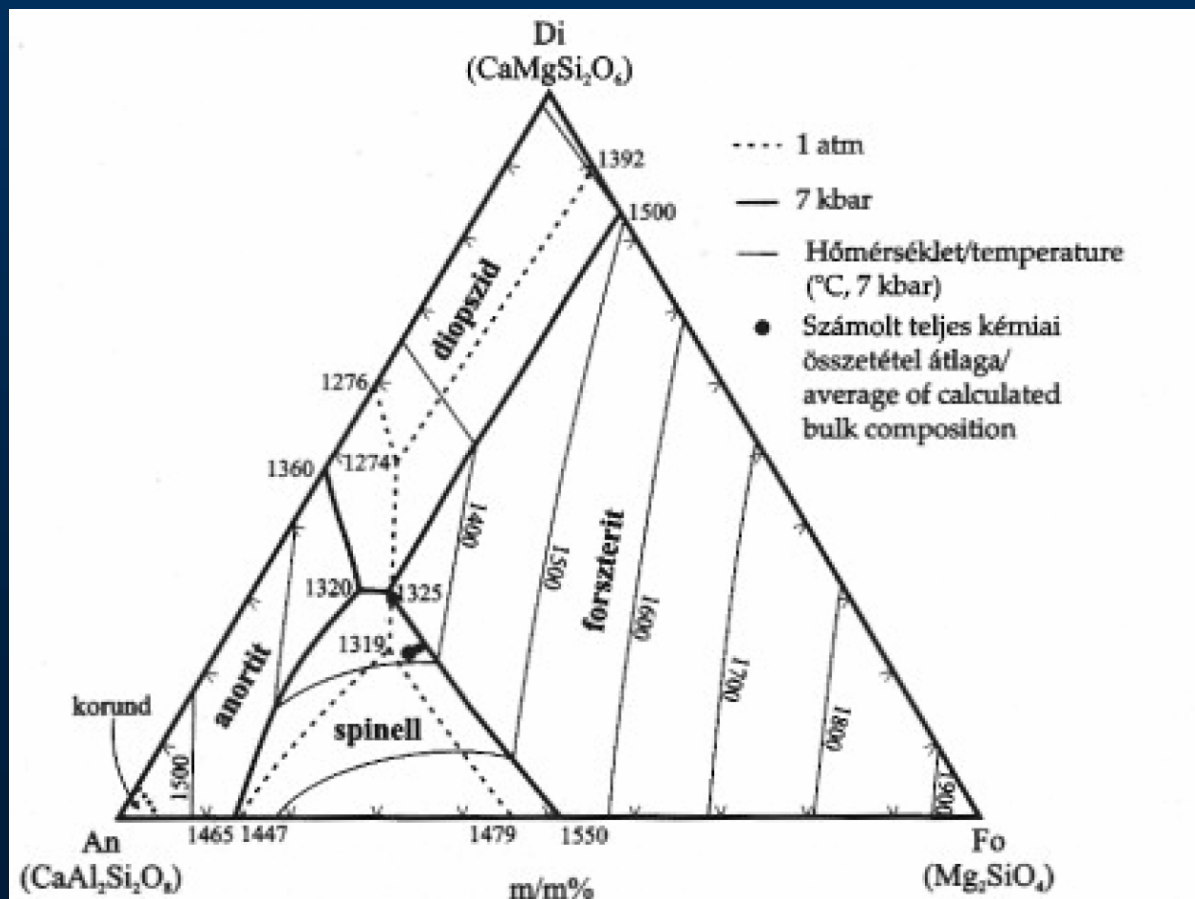
Equilibrium melting

Partial Melting

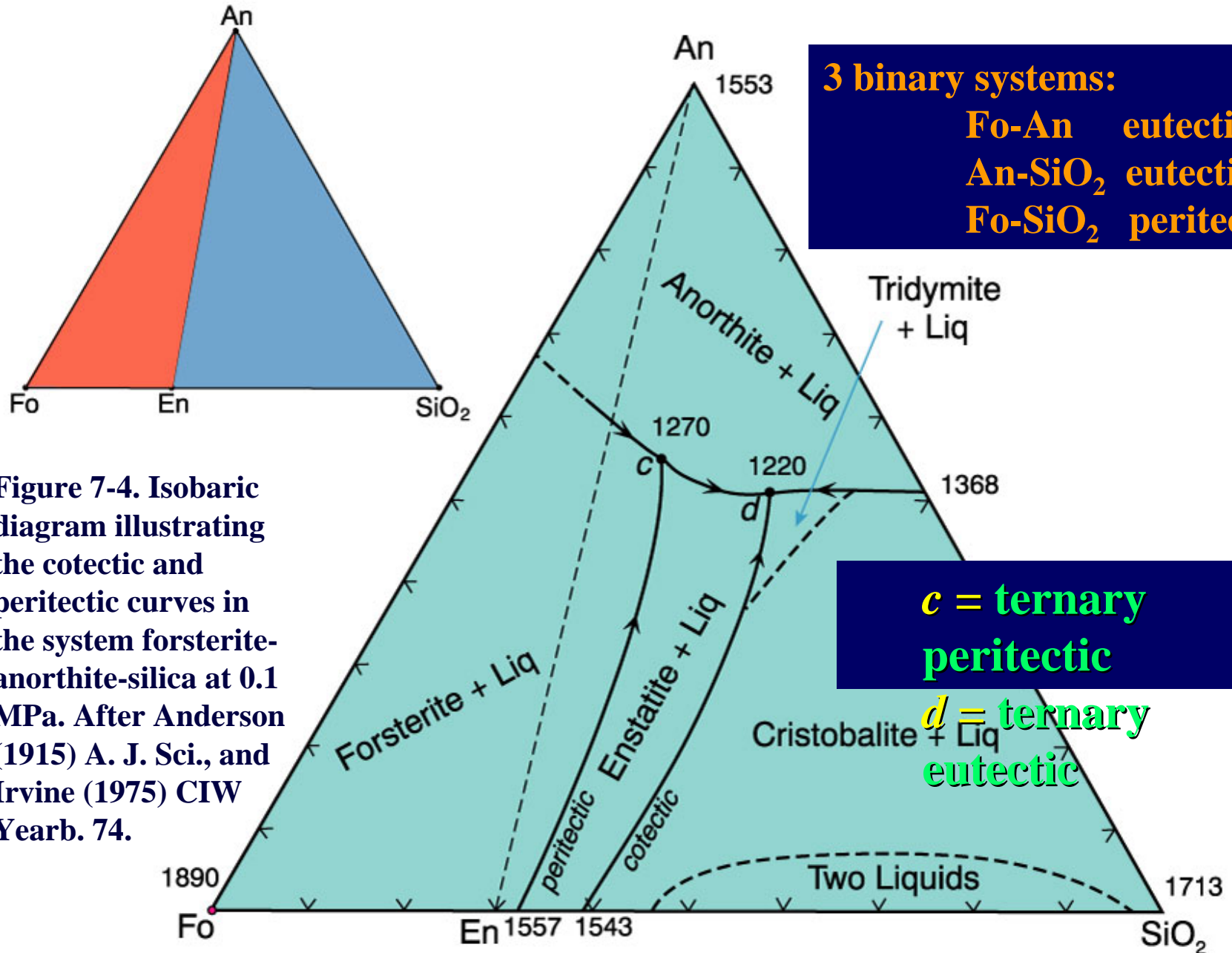


Forsterite-diopside-anorthite (Fo-Di-An)

diagram showing phases determined by
low P (1 atm, Osborn & Tait, 1952) and
high P (0.7 GPa, Presnall et al., 1978)



Ternary Peritectic Systems: (at 0.1 MPa)



3 binary systems:
Fo-An eutectic
An-SiO₂ eutectic
Fo-SiO₂ peritectic

c = ternary peritectic

d = ternary eutectic

Figure 7-4. Isobaric diagram illustrating the cotectic and peritectic curves in the system forsterite-anorthite-silica at 0.1 MPa. After Anderson (1915) A. J. Sci., and Irvine (1975) CIW Yearb. 74.

Begin with
composition *a*

Forsterite
crystallizes
first

$\phi = 2$

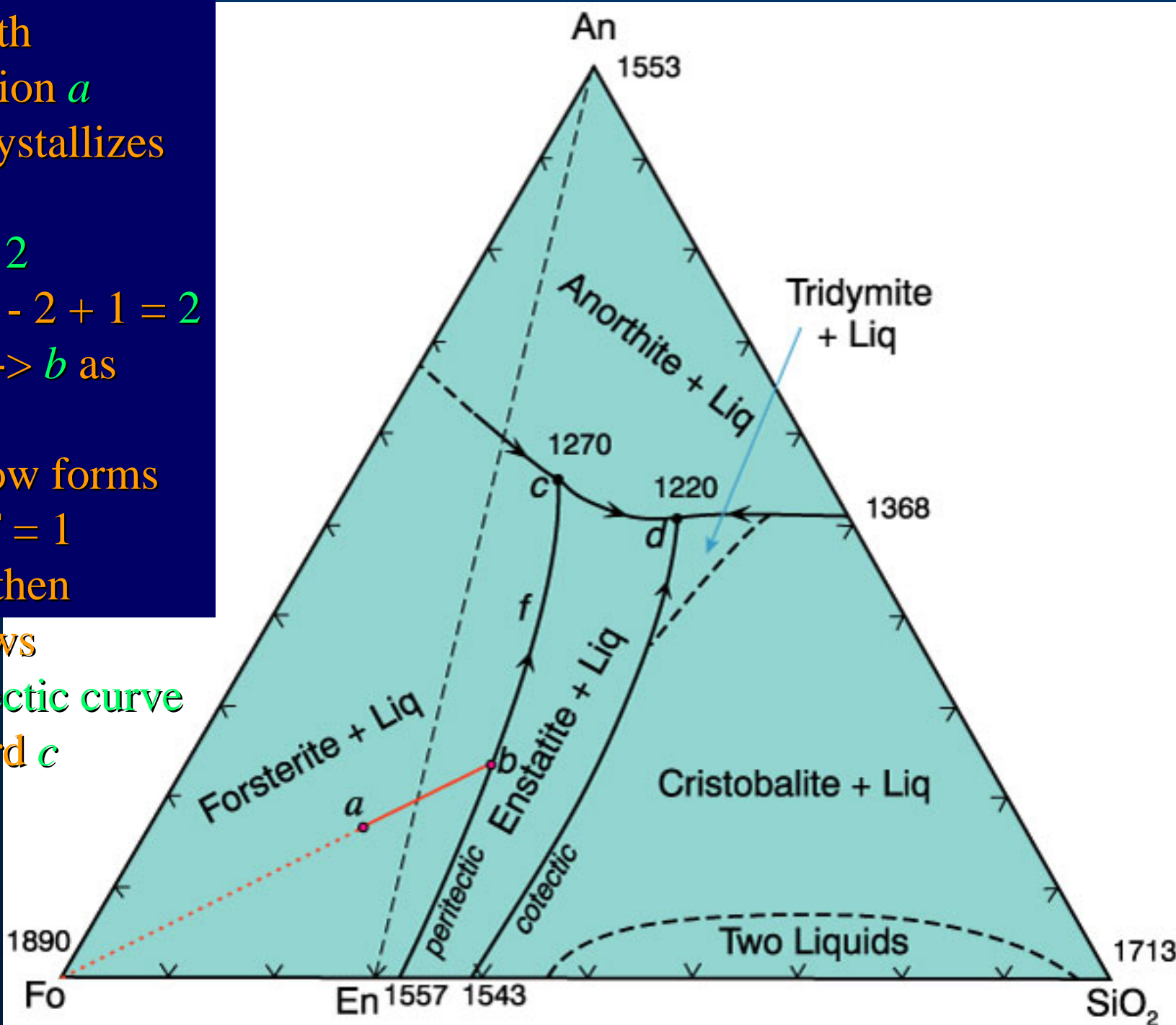
$F = 3 - 2 + 1 = 2$

$X_{\text{liq}} \rightarrow b$ as
cool

Enstatite
now forms
and $F = 1$

X_{liq} then
follows

peritectic curve
toward *c*



As X_{liq} follows peritectic can get bulk solid extract at any T by tangent method
 example at point x the tangent \rightarrow
 y as bulk solid

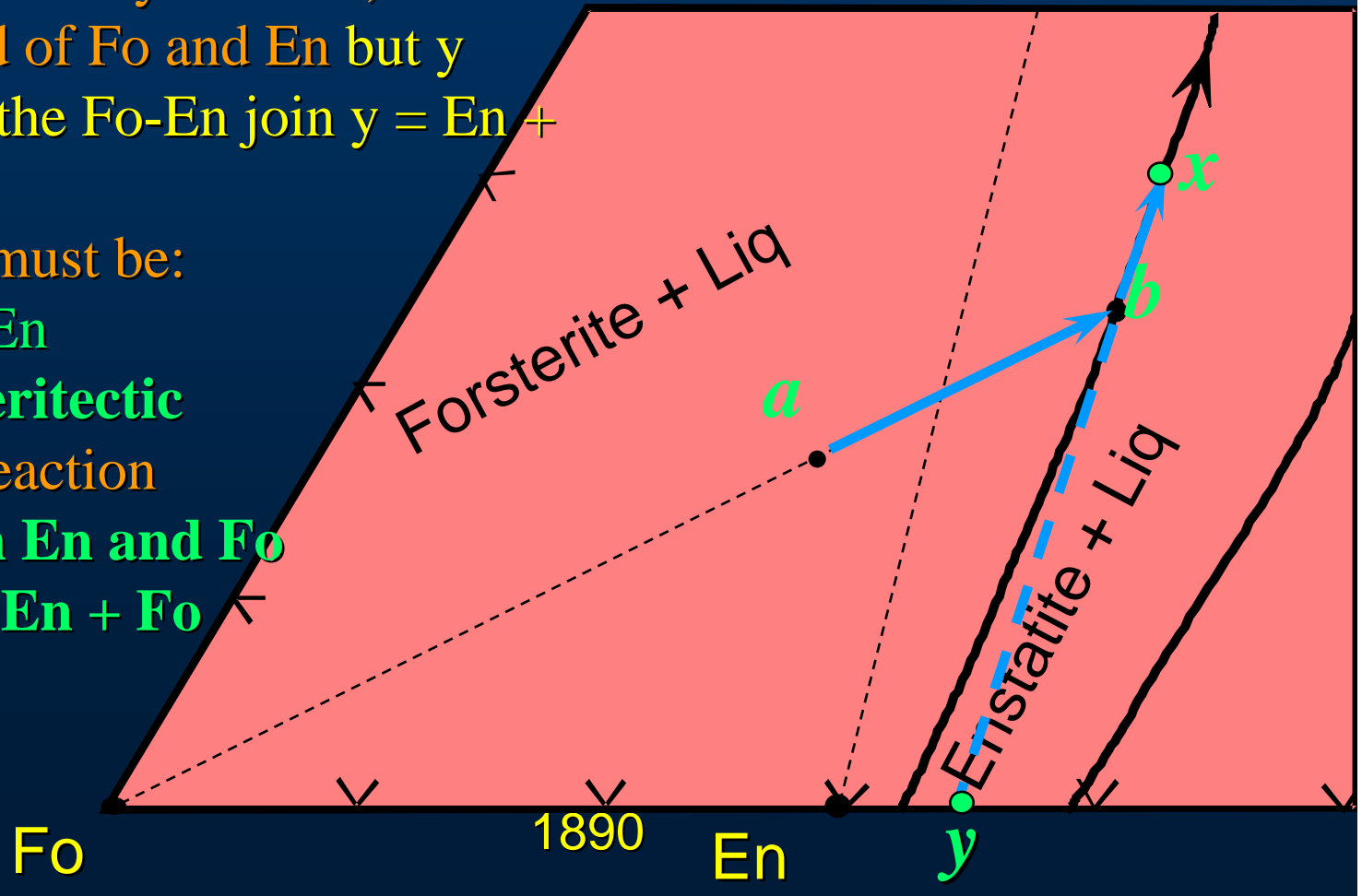
We know Fo, En, and Liq are the three phases since $y = \text{solids}$, it must be comprised of Fo and En but y falls outside the Fo-En join $y = \text{En} + (-\text{Fo})$

the reaction must be:



which is a **peritectic** continuous reaction

If y fell between En and Fo it would be $L = \text{En} + \text{Fo}$



Continue cooling with continuous reaction until X_{liq} reaches c at 1270°C

Now get $An + En + Fo + Liq$

$\phi = 4$

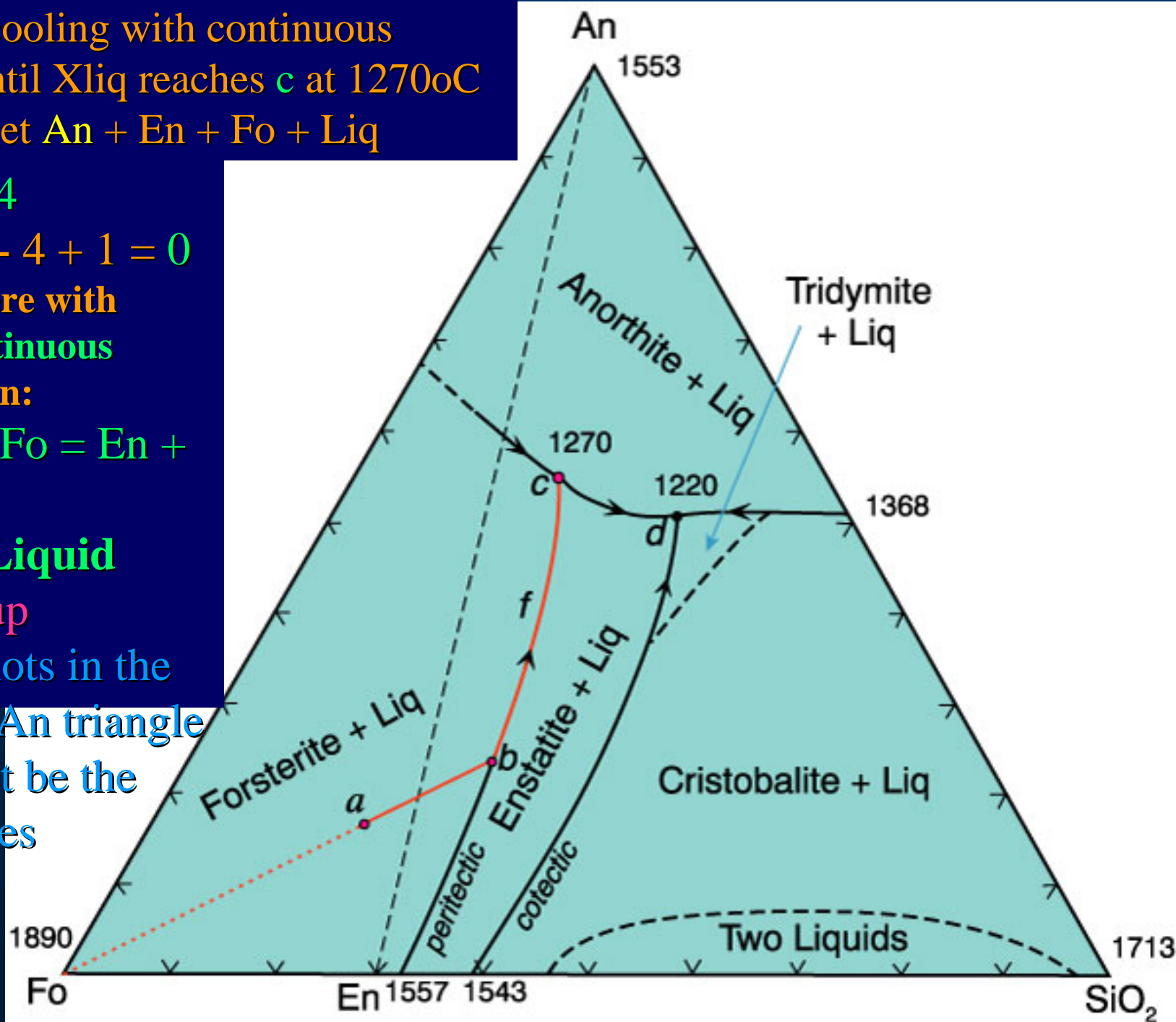
$F = 3 - 4 + 1 = 0$

stay here with discontinuous reaction:

$Liq + Fo = En + An$

until **Liquid** used up

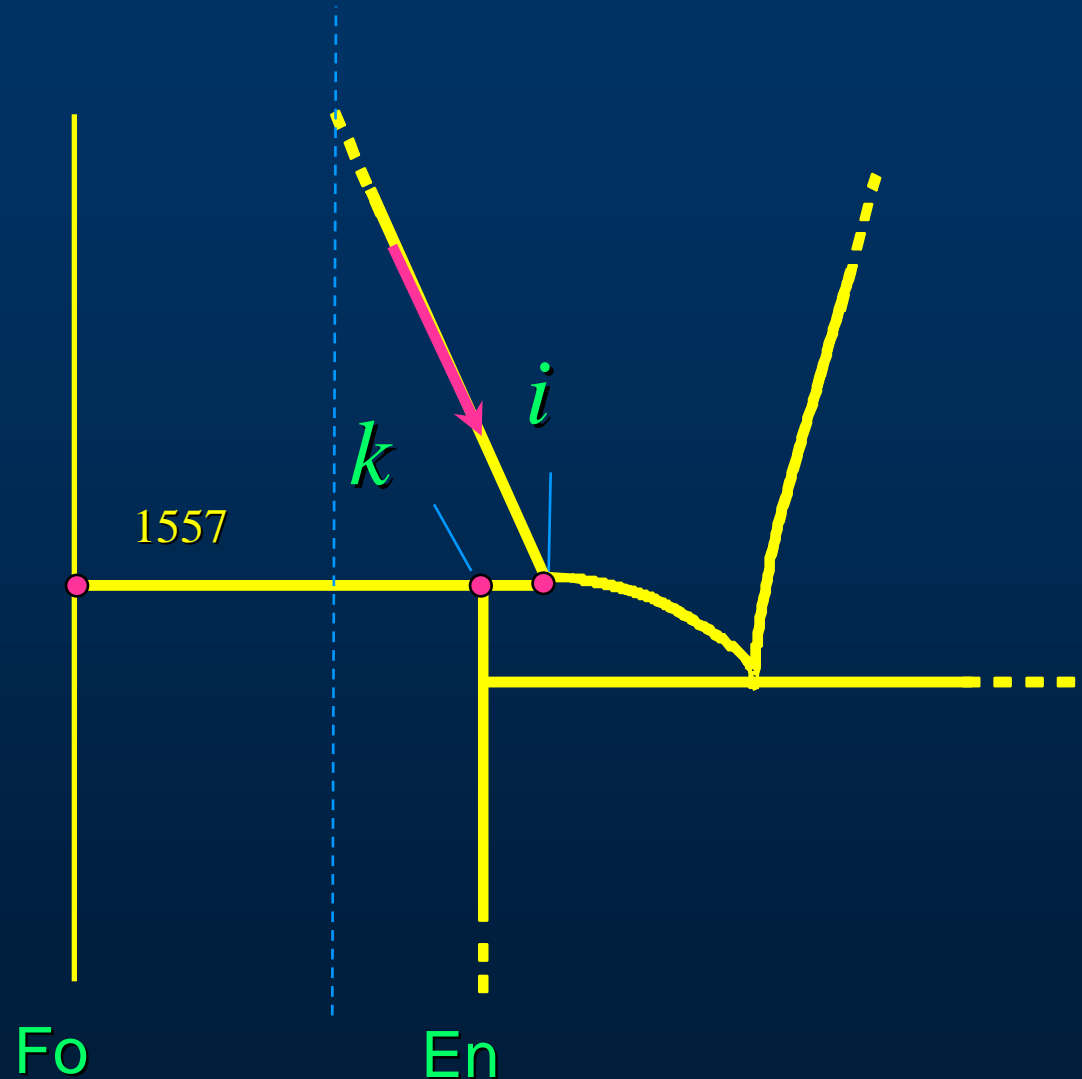
Since a plots in the $Fo - En - An$ triangle these must be the final phases



Works the same way as the Fo - En - SiO₂ binary

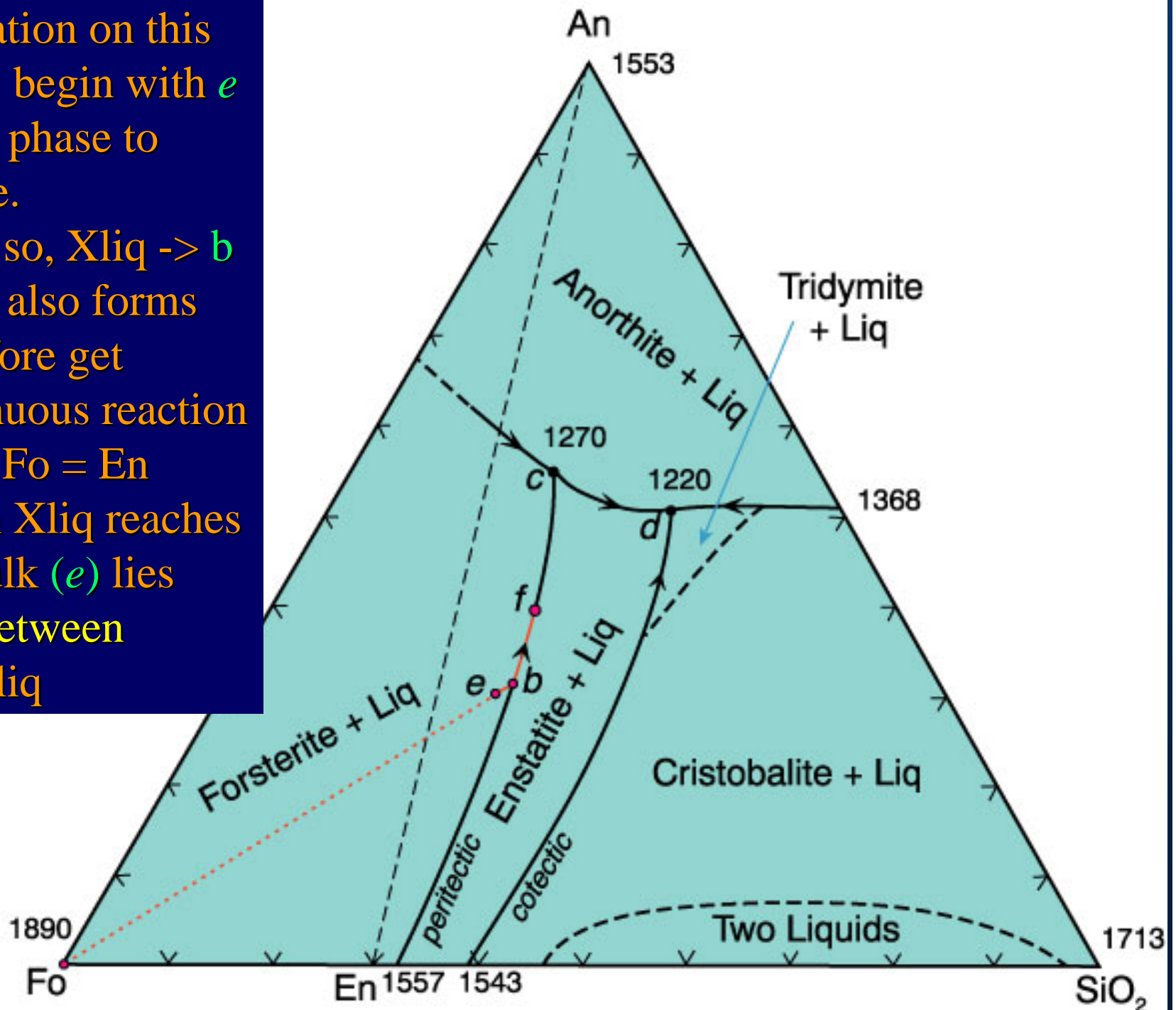
If the bulk X is between Fo and En the liquid disappears first at the peritectic temperature and Fo + En remain as the final solids

If, on the other hand, the bulk X lies to the right of En, then Fo is consumed first and the liquid continues to evolve toward the eutectic



As a variation on this sequence: begin with *e*
Fo is first phase to crystallize.

as it does so, $X_{\text{liq}} \rightarrow b$
where En also forms
as before get
continuous reaction
 $\text{Liq} + \text{Fo} = \text{En}$
but, when X_{liq} reaches
f the X_{bulk} (*e*) lies
directly between
En and X_{liq}



Xliq \rightarrow g where **An** joins En +Liq as before get **continuous** reaction

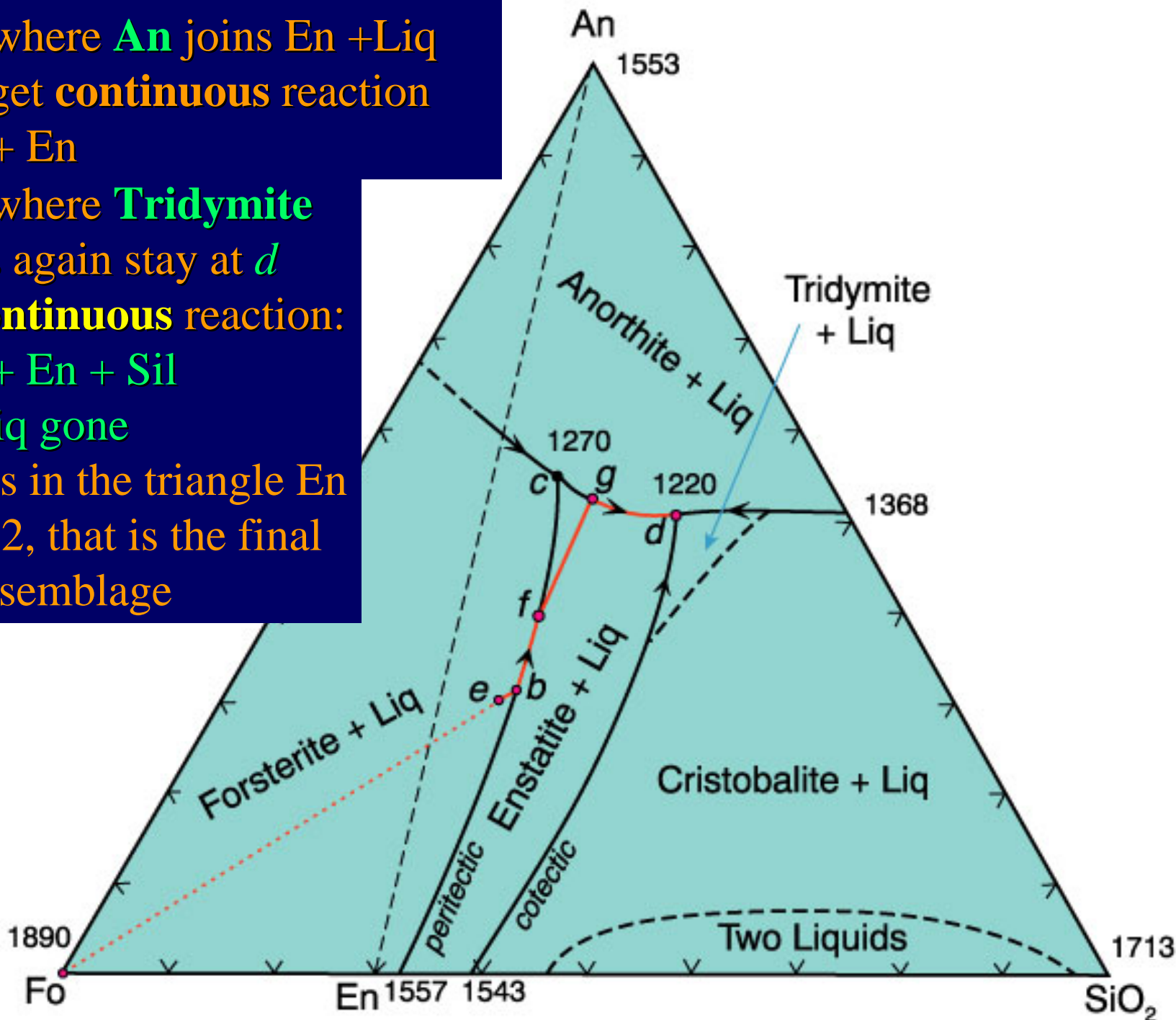
Liq = An + En

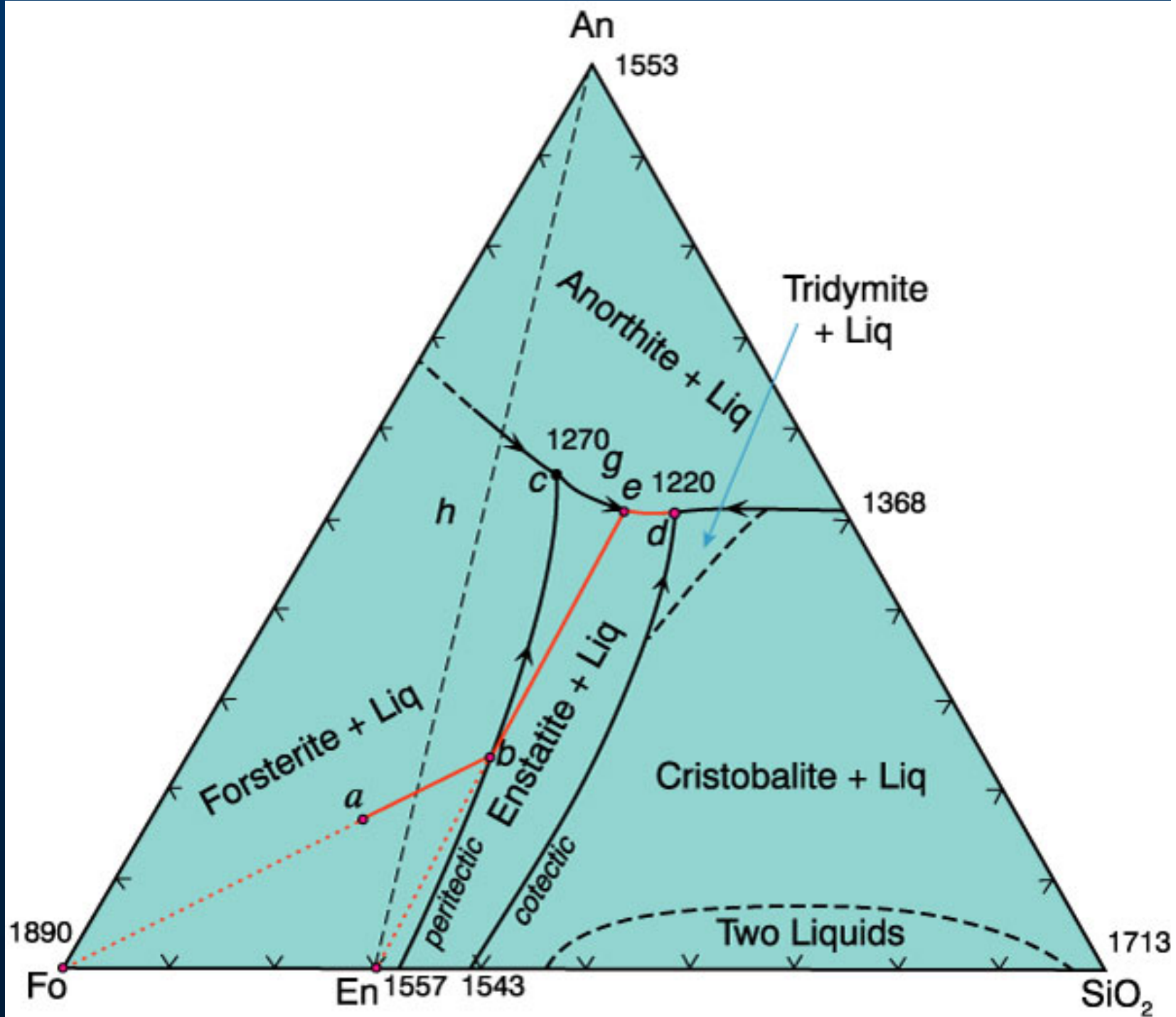
Xliq \rightarrow d where **Tridymite** also forms again stay at d with **discontinuous** reaction:

Liq = An + En + Sil

until last liq gone

Since e lies in the triangle En - An - SiO₂, that is the final mineral assemblage





Other areas are relatively simple

Liq h

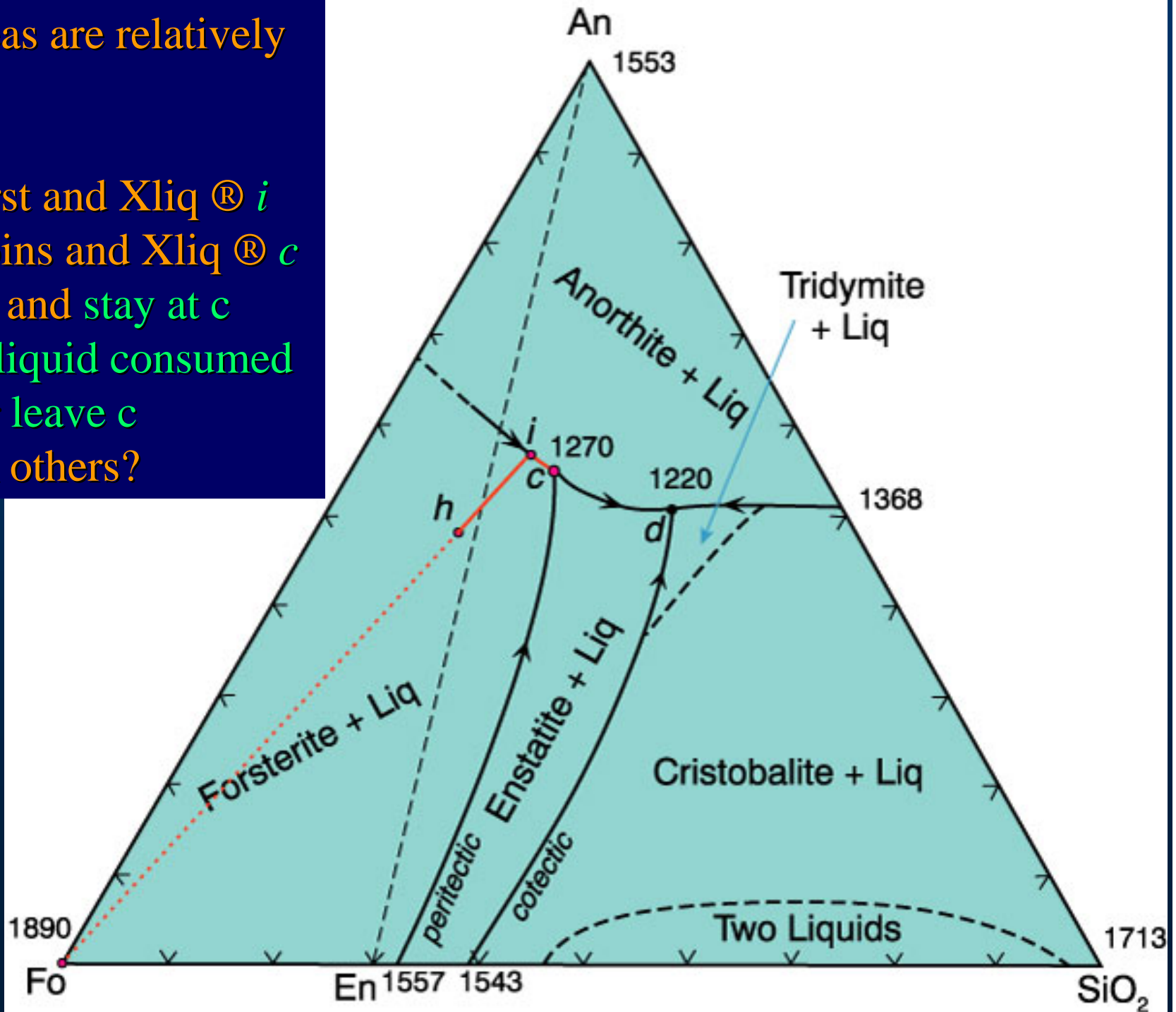
Fo first and $X_{\text{liq}} @ i$

An joins and $X_{\text{liq}} @ c$

$F = 0$ and stay at c

until liquid consumed
never leave c

You pick others?



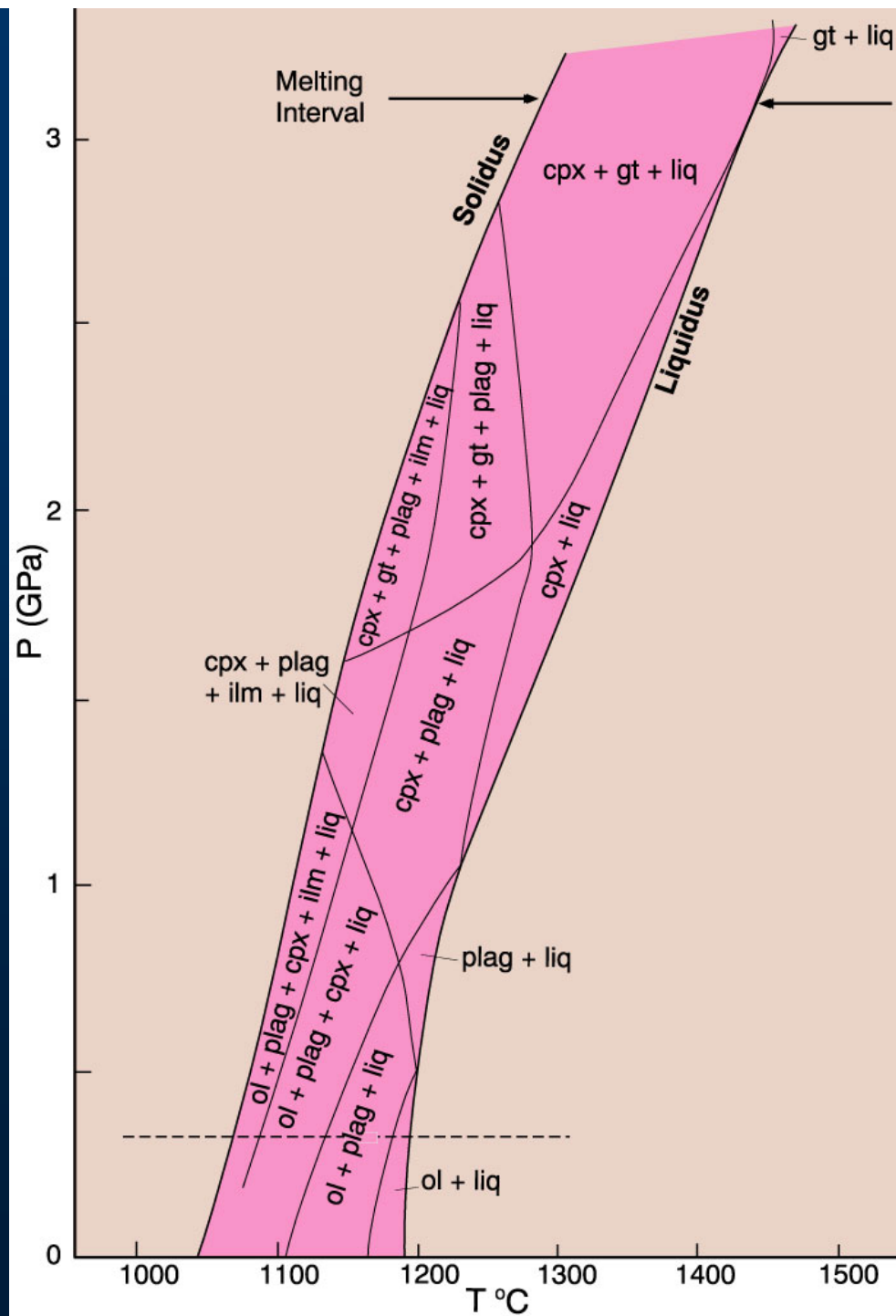
Note:

Binary character is usually maintained when a new component is added

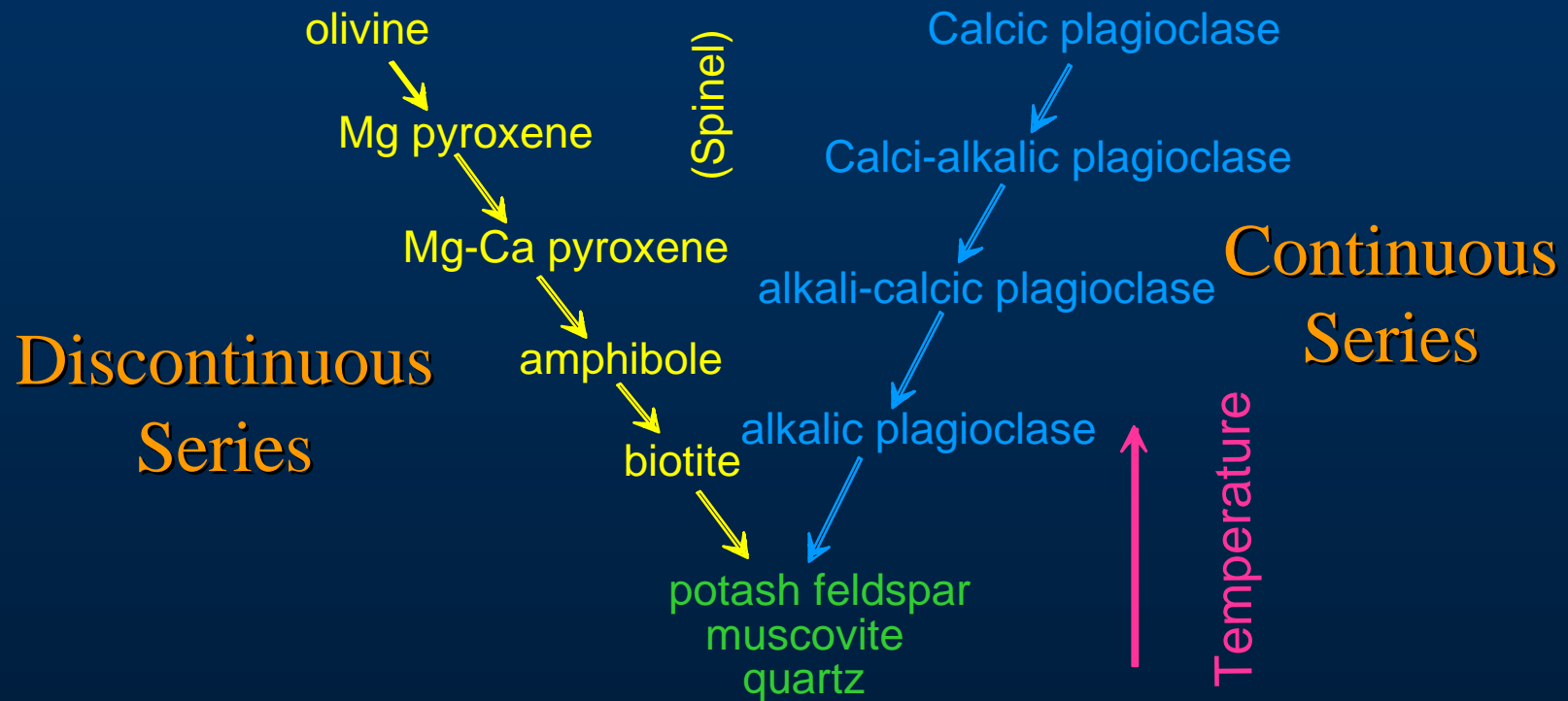
- ➡ **Eutectic behavior remains eutectic**
- ➡ **Peritectic behavior remains peritectic**
- ➡ **Solid solutions remain so as well**

> 4 Components

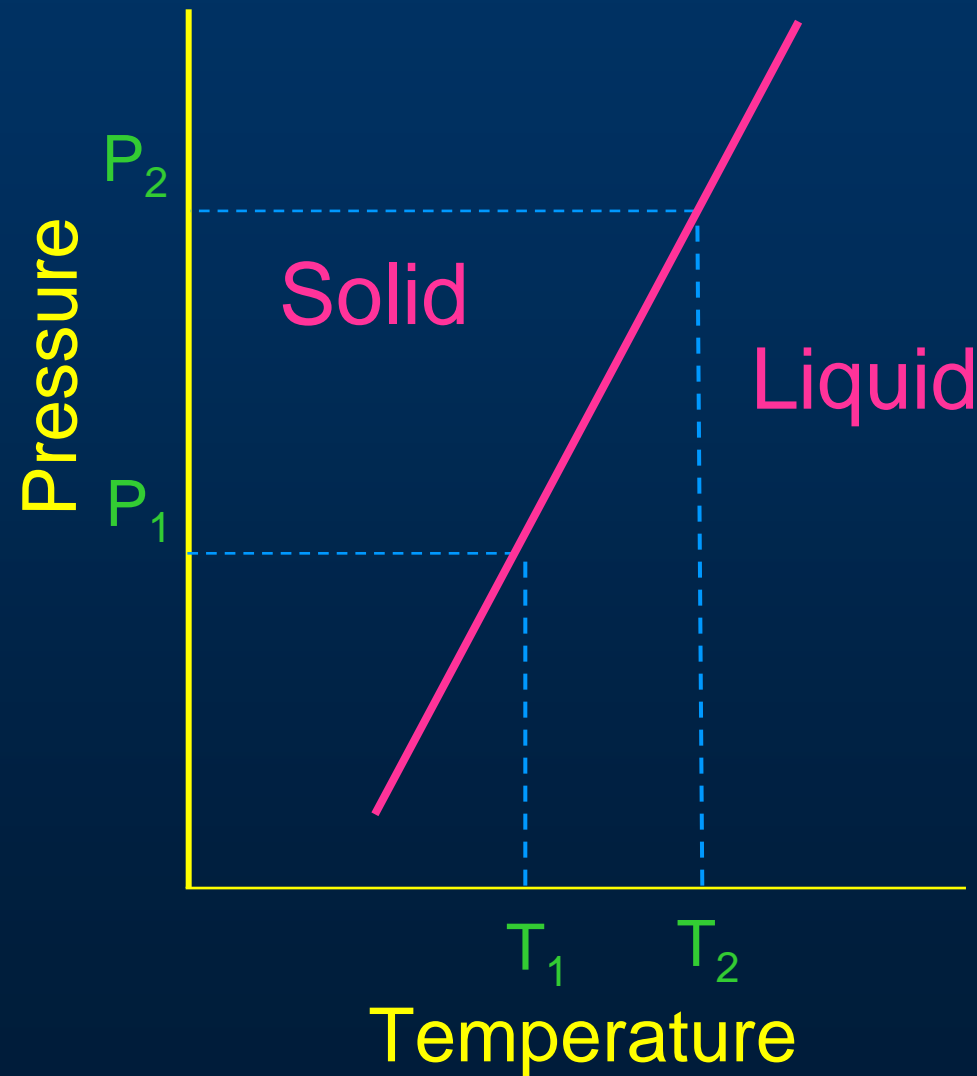
Figure 7-13. Pressure-temperature phase diagram for the melting of a Snake River (Idaho, USA) tholeiitic basalt under anhydrous conditions. After Thompson (1972). Carnegie Inst. Wash Yb. 71



Bowen's Reaction Series



The Effect of Pressure



The Effect of Water on Melting

Dry melting: solid \rightarrow liquid

Add water- water enters the melt

Reaction becomes:

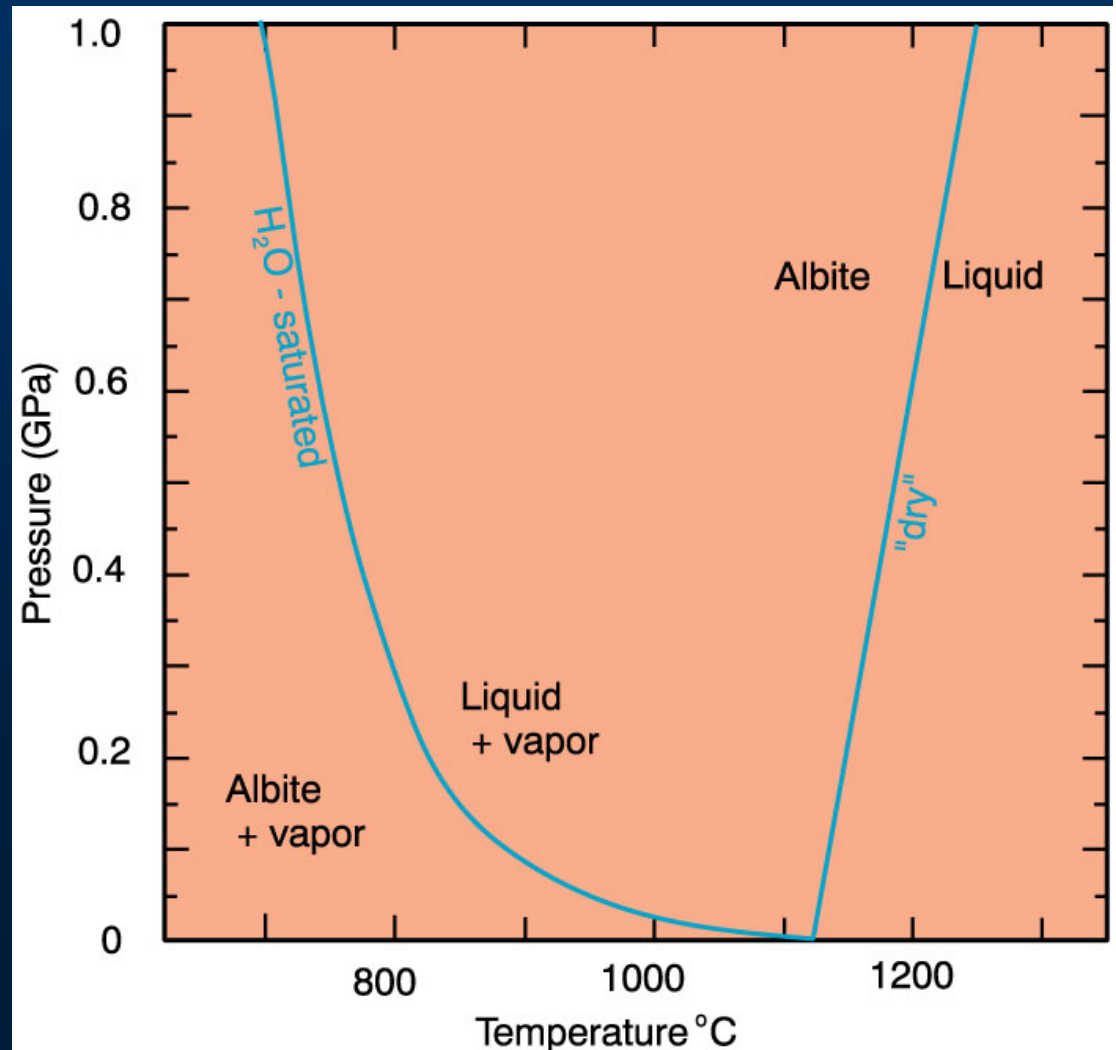


Figure 7-19. The effect of H₂O saturation on the melting of albite, from the experiments by Burnham and Davis (1974). *A J Sci* 274, 902-940. The “dry” melting curve is from Boyd and England (1963). *JGR* 68, 311-323.

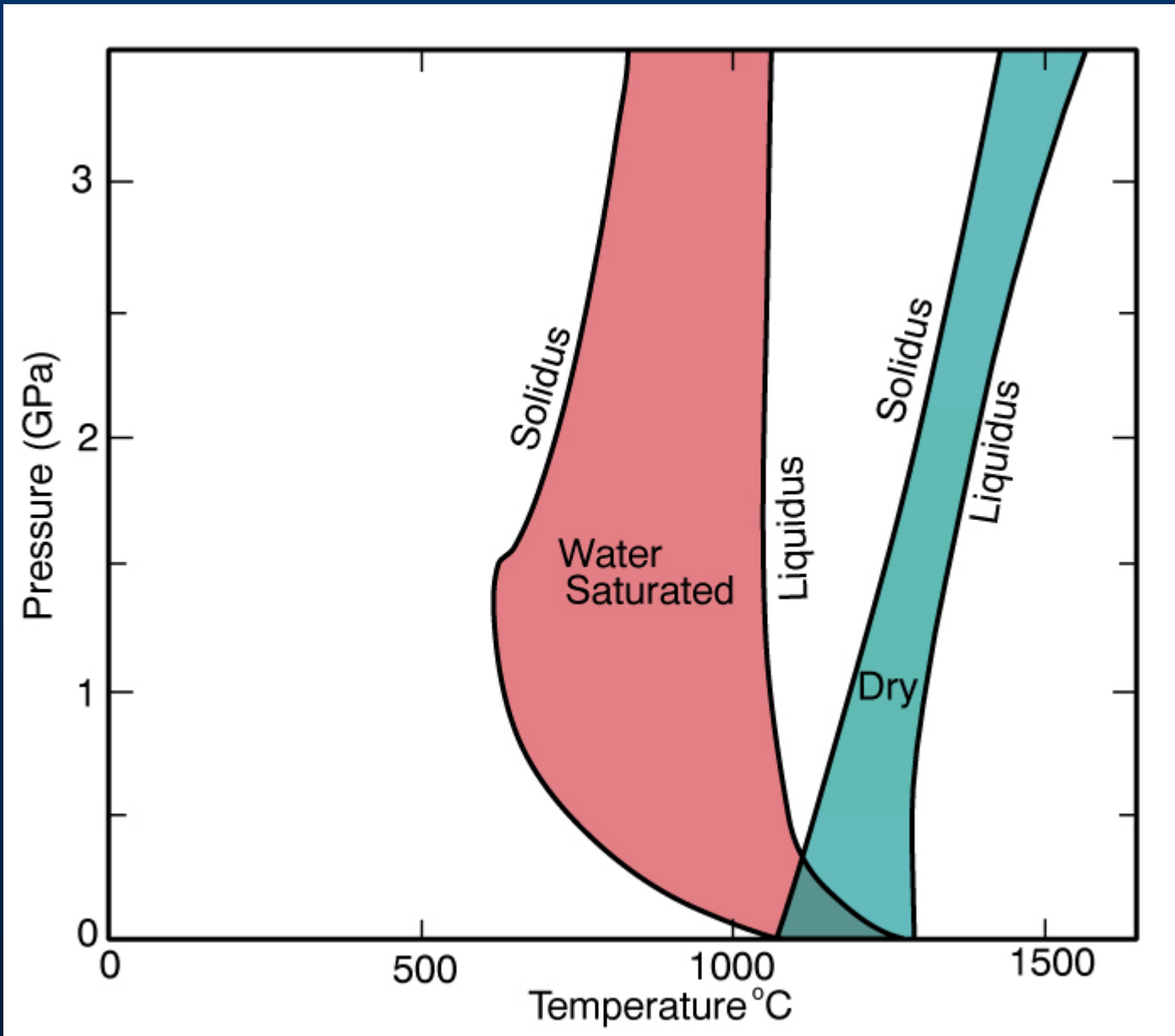


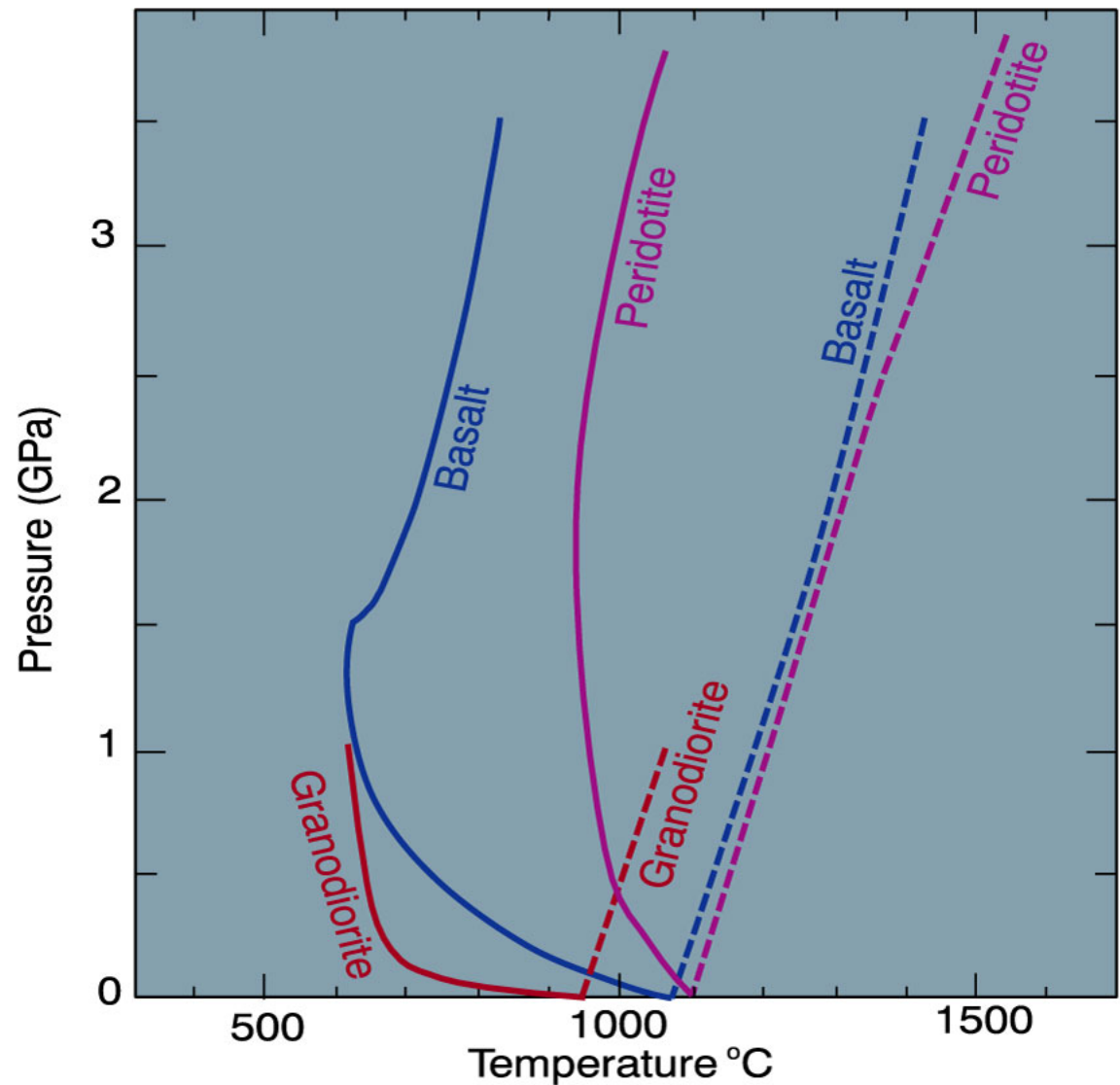
Figure 7-20. Experimentally determined melting intervals of gabbro under H₂O-free (“dry”), and H₂O-saturated conditions. After Lambert and Wyllie (1972). *J. Geol.*, 80, 693-708.

Dry and water-saturated solidi for some common rock types

More mafic rocks have higher melting point

All solidi are greatly lowered by water

Figure 7-21. H₂O-saturated (solid) and H₂O-free (dashed) solidi (beginning of melting) for granodiorite (Robertson and Wyllie, 1971), gabbro (Lambert and Wyllie, 1972) and peridotite (H₂O-saturated: Kushiro *et al.*, 1968; dry: Ito and Kennedy, 1967).



We know the behavior of water-free and water-saturated melting by experiments, which are easy to control by performing them in dry and wet sealed vessels

What about real rocks?

Some may be dry, some saturated, but most are more likely to be in between these extremes

- a fixed water content $<$ saturation levels
- a fixed water activity