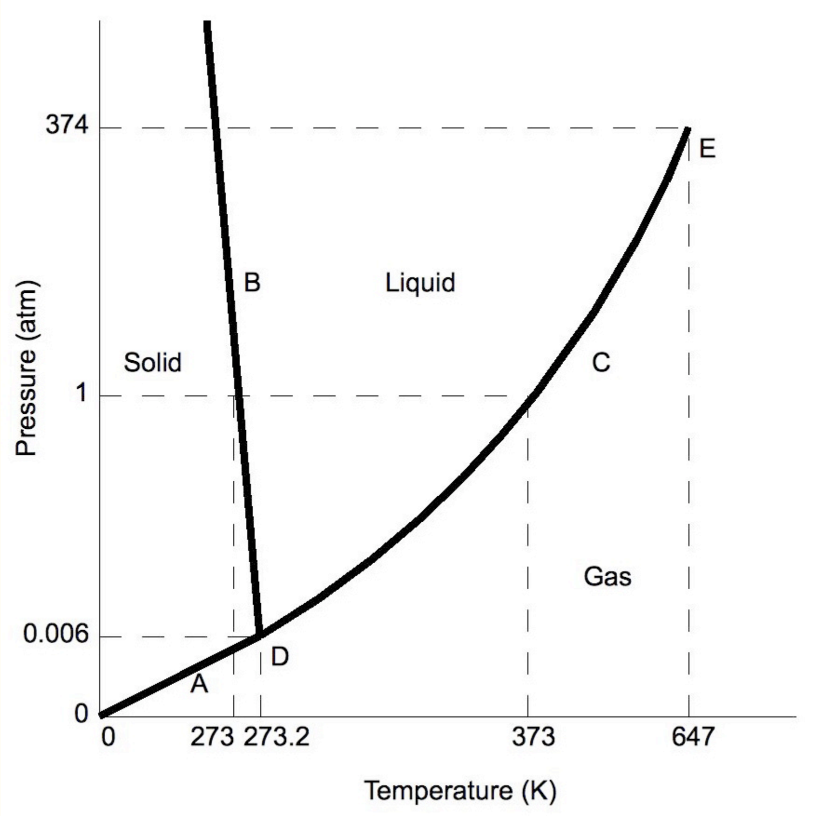
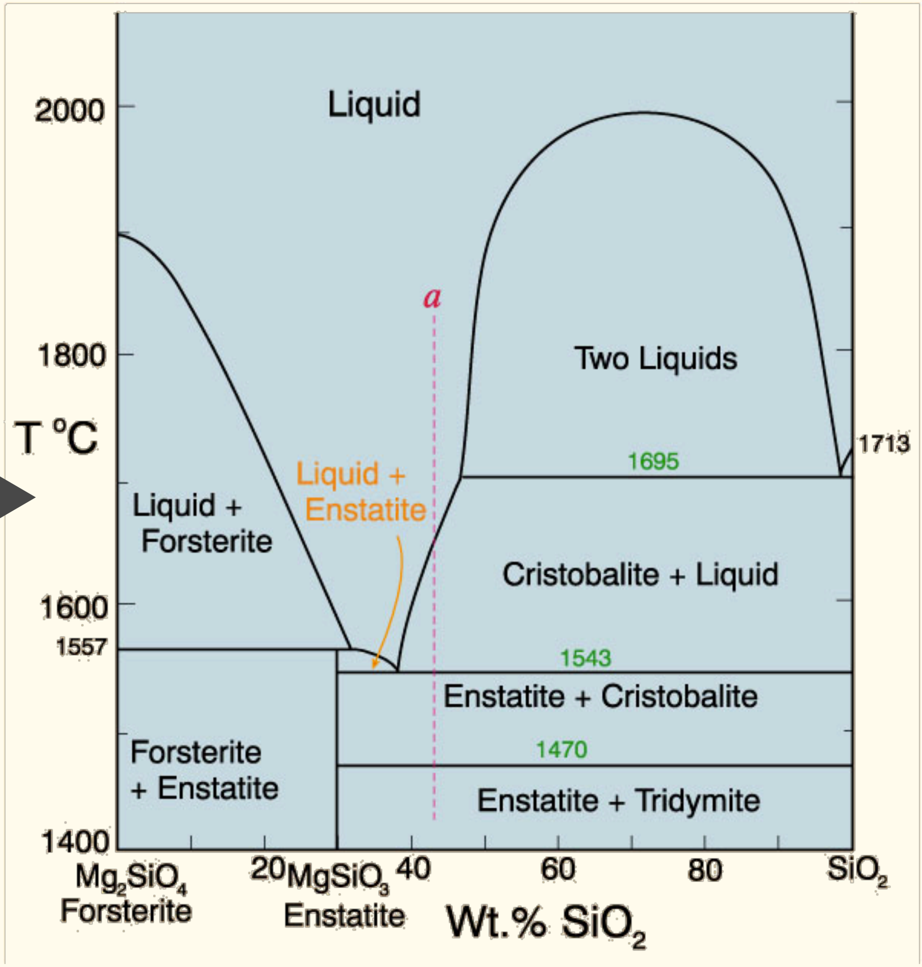
Phase Equilibrium

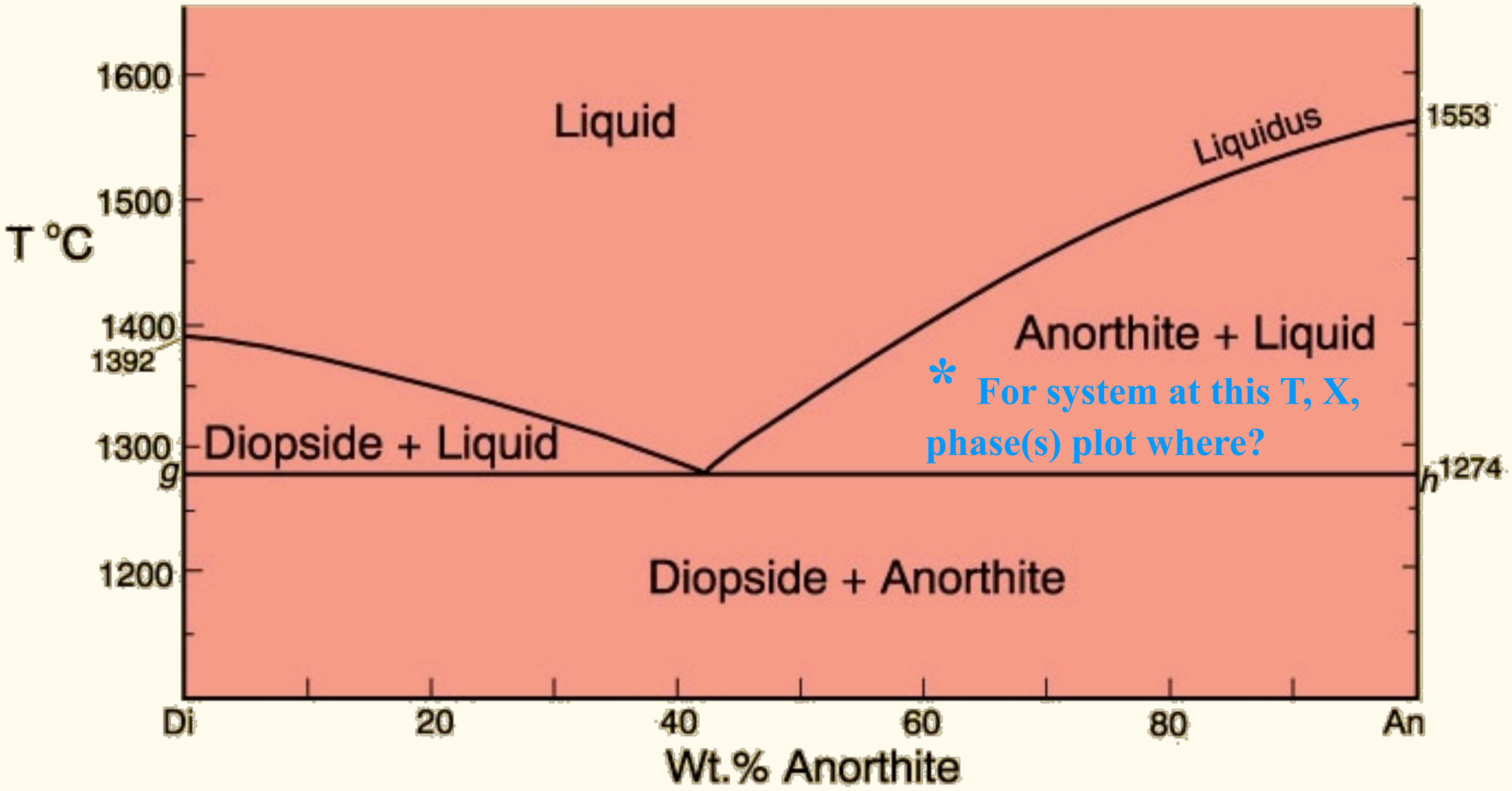




2-C Eutectic Systems

Example: Diopside - Anorthite

No solid solution

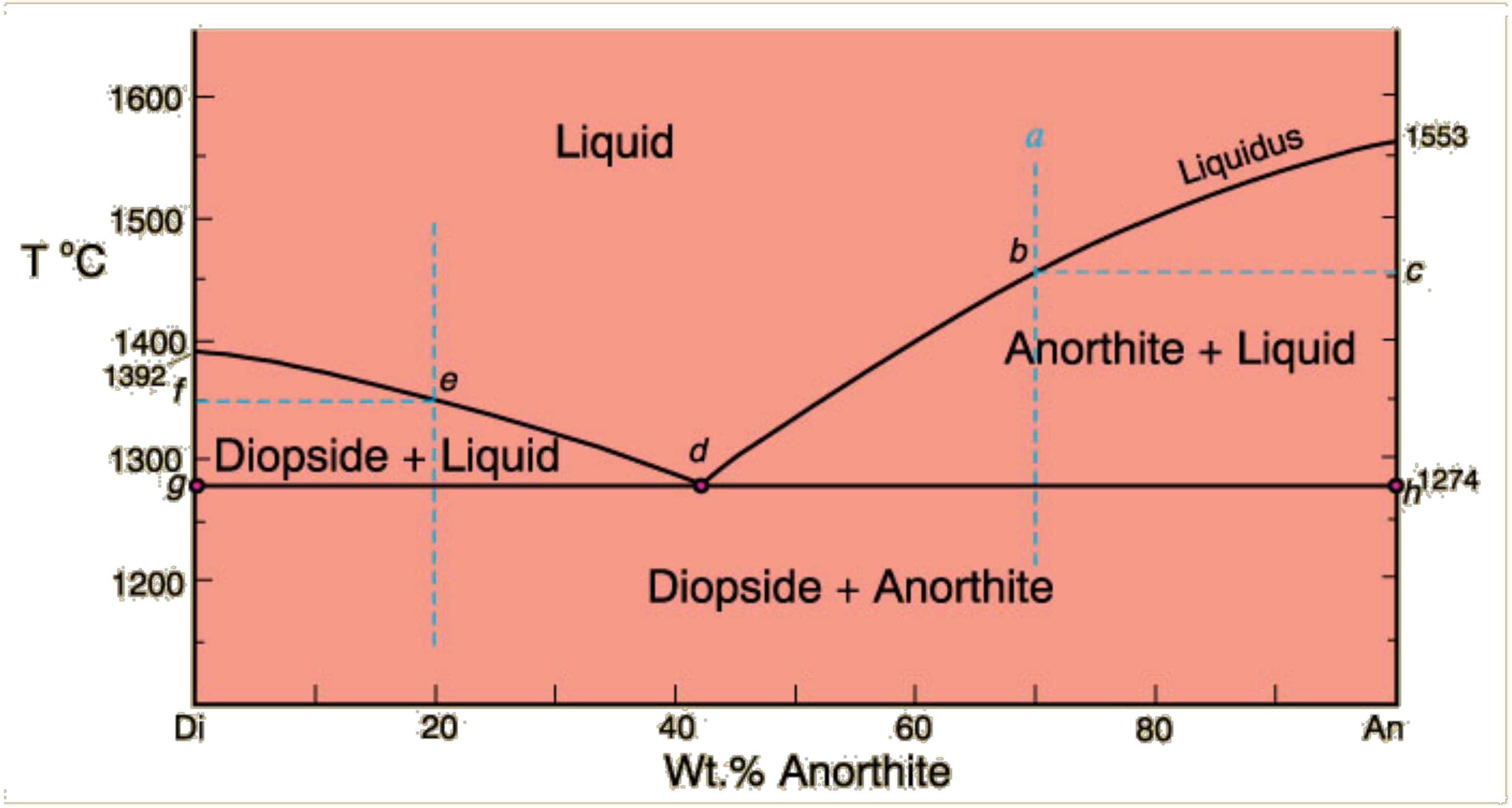


* For system at this T, X, phase(s) plot where?

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

Also note:

- The last melt to crystallize in any binary eutectic mixture is the eutectic composition
- Equilibrium melting is the opposite of equilibrium crystallization
  - Thus the first melt of any mixture of Di and An must be the eutectic composition as well



Fractional crystallization:

Since solids are not reactants in eutectic-type continuous reactions (e.g., $liq_A \rightarrow$ anorthite + liq_B), the liquid path is not changed

Only the final rock will differ: = *eutectic* X, and not *bulk* X

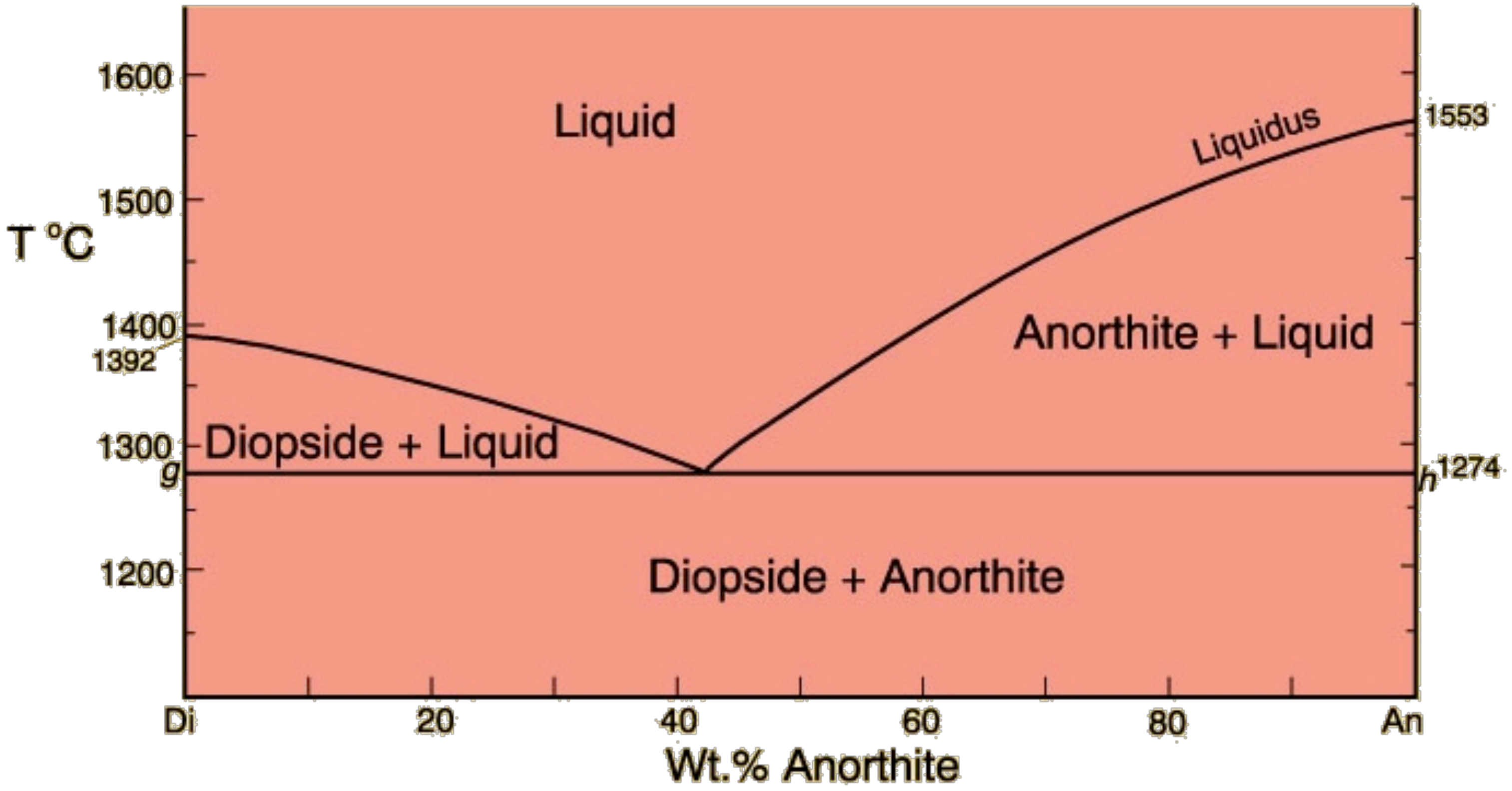
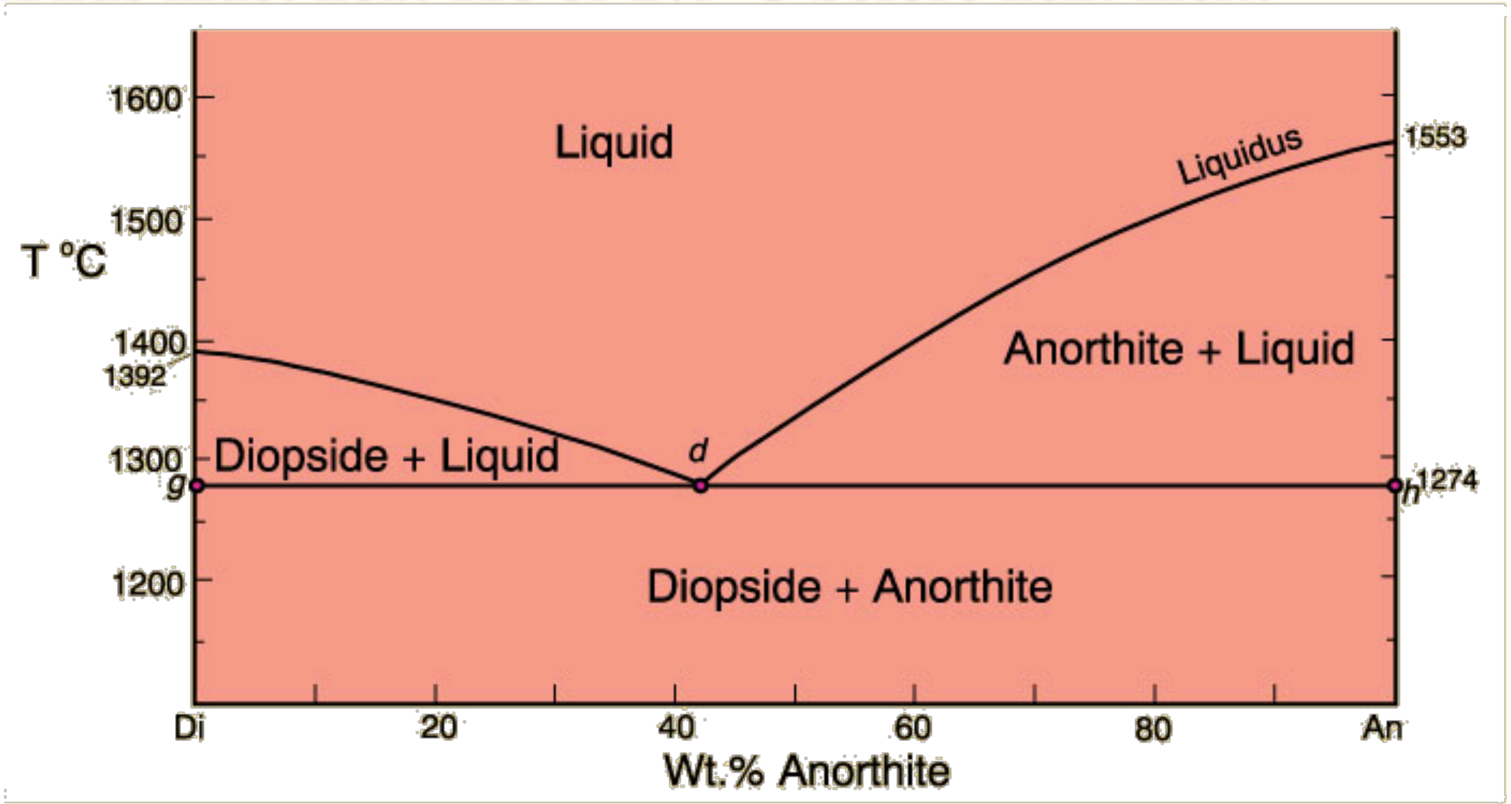


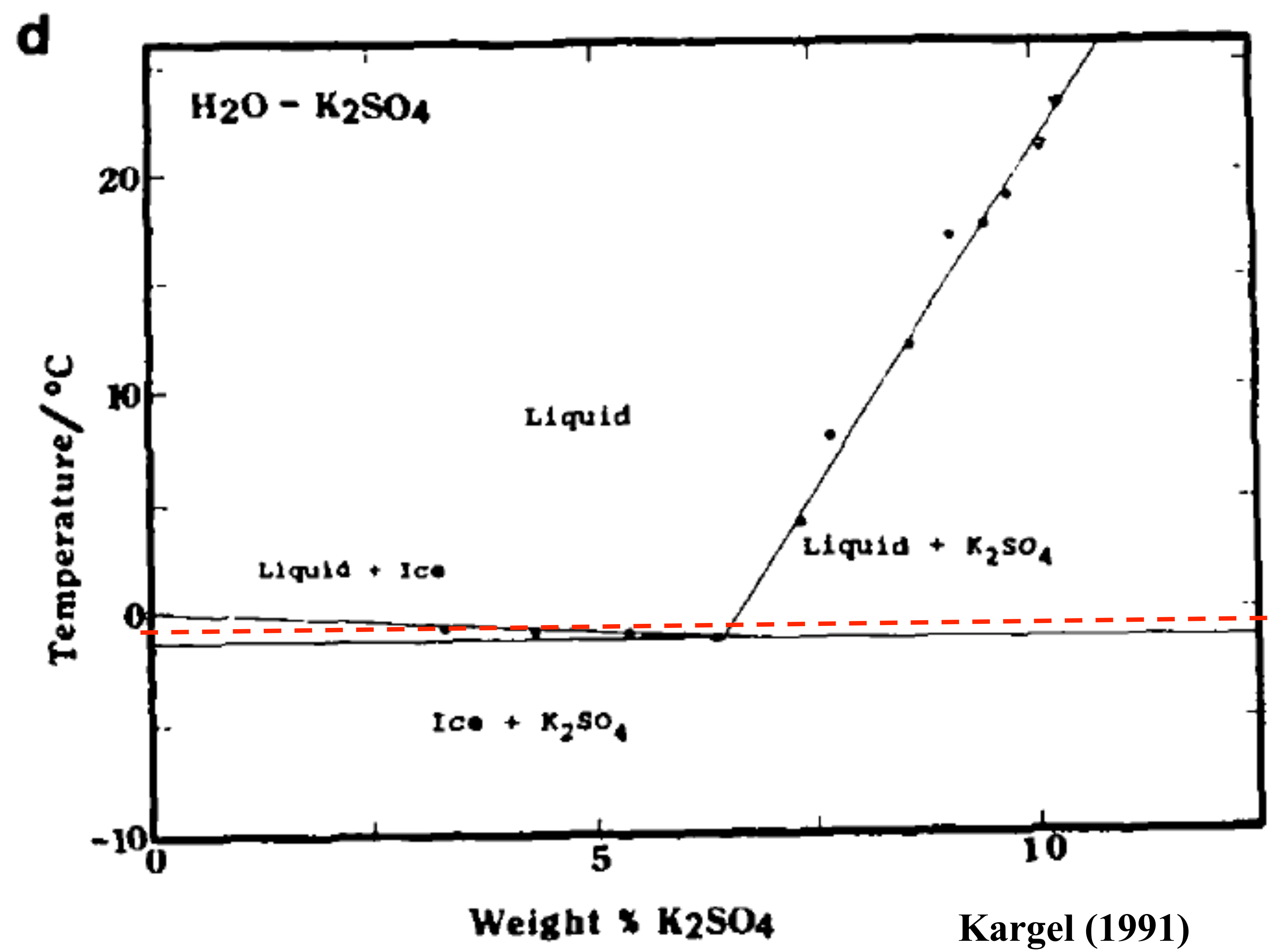
Fig. 6.11. **Isobaric T-X phase diagram at atmospheric pressure. After Bowen (1915), Amer. J. Sci. 40, 161-185.**

Partial Melting:

- if remove liquid perfectly as soon as it forms:
- melt Di + An to 1274°C
    - discontinuous reaction: Di + An -> eutectic liquid d
    - consume *either* Di *or* An first *depending on bulk X*
    - then melting solid = pure Di or An, jump to 1-C system
    - Thus must heat 118 or 279°C before next melt!

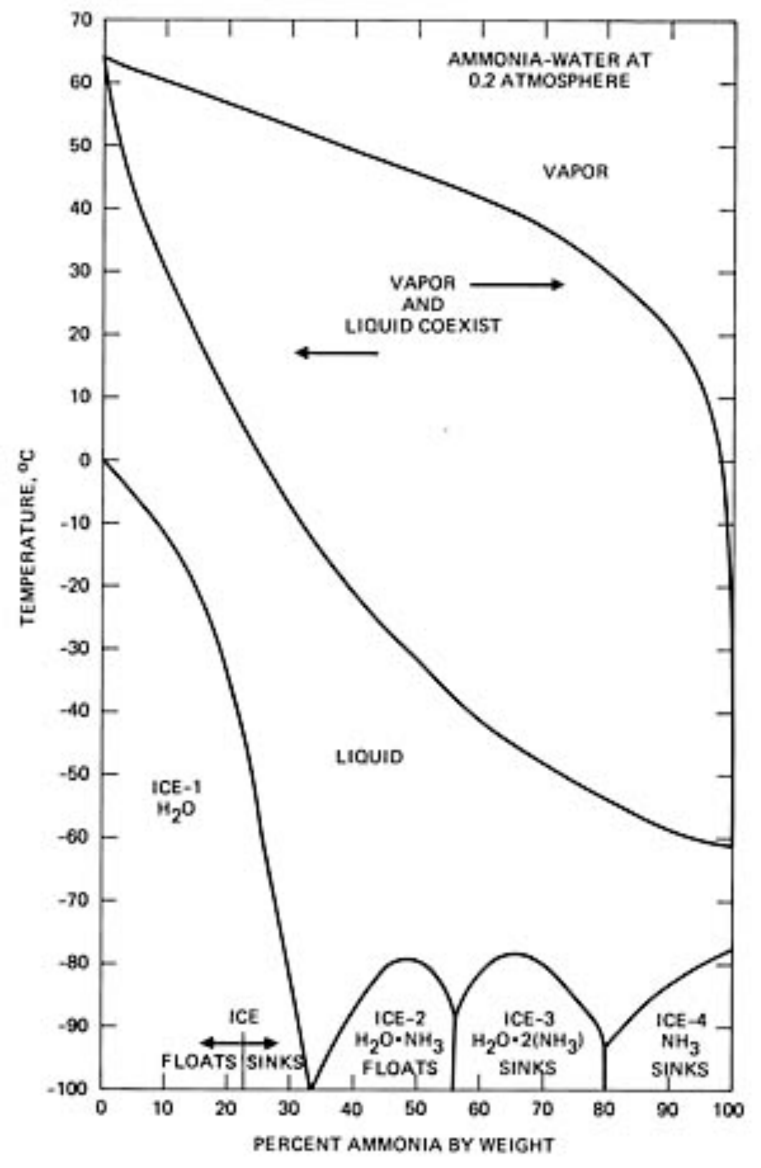


Water-Salt Eutectic Systems



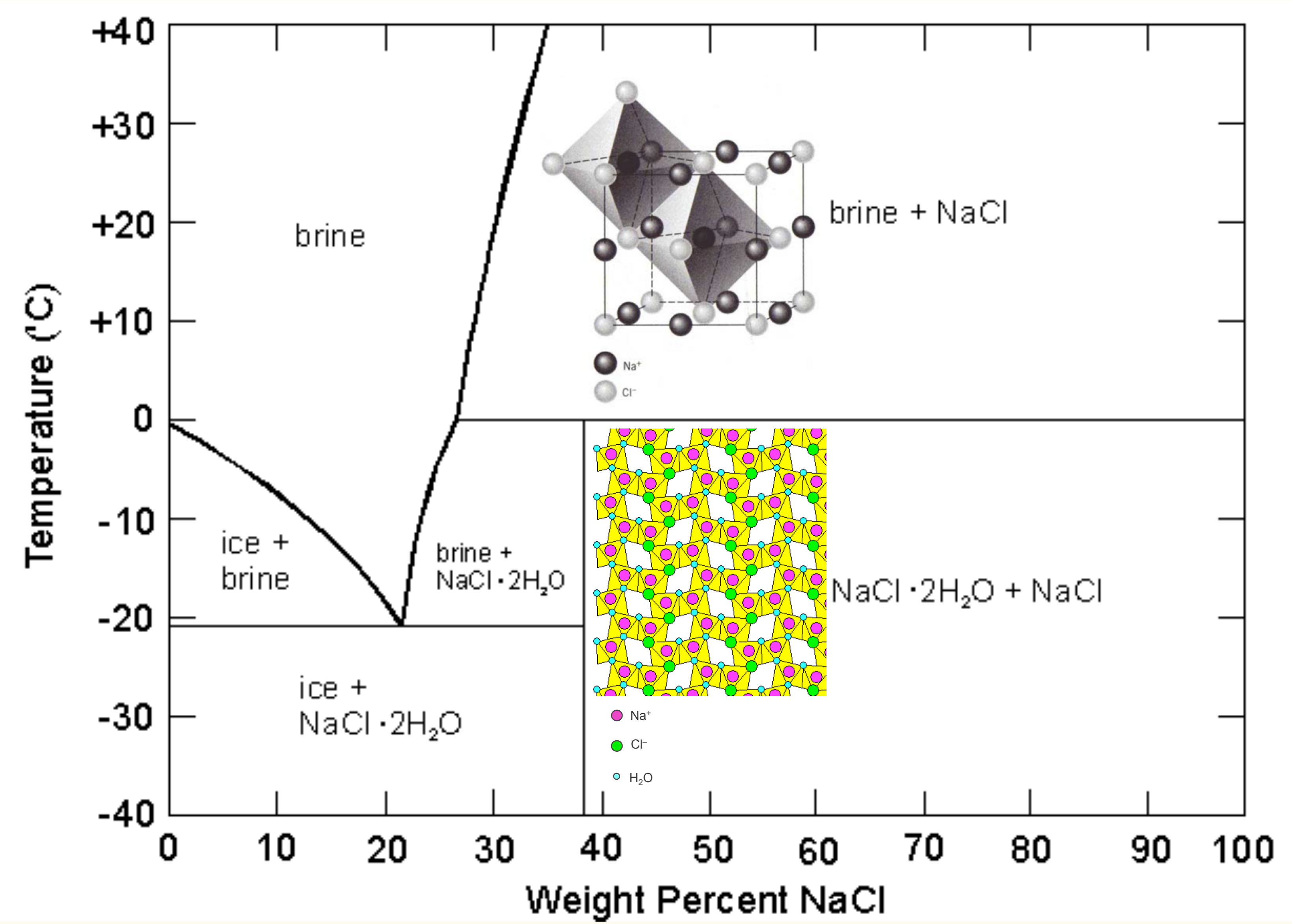
Kargel (1991)

Ammonium Hydroxide System



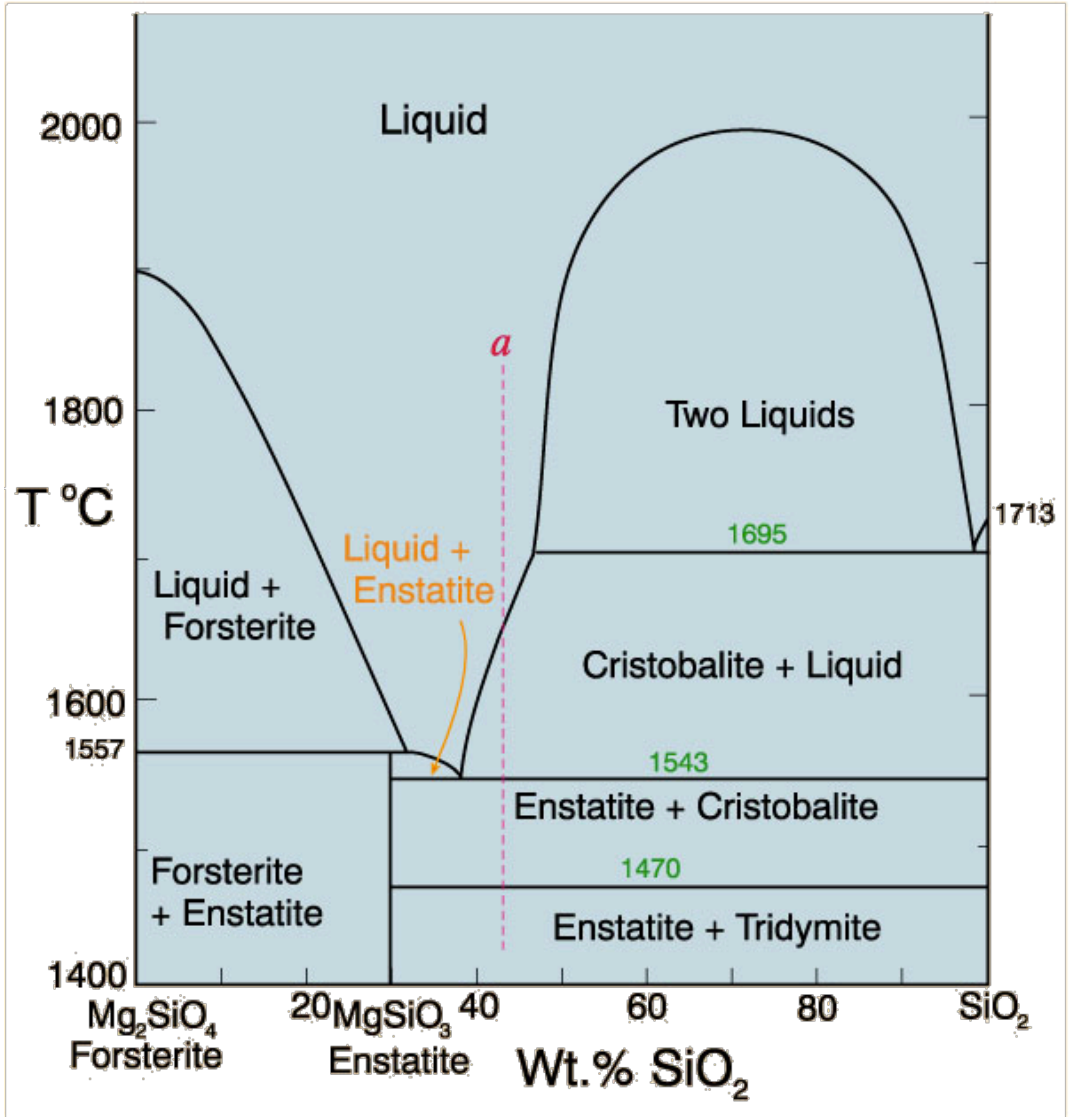
- Household cleaning products
- Outer solar system, where cold enough for NH_3 to condense from solar nebula
  - Solar [O]/[N] ≈ 10 ➔ low %NH_3
- Eutectic at -100°C may help sustain liquids on, e.g., Enceladus

Hydrated Salt Peritectic Systems



C. Binary Peritectic Systems

Three phases, enstatite = forsterite + SiO_2



Reaction runs to the left
→ no Fo + Qtz igneous rocks!

Figure 6.12. Isobaric T-X phase diagram of the system Fo-Silica at 0.1 MPa. After Bowen and Anderson (1914) and Grieg (1927). Amer. J. Sci.

Desert soils = non-equilibrium assemblages

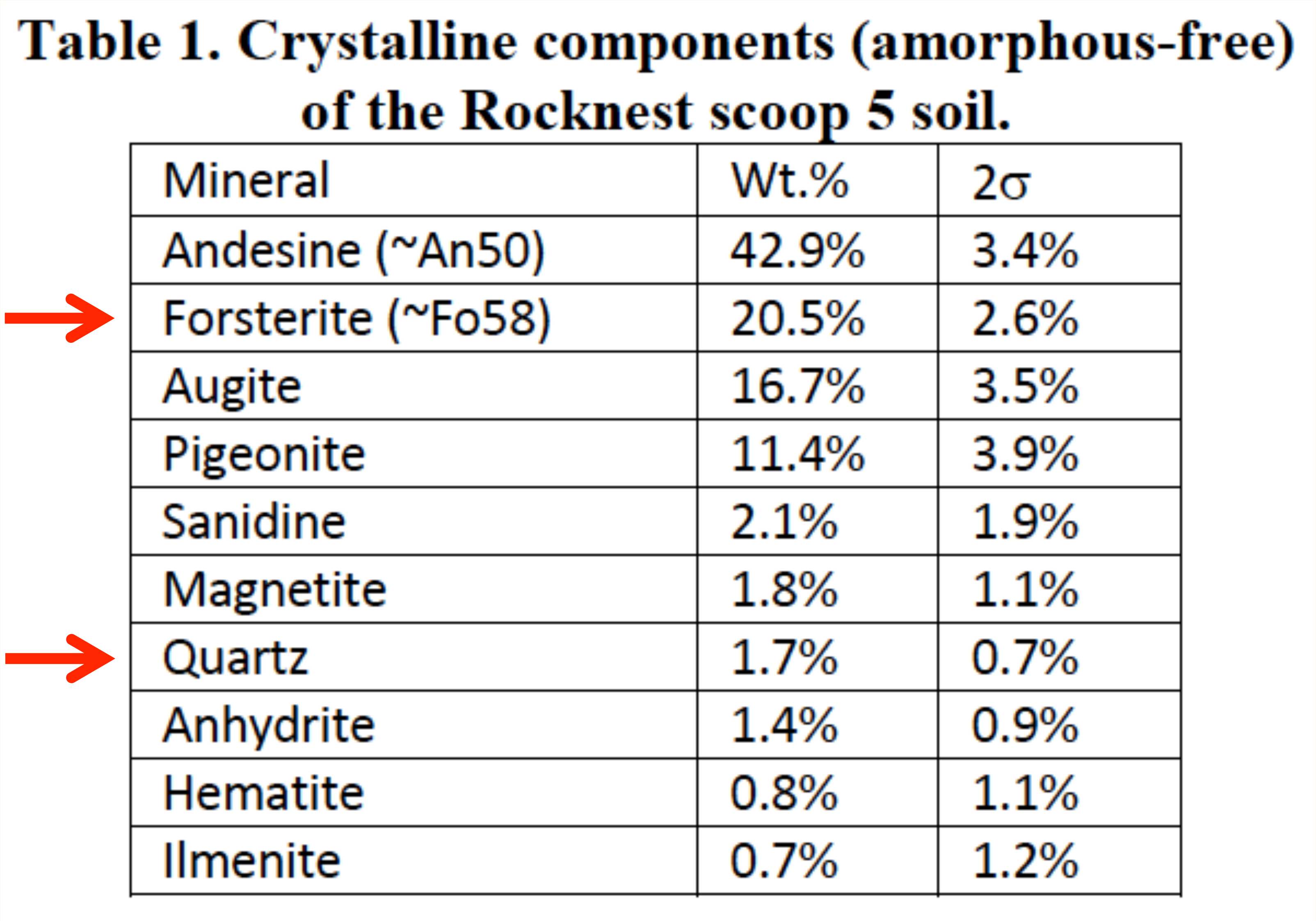


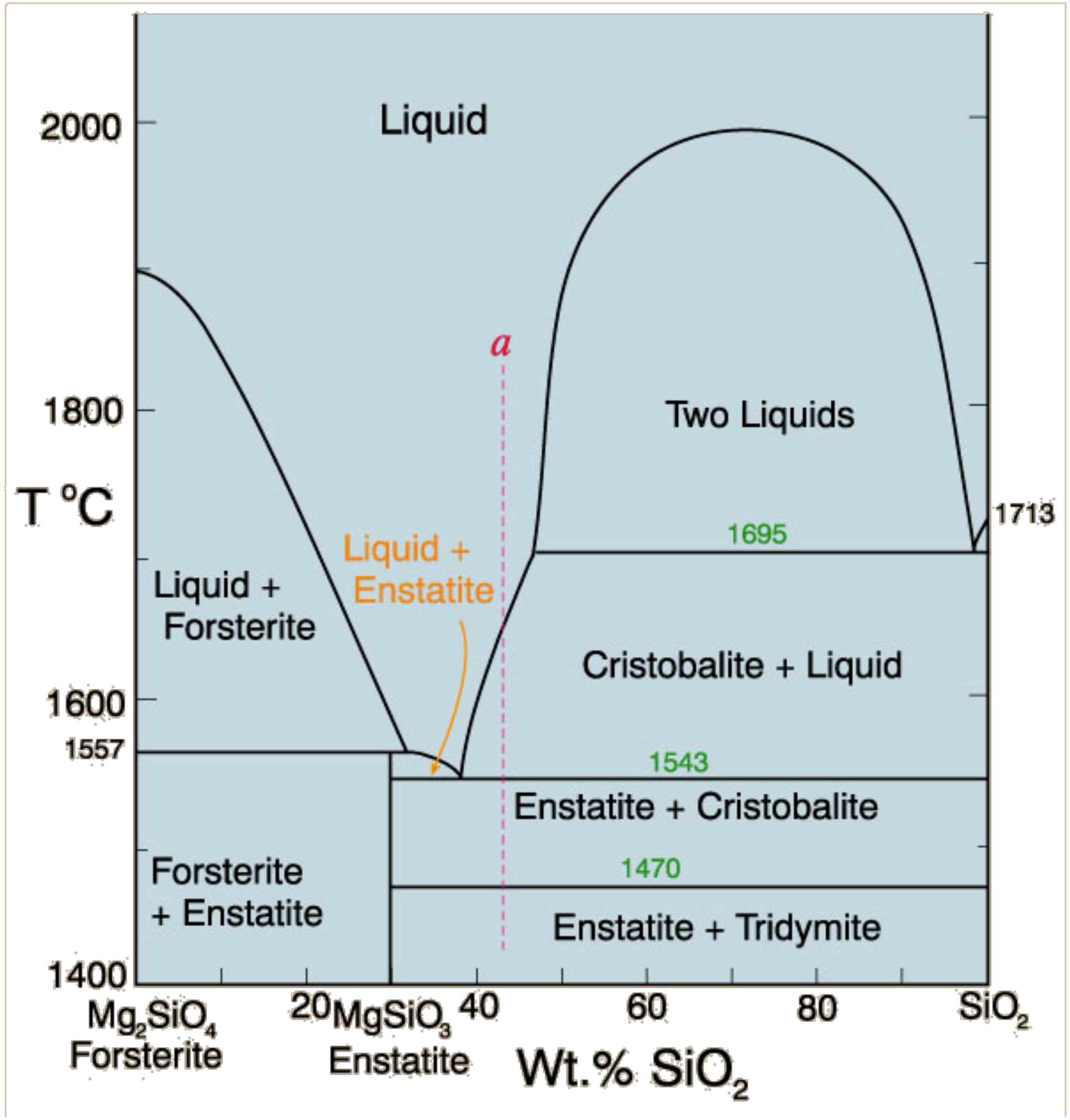
Table 1. Crystalline components (amorphous-free) of the Rocknest scoop 5 soil.

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%

Bish et al. (2013)

C. Binary Peritectic Systems

Three phases, enstatite = forsterite + SiO_2



Start with liquid, assume isobaric:

F = C – ρ + 1 = ?

2!

Cool bulk composition a (42%) to 1660°C:

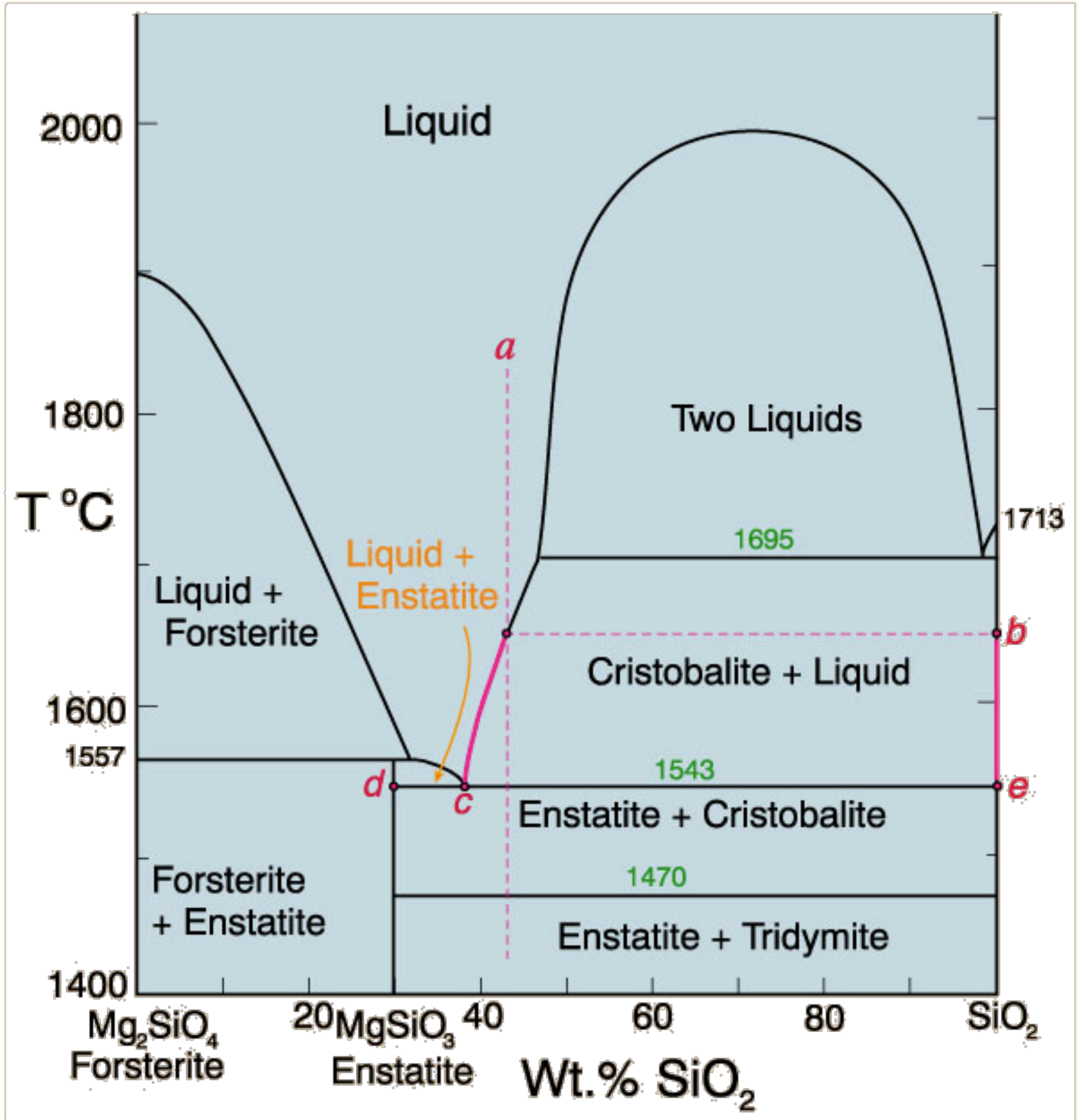
Cristobalite forms

ϕ = 2

F = 2 - 2 + 1 = 1

X_{liq} = f(T)

C. Binary Peritectic Systems



As T lowered, X_{liq} follows path to c, the eutectic

At 1543°C, enstatite forms: d

Now $\phi = 3$ and $F = 2 - 3 + 1 = 0$

invariant

Discontinuous reaction:

liq = En + Crst

Stay at this T until liq is consumed

Then have En + Crst

$\phi = 2$

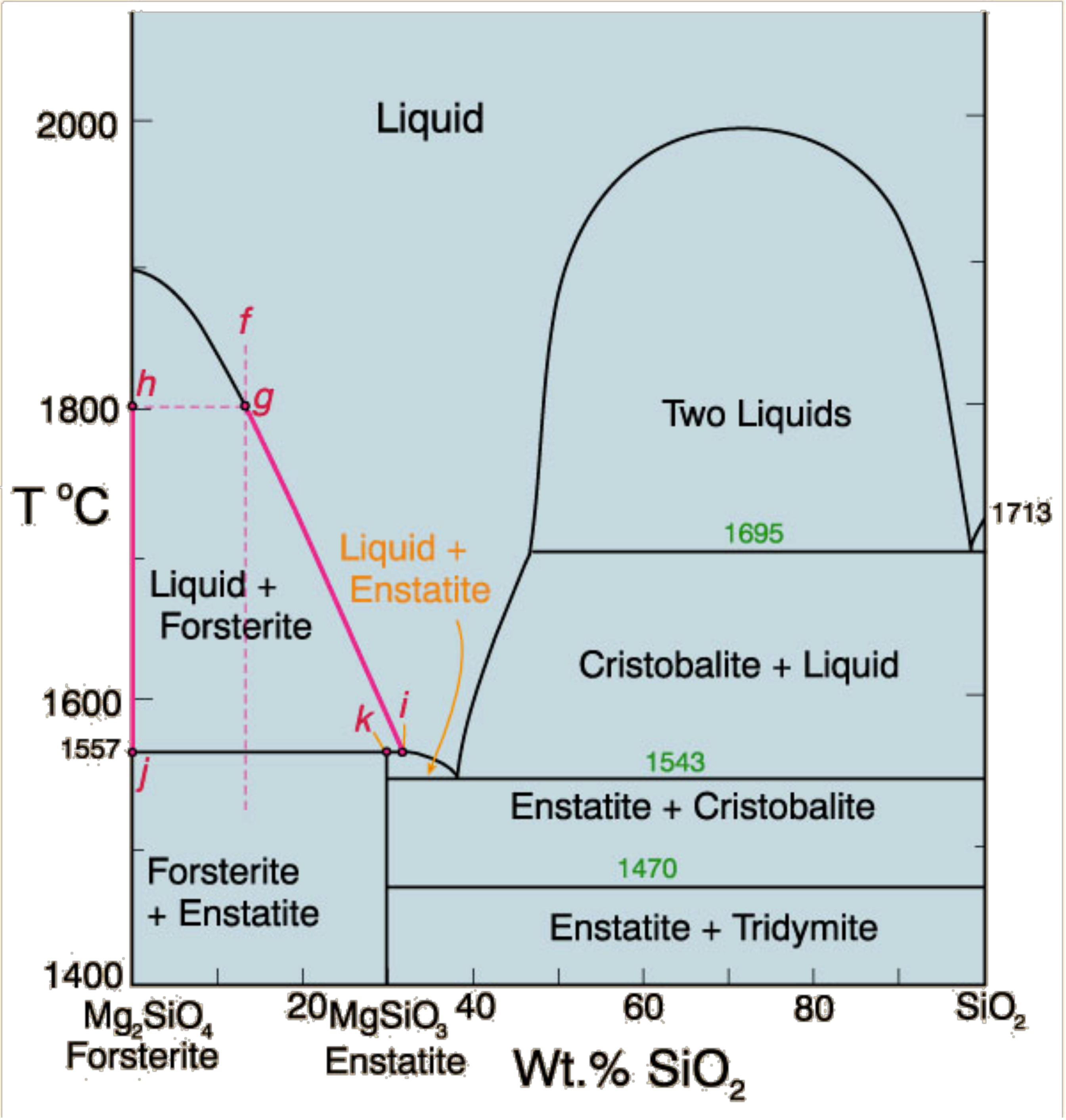
$F = 2 - 2 + 1 = 1$

univariant

At 1470°C get polymorphic transition

Crst -> Trid

Another invariant discontinuous rxn



Next cool *f* = 13 wt. %

At 1800°C get olivine (Fo) forming

$\phi = 2$

F = 2 - 2 + 1 = 1

univariant

$X_{liq} = f(T)$

At 1557°C …

Opx (En) forms

$\phi = 3$

F = 2 - 2 + 1 = 0

invariant

i = "peritectic" point

At 1557°C have colinear Fo-En-liq

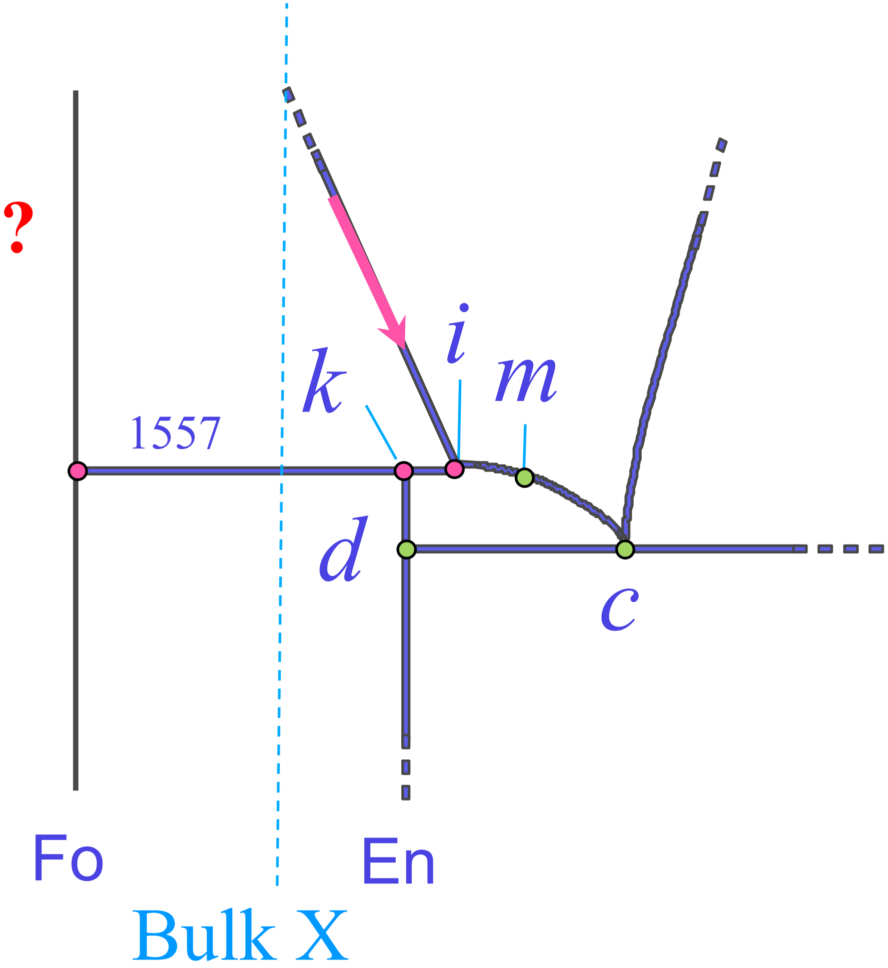
- geometry indicates a reaction: Fo + liq = En
- consumes olivine (and liquid) → resorbed textures

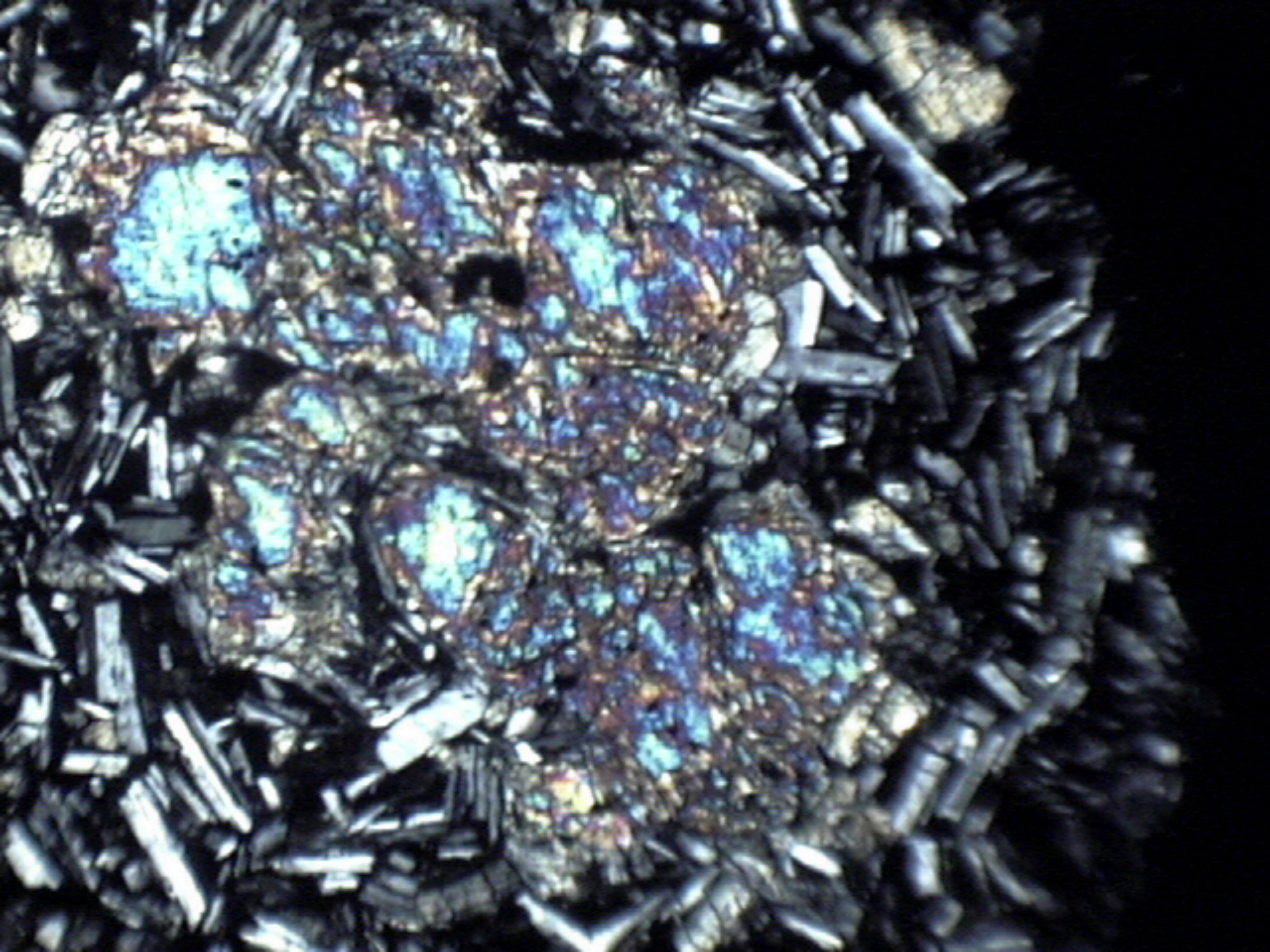
When is the reaction finished?

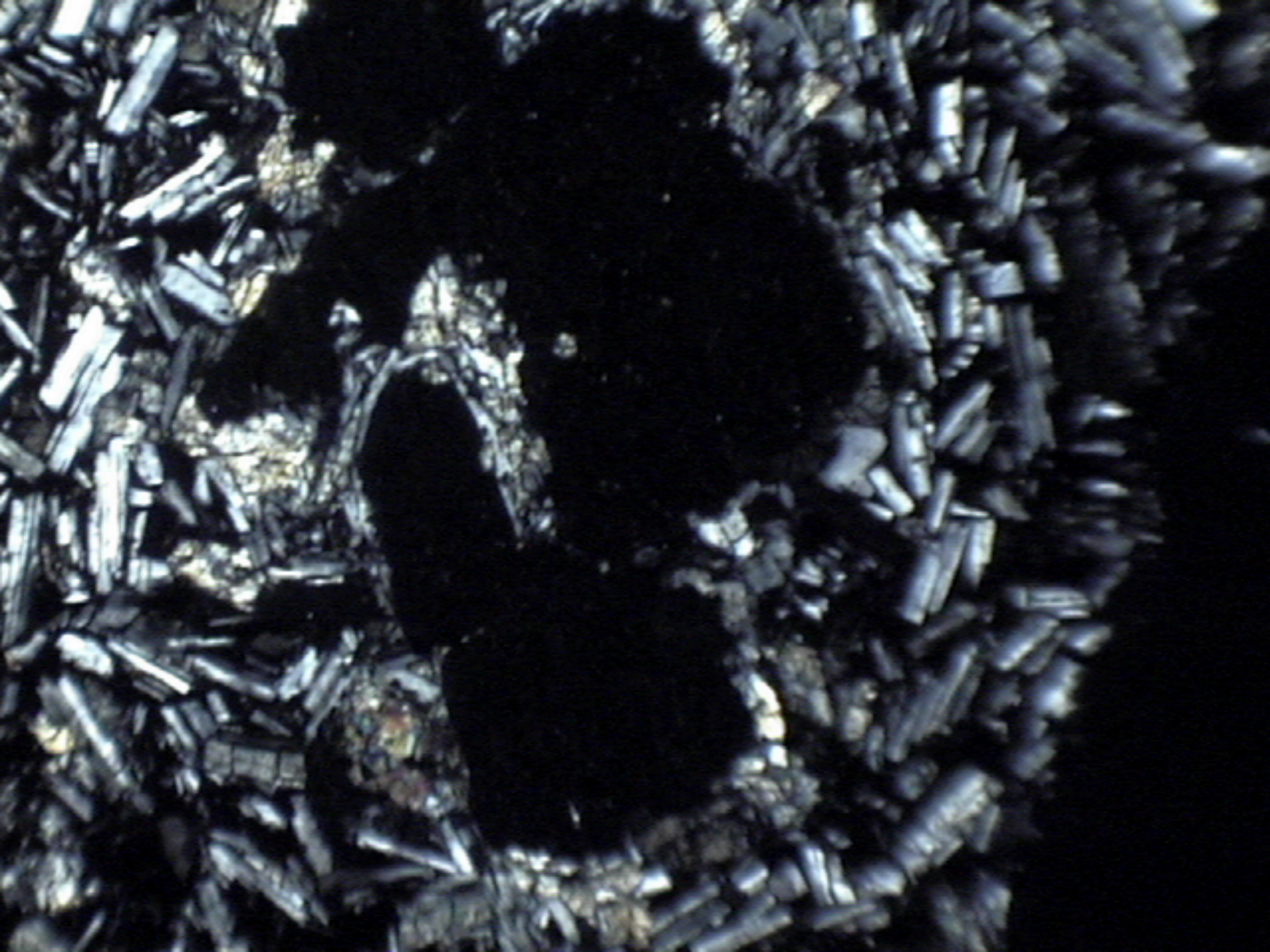
When a phase is used up

Which phase will it be?

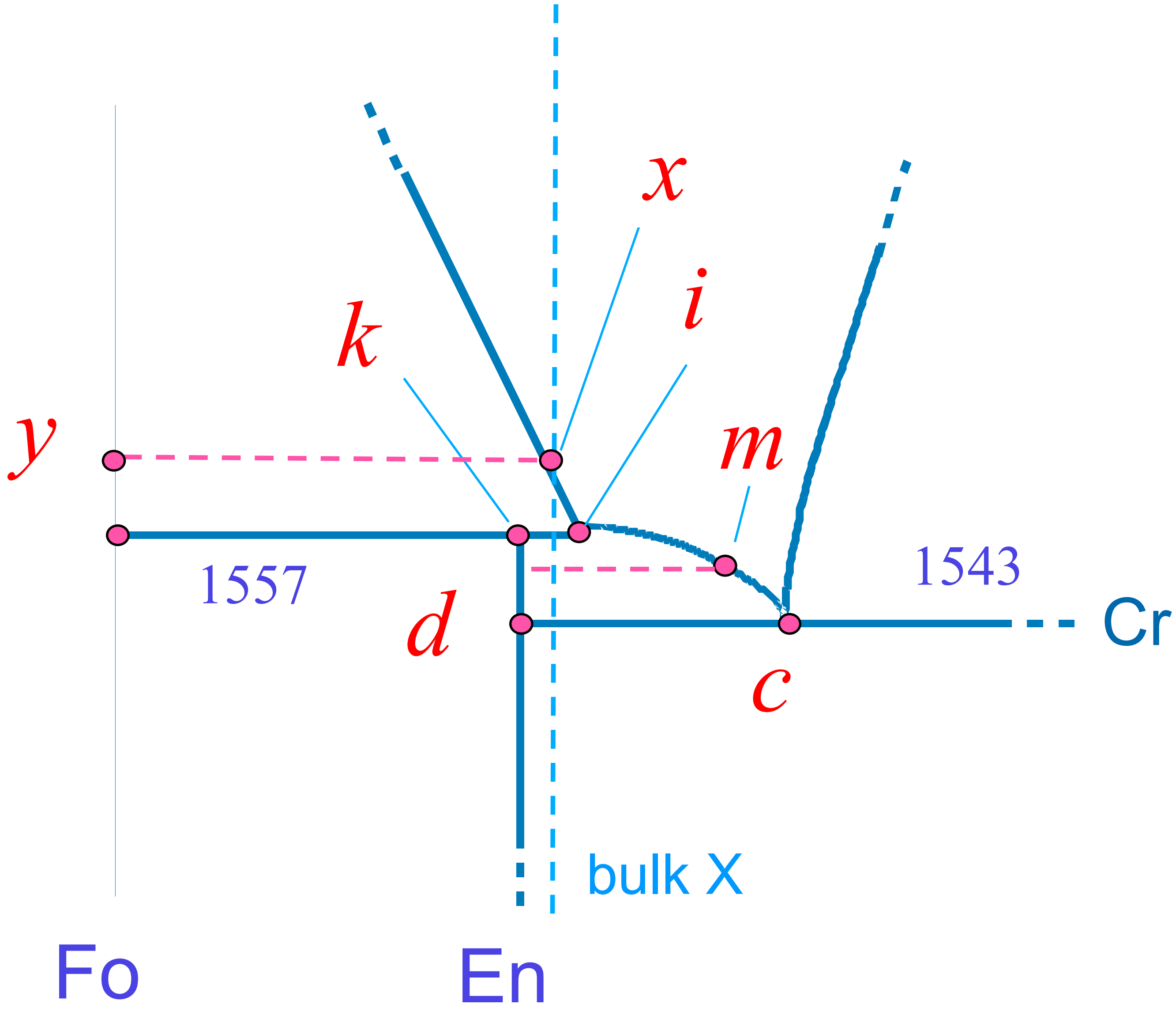
Since the bulk composition lies between En and Fo, liq must be used up first







What happens in this case?

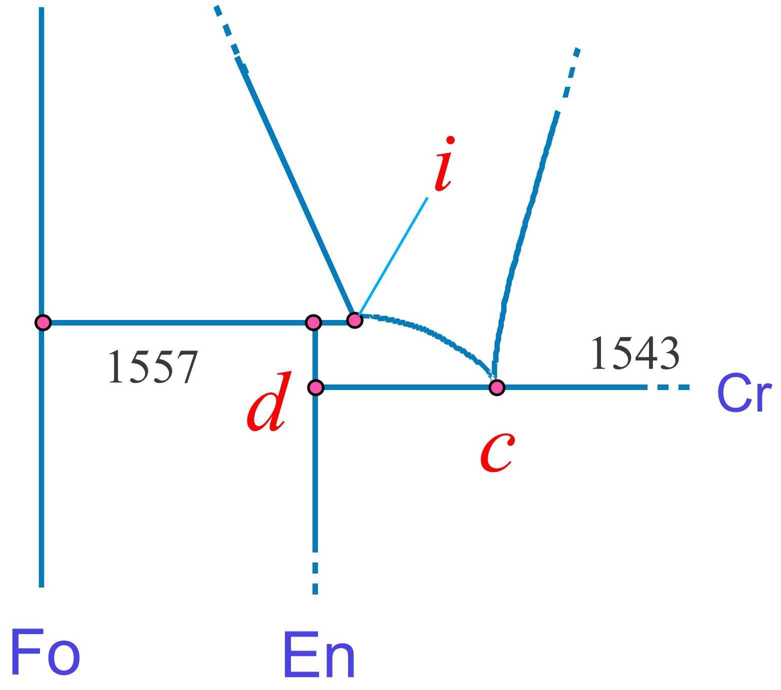


Incongruent Melting of Enstatite

- Melt of En does not → melt of same composition
- Rather En → Fo + Liq *i* at the peritectic

Partial Melting of Fo + En (harzburgite) mantle

- En + Fo also → first liq = *i*
- Remove *i* and cool
- Result = ?



Pressure Effects

Higher P:

- Raises melting point
- Shifts eutectic position (and thus X of first melt)
- Can change peritectic → double eutectic

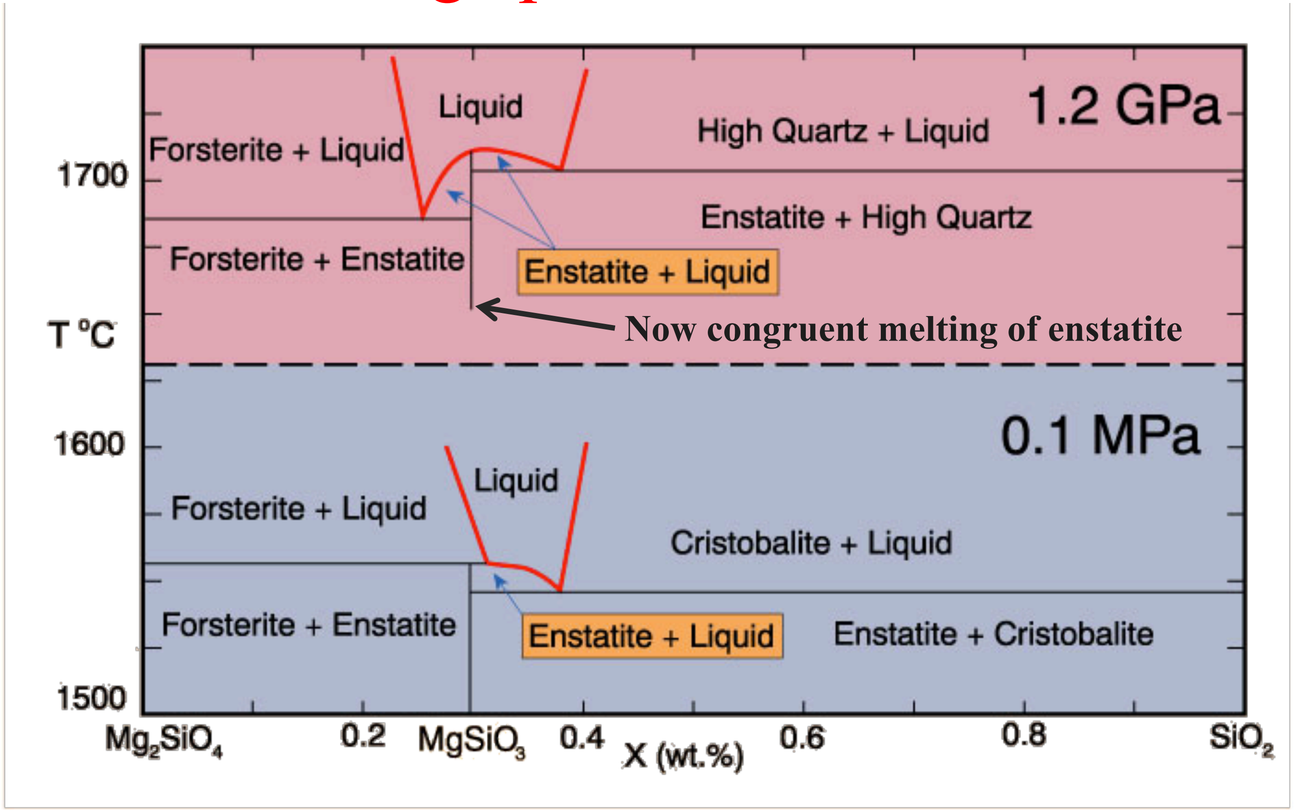


Figure 6.15. The system Fo-SiO_2 at atmospheric pressure and 1.2 GPa. After Bowen and Schairer (1935), Am. J. Sci., Chen and Presnall (1975) Am. Min.

Immiscible Liquids

Cool X = n

- At 1960°C hit solvus

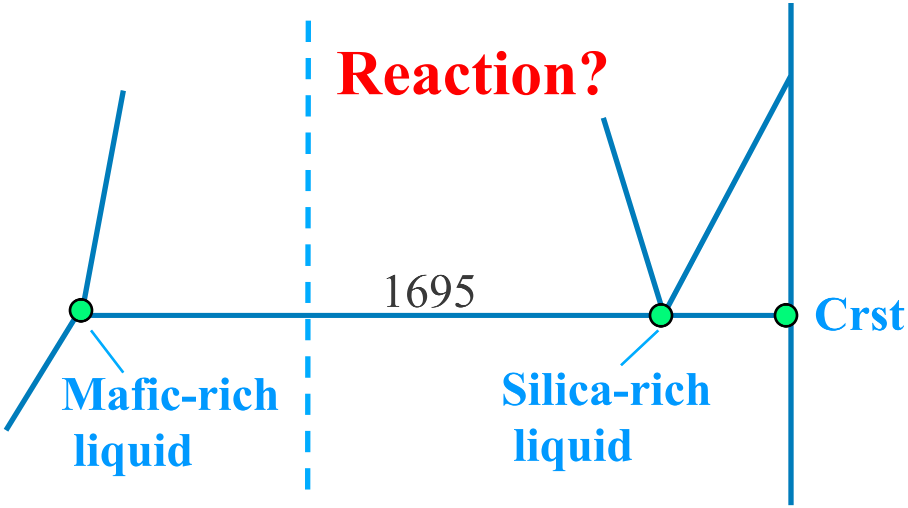
  exsolution

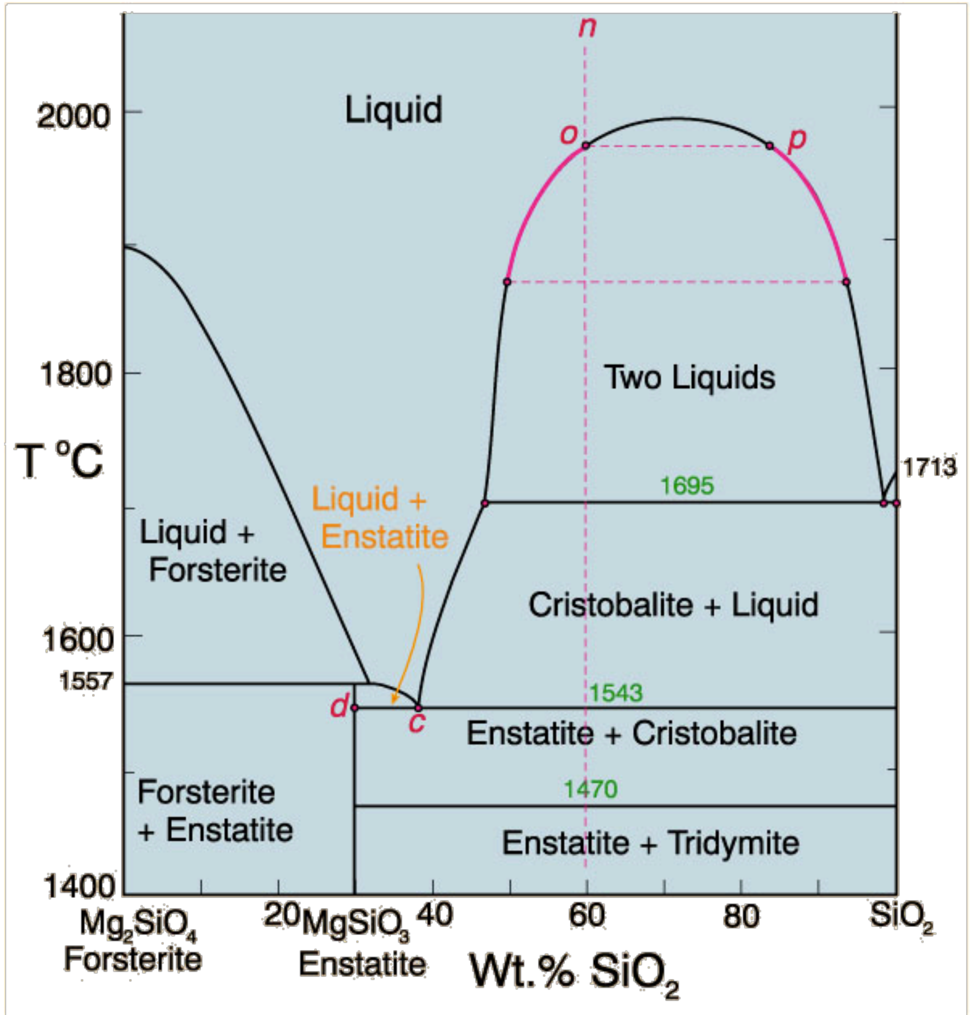
  → 2 liquids o and p

  $\phi = 2 \quad F = 1$

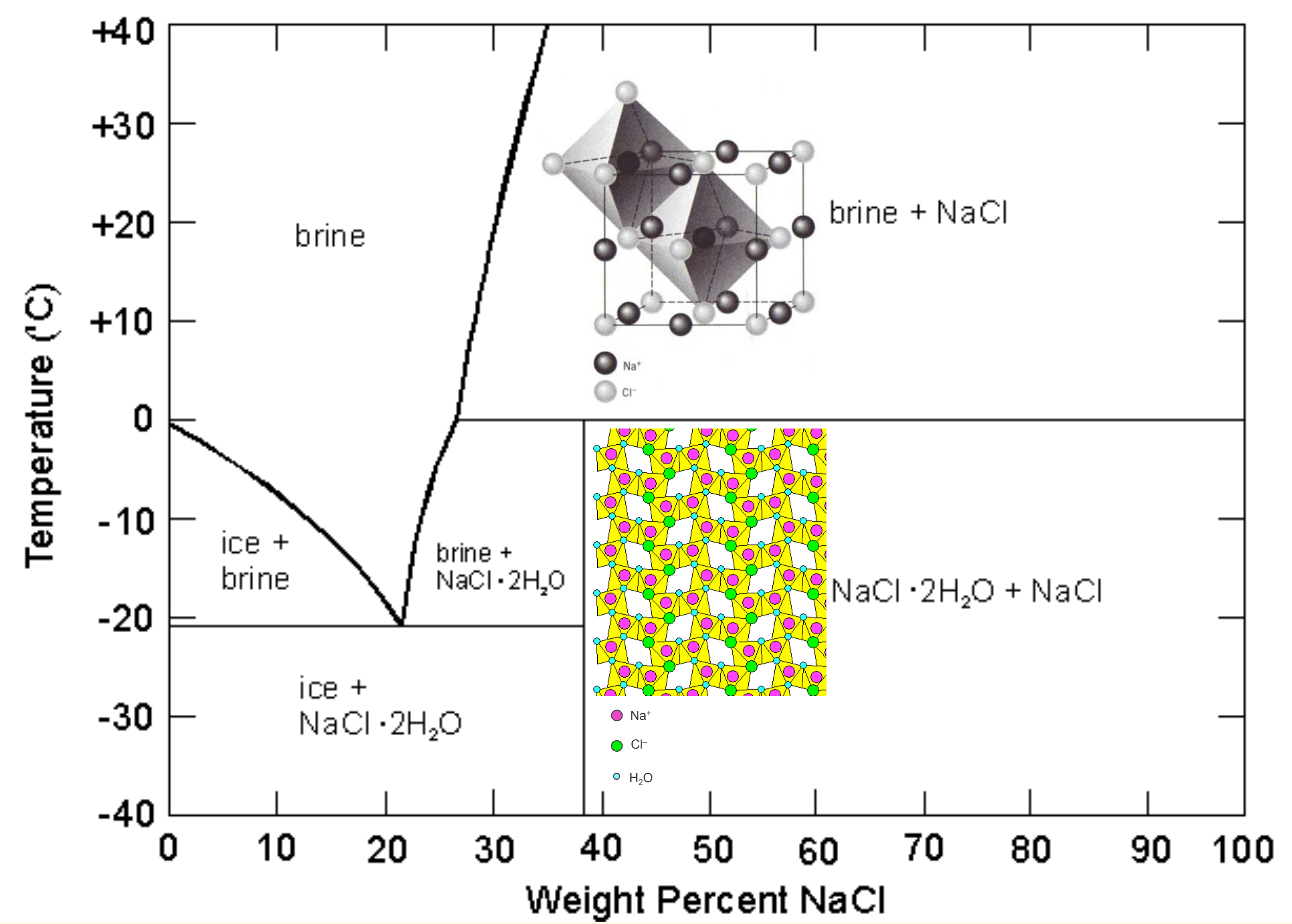
  both liquids follow solvus

At 1695°C get Crst also

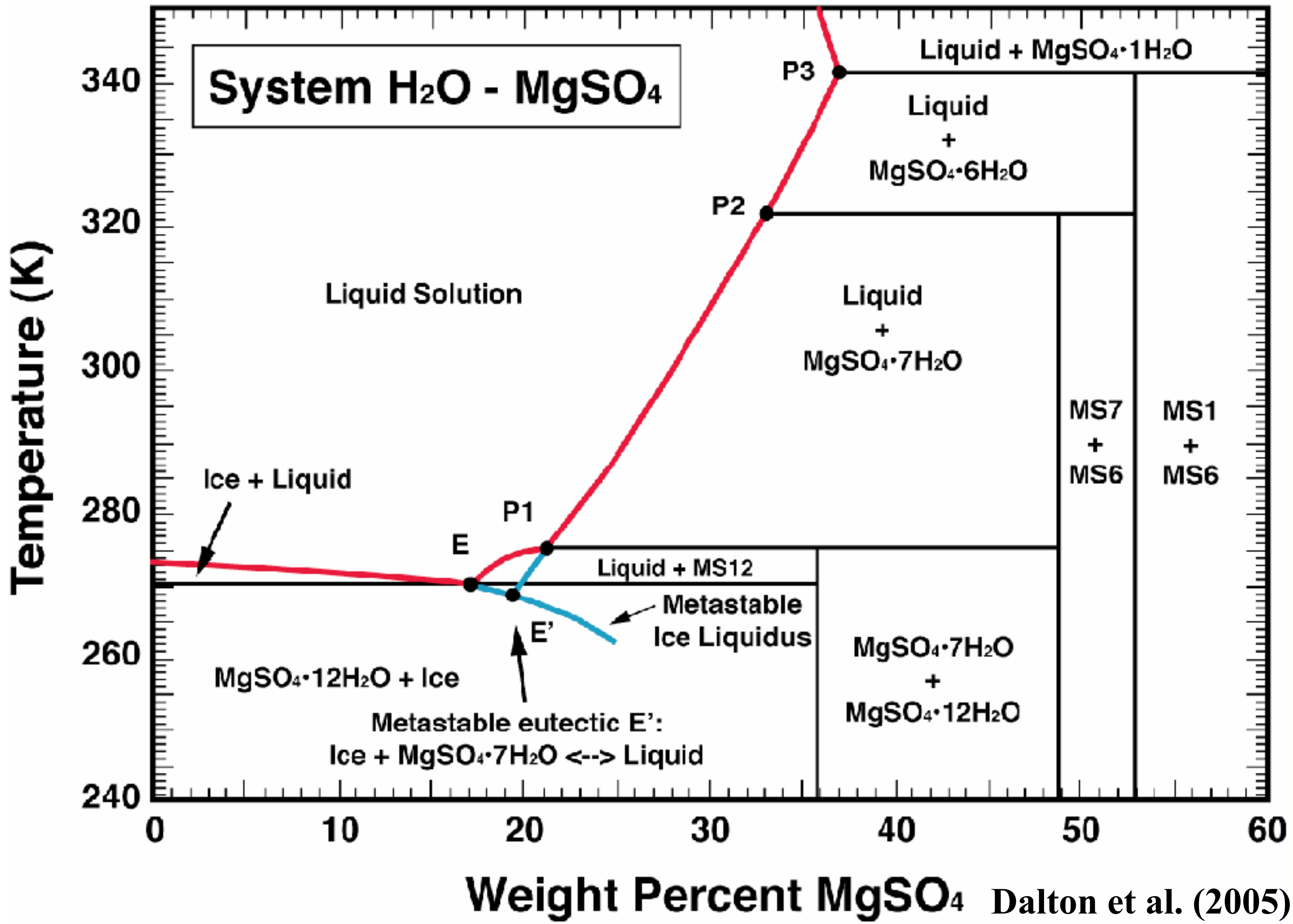




Hydrated Salt Peritectic Systems

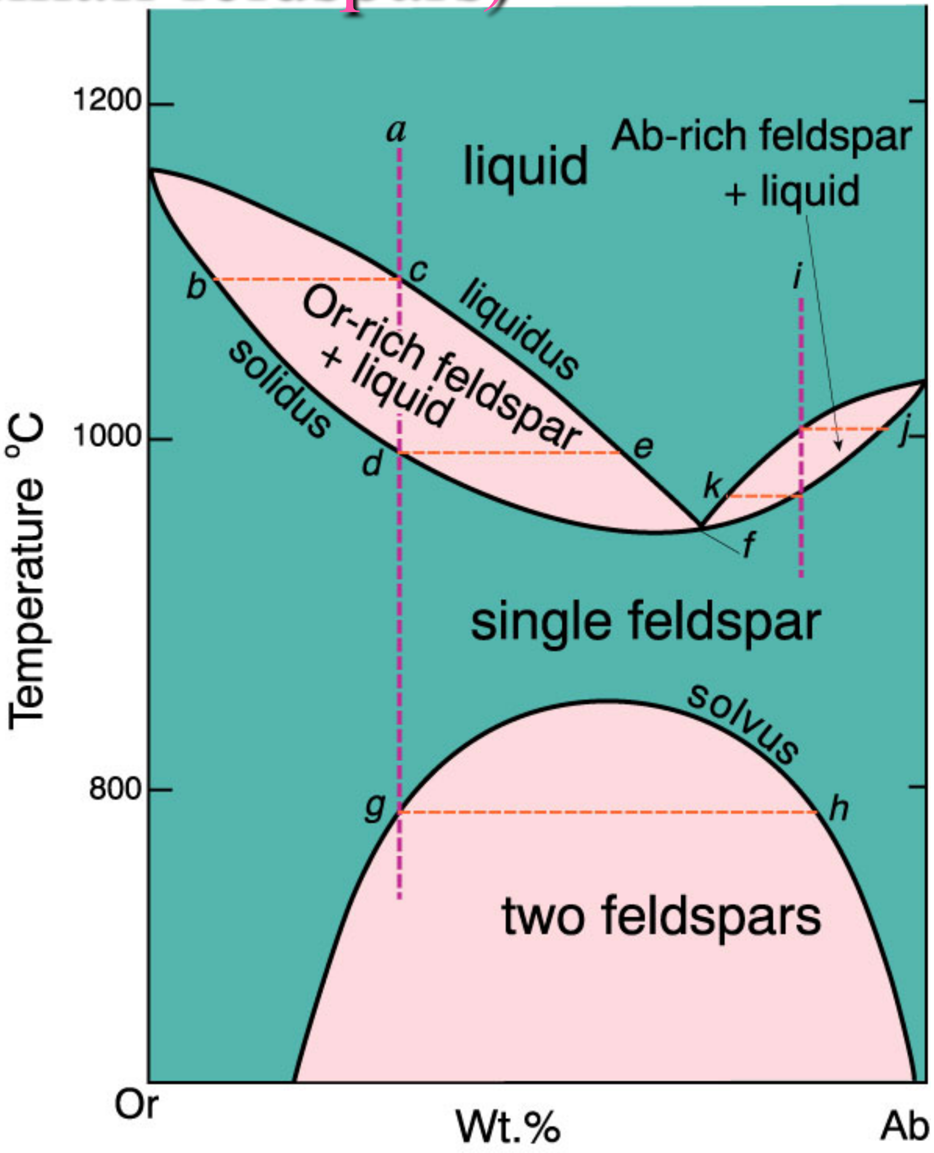


Hydrated Salt Peritectic Systems



Dalton et al. (2005)

D. Solid Solution with Eutectic: Ab-Or (the alkali feldspars)



Eutectic liquidus minimum

Cool composition a:

first solid at b: 1090°C

last liquid at e: 1000°C

don't reach eutectic point

final solid = d

780°C intersect solvus

–> 2 solid phases: exsolution (perthite)

➔ Mineral-pair geothermometry

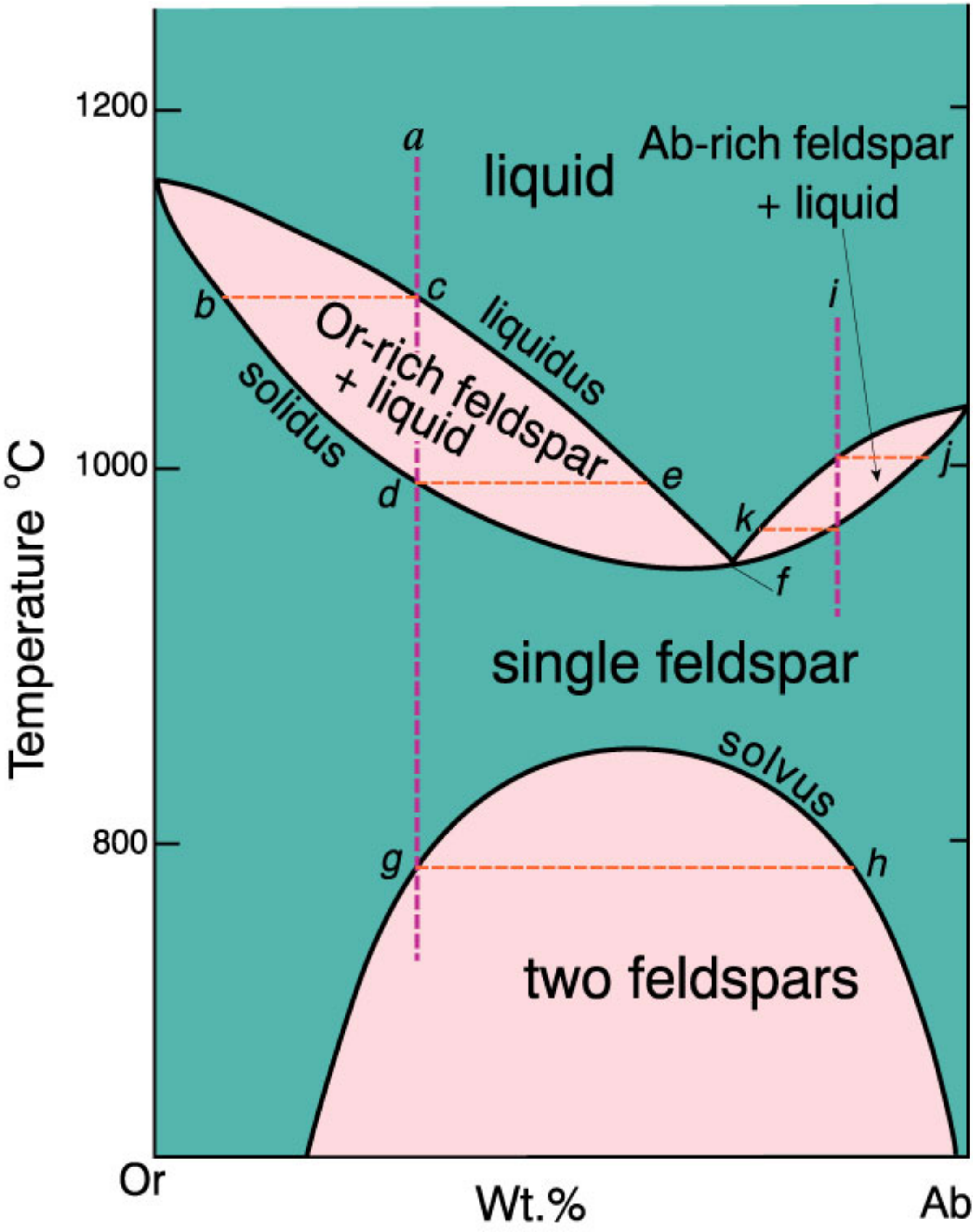
Figure 6.16. T-X phase diagram of the system albite-orthoclase at 0.2 GPa H_2O pressure. After Bowen and Tuttle (1950). J. Geology.

Cool composition i:

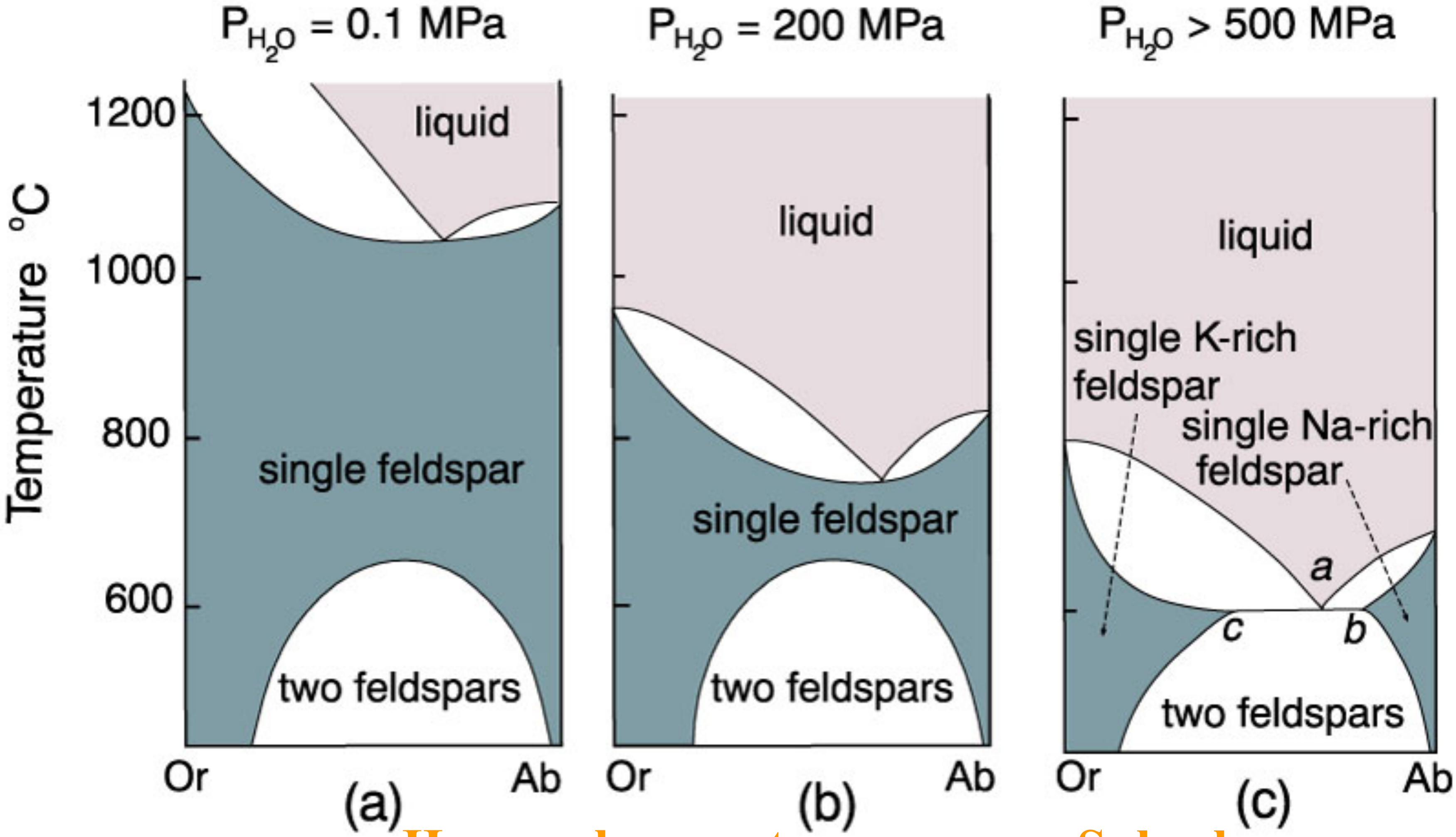
- first solid at j: 1020^{o}C
- last liquid at k: 970^{o}C
  - now liq evolves -> more Or
  - don't reach eutectic point
- final solid = X_i
- also intersect **solvus**
- -> exsolution **(antiperthite)**

How might we reach the eutectic?

Fractional crystallization



Effect of P_{H_2O} on Ab-Or



Hypersolvus systems **Subsolvus**

Figure 6.17. The Albite-K-feldspar system at various H_2O pressures. (a) and (b) after Bowen and Tuttle (1950), J. Geol, (c) after Morse (1970) J. Petrol.