Compositional relationships between meteorites and planets I

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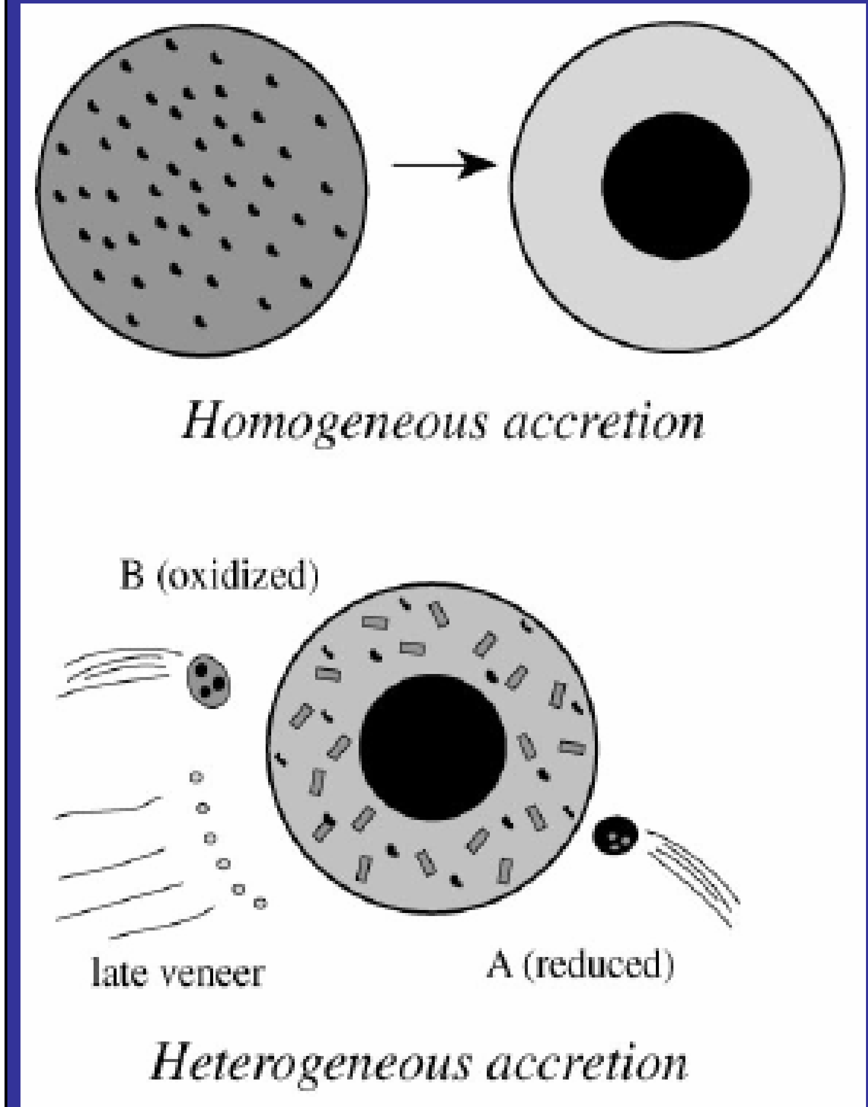
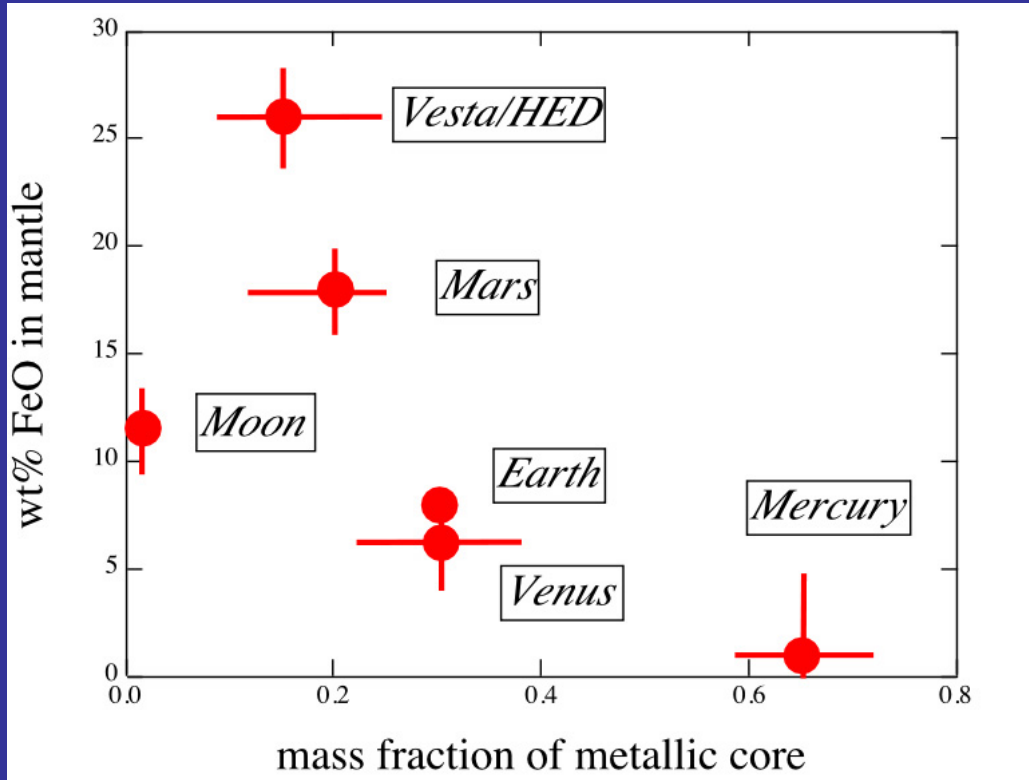
ASTROMATERIALS RESEARCH & EXPLORATION SCIENCE

Accretion models for terrestrial planets

Can we make planets from meteorites?





What are the outstanding problems?

Overview

1st lecture – Thursday

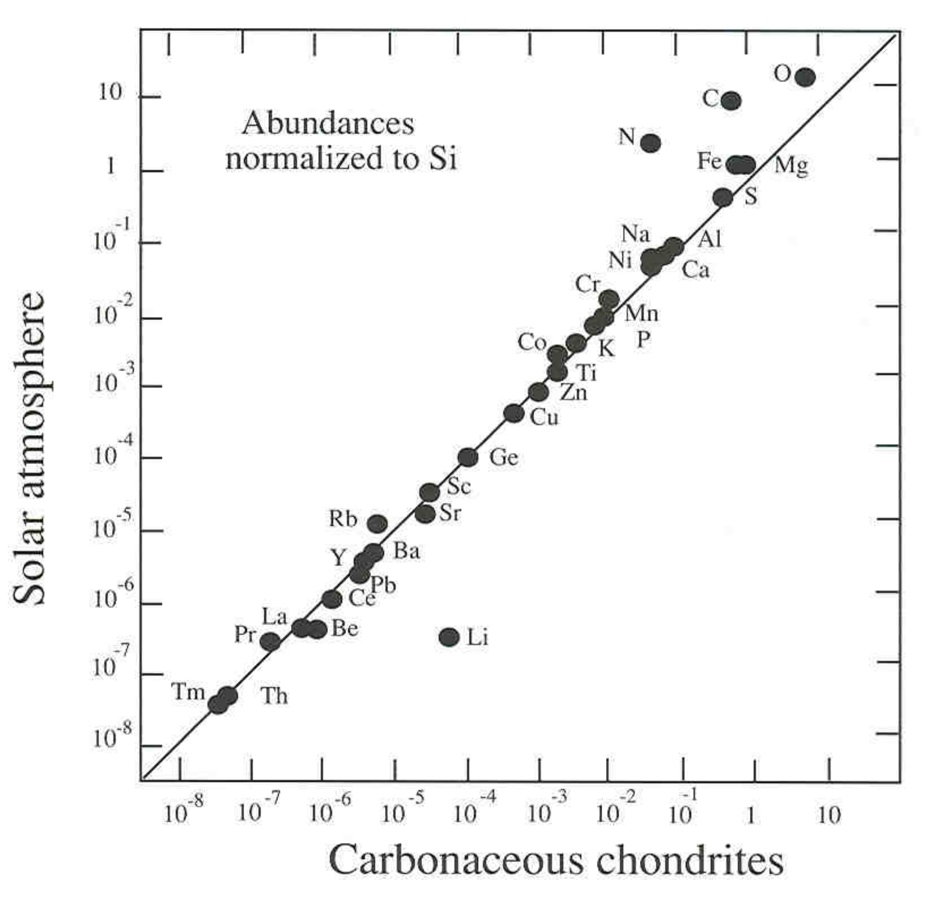
a) Starting materials and conditions
   Building blocks
   Physical and timing constraints
   Thermal constraints

b) How chondrites are modified
   Processes (melting, fractionation, residues)
   Controlling variables – T, P, fO_2, water

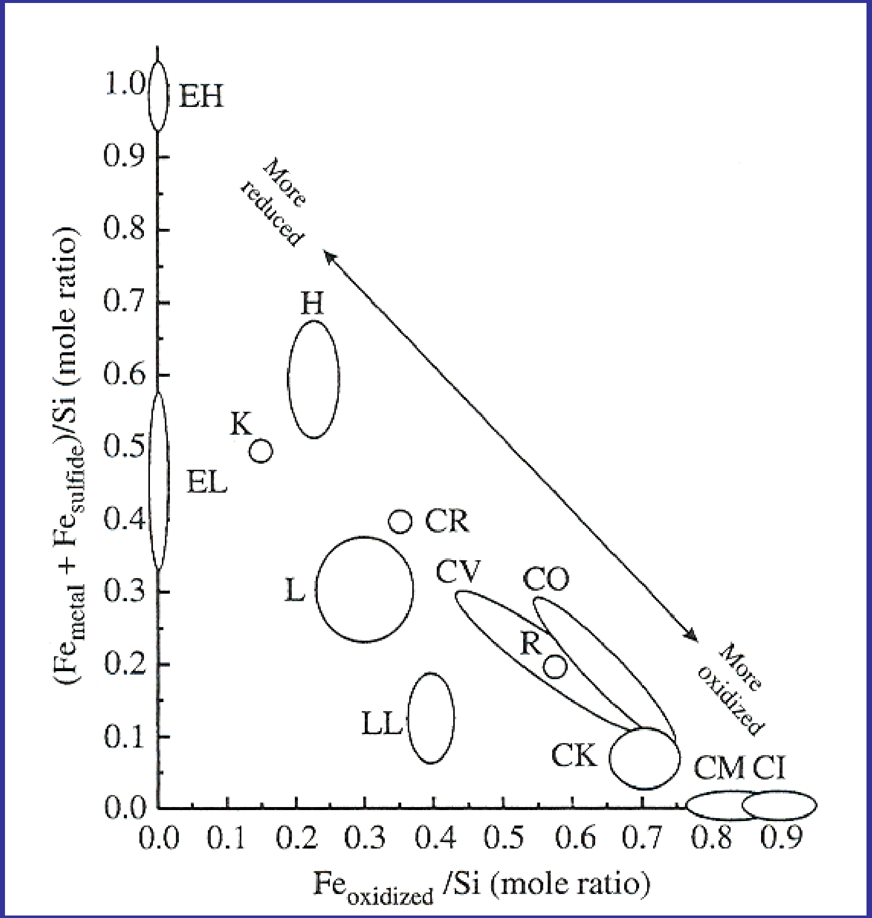
c) Key parameters for defining bulk compositions

d) Example 1: Vesta

Building blocks

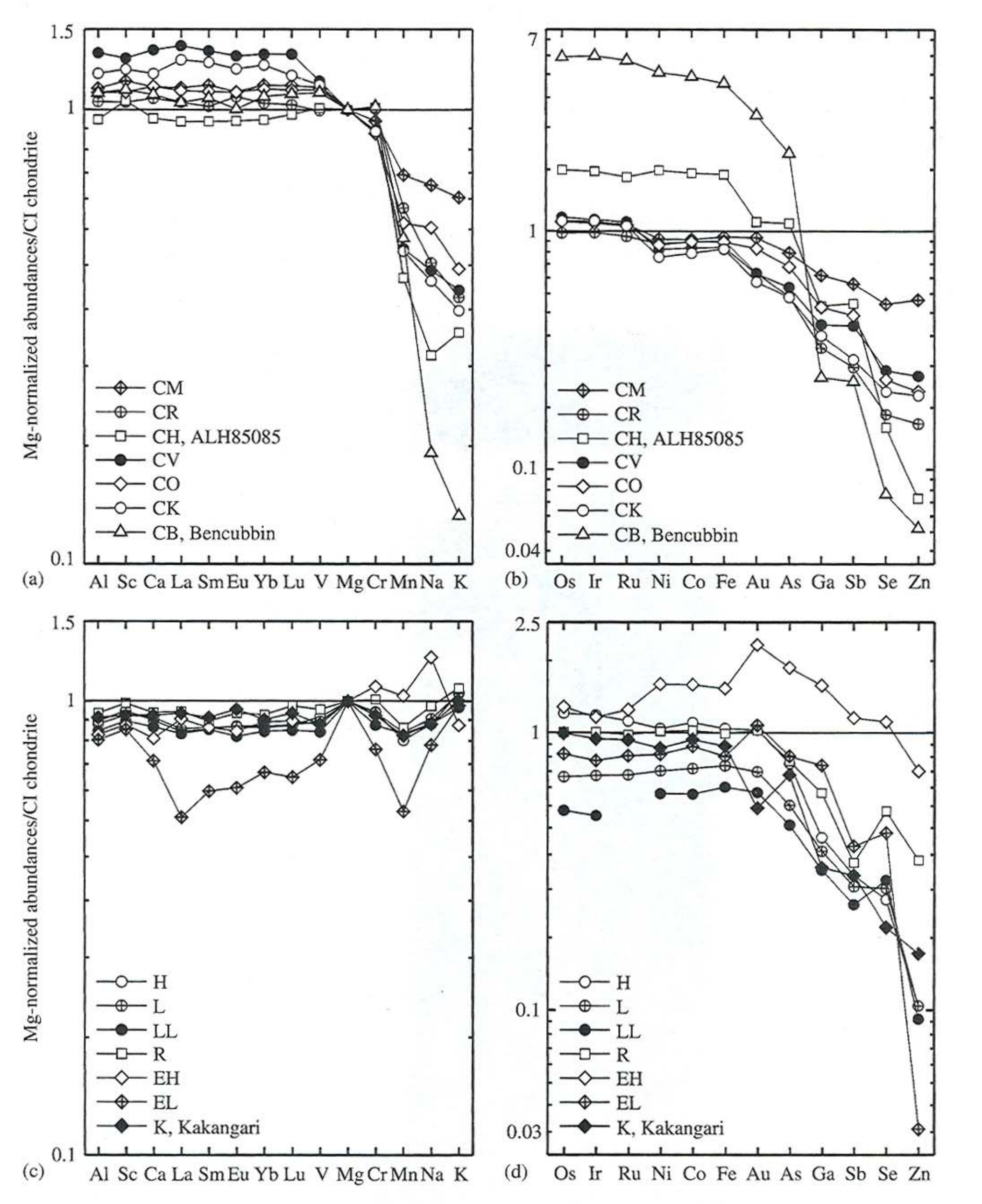


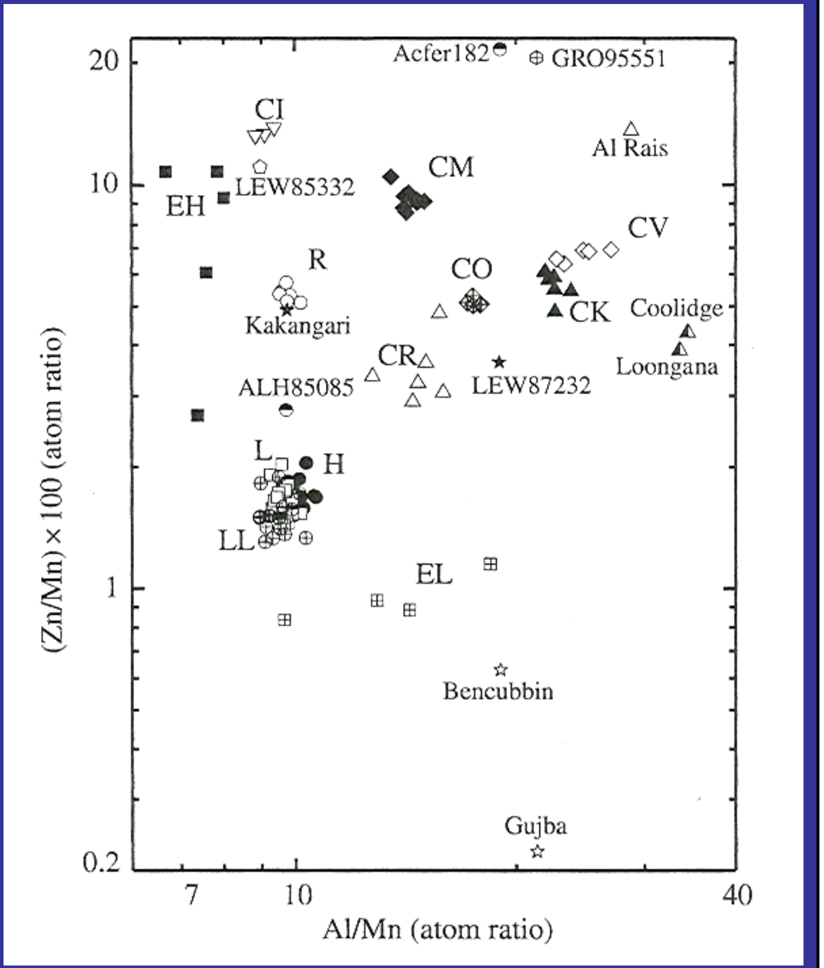
After Ringwood (1977)



From Krot et al. (2003)

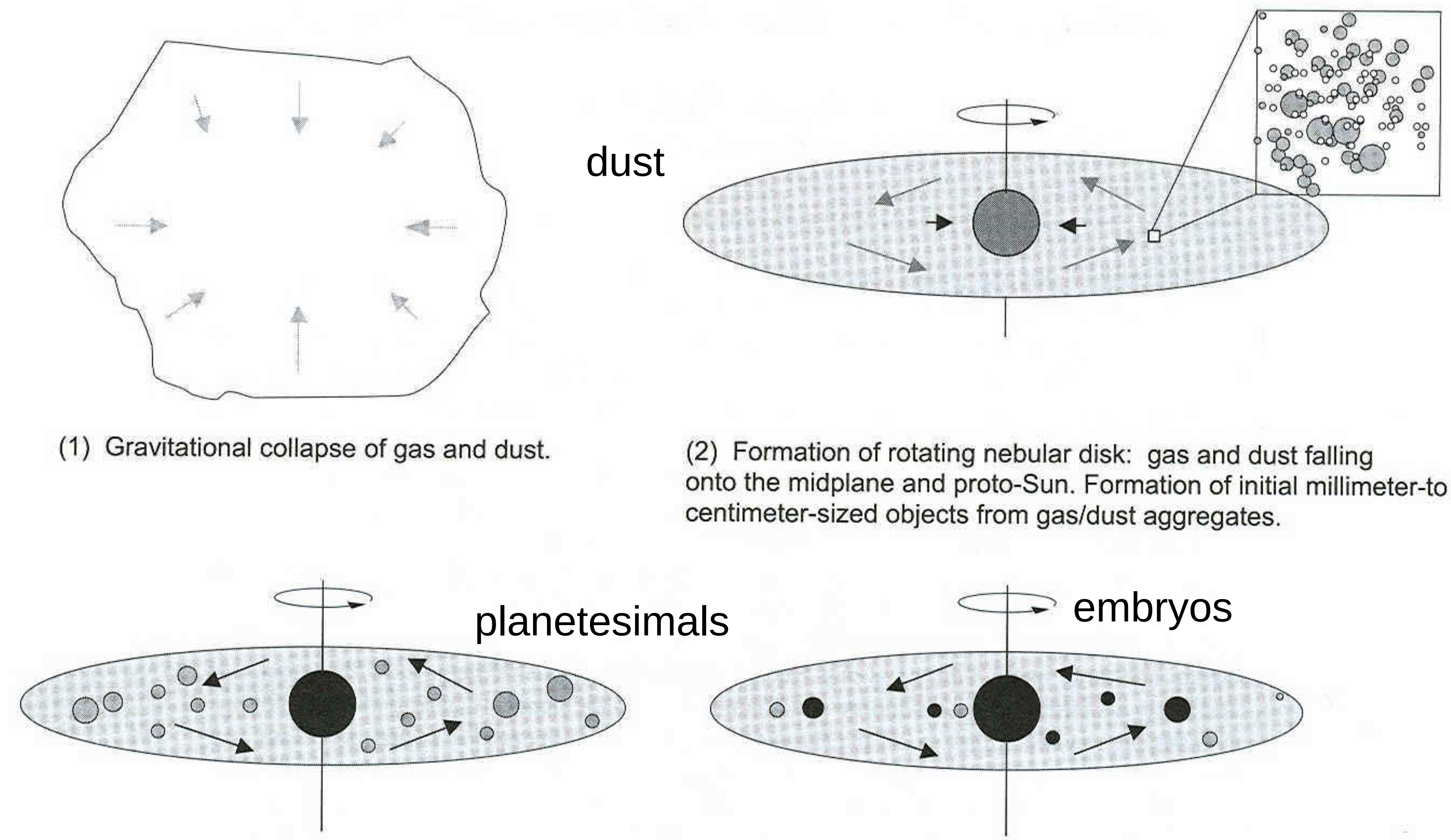
Building blocks





From Krot et al. (2003)

Stages in the accretion process



(1) Gravitational collapse of gas and dust.

(2) Formation of rotating nebular disk: gas and dust falling onto the midplane and proto-Sun. Formation of initial millimeter-to centimeter-sized objects from gas/dust aggregates.

(3) Protoplanetary disk: Gravitational accretion of 10–100-m objects upto 10–100 km.

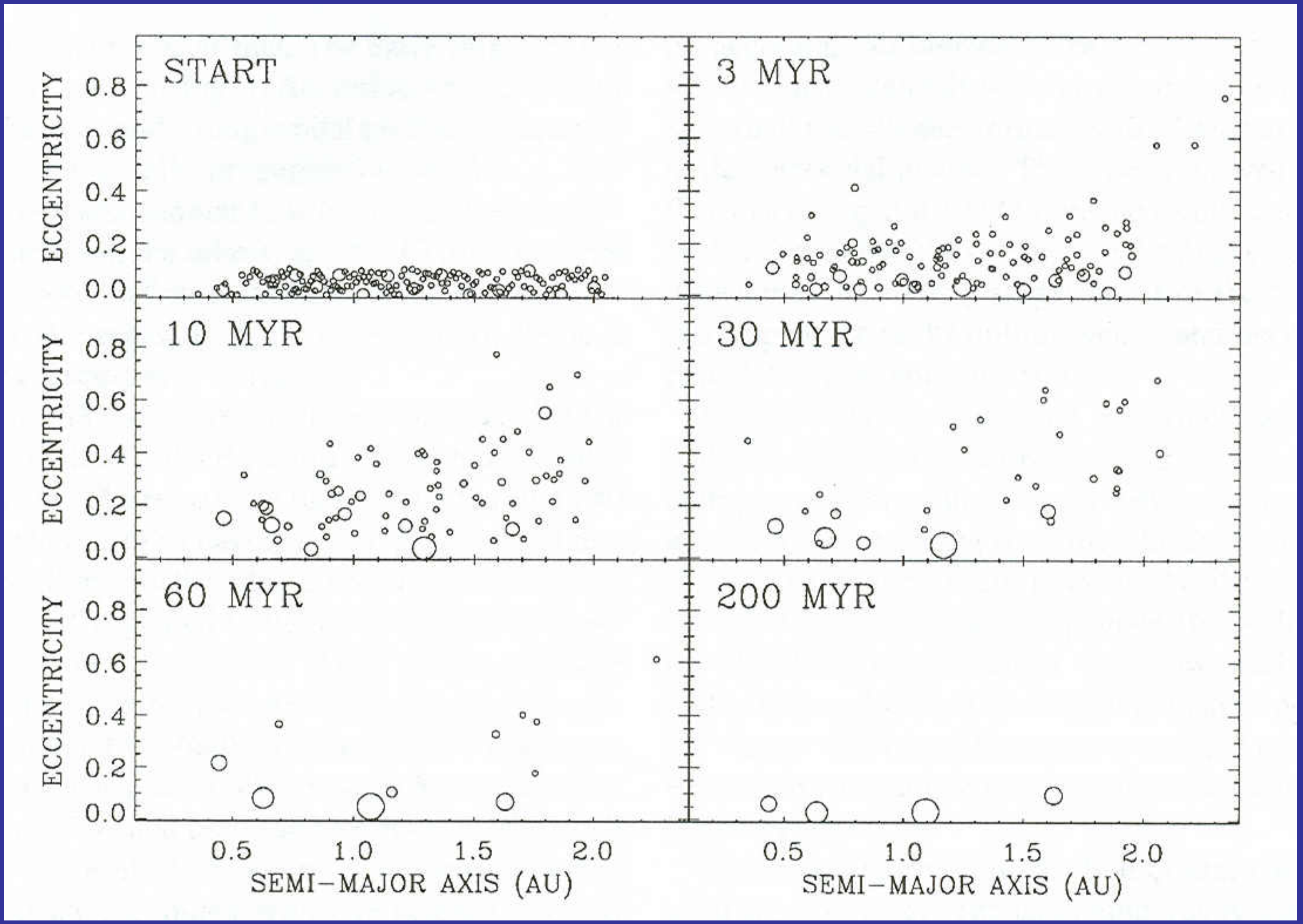
(4) Evolved disk: Nebular gas cleared, collisions and secondary impacts and planetary/post-planetary formation.

From Nichols (2006)

Timescales of accretion process

Hierarchy of materials	mass	timeframe (yrs)
a) gas/dust to planetesimals	10^{12}-10^{18} g	~10^5
b) planetesimals to embryos	10^{26}-10^{27} g	~10^6
c) embryos to proto/planets	10^{27}-10^{28} g	~10^7

Embryos to solar systems



Results of N-body simulations

From Chambers (2003)

How chondrites are modified

Low temperature and aqueous alteration processes – covered by Adrian and Sasha

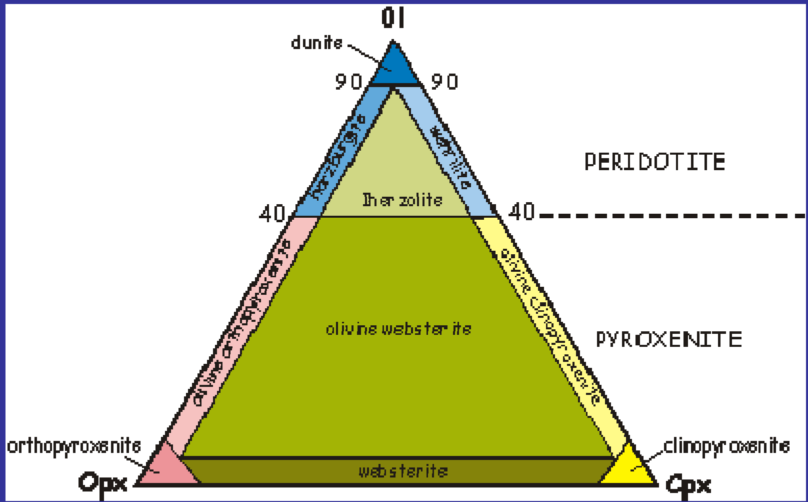
Shock processes – Tom Sharp

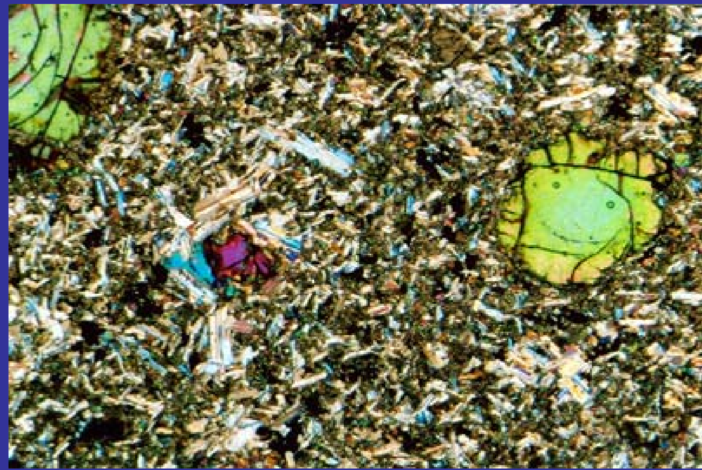
Igneous processes
- Melting
- Fractionation and accumulation
- Residua

-What evidence is there in the meteorite collections? [compare to Earth]

Melting

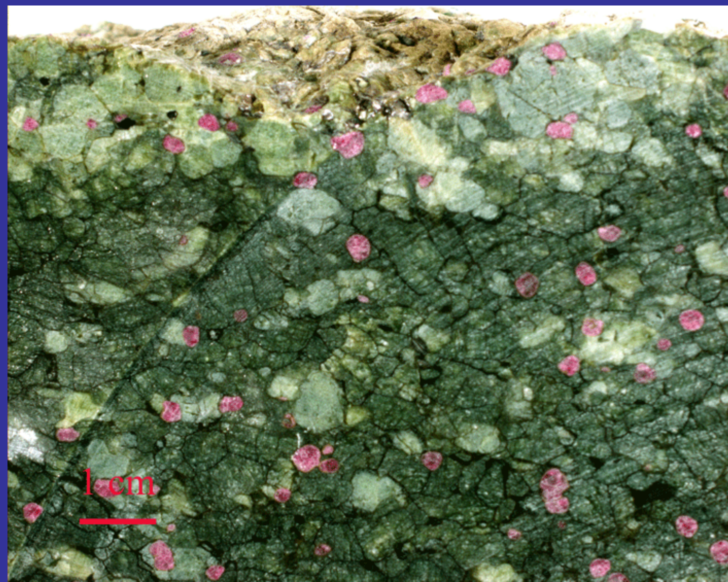
Terrestrial basalts and residues





Basalt (melt) 1 mm

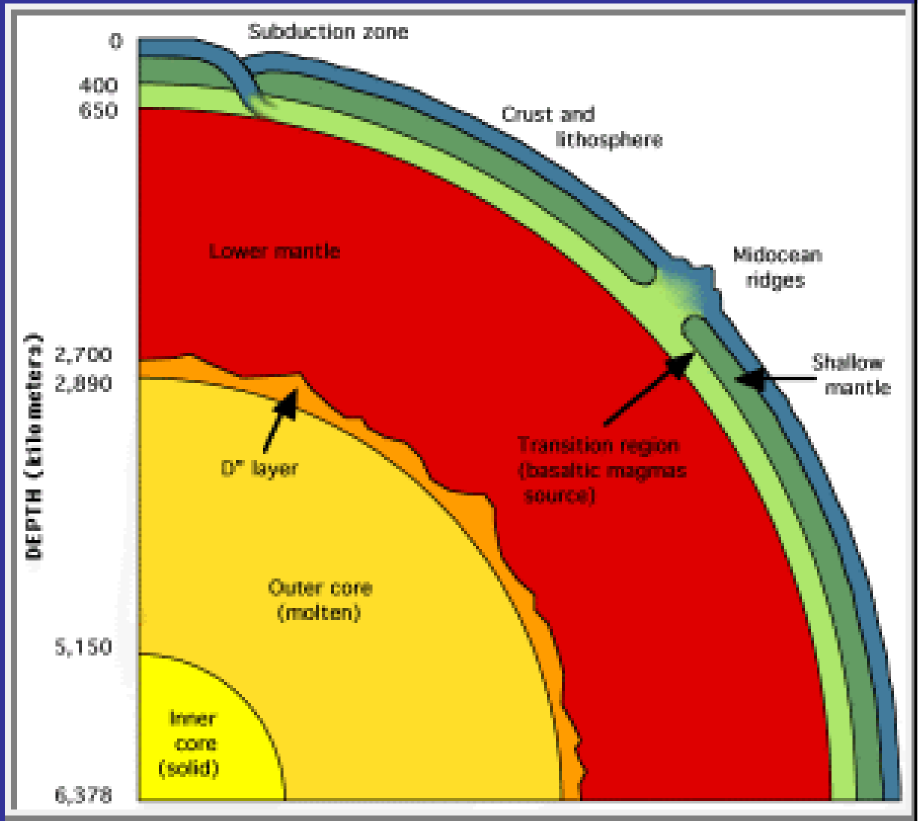
Peridotite (unmelted mantle) 3 mm



Harzburgite (residue)

Melting on the Earth has many potential mechanisms – current day

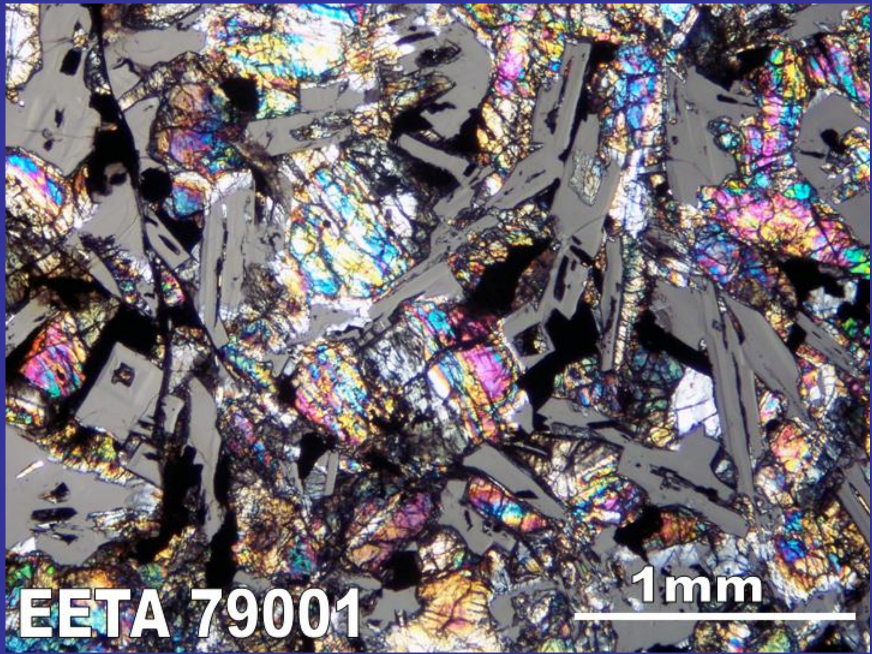
- Stress relief
- Convective rise
- Frictional heating (plate tectonics)
- Compositional change (diffusion, volatile addition)
- Radioactive heat

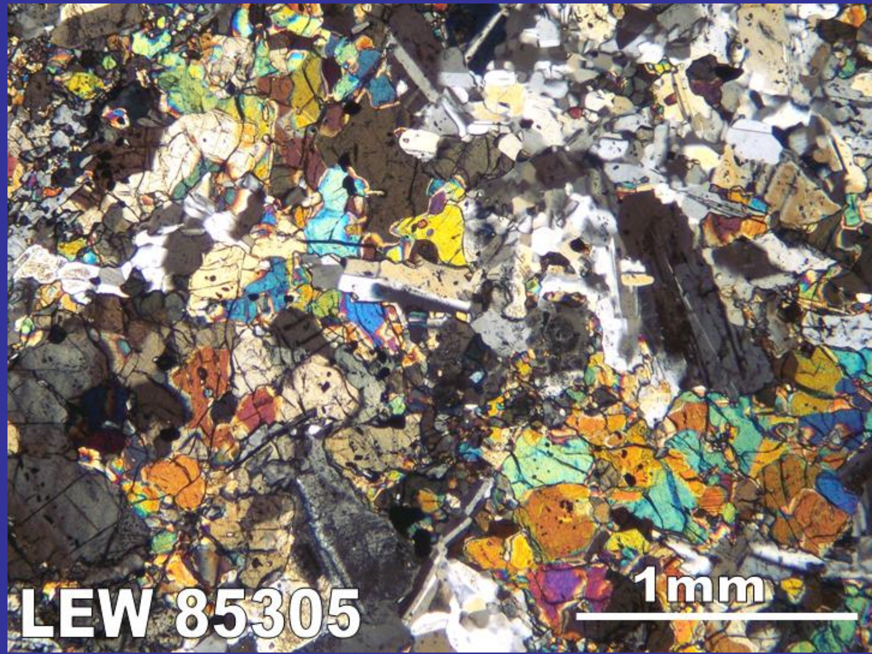


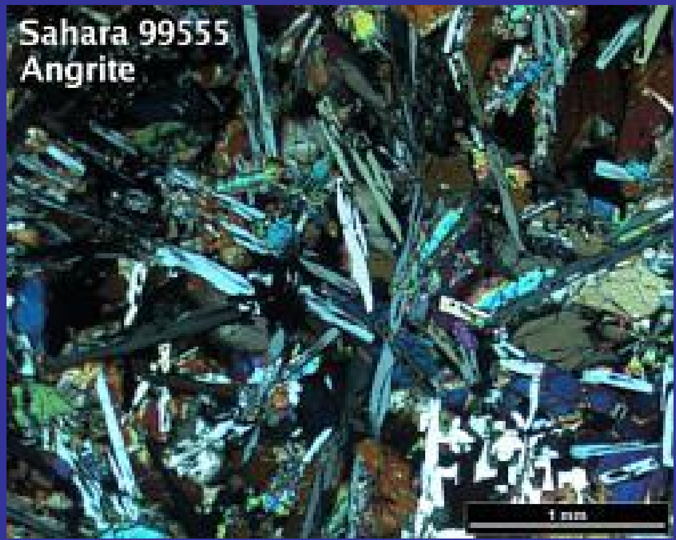
What about asteroids and other planets?

Melting

Meteoritic basalts – eucrites, shergottites, angrites

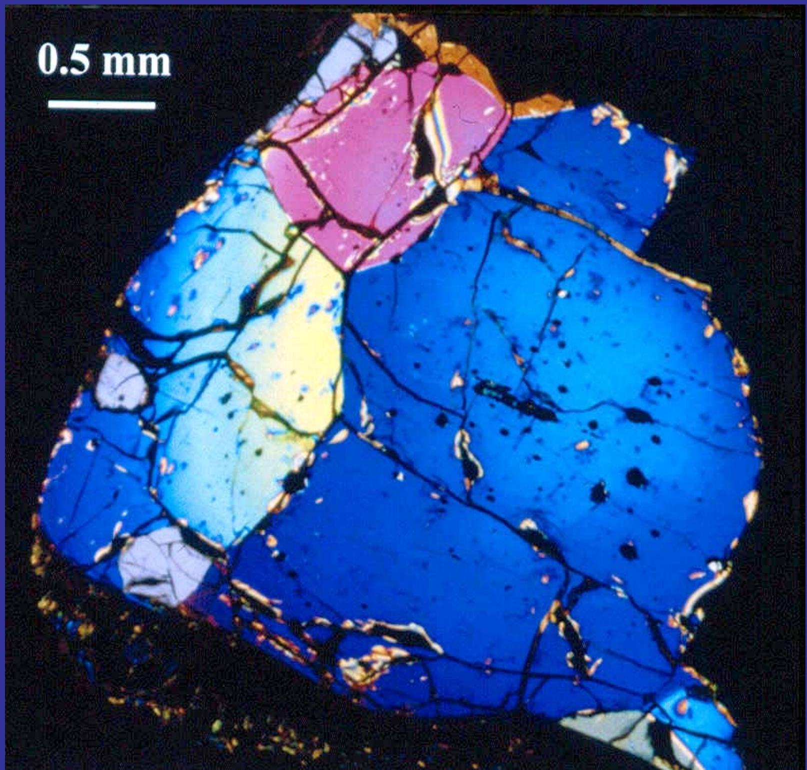




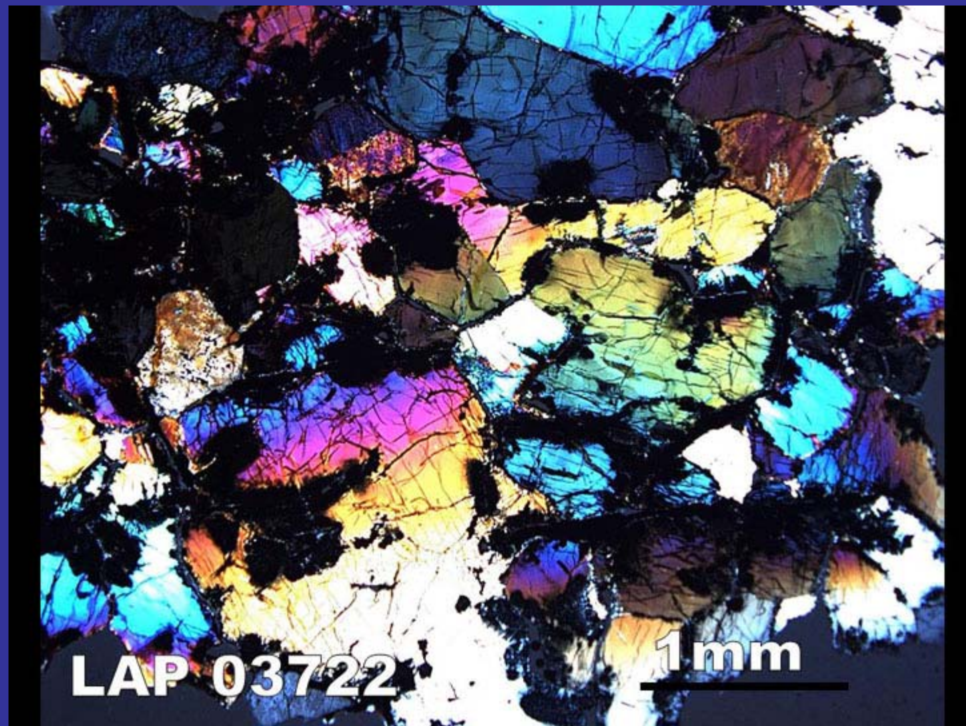


Melting residua

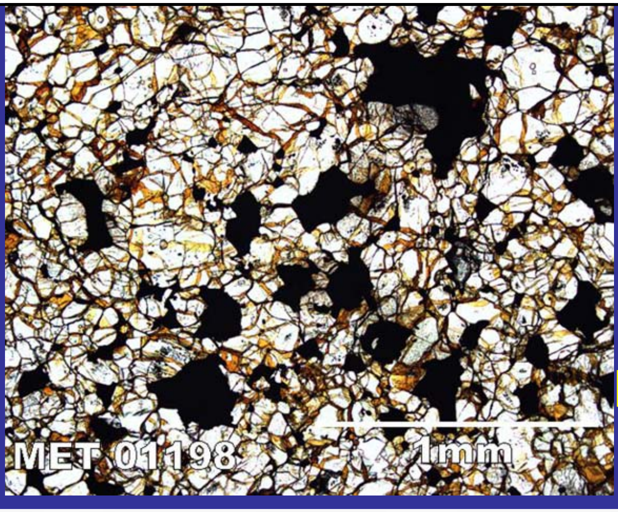
Meteoritic residua – ureilites, lodranites, acapulcoites



Ungrouped ultramafic achondrite



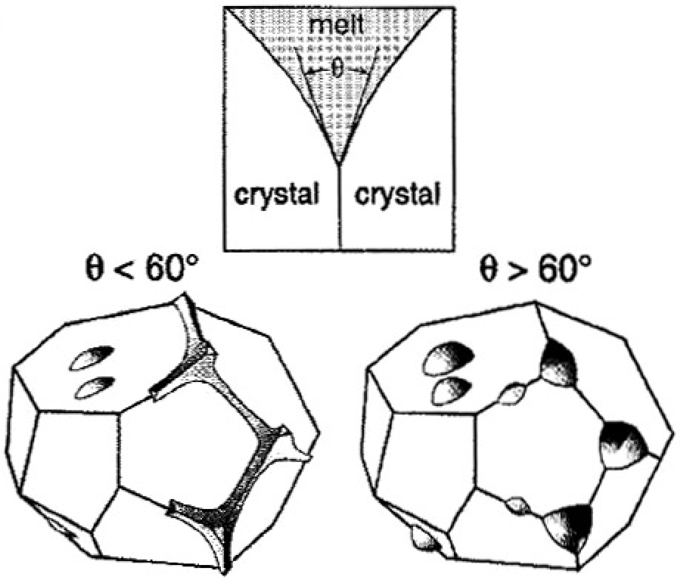
ureilite

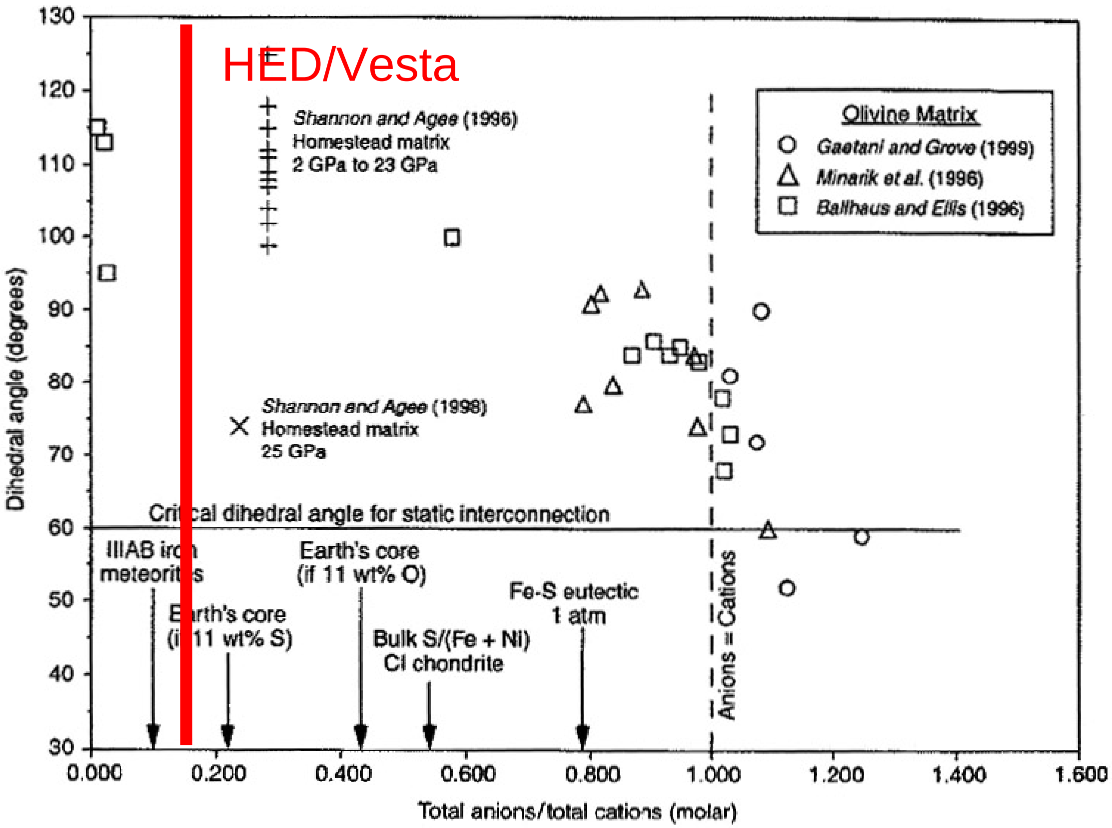


Melting residua

Meteoritic residua – ureilites, lodranites, acapulcoites

Meteoritic examples have added complication of metal – metal can be trapped (dihedral angles)

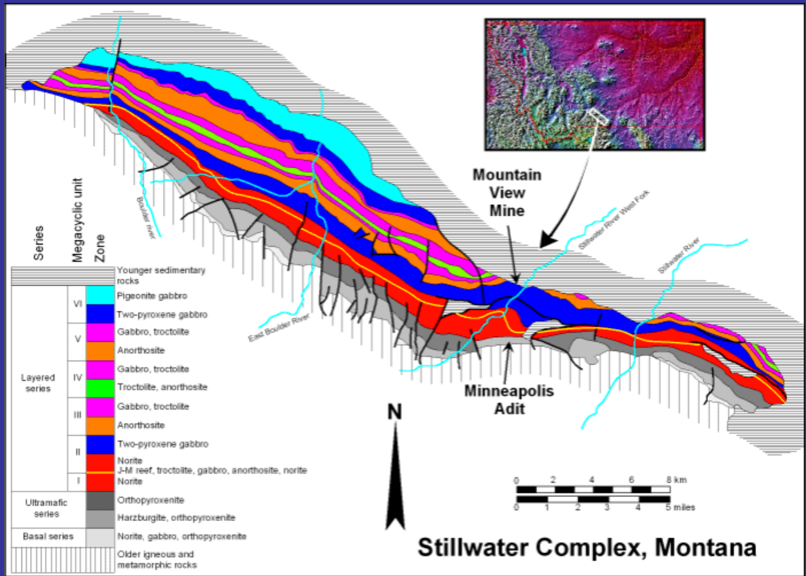


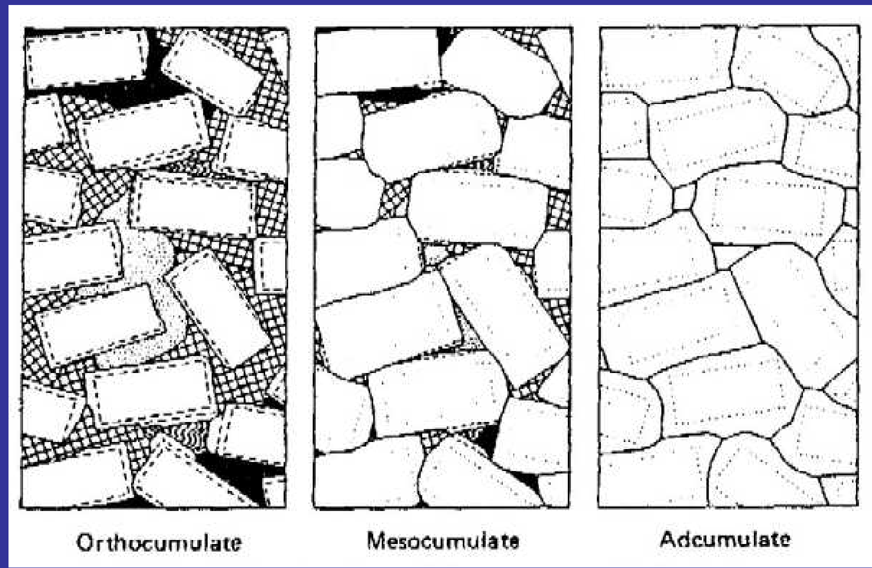


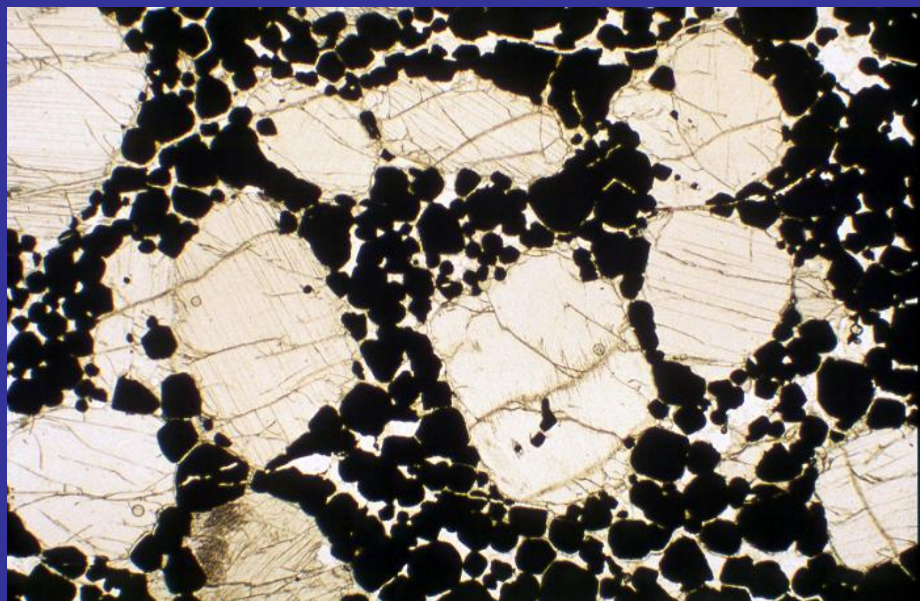
from Righter (2003)

Fractionation and accumulation

Terrestrial cumulate – Stillwater Complex, Montana





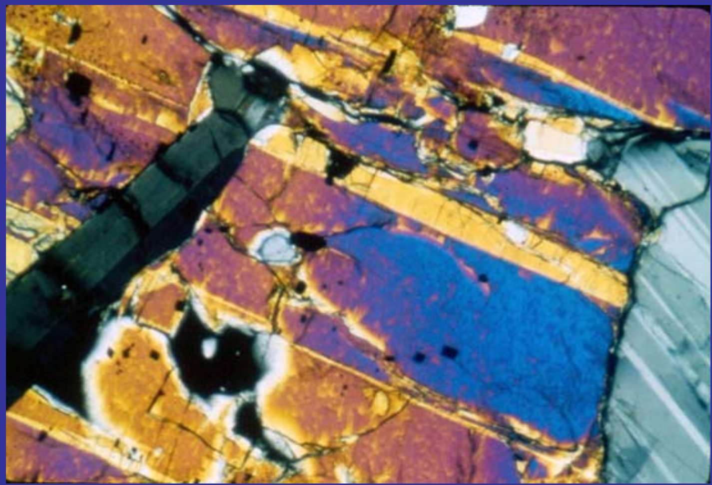


Cumulate
olivine and chromite

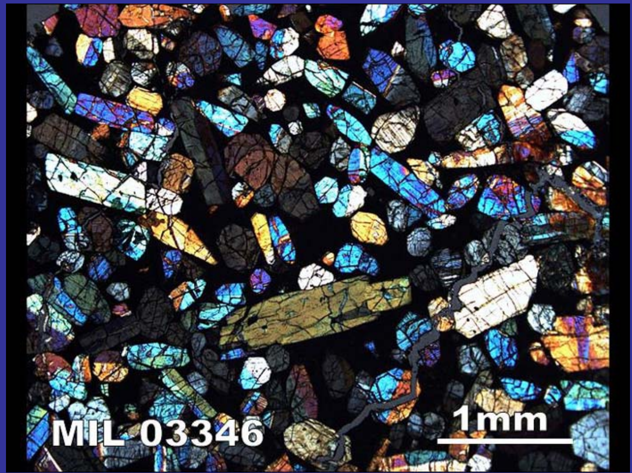
Fractionation and accumulation

Meteoritic cumulates – eucrites, nahklites, pallasites

Pallasite – olivine orthocumulate



Cumulate eucrite - adcumulate



Nakhlite – clinopyroxene mesocumulate

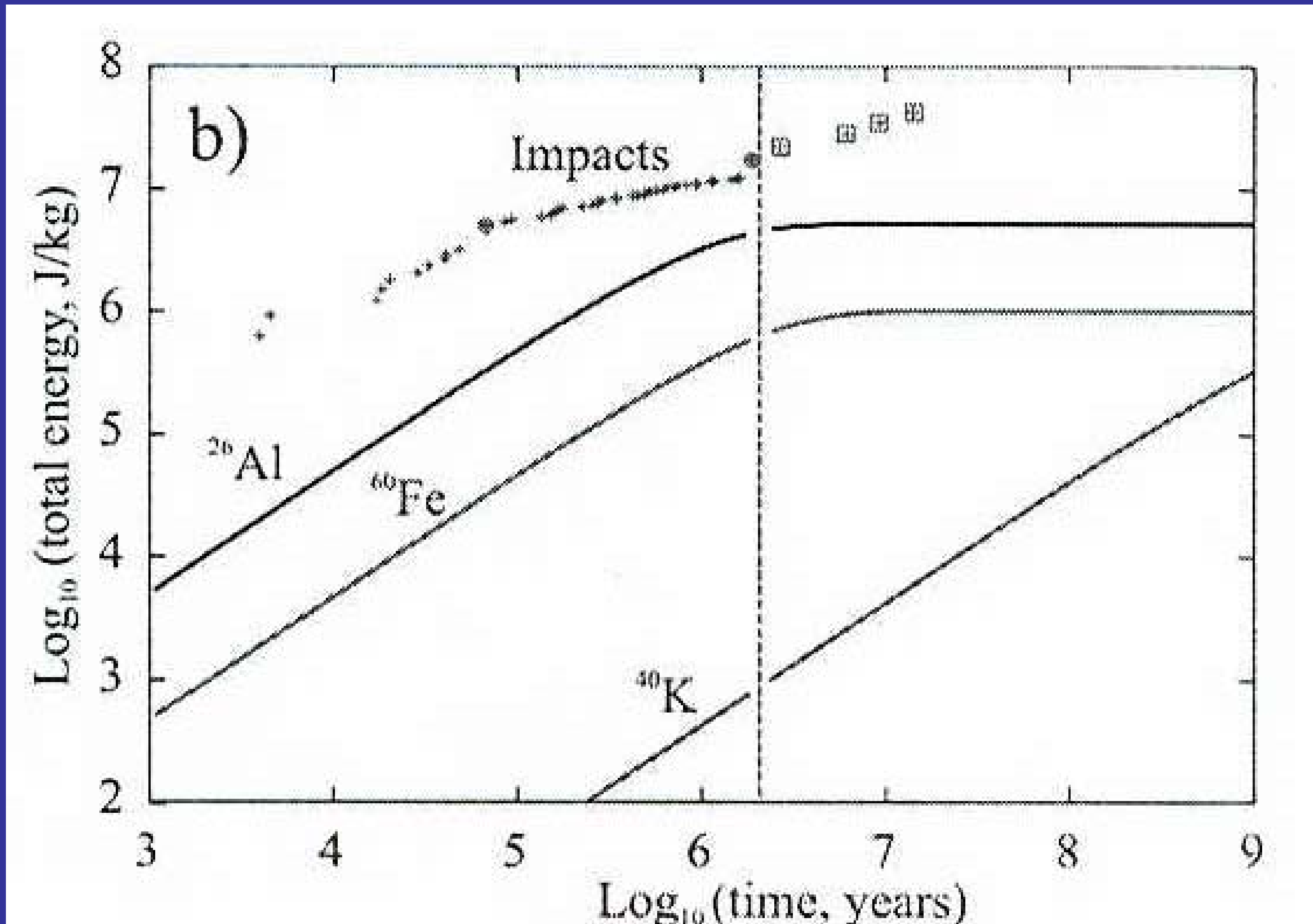
There is clear evidence for melting in the meteorite record, so what factors are involved?

- Temperature (radioactivity, impacts, gravity)
- Pressure
- Oxygen fugacity (or pressure)
- Water (and other volatiles)

Thermal constraints and heat sources

Radioactivity: ^{26}Al, ^{60}Fe, other short lived

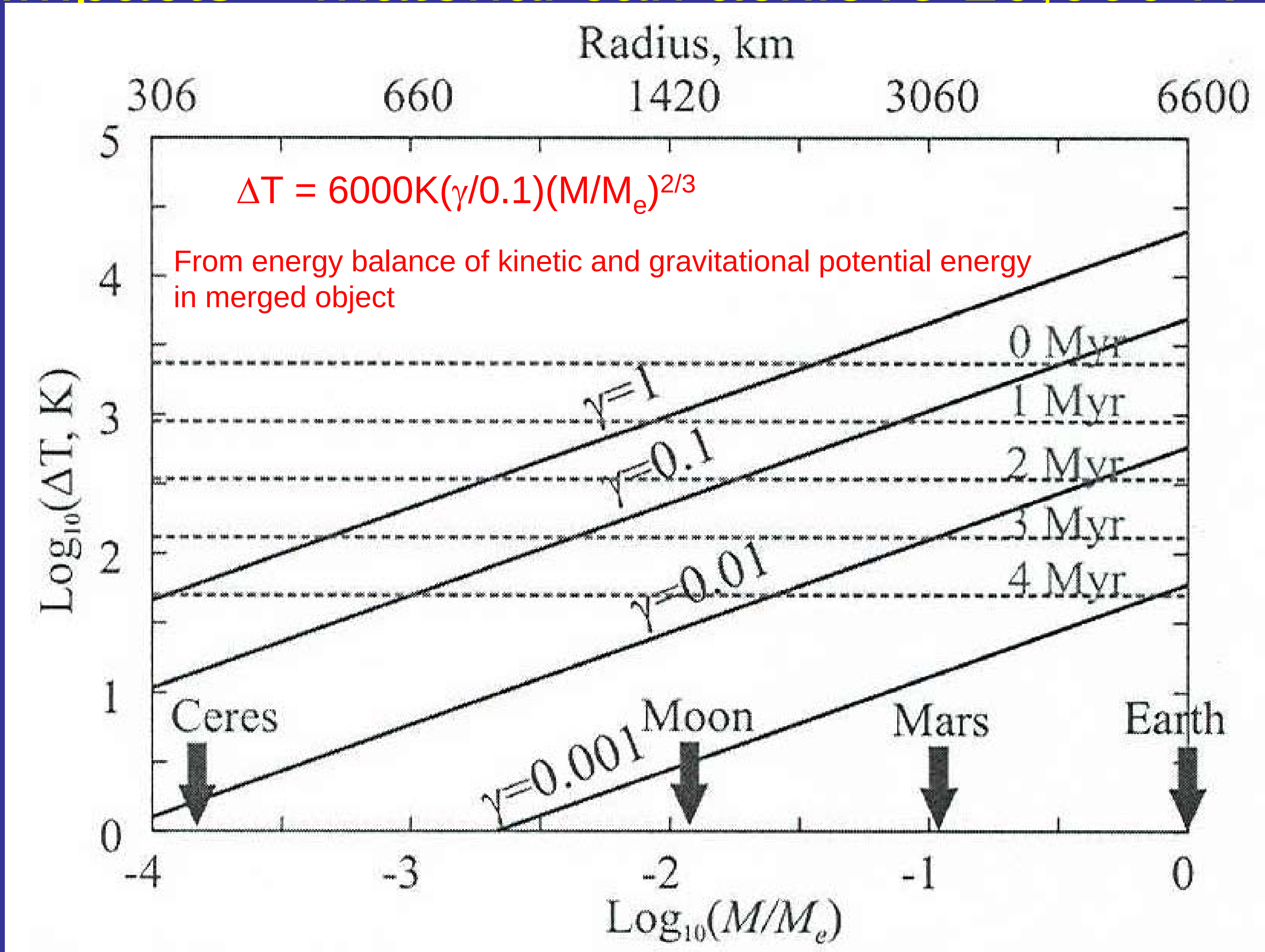
^{40}K, ^{238}U, ^{235}U, ^{232}Th – long lived



From Rubie et al. (2007)

Thermal constraints and heat sources

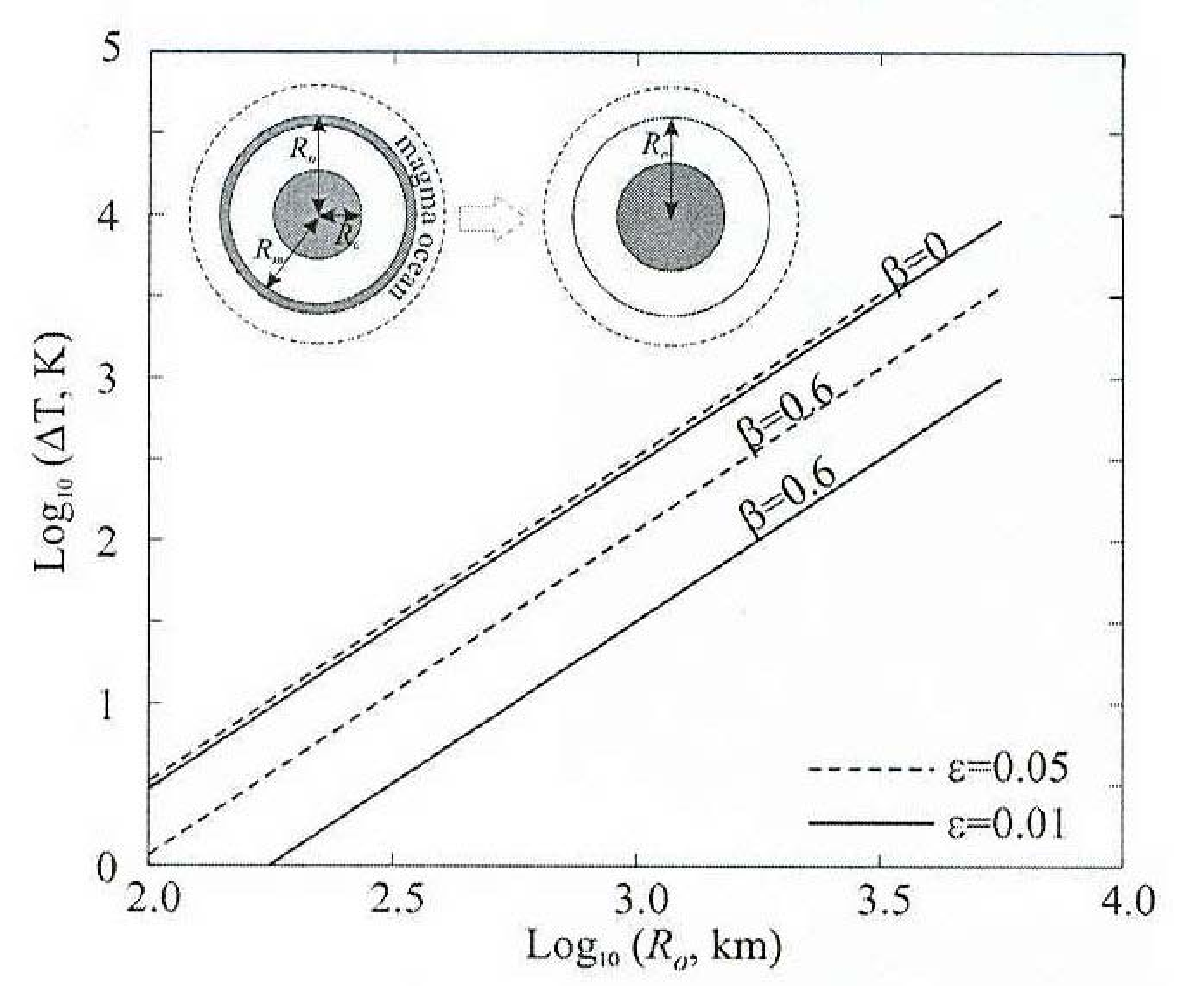
Impacts – material can achieve 10,000 K



From Rubie et al. (2007)

Thermal constraints and heat sources

Gravitational – once core formation starts it is an "energetic cascade"



Moving metal from the base of a magma ocean through the solid lower mantle to the core will result in a situation with lower potential energy. Energy derived through such a process can cause temperature changes of several hundred to a few thousand K

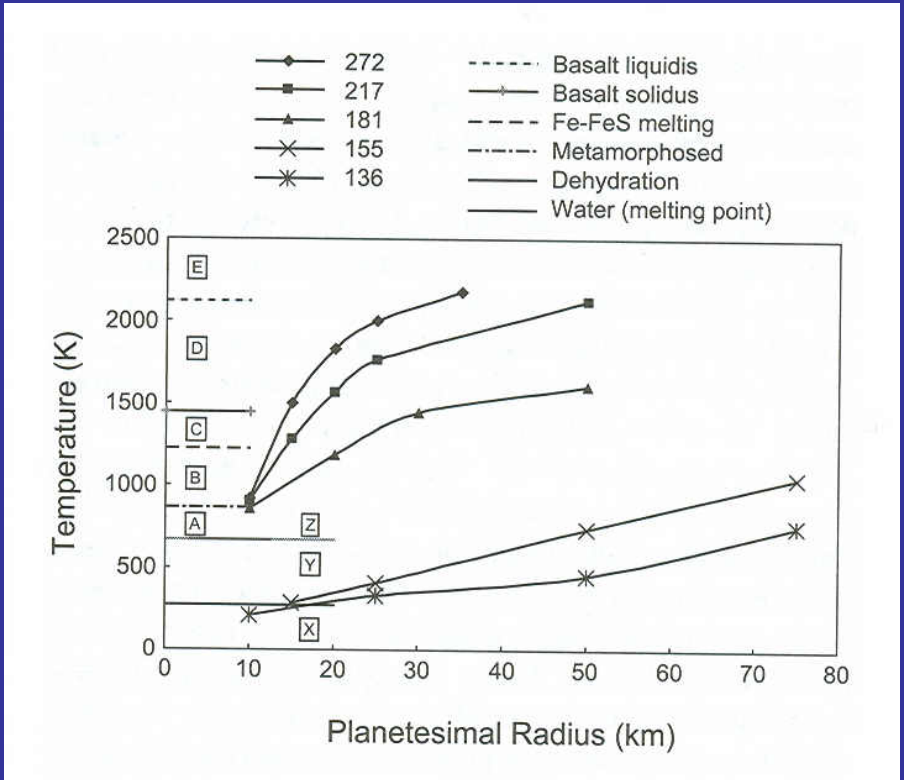
ε= thickness of metal layer

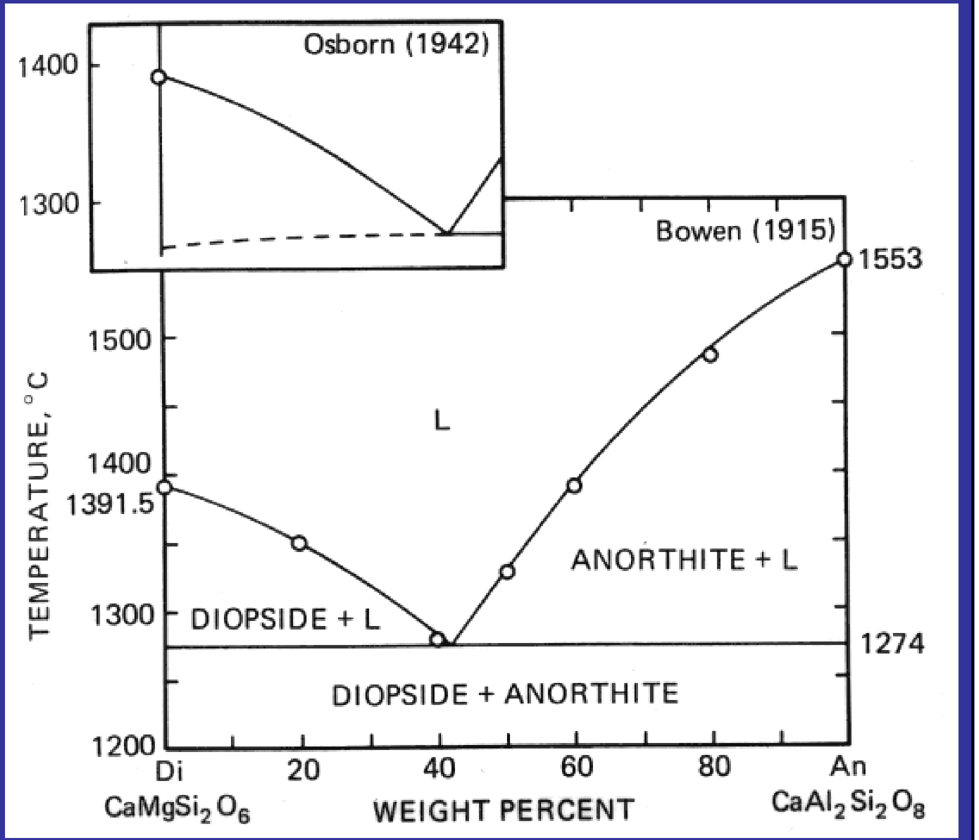
β = initial core radius

From Rubie et al. (2007)

Temperature

Heating models in comparison to basaltic phase equilibria

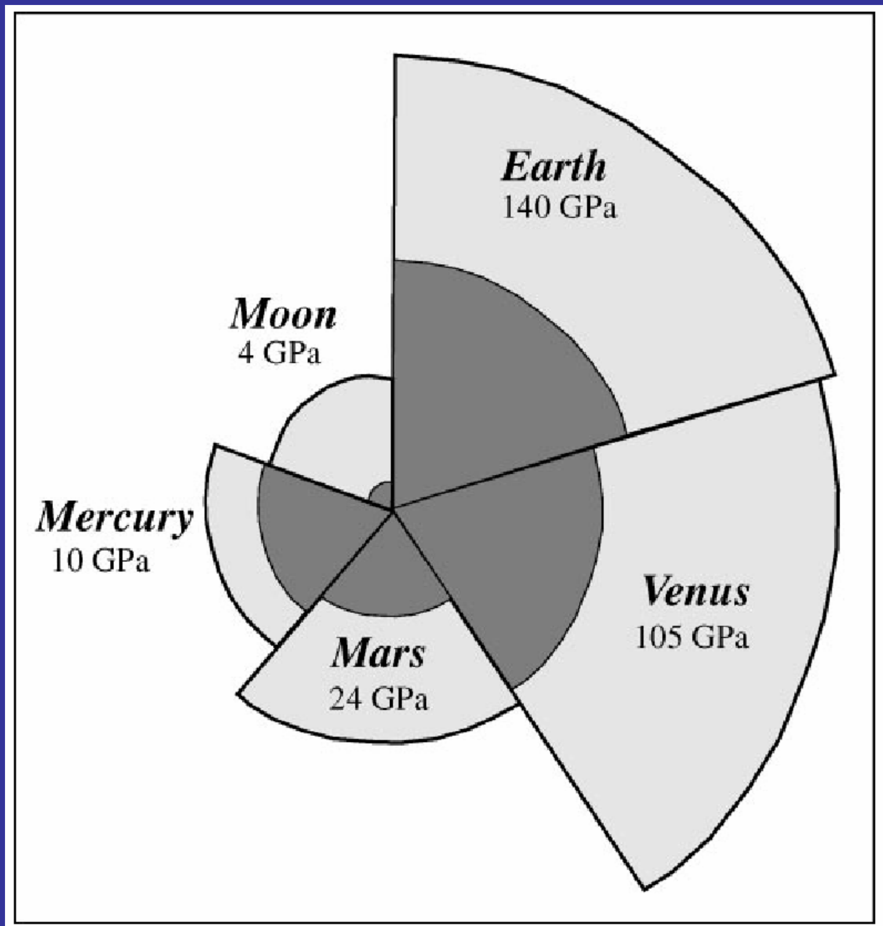




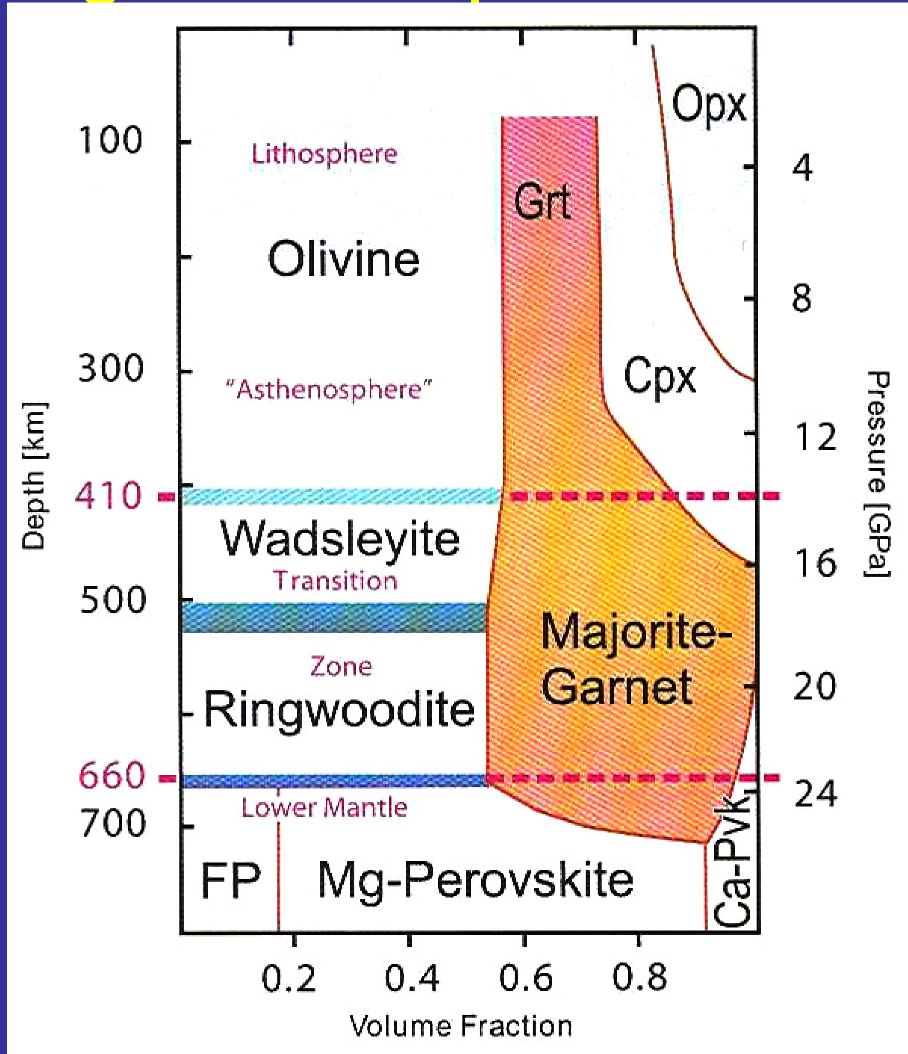
From Ghosh et al. (2006)

Pressure

Pressure to core-mantle boundary in planets and mineralogy change with depth

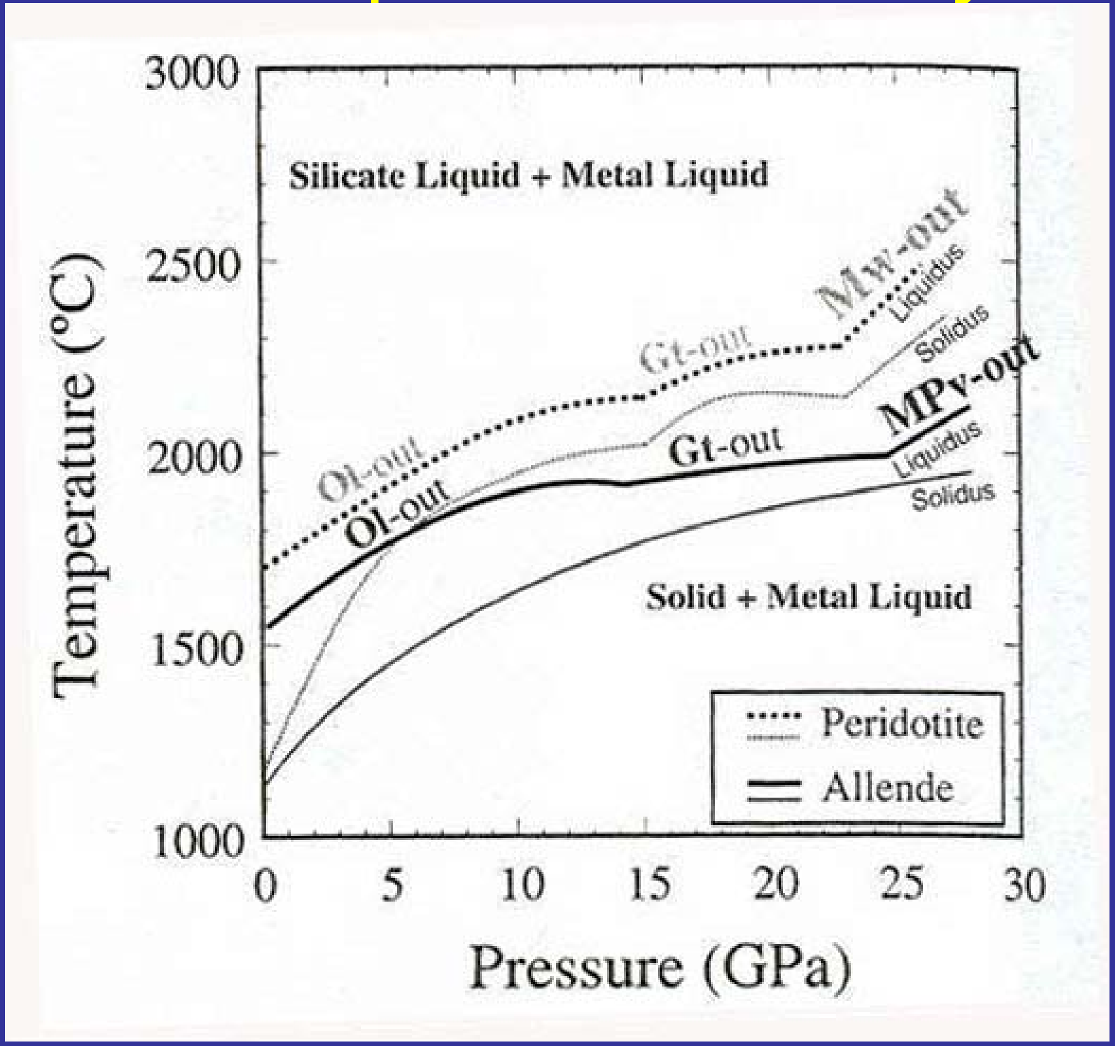


From Righter (2003)



Pressure

Understanding of melting at high pressures and temperatures is very limited



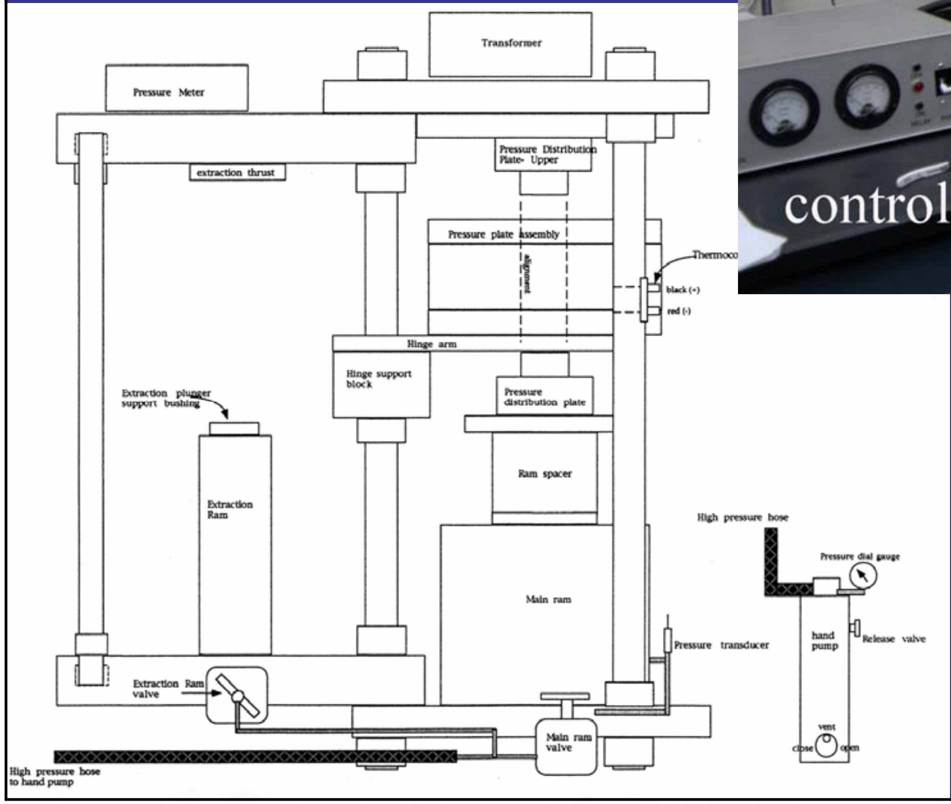
From Asahara et al. (2004)

High pressure experiments

NASA-JSC laboratory

0.3 to 3.0 GPa
(10 to 100 km depth)

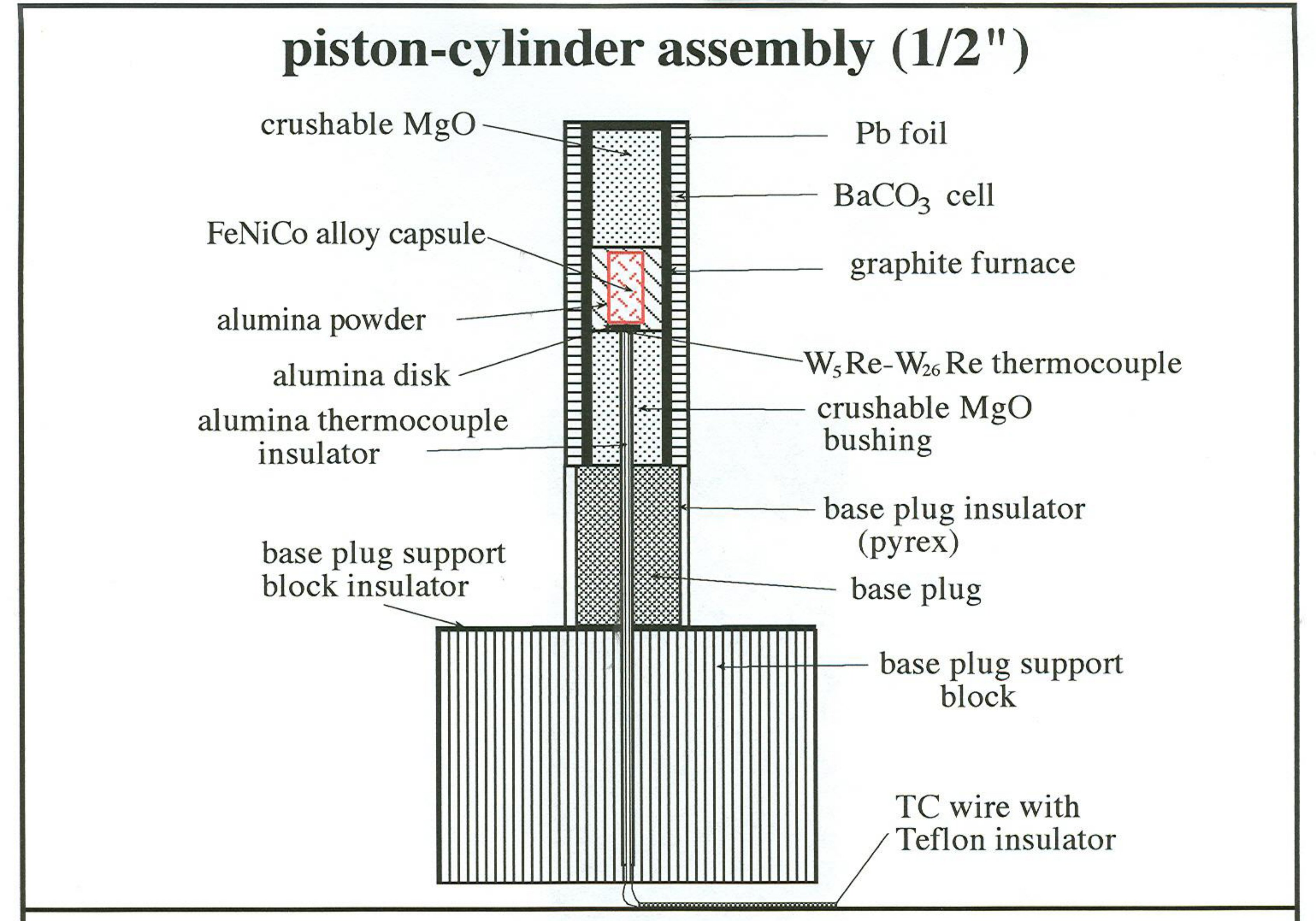
1200 to 2500 °C



Used to study

-Mantle melting
-Chondrite phase equilibria
-Metal-silicate equilibrium (core formation)
-Diffusion of Ru, Ir, Ga, Co, in FeNi metal

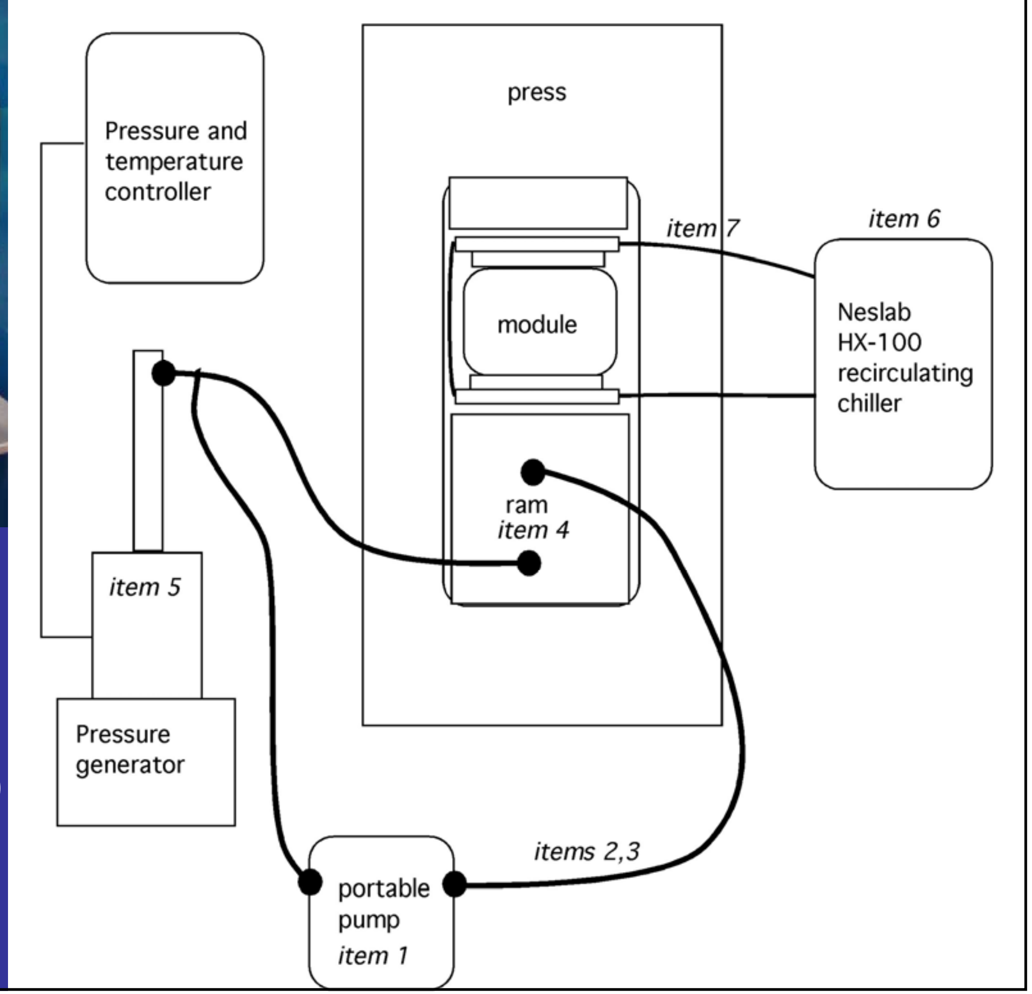
Experimental techniques



High pressure experiments

Pressure: 3.0 to 30.0 GPa
Temperature: up to 2800 ° C

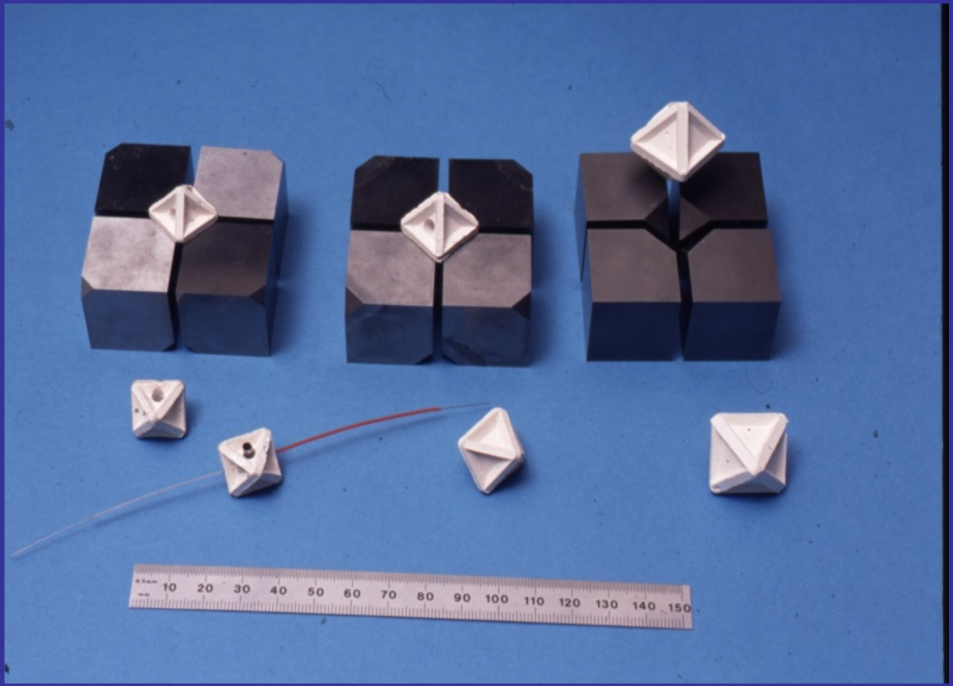
Schematic diagram for Rockland Research Multi-anvil system



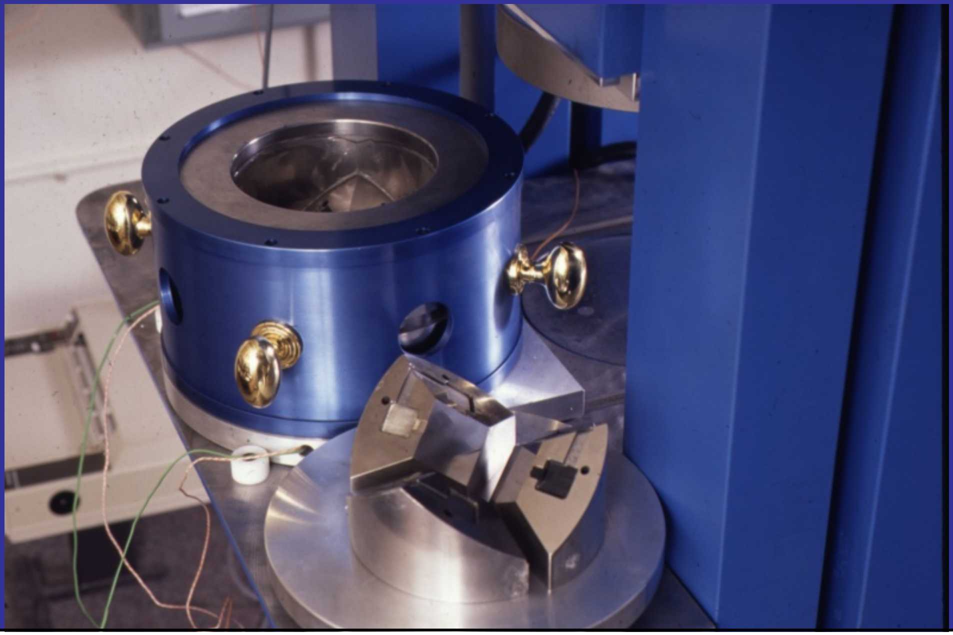
Used to study

-Chondrite phase equilibria (H, E)
-Metal-silicate equilibrium (core formation)
Au, Pd, Re, Os

Multi-anvil assemblies

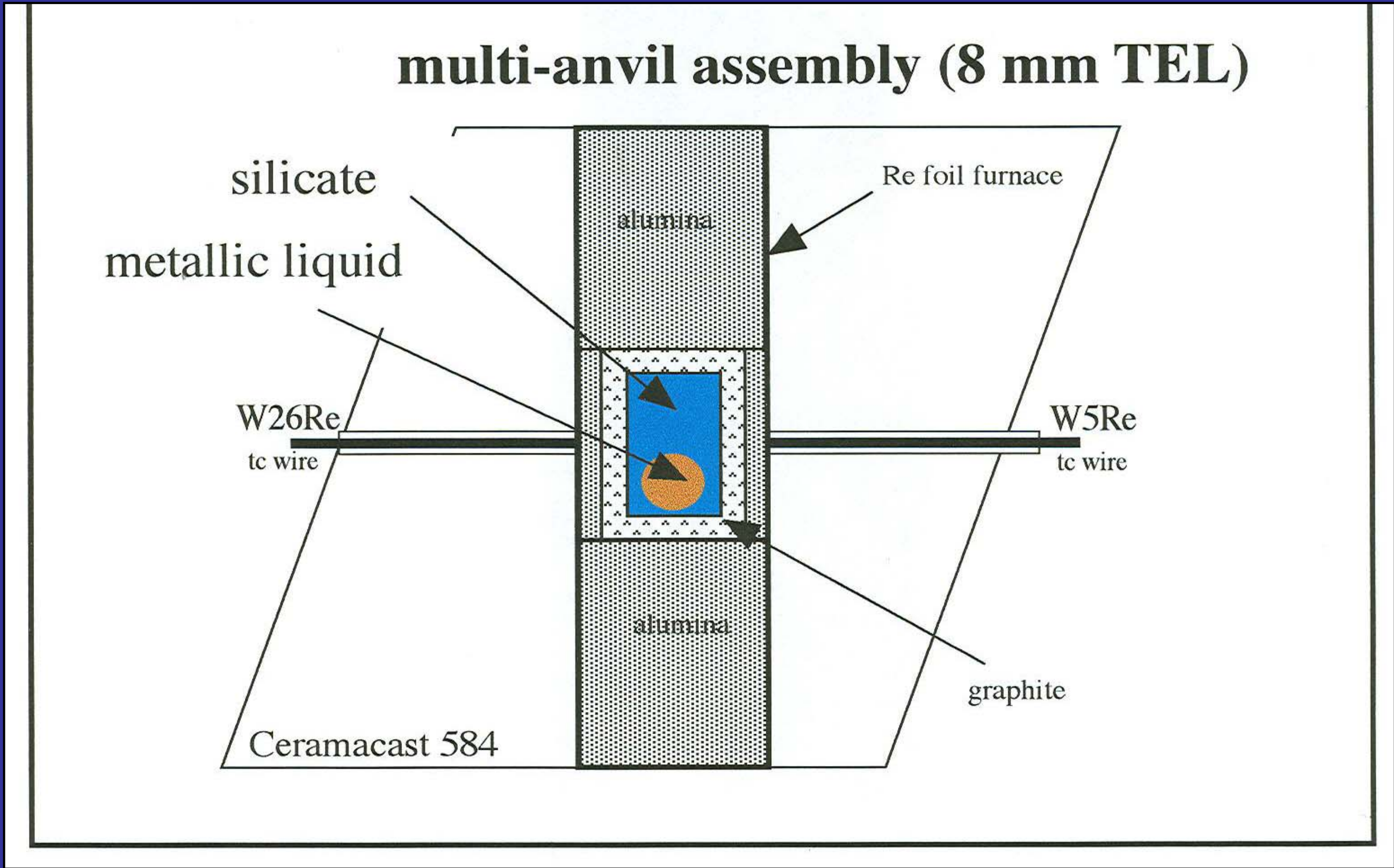


Octahedral pressure medium and tungsten carbide cubes

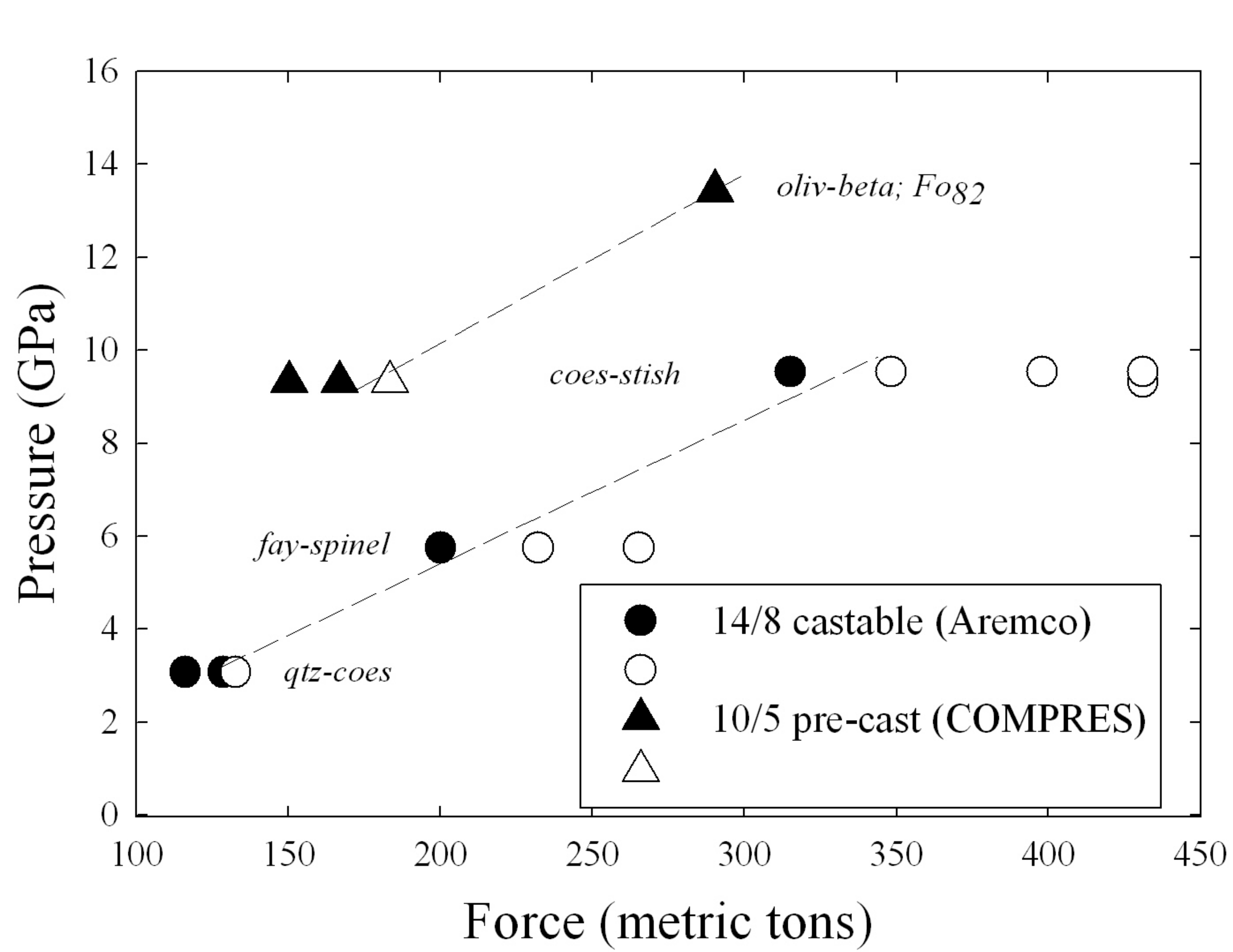


Pressure module and 6 wedges

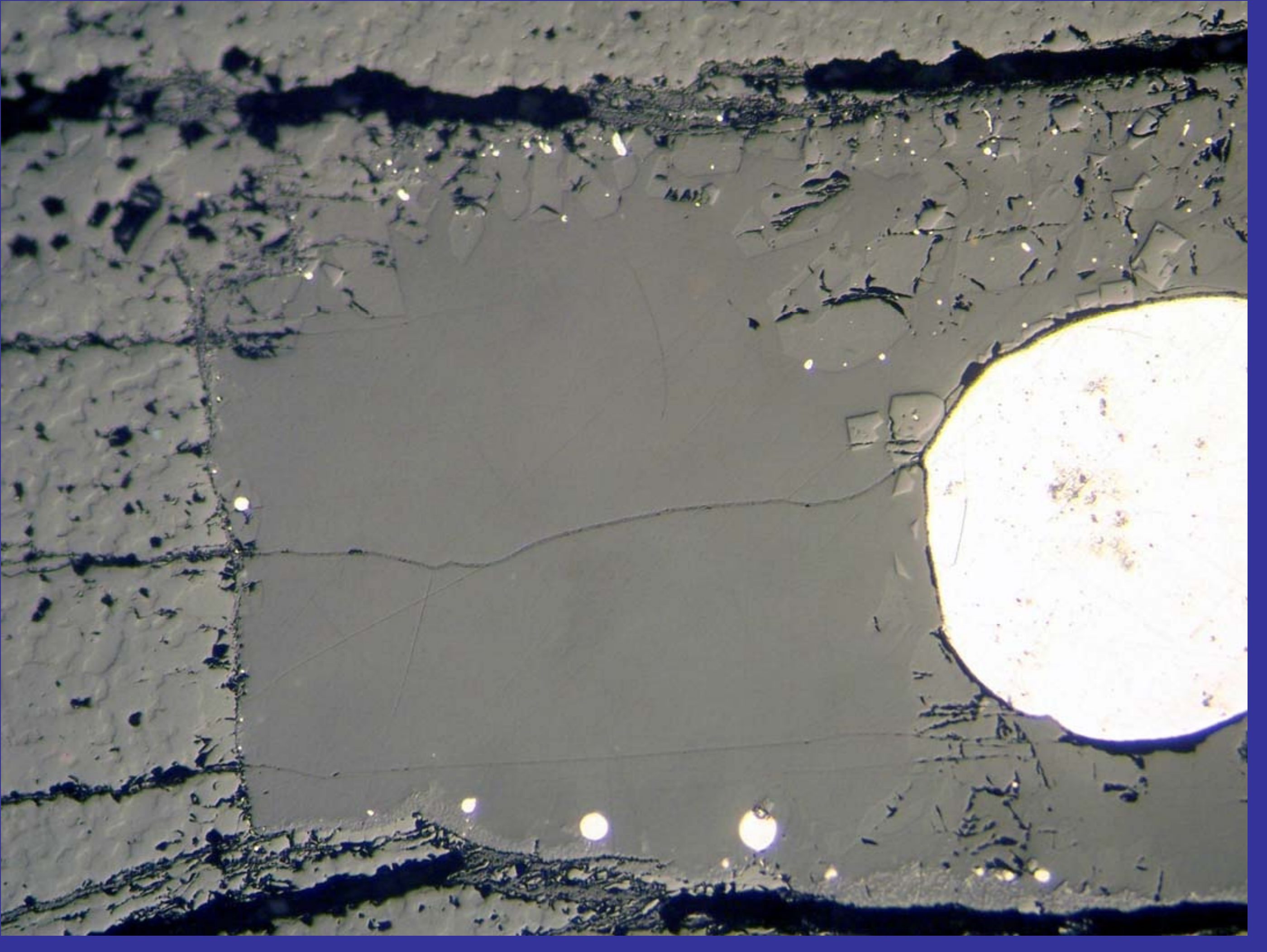
Experimental techniques



Pressure calibration by phase bracketing



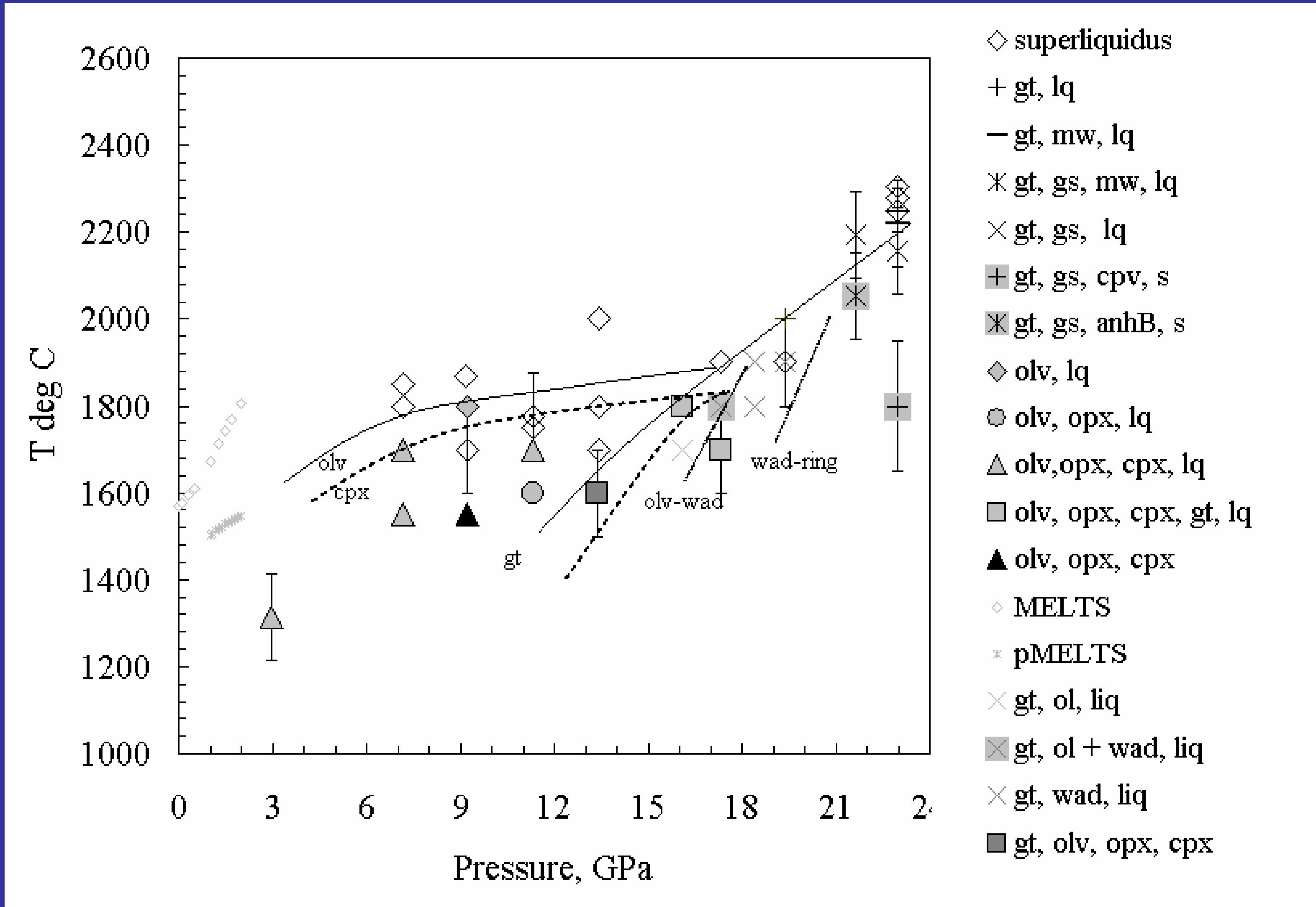
Run products can be cut and polished and analyzed using EMPA, SIMS, LA-ICP-MS, SEM, etc.



1.5 GPa, 1800 °C, basalt and metal

1 mm

High PT phase diagram for Richardton H5

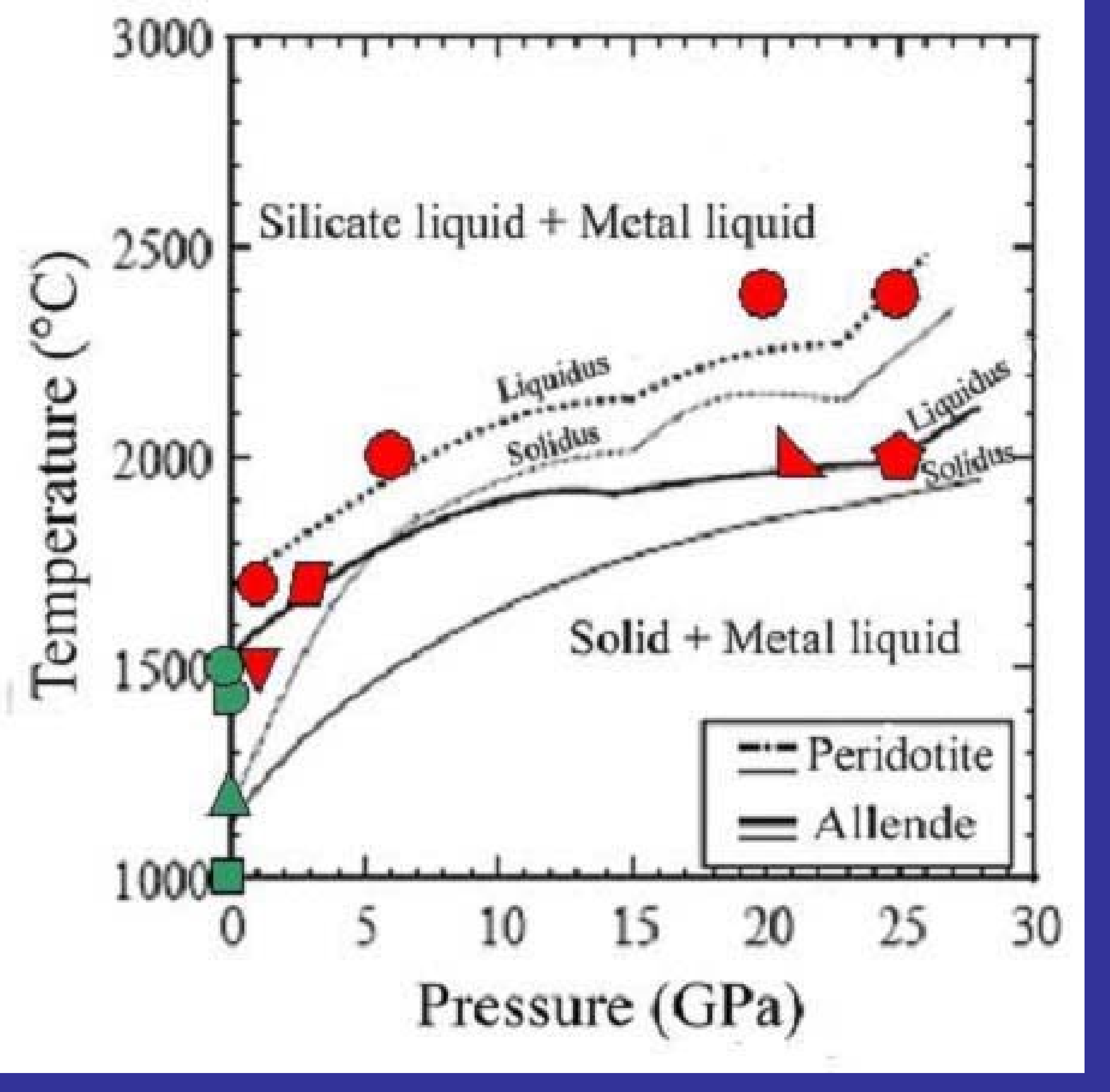


From Lisa Danielson, Melanie Channon, Josh Garber

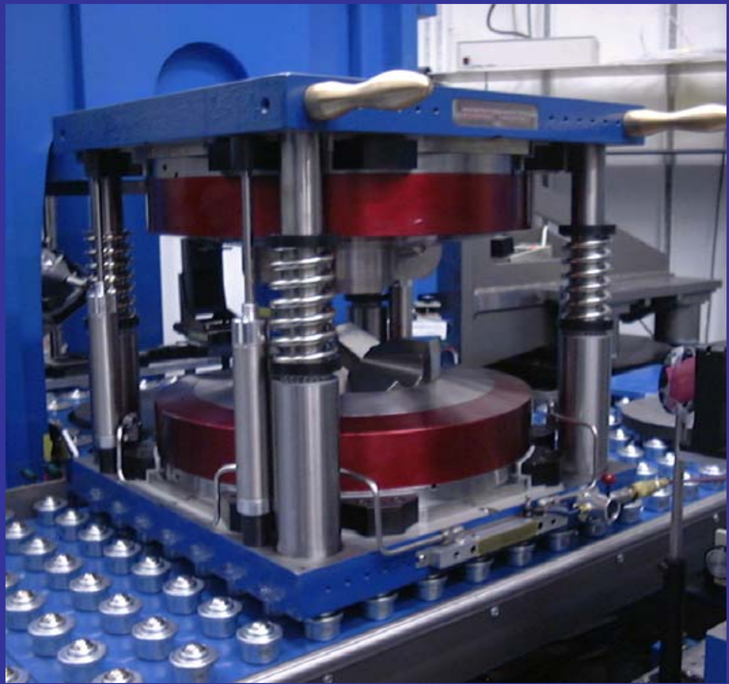
High PT phase equilibria of enstatite chondrites

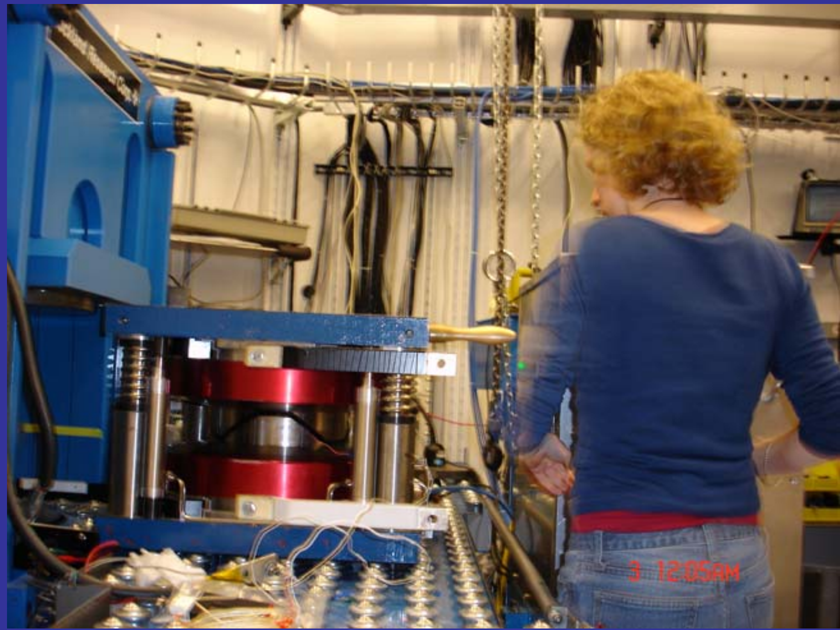
From Sophie Berthet

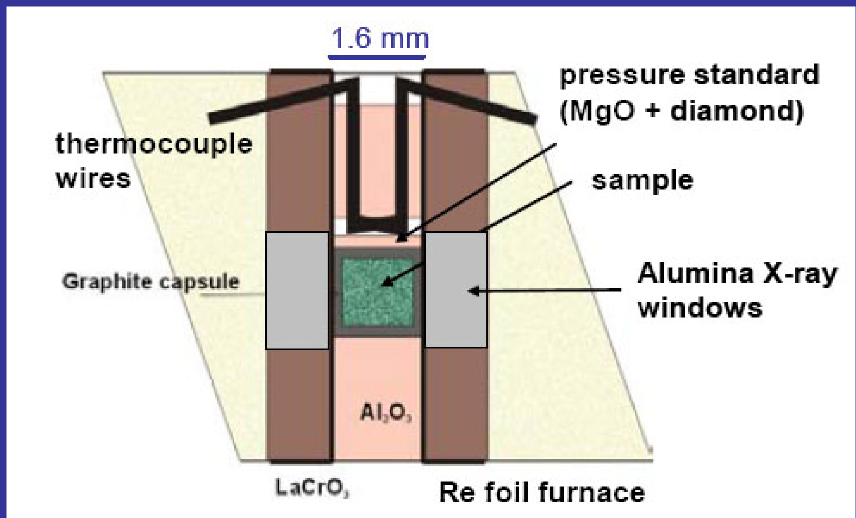
Ph.D. thesis research



In situ phase equilibria – Argonne National Lab







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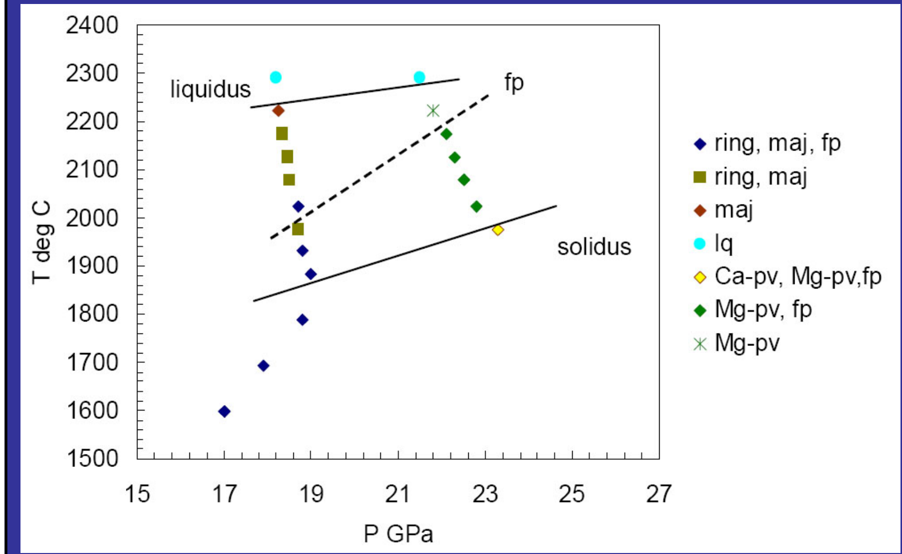
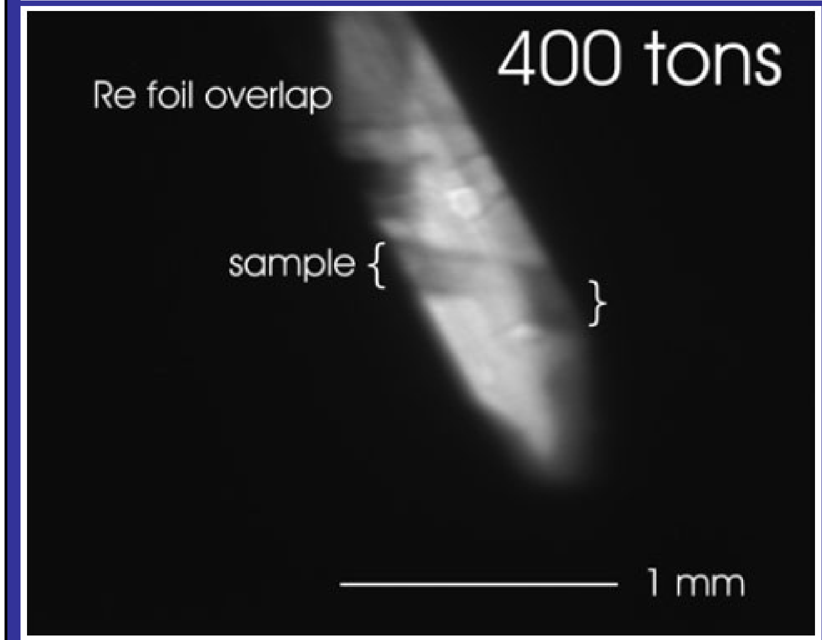
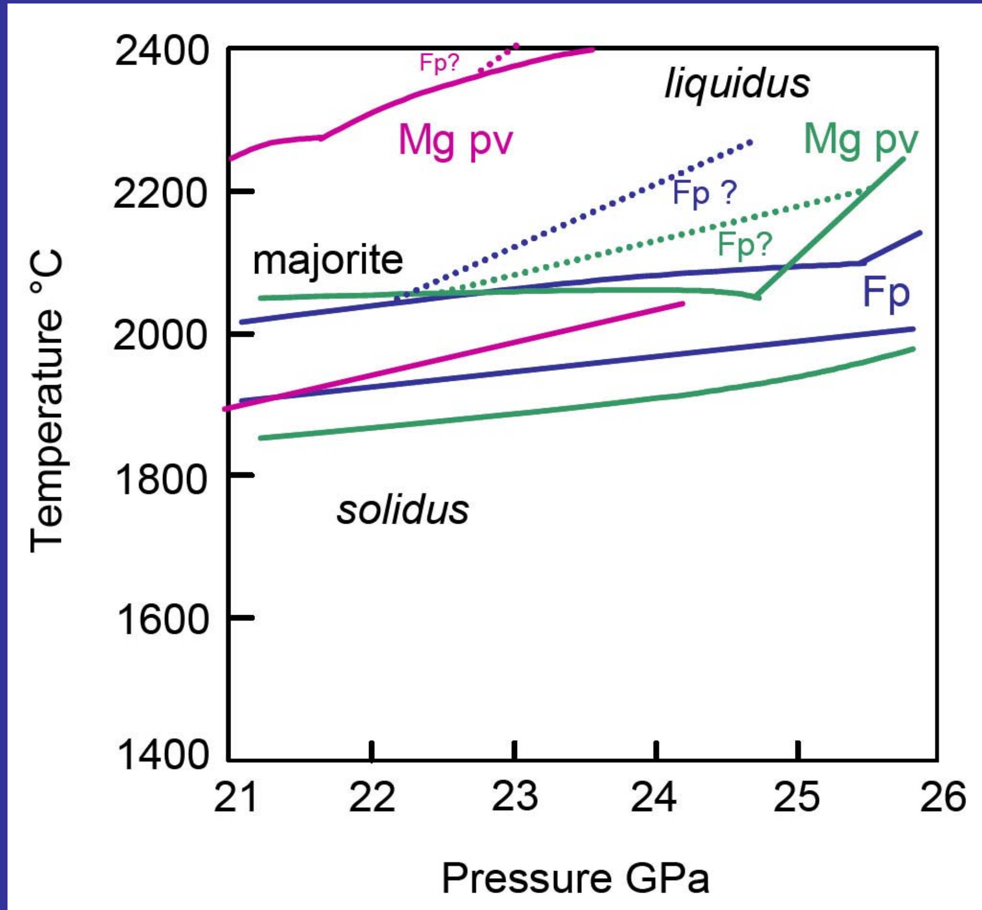






From Danielson et al. (2006)

Oxygen fugacity (fO_2)

$$2Fe + O_2 = 2FeO$$

(solid) (gas) (solid)

1) Fugacity is really just pressure

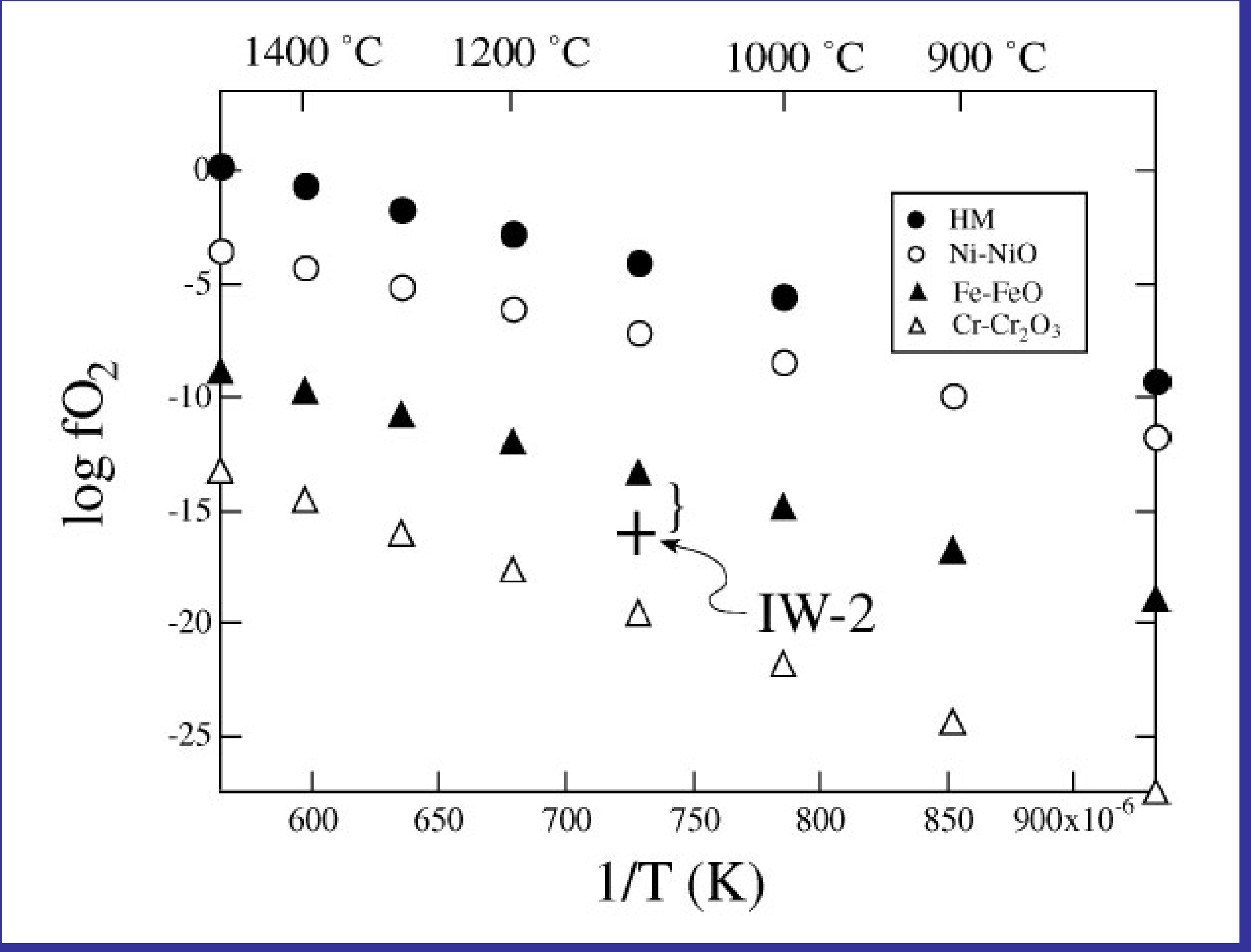
(ideal gas has a fugacity = pressure;

non-ideal gas has fugacity ≠ pressure)

2) The above equilibrium is called a “buffer” – will stay at the same value of fO_2, regardless of how much Fe or FeO is added

Oxygen fugacity

Absolute, relative



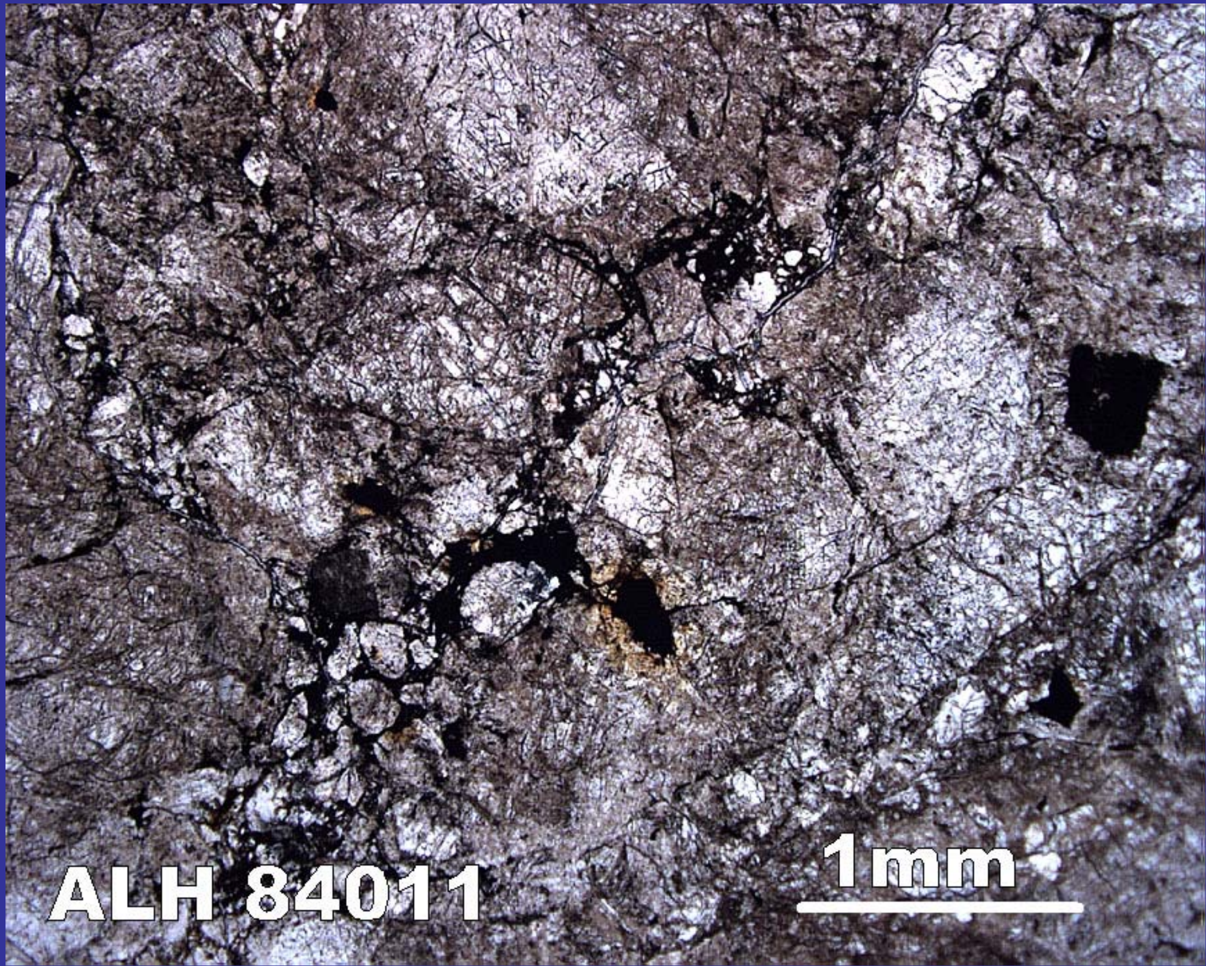
Fe-FeO

Iron-wüstite
or
"IW"

From Righter (2003)

Oxygen fugacity – reduced example

$$\underset{\text{metal}}{Si} + \underset{\text{metal}}{Fe} + \underset{\text{gas}}{3/2\, O_2} = \underset{\text{orthopyroxene}}{FeSiO_3}$$

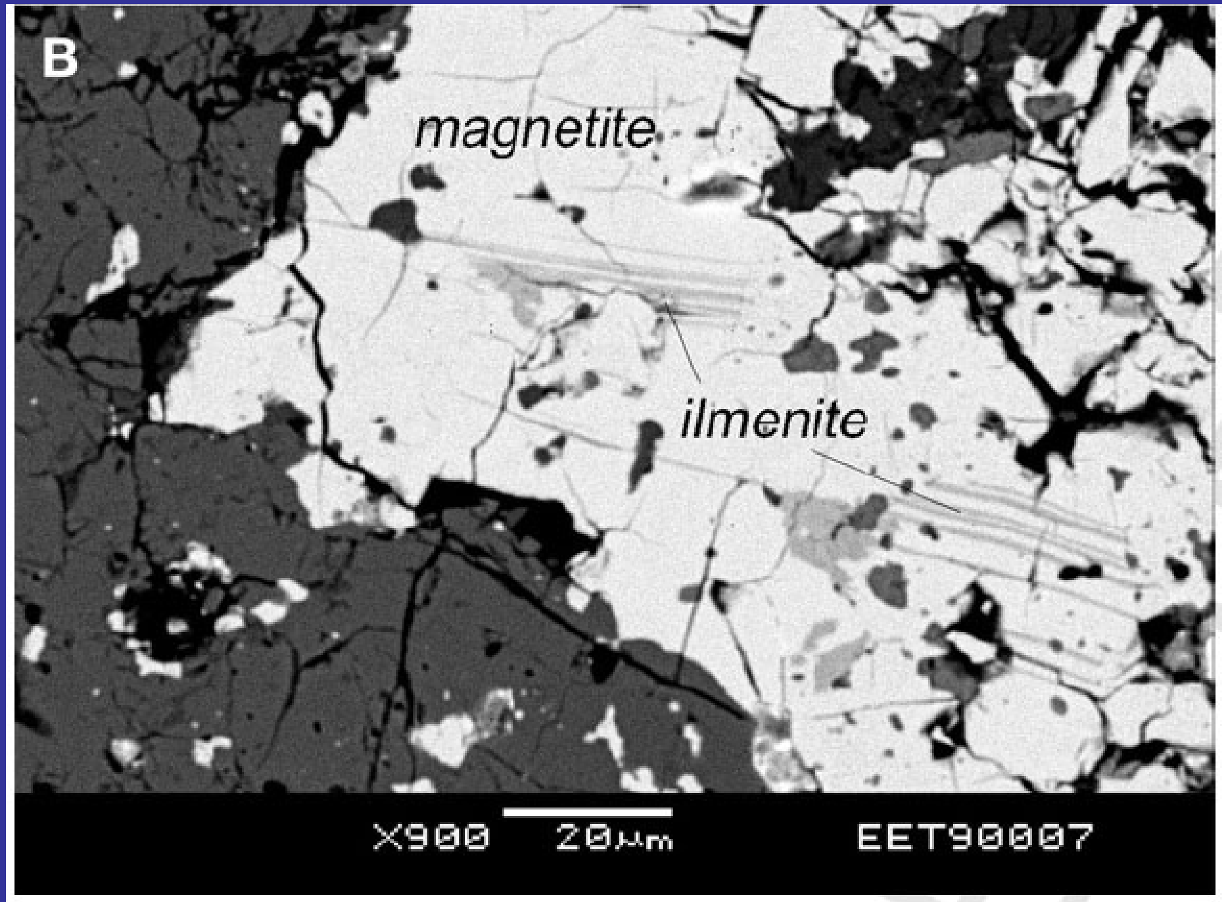


Aubrite or “enstatite achondrite” ALH 84011

Oxygen fugacity – oxidized example

$$2\ Fe_3O_4 + \tfrac{1}{2}\ O_2 = 3\ Fe_2O_3$$

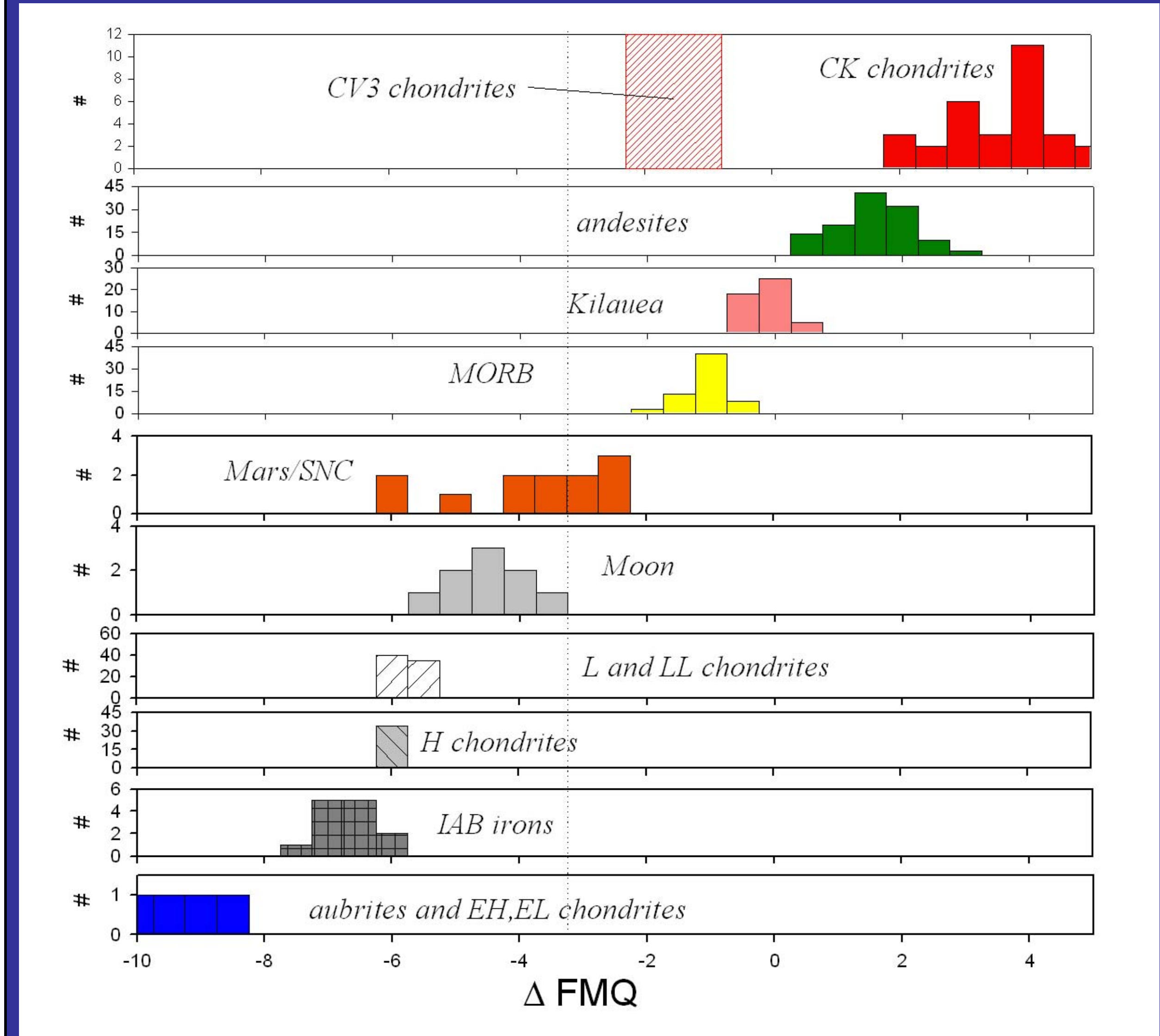
magnetite gas hematite



From Righter and Neff (2007)

CK chondrite EET 90007

Oxygen fugacity

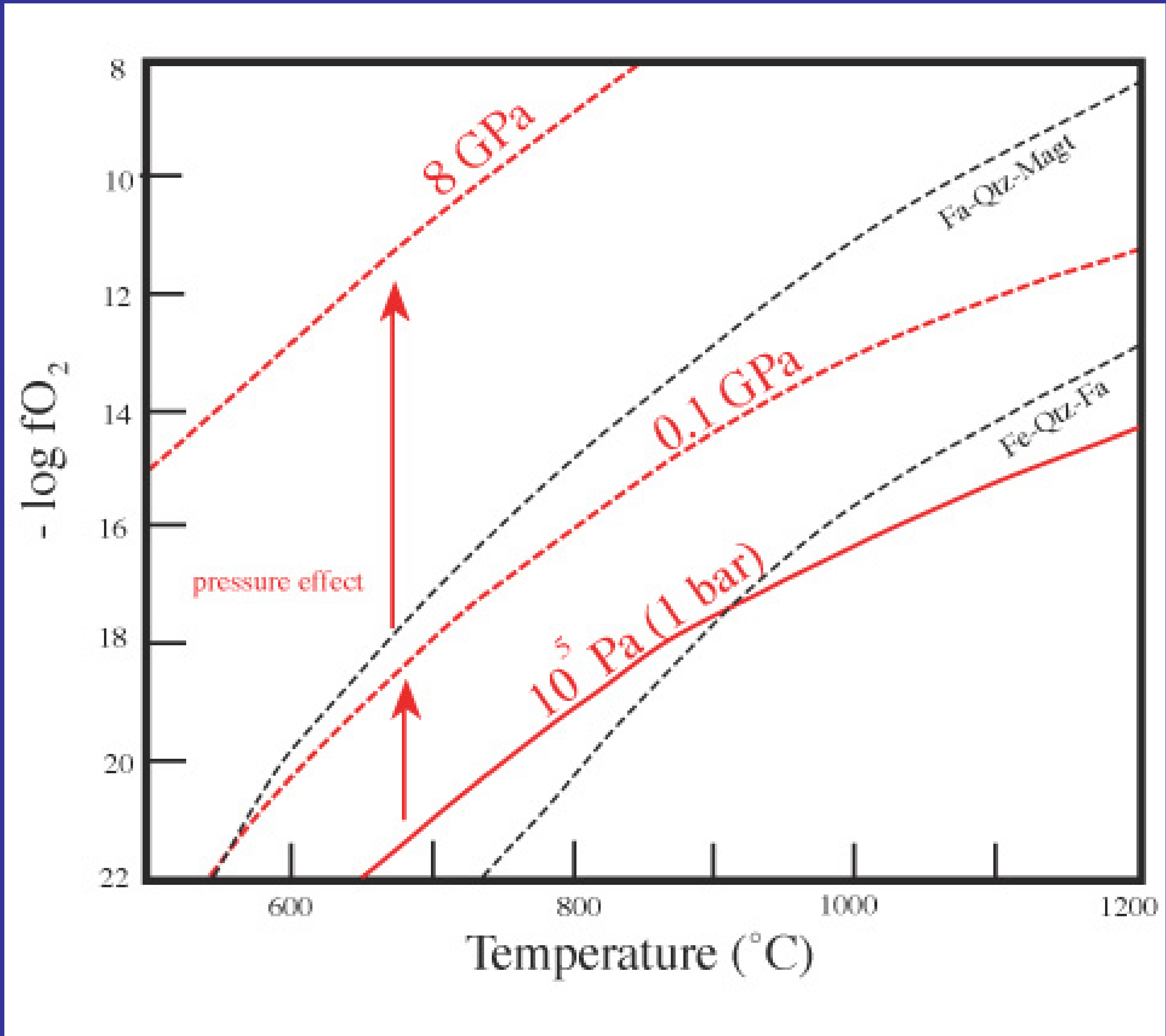


Oxygen fugacity varies within chondrite groups by 15 orders of magnitude

From Righter and Neff (2007)

Oxygen fugacity

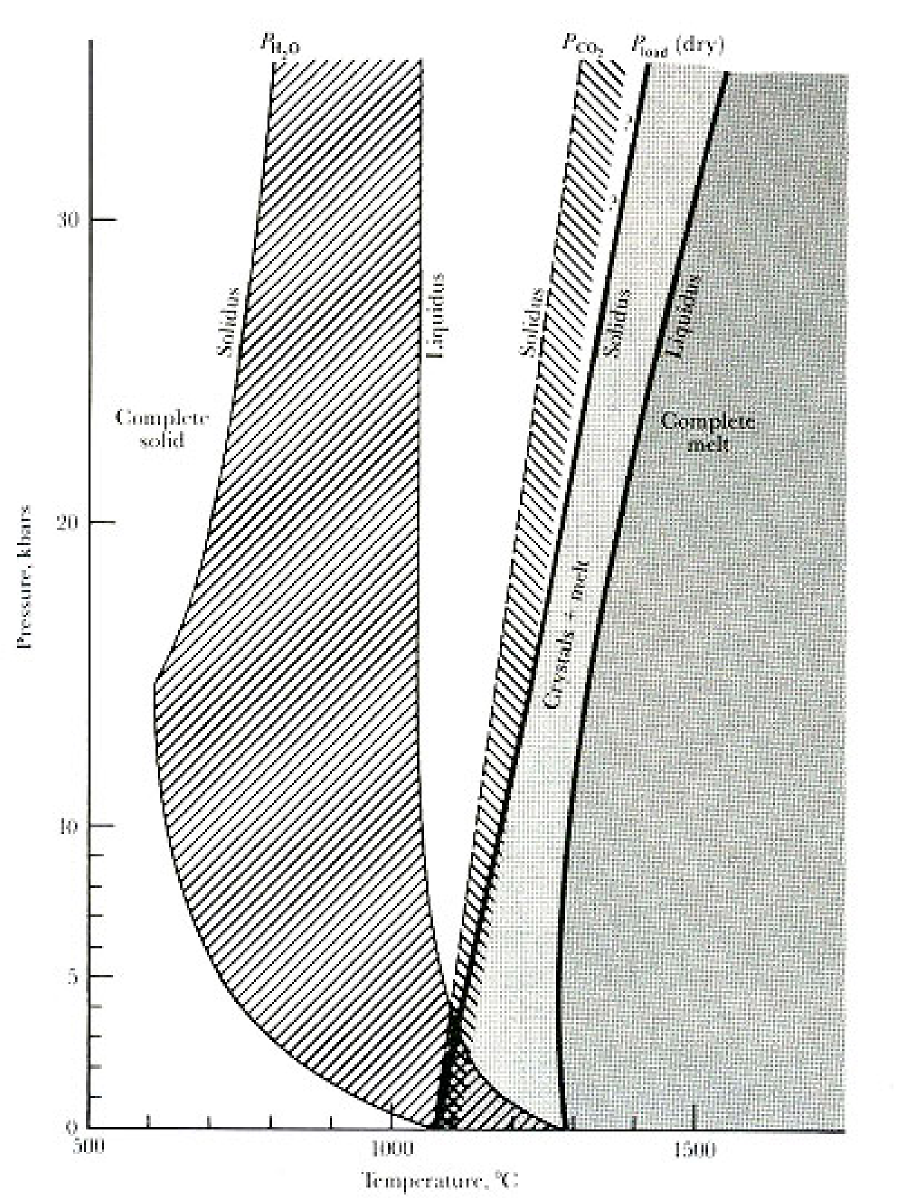
P, fO_2, and C-CO-CO_2 system



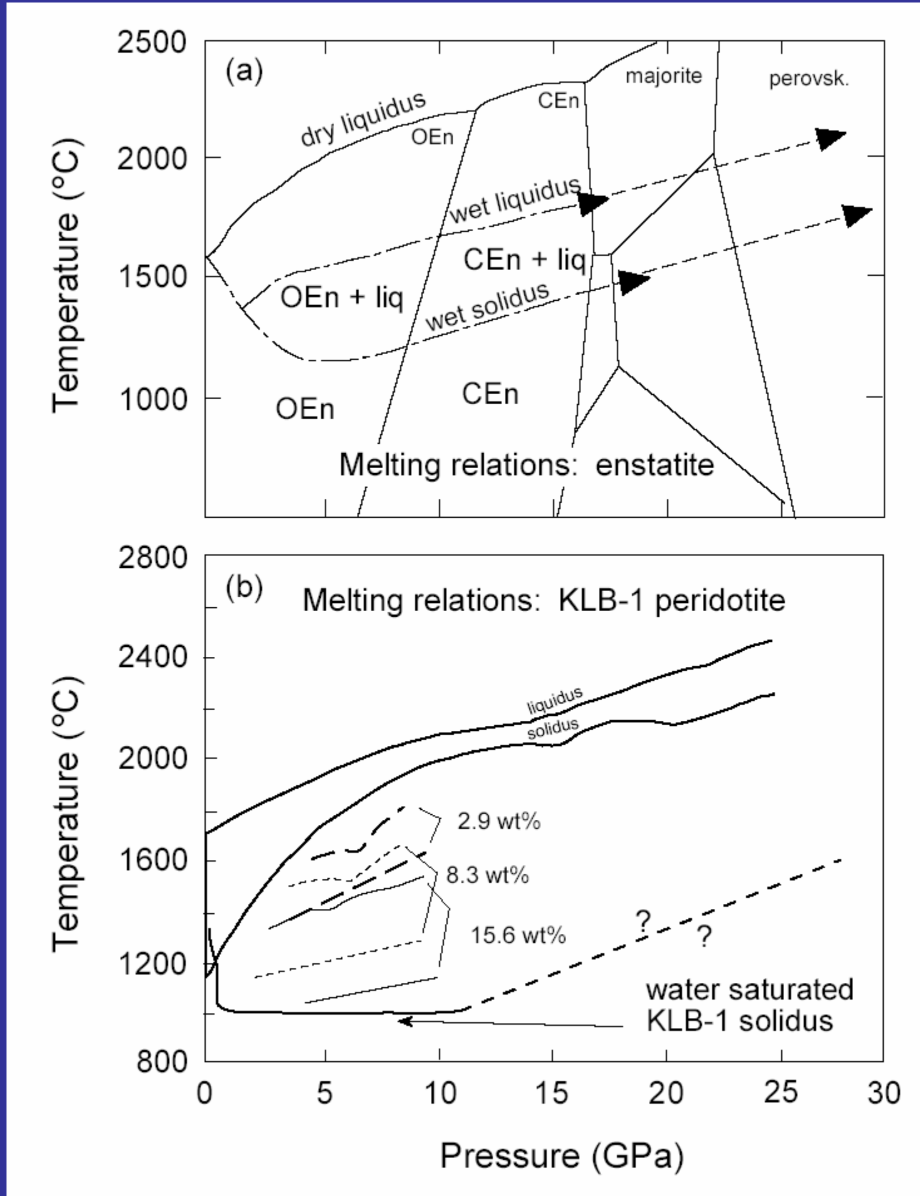
Graphite can buffer fO_2
Below metal stability field at low pressures.

And above metal stability at high pressure.

Water Depresses liquidus and solidus



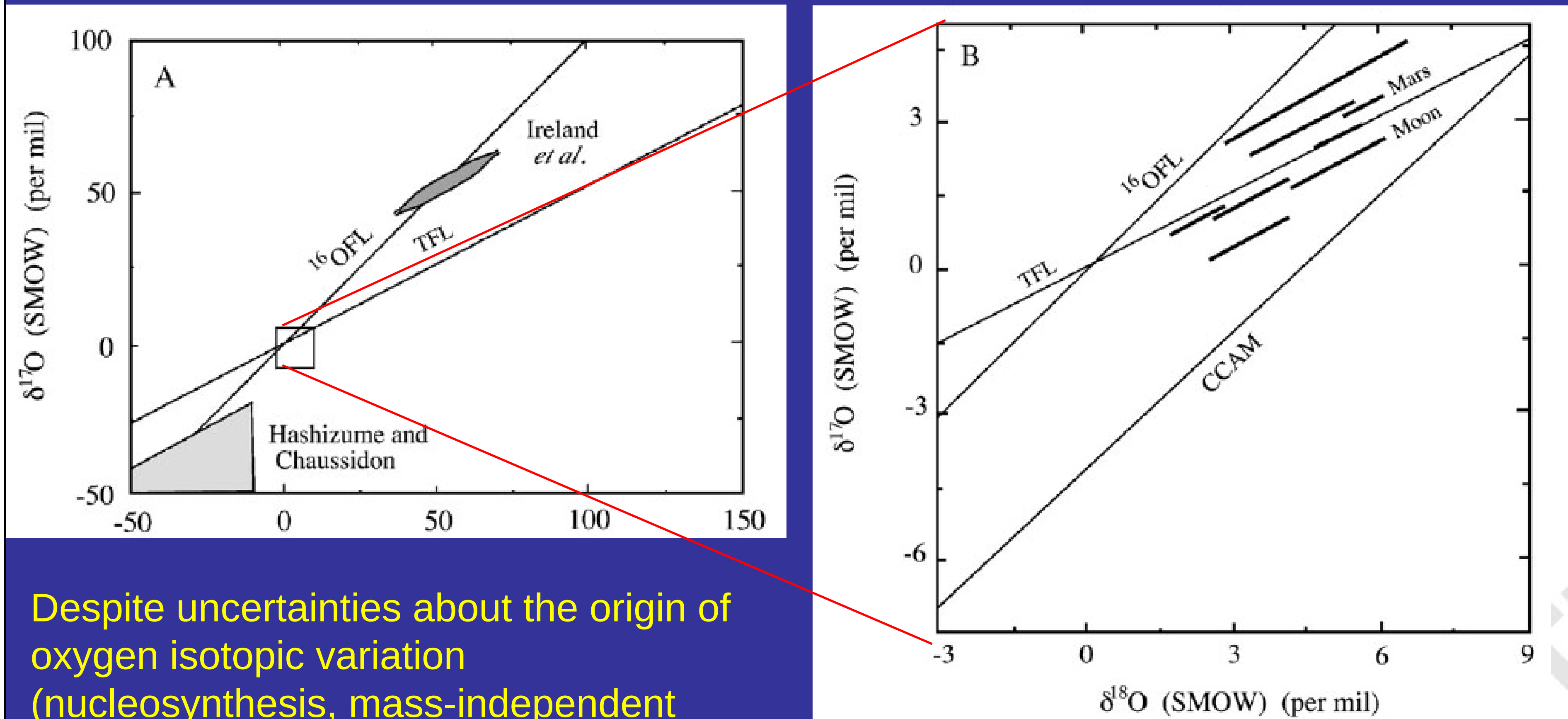
From Hyndman (1986)



From Abe et al. (2000)

Key parameters in defining bulk composition

Oxygen isotopes

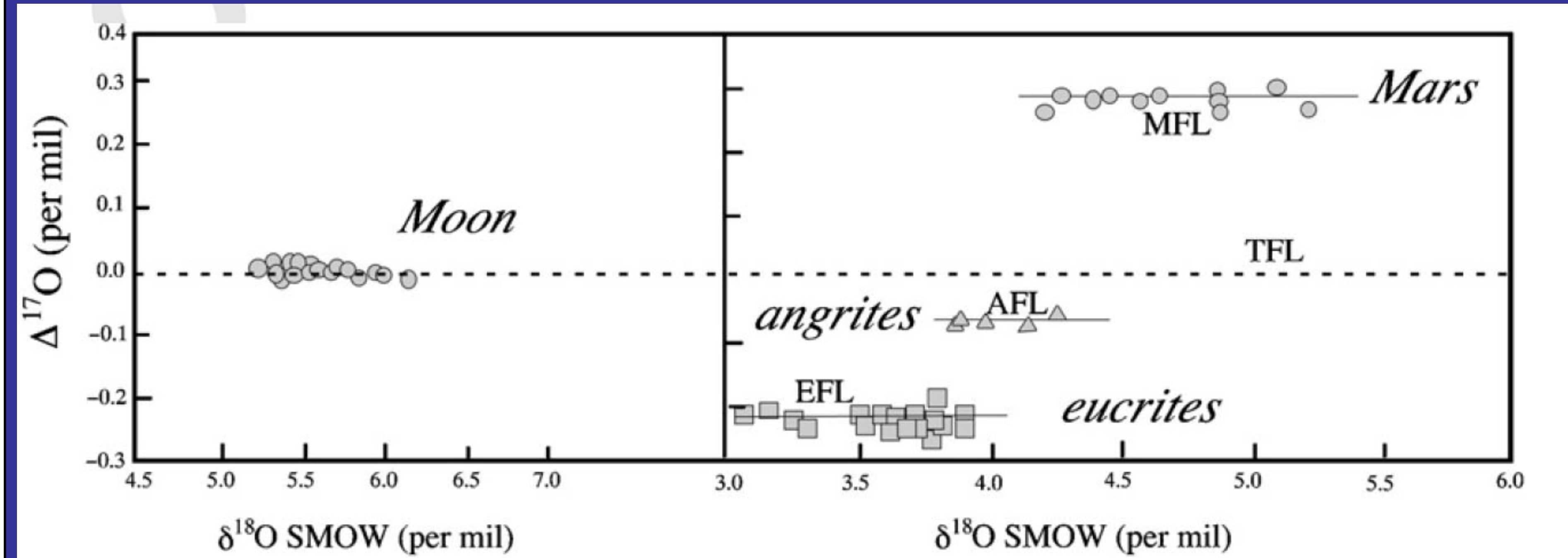


Despite uncertainties about the origin of oxygen isotopic variation (nucleosynthesis, mass-independent fractionation, or self-shielding), oxygen can be used to constrain source materials

From Righter (2007)

Key parameters in defining bulk composition

Oxygen isotopes

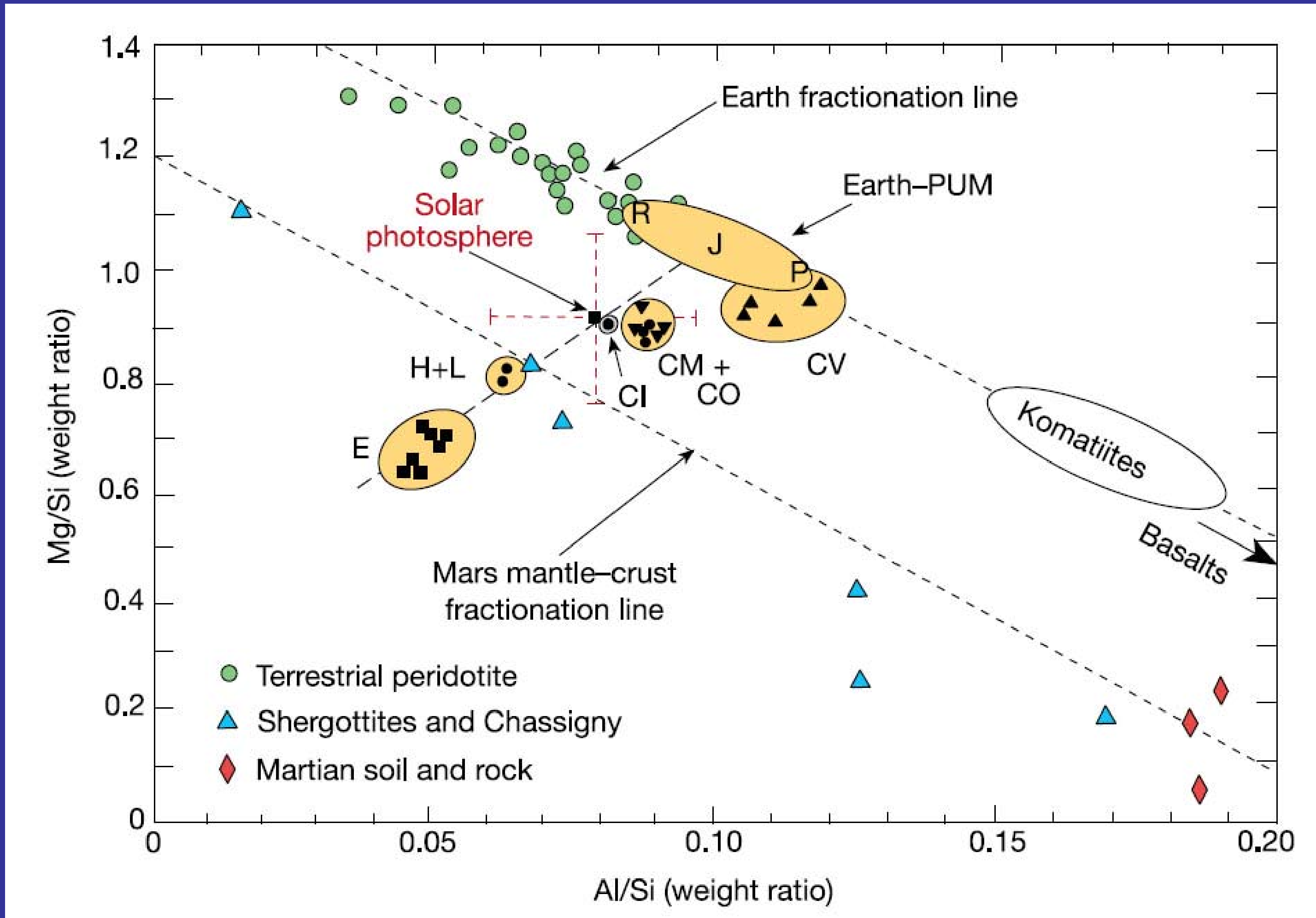


Differences between Mars, Earth-Moon, angrites and eucrites are small but measurable

From Righter (2007)

Key parameters in defining bulk composition

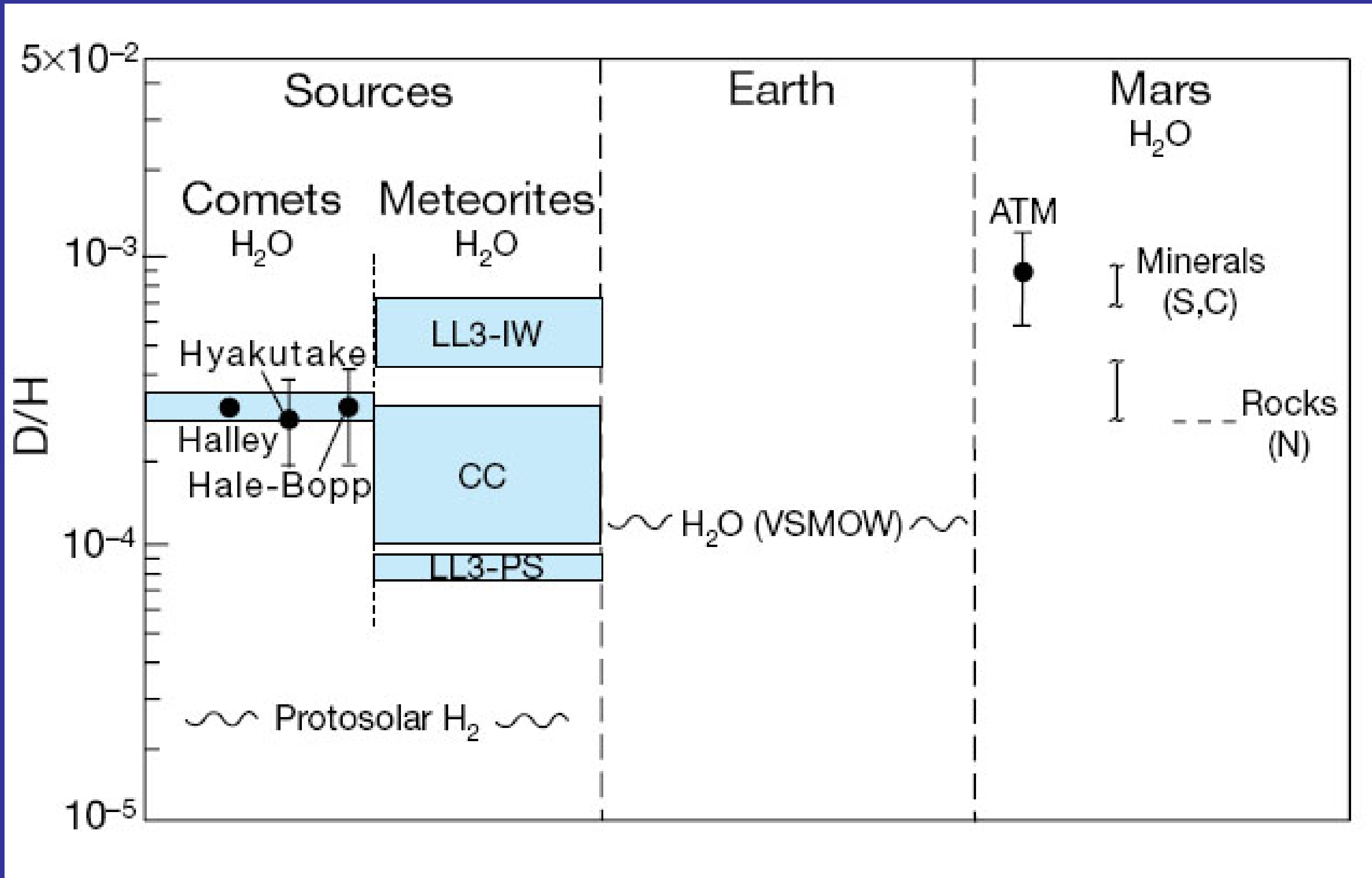
major elements



From Drake and Righter (2002)

Key parameters in defining bulk composition

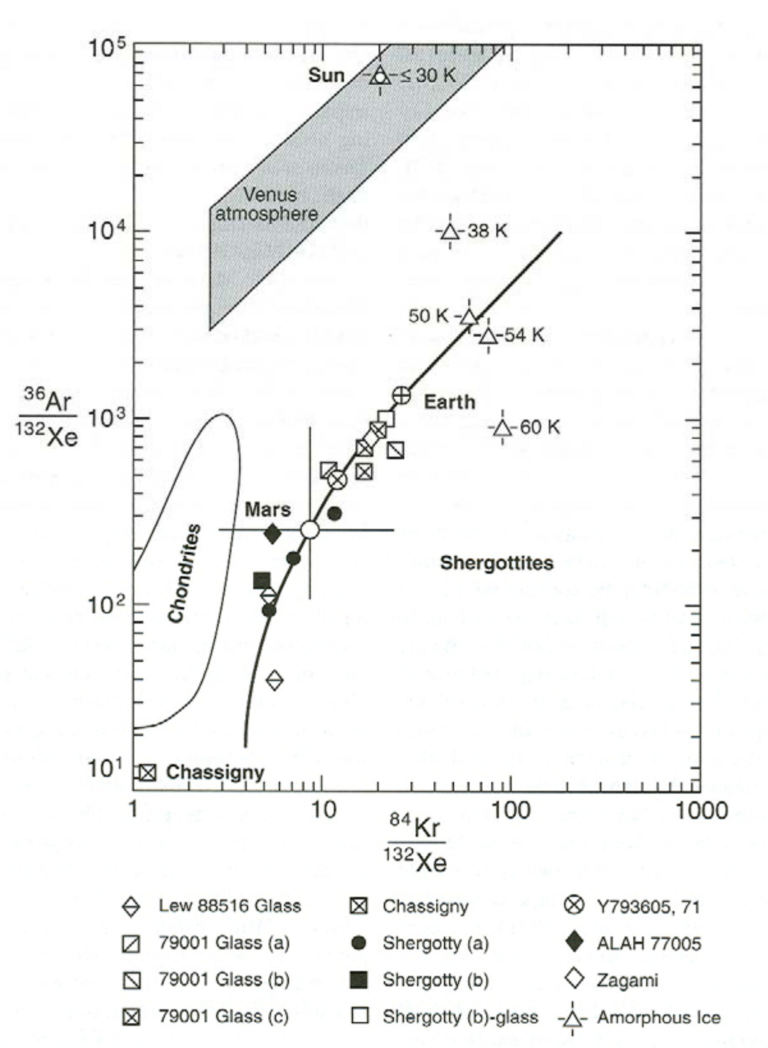
D/H and noble gases for volatile-bearing planets

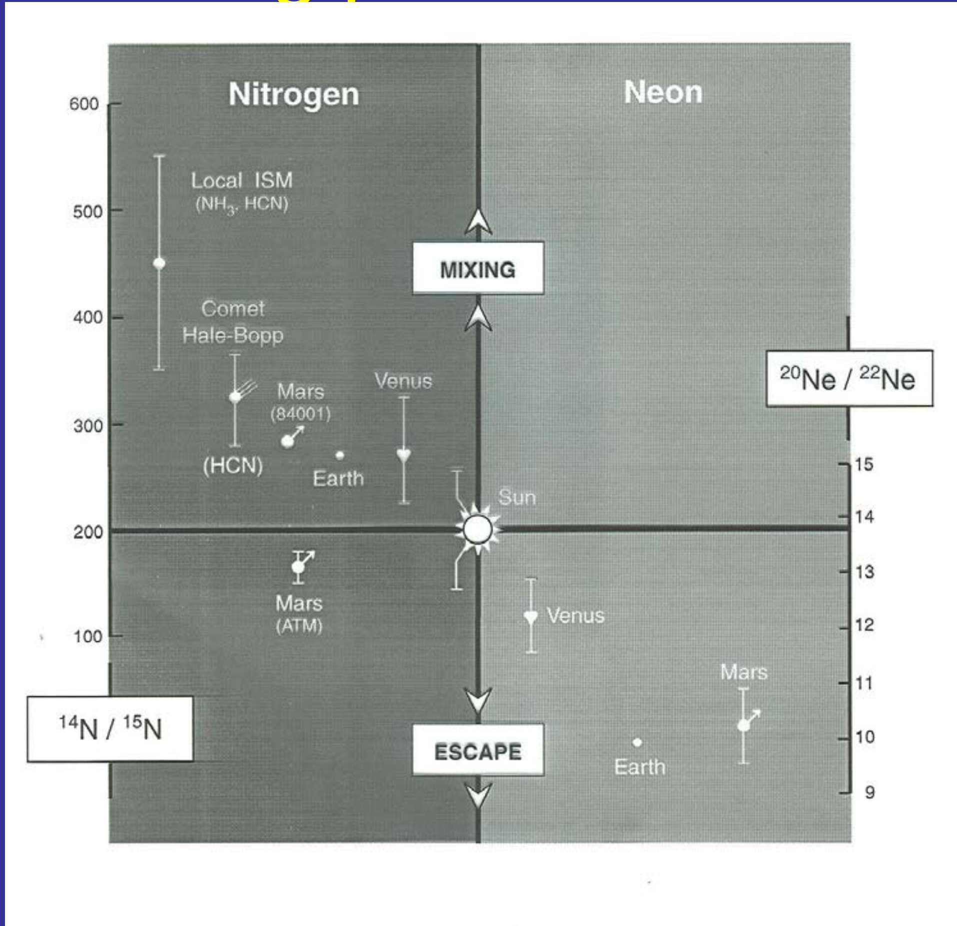


From Drake and Righter (2002)

Key parameters in defining bulk composition

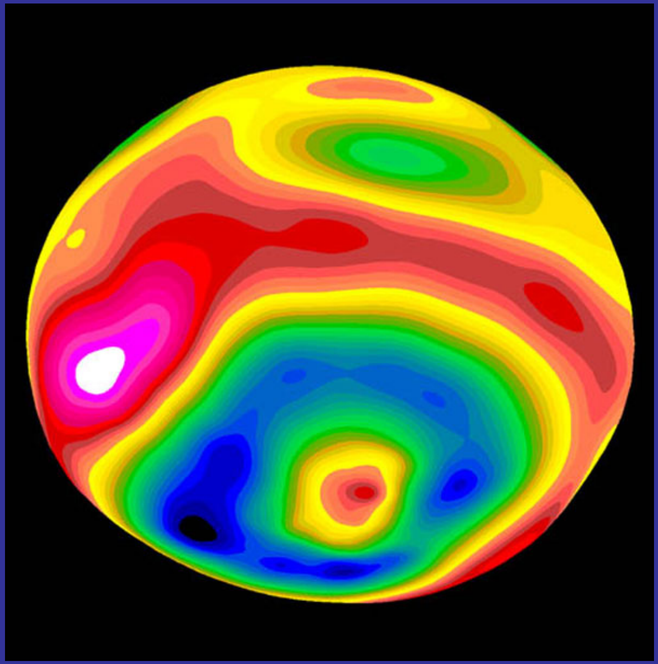
D/H and noble gases for volatile-bearing planets





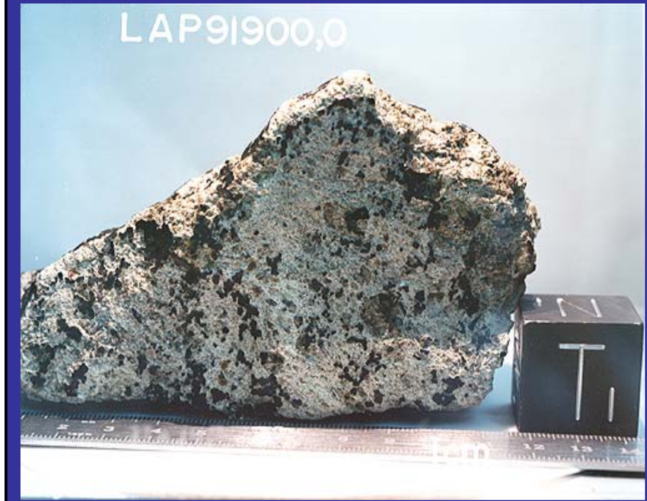
From Owen and Bar-nun (2000)

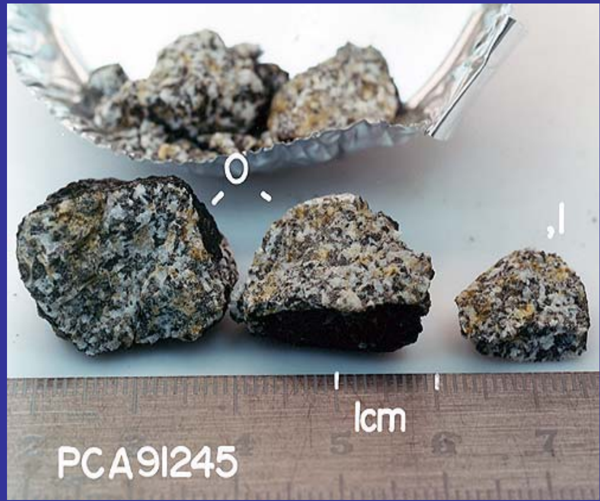
Example 1: 4 Vesta (HED parent body)



Enhanced from Hubble Space Telescope imaging – 1995 and 1996

Introduction: What are the HED meteorites ?

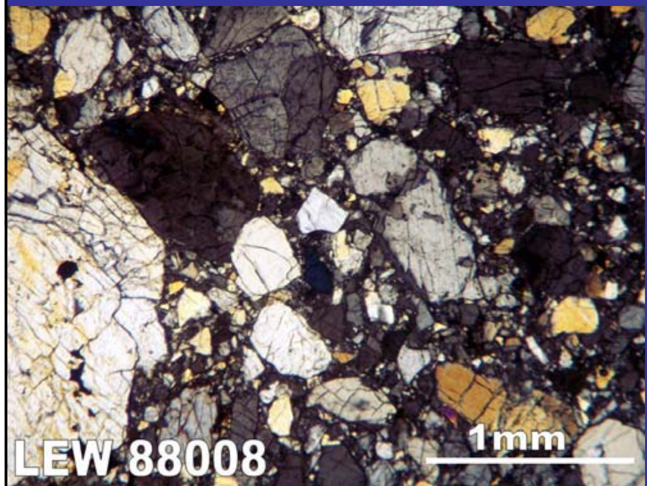


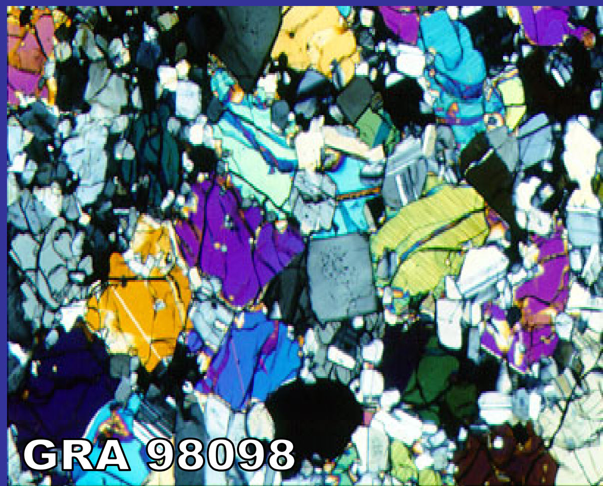


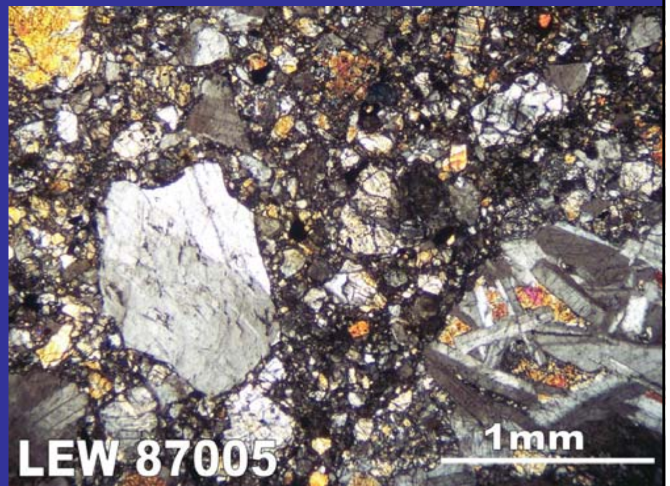
diogenite

eucrite

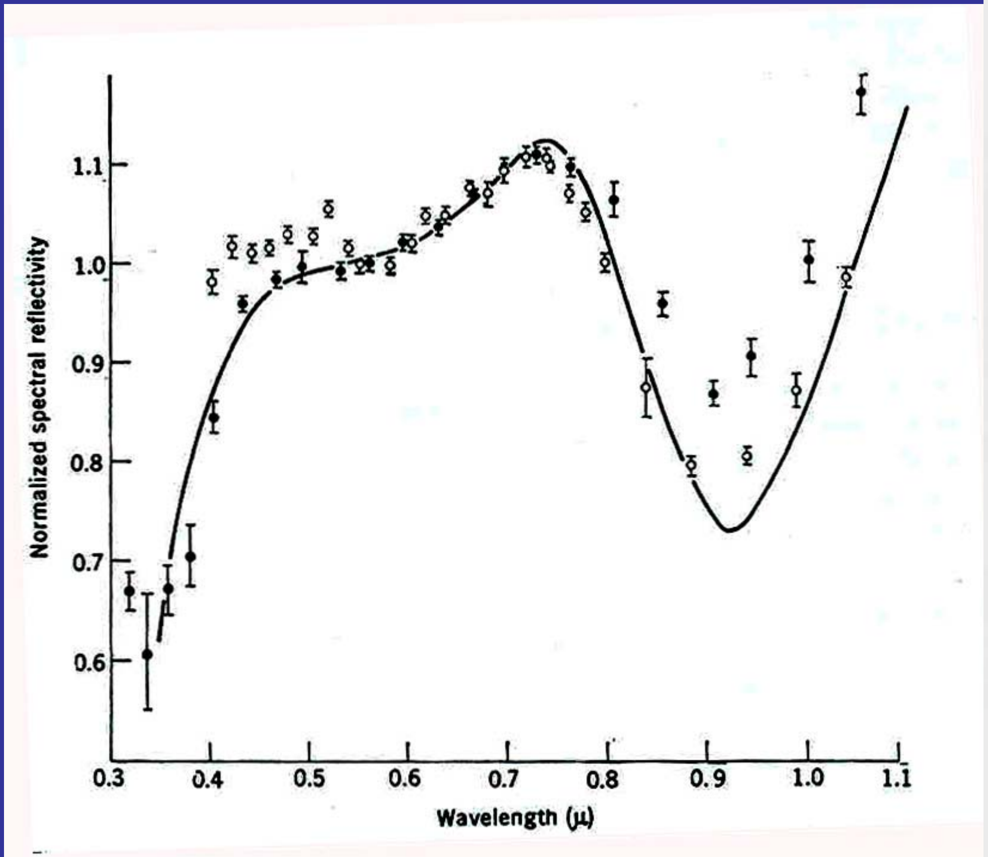
howardite



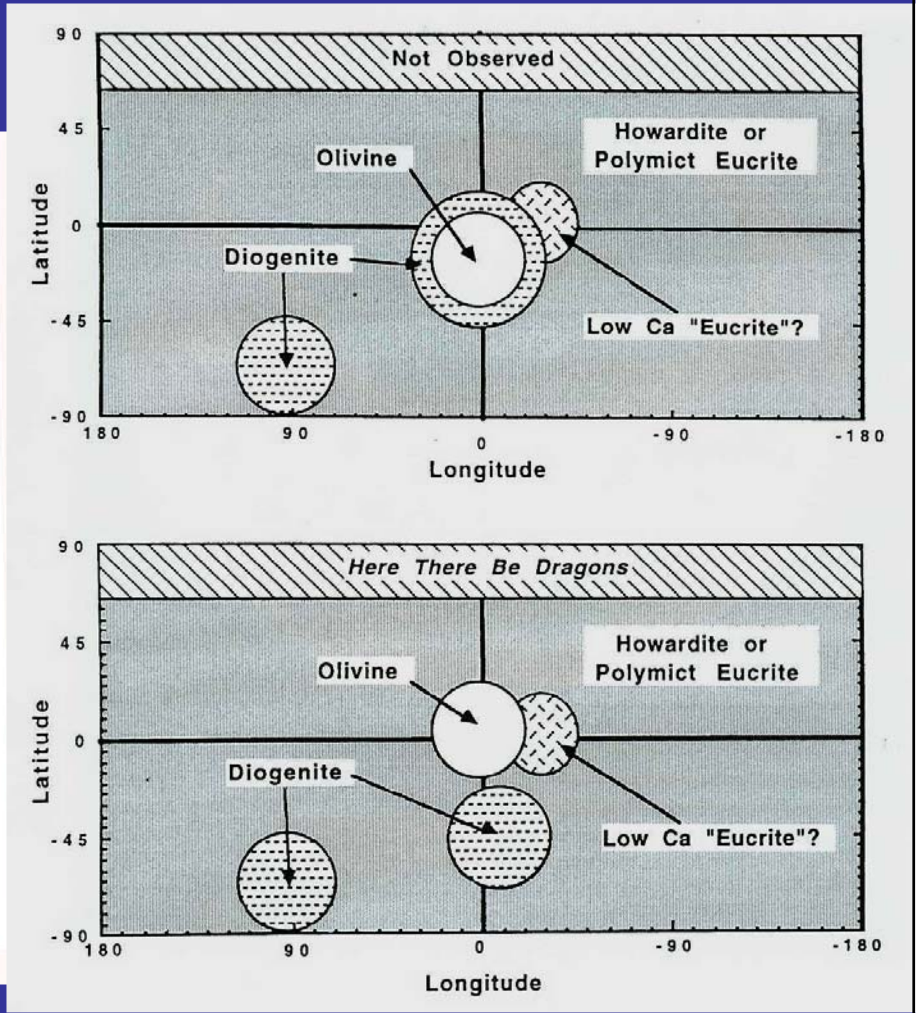




Vesta/HED link and history



McCord et al. (1970)

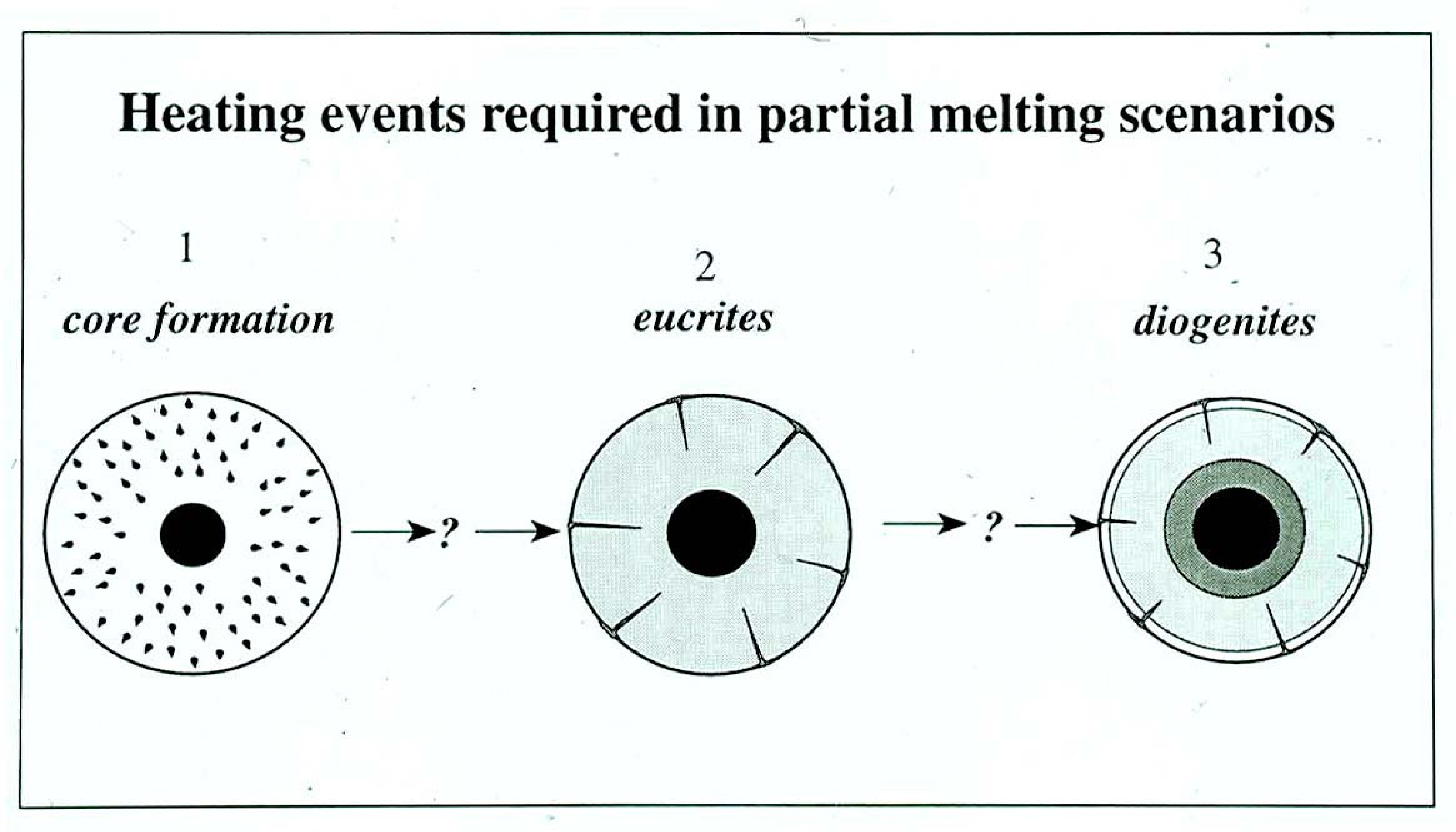


Gaffey (1997)

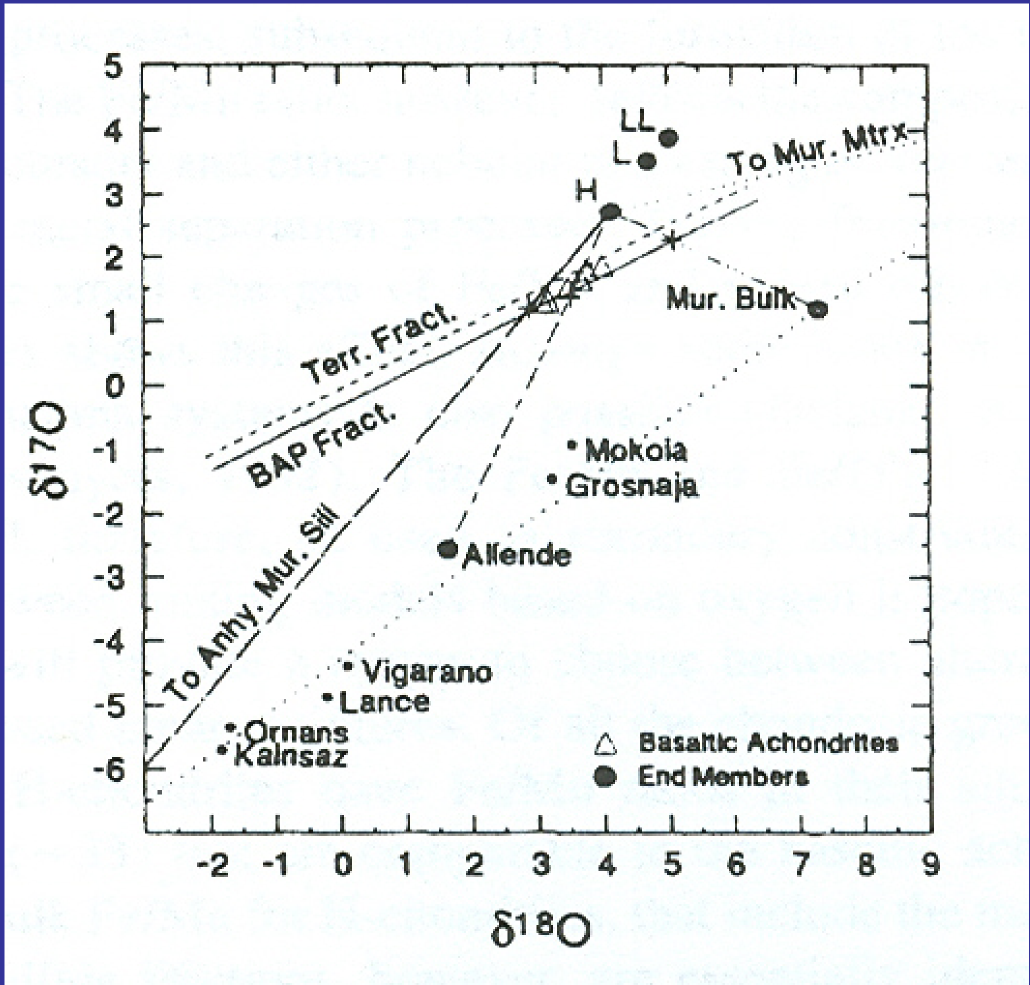
Vesta/HED problems

Should be a relatively simple case: low pressure and dry

- multiple heating?
- core formed?
- if partially melted, where are the residues?



Vesta: oxygen isotopes



Mixtures that satisfy
O isotopes

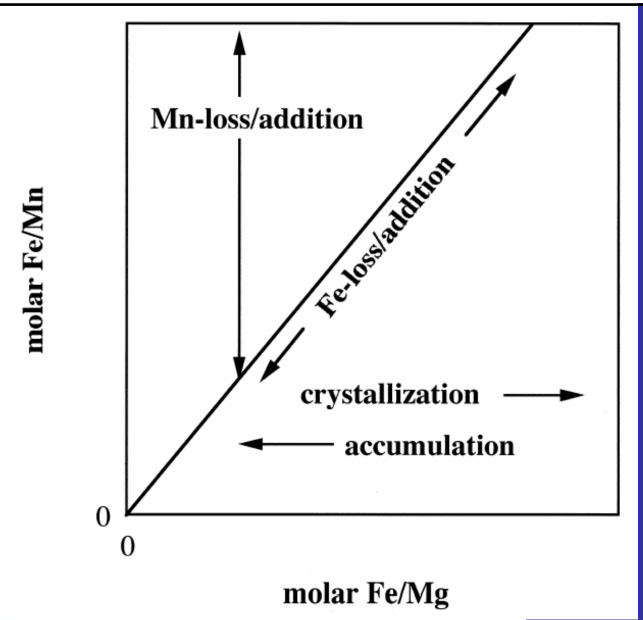
H-CV
L-CV
LL,L,H-CO

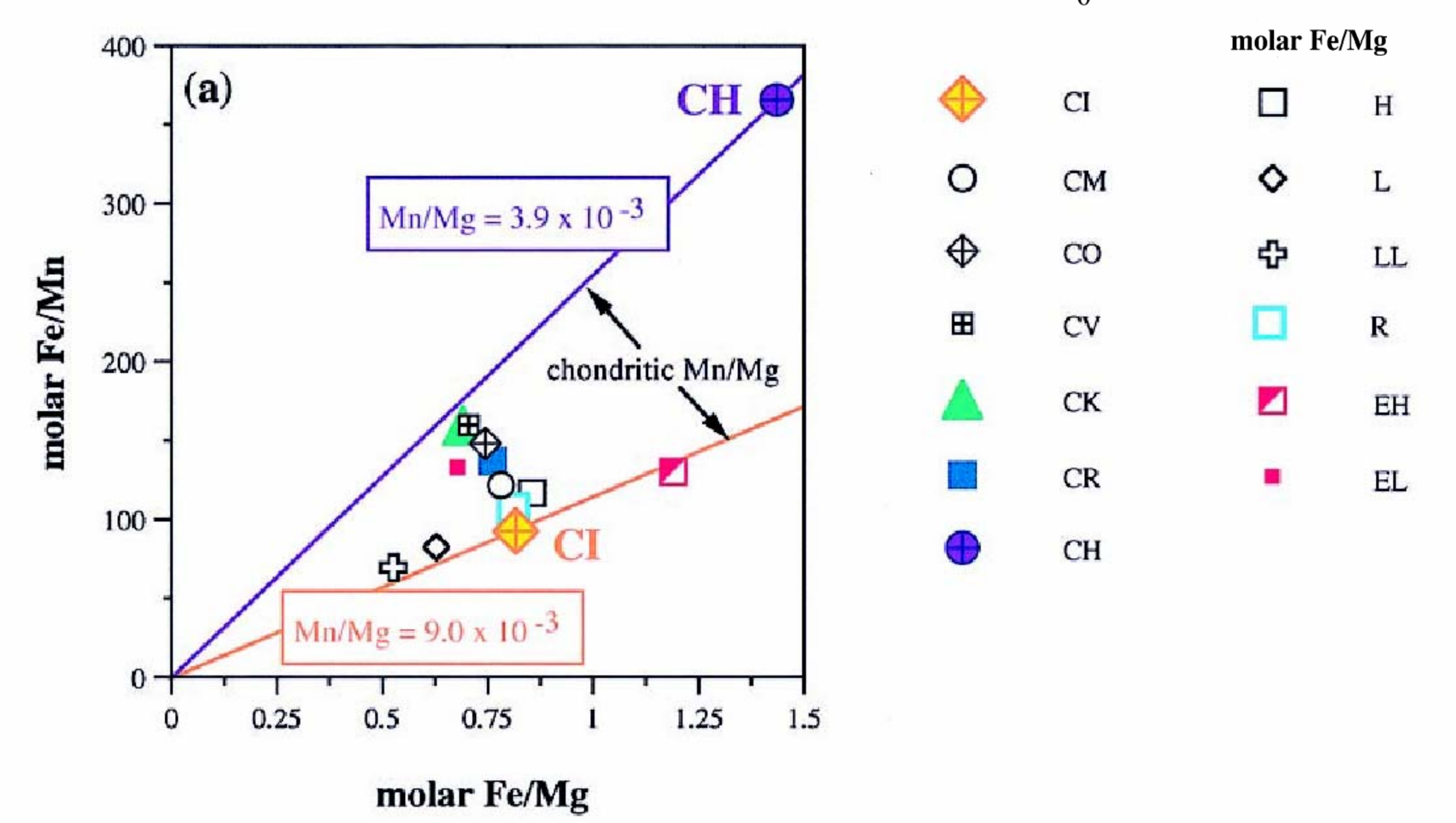
Boesenberg and Delaney (1997)

Fe/Mn relations

Mixtures that satisfy Fe/Mn

Goodrich and Delaney (2000)

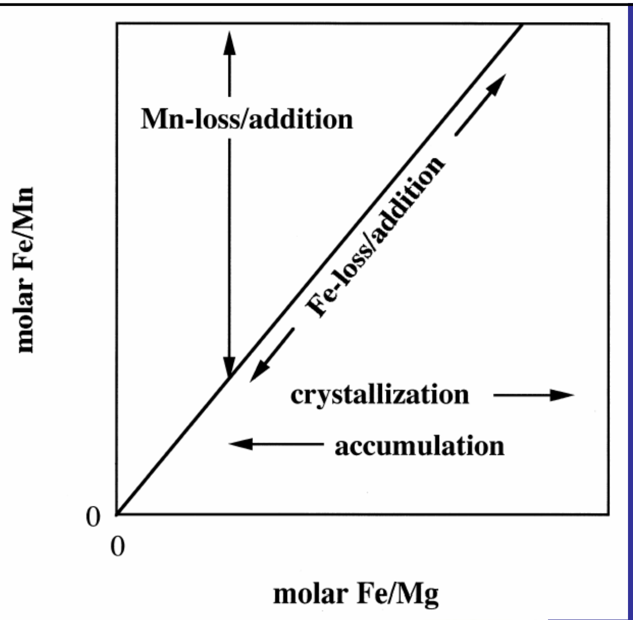


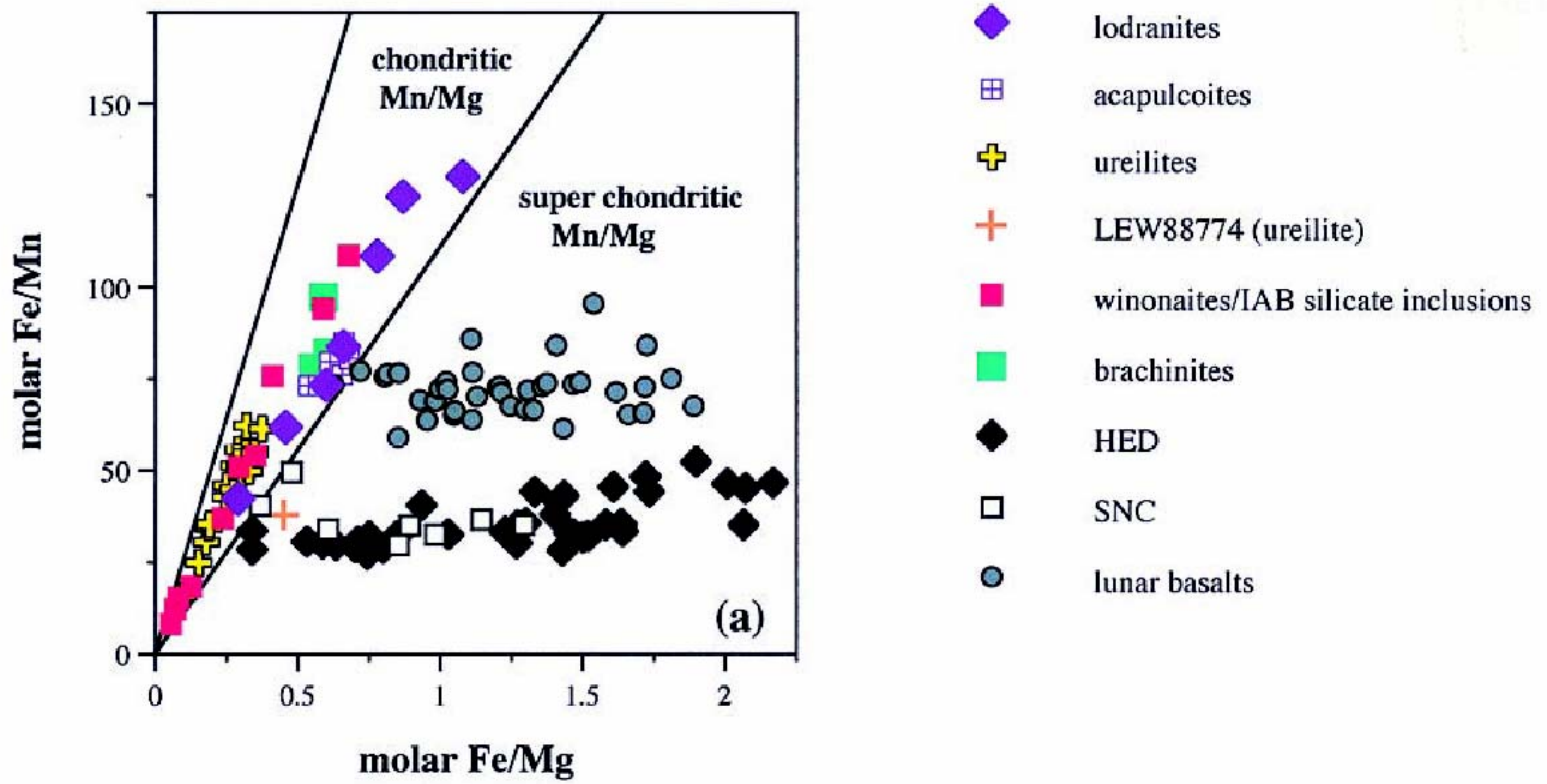


Fe/Mn relations

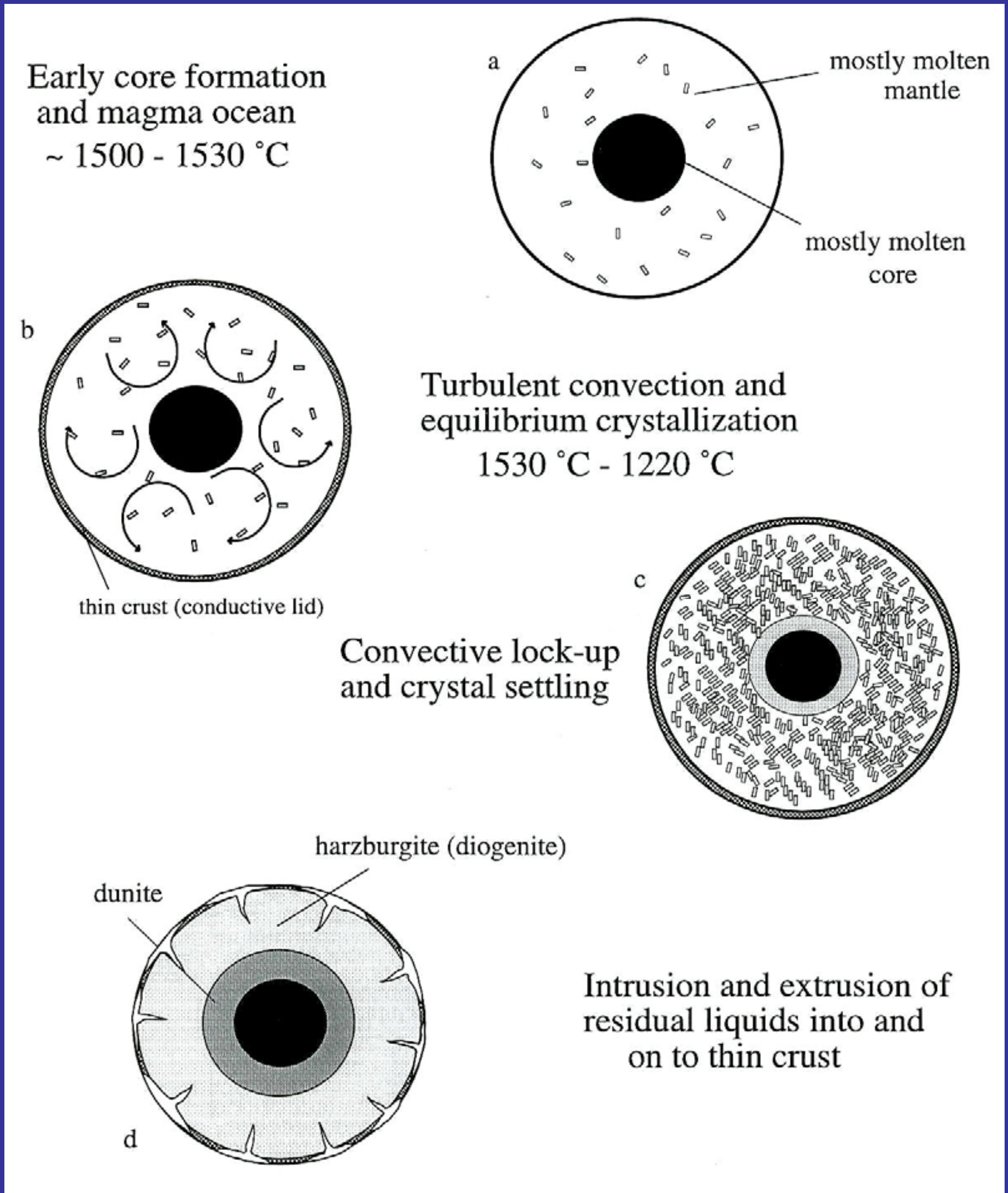
Mixtures that satisfy Fe/Mn

Goodrich and Delaney (2000)





Formation model for HED/Vesta



Can explain diogenites, later eucrites and later mixing of two to form howardites

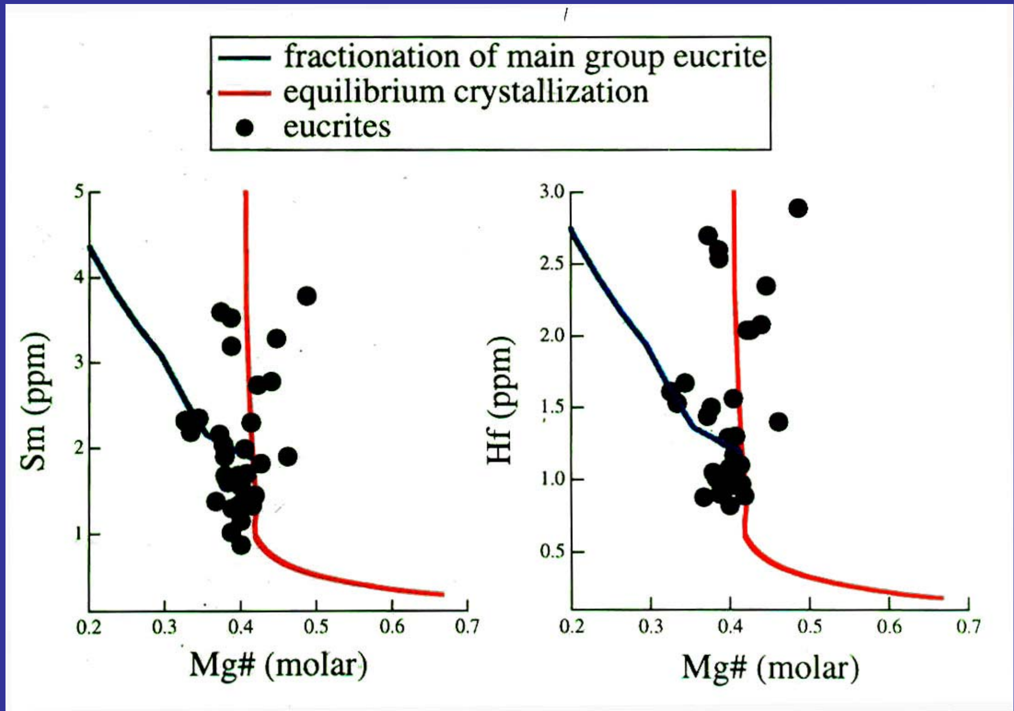
Satisfies

O and Fe/Mn

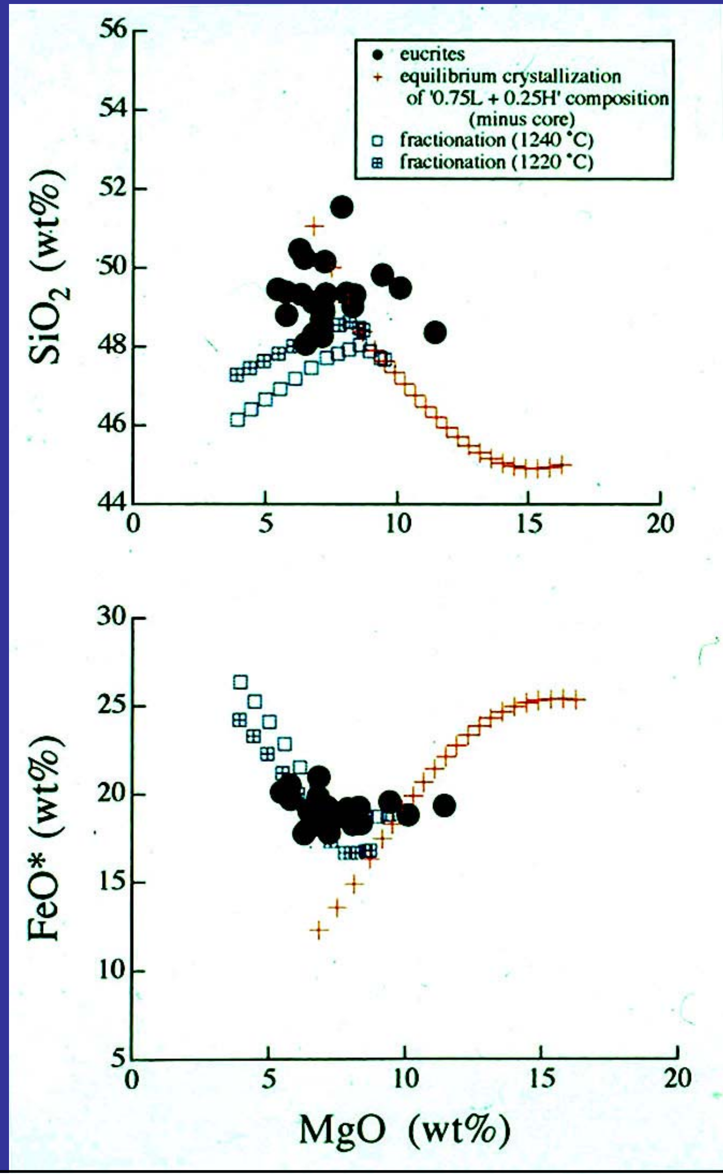
From Righter and Drake (1997)

Major element evolution diagram

Equilibrium with later fractionation

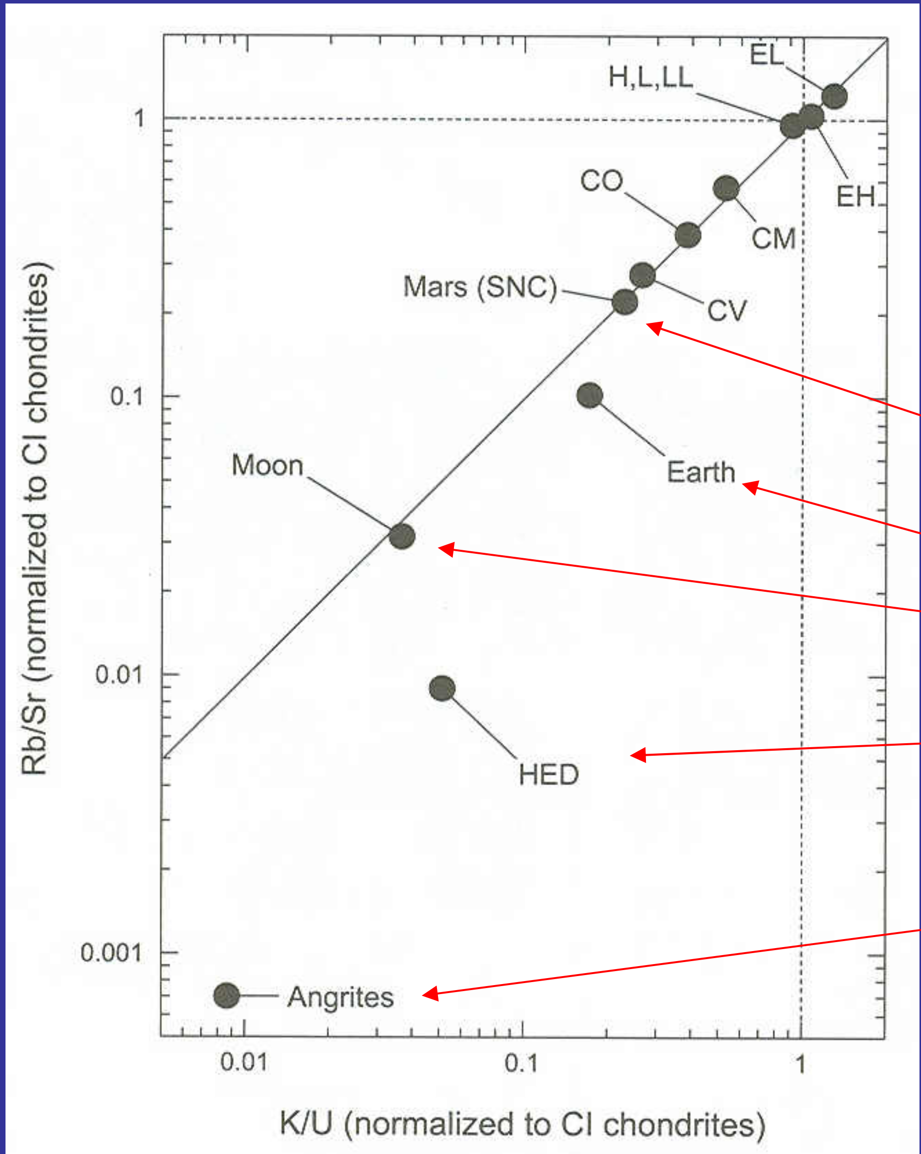


From Righter and Drake (1997)



Outstanding problems

Volatile element depletion



Vesta/HED is volatile element depleted, but so are all of the terrestrial planets so far, compared to chondrites

Mars

Earth

Moon

HED

angrites

From O'Neill and Palme (2003)

DAWN mission

May be able to resolve some of these outstanding questions

C/MR^2
Vesta mantle composition
Volatile elements
Th, K, U