**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
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.

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
Cool composition of a from 2000 °C

At 2000 °C:

\[ \phi = ? \]

\[ F = ? \]

\[ F = C - f + 1 = 3 - 1 + 1 = 3 \]

\[ \frac{T}{T} = \frac{T}{T} \]

\[ X(\text{An}) \text{Liq}, X(\text{Di}) \text{Liq}, \text{and} X(\text{Fo}) \text{Liq} \]

only 2 of 3 X’s are independent

Next cool to 1700 °C

intersect liquidus surface

What happens??
\( \phi = 2 \text{ (Fo + Liq)} \)

\( F = 3 - 2 + 1 = 2 \)

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

- \( T \) and \( X_{An}^{\text{liq}} \) or
- \( X_{Di}^{\text{liq}} \) and \( X_{Fo}^{\text{liq}} \)

\( X \) of pure Fo is fixed
Continue to cool; Fo crystallizes and liquid loses Fo component \( X_{\text{liq}} \) moves directly away from Fo corner “Liquid line of descent” is \( \text{a} \rightarrow \text{b} \).

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

\[
\text{LiqA} \rightarrow \text{LiqB} + \text{Fo}
\]
Lever principle $\rightarrow$ relative proportions of liquid & Fo

- **At 1500 °C**

- \[ \text{Liq} \times + \text{Fo} = \text{bulk} \ a \]
- \[ \frac{\text{Liq} \times}{\text{Fo}} = \frac{a-\text{Fo}}{x-a} \]

At any point can use the lever principle to determine the relative proportions of liquid and Fo
What happens next at 1350 °C?

Pure diopside joins olivine + liquid

\[ \phi = 3 \]

\[ F = 3 - 3 + 1 = 1 \]  
(univariant at constant P)

\[ X_{\text{liq}} = F(T) \text{ only} \]

Liquid line of descent follows cotectic -> M
- New continuous reaction as liquid follows cotectic:
  \[ \text{Liq}_A \rightarrow \text{Liq}_B + \text{Fo} + \text{Di} \]
- Bulk solid extract
- Di/Fo in bulk solid extract using lever principle

\[ \text{instantaneous ratio} \]
\[ \frac{\text{Fo-c}}{\text{Di-c}} \]
At 1270 °C reach M the ternary eutectic anorthite joins liquid + forsterite + diopside
\[ \phi = 4, \quad F = 3 - 4 + 1 = 0 \]

**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

Try bulk = \(a\)
First melt at M
(1270 °C)
Stay at M until
consume one phase
(An) Why An?
Only Di and Fo left
Jump to Di-Fo binary
No further melt until
N at 1387 °C
Stay at N until
consume one phase
(Di)
Only Fo left
No further melt until
1890 °C
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)
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
May as well melt real rocks
On right is a P-T diagram for the **melting** of a Snake River basalt.
Each curve represents the loss of a phase as heat system.
- Compare to simpler systems

Note pressure effects
Ol - Plag - Cpx at low P
Garnet at high P (eclogite)

**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
The Effect of Water on Melting

Dry melting: solid → liquid
Add water- water enters the melt
Reaction becomes:

\[ \text{solid} + \text{water} = \text{liq}_{(aq)} \]

Thus adding water drives the reaction to the right.
Liquid is stabilized at the expense of the solid.
The result is to lower the melting point.
Pressure is required to hold the water in the melt, so increased pressure allows more water to enter the melt and this increases the melting point depression.

Figure 7-20. Experimentally determined melting intervals of gabbro under H$_2$O-free (“dry”), and H$_2$O-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