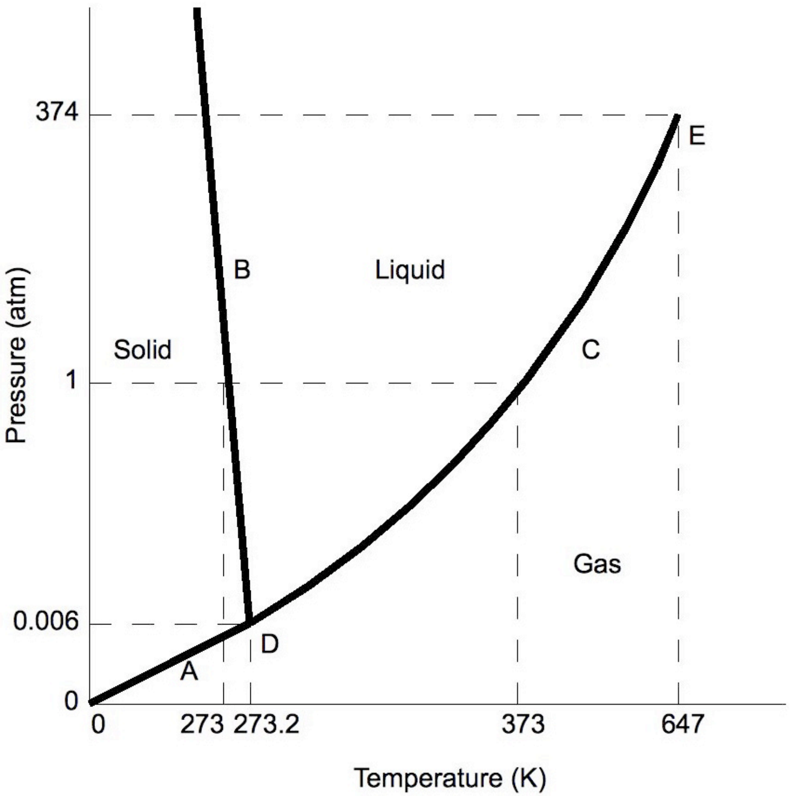
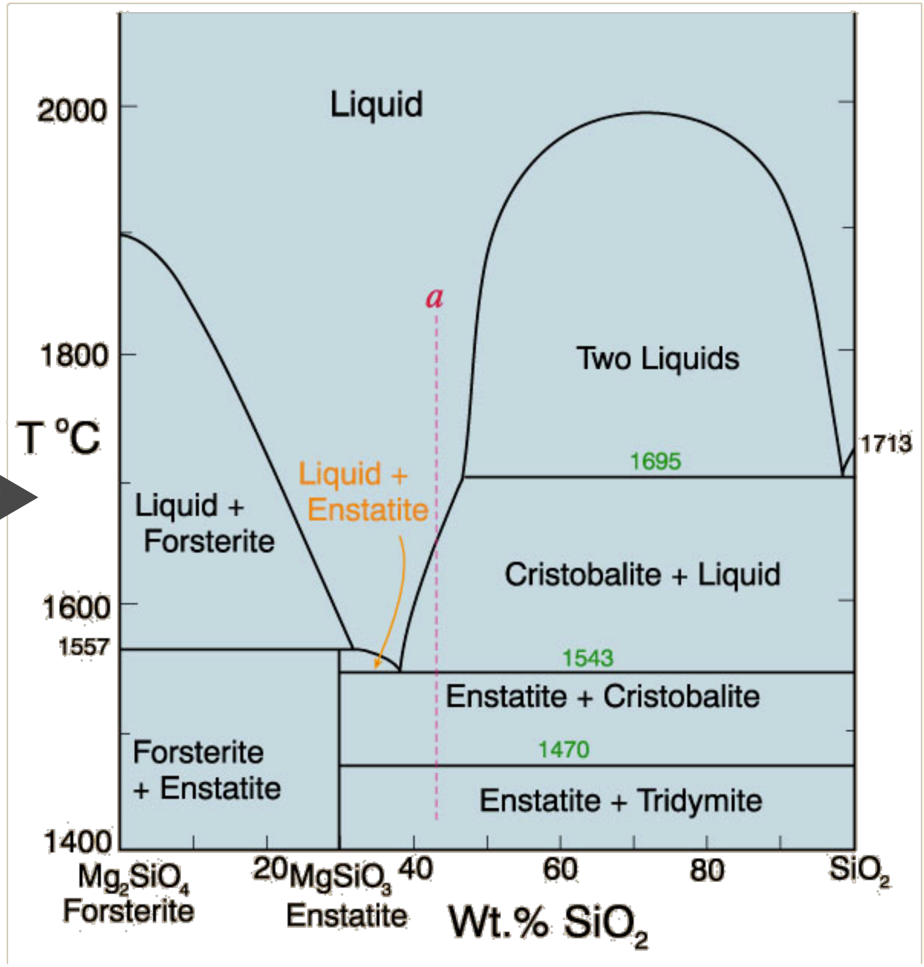
Phase Equilibrium





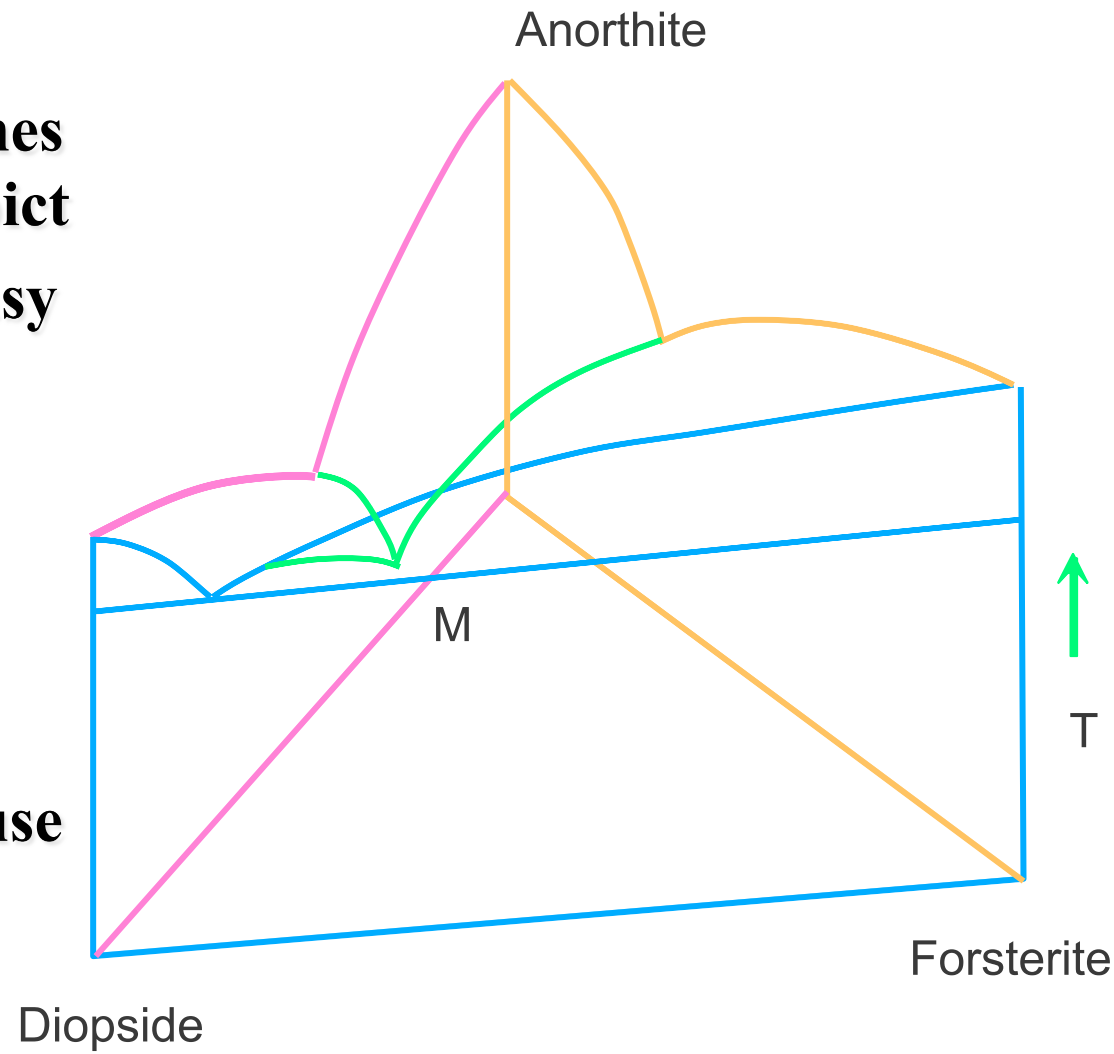
C = 3: Ternary Systems:

Example 1: Ternary Eutectic

Di - An - Fo

Adding 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
  - Project? Hard to use as shown



C = 3: Ternary Systems:

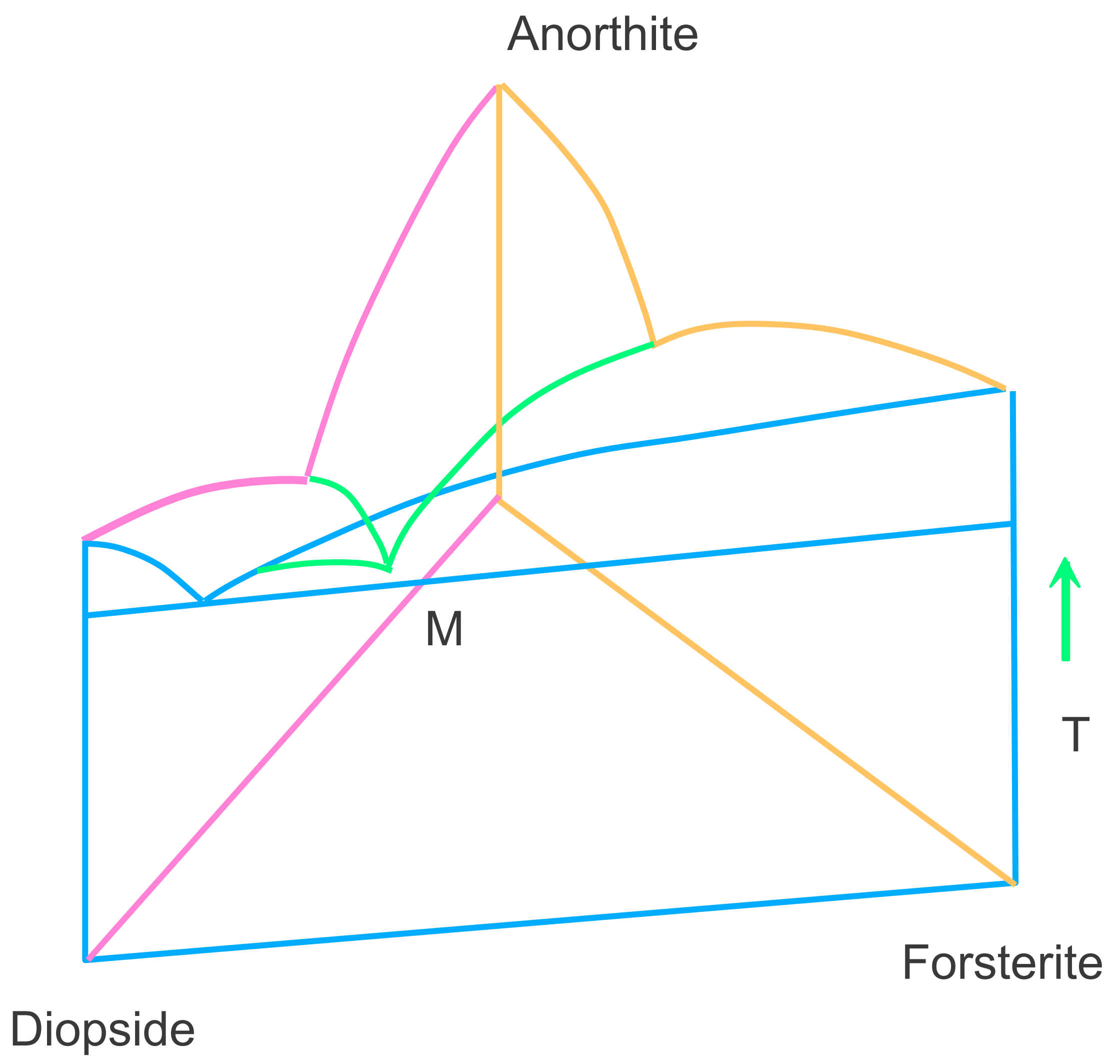
Example 1: Ternary Eutectic

Di - An - Fo

Note three binary eutectics

No solid solution

Ternary eutectic = M



T - X Projection of Di - An - Fo

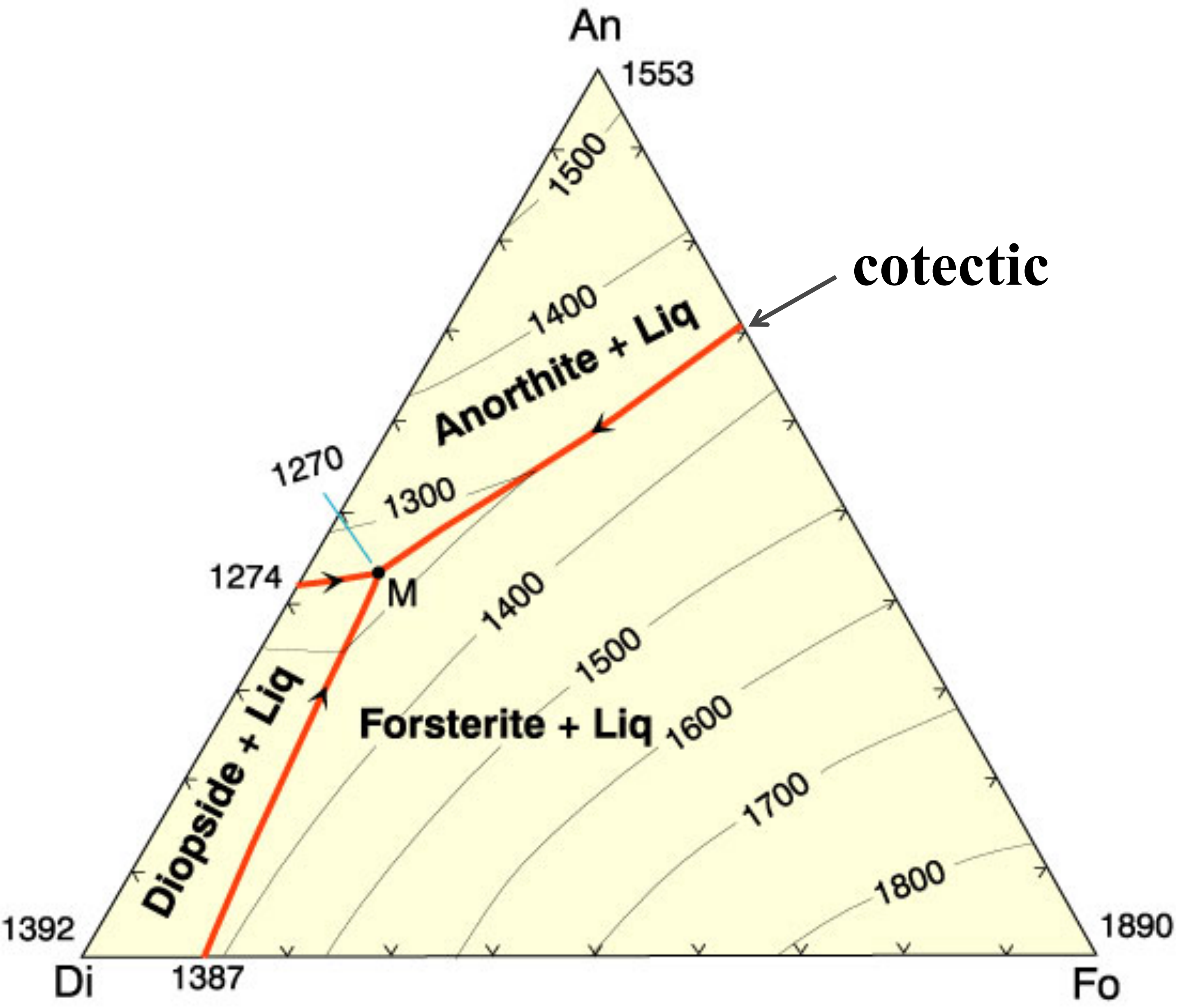
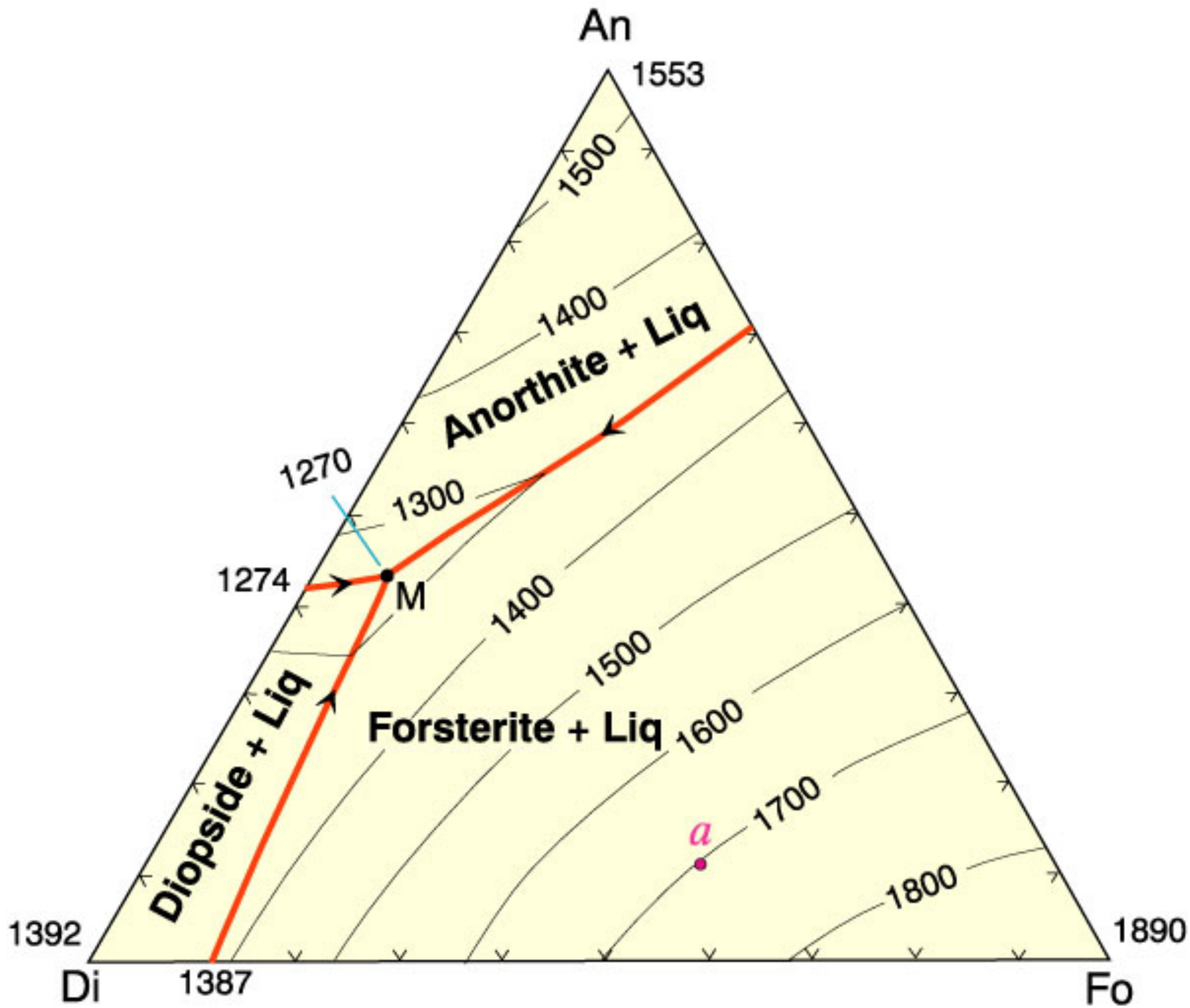
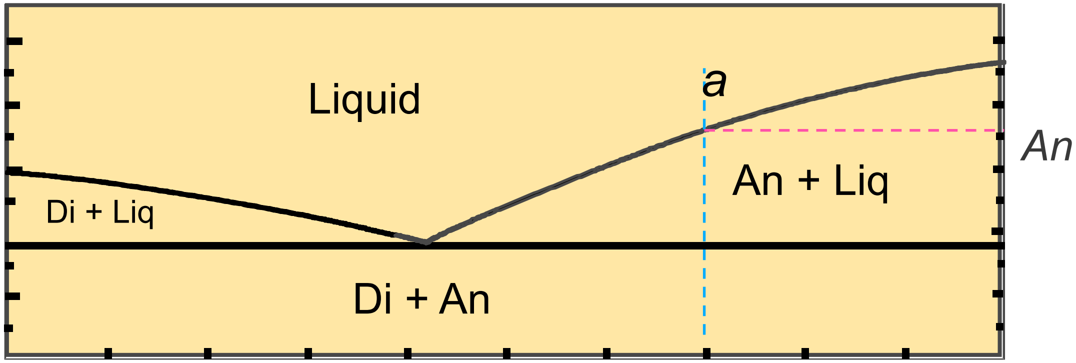


Figure 7.2. Isobaric diagram illustrating the liquidus temperatures in the Di-An-Fo system at atmospheric pressure (0.1 MPa). After Bowen (1915), A. J. Sci., and Morse (1994), Basalts and Phase Diagrams. Krieger Publishers.

Crystallization Relationships



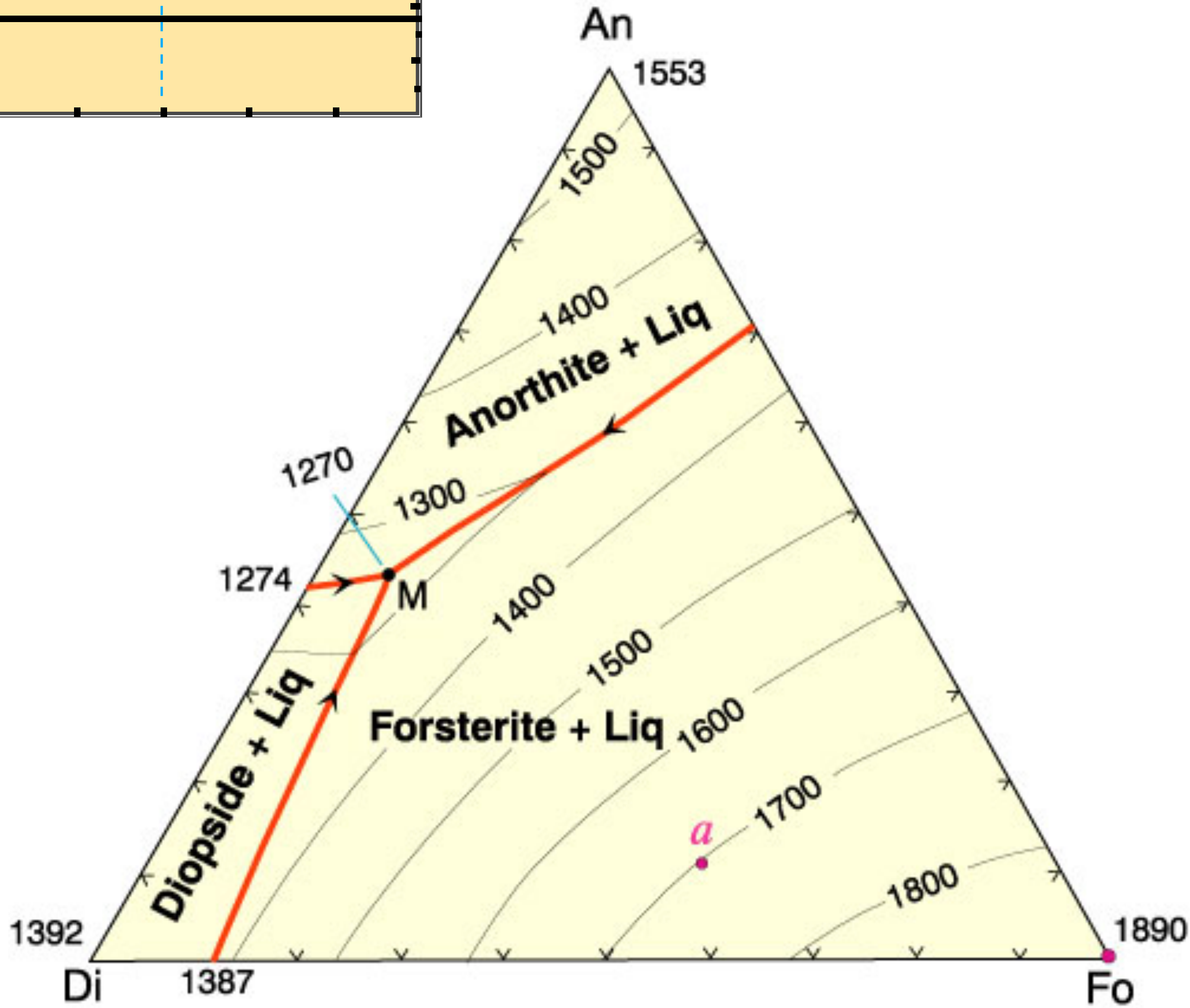


Pure Fo forms

Just as in binary

ϕ = ?

F = ?

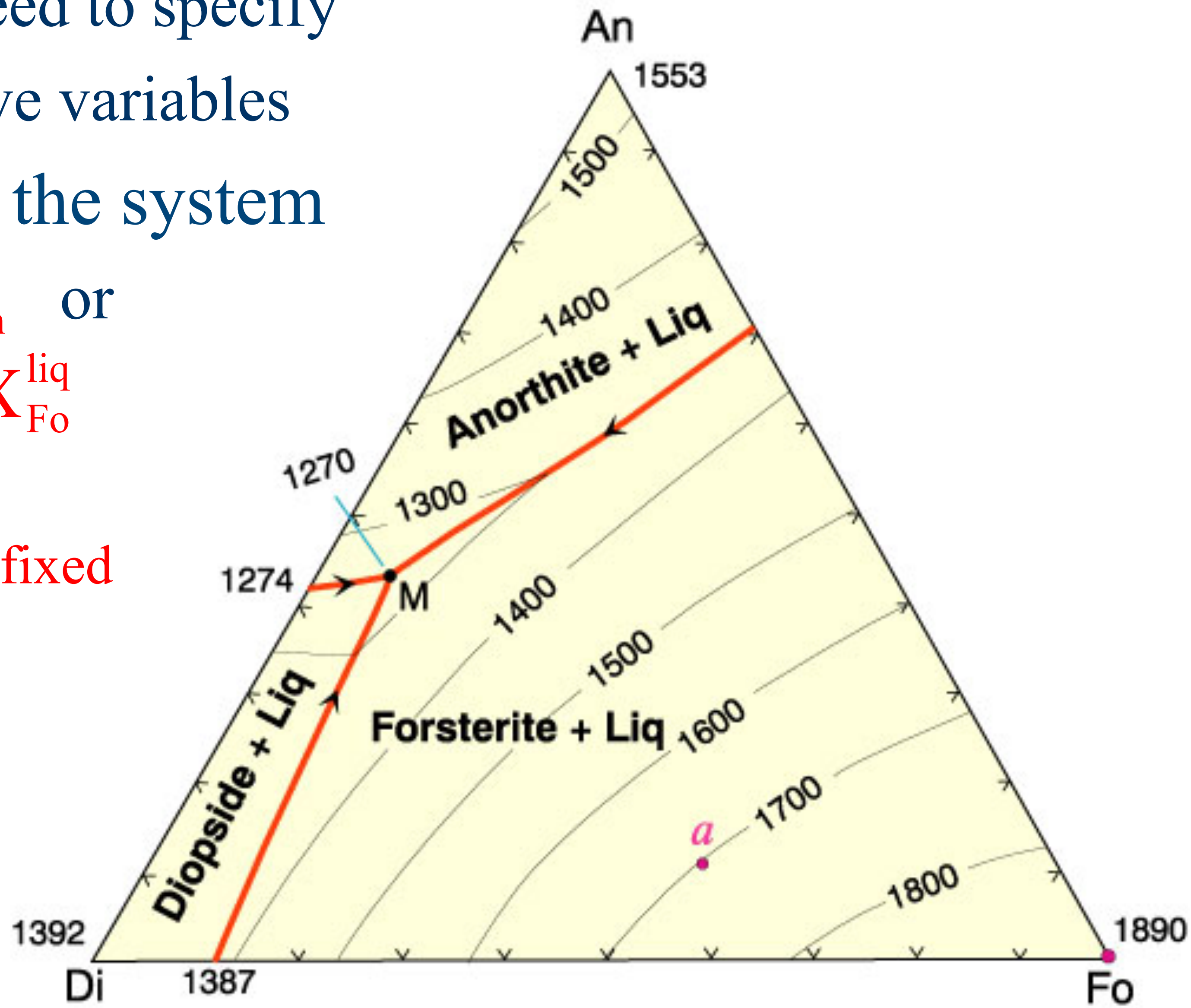


- $\phi = 2$ (Fo + Liq)
- $F = 3 - 2 + 1 = 2$

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

- T and X^{liq}_{An} or
- X^{liq}_{An} and X^{liq}_{Fo}

X of pure Fo is fixed

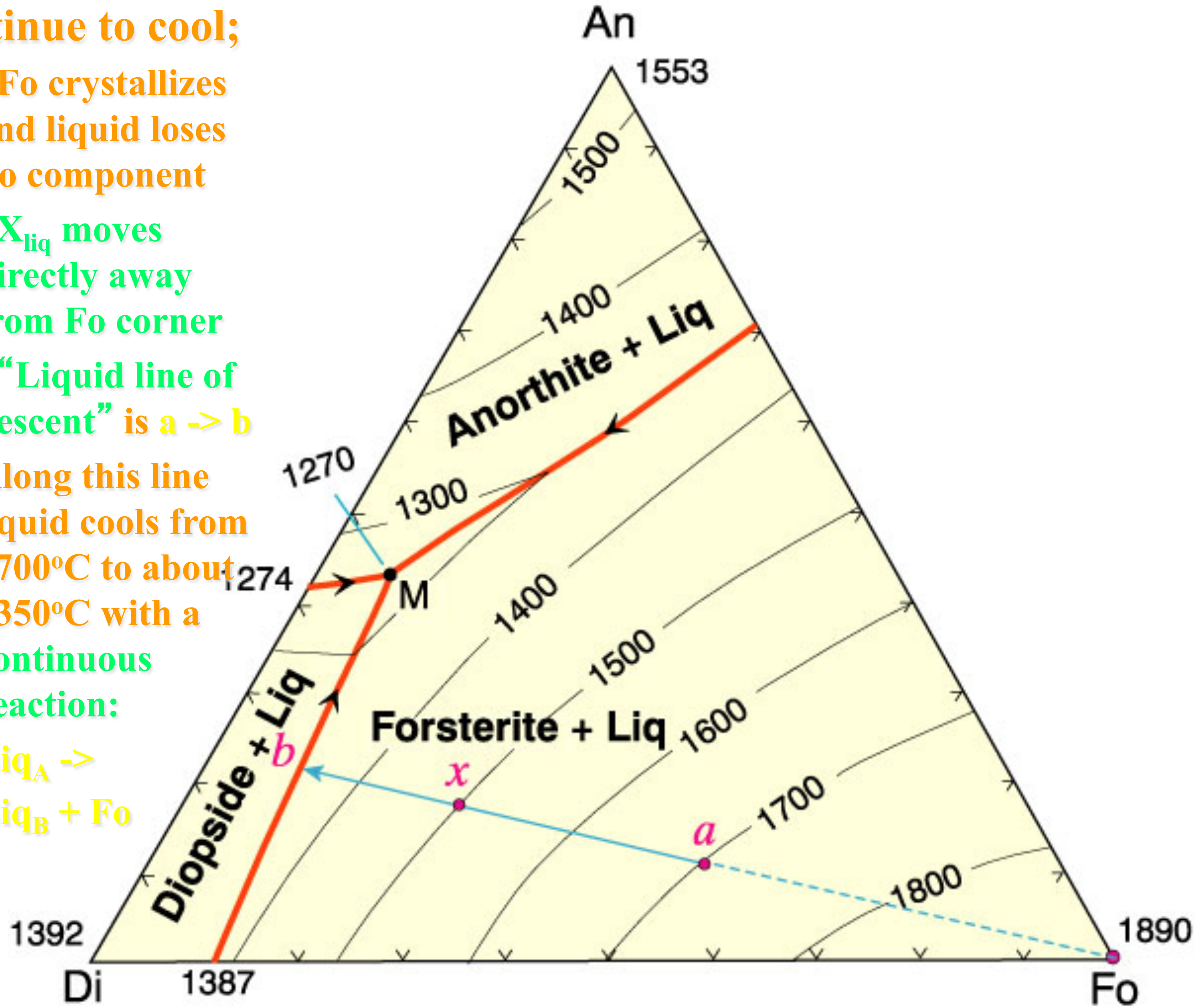


Continue to cool;

- Fo crystallizes and liquid loses Fo component
- X_{liq} moves directly away from Fo corner
- "Liquid line of descent" is a -> b

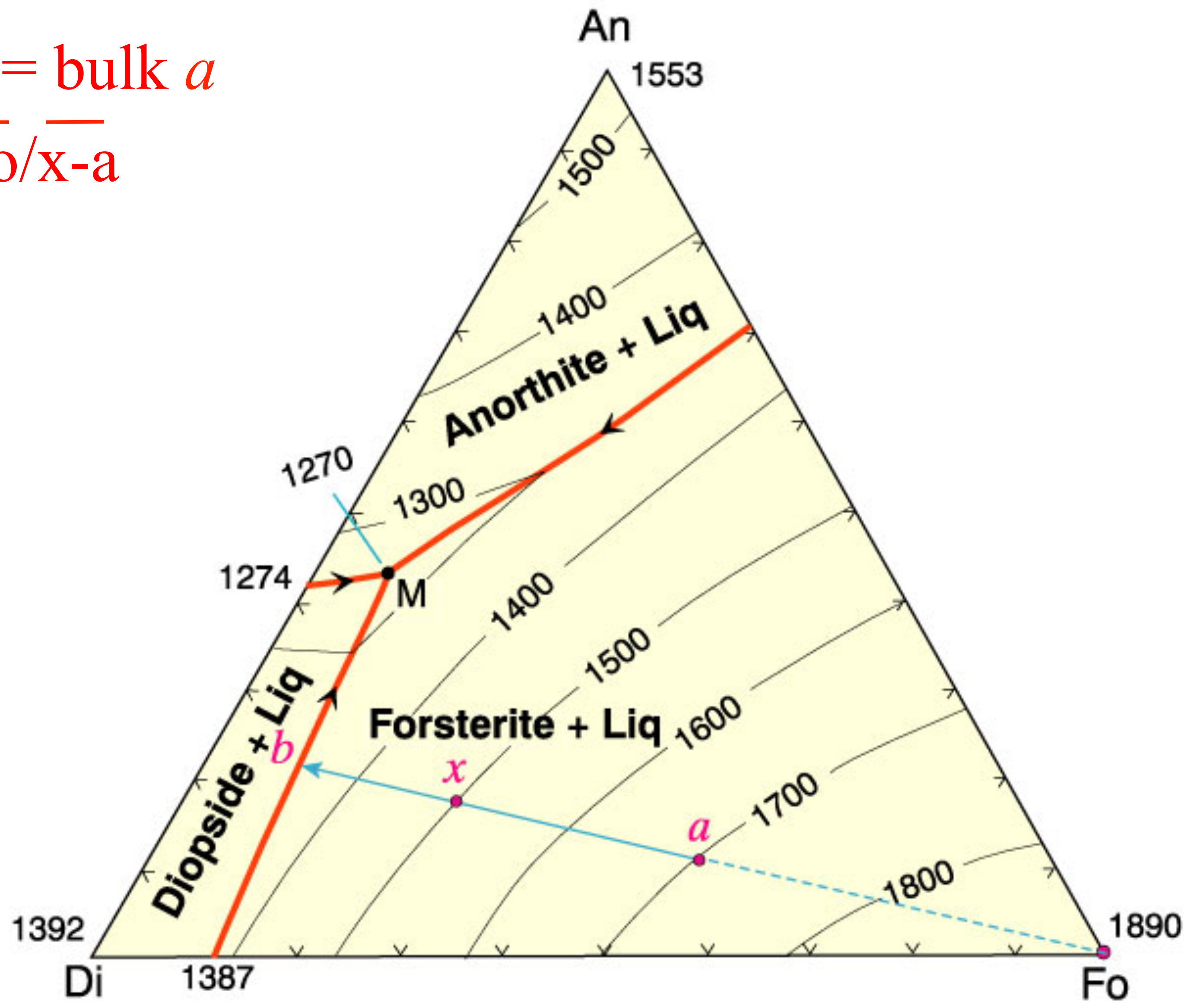
Along this line liquid cools from 1700°C to about 1350°C with a continuous reaction:

Liq_A -> Liq_B + Fo



Lever principle → relative proportions of liquid & Fo

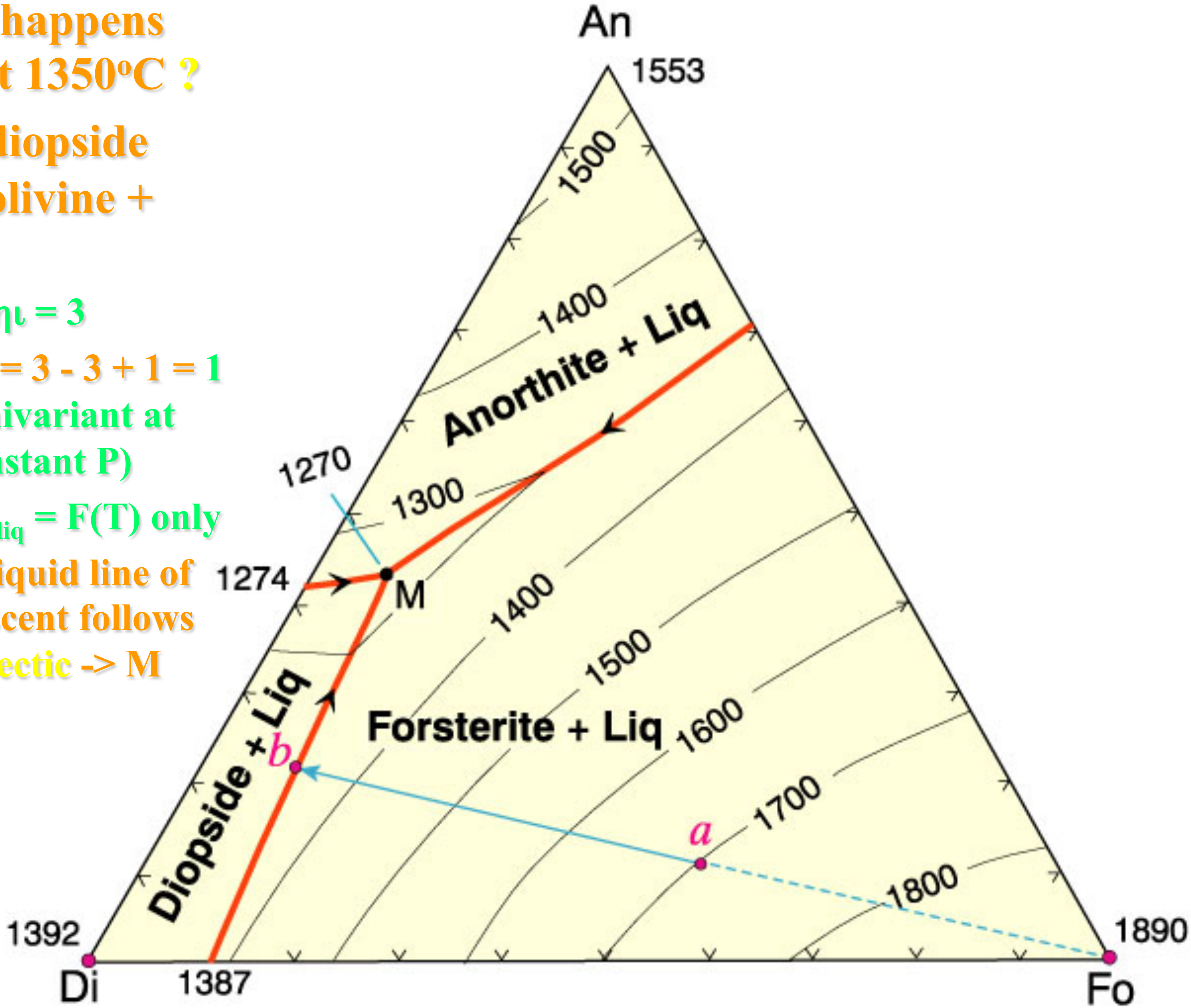
- At 1500°C
  - Liq *x* + Fo = bulk *a*
  - x/Fo = $\overline{\text{a-Fo}}/\overline{\text{x-a}}$



What happens next at 1350°C ?

Pure diopside joins olivine + liquid

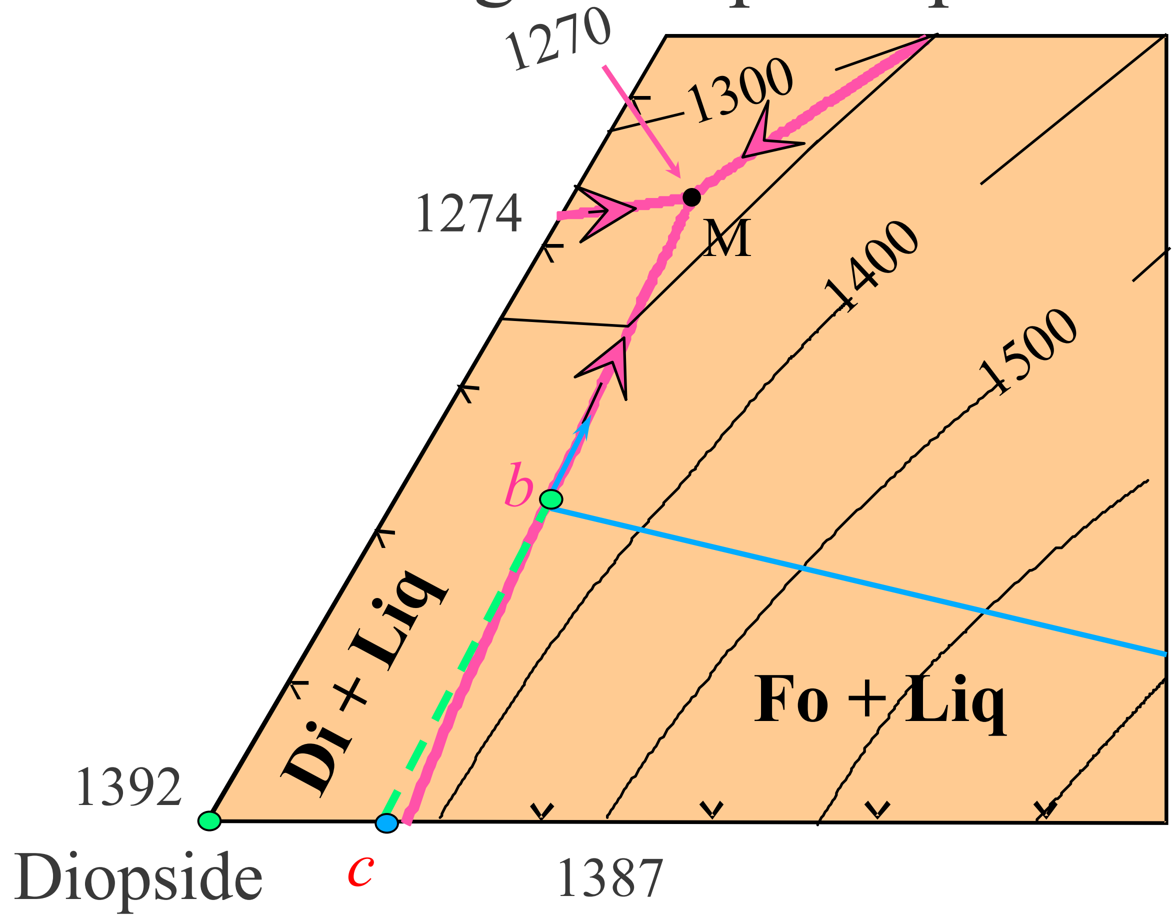
- πηι = 3
- F = 3 - 3 + 1 = 1 (univariant at constant P)
- X_{liq} = F(T) only
- Liquid line of descent follows cotectic -> M



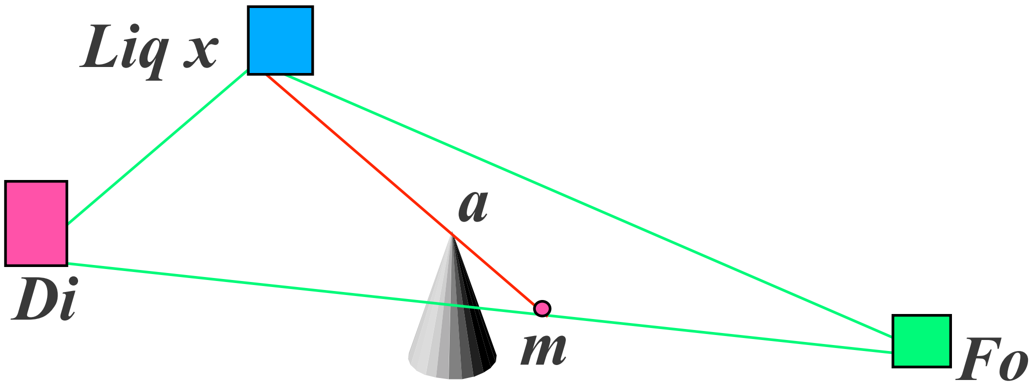
- New continuous reaction as liquid follows cotectic:

  $Liq_A \rightarrow Liq_B + Fo + Di$

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

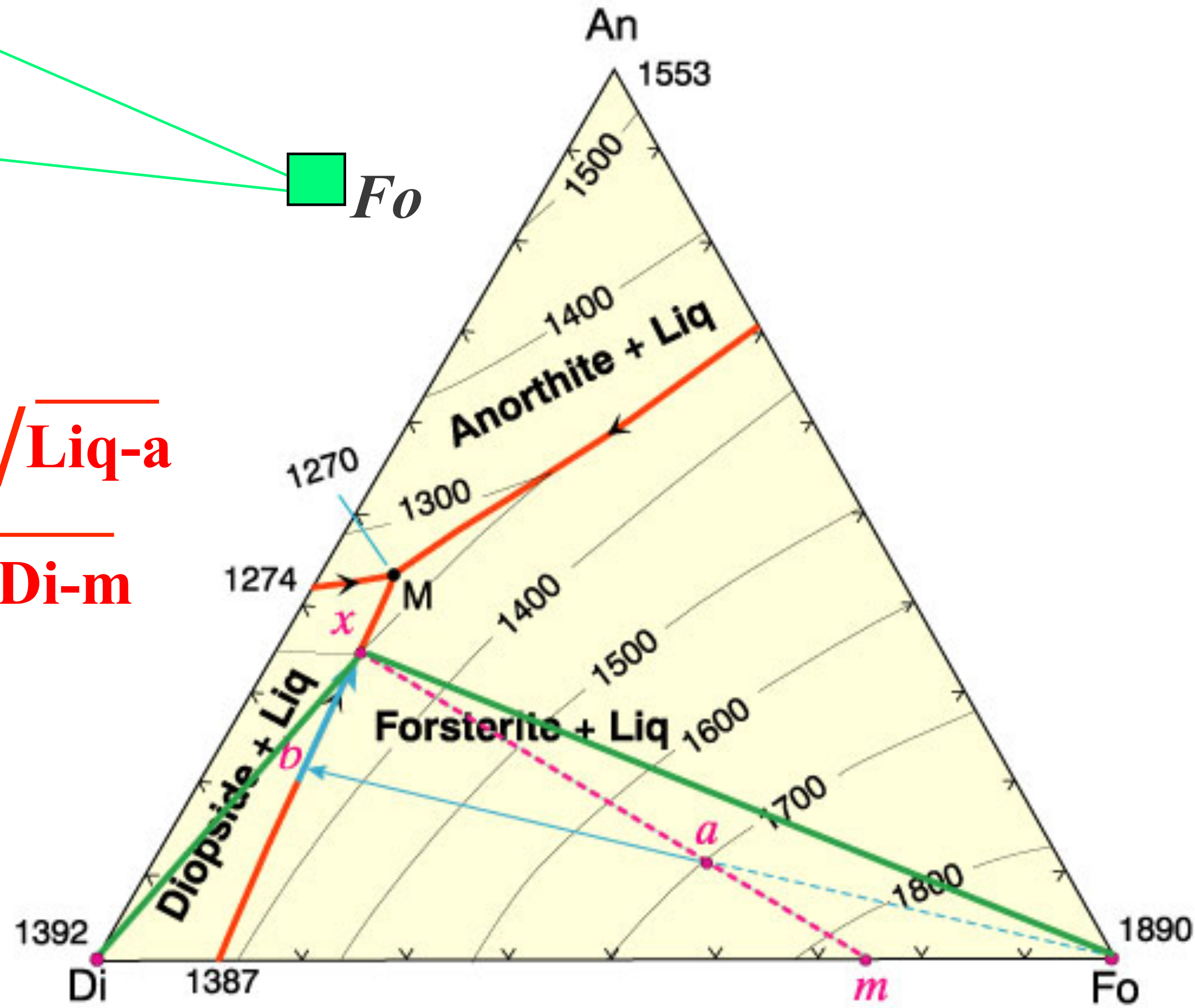


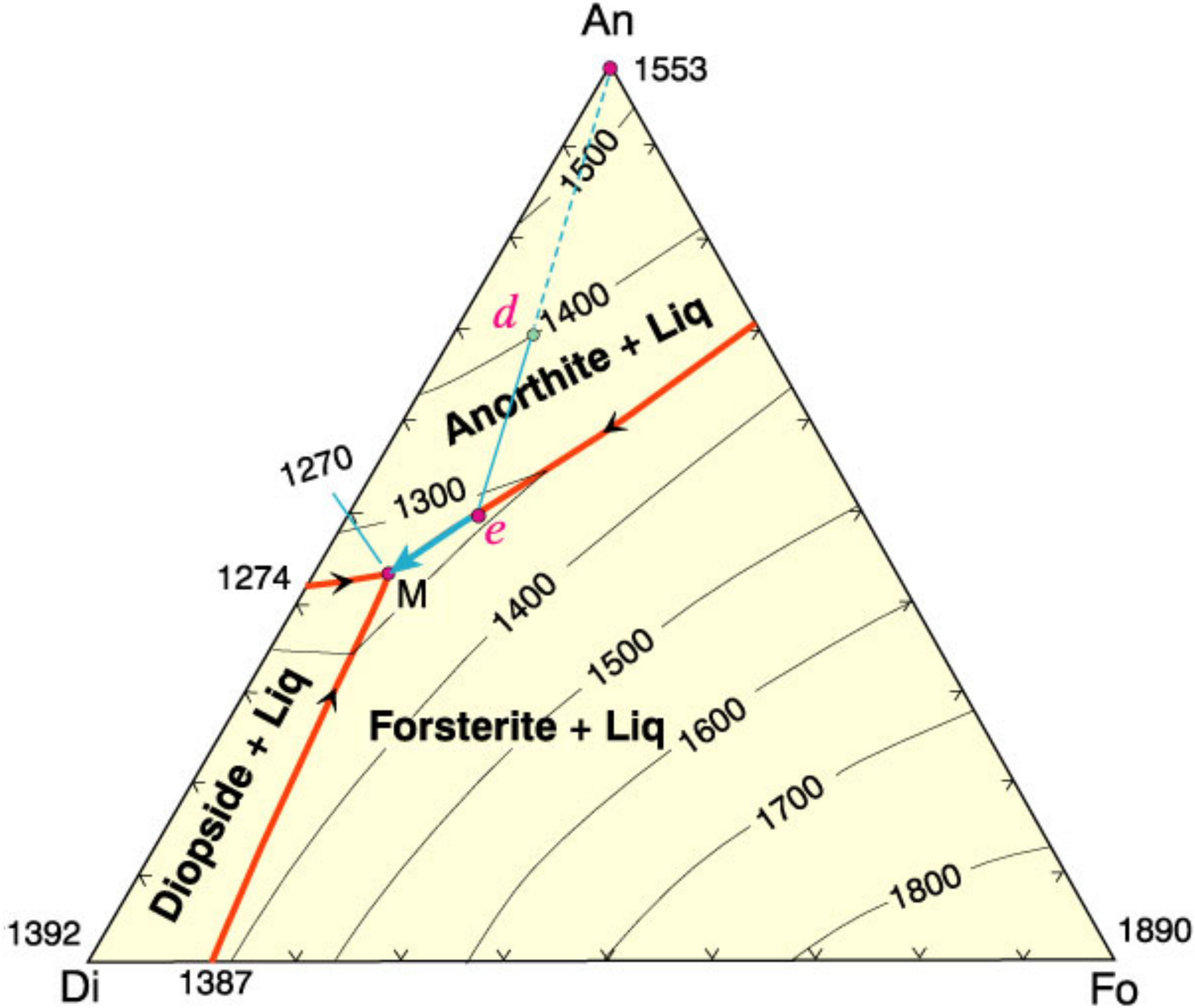
- At 1300°C liquid = X
- Imagine triangular plane X - Di - Fo balanced on bulk *a*



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

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

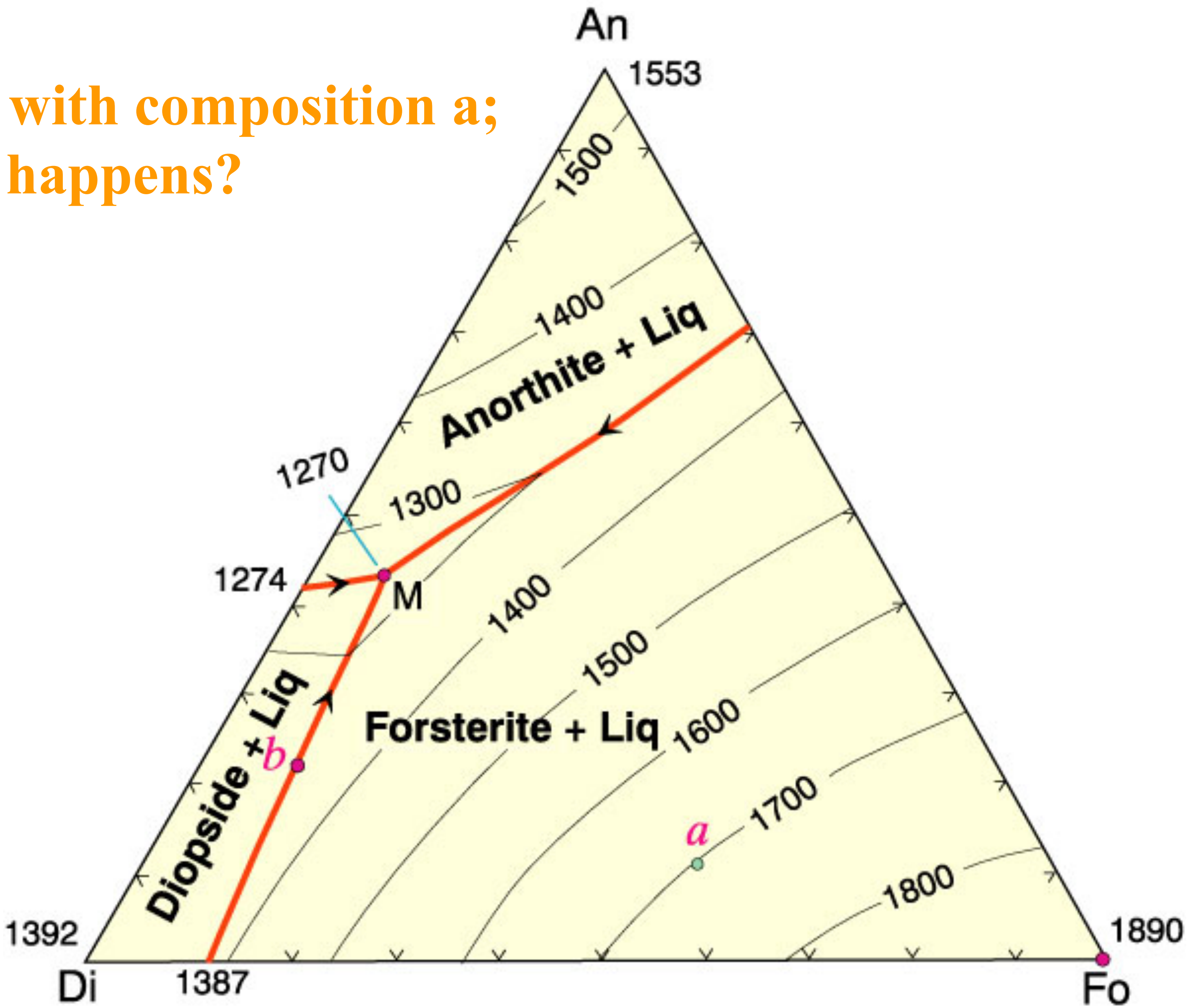




An
1553
1500
1400
d
Anorthite + Liq
1270
1300
e
1274
M
1400
1500
Diopside + Liq
Forsterite + Liq
1600
1700
1800
1392
1890
Di
1387
Fo

Partial Melting (remove melt):

Start with composition a; what happens?

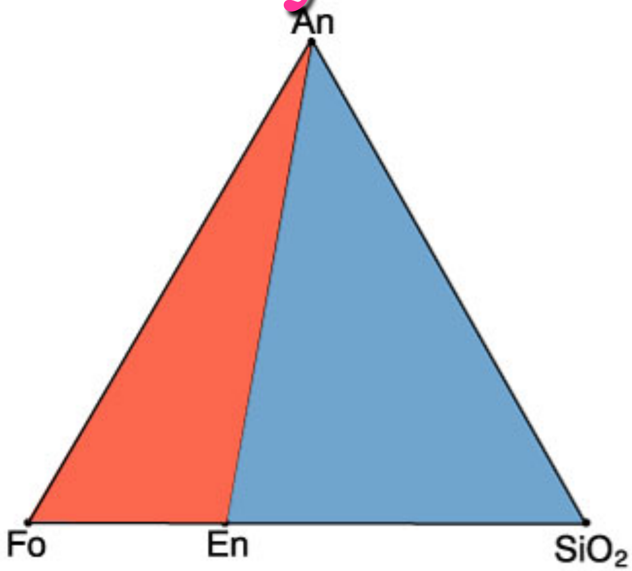


Ternary Peritectic Systems:

(at 0.1 MPa)

3 binary systems:

Fo-An eutectic
An-SiO_2 eutectic
Fo-SiO_2 peritectic



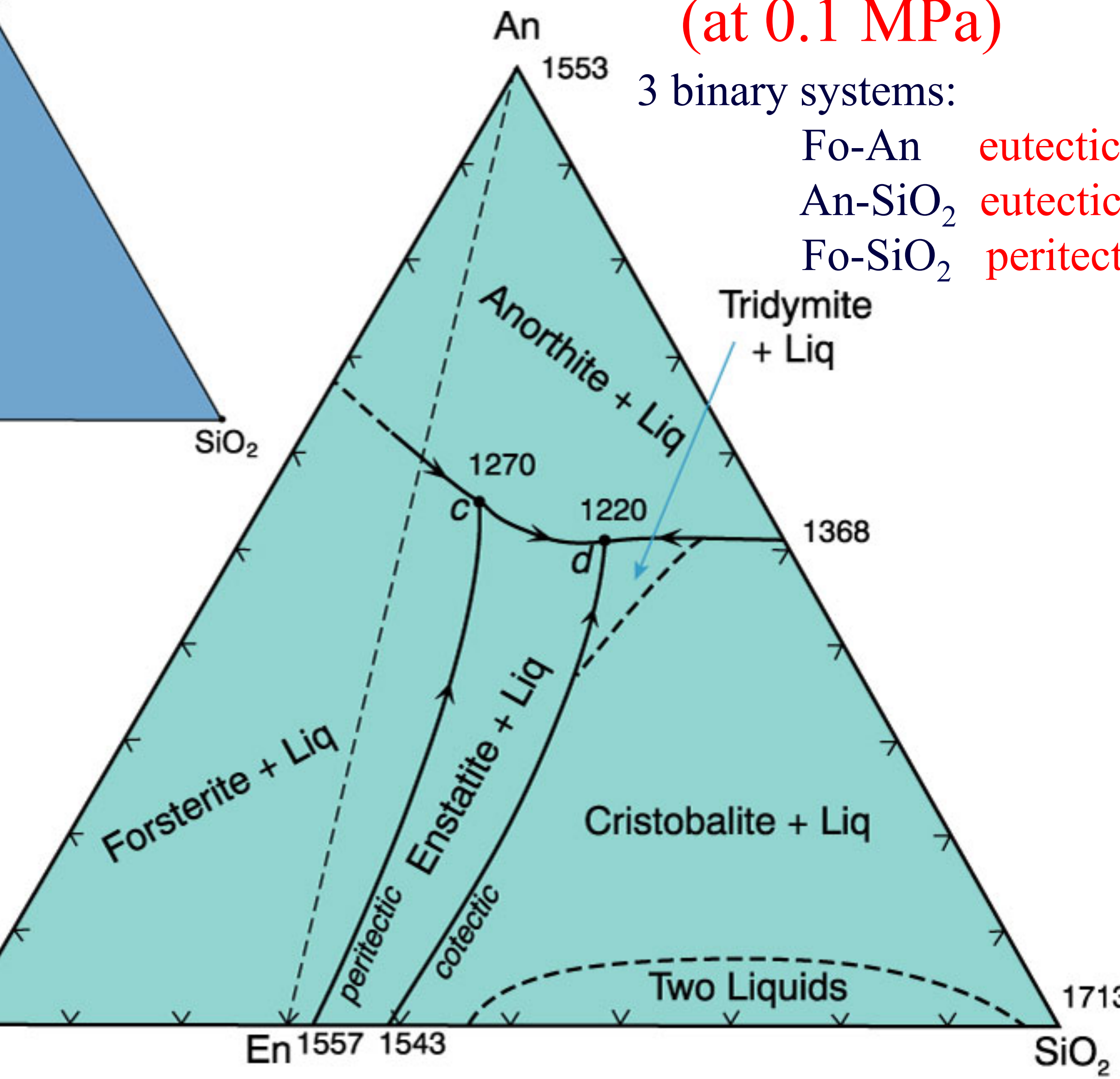
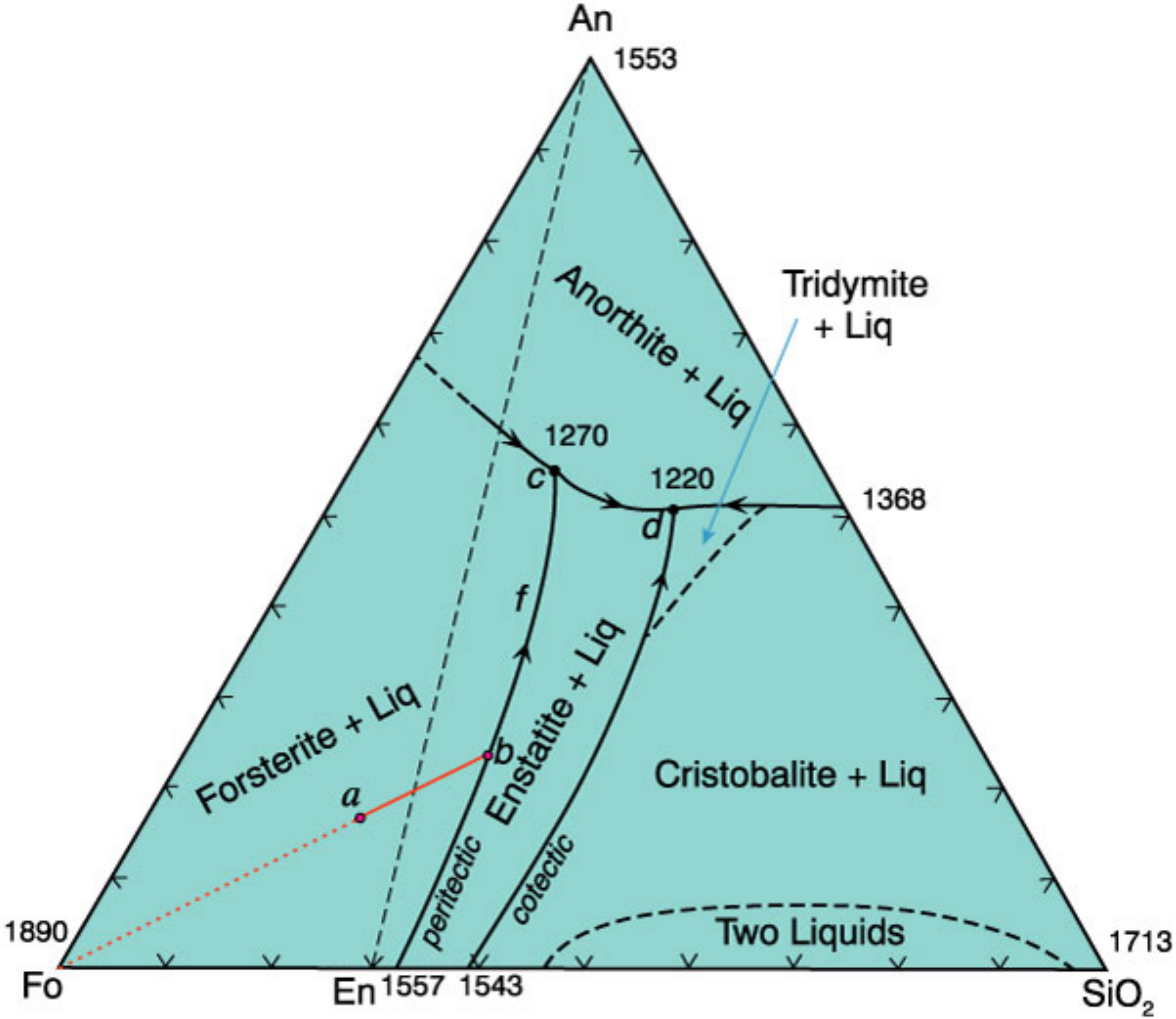
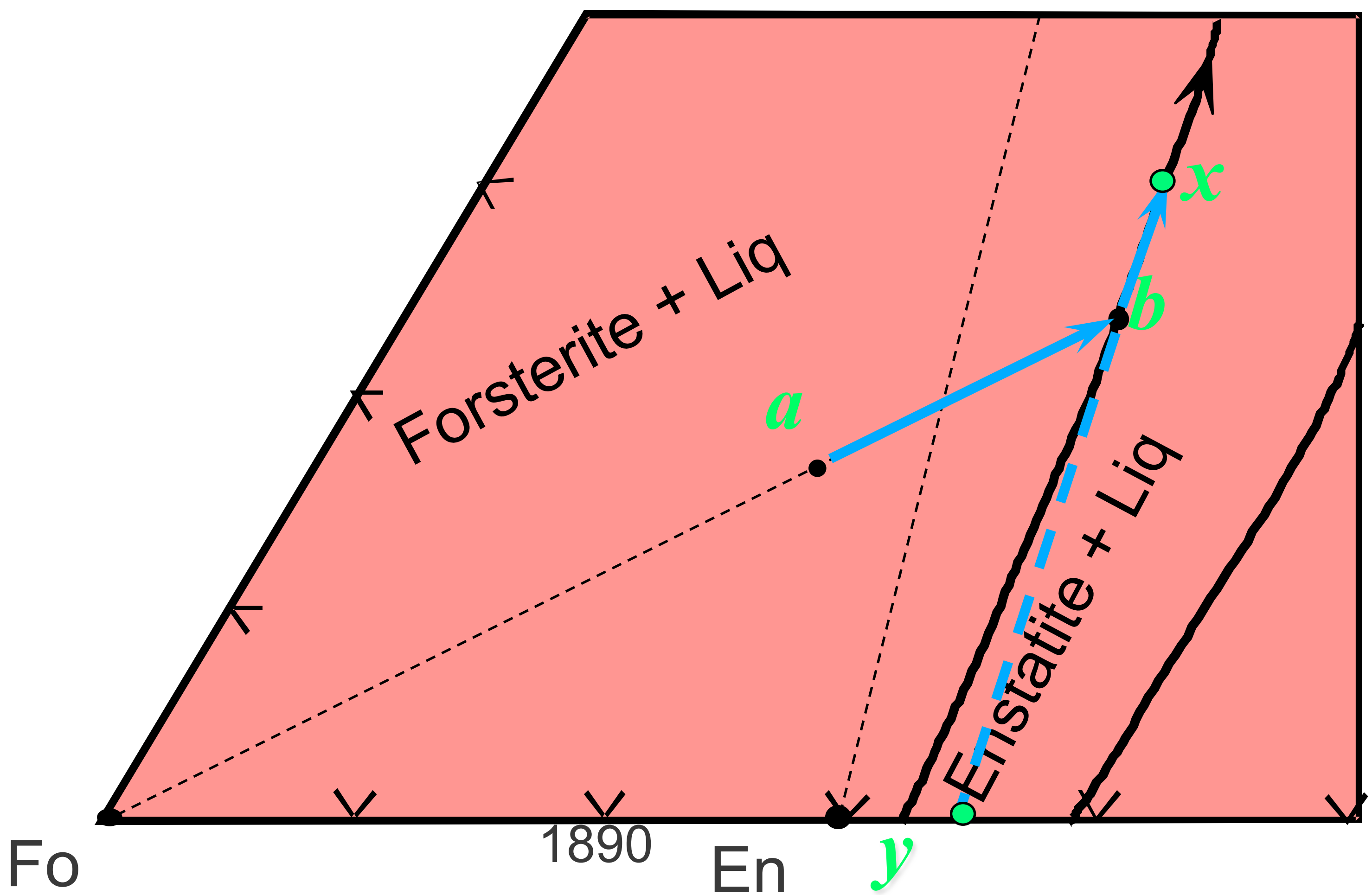
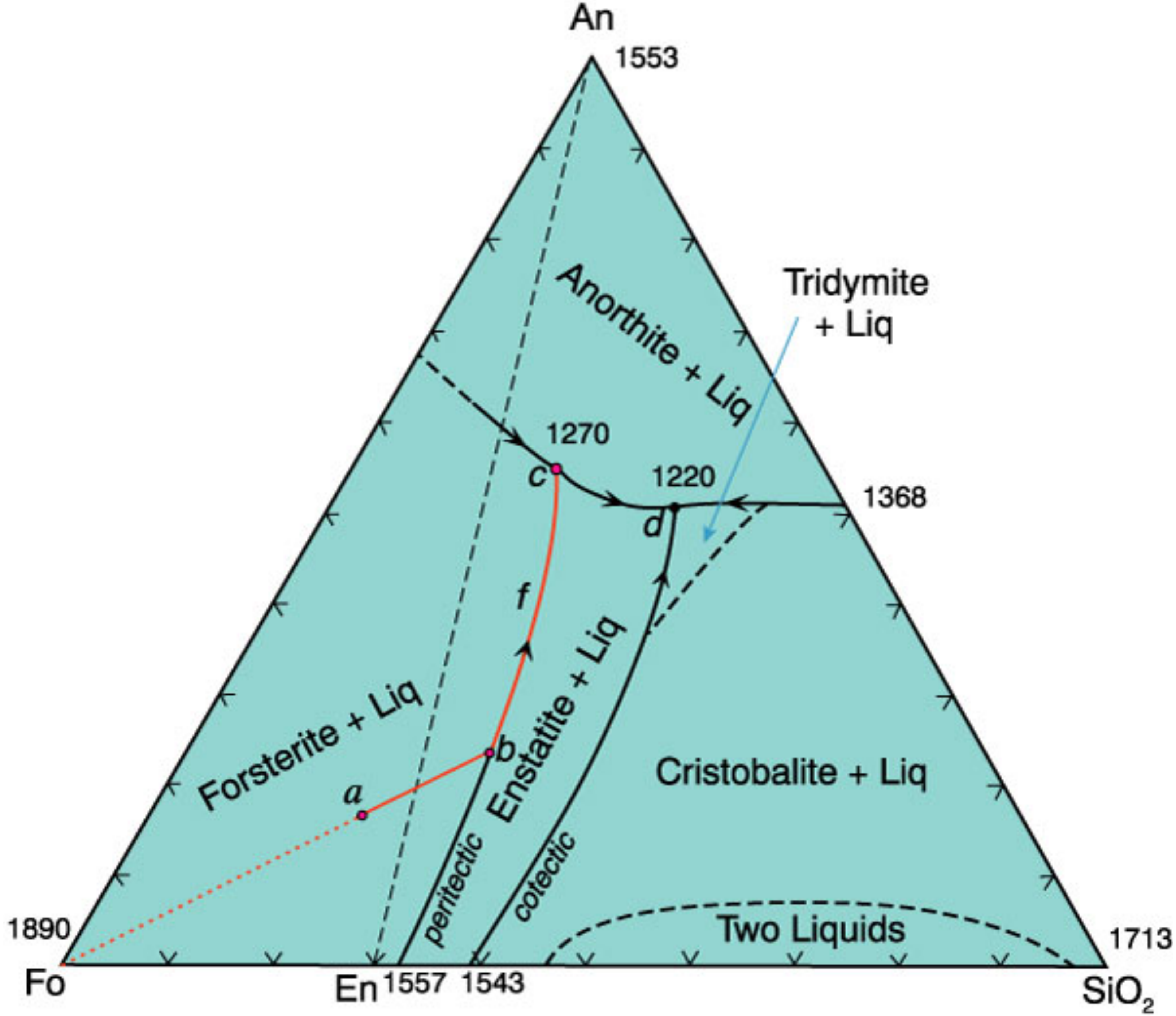


Figure 7.4. Isobaric diagram illustrating the cotectic and peritectic curves in the system forsterite-anorthite-silica at 0.1 MPa. After Anderson (1915) A. J. Sci., and Irvine (1975) CIW Yearb. 74.

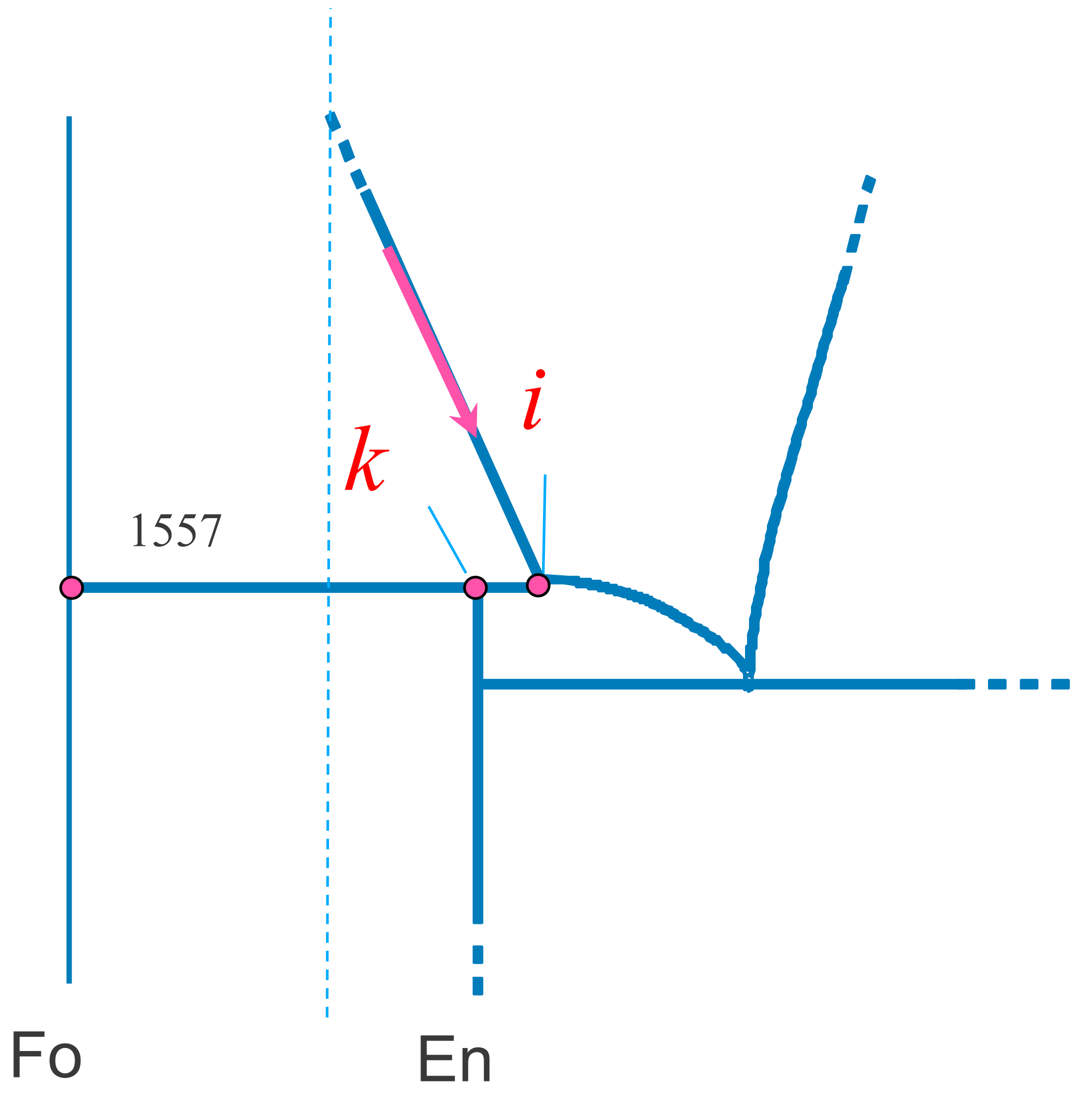

An
1553
Anorthite + Liq
Tridymite
+ Liq
1270
c
1220
d
1368
f
Forsterite + Liq
Enstatite + Liq
b
a
Cristobalite + Liq
peritectic
cotectic
Two Liquids
1890
1713
Fo
En
1557
1543
SiO2

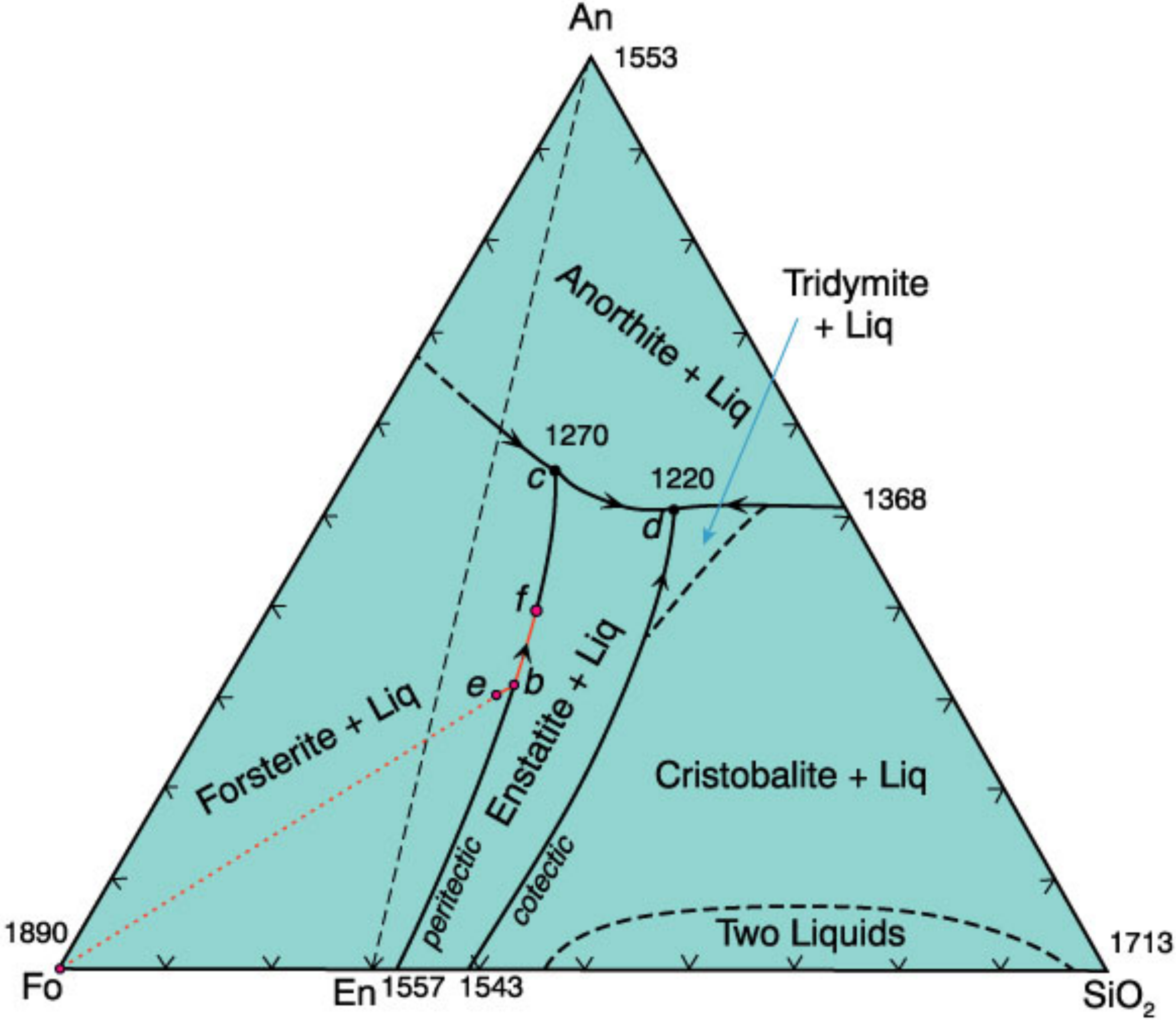

Forsterite + Liq
Enstatite + Liq
a
b
x
y
Fo
1890
En



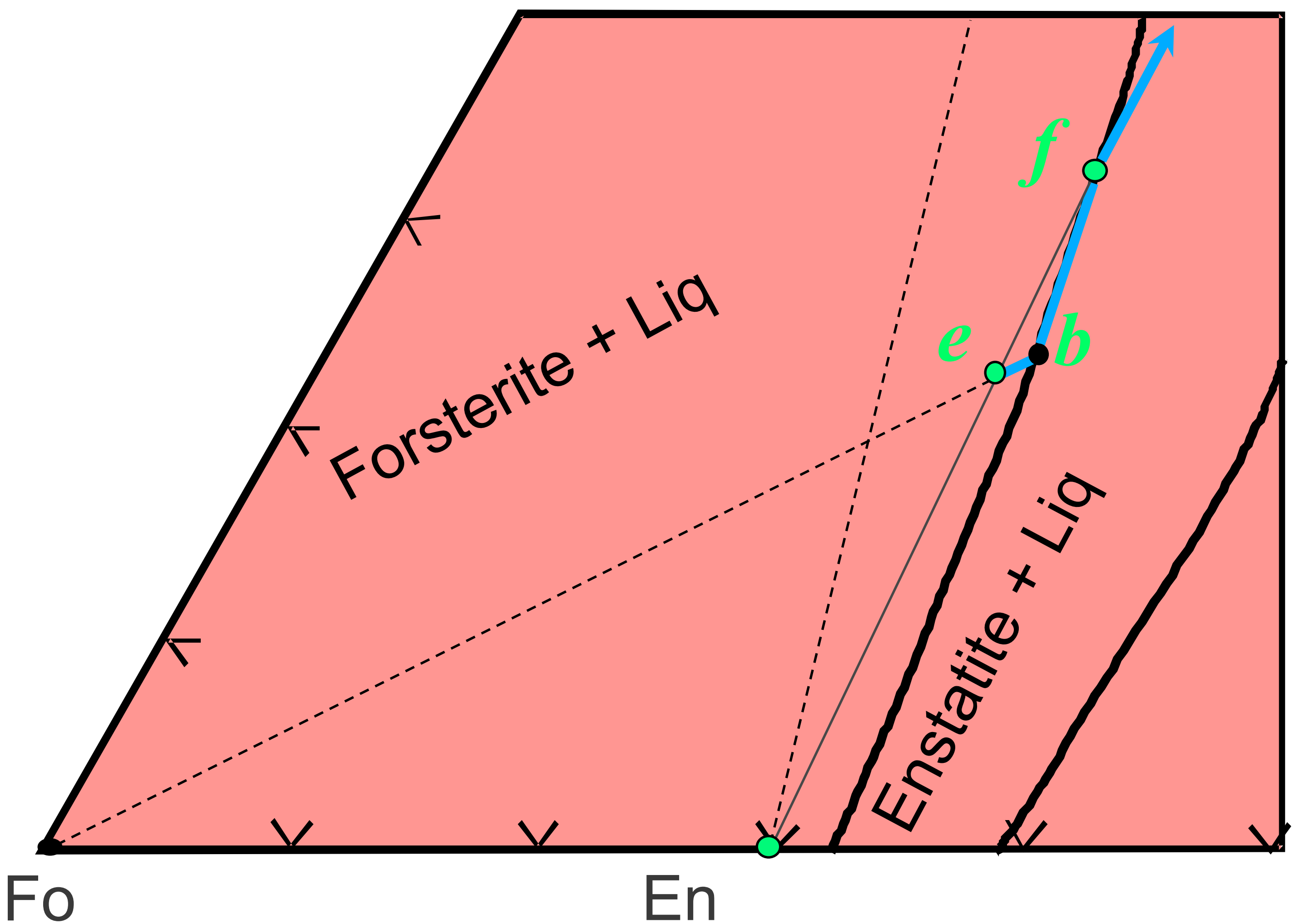
An
1553
Anorthite + Liq
Tridymite
+ Liq
1270
c
1220
d
1368
f
Forsterite + Liq
Enstatite + Liq
b
a
Cristobalite + Liq
peritectic
cotectic
Two Liquids
1890
1713
Fo
En
1557
1543
SiO_2

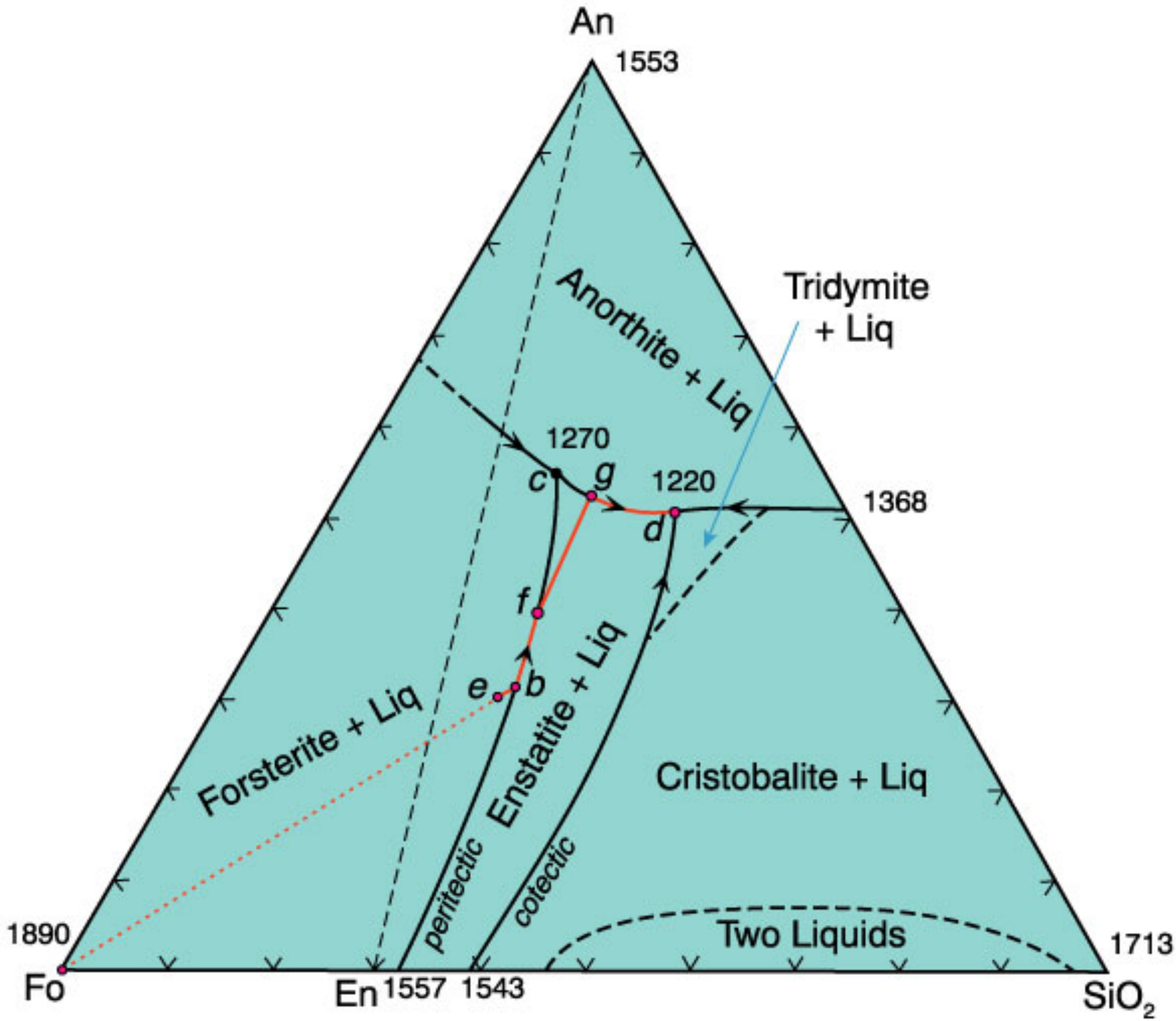
Works the same way as the Fo - En - SiO_2 binary



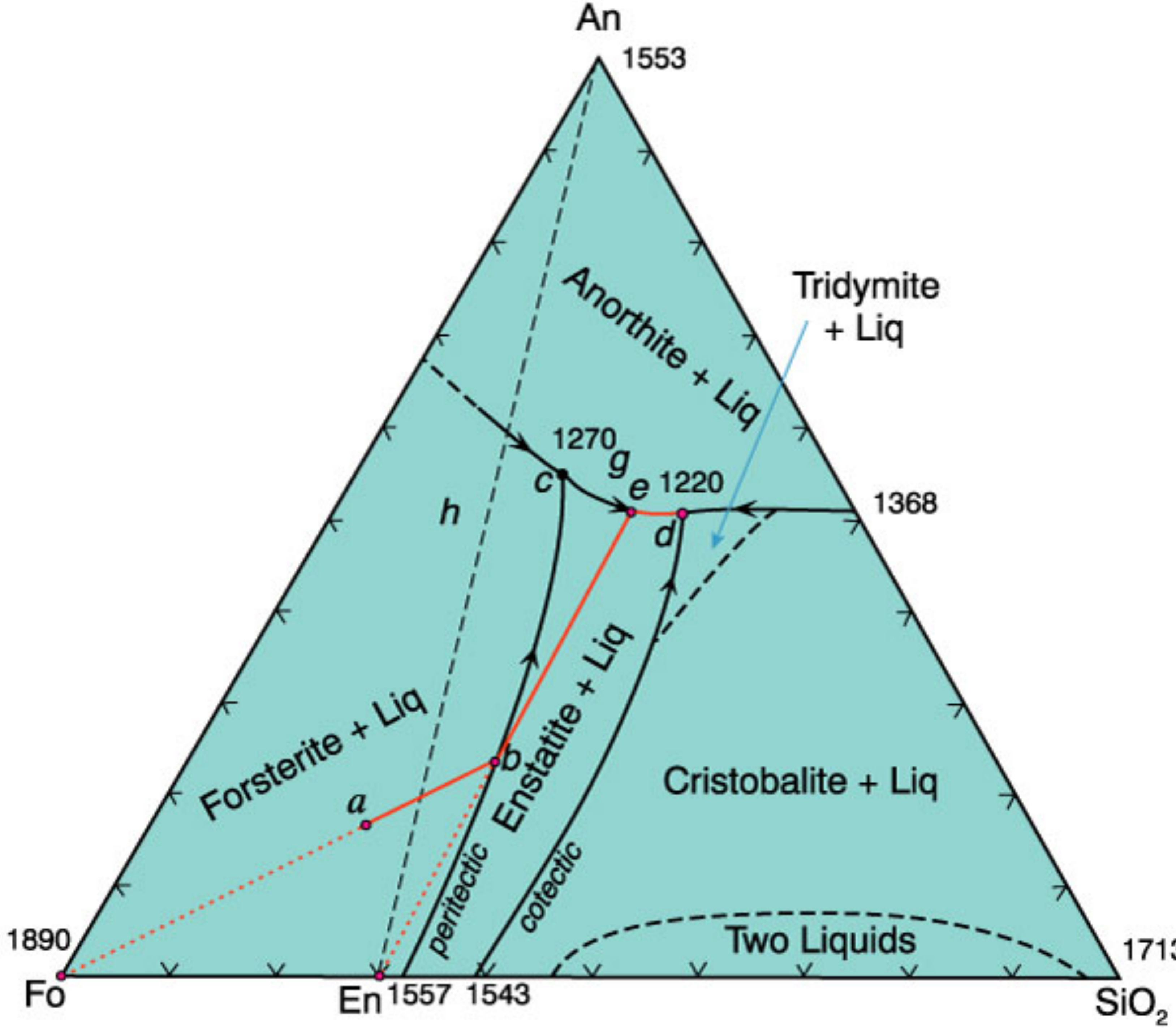


An
1553
Anorthite + Liq
Tridymite
+ Liq
1270
c
1220
d
1368
f
e
b
Forsterite + Liq
Enstatite + Liq
Cristobalite + Liq
peritectic
cotectic
Two Liquids
1890
Fo
En
1557
1543
1713
SiO2


Forsterite + Liq
Enstatite + Liq
f
e
b
Fo
En



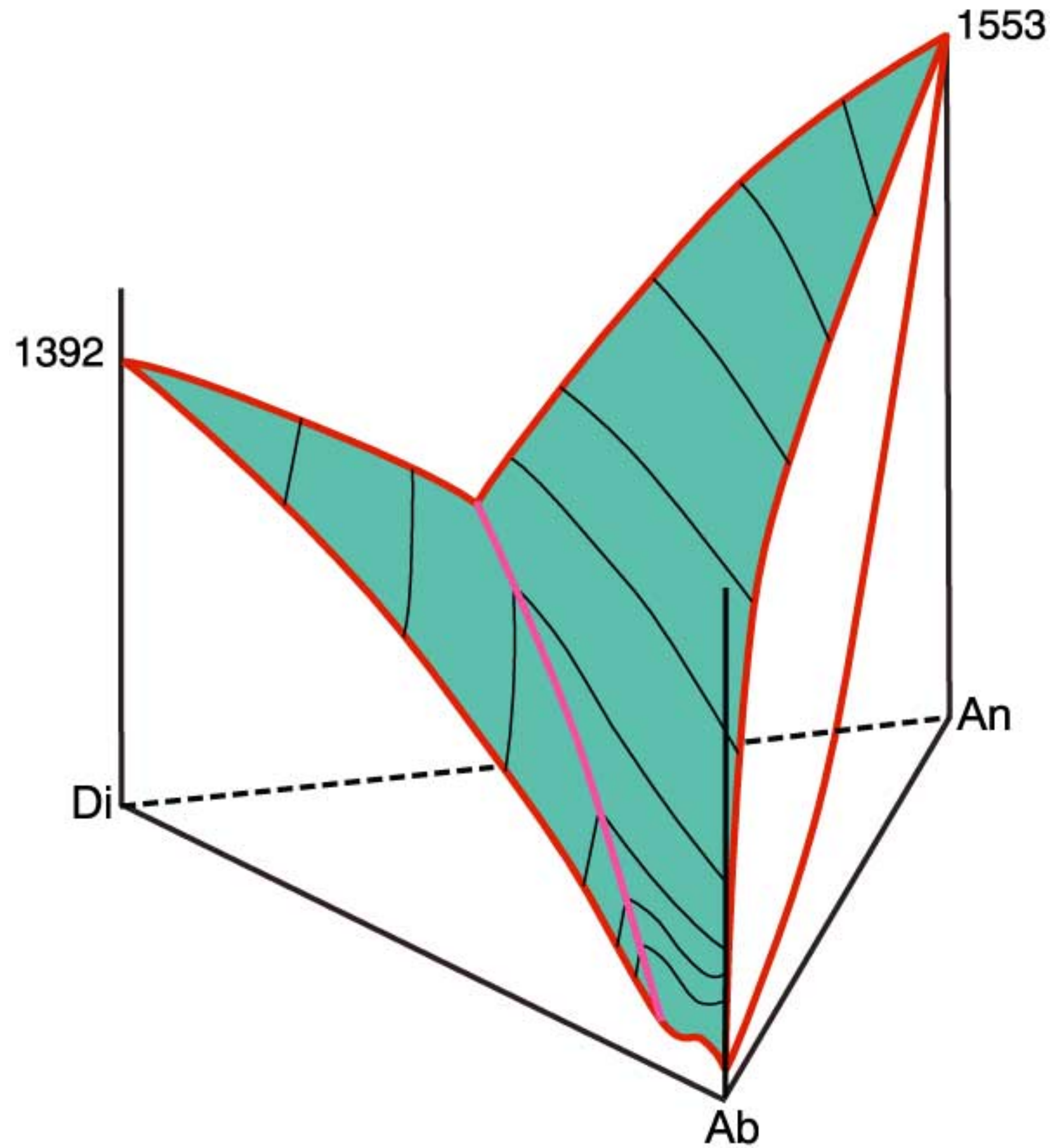
An
1553
Anorthite + Liq
Tridymite
+ Liq
1270
c
g
1220
1368
d
f
Enstatite + Liq
e
b
Forsterite + Liq
Cristobalite + Liq
peritectic
cotectic
Two Liquids
1890
1713
Fo
En
1557
1543
SiO2



An
1553
Anorthite + Liq
Tridymite
+ Liq
1270
g
c
e
1220
1368
h
d
Forsterite + Liq
Enstatite + Liq
b
a
Cristobalite + Liq
peritectic
cotectic
Two Liquids
1890
Fo
En
1557
1543
SiO2

Diopside-Albite-Anorthite

Figure 7.5. Isobaric diagram illustrating the liquidus temperatures in the system diopside-anorthite-albite at atmospheric pressure (0.1 MPa). After Morse (1994), Basalts and Phase Diagrams. Krieger Publushers



Di - An eutectic
Di - Ab eutectic
Ab - An solid solution

Isobaric polythermal projection

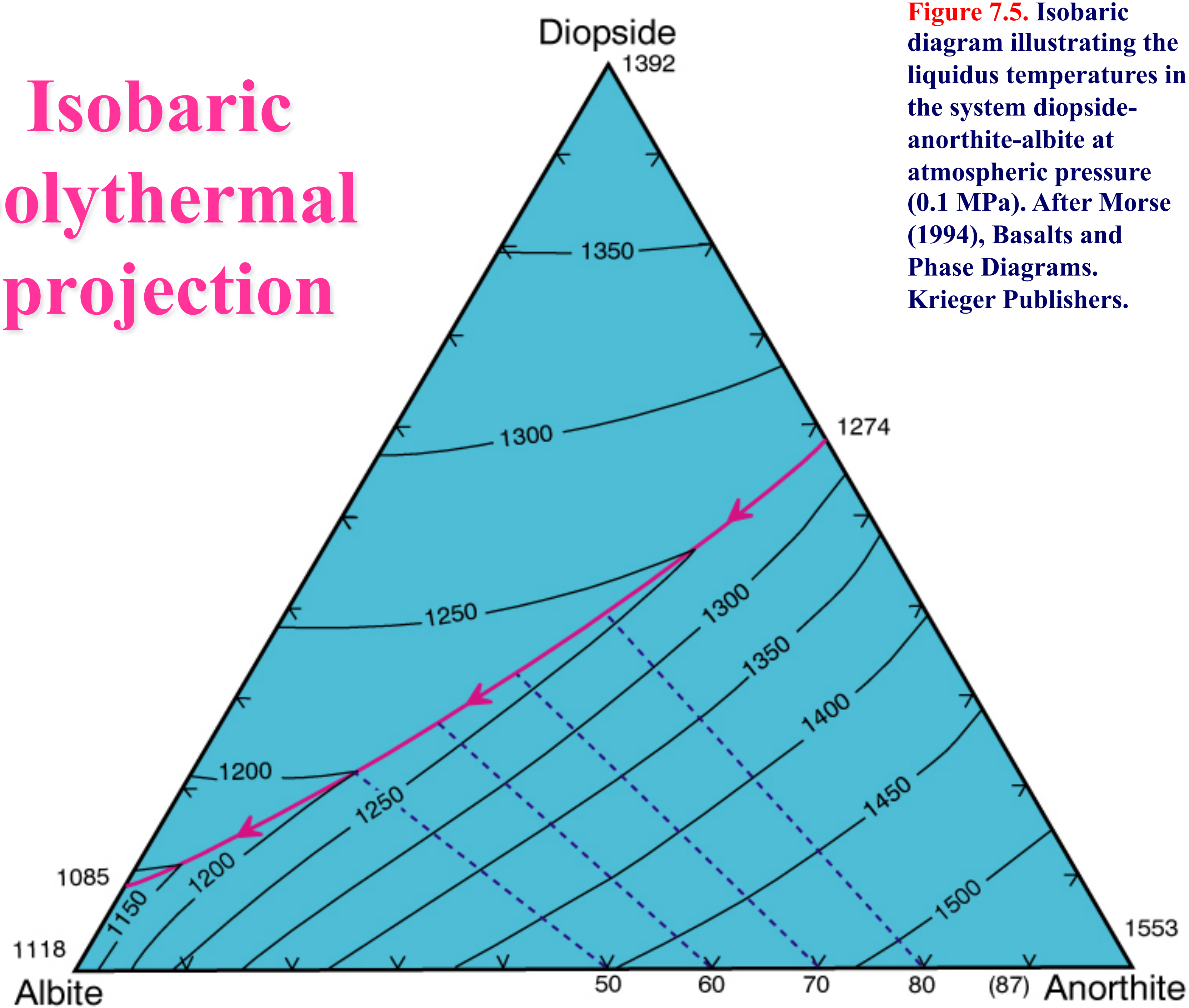
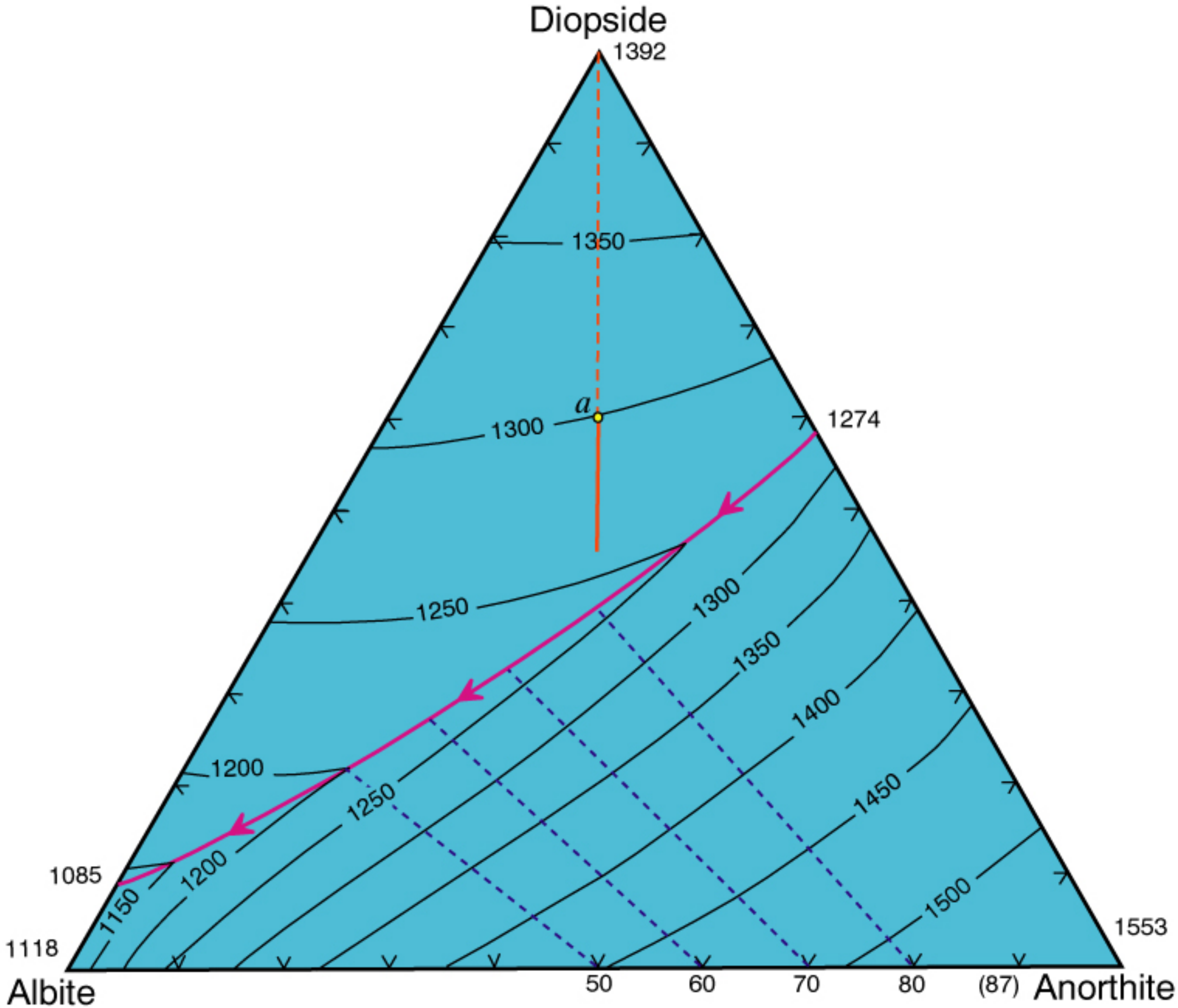
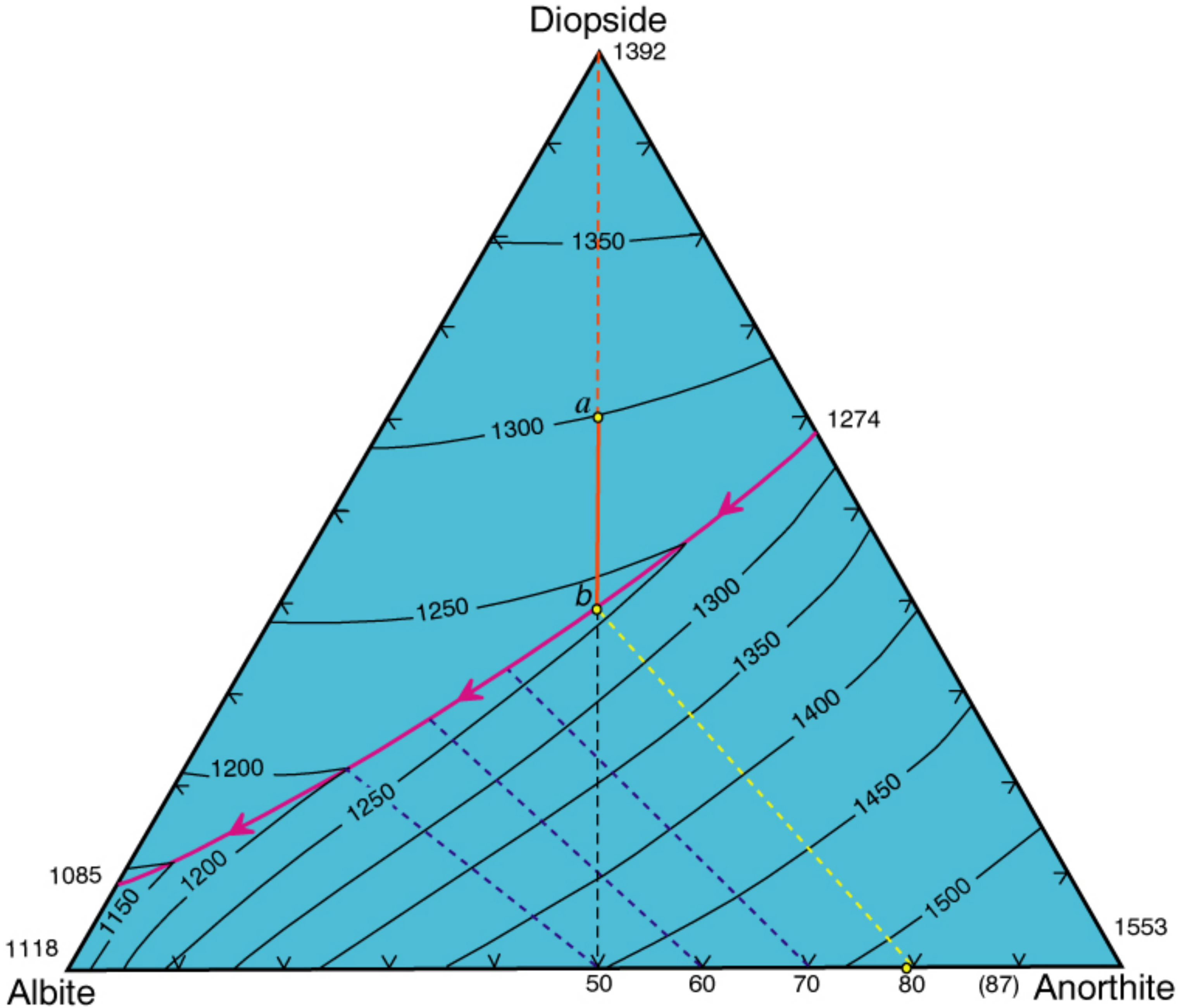


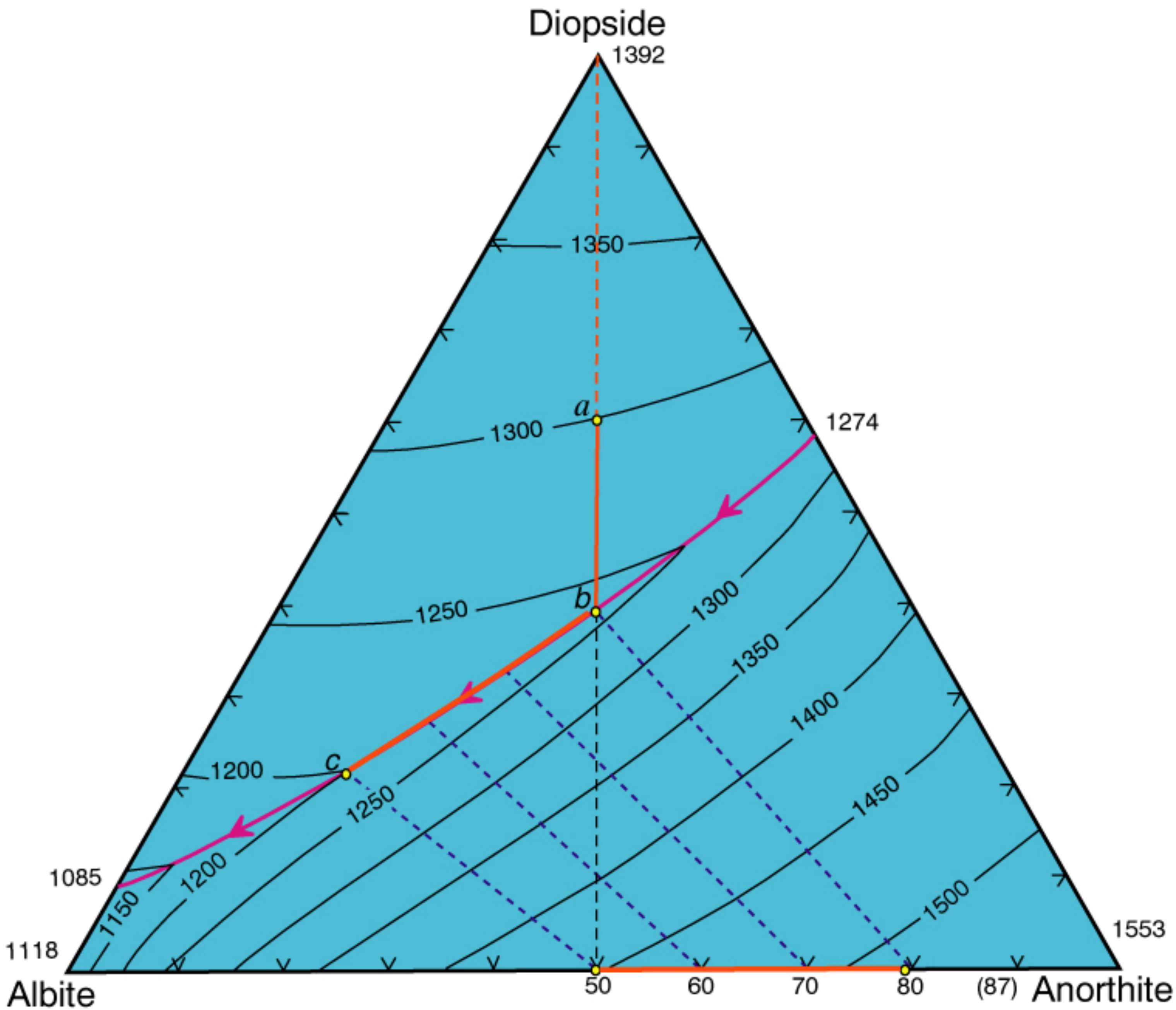
Figure 7.5. Isobaric diagram illustrating the liquidus temperatures in the system diopside-anorthite-albite at atmospheric pressure (0.1 MPa). After Morse (1994), Basalts and Phase Diagrams. Krieger Publishers.



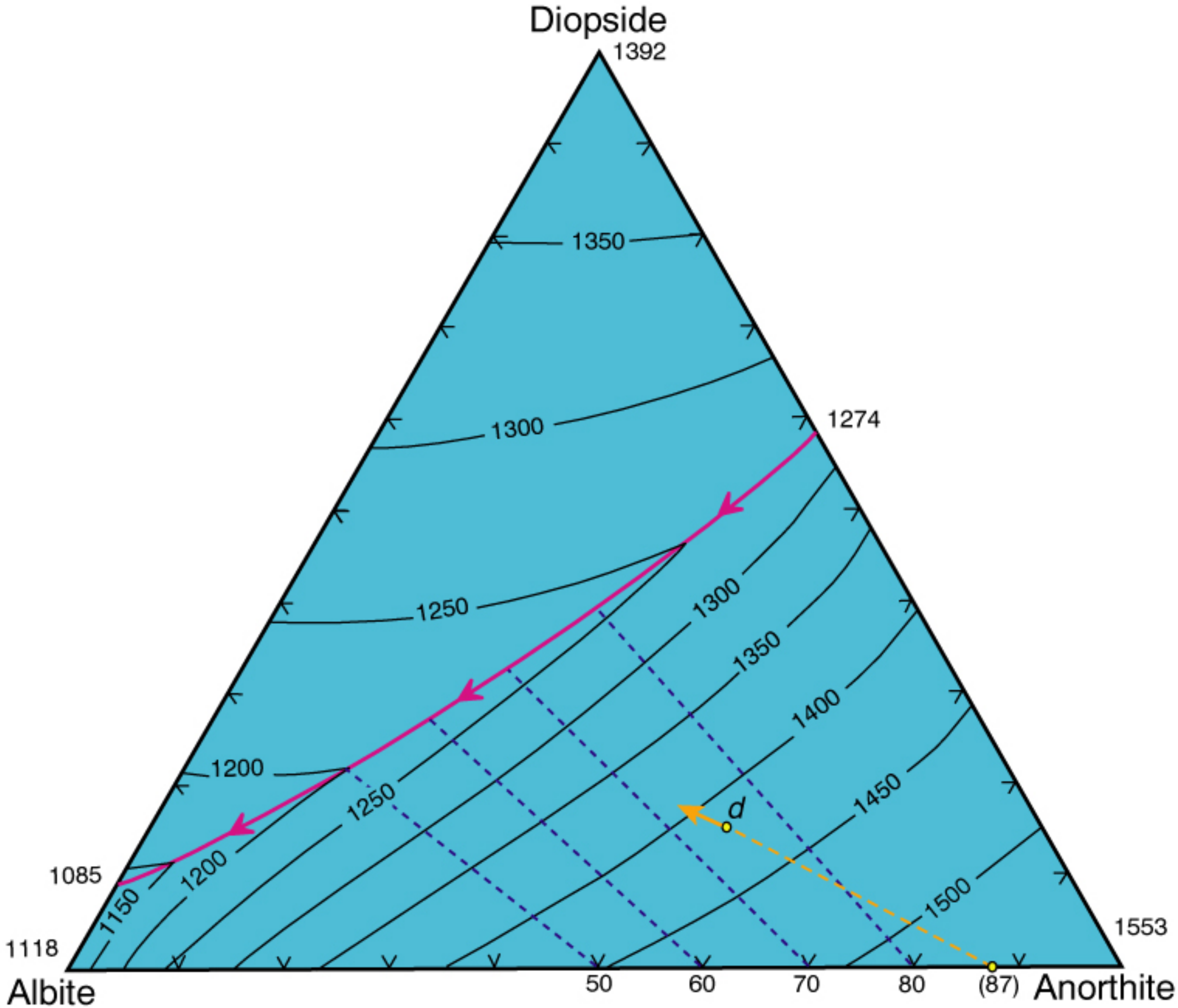
Diopside
1392
1350
a
1300
1274
1250
1300
1350
1400
1200
1250
1450
1085
1200
1150
1500
1553
1118
Albite
50
60
70
80
(87)
Anorthite



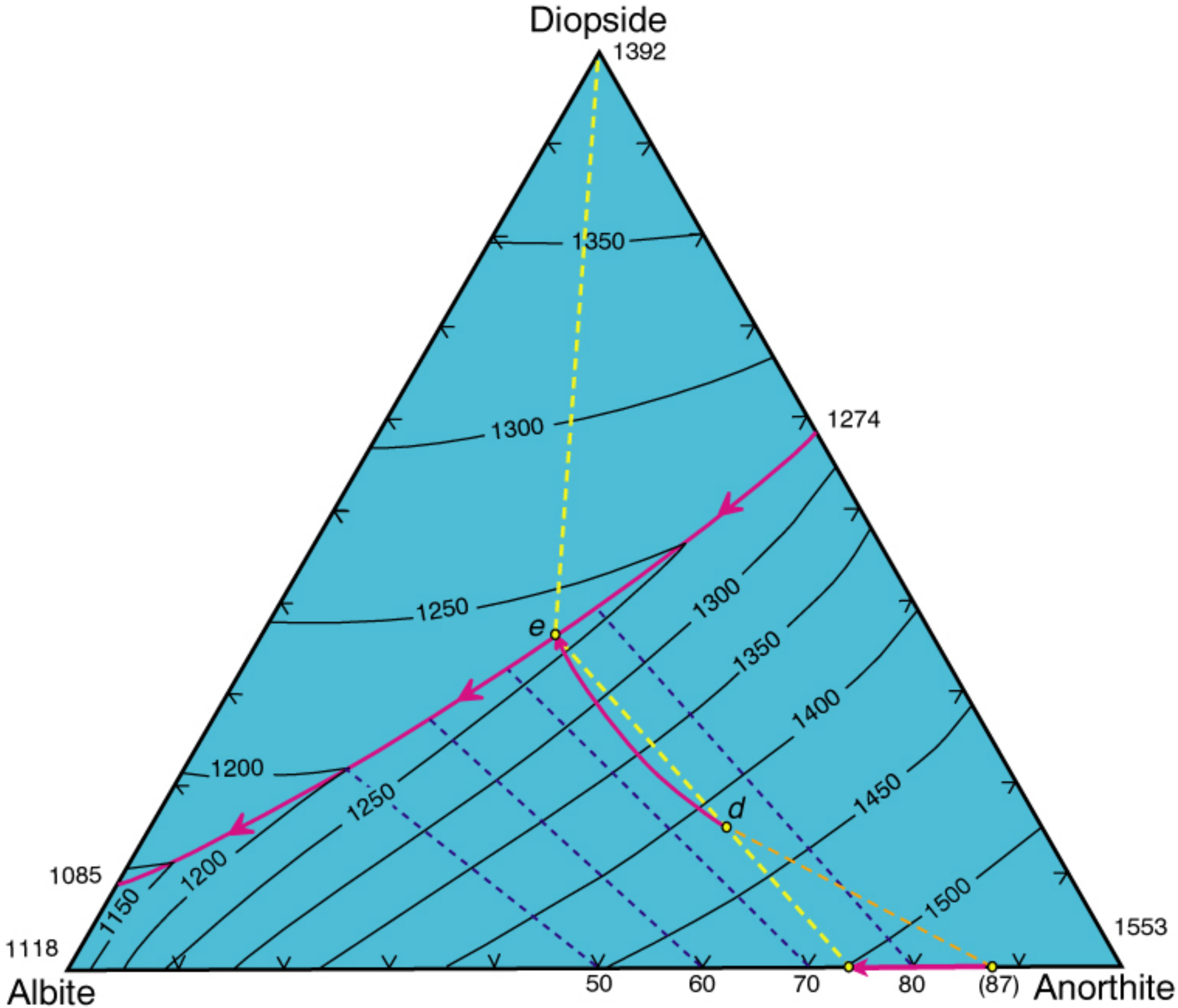
Diopside
1392
1350
1300
a
1274
1250
b
1300
1350
1400
1200
1250
1450
1085
1200
1150
1500
1553
1118
Albite
50
60
70
80
(87)
Anorthite



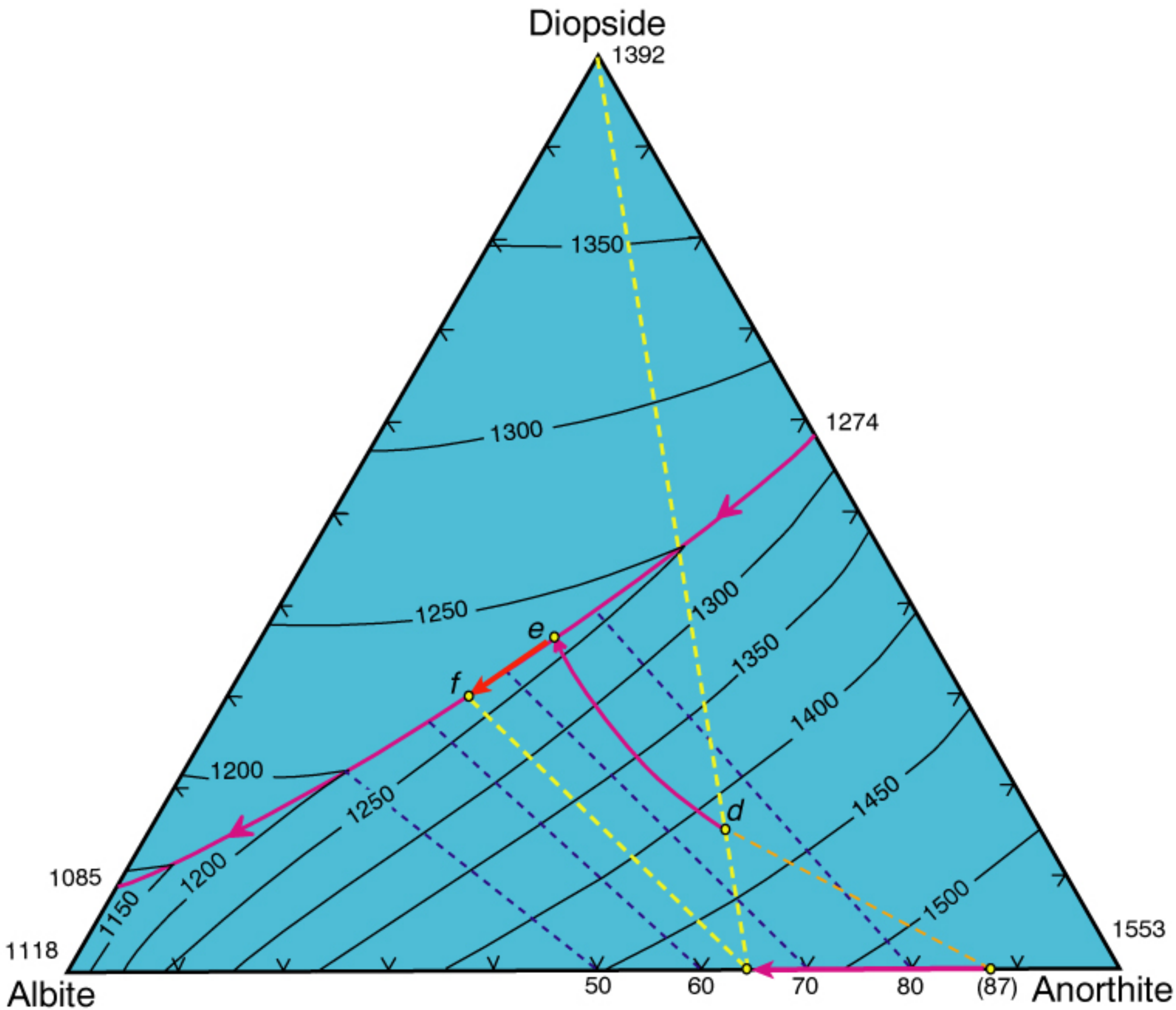
Diopside
1392
1350
a
1300
1274
1250
b
1300
1350
1400
c
1200
1250
1450
1085
1200
1150
1500
1118
1553
Albite
50
60
70
80
(87)
Anorthite



Diopside
1392
1350
1300
1274
1250
1300
1350
1400
1200
1250
1450
1085
1200
1150
1500
1118
1553
Albite
50
60
70
80
(87)
Anorthite



Diopside
1392
1350
1300
1274
1250
e
1300
1350
1400
1200
1250
d
1450
1085
1200
1150
1500
1118
1553
Albite
50
60
70
80
(87)
Anorthite



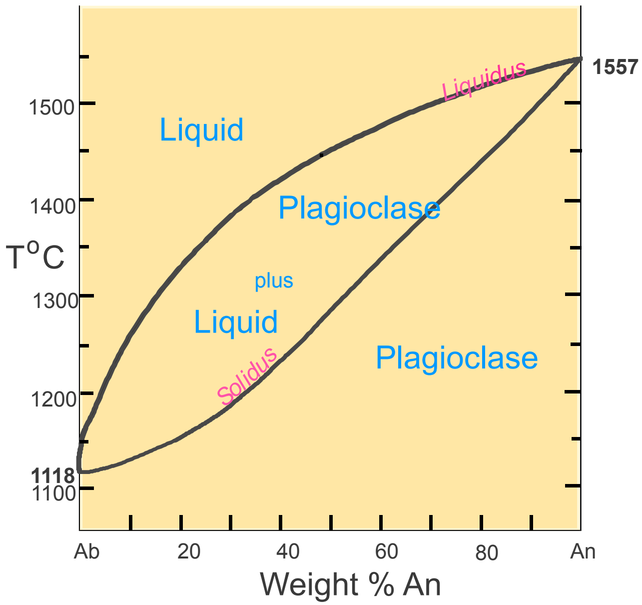
Diopside
1392
1350
1300
1274
1250
1300
e
1350
f
1400
1200
1250
d
1450
1085
1200
1150
1500
1553
1118
Albite
50
60
70
80
(87)
Anorthite

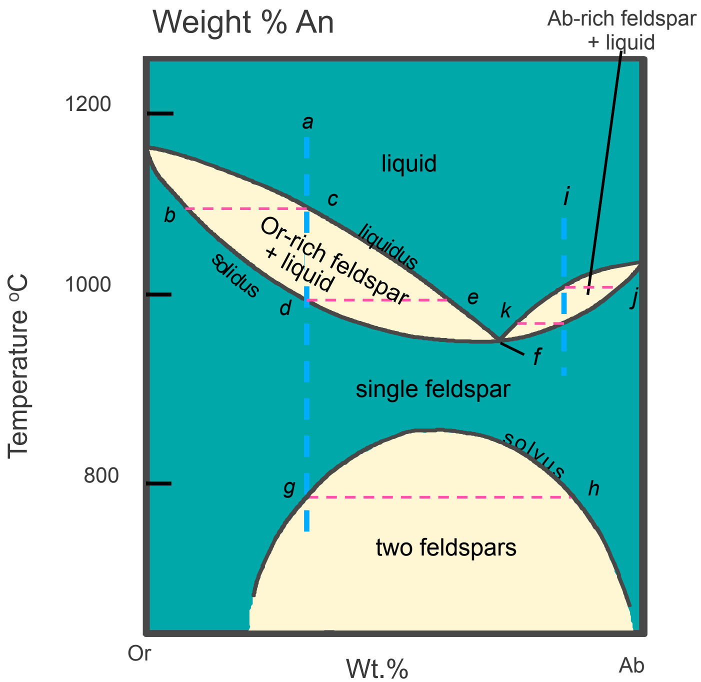
Note:

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**

Ternary Feldspars





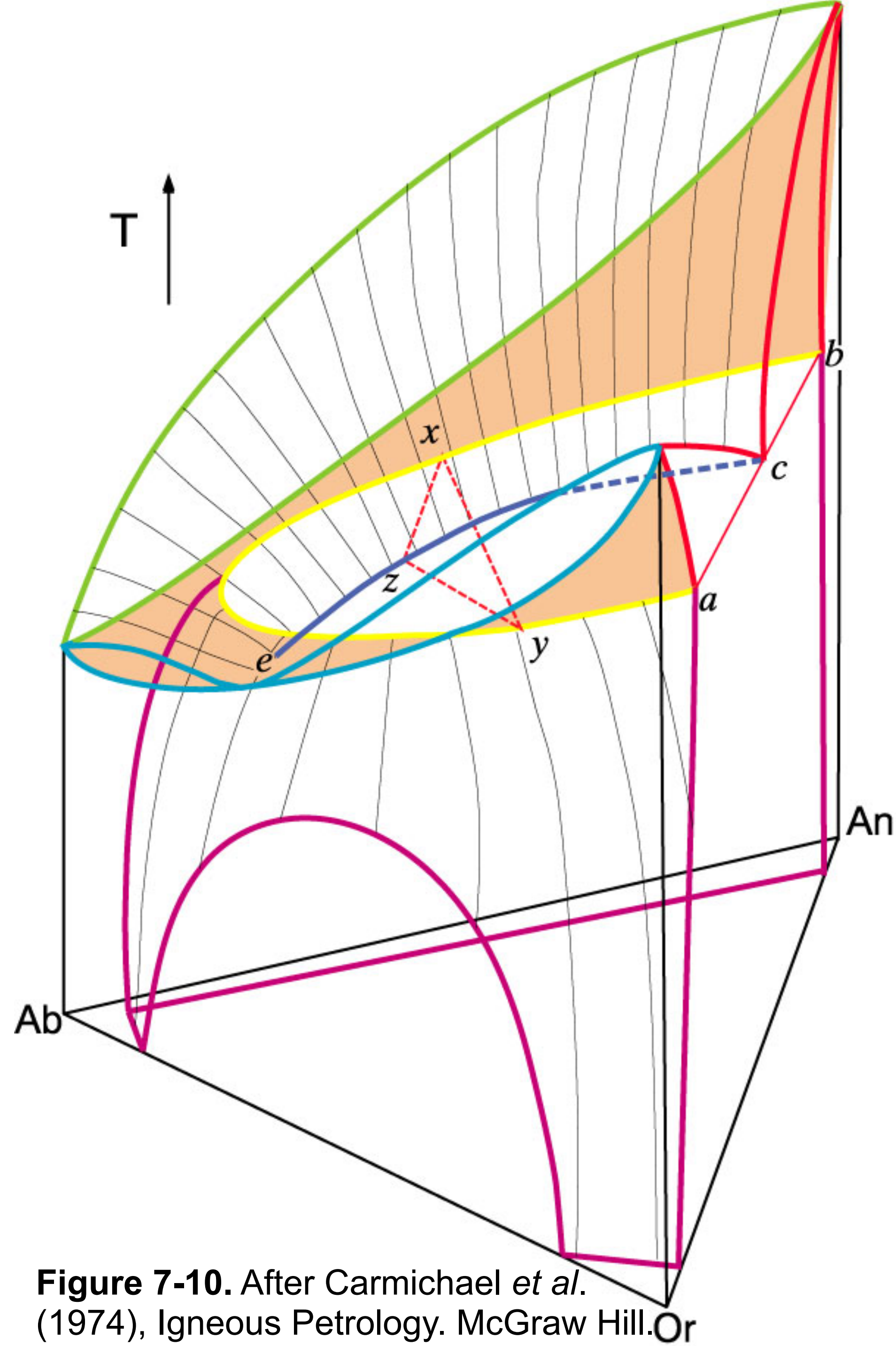
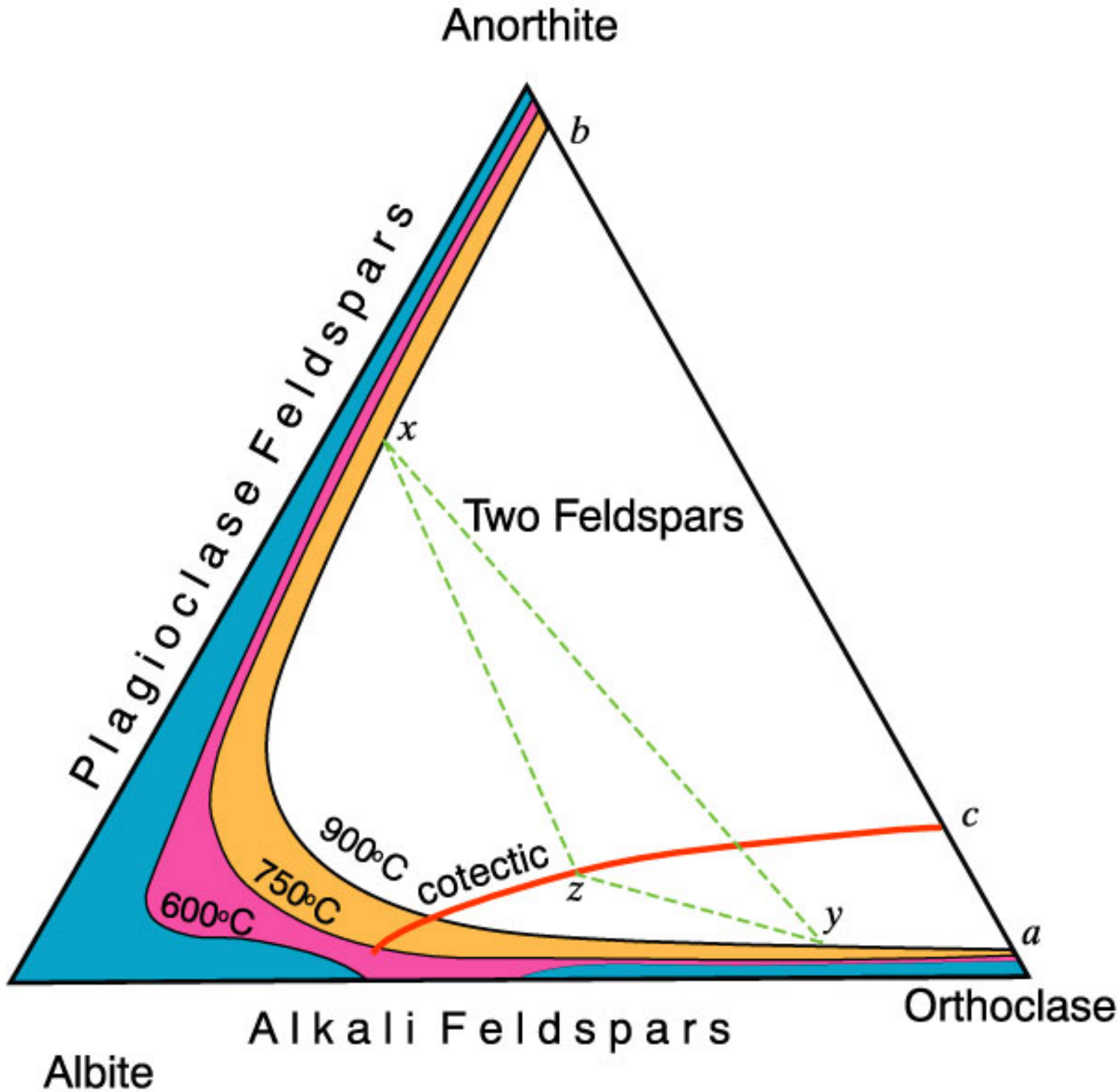


Figure 7-10. After Carmichael *et al.* (1974), Igneous Petrology. McGraw Hill.

Ternary Feldspars

Trace of solvus at three temperature intervals



Triangle shows coexisting feldspars and liquid at 900°C

Figure 7.11. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

4 - Component Diagrams

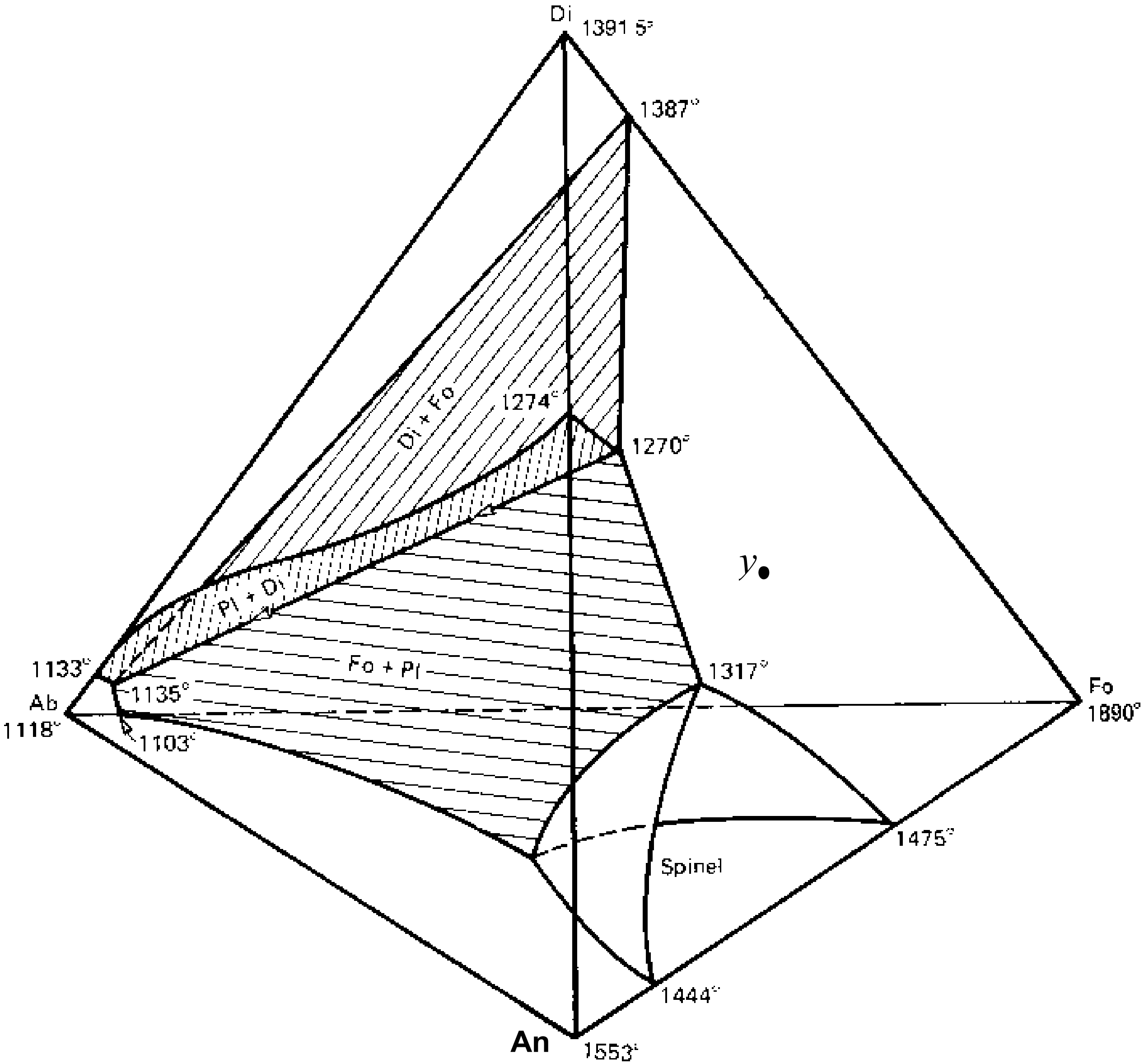


Figure 7.12. The system diopside-anorthite-albite-forsterite. After Yoder and Tilley (1962). J. Petrol.

> 4 Components

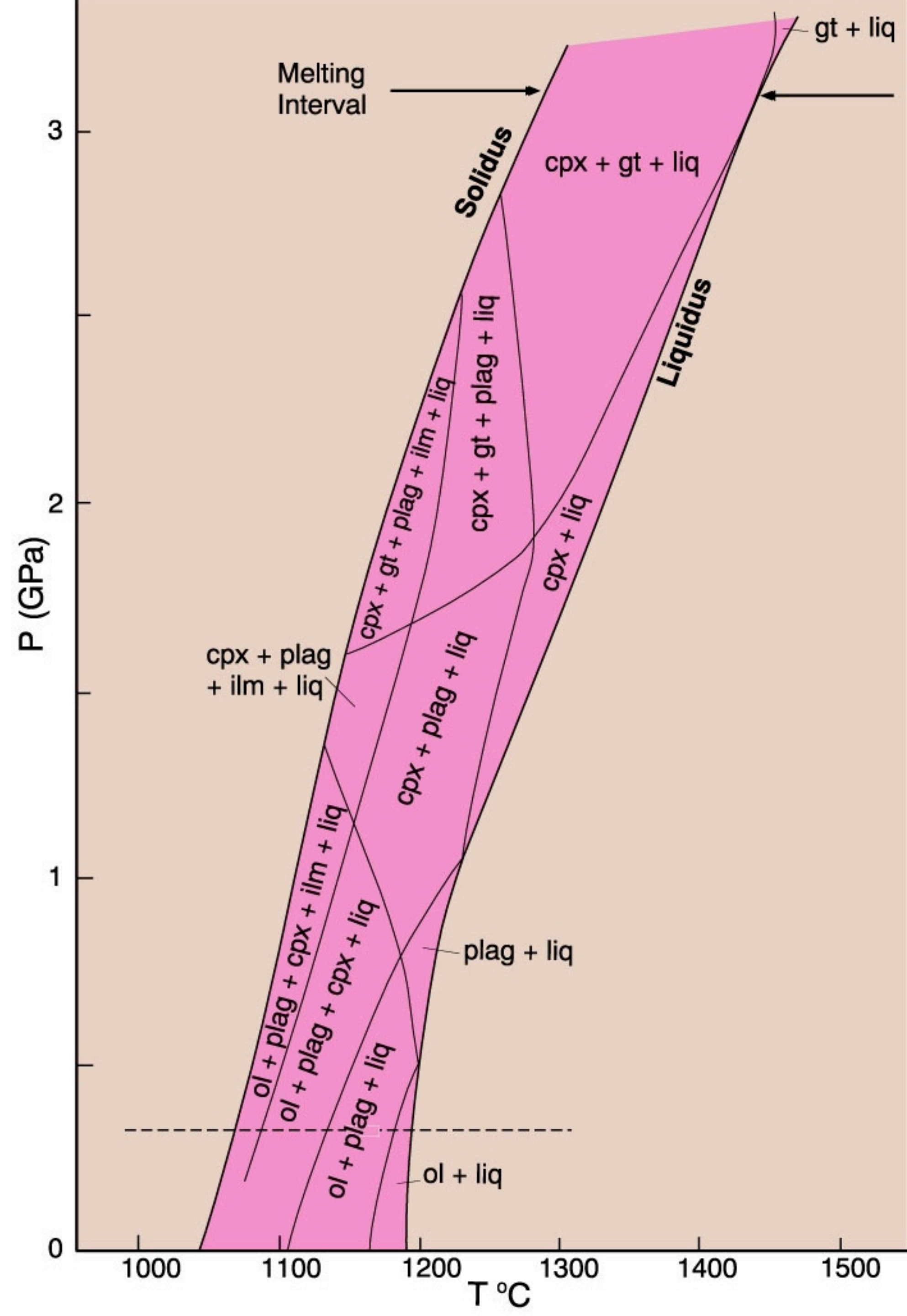
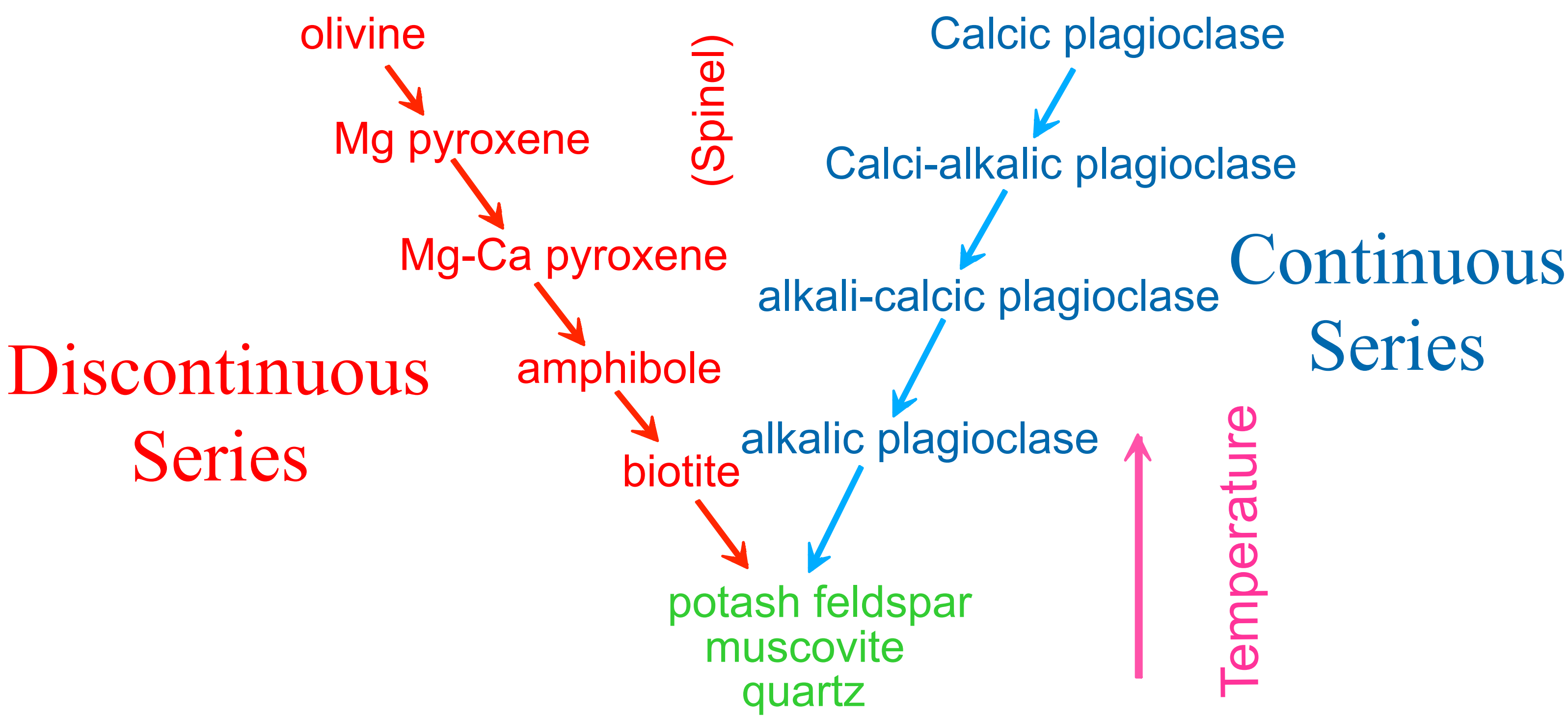
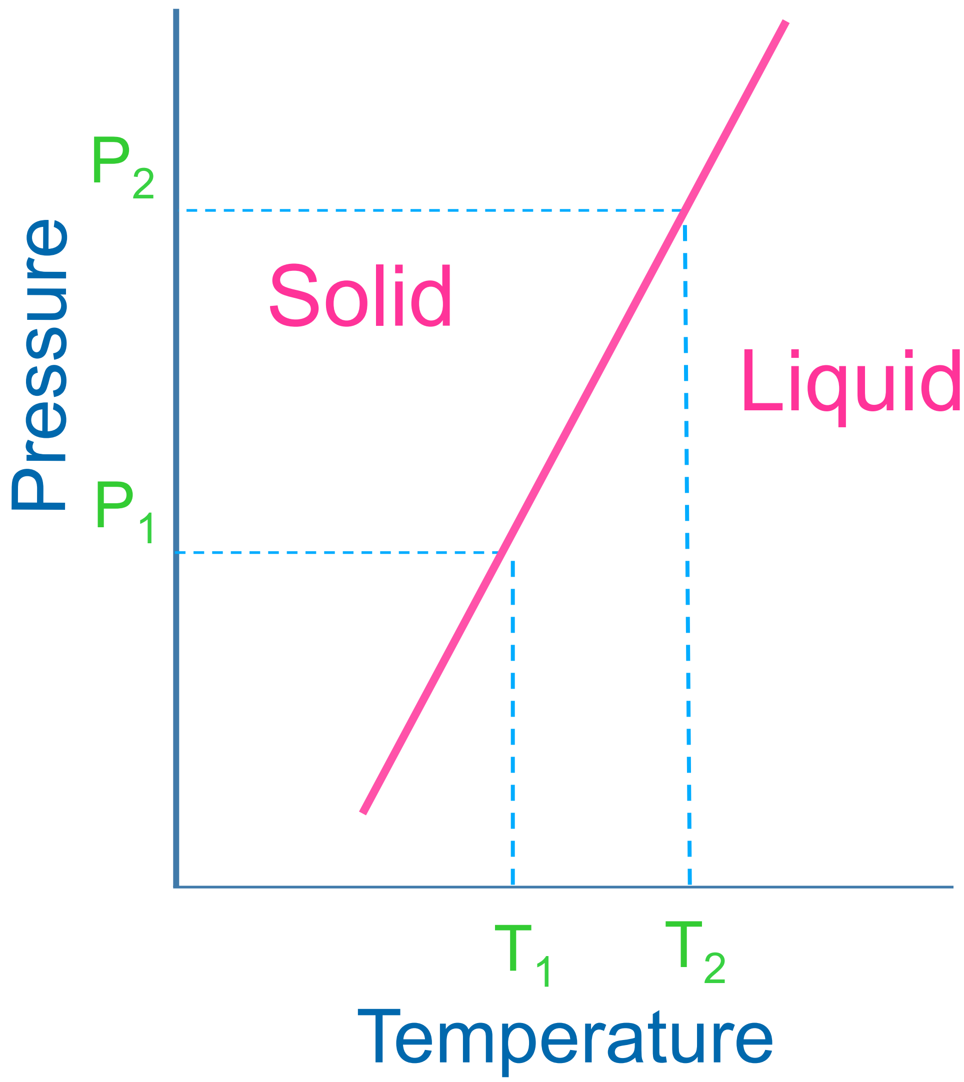


Figure 7.13. **Pressure-temperature phase diagram for the melting of a Snake River (Idaho, USA) tholeiitic basalt under anhydrous conditions. After Thompson (1972). Carnegie Inst. Wash Yb. 71**

Bowen's Reaction Series



The Effect of Pressure



Eutectic system

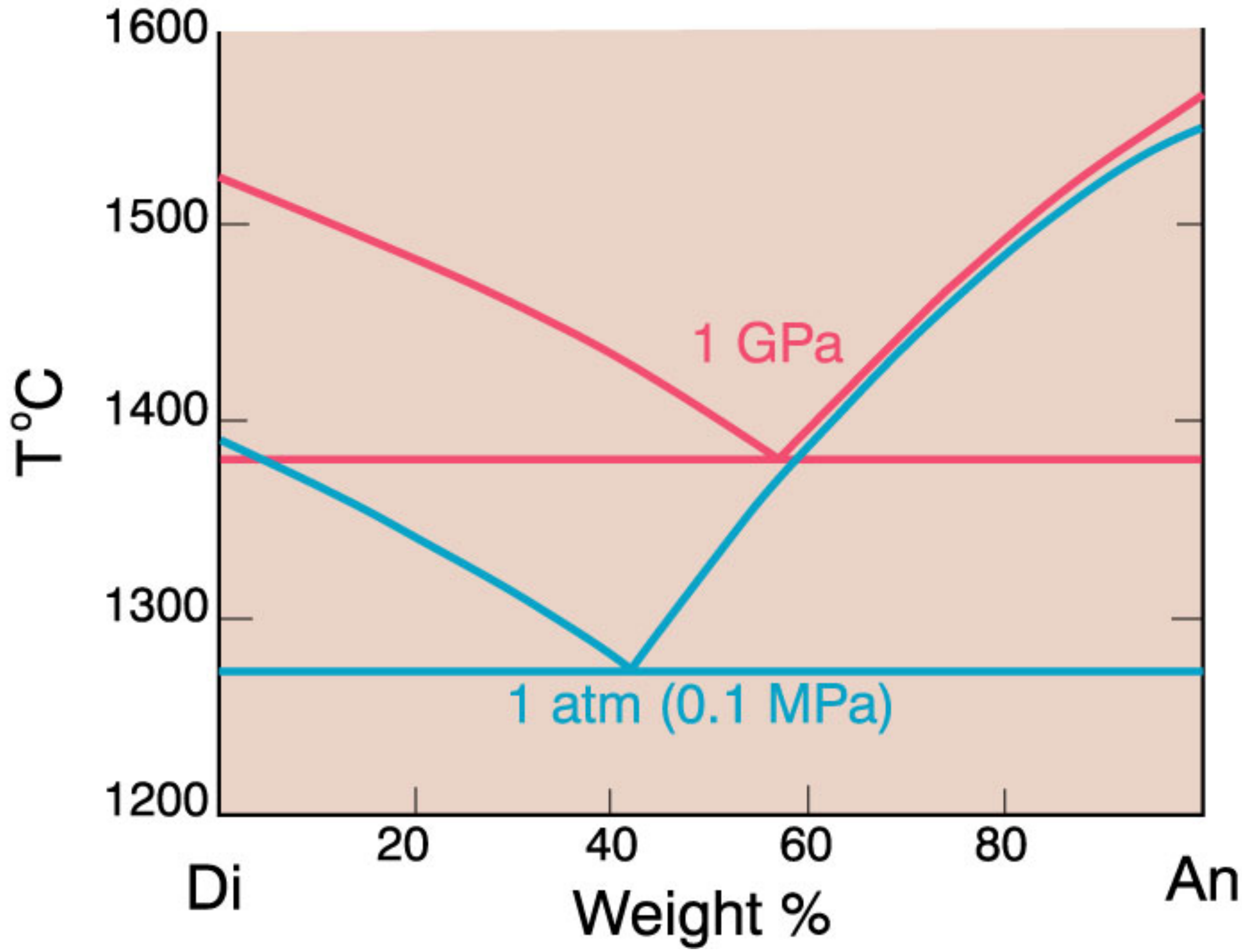


Figure 7.16. Effect of lithostatic pressure on the liquidus and eutectic composition in the diopside-anorthite system. 1 GPa data from Presnall *et al.* (1978). Contr. Min. Pet., 66, 203-220.

The Effect of Water on Melting

Dry melting: solid → liquid

Add water- water enters the melt

Reaction becomes:

$$solid + water = liq_{(aq)}$$

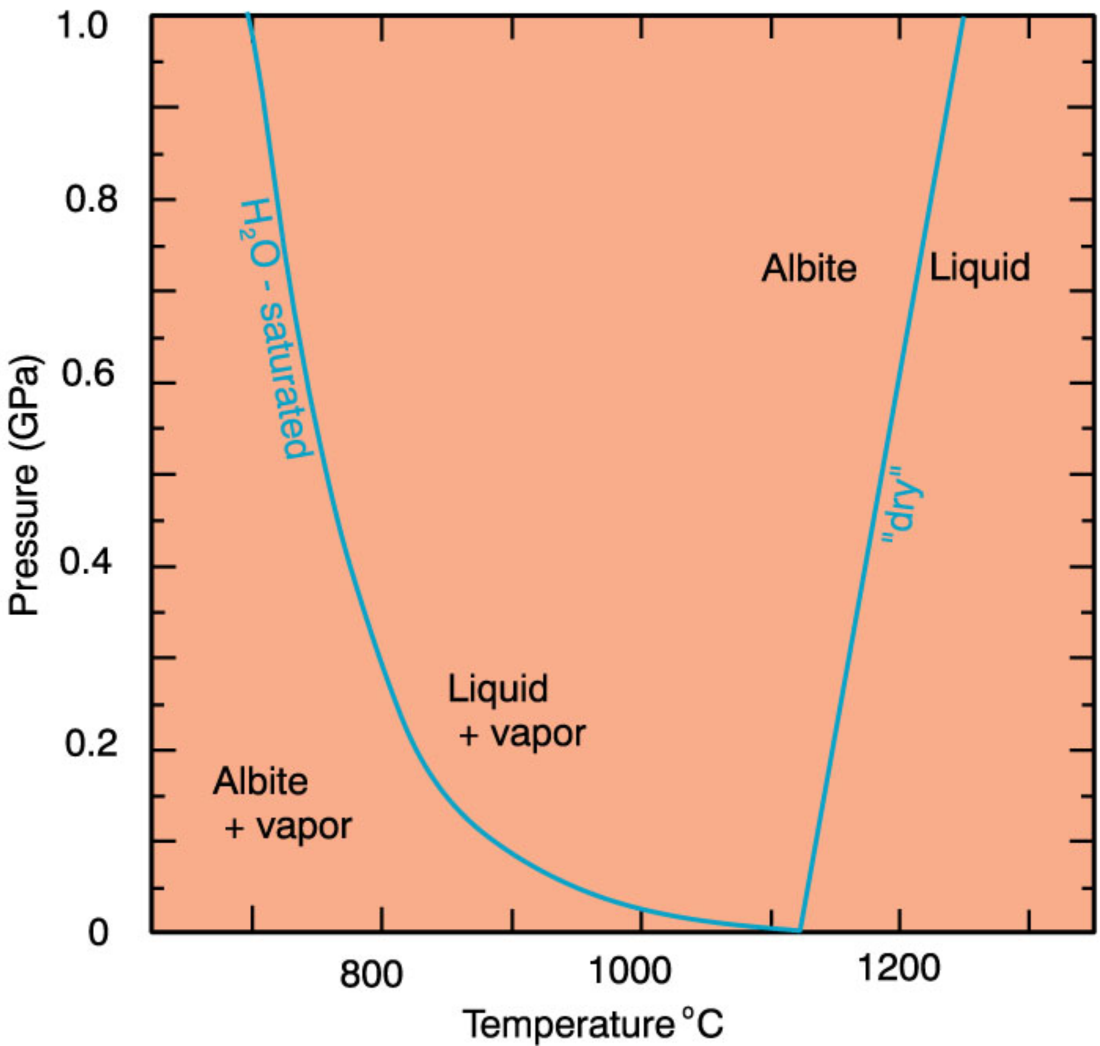


Figure 7.19. **The effect of H_2O saturation on the melting of albite, from the experiments by Burnham and Davis (1974). A J Sci 274, 902-940. The "dry" melting curve is from Boyd and England (1963). JGR 68, 311-323.**

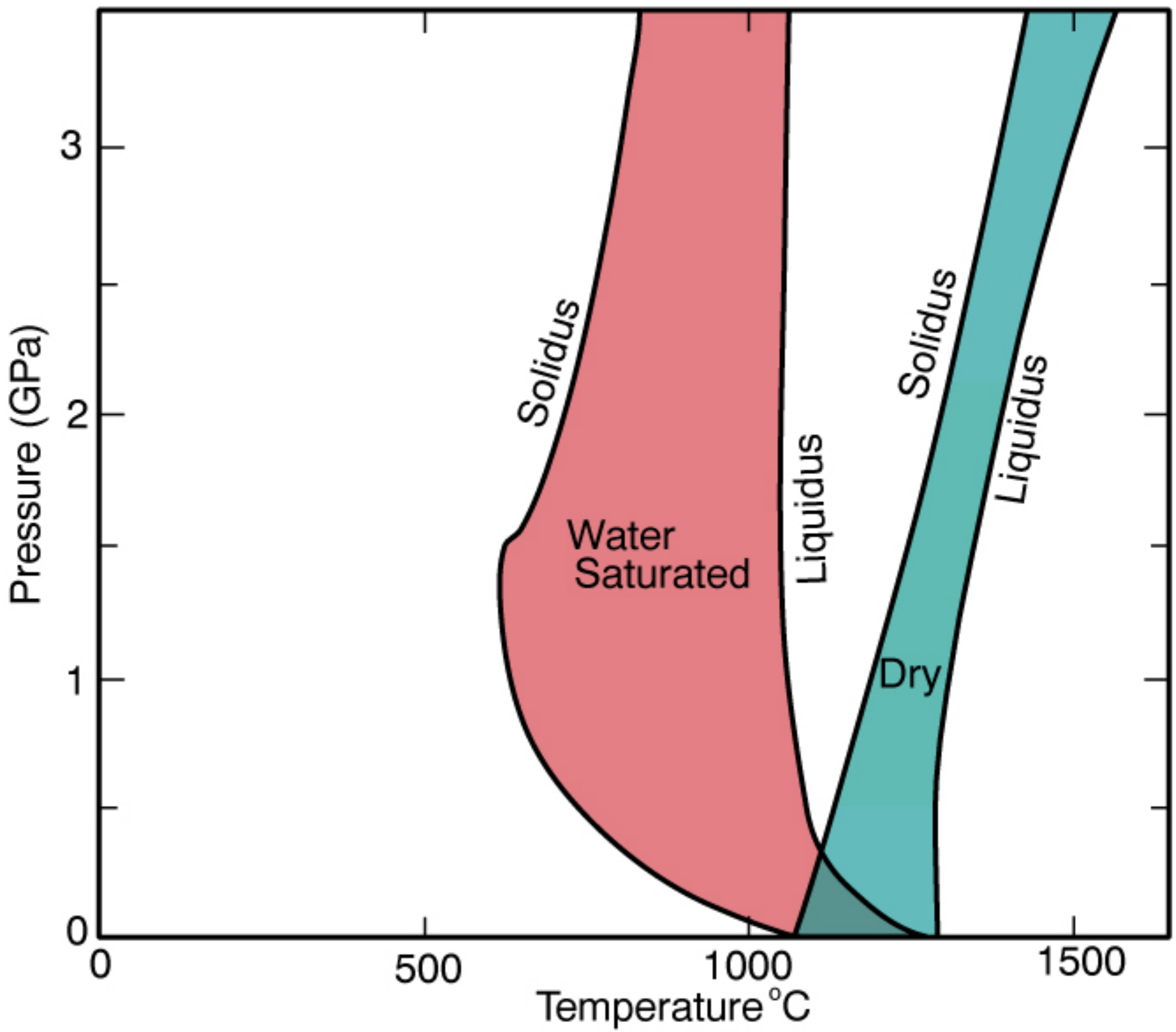


Figure 7.20. Experimentally determined melting intervals of gabbro under H_2O-free ("dry"), and H_2O-saturated conditions. After Lambert and Wyllie (1972). J. Geol., 80, 693-708.

Dry and water-saturated solidi for some common rock types

The more mafic the rock the higher the melting point

All solidi are greatly lowered by water

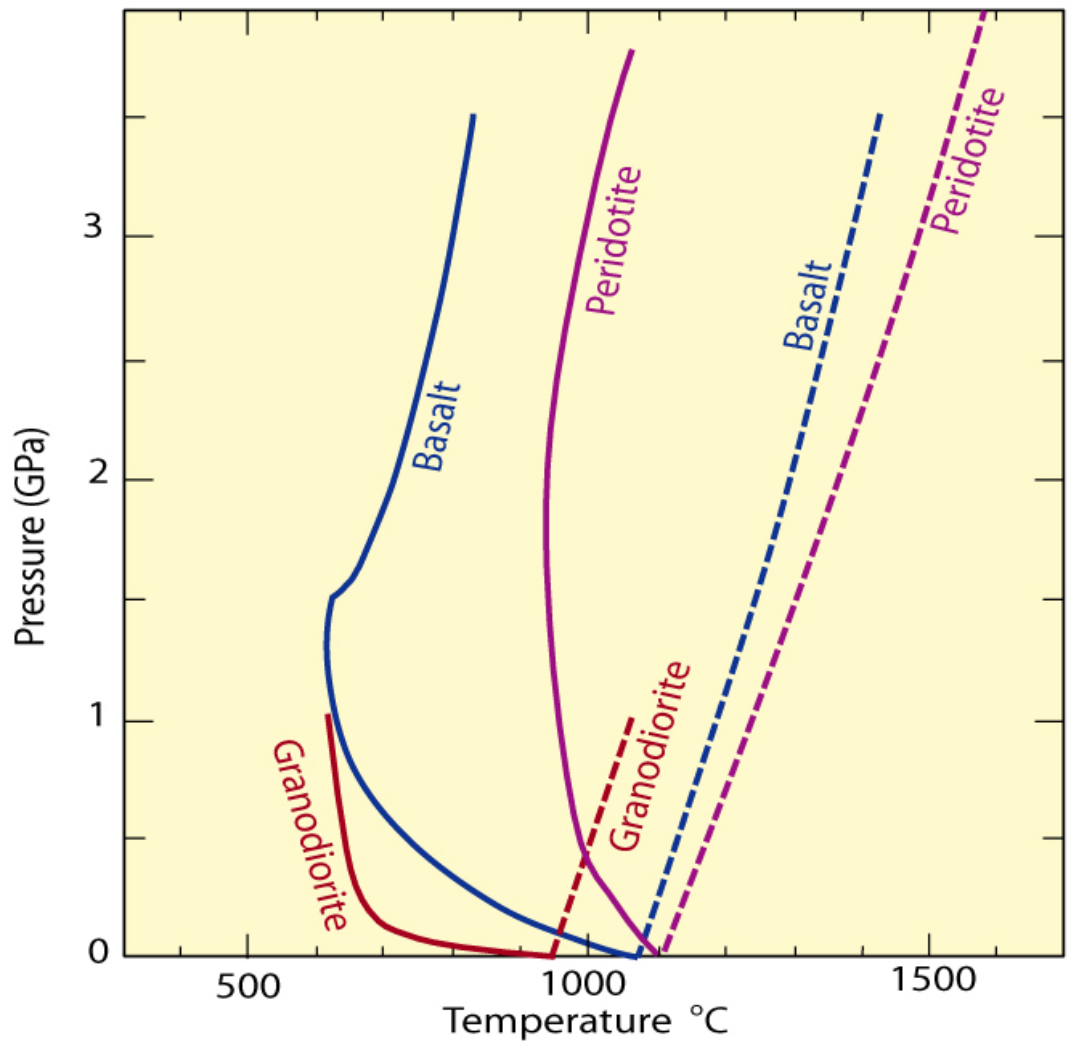


Figure 7-21. H_2O-saturated (solid) and H_2O-free (dashed) solidi (beginning of melting) for granodiorite (Robertson and Wyllie, 1971), gabbro (Lambert and Wyllie, 1972) and peridotite (H_2O-saturated: Kushiro *et al.*, 1968; dry: Hirschman, 2000).

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

The solubility of water in a melt depends on the structure of the melt (which reflects the structure of the mineralogical equivalent)

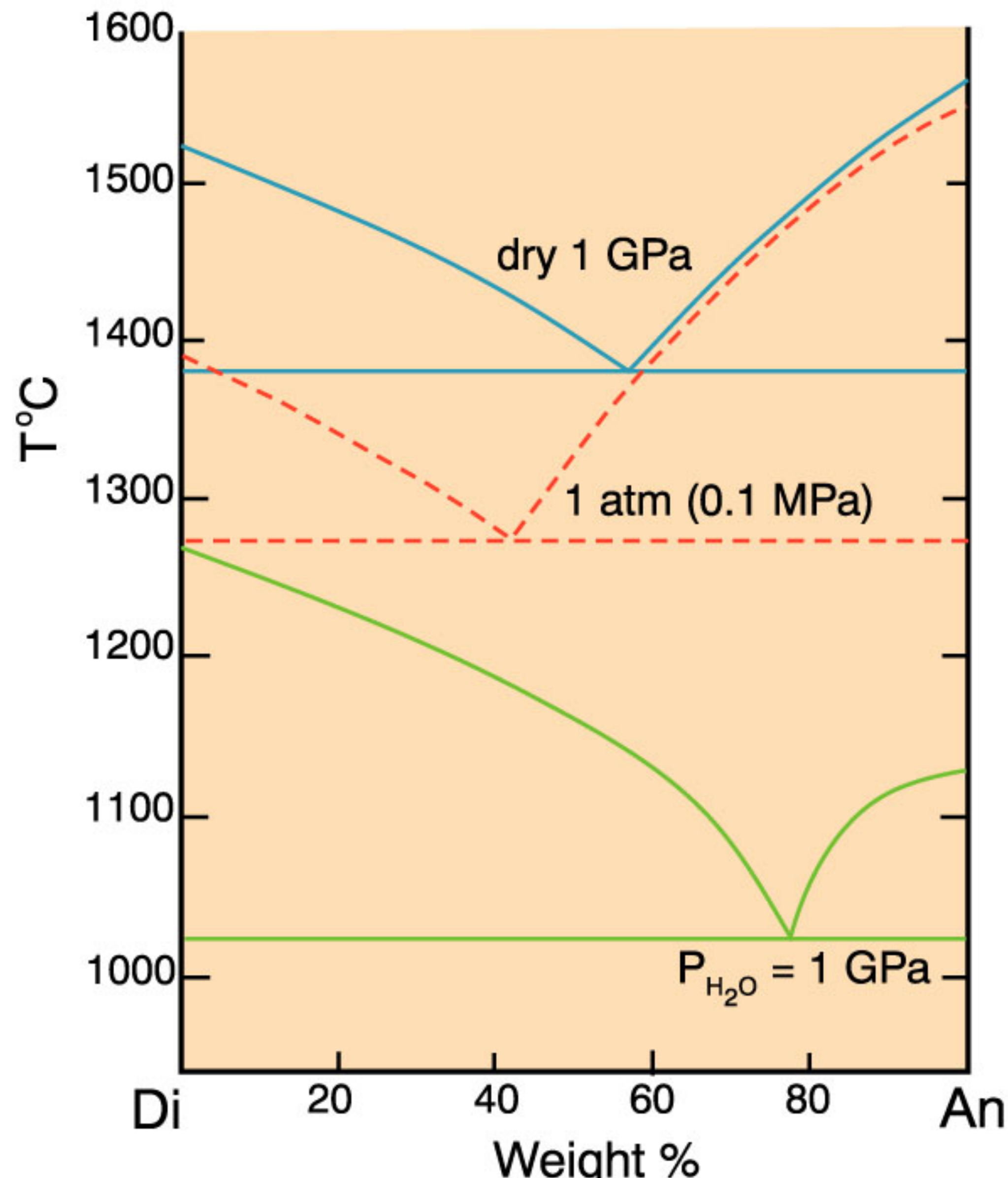
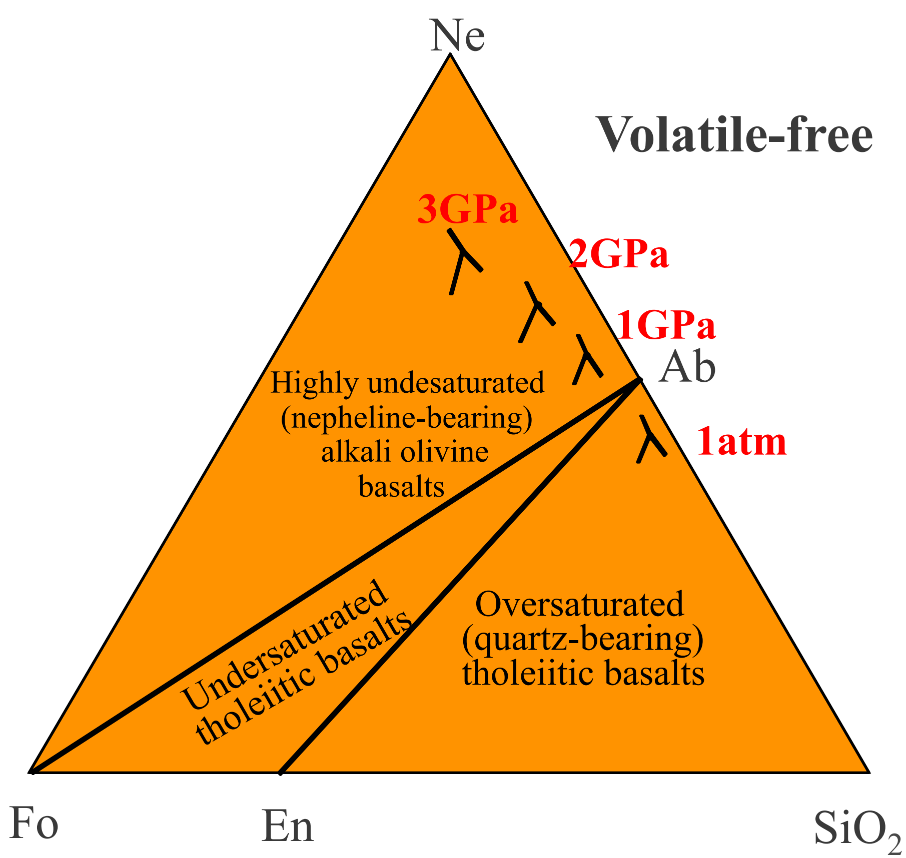


Figure 7.25. **The effect of H_2O on the diopside-anorthite liquidus. Dry and 1 atm from Figure 7-16, $P_{H2O} = P_{total}$ curve for 1 GPa from Yoder (1965). CIW Yb 64.**

Effect of Pressure, Water, and CO_2 on the position of the eutectic in the basalt system

Increased pressure moves the ternary eutectic (first melt) from silica-saturated to highly undersat. alkaline basalts



Water moves the (2 GPa) eutectic toward higher silica, while CO_2 moves it to more alkaline types