Lectures 1-5: the chemical composition of Earth

1. Introductions
    - A. Who am I?
    - B. Who are you?
2. Course structure
3. Making the Earth
    - A. Chemical composition of the solar system
    - B. Refractory and volatile elements
    - C. Lithophile and Siderophile
4. Primitive Mantle
    - A. Melting Olivine
    - B. Pyrolite model

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.

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    - I prefer Blake over Dr. Dyer or Professor Dyer

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- PhD at Princeton University 2010-2015
- Postdoc at LDEO (Columbia University) 2016-2019
- Started in SEOS at UVic in Nov 2019
- Fifth time teaching EOS 240
    - Also teach Advanced Sed/Strat, Marine Geology, and The Dynamic Earth

Research interests: the geologic history of climate and life

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Who are you?

Some optional prompts:

- Name
- Why are you here?
    - What program are you in and/or why?
    - What do you hope to learn in EOS 240?
    - What challenges do you anticipate?

Geochemistry: a *toolset* for investigating Earth systems

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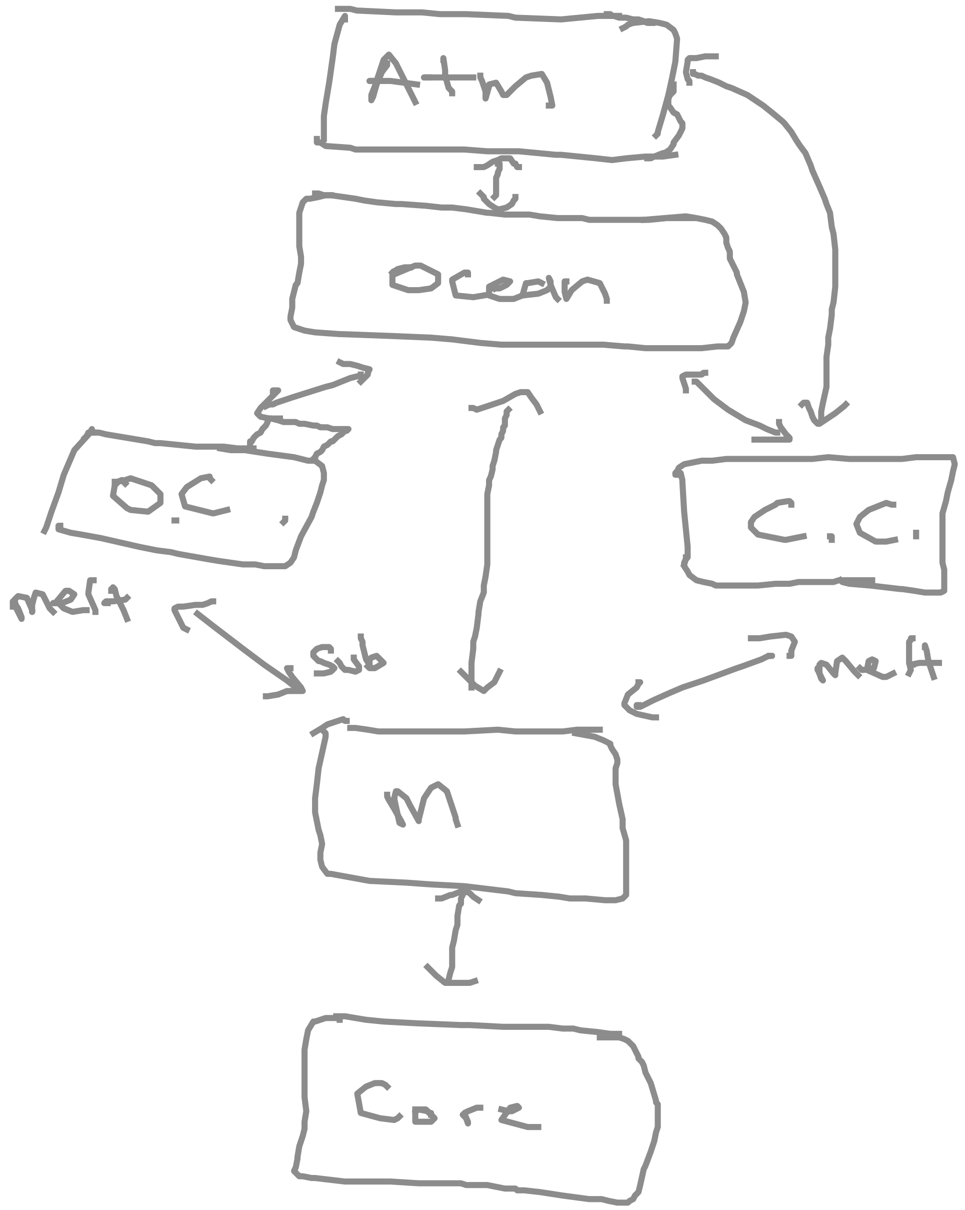
4. How has climate changed in the past?

Geochemistry: a *toolset* for investigating Earth systems

1. How and when did the Earth form?
2. What about the continents?
3. When did life on Earth begin?
4. How has climate changed in the past?
5. Where should we look for habitable planets?

Schematic of Earth.

Core < inner / outer
Mantle
Crust < oceanic / continental
Oceans
Atmosphere

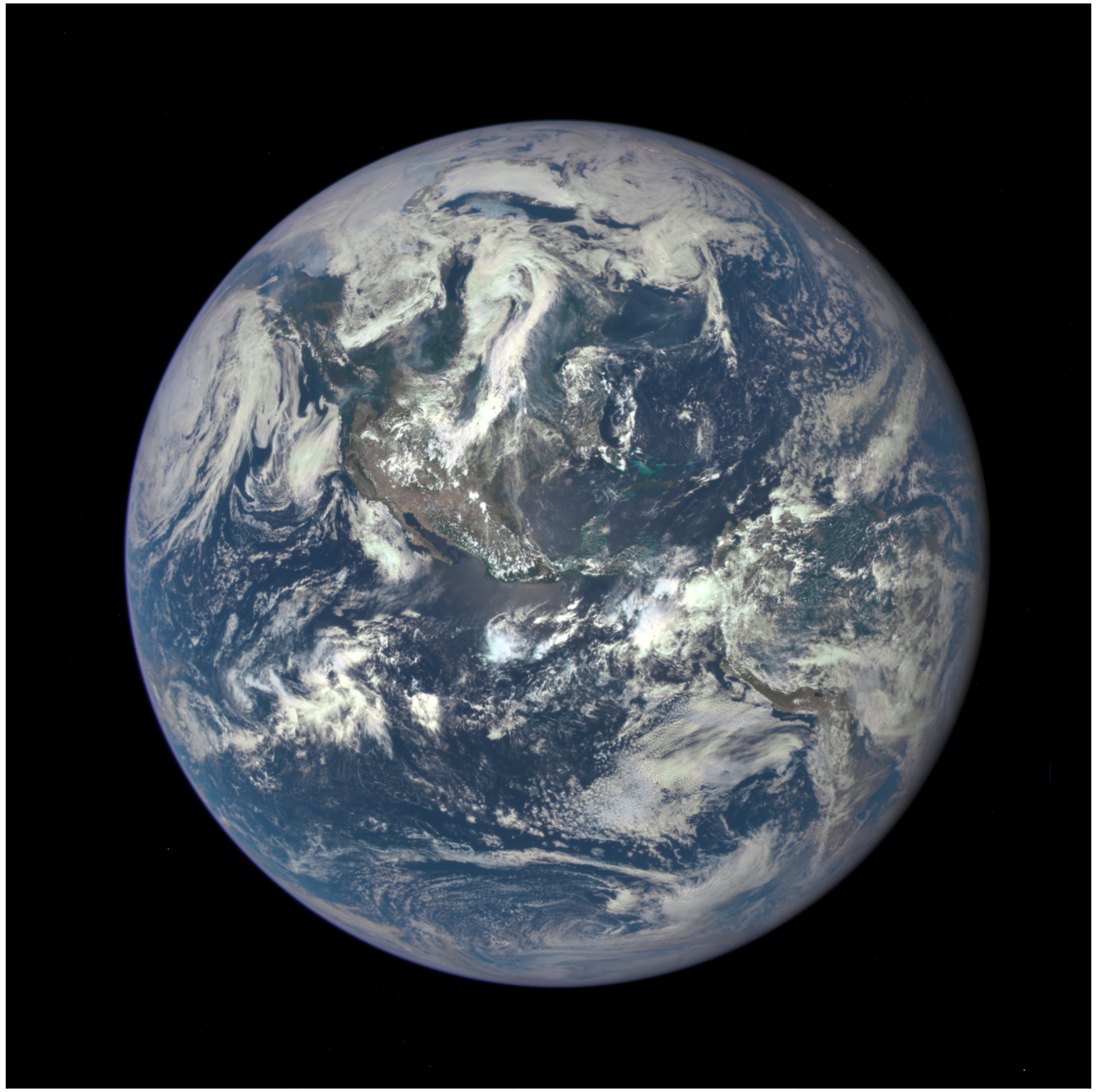


Bulk Earth

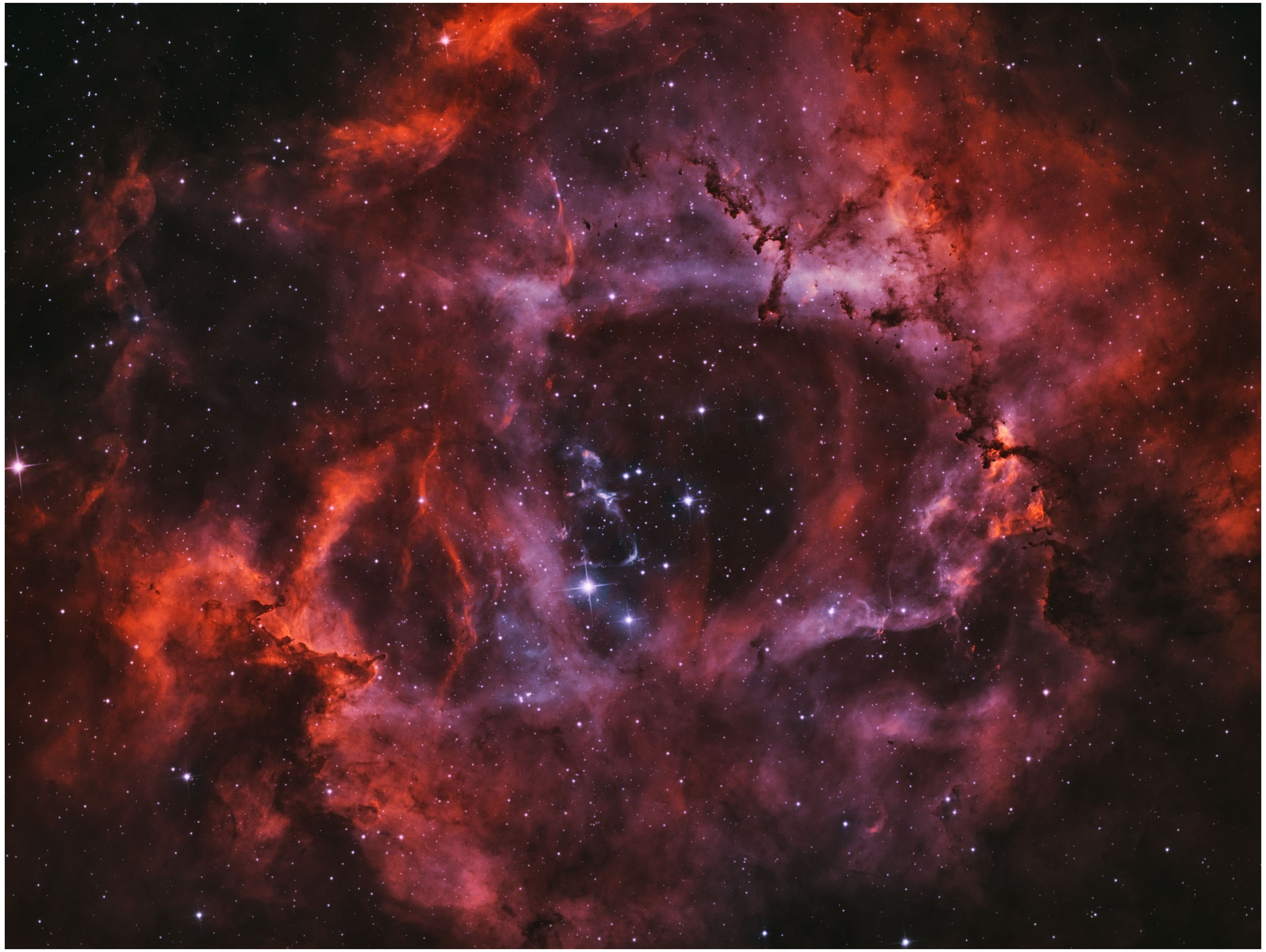
?

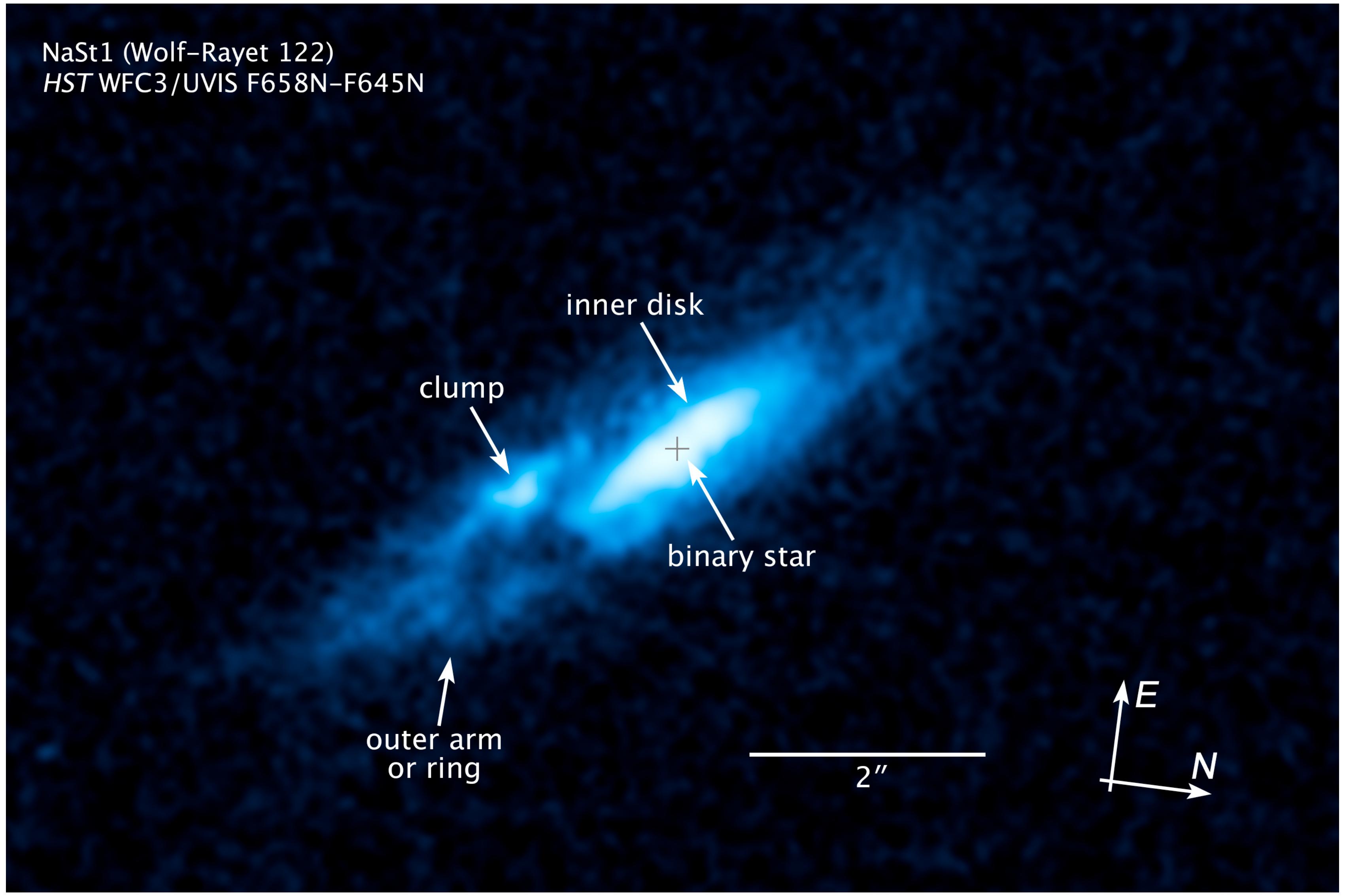
What is the chemistry of Bulk Earth

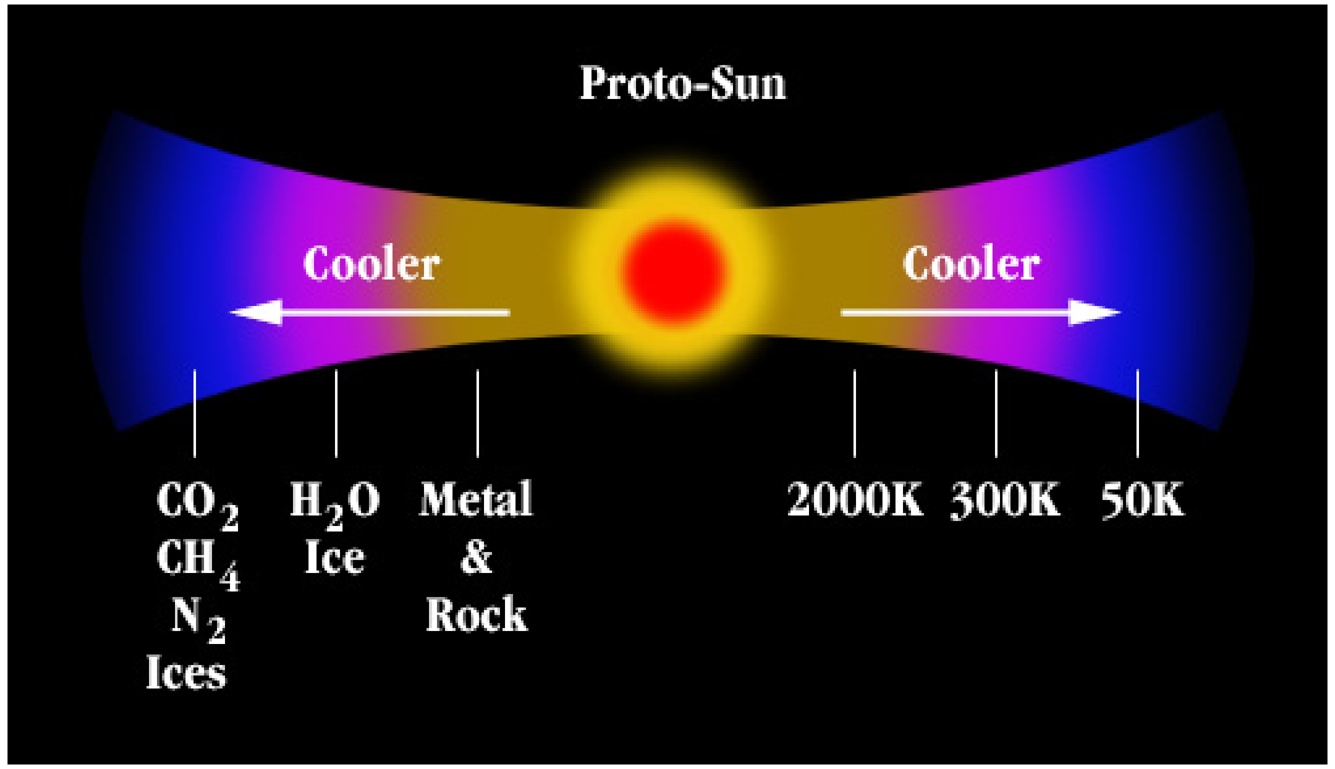
What is the chemical composition of Earth?



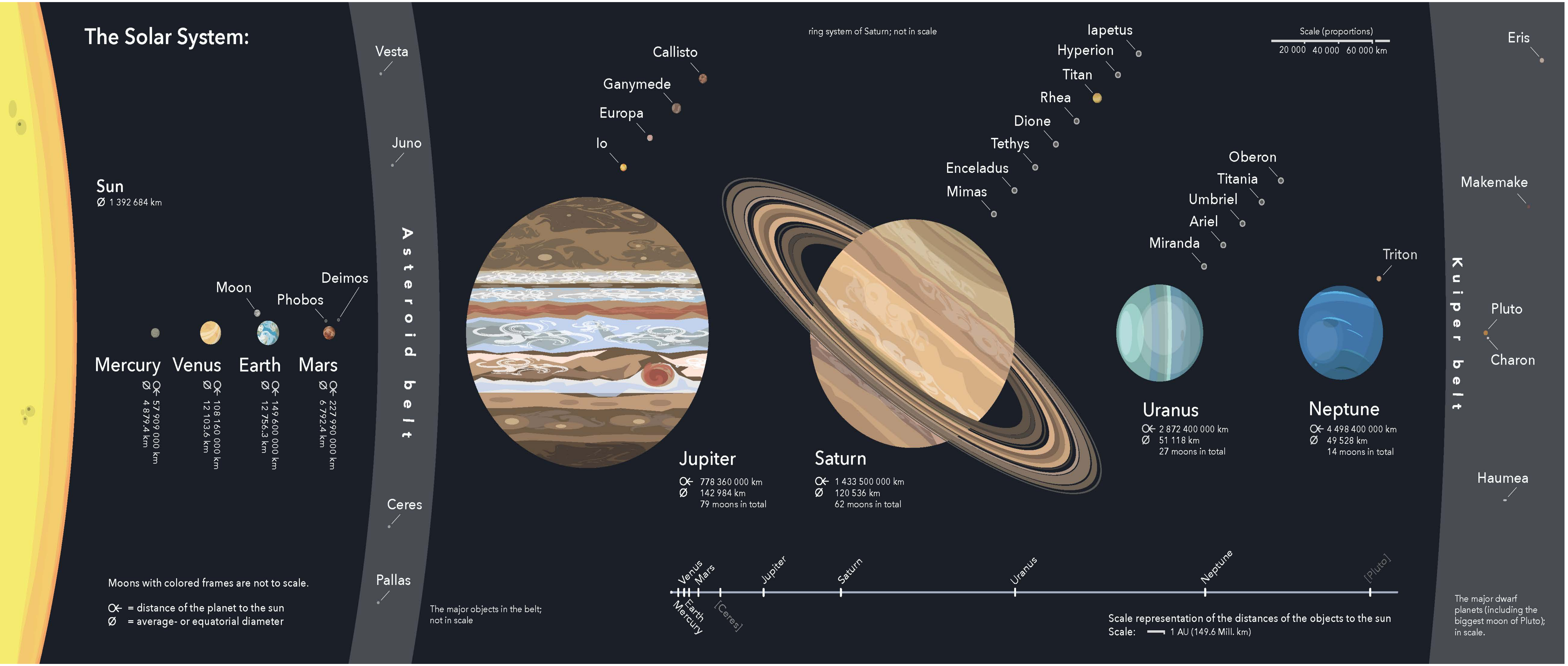
What is the black rock? What are the green bits?

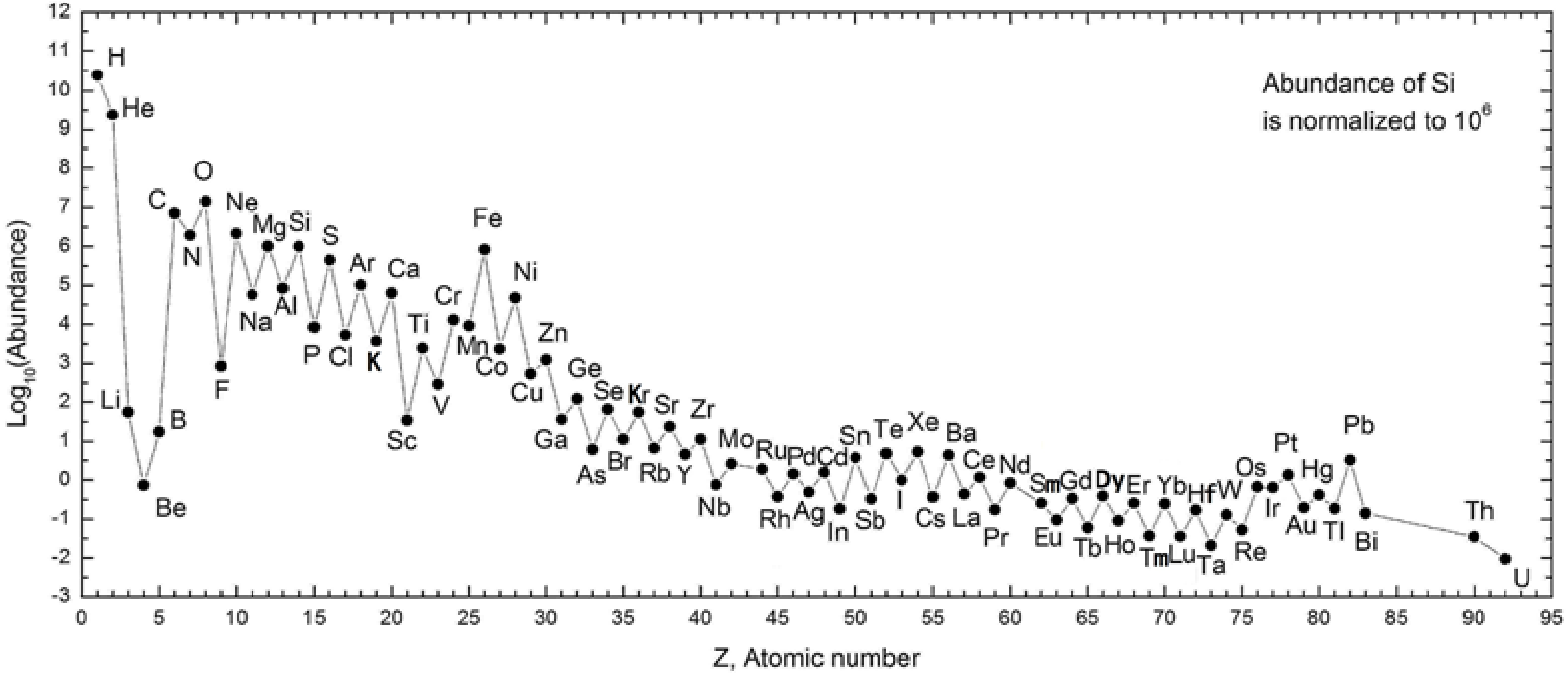



NaSt1 (Wolf-Rayet 122)
HST WFC3/UVIS F658N-F645N
inner disk
clump
binary star
outer arm
or ring
2″
E
N



The hot disk begins to emit radiation to space, rapidly cools, and a temperature gradient develops.


The Solar System:
Sun
Ø 1 392 684 km
Mercury
57 909 000 km
4 879.4 km
Venus
108 160 000 km
12 103.6 km
Earth
149 600 000 km
12 756.3 km
Mars
227 990 000 km
6 792.4 km
Moon
Phobos
Deimos
Moons with colored frames are not to scale.
= distance of the planet to the sun
Ø = average- or equatorial diameter
Vesta
Juno
Asteroid belt
Ceres
Pallas
The major objects in the belt; not in scale
Callisto
Ganymede
Europa
Io
Jupiter
778 360 000 km
Ø 142 984 km
79 moons in total
ring system of Saturn; not in scale
Iapetus
Hyperion
Titan
Rhea
Dione
Tethys
Enceladus
Mimas
Saturn
1 433 500 000 km
Ø 120 536 km
62 moons in total
Oberon
Titania
Umbriel
Ariel
Miranda
Uranus
2 872 400 000 km
Ø 51 118 km
27 moons in total
Triton
Neptune
4 498 400 000 km
Ø 49 528 km
14 moons in total
Scale (proportions)
20 000 40 000 60 000 km
Venus Mars Jupiter Saturn Uranus Neptune [Pluto]
Mercury Earth [Ceres]
Scale representation of the distances of the objects to the sun
Scale: 1 AU (149.6 Mill. km)
Eris
Makemake
Kuiper belt
Pluto
Charon
Haumea
The major dwarf planets (including the biggest moon of Pluto); in scale.



Abundance of Si
is normalized to 10^6
Log10(Abundance)
Z, Atomic number
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U

1905 - $e = mc^2$

mass deficit

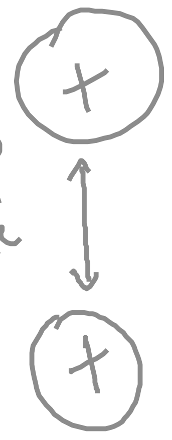
fusion

b.e. - binding energy

nuclear force

fusion

electro static force



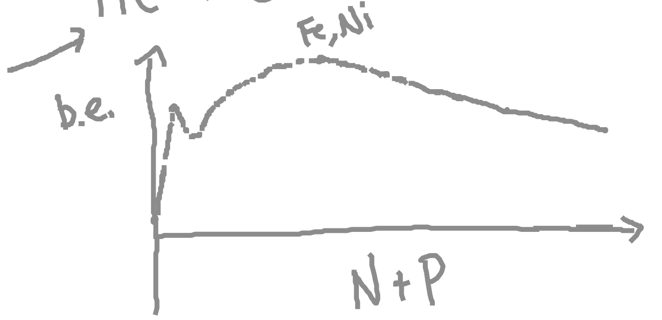
High T,P

$${}^2H + {}^2H \to {}^4He + e$$

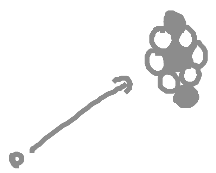
Supernova

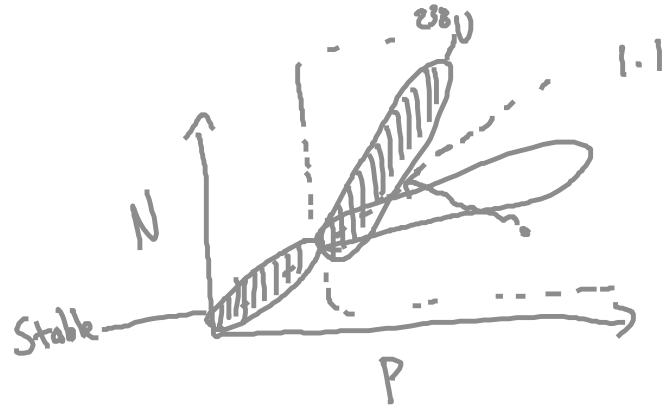
↳ r-process

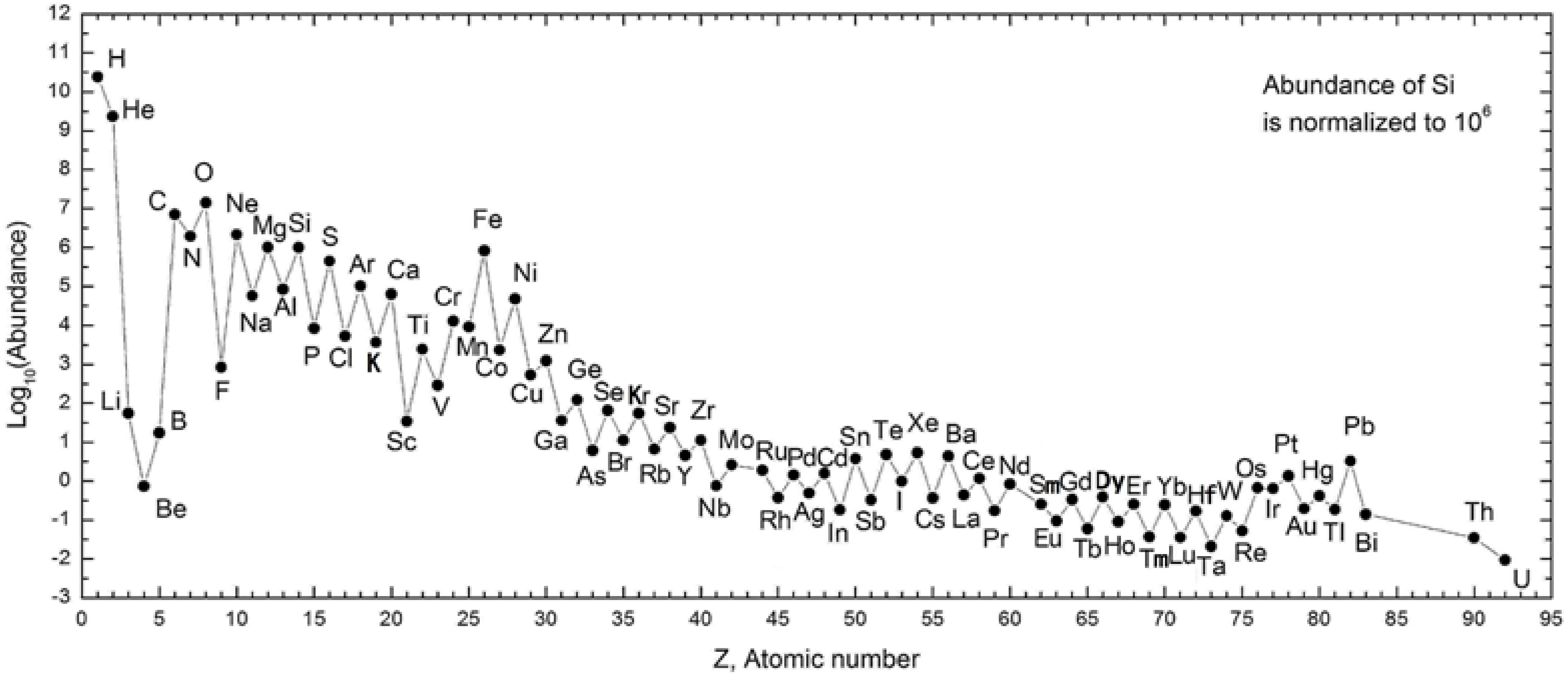
↳ s-process



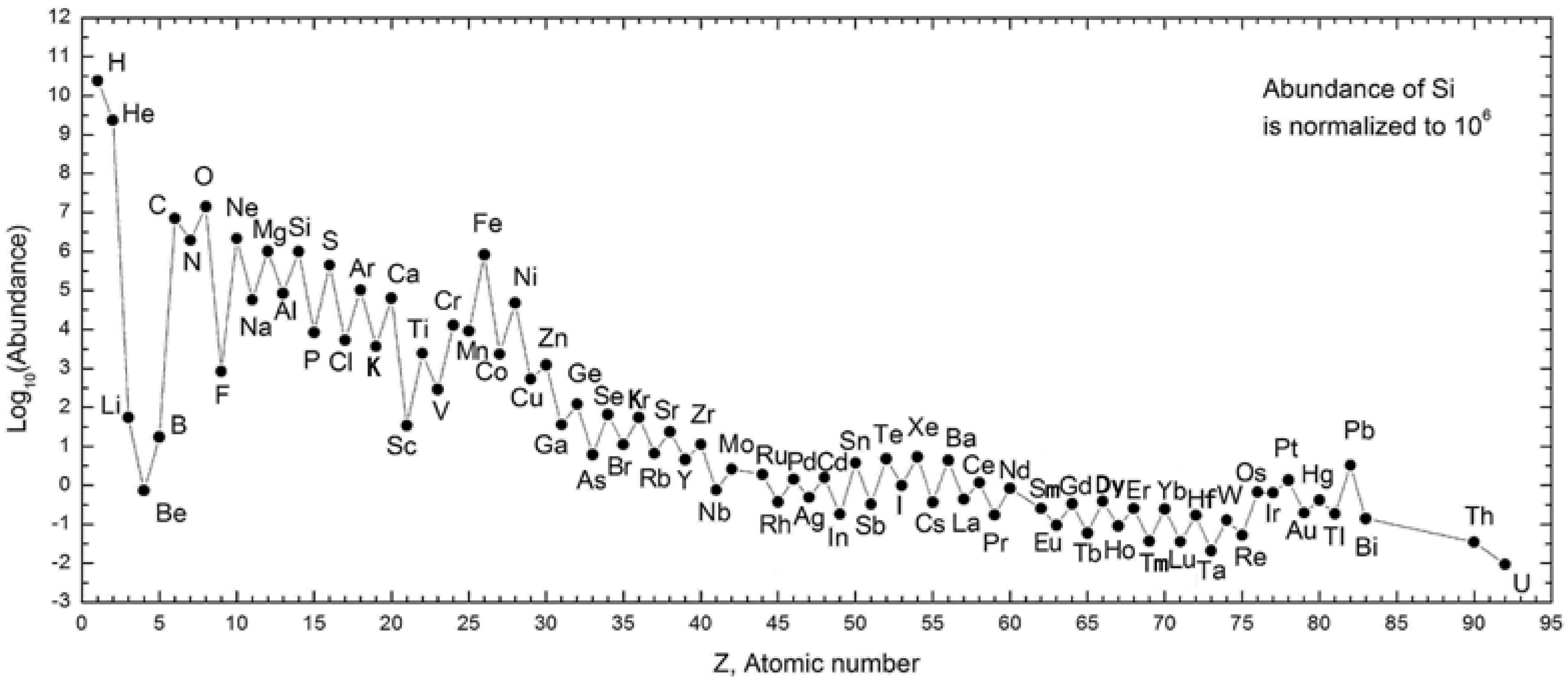
● - Proton



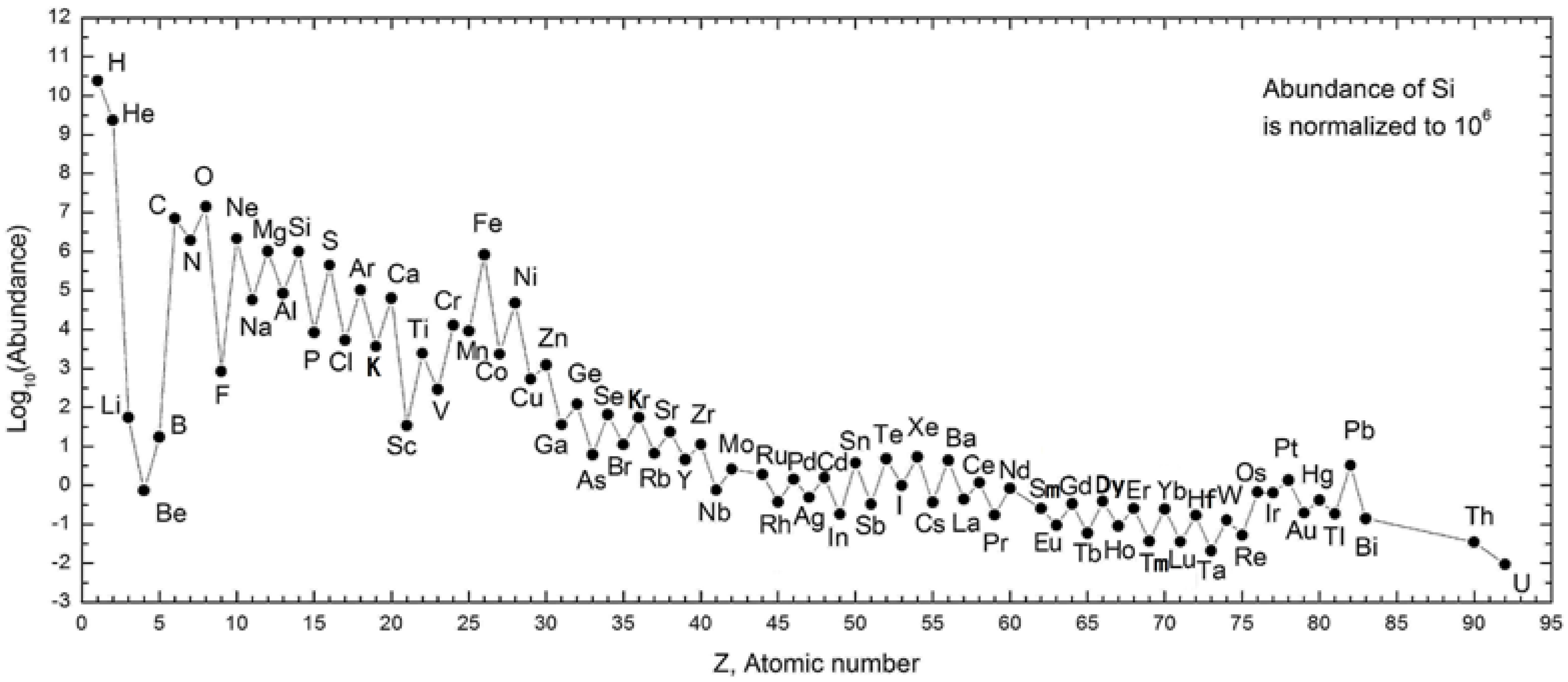




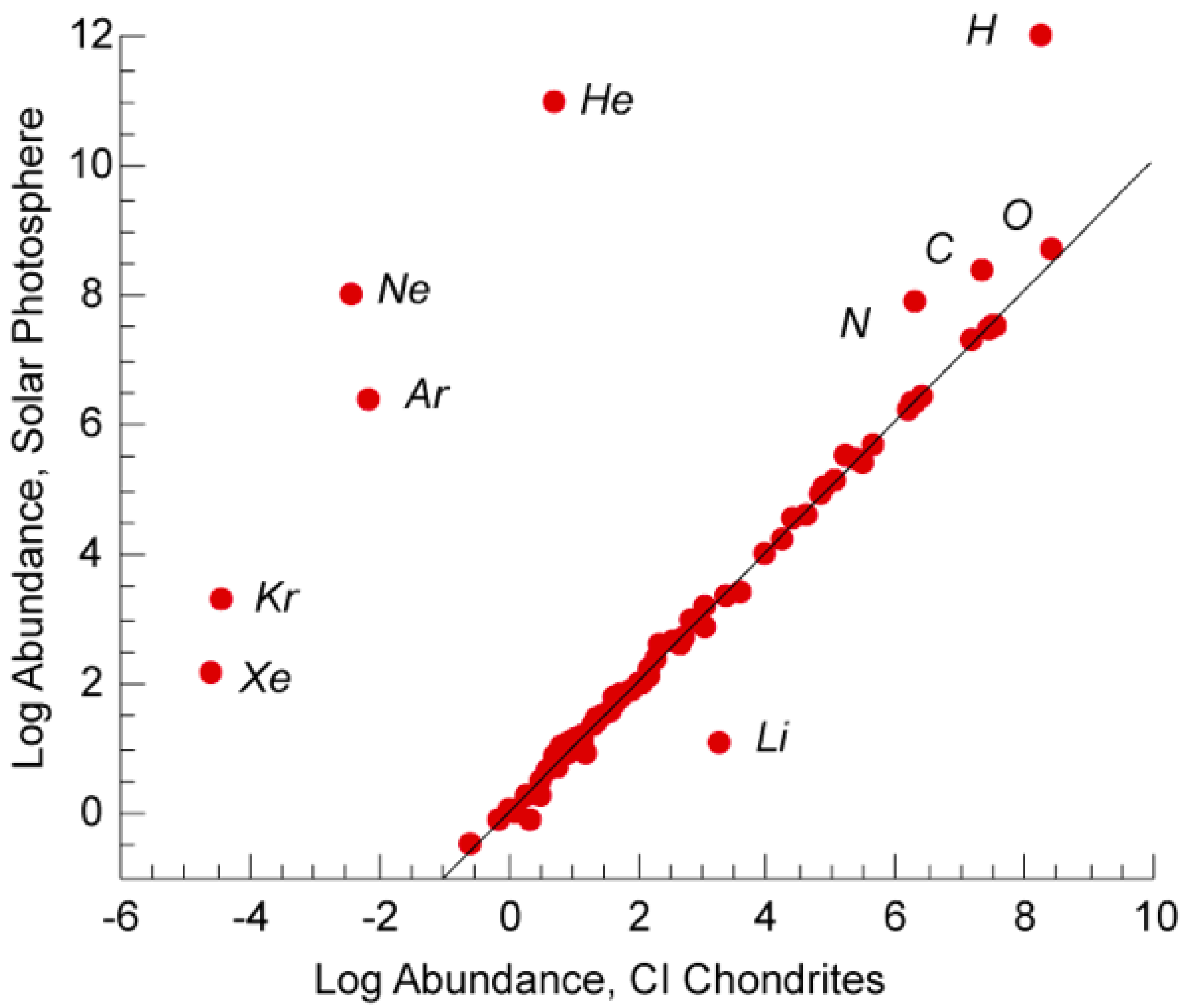
What are the major rock forming elements on Earth?



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

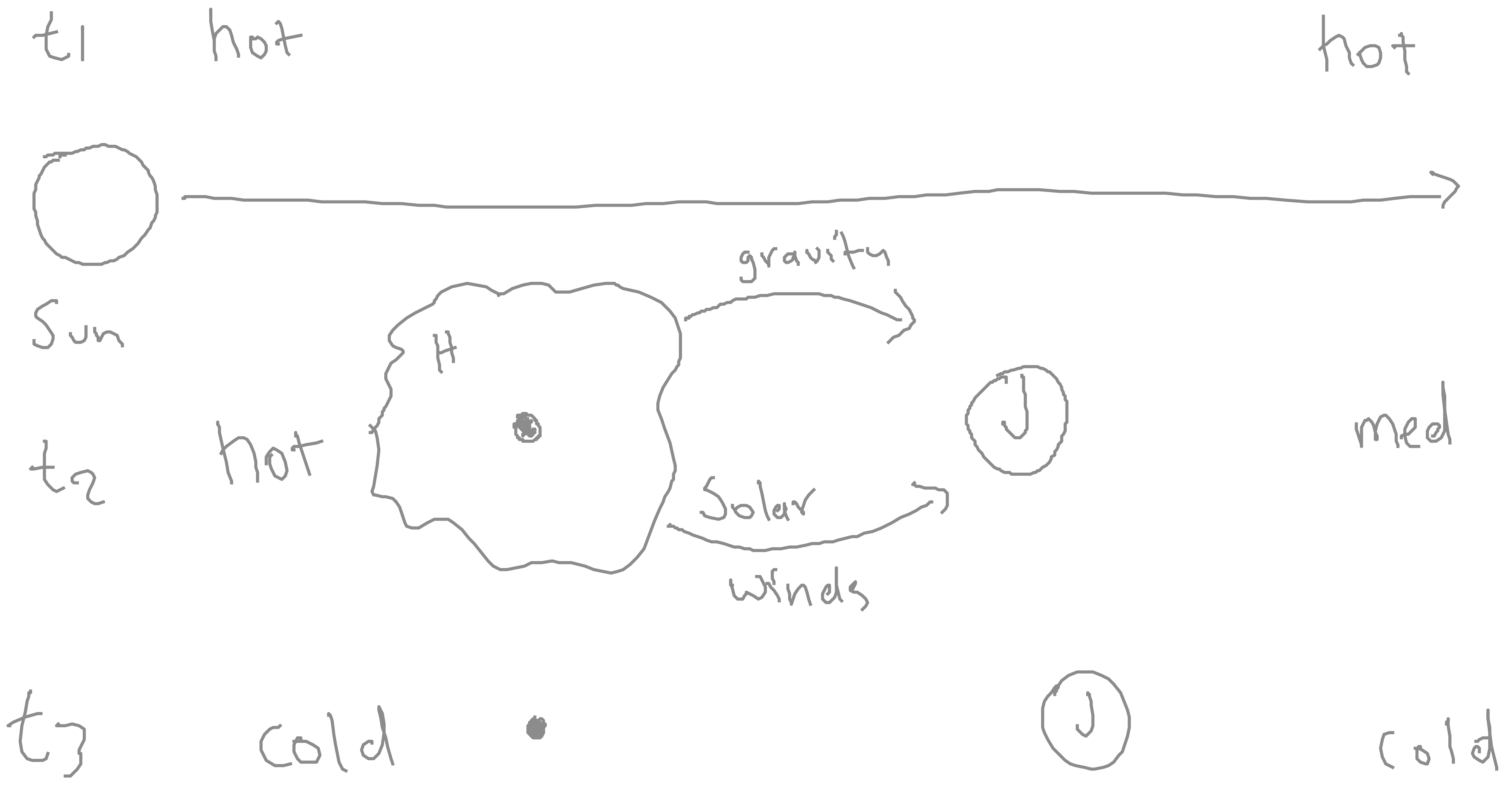


Should the Sun and Earth have the same chemistry? How could we check?



H
He
O
C
Ne
N
Ar
Kr
Xe
Li
12
10
8
6
4
2
0
-6
-4
-2
0
2
4
6
8
10
Log Abundance, Solar Photosphere
Log Abundance, CI Chondrites

Planetary Formation



Condensation sequence calculations

$PV = nRT$

$Al \xleftrightarrow[K_{eq}]{} AlH \xleftrightarrow[K_{eq}]{} AlF \leftrightarrow$

$> 2000\ K$

10^{-3} to 10^{-4} atm

Condensation of corundum

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

Mass action equation

$$Q_{RXN} = \frac{\{Al_2O_3\}}{\{Al\}^2\{O\}^3} = \frac{1}{\{Al\}^2\{O\}^3} = \frac{1}{P_{Al}^2 P_O^3}$$

Assume ideal gas

$\{X\} = P_X$

okay at high T, low P

Nebula chemistry = Sun

$P_H \approx P_T$

$P_{Al} = \frac{n_{Al}}{n_H} \cdot P_H$

solar abundance $\frac{P_X}{P_H} = \frac{n_X}{n_H}$

what partial pressure, T, do we reach equilibrium?

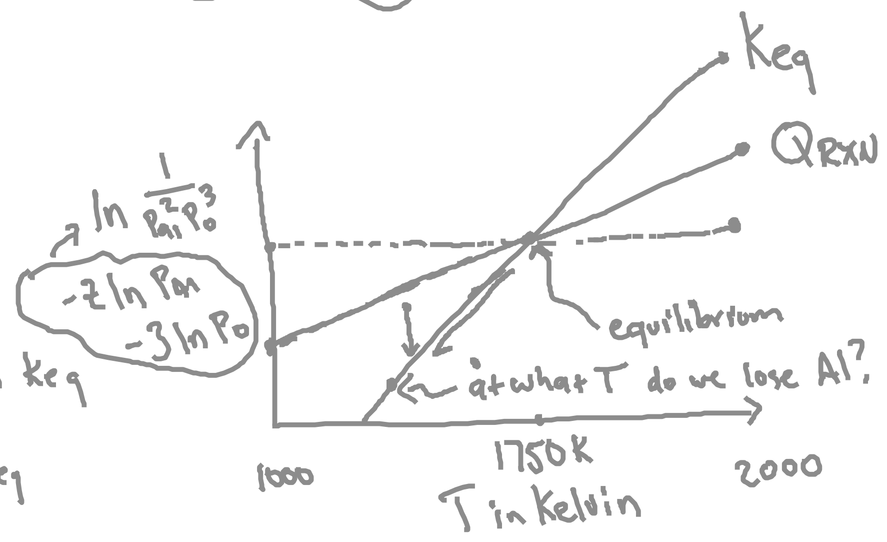
$$K_{eq} = \frac{1}{P_{Al}^2 P_O^3}$$

Gibb's free energy

$$\Delta G = 0 = -RT \ln K_{eq}$$

$$\Delta G = 0 = \Delta G_f^\circ + RT \ln K_{eq}$$

$$\Delta G_f^\circ = -\underbrace{R}_{\text{gas constant}}T \ln K_{eq}$$



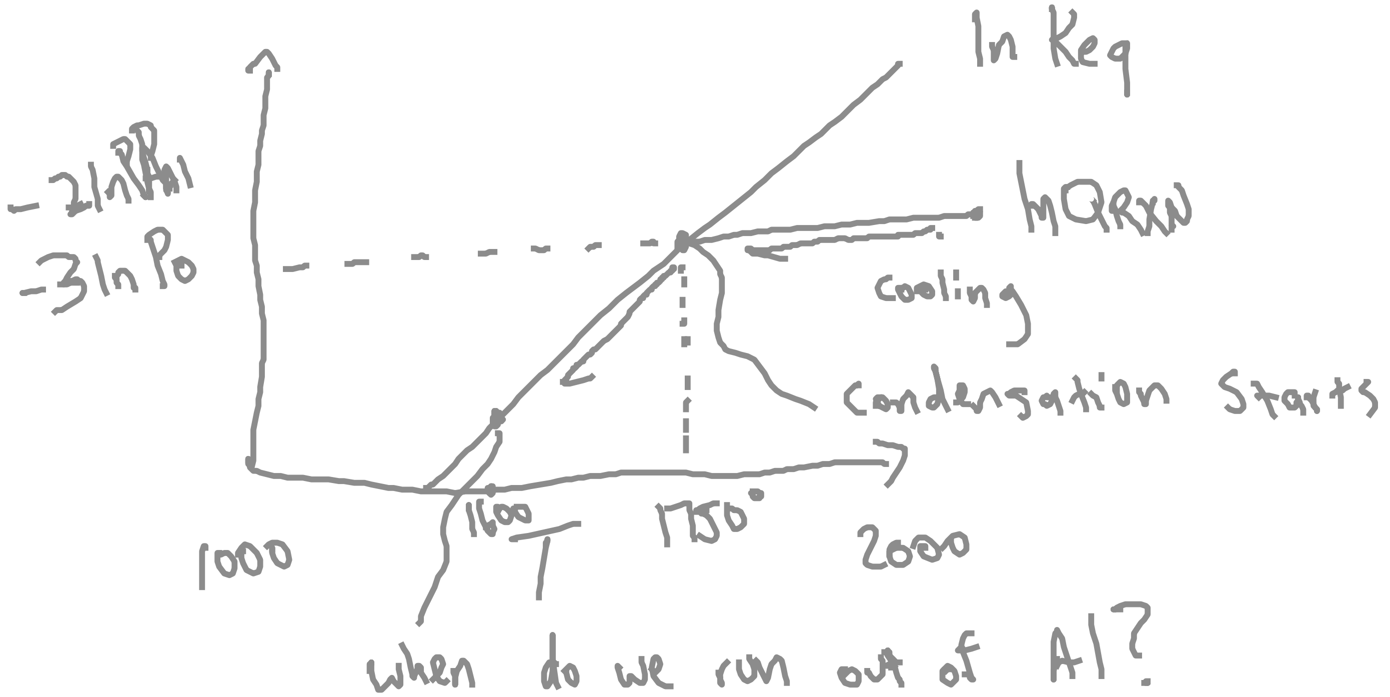
Condensation sequence calculations

$$\ln \frac{1}{P_{Al}^2} = -2 \ln P_{Al}$$

$$\Delta G = -RT \ln K_{eq}$$

$$e^{-\frac{\Delta G}{RT}} = K_{eq} = \frac{1}{P_{Al}^2 \, P_O^3}$$

$$2Al + 3O \longleftrightarrow Al_2O_3$$



P_{Al}° = starting P_{Al} in the nebula

$$2X = .99\, P_{Al}^{\circ}$$

$$e^{-\frac{\Delta G}{RT}} = \frac{1}{(P_{Al}^{\circ} - 2x)^2 (P_O^{\circ} - 3x)^3}$$

$$T \approx 1600 \text{ K}$$

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):

$$2\mathrm{Al} + 3\mathrm{O} \leftrightarrow \mathrm{Al_2O_3}$$

- Solar abundance (atoms) of Al: 8.51 x 10^4
- Solar abundance (atoms) of O: 2.36 x 10^7
- Solar abundance (atoms) of H: 2.6 x 10^{10}
- Pressure in the nebula: 10^{-3} atm
- Gas constant (R): 8.314 J/mol K
- ΔG° (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?

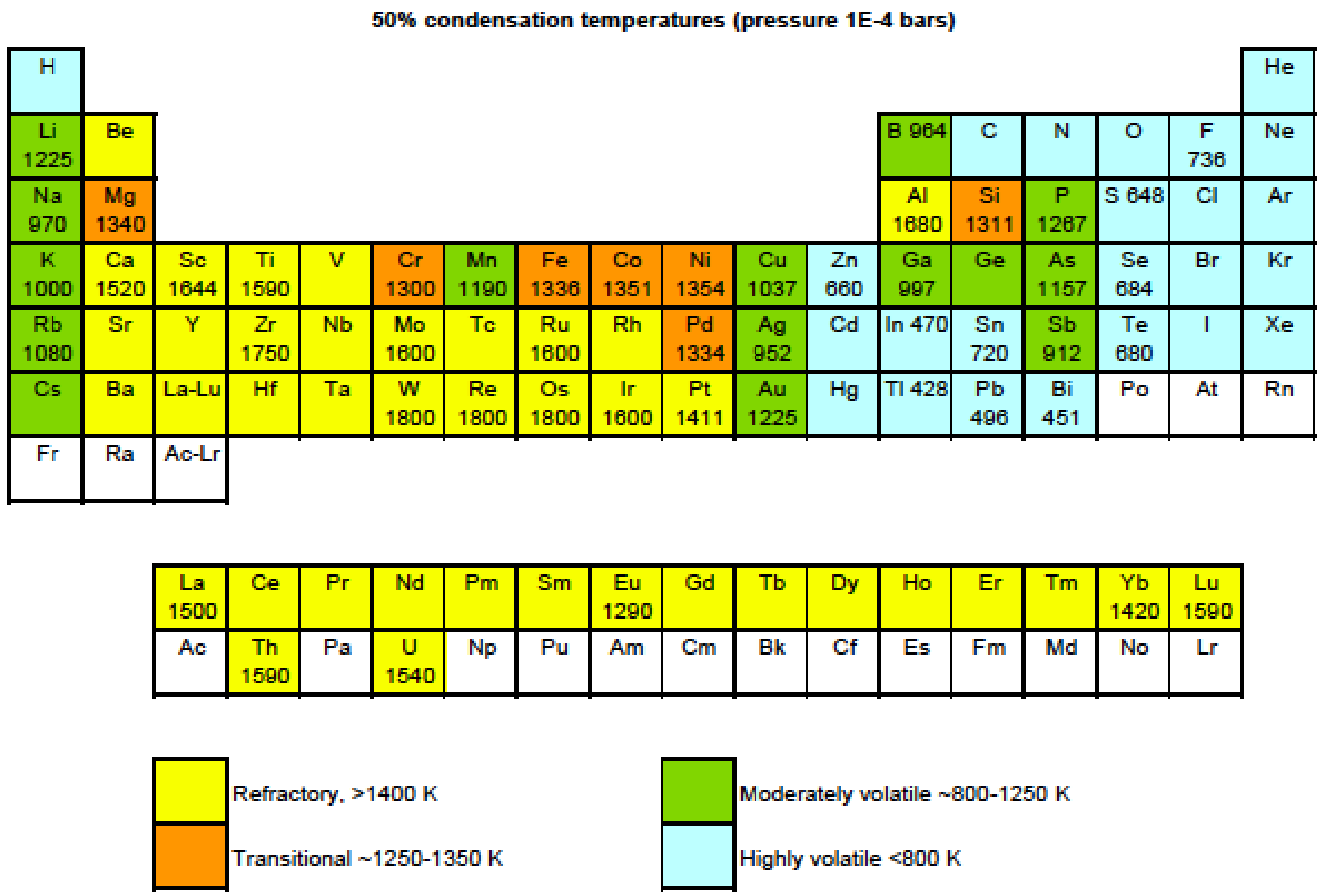


Figure 2.13. 50% condensation temperatures taken from [*Wasson*, 1985] and [*O'Neill and Palme*, 1998].

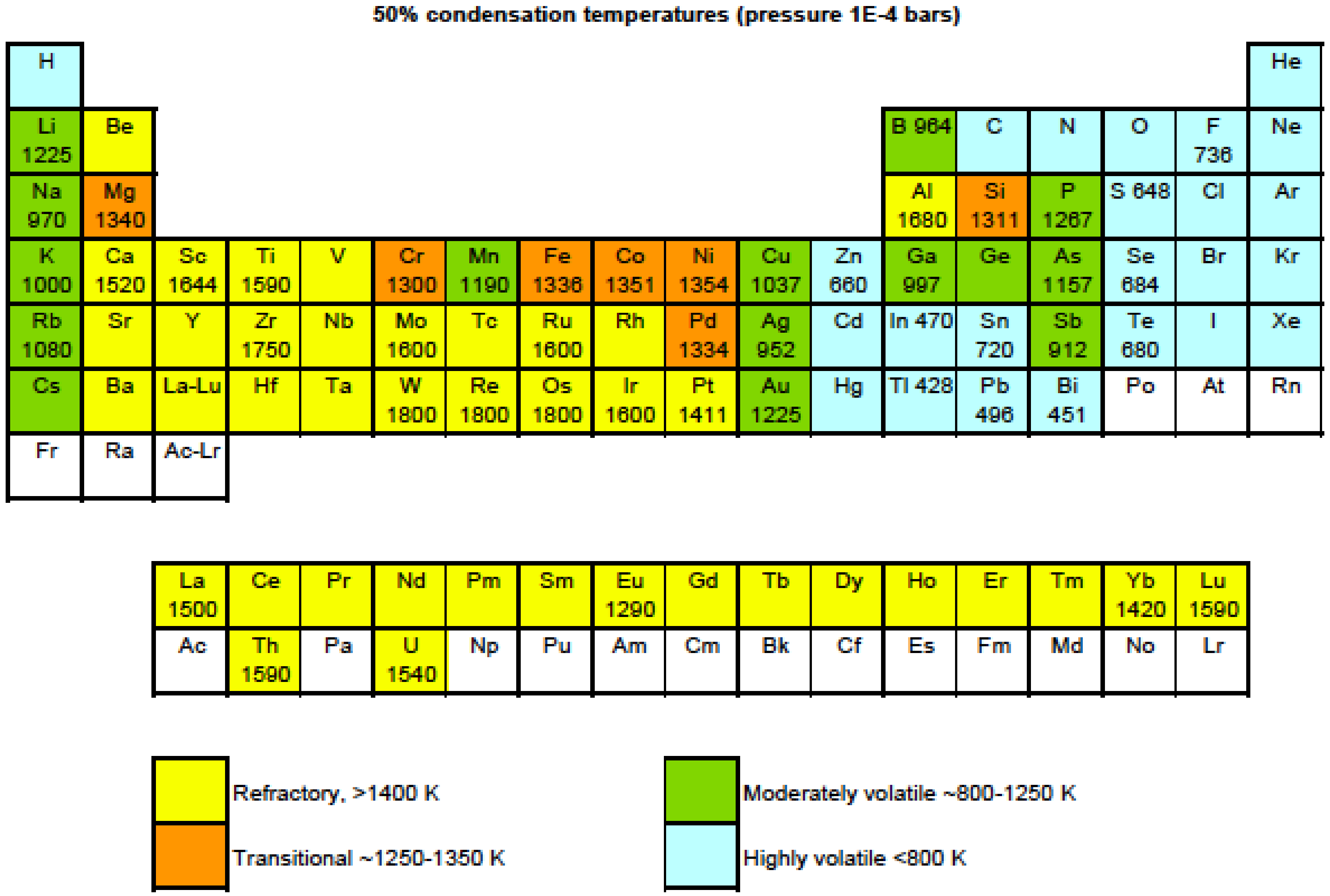


Figure 2.13. 50% condensation temperatures taken from [*Wasson*, 1985] and [*O'Neill and Palme*, 1998].

Recall: Earth ≈ $MgO + CaO + SiO_2 + Al_2O_3 + FeO$

In [1]:

```python
from IPython.display import HTML

HTML(
    """
<center>
<div align="middle;height:10vh;">
<video width="60%" controls>
      <source src="videos/planet_formation.mp4" type="video/webm">
</video></div></center>"""
)
```

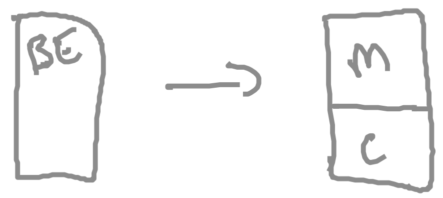
Out[1]:

Wt % Mg in MgO?

$$\frac{\text{Atomic Mass of Mg}}{\text{Atomic Mass of MgO}} \cdot 100$$

$$\frac{24.3}{24.3+16} \cdot 100 = \text{wt\% Mg in MgO}$$

$$\text{MgO wt\%} = \frac{\text{Mass MgO}}{\text{mass Bulk Earth}}$$

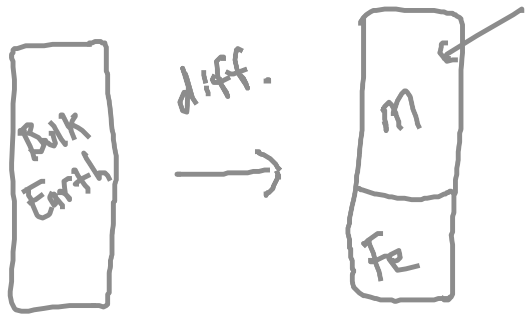


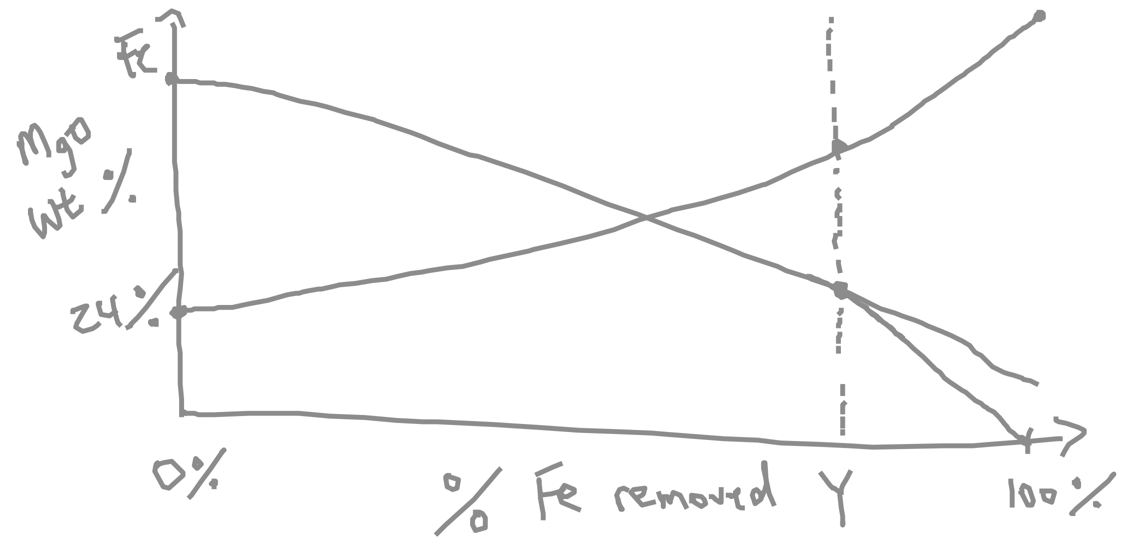
Solar abundance Mg

mass MgO/mol

$$\text{MgO wt \%} = \frac{104 \cdot 40.3}{104 \cdot 40.3 + 86 \cdot 72 + 100 \cdot 60 + 62 \cdot 56 + \frac{1}{2} \cdot 8.4 \cdot 102}$$

MgO FeO SiO_2 CaO Al_2O_3

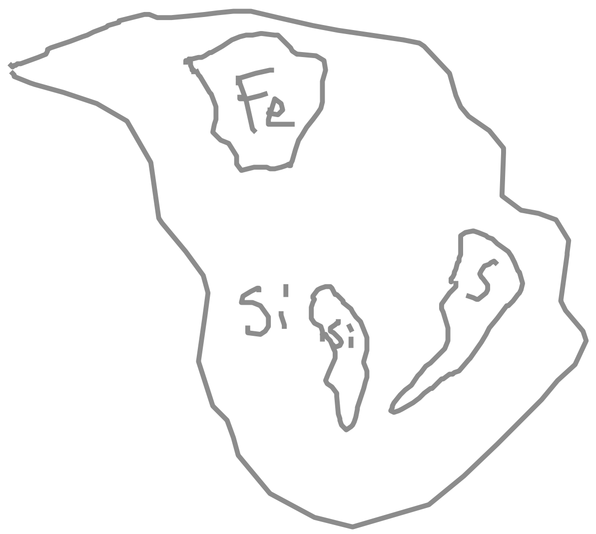




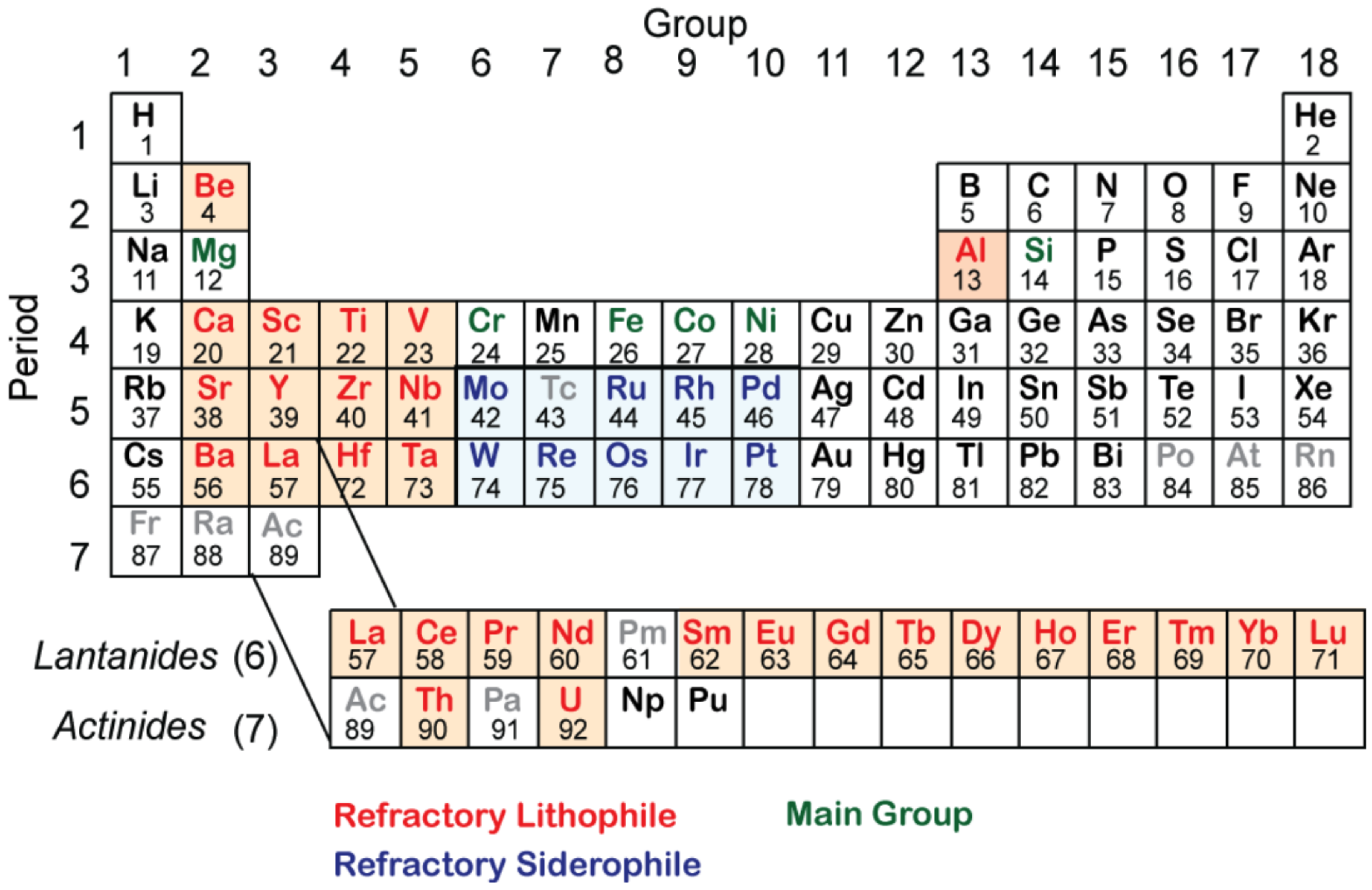
$86 \cdot (1 - x)$

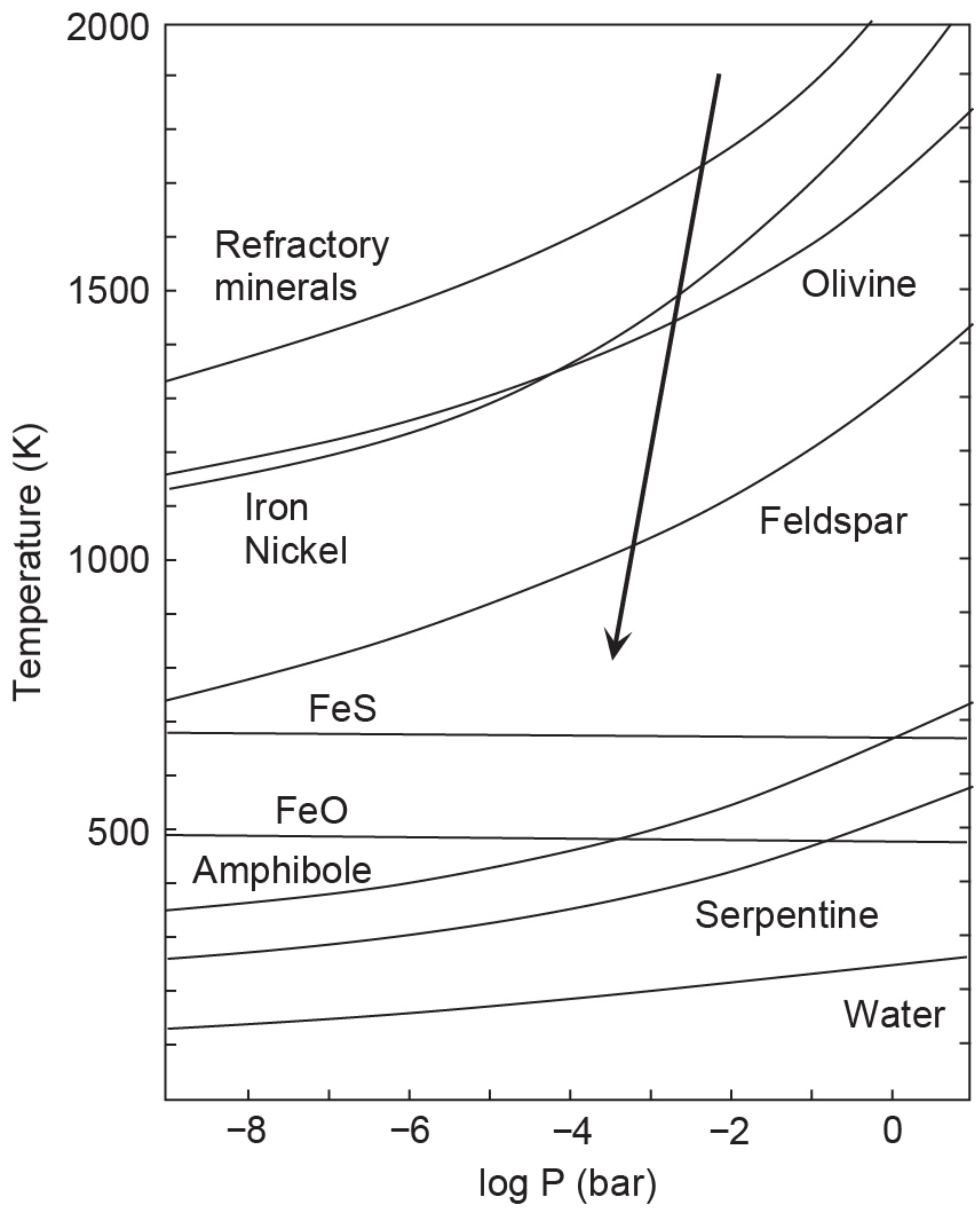
Define Goldschmidt classification.

Lithophile : rock-loving / silica loving
Siderophile : Fe-loving
Chalcophile : S-loving



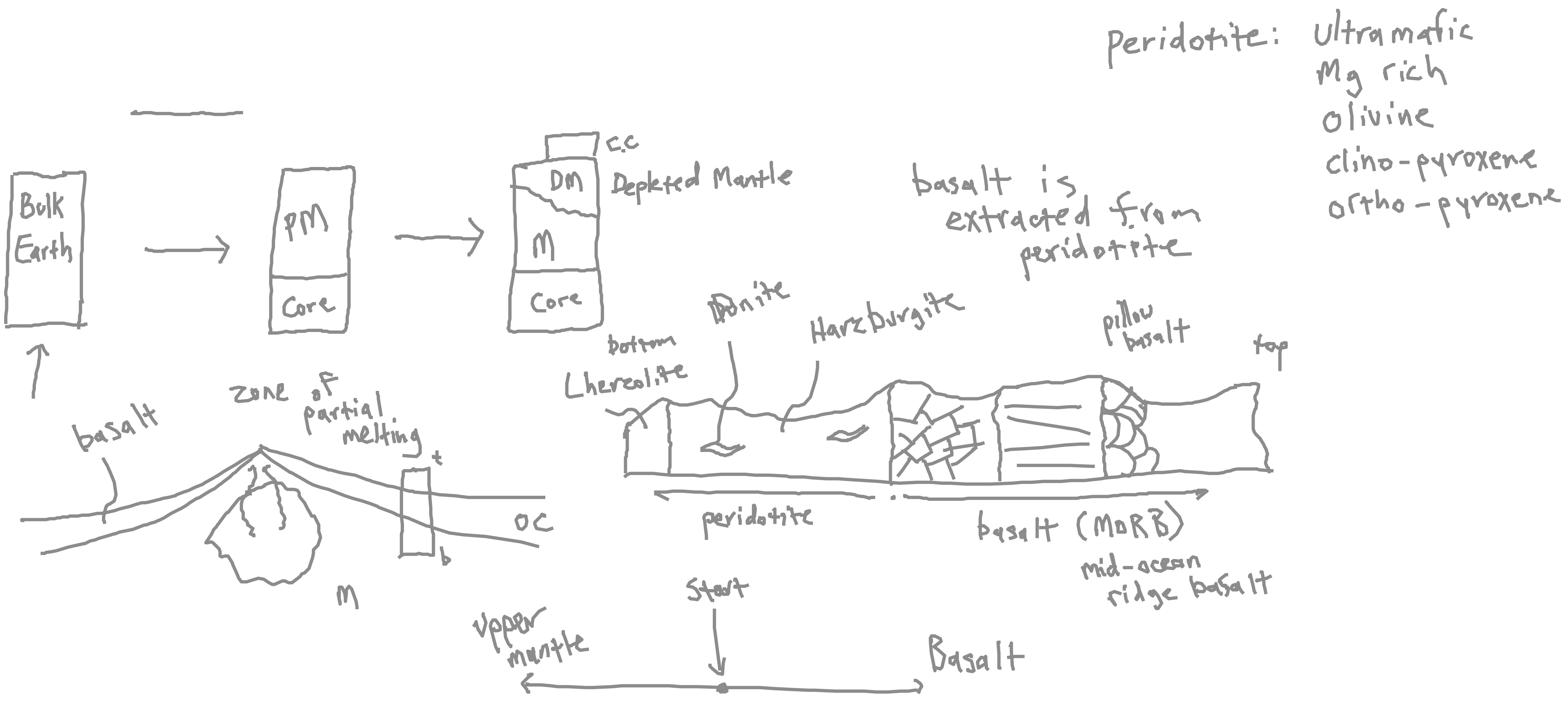
Define Goldschmidt classification.



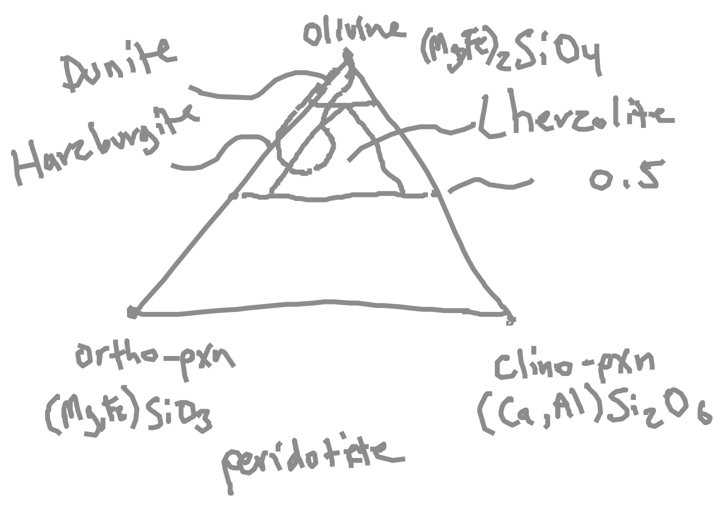


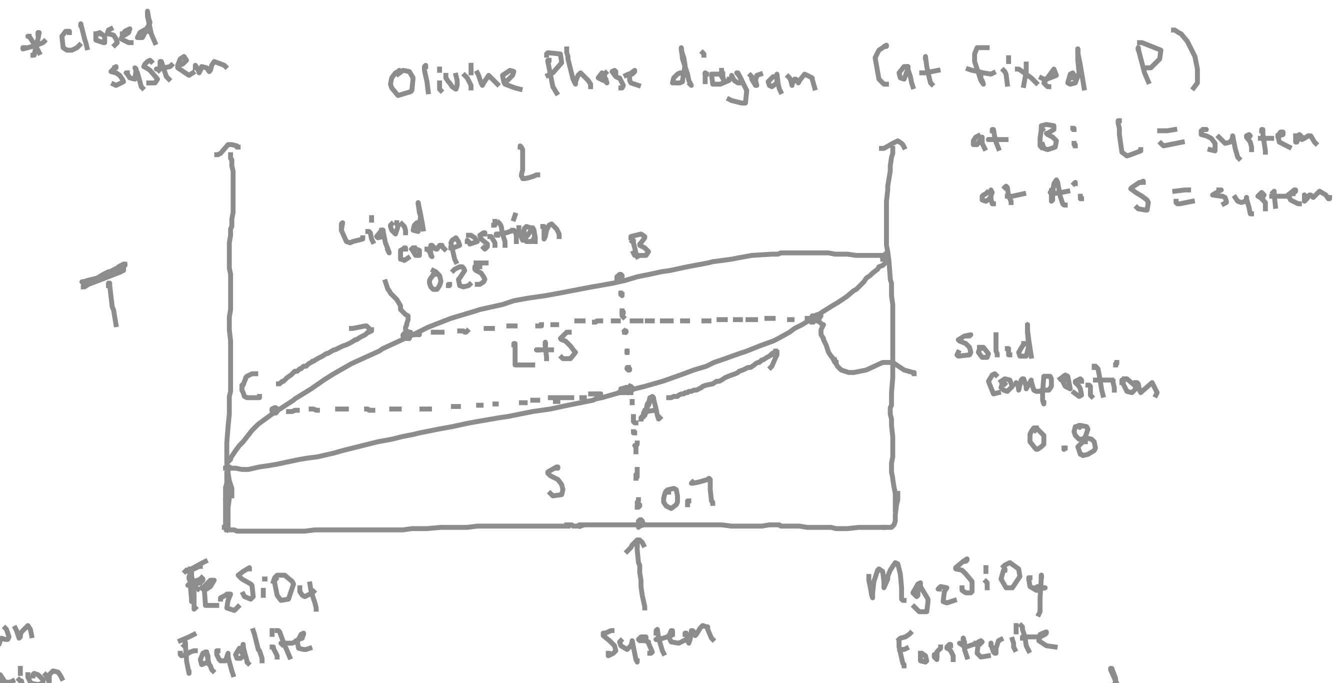
2000
1500
1000
500
Temperature (K)
Refractory
minerals
Olivine
Iron
Nickel
Feldspar
FeS
FeO
Amphibole
Serpentine
Water
−8
−6
−4
−2
0
log P (bar)

Define Primitive Mantle. What do we know about the modern mantle?



Olivine Solid Solution Phase Diagram.





Lever Rule:
(mass balance)

unknown fraction

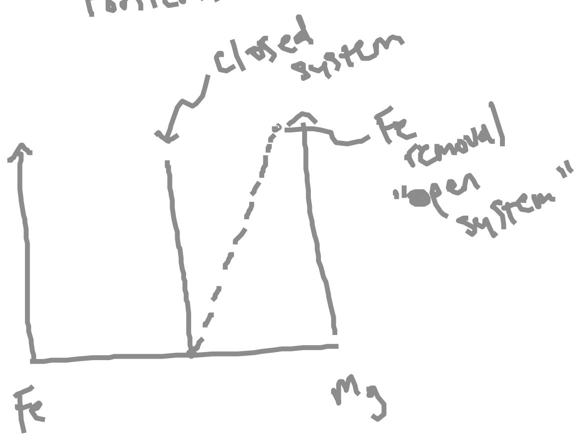
$\underline{a} \cdot L + \underline{b}\, S =$ system

$a + b = 1$ mass balance

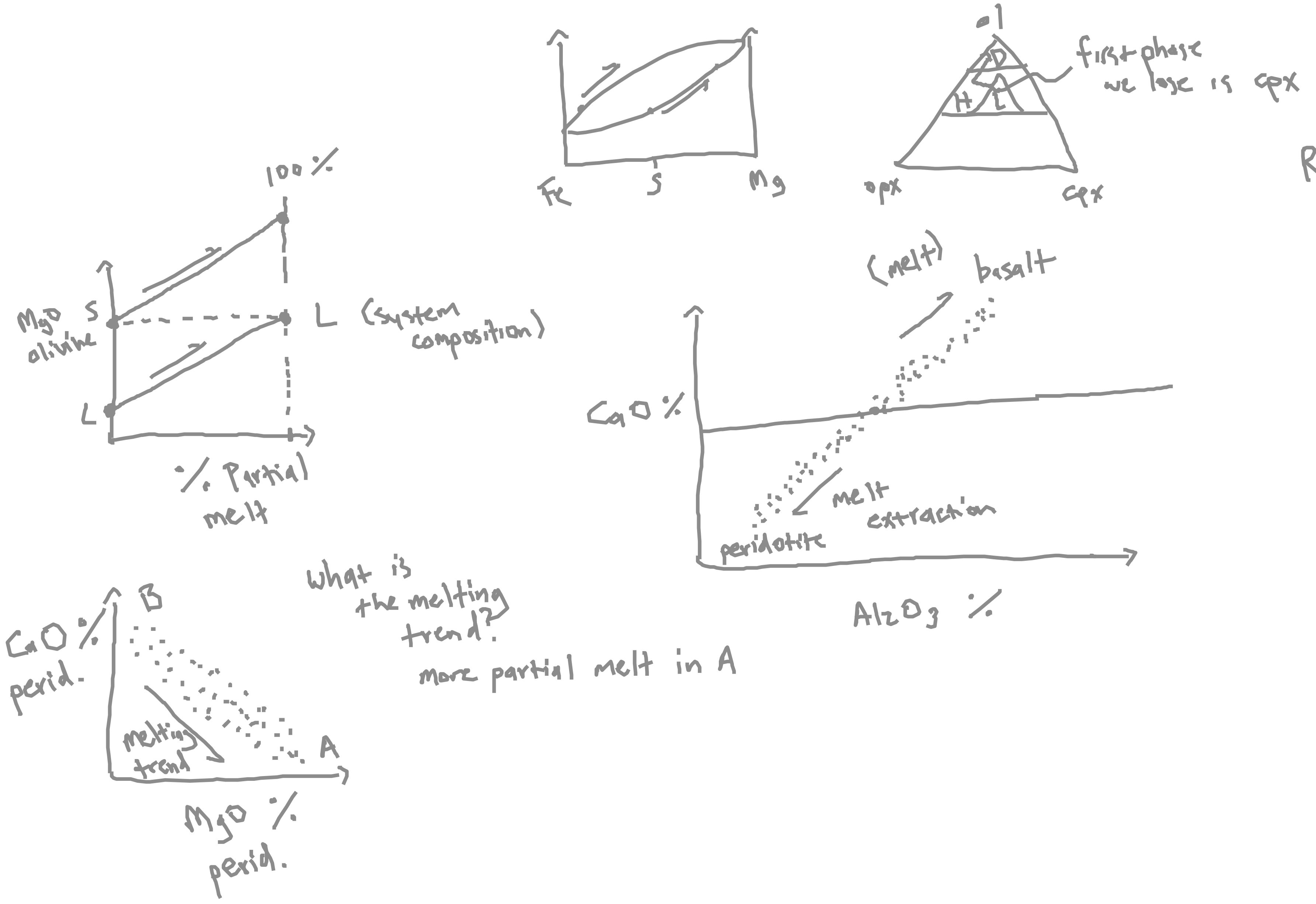
$b = 1 - a$

$aL + (1-a)S =$ system

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

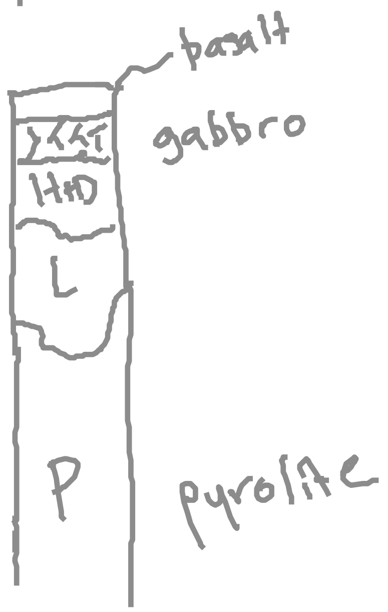


Melting trends.



RLE: Refractory lithophile element

Pyrolite Model

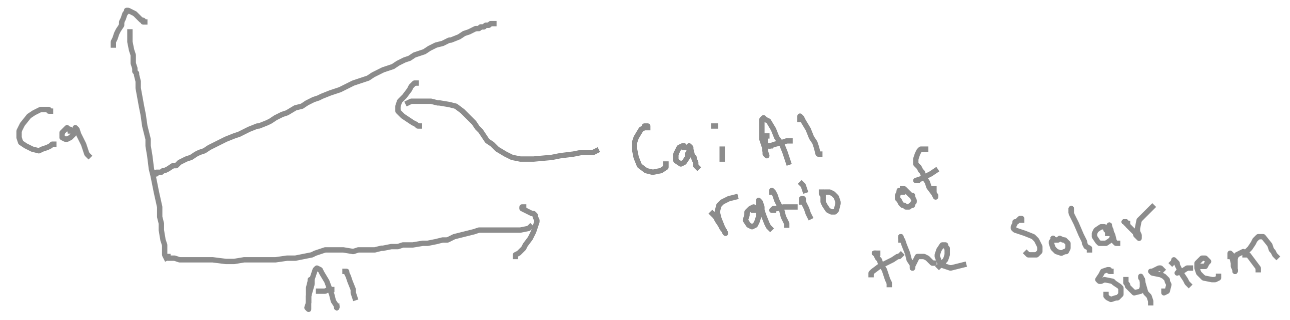


how can we estimate these coefficients

pyrolite = $\underline{a}$ MORB + $\underline{b}$ DUNITE

$a + b = 1$ (mass balance)

1. make an assumption about pyrolite

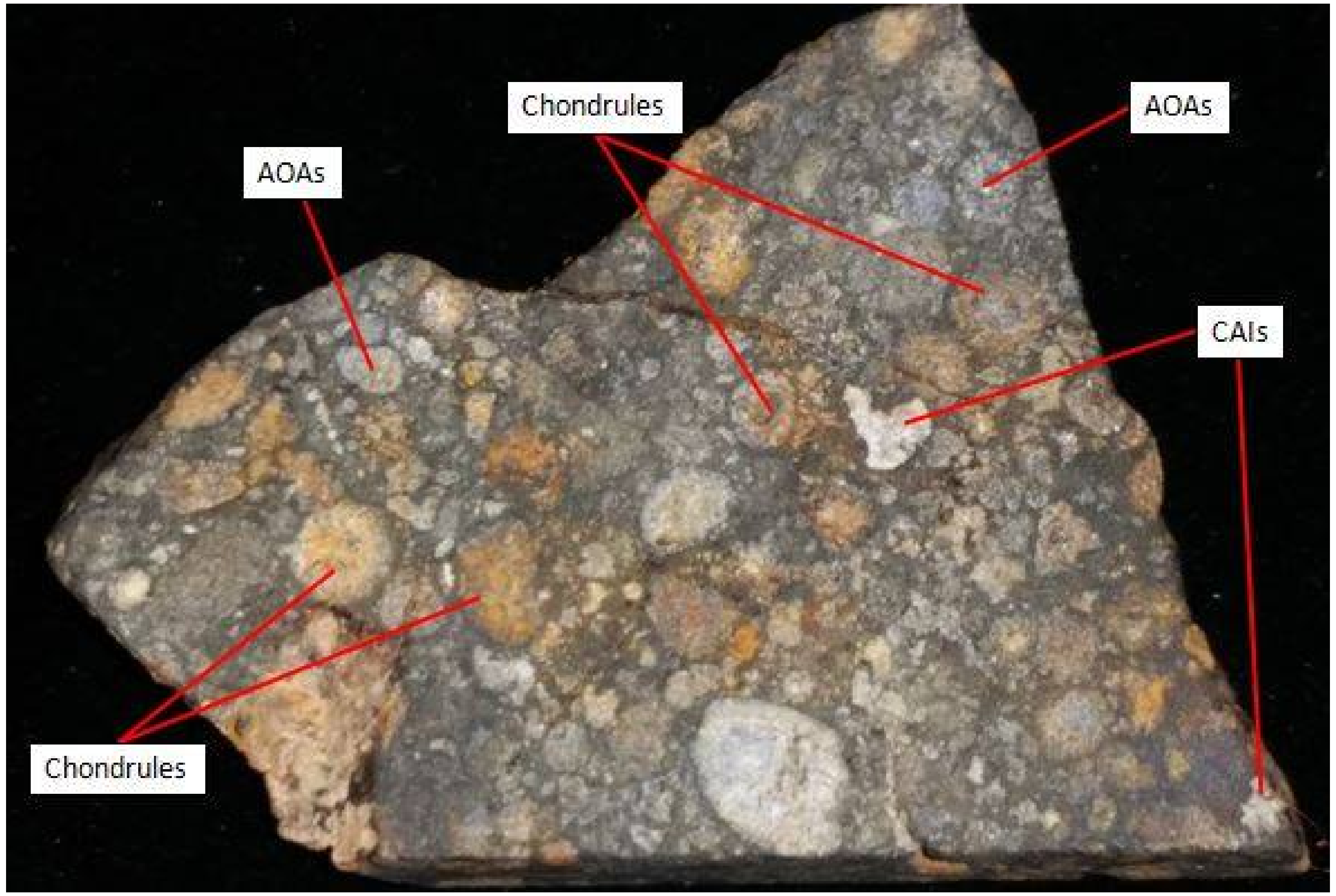


why Ca:Al?

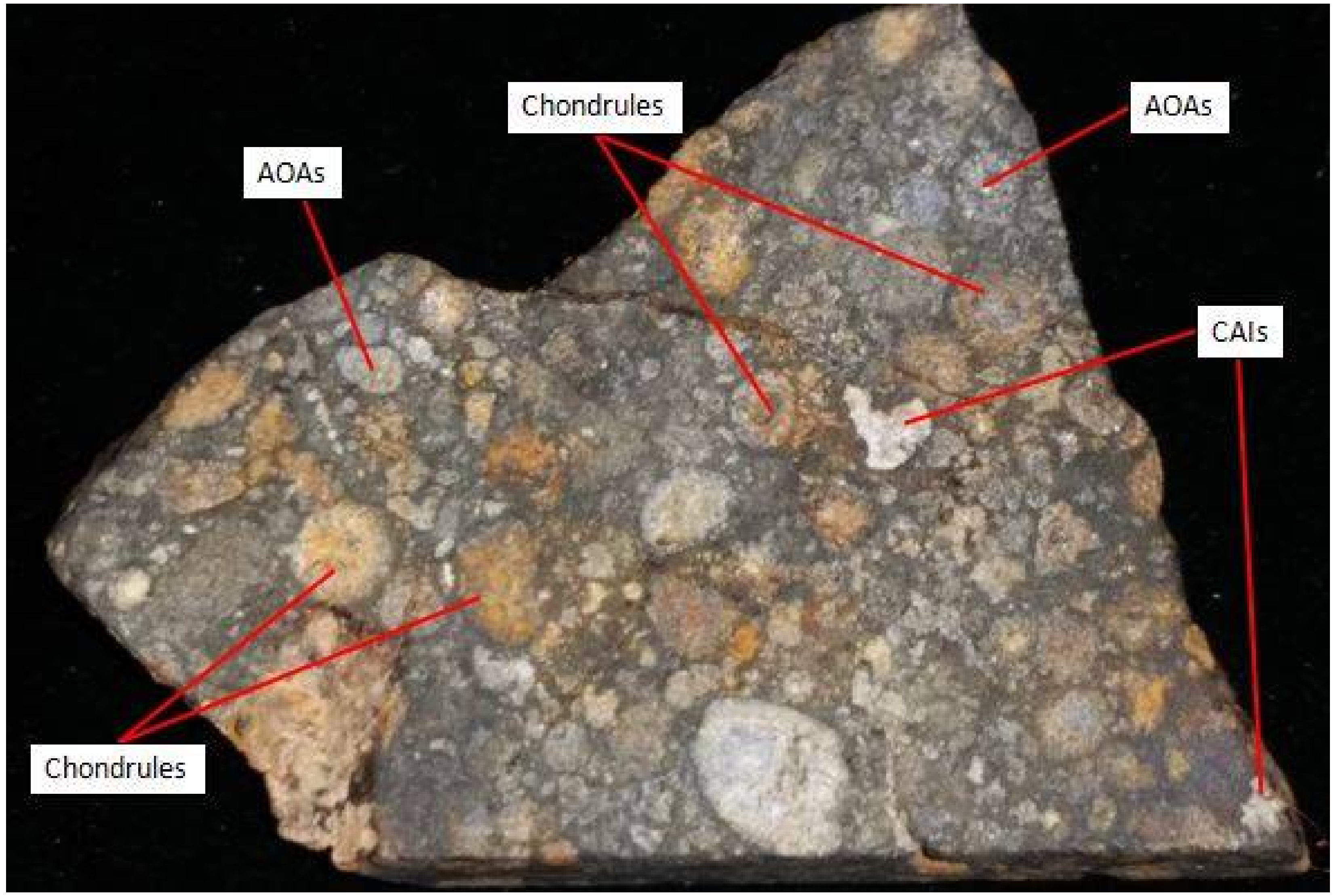
- Refractory
- Lithophile
- Major elements

Pyrolite Model: Ringwood, A.E., 1962. **A model for the upper mantle**. *Journal of Geophysical Research*.

Chondrites



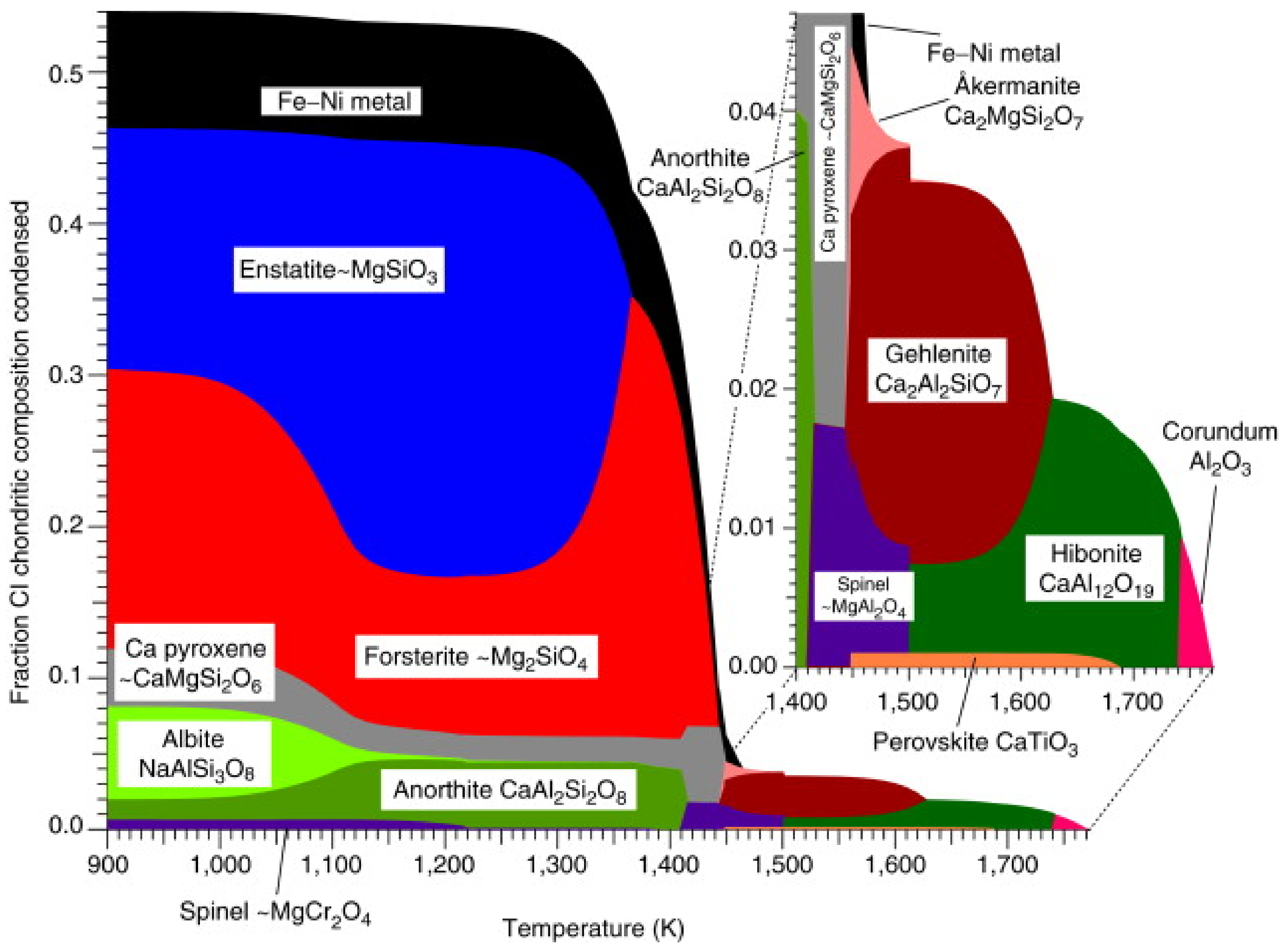
Chondrites



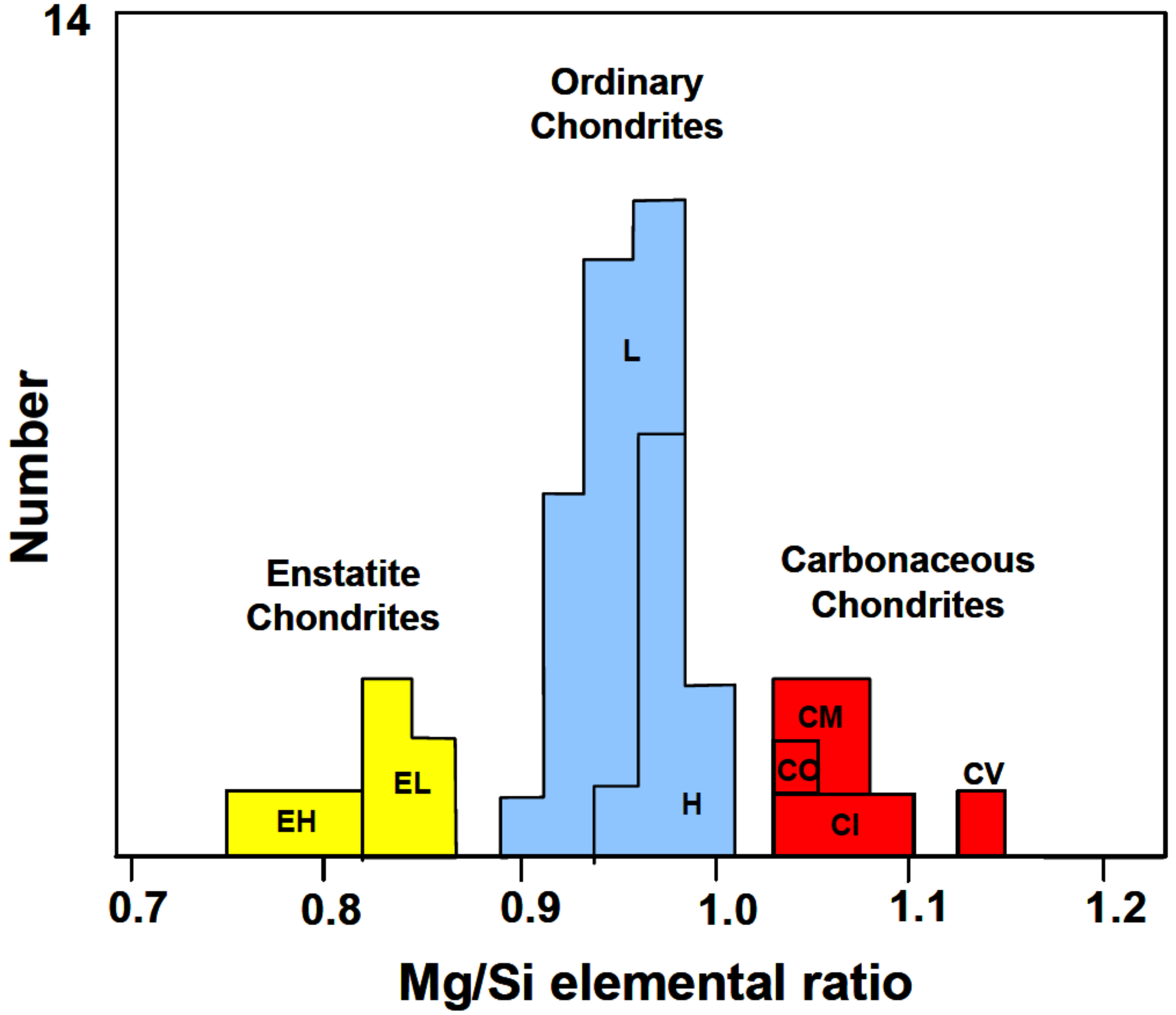
Chondrules: molten 'droplets' of nebular dust

AOAs: Ameboidal Olivine Aggregates ~100% olivine

Mineralogy of Chondrite phases



Chondrites have variable composition



Practice problem

The observed chondritic mass abundances for Calcium and Aluminum are:

Element	wt % in Chondrite	Atomic Mass
Ca	0.92	40.1
Al	0.85	27

The average wt % of CaO and Al_2O_3 in Basalt and Harzburgite:

Oxide	wt % in Basalt	wt % in Harzburgite
CaO	11.3	6.1
Al_2O_3	15.1	5.1

What ratio do you need to mix basalt and harzburgite back together to get the composition of the mantle before melt was removed? Assumptions:

- Pyrolite is a combination of melt (basalt) and melted mantle (harzburgites)
- Earth has the same Refractory Lithophile Elemental (RLE) abundances as Chondrites

Solution.

$$\left(\frac{0.92}{40.1}\right)(40.1+16) = CaO \text{ wt\%}$$

moles

$\frac{CaO}{Al_2O_3}$ wt% of Chon.

pyrolite

basalt

melted mantle

(H)

16 pyrolite $= \underline{a}\,B + \underline{b} \cdot H$

solve for a, b

Solution.

Basalt $\frac{CaO}{Al_2O_3}$ ratio: M

Harz. $\frac{CaO}{Al_2O_3}$ ratio: H

$$1\text{ mol Al}\left(\frac{Al_2O_3}{2\text{ mol Al}}\right) = 0.5\text{ mol }Al_2O_3$$

$$\frac{0.85\text{ g Al}}{27\text{ g Al}}\left(\frac{1\text{ mol }Al_2O_3}{2\text{ mol Al}}\right)\left(\frac{2\cdot 27+3\cdot 16\text{ g}}{1\text{ mol }Al_2O_3}\right) = 1.6$$

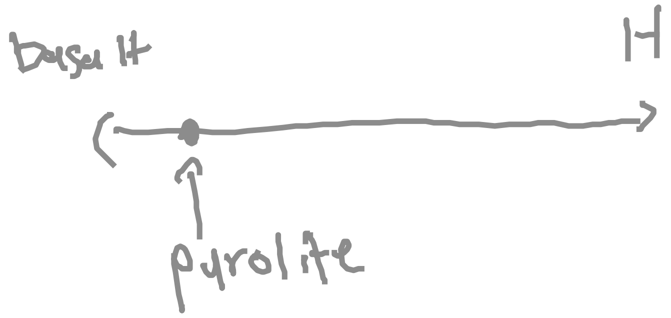
1. $p = a M + b \cdot H$

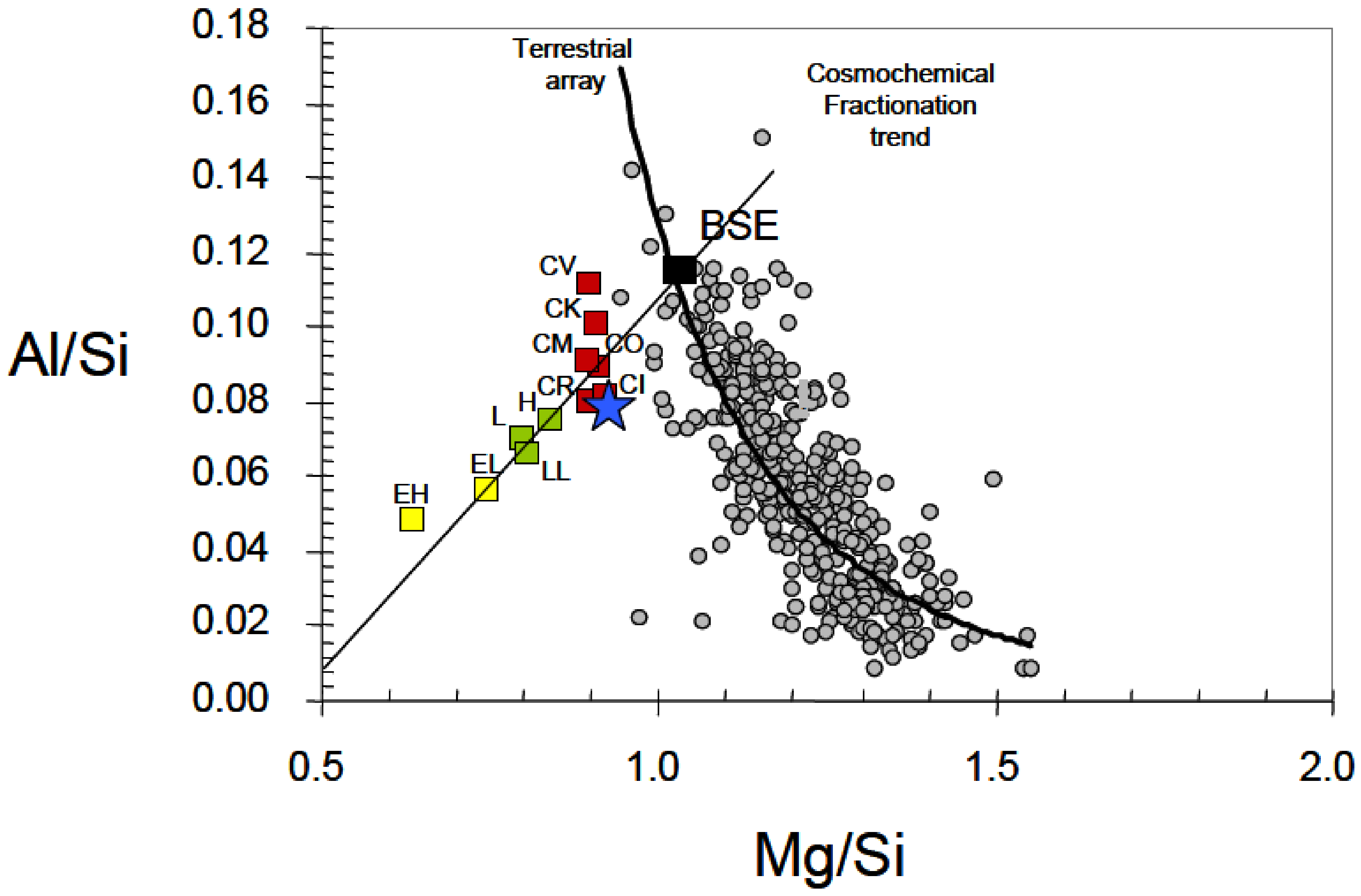
$a + b = 1, \quad b = 1 - a$

1. $p = a \cdot M + (1-a)\cdot H$

$0.8 = a \cdot 0.75 + (1-a)\cdot 1.2$

$0.89 = a$




Al/Si
Mg/Si
Terrestrial array
Cosmochemical Fractionation trend
BSE
CV
CK
CM
CO
CR
CI
L
H
LL
EL
EH
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.5
1.0
1.5
2.0