Lecture 4: Condensation

1. Condensation of corundum
2. Condensation temperatures
    A. Refractory vs volatile elements
3. Planet formation
4. Goldschmidt classification
5. The primitive mantle

We acknowledge and respect the ləkʷəŋən peoples on whose traditional territory the university stands and the Songhees, Esquimalt and W̱SÁNEĆ peoples whose historical relationships with the land continue to this day.

Practice Problem: Condensation of Corundum from the Solar Nebula

Q1: Calculate the temperature that Corundum (Al_2O_3) begins condensing from the solar nebula using the following values (assume no other reactions):

$$2\mathrm{Al} + 3\mathrm{O} \leftrightarrow \mathrm{Al}_2\mathrm{O}_3$$

- Solar abundance (molar abundance) of Al: 8.51 x 10^4
- Solar abundance (molar abundance) of O: 2.36 x 10^7
- Solar abundance (molar abundance) of H: 2.6 x 10^{10}
- Pressure in the nebula: 10^{-3} atm
- Gas constant (R): 8.314 J/mol K
- $\Delta G°$ (standard free energy of reaction) for condensation of Al_2O_3: -1.23 x 10^6 J/mol

Q2: At what temperature will this reaction finish condensing all of the Aluminum in the nebula?

Condensation of corundum (ruby/sapphire)

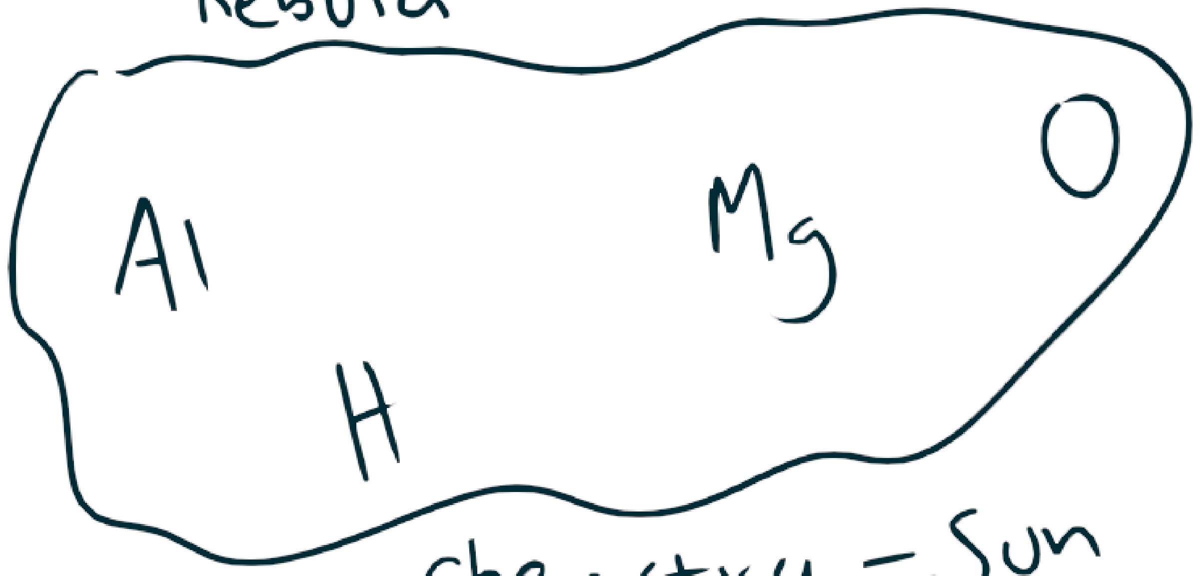
$$2\,Al_{(g)} + 3\,O_{(g)} \longleftrightarrow Al_2O_{3\,(c)}$$

$$Q = \frac{\{Al_2O_3\}}{\{Al\}^2\{O\}^3} = \frac{1}{P_{Al}^2 \cdot P_O^3}$$

at high T, low P safe to assume ideal gas

$$\{x\} = P_x$$

nebula



chemistry = Sun

$P_T = 10^{-3}$ atm

assumption: $P_T = P_{H_2}$

$$\frac{P_x}{P_{H_2}} = \frac{N_x}{N_{H_2}} \qquad N_{H_2} = \frac{1}{2} N_H$$

$$P_{Al} = \frac{N_{Al}}{\frac{1}{2} N_H} \cdot P_{H_2} = \frac{2\,N_{Al}}{N_H} \cdot P_T$$

$$\Delta G^\circ = -RT \ln K$$

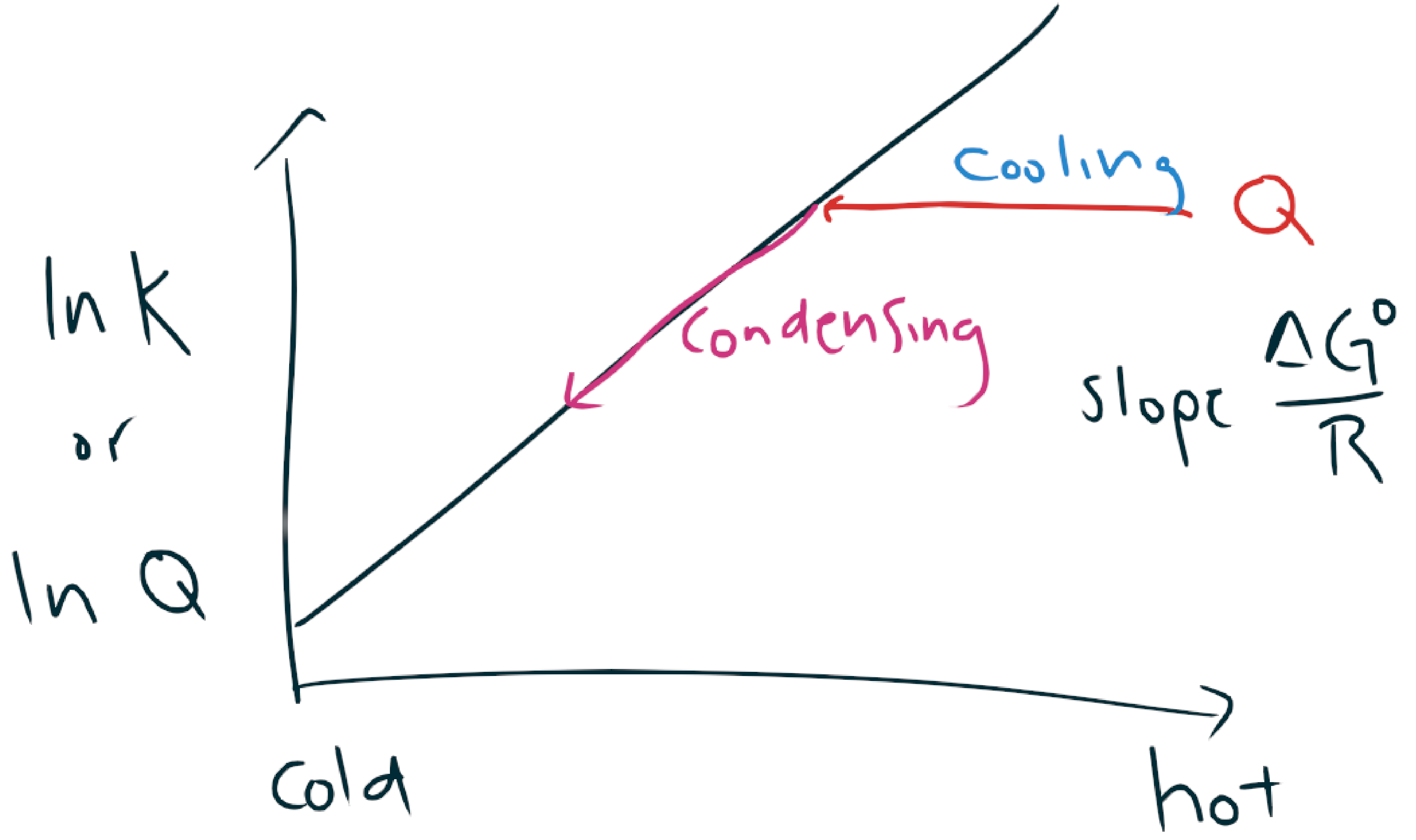
$$-\frac{\Delta G^\circ}{RT} = \ln K$$

let:

this sign corresponds to reaction direction

$$x = \frac{-1}{T} \qquad y = -\ln K$$

$$x \, \frac{-\Delta G^\circ}{R} = y$$



Condensation of corundum (ruby/sapphire)

$$2Al_{(g)} + 3O_{(g)} \longleftrightarrow Al_2O_{3\,(c)}$$

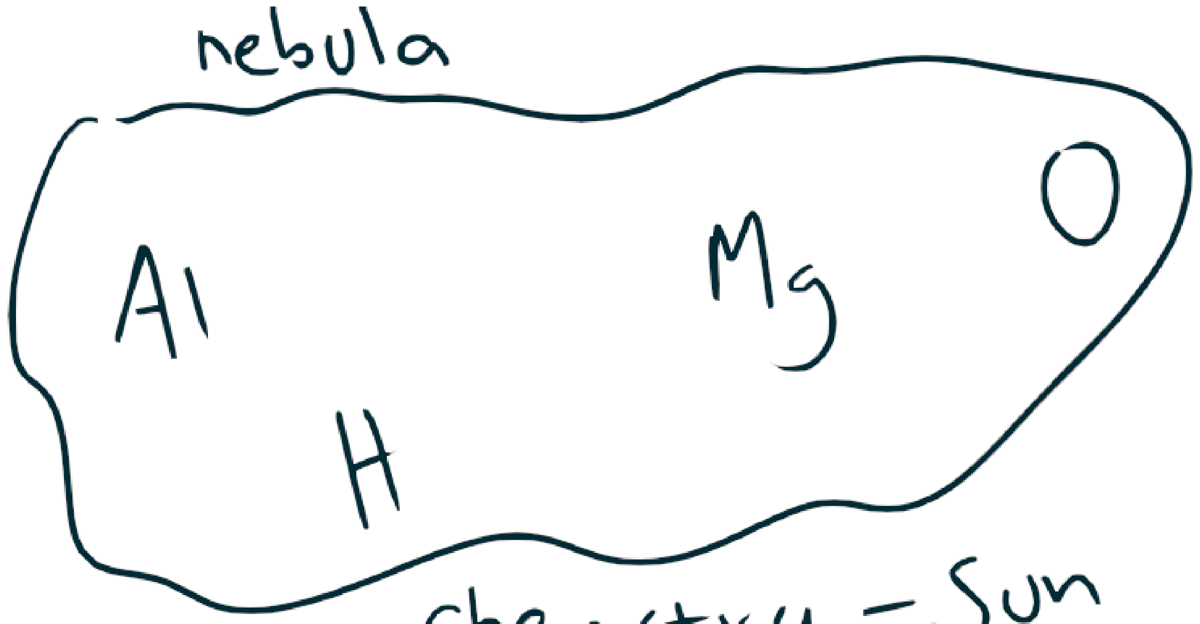
$$Q = \frac{\{Al_2O_3\}}{\{Al\}^2\{O\}^3} = \frac{1}{P_{Al}^2 \cdot P_O^3}$$

$$\frac{-\Delta G^\circ}{RT} = \ln \frac{1}{(6.5e^{-9})^2(1.8e^{-6})^3}$$

$$\frac{-\Delta G^\circ}{RT} = 77.3$$

*ΔG given in problem

$$\frac{-(-1.23e6)}{8.314 \cdot 77.3} = T \approx 1913 \text{ Kelvin}$$



chemistry = Sun

$$\frac{P_x}{P_{H_2}} = \frac{N_x}{N_{H_2}} \qquad P_T = 10^{-3}\text{ atm}$$

assumption: $P_T = P_{H_2}$

$$N_{H_2} = \frac{1}{2} N_H$$

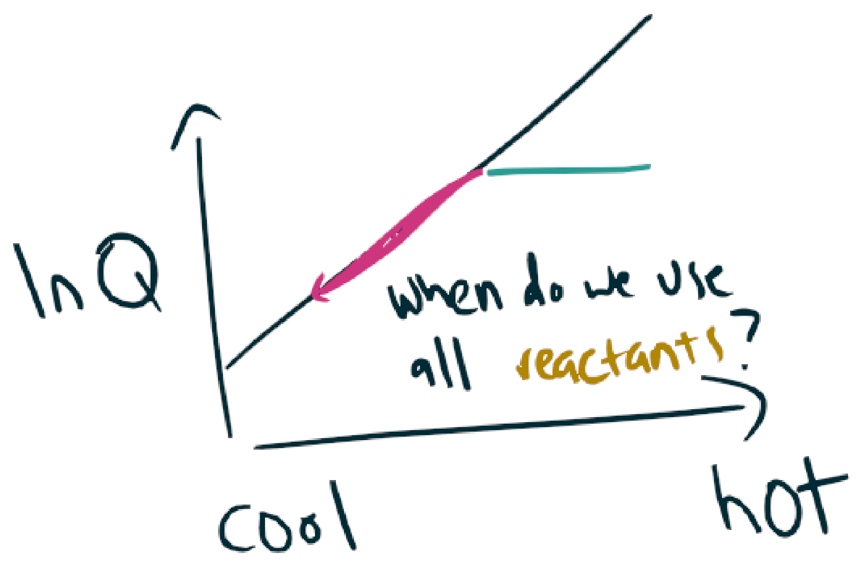
$$6.5e^{-9} = P_{Al} = \frac{N_{Al}}{\frac{1}{2}N_H} \cdot P_{H_2} = \frac{2N_{Al}}{N_H} \cdot P_T$$

$$1.8e^{-6} = P_O = \frac{2N_O}{N_H} \cdot P_T$$

Condensation of corundum (ruby/sapphire)

$$2\,Al(g) + 3\,O(g) \longleftrightarrow Al_2O_3(c)$$

$$Q = \frac{\{Al_2O_3\}}{\{Al\}^2\{O\}^3} = \frac{1}{P_{Al}^2 \cdot P_O^3}$$



$$P_{Al} = \frac{2N_{Al}}{N_H} \cdot P_T$$

$$P_O = \frac{2N_O}{N_H} \cdot P_T$$

Al is limiting $\frac{N_{Al}}{N_O} < \frac{2}{3}$

What is P_{Al} when all Al condensed? ~ 0 atm $= P_{Al} - 0.99P_{Al}$

What is P_O when all Al condensed? > 0 atm $= P_O - \frac{3}{2}(0.99P_{Al})$

$$\frac{-\Delta G^\circ}{RT} = \ln \frac{1}{(P_{Al} - 0.99P_{Al})^2\left(P_O - \frac{3}{2}(0.99P_{Al})\right)^3}$$

$T \simeq 1710$ K

50 % condensation

$\simeq 1880$ K

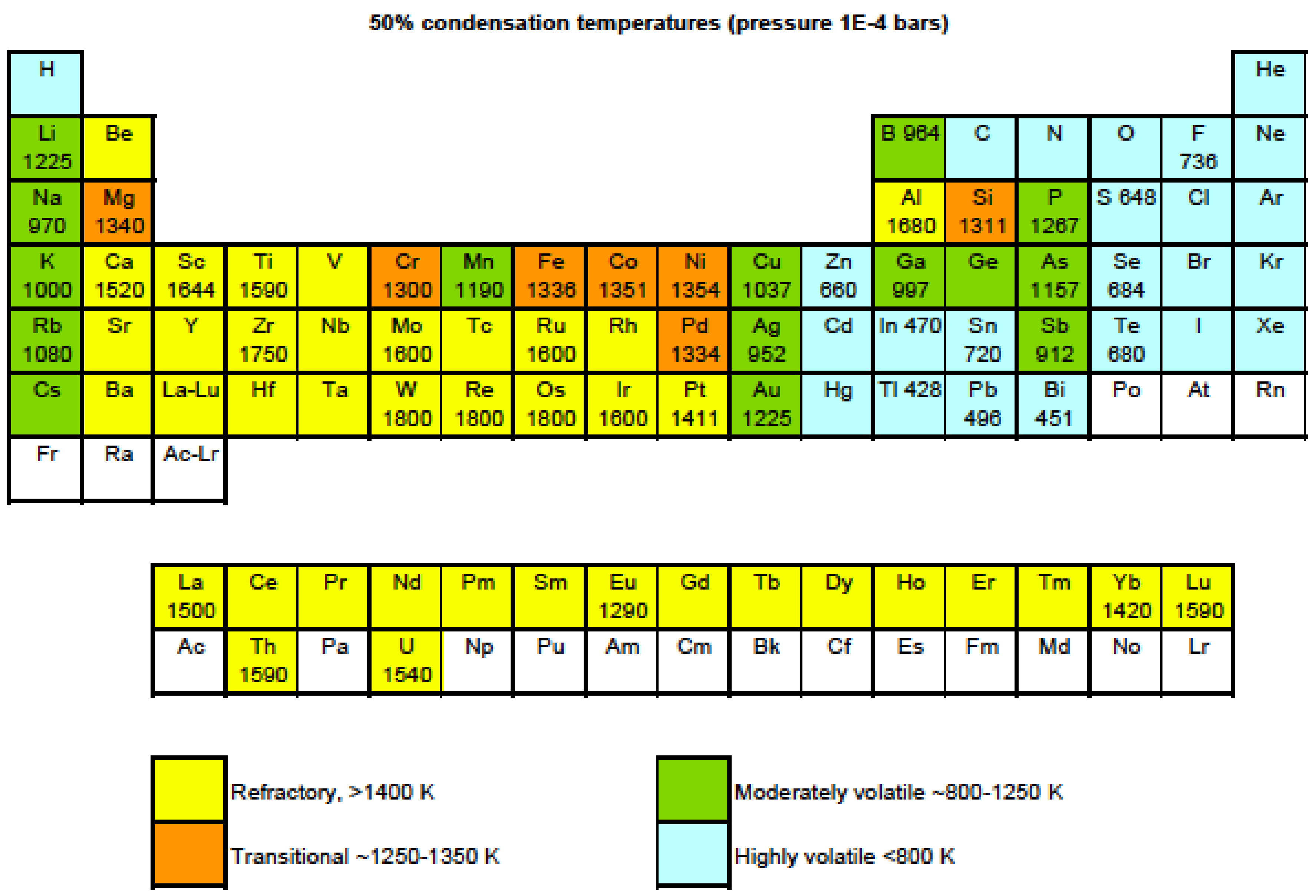


Figure 2.13. 50% condensation temperatures taken from [*Wasson*, 1985] and [*O'Neill and Palme*, 1998].

Not quite as simple as our example..

Table 1. Gaseous species contributing more than 10^{-7} of the total moles of their common constituent element between 2000°K and 1200°K.

Element	Abundance* (Si = 10^6)	Gaseous species
Hydrogen	$2{\cdot}6 \times 10^{10}$	H_2, H, H_2O, HF, HCl, MgH, HS, H_2S, MgOH
Oxygen	$2{\cdot}36 \times 10^7$	CO, SiO, H_2O, TiO, OH, HCO, CO_2, PO, CaO, COS, MgO, SiO_2, AlOH, SO NaOH, MgOH, PO_2, $Mg(OH)_2$, AlO_2H
Carbon	$1{\cdot}35 \times 10^7$	CO, HCN, CS, HCO, CO_2, COS, HCP
Nitrogen	$2{\cdot}44 \times 10^6$	N_2, HCN, PN, NH_3, NH_2
Magnesium	$1{\cdot}05 \times 10^6$	Mg, MgH, MgS, MgF, MgCl, MgO, MgOH, $Mg(OH)_2$
Silicon	$1{\cdot}00 \times 10^6$	Si, SiS, SiO, SiO_2
Iron	$8{\cdot}90 \times 10^5$	Fe
Sulfur	$5{\cdot}06 \times 10^5$	SiS, CS, S, HS, H_2S, PS, AlS, MgS, NS, S_2, COS, SO, CS_2, SO_2
Aluminum	$8{\cdot}51 \times 10^4$	Al, AlH, AlF, AlCl, AlS, AlO, Al_2O, AlOH, AlOF, AlO_2H
Calcium	$7{\cdot}36 \times 10^4$	Ca, CaF, CaO, $CaCl_2$
Sodium	$6{\cdot}32 \times 10^4$	Na, NaH, NaCl, NaF, NaOH
Nickel	$4{\cdot}57 \times 10^4$	Ni
Phosphorus	$1{\cdot}27 \times 10^4$	P, PN, PH, P_2, PH_2, PS, PO, PH_3, PO_2, HCP
Chromium	$1{\cdot}24 \times 10^4$	Cr
Manganese	8800	Mn
Fluorine	3630	HF, AlF, CaF, F, MgF, NaF, NF, KF, PF, CaF_2, AlOF, TiF_2, MgF_2, MgClF, TiF
Potassium	3240	K, KH, KCl, KF, KOH
Titanium	2300	Ti, TiO, TiF_2, TiO_2, TiF
Cobalt	2300	Co
Chlorine	1970	HCl, Cl, AlCl, NaCl, KCl, MgCl, $CaCl_2$, $MgCl_2$, AlOCl, MgClF

* From CAMERON (1968).

table from *Condensation in the primitive solar nebula* by Lawrence Grossman in GCA (1972)

Not quite as simple as our example..

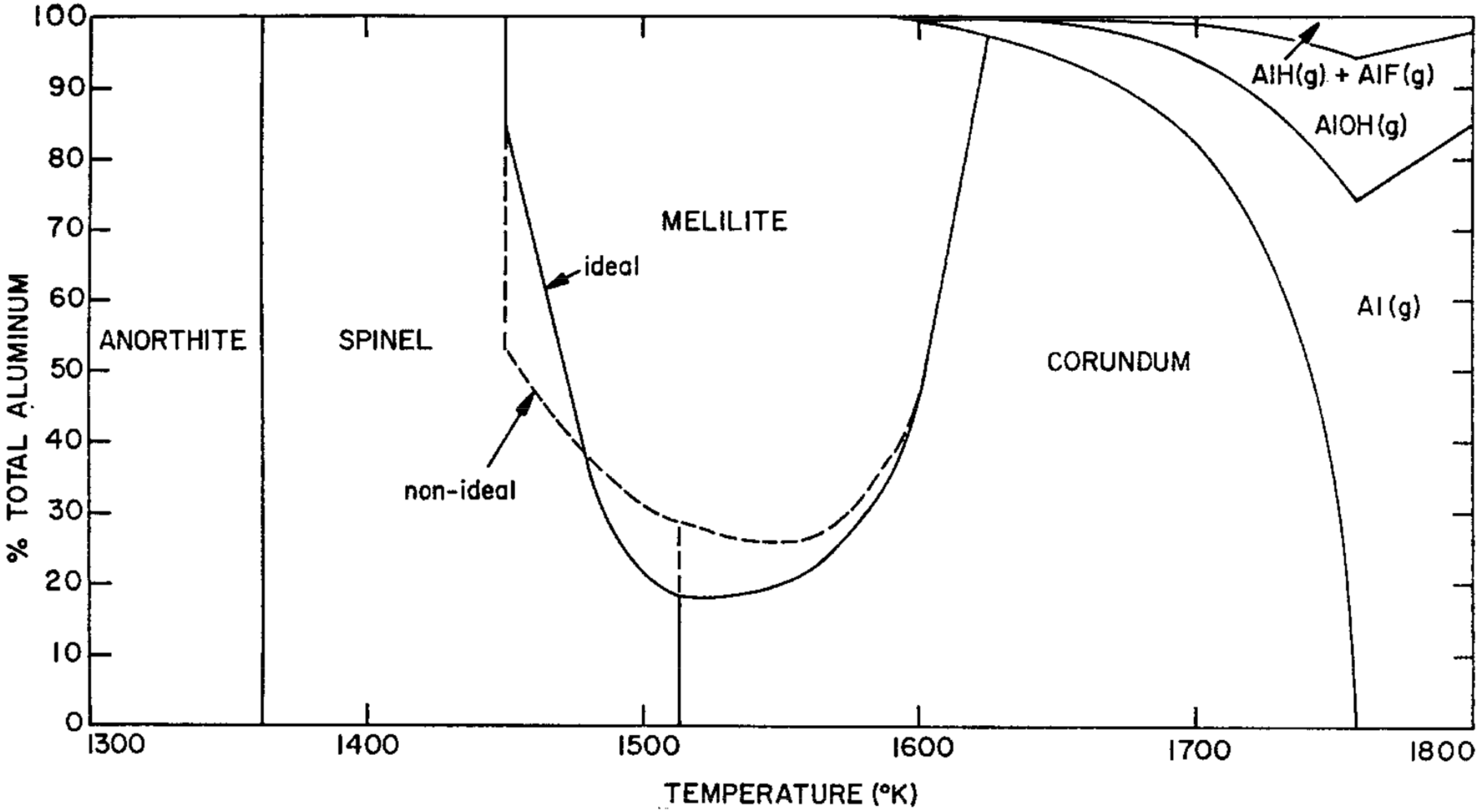


figure from *Condensation in the primitive solar nebula* by Lawrence Grossman in GCA (1972)

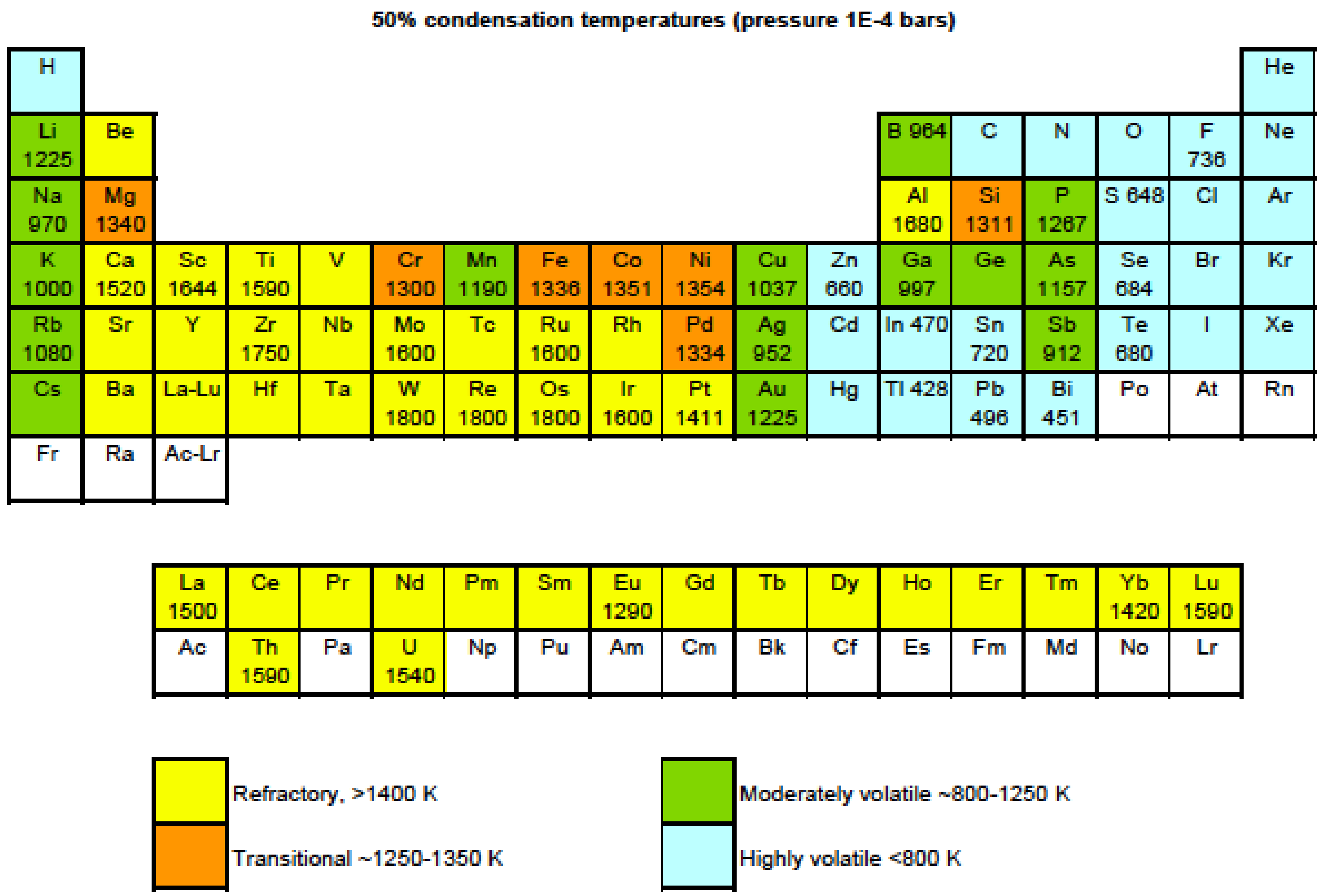


Figure 2.13. 50% condensation temperatures taken from [*Wasson*, 1985] and [*O'Neill and Palme*, 1998].

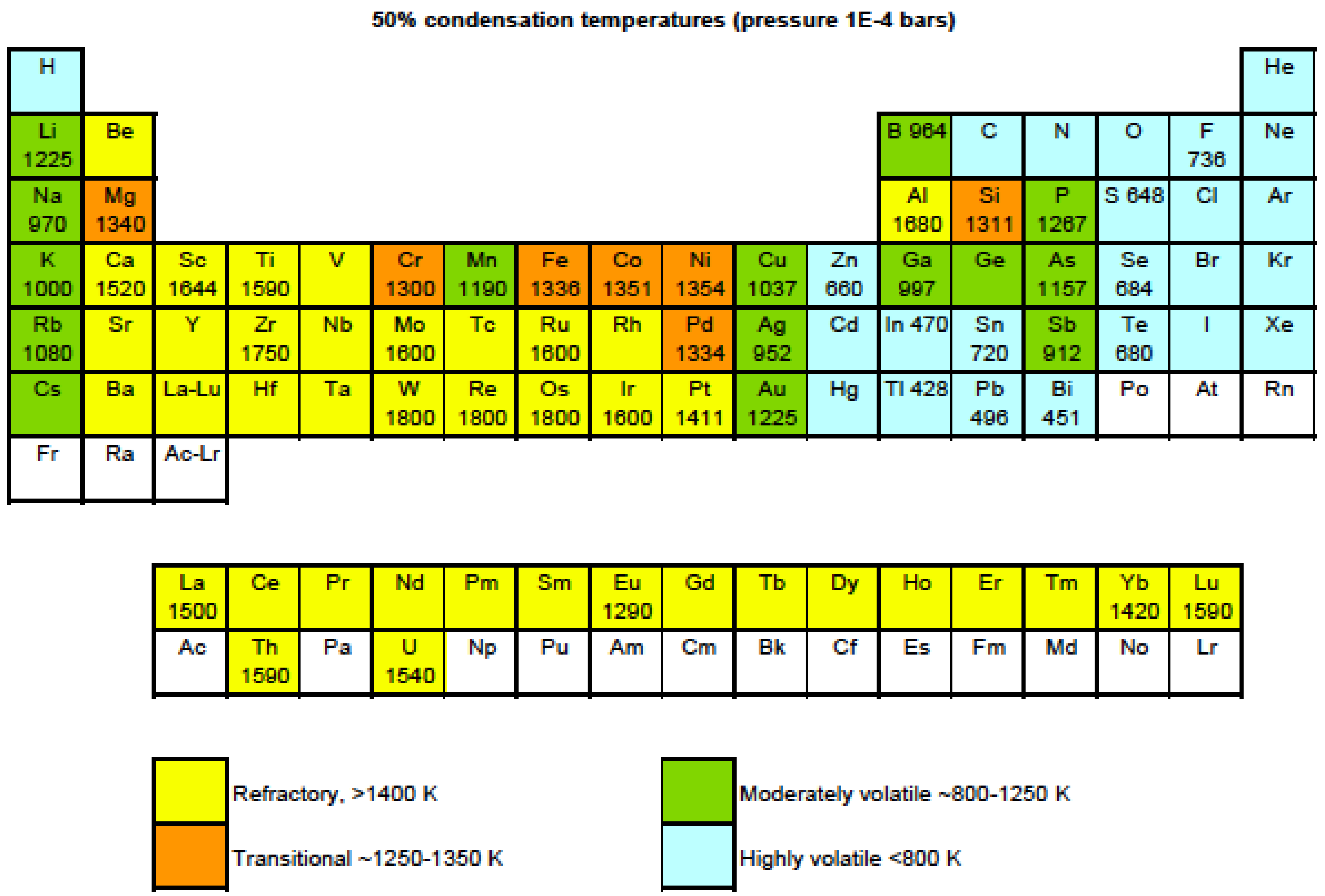
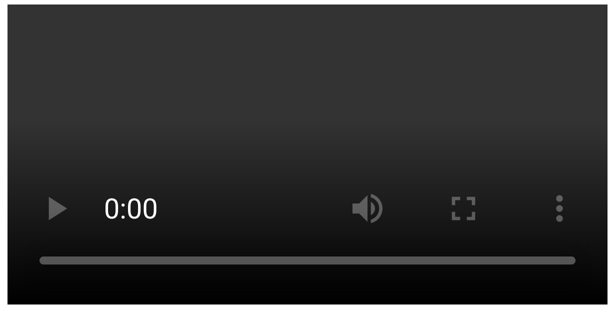


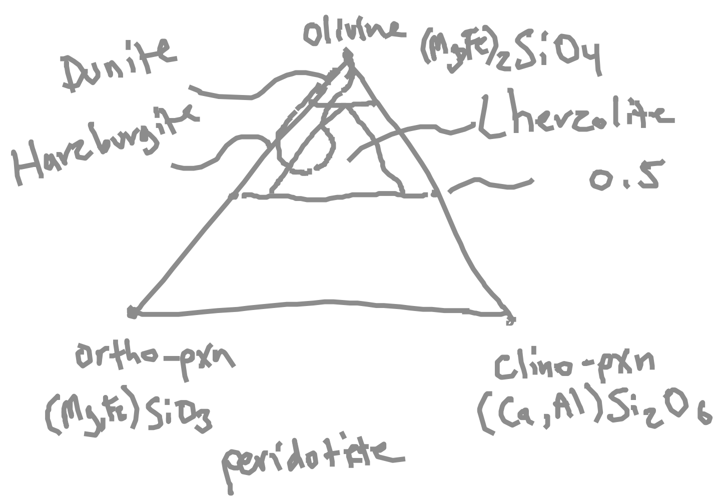
Figure 2.13. 50% condensation temperatures taken from [*Wasson*, 1985] and [*O'Neill and Palme*, 1998].

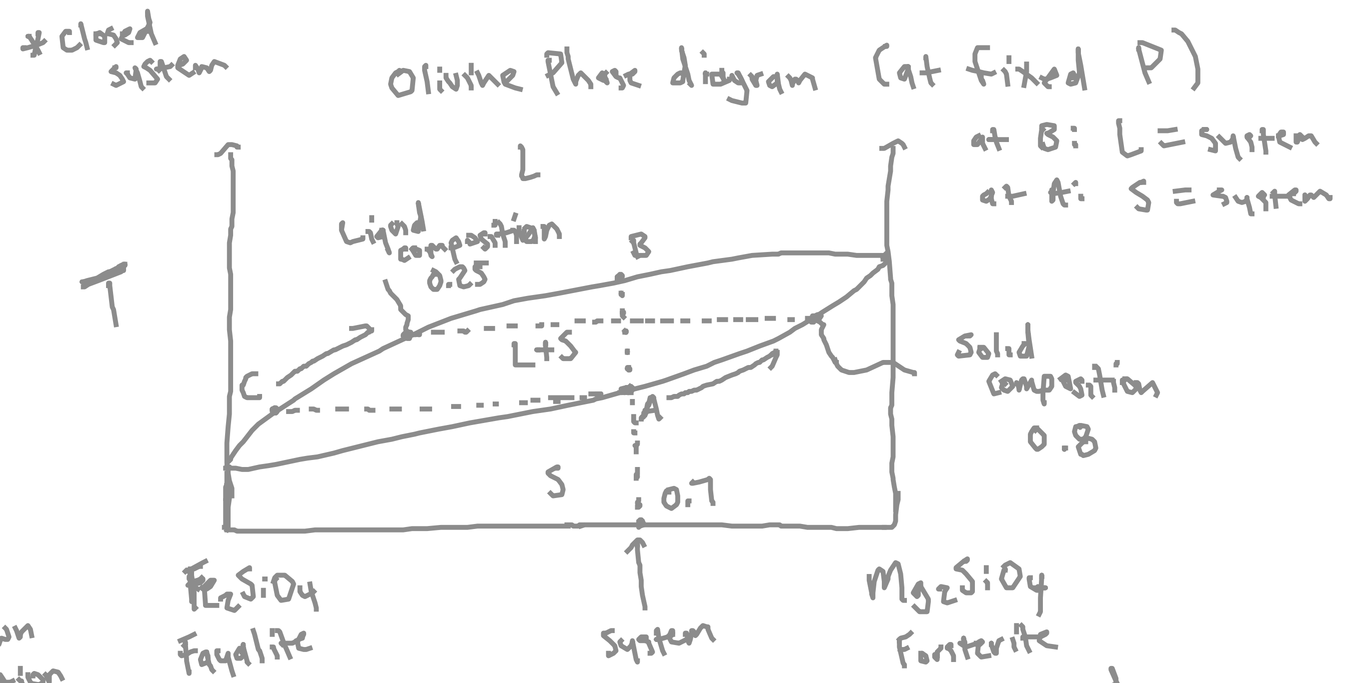
$$\text{Earth} \approx MgO + CaO + SiO_2 + Al_2O_3 + FeO$$

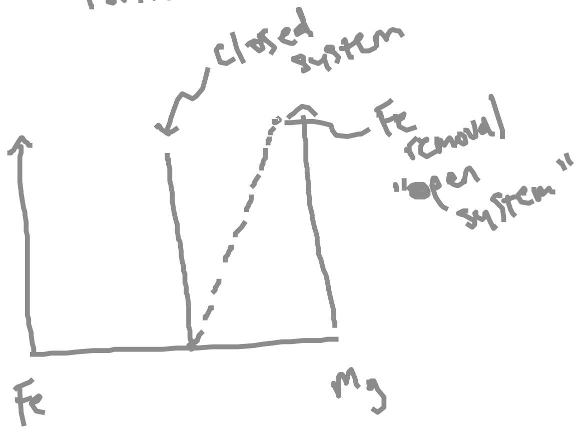
Forming the planets



Olivine Solid Solution Phase Diagram.







Lever Rule:
(mass balance)

unknown fraction

$\underline{a} \cdot L + \underline{b}\, S = \text{system}$

$a + b = 1$ mass balance

$b = 1 - a$

$a L + (1-a) S = \text{system}$

$a\, 0.25 + (1-a)\, 0.8 = 0.7$