# Compositional relationships between meteorites and planets
# II

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ARES

ASTROMATERIALS RESEARCH & EXPLORATION SCIENCE

# 2nd lecture – Friday

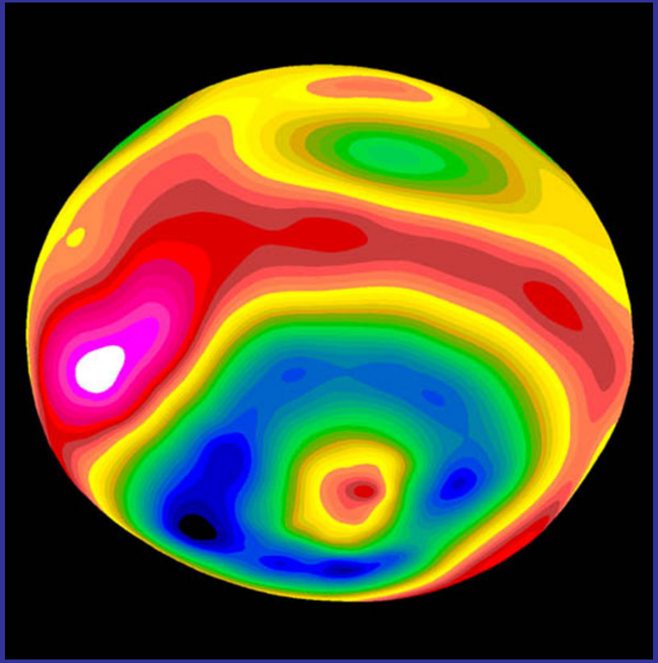
a) Example 2: Mars – how can we make it?
Core size, mass and composition constraints
Mantle constraints (from SNC)
Crustal constraints (new datasets)
Problems in defining the martian bulk composition

b) Example 3: Earth-Moon system
Earth bulk X models – upper and lower mantle, core and crust
Moon bulk X models – core size from siderophile elements and seismology
Bulk composition estimates

c) Origin models for Earth-Moon
Fission, capture, co-accretion do not work
Giant impact satisfies many key parameters
Lingering problems! (volatile elements, atmosphere, age of lunar materials)

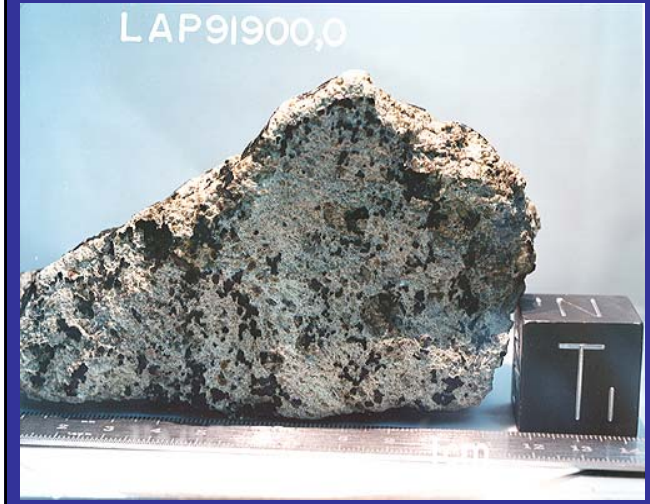
d) What we don't know
Venus, Mercury and inner solar system
No models take metal + silicate together !
Water storage (phyllosilicates…..??????.......hornblende)

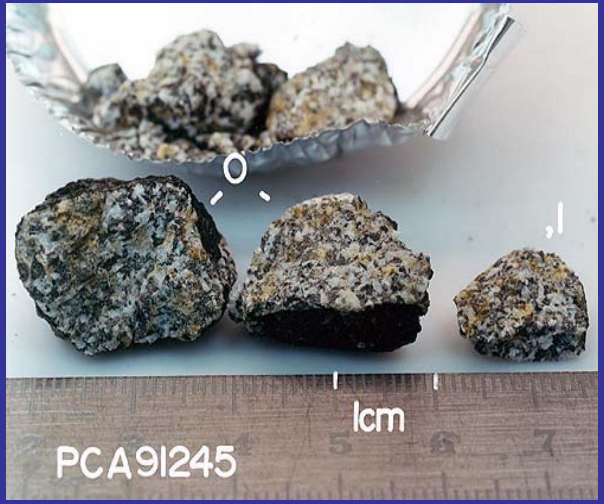
# Example 1: 4 Vesta (HED parent body)



Enhanced from Hubble Space Telescope imaging – 1995 and 1996

# Introduction: What are the HED meteorites ?

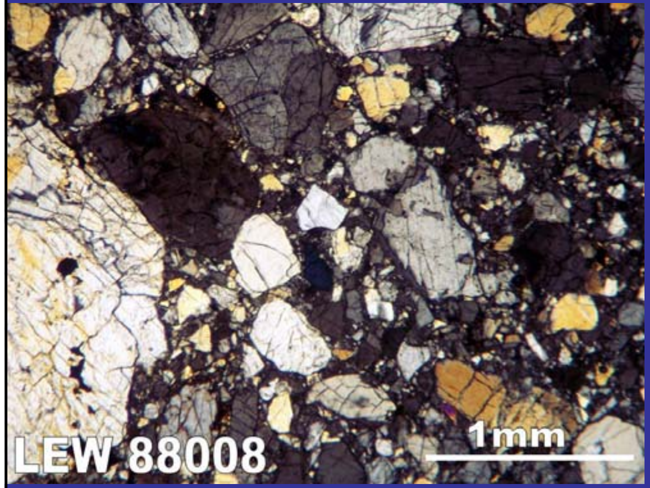


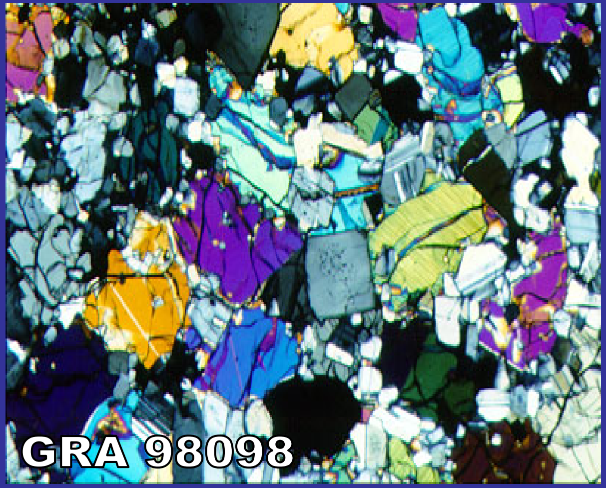


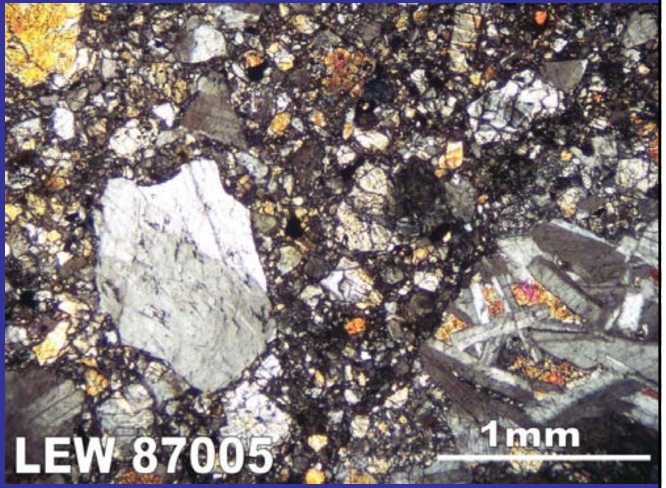
diogenite

eucrite

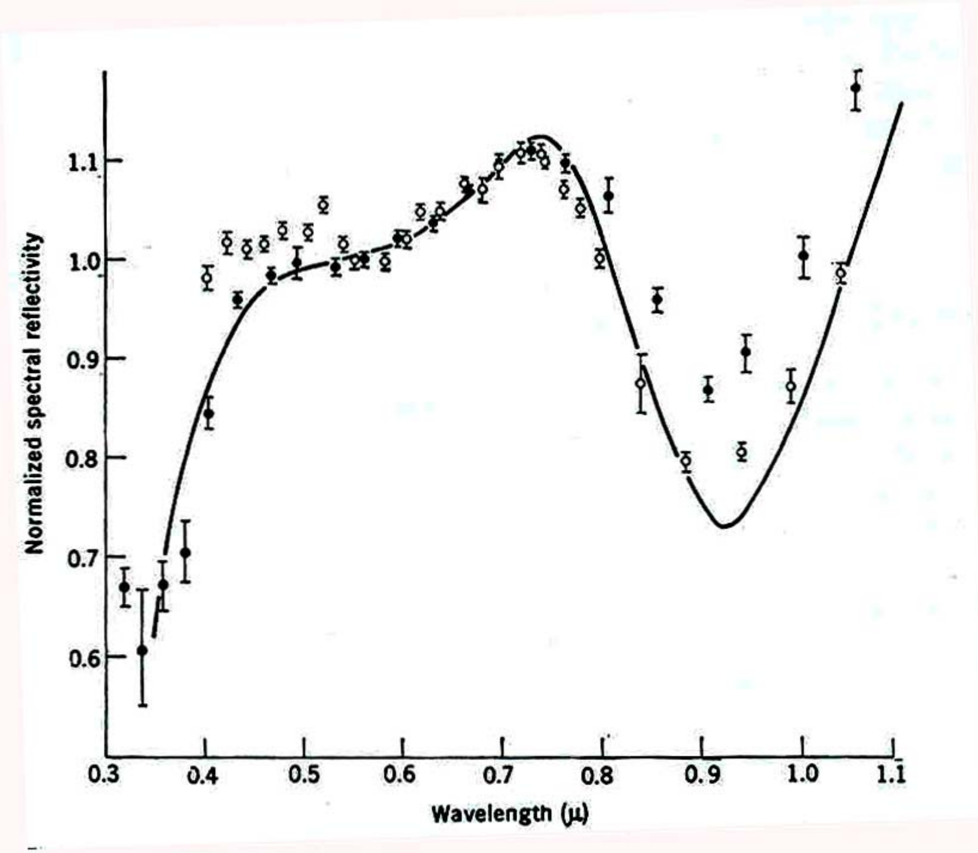
howardite



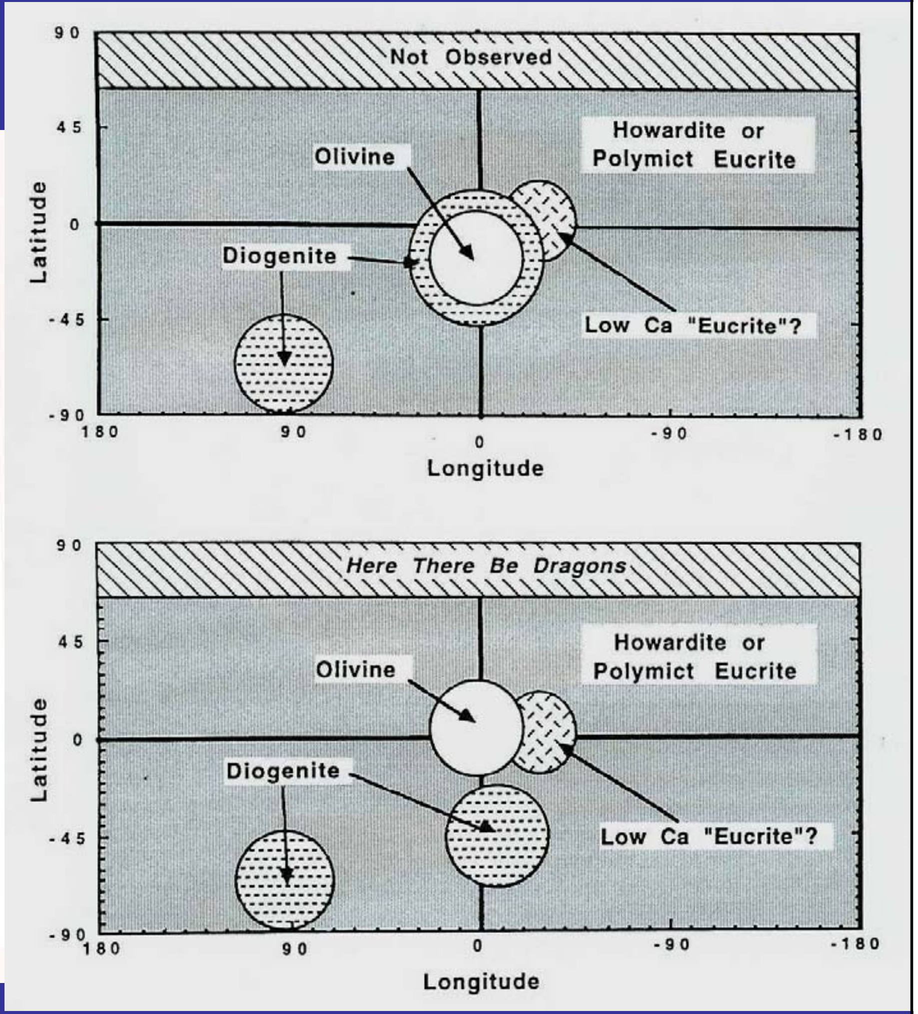




# Vesta/HED link and history



McCord et al. (1970)

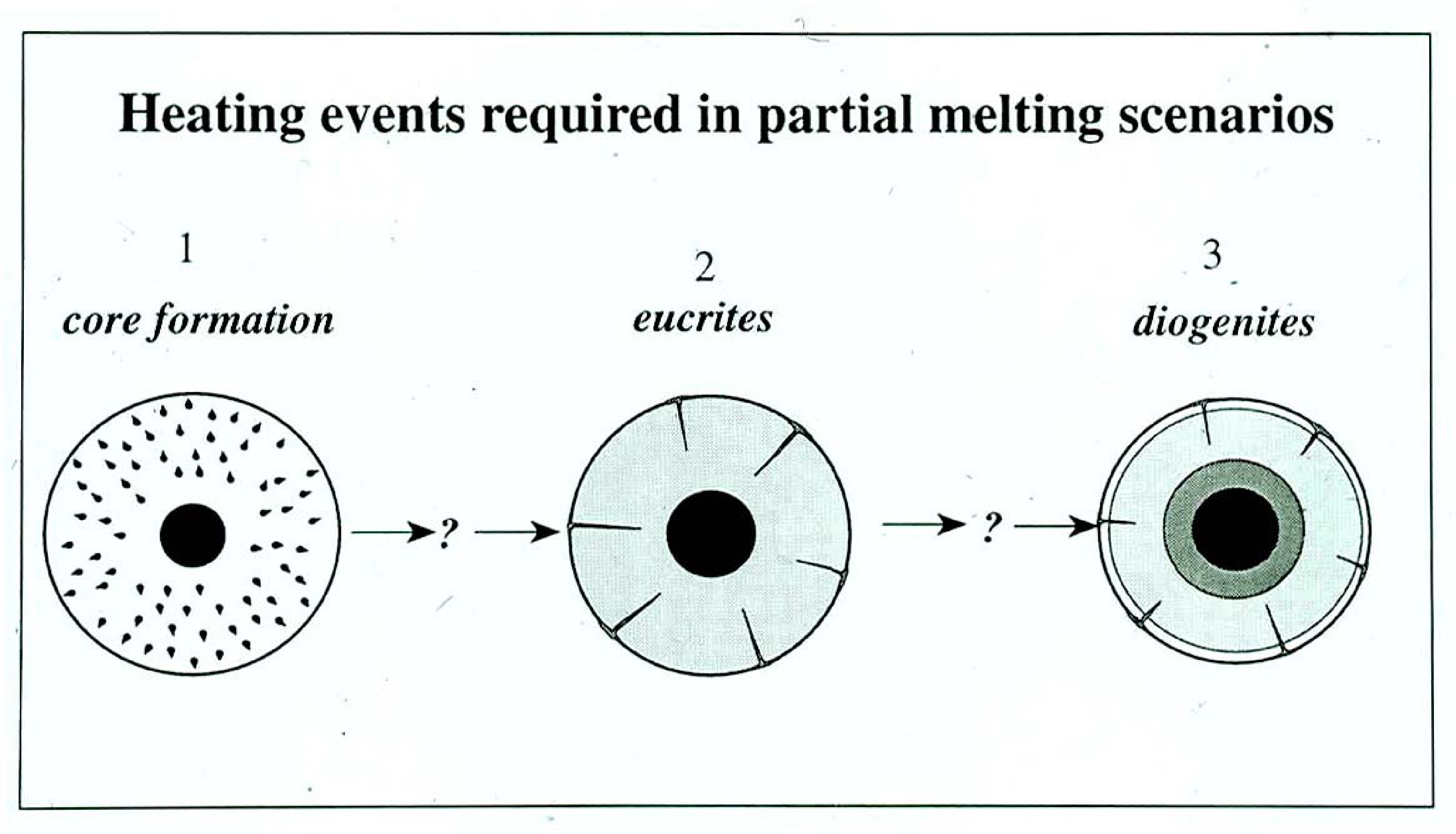


Gaffey (1997)

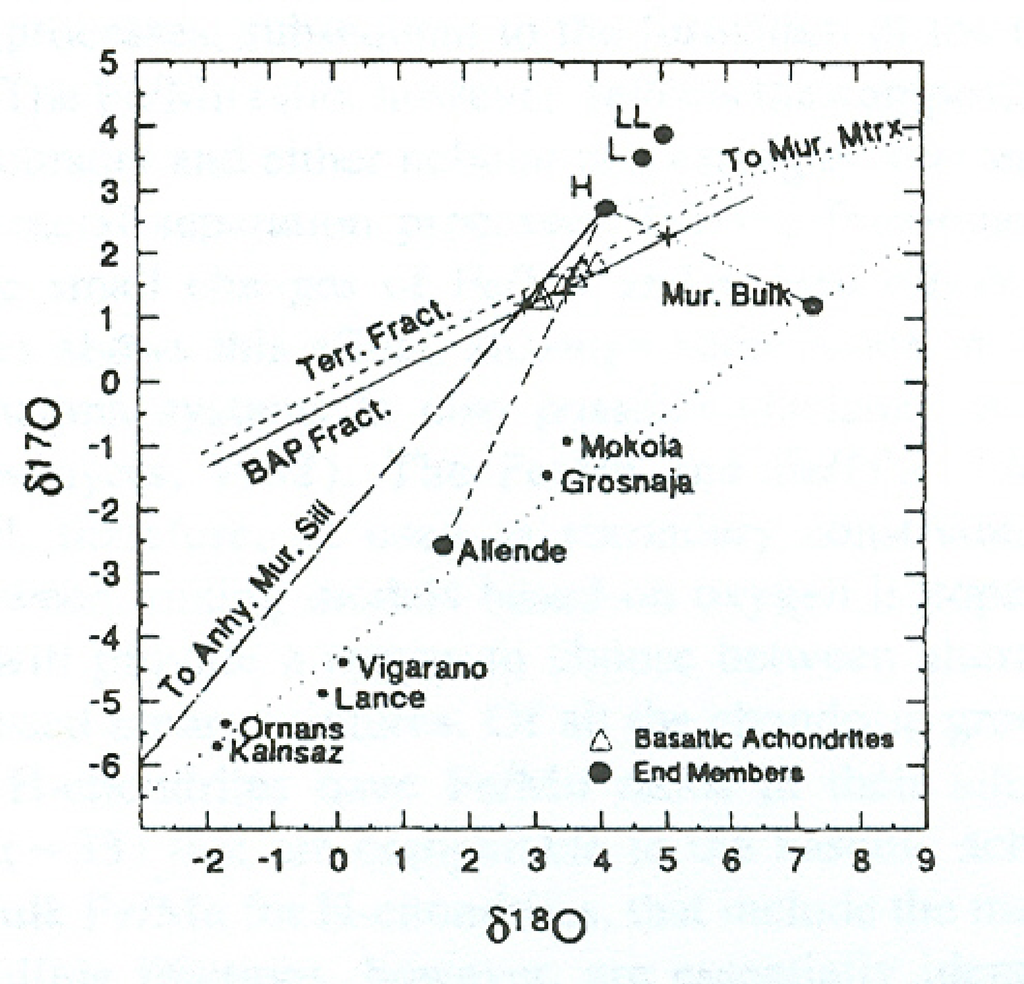
# Vesta/HED problems

Should be a relatively simple case: low pressure and dry

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



# Vesta: oxygen isotopes

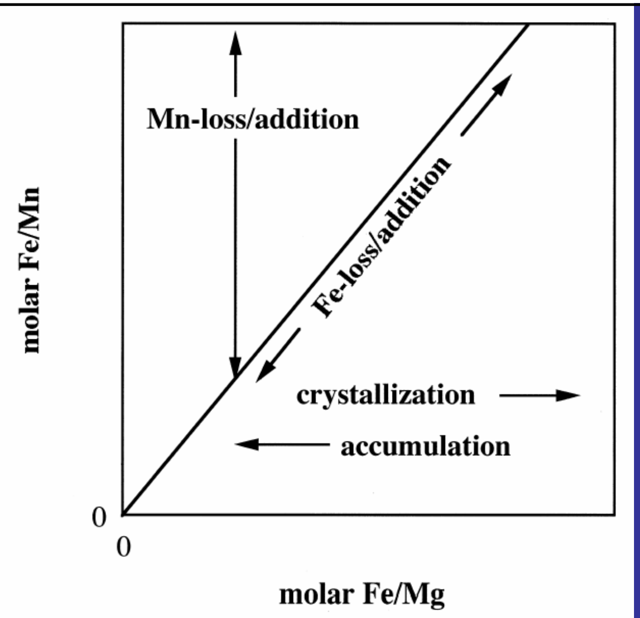


Mixtures that satisfy
O isotopes

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

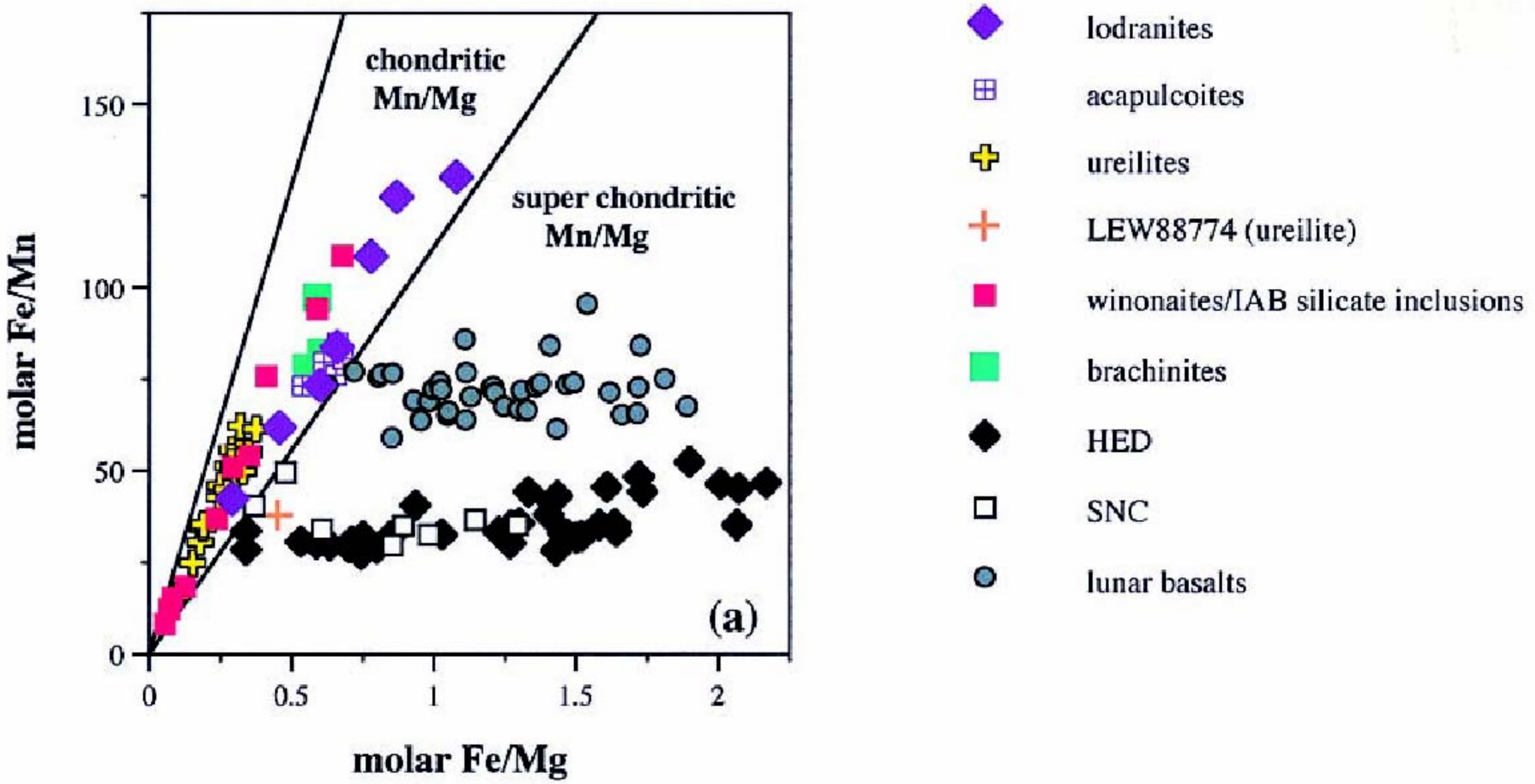
Boesenberg and Delaney (1997)

# Fe/Mn relations



Mixtures that satisfy Fe/Mn

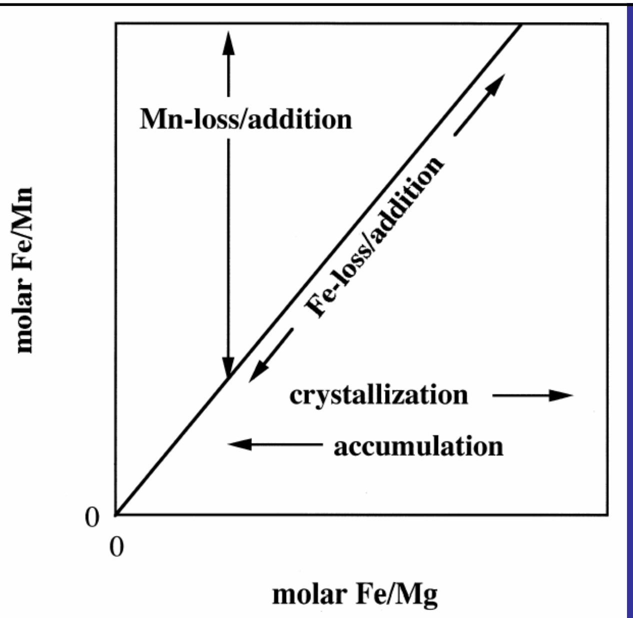
Goodrich and Delaney (2000)

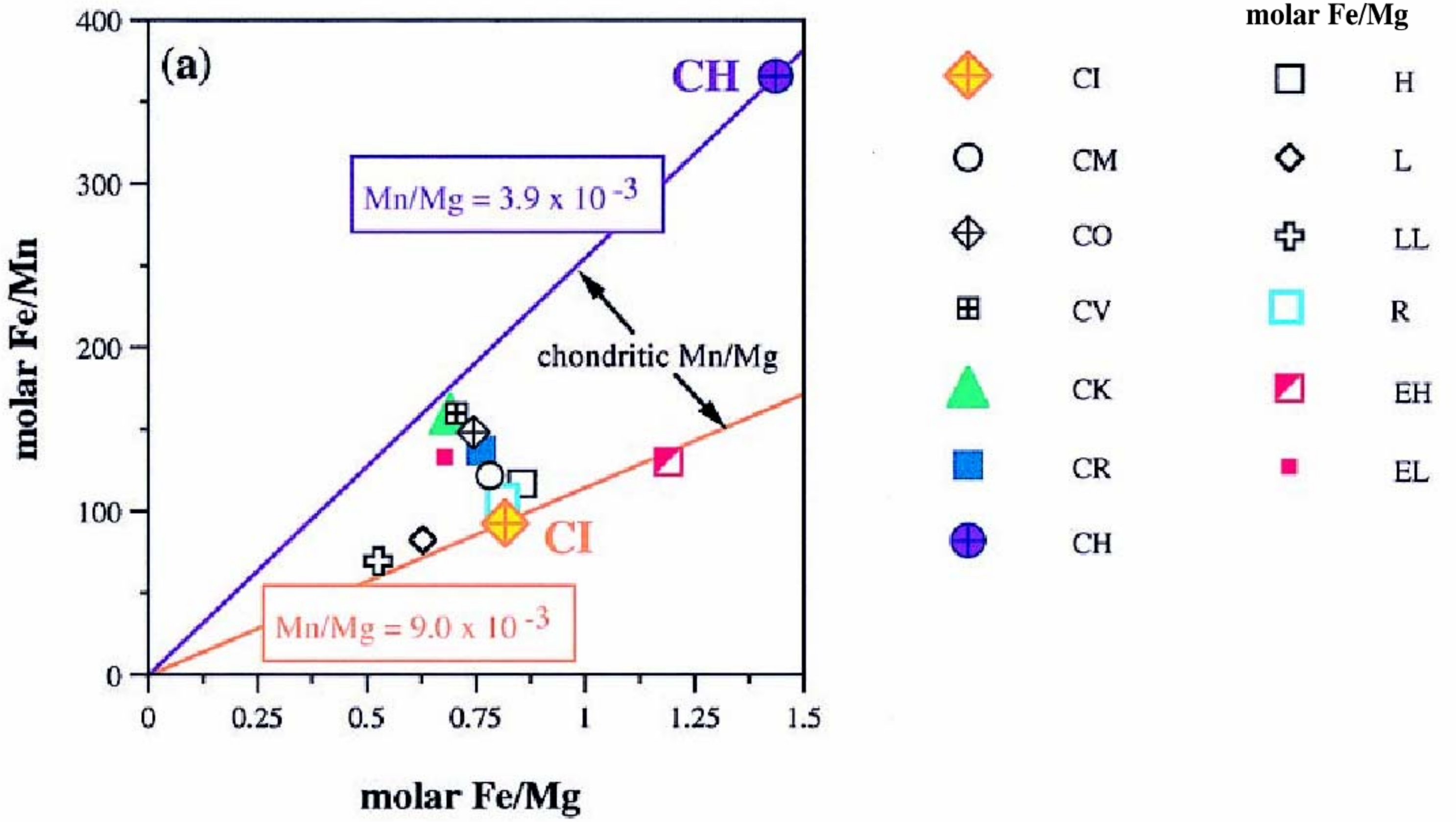


# Fe/Mn relations

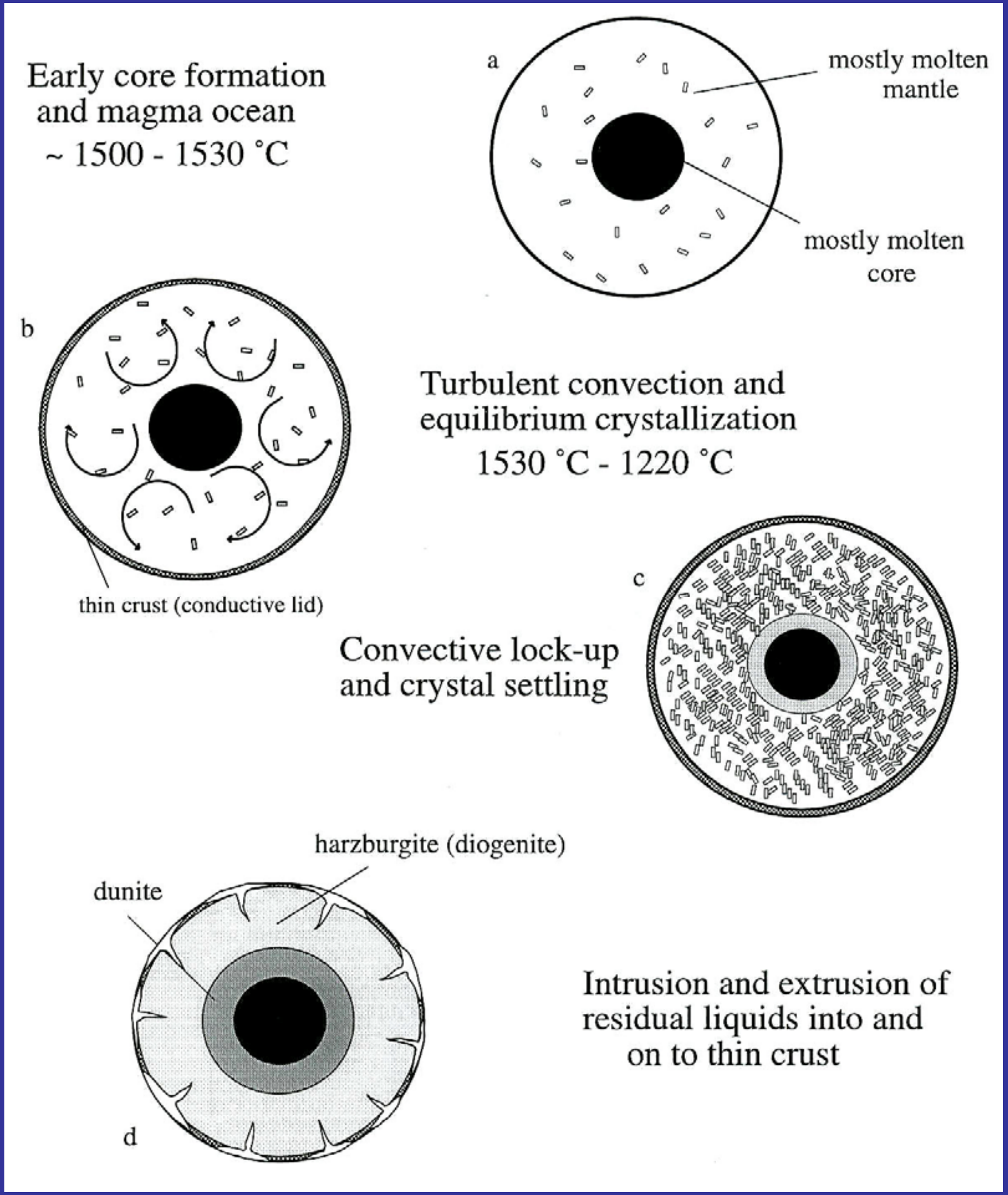
Mixtures that satisfy Fe/Mn

Goodrich and Delaney (2000)





# Formation model for HED/Vesta



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

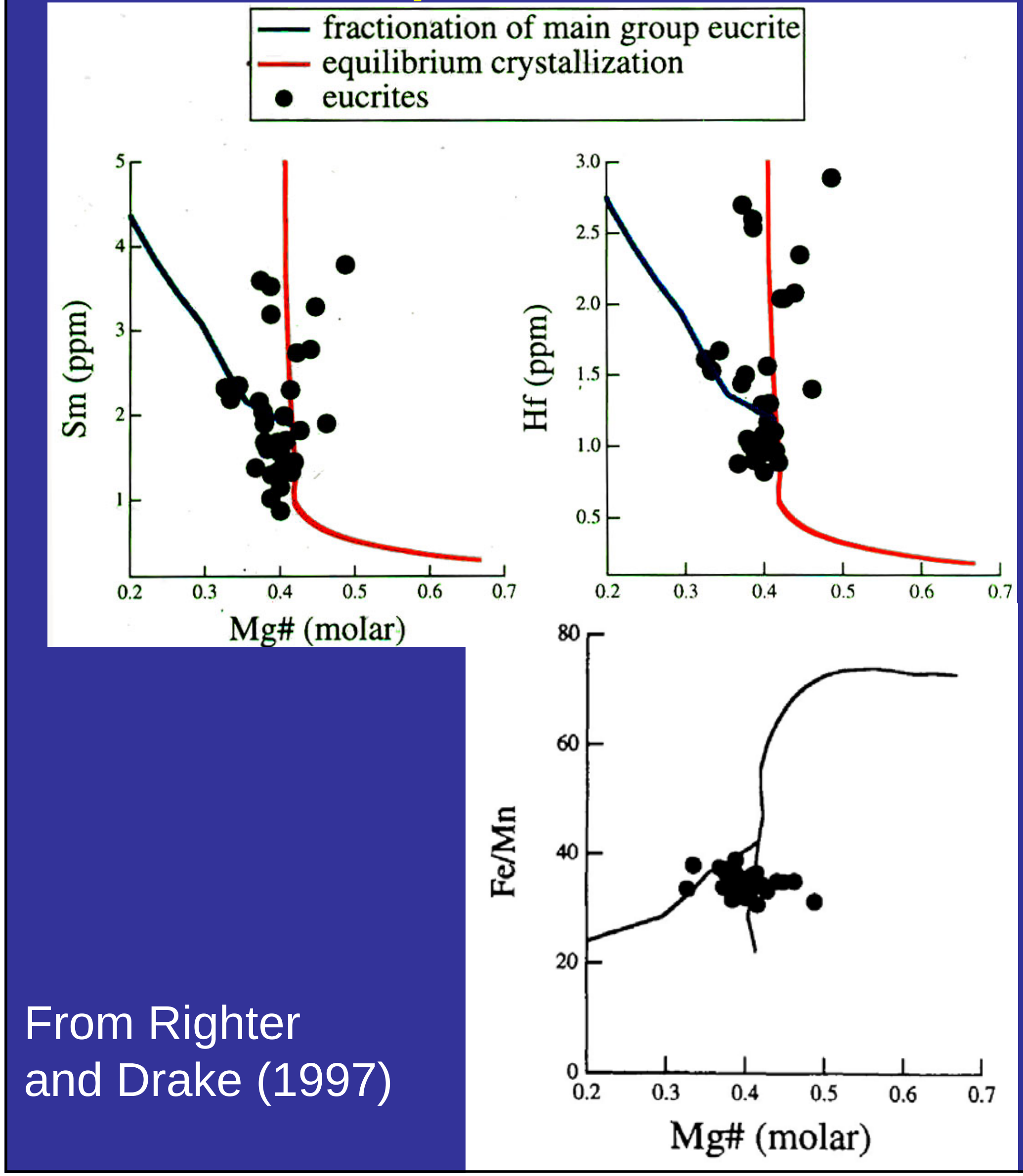
Satisfies

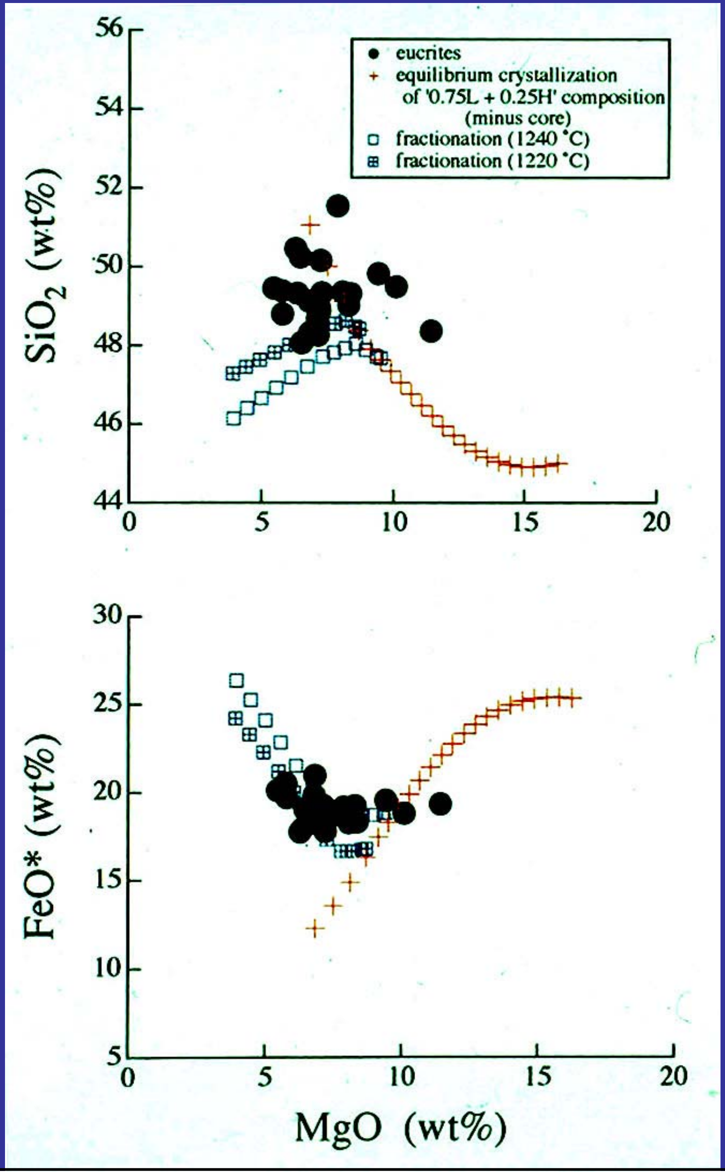
O and Fe/Mn

From Righter and Drake (1997)

# Major element evolution diagram

## Equilibrium with later fractionation

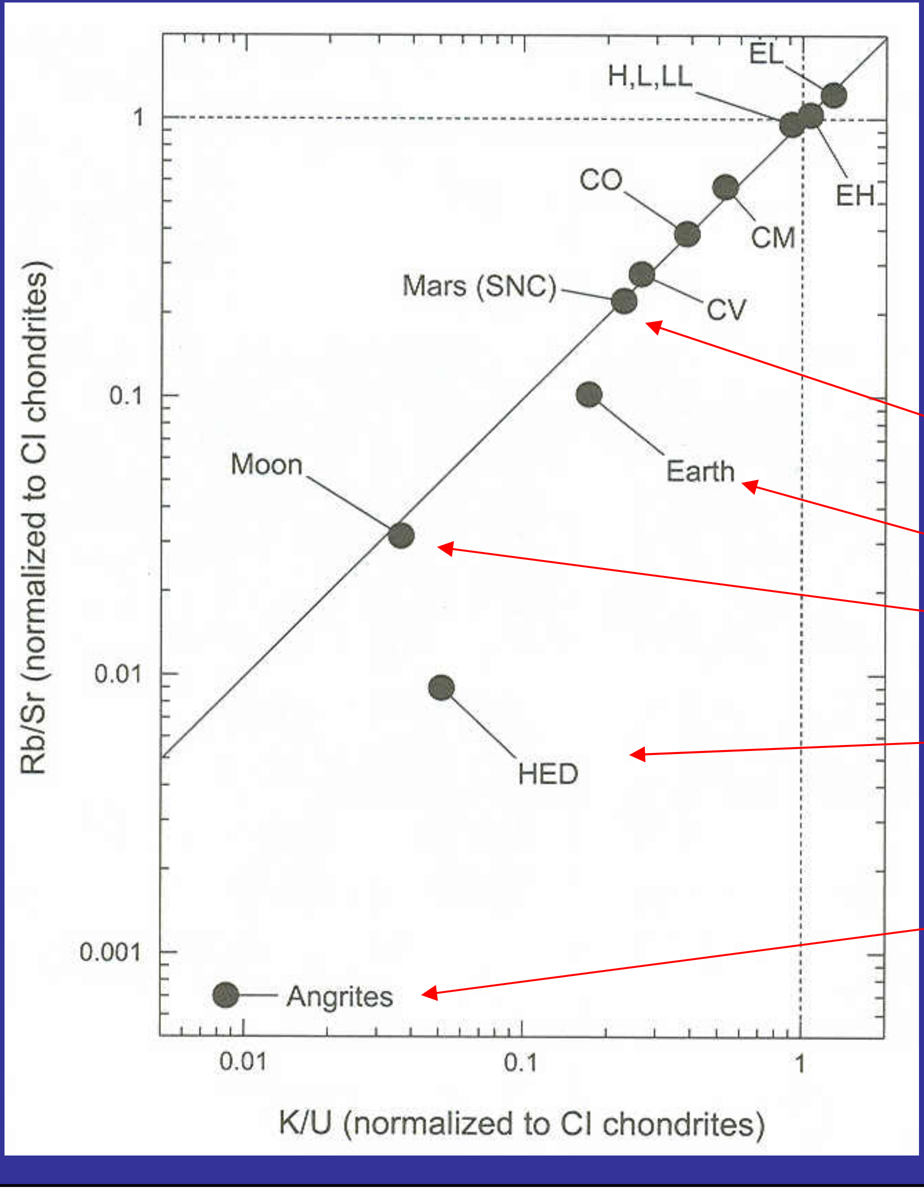




From Righter
and Drake (1997)

# 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

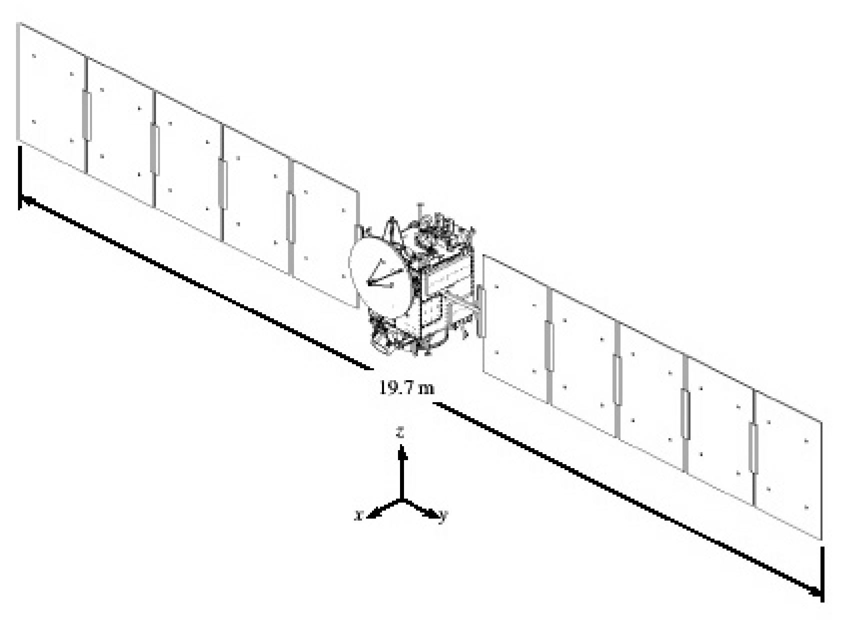
May be able to resolve some of these outstanding questions

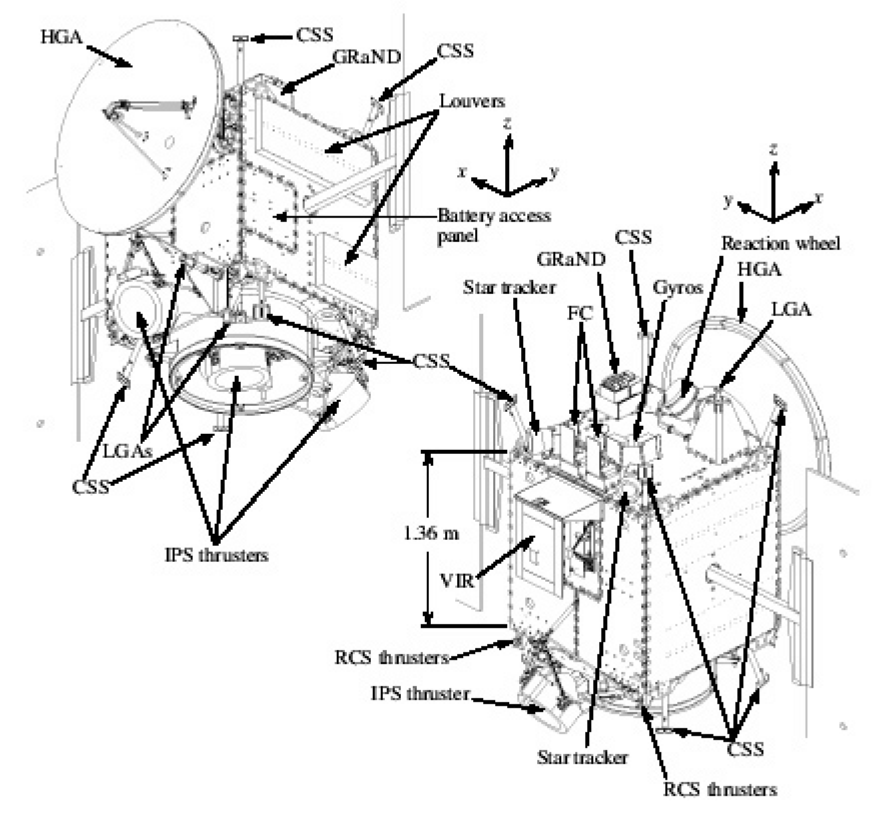
$I = Cmr^2$

Vesta mantle composition

Volatile elements

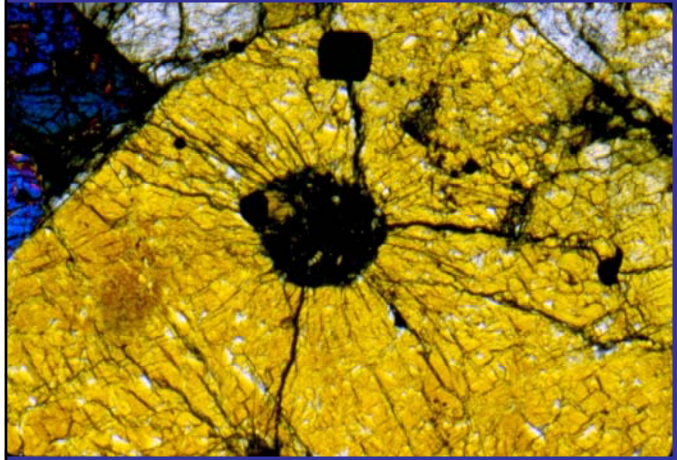
Th, K, U





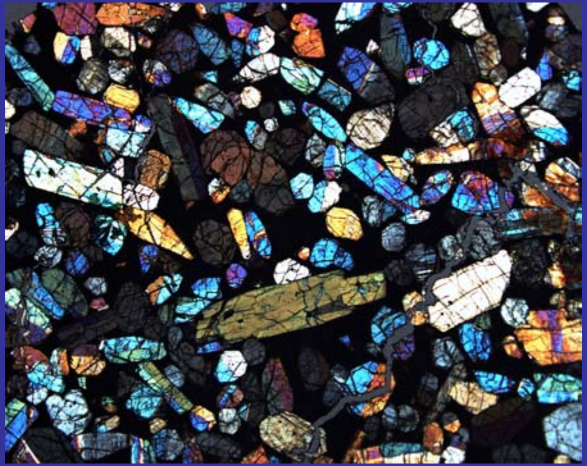
# Example 2: Mars

## Martian meteorites (SNC's) n = 44 ?



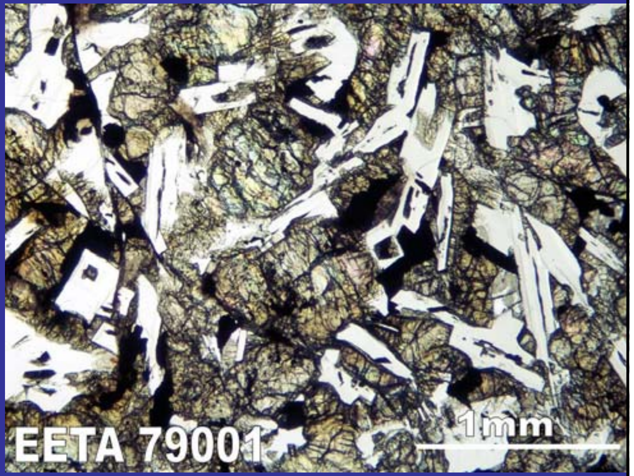
Chassigny

*Olivine cumulate*



Nakhlites

*Clinopyroxene (olivine) cumulate*



Shergottites

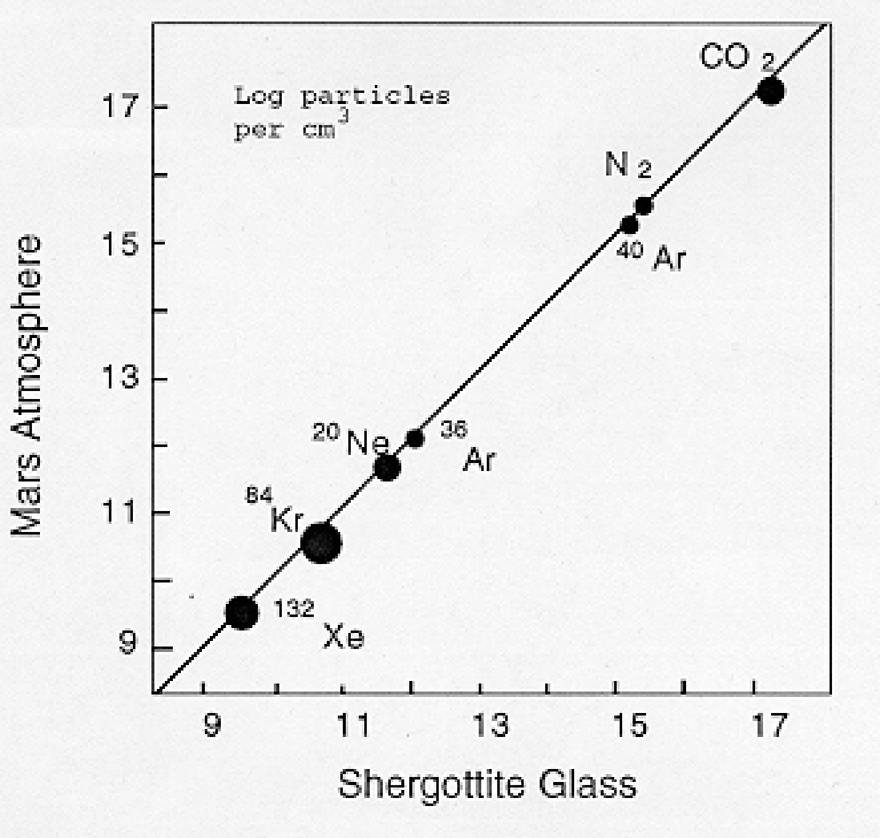
*Basalts*

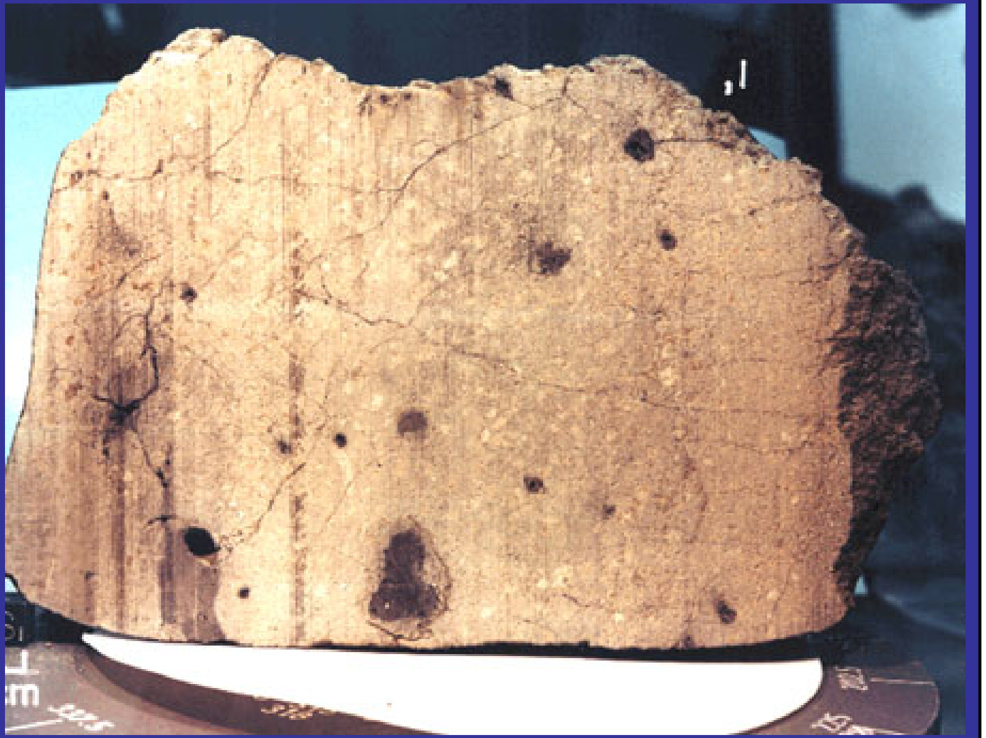
*Olivine phyric*
*Olivine, Opx phyric*
*basaltic*

# Example 2: Mars

## How do we know these are from Mars ?

*1) Noble gas composition*
*2) Young ages (180 Ma, 1.3 Ga)*
*3) Oxygen isotopes*





Bogard and Johnson (1986)
Becker and Pepin (1985)

# Example 2: Mars

*New missions*

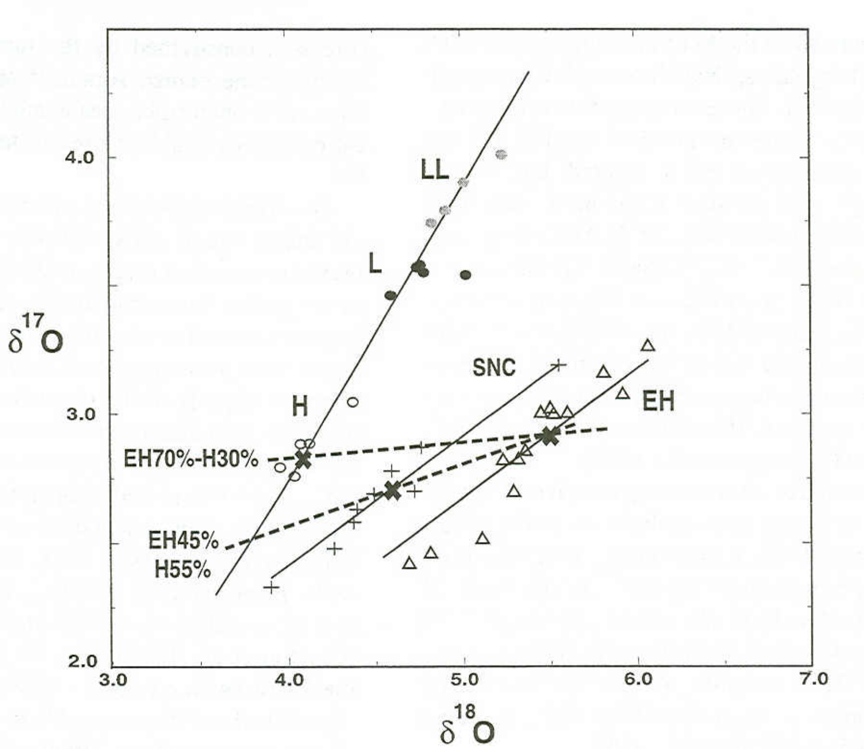
*New meteorites*

*MER*

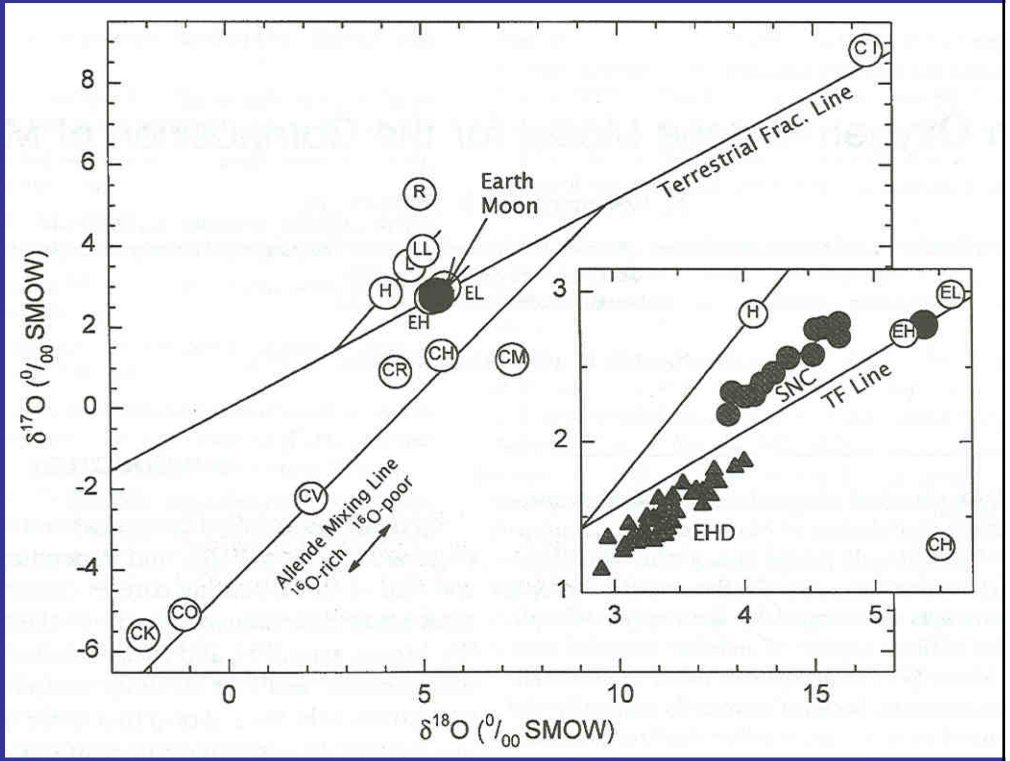
*Yamato 980459*

# Example 2: Mars

## Oxygen isotope models



From Sanloup et al. (1999)



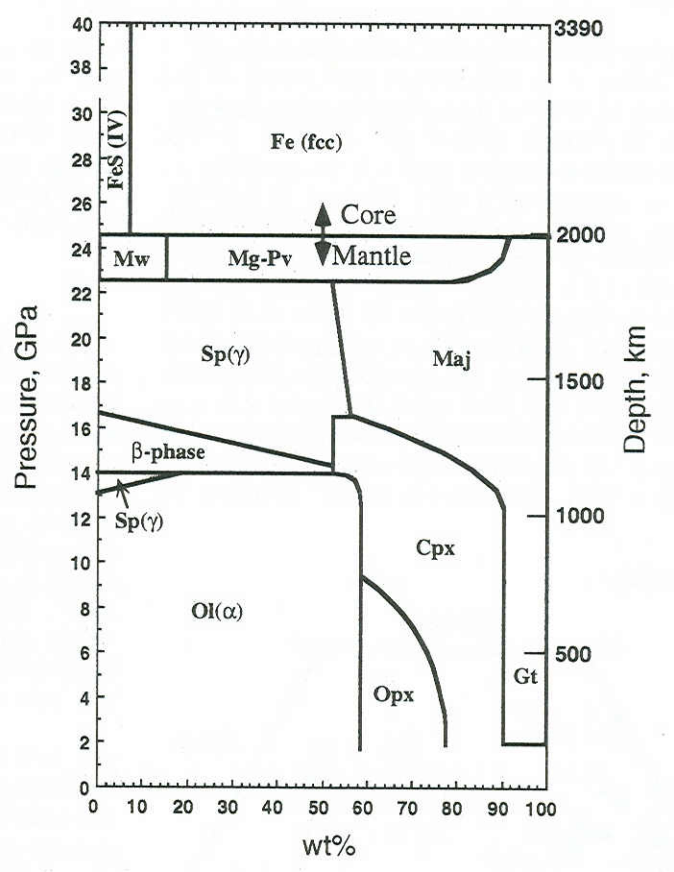
From Lodders and Fegley (1997)

# Example 2: Mars

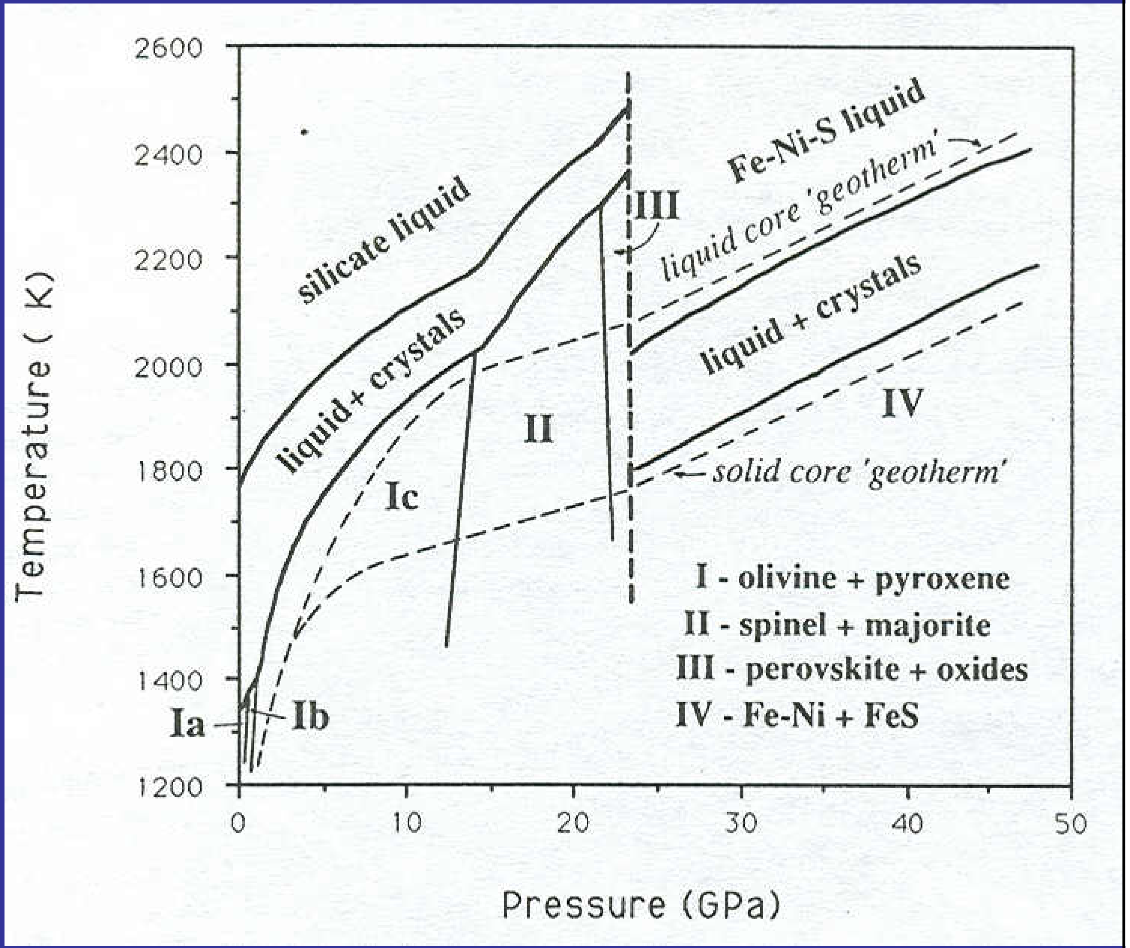
## Bulk composition from oxygen isotope models

| | Sanloup et al. (1999) | Lodders and Fegley (1997) | Dreibus and Wanke |
|---|---|---|---|
| $SiO_2$ | 37.33 | 36.03 | 34.8 |
| $Al_2O_3$ | 1.89 | 2.29 | 2.3 |
| MgO | 20.90 | 23.58 | 23.6 |
| FeO | 36.66 | 34.76 | 30.98 |
| composition | H45, EH55 | H85,CV11,CI4 | SNC |

# Phase diagrams for martian mantle

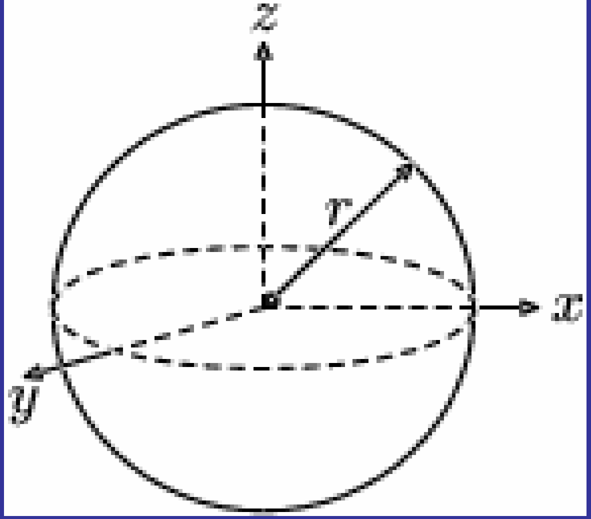


From Bertka and Fei (1997)



From Longhi et al. (1992)

# Moment of inertia



$I = Cmr^2$

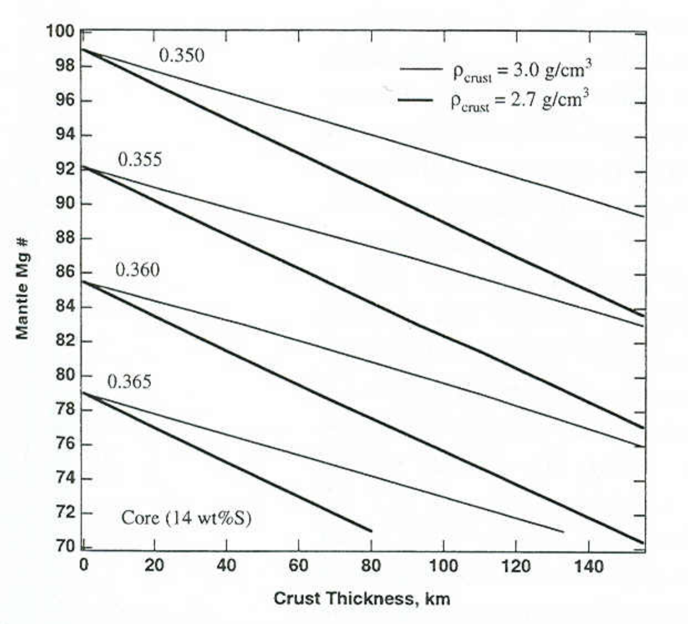
For a homogeneous sphere, C = 2/5

Spacecraft (Viking and Pathfinder) positional data allowed C to be determined for Mars (precession of rotational axis)

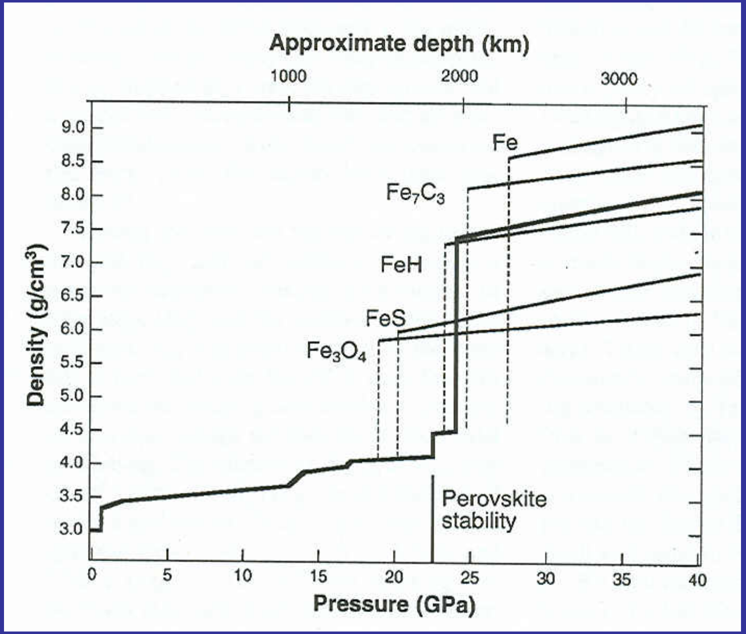
➔ 0.365 (can help to constrain the core size)

- Recent clues to the structure of Mars' interior came from the Pathfinder spacecraft, which helped establish the planet's "moment of inertia." Objects with mass concentrated at their centers will have lower moments of inertia and will spin faster than objects with mass distributed more to the outside, even if the size, shape and total mass are the same. Based on the moment of inertia of Mars, estimates of the radius of the central metallic core range from 1,300 to 2,400 kilometers (806 to 1,488 miles), compared to the Earth's 3,500-kilometer (2,170-mile) core.

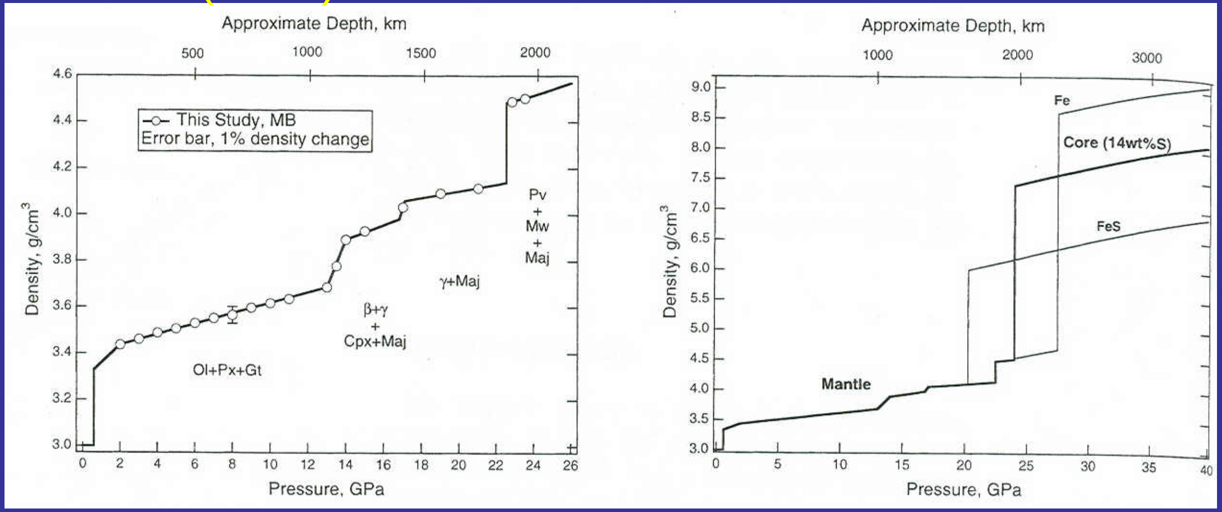
# Martian mantle composition



Bertka and Fei (1998)

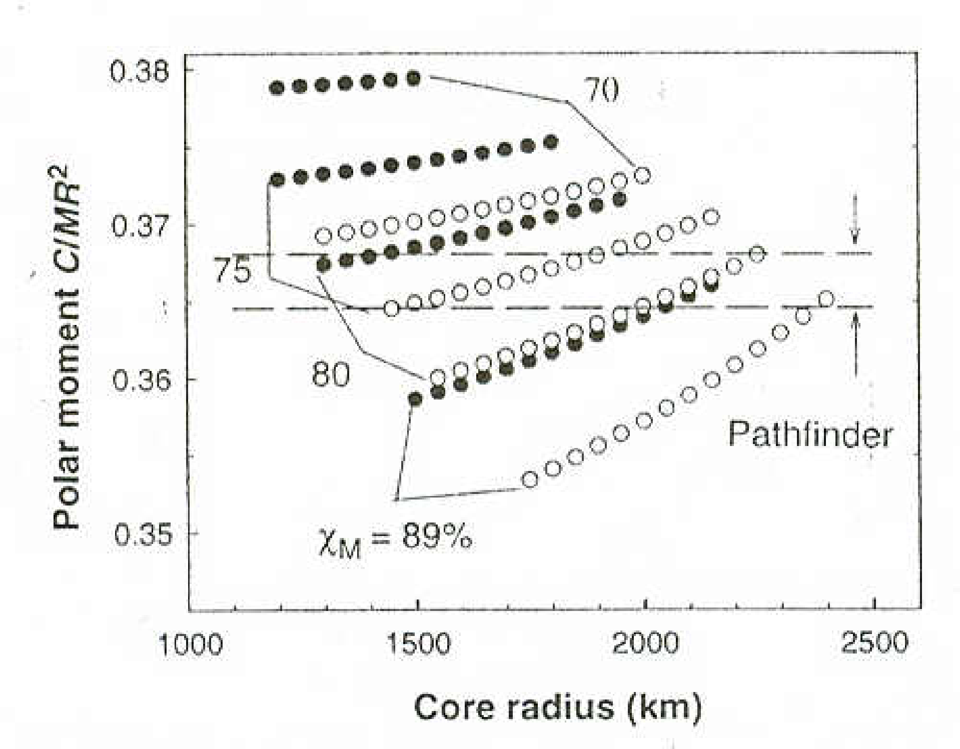


Bertka and Fei (1998)

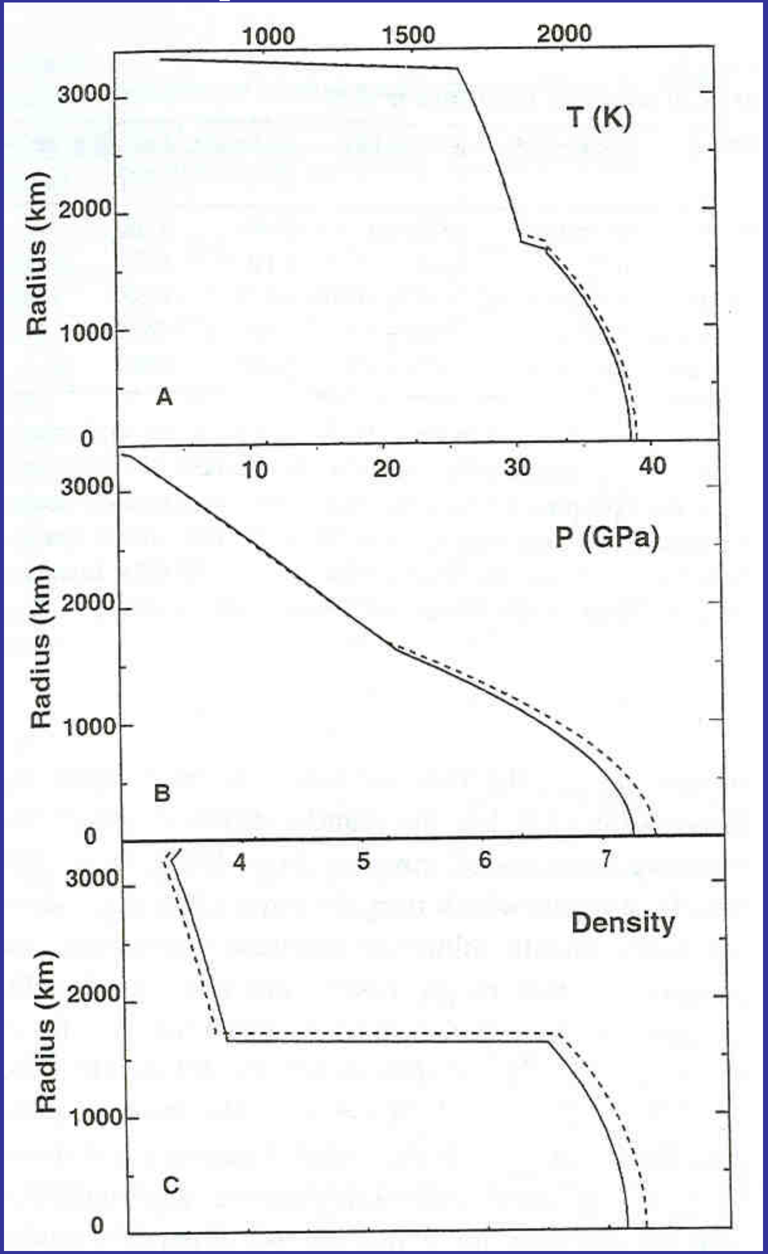


Bertka and Fei (1998)

# Martian mantle composition



Bertka and Fei (1998)



Sanloup et al. (1999)

# Summary for Mars

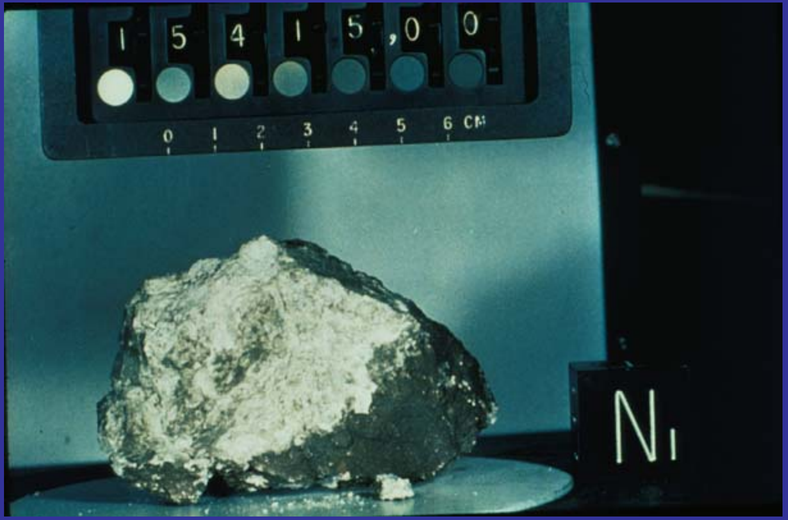
It is possible to constrain the mantle composition for Mars – it must satisfy spacecraft data, meteorites, cosmochemical constraints, and mineral physics.

But there is uncertainty introduced by composition of the metallic core

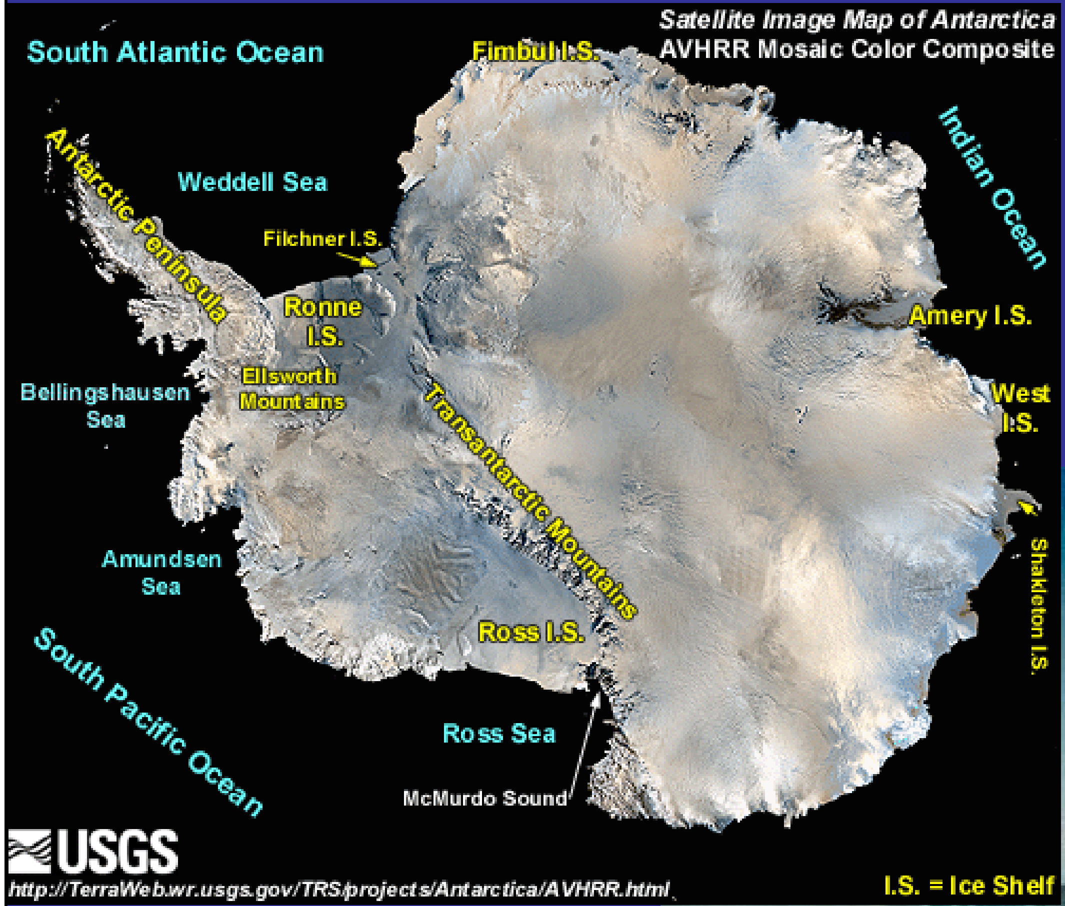
# Apollo samples from the Moon

**6 missions, 382 kg of samples**

**What did we find?**
- **Basalt - volcanism**
- **Anorthosite – ancient crust**
- **Breccia – mixture of two from impacts**

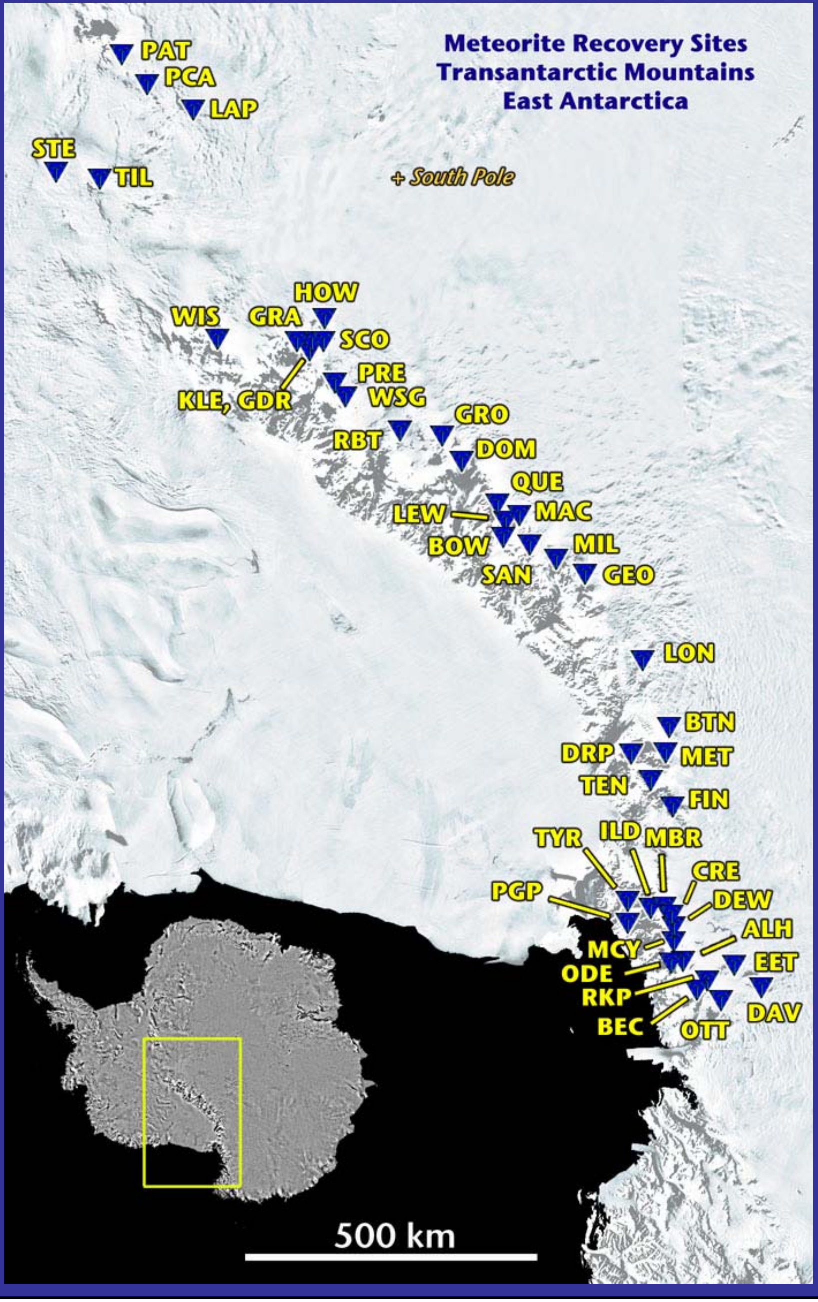


# Meteorites from the Moon



# Meteorites from the Moon

LAP 02205 – mare basalt



# Exploration of the Moon - Meteorites

**84 individual samples, 37 with pairings**

**41 kg compared to 382 kg of Apollo samples,**

Mare basalts (5)
LAP02205, Y793169, A881757, NWA032*, Dho287

Feldspathic breccias (21)
Dho081*, Dho026*, NWA2200, Dho302*, Dho489, DaG400, NWA482, MAC88105*, Y86032*, Kalahari 008, QUE93069*, DaG262, 1153, Dho025*, NEA001, PCA02007, Y791197, ALH81005, Dho733, Dho490*, Dho925*

Mixed breccias (11)
Dho1180, Y983885, Calcalong Creek, Y793274*, SaU169, QUE94281, MET01210, NWA3136, EET87521*, Kalahari 009, NWA773

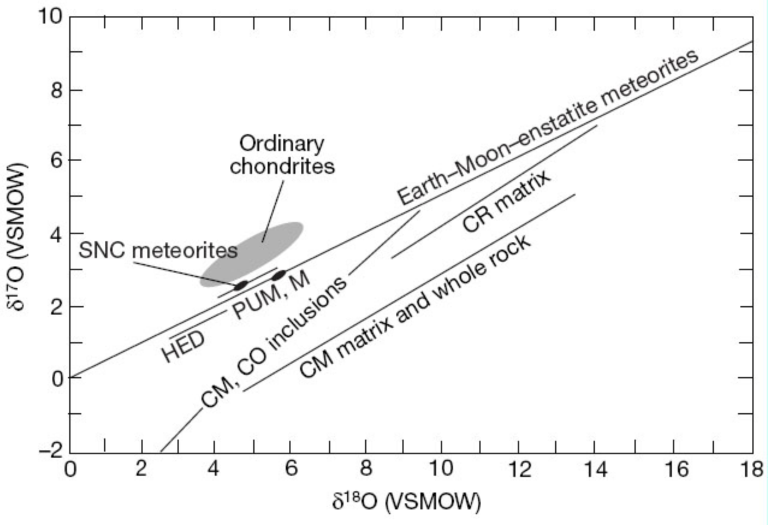
* = pairing group

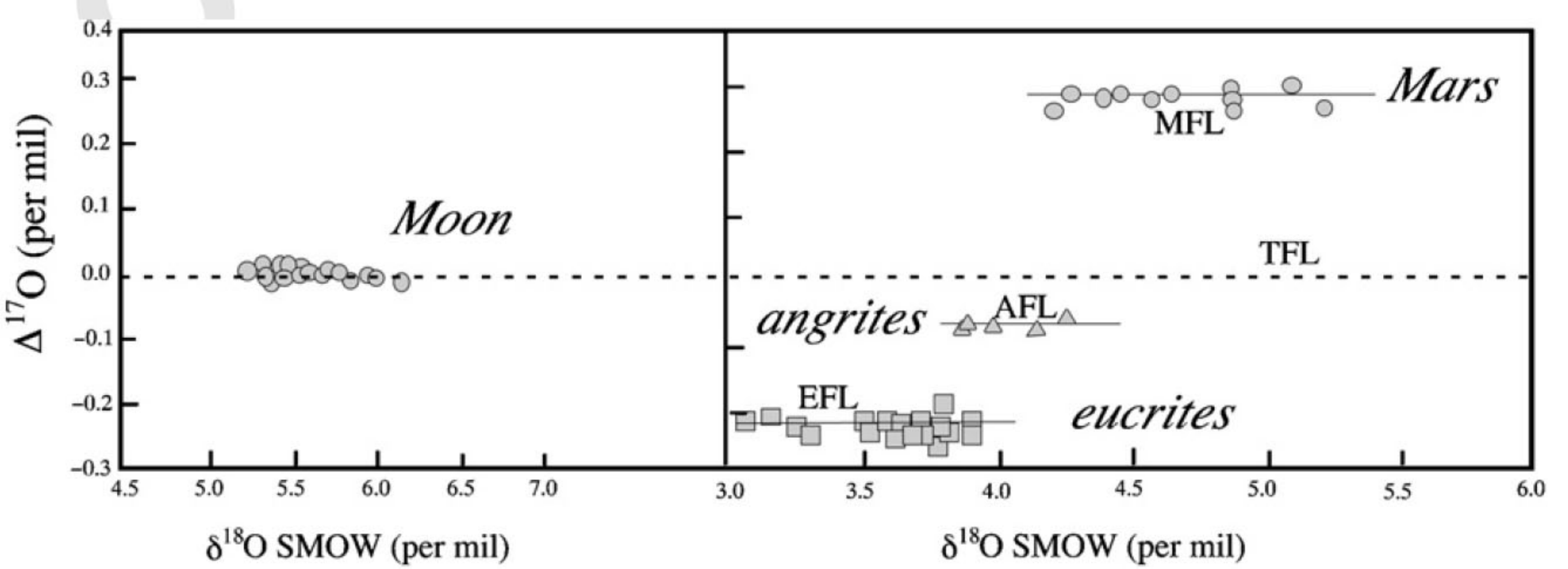
# Earth – Moon system

Earth and Moon have same oxygen isotopes

Moon = dry, Earth = wet
Moon = small core (1%), Earth = large core (32%)
Silicate Earth 8% FeO, Moon 14% FeO

Small core makes Moon Fe-depleted overall





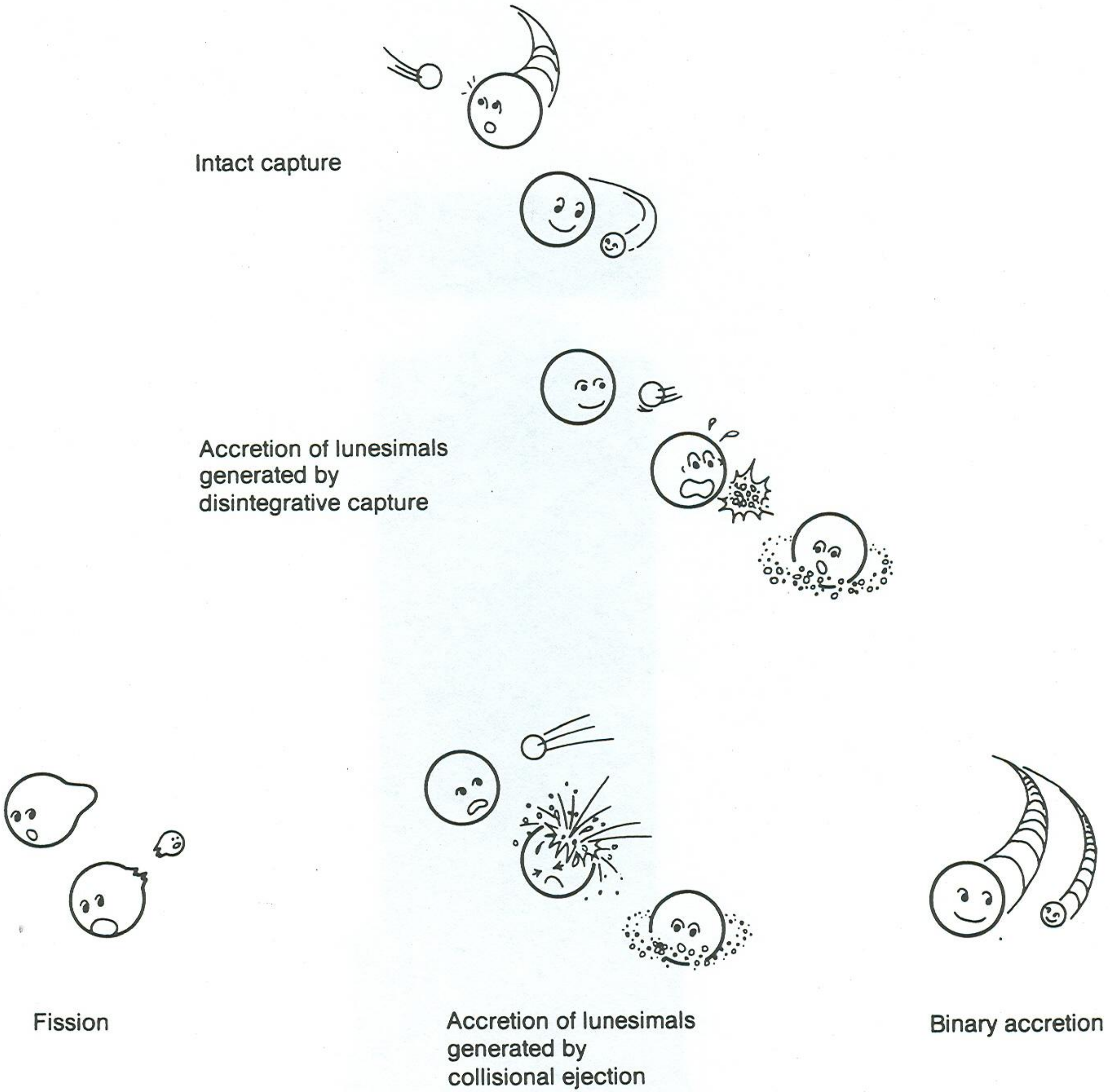
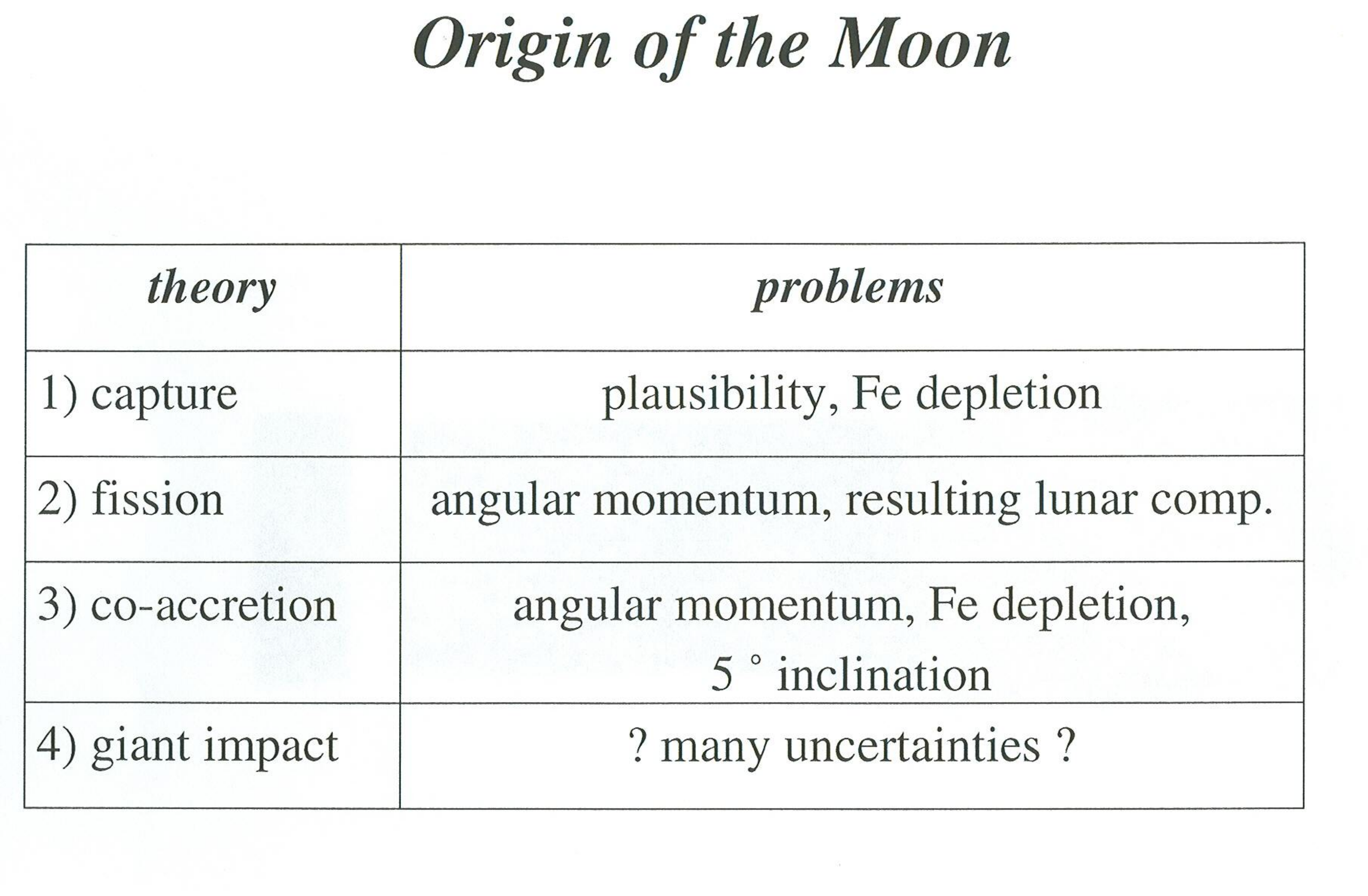


*Fig. 1. A cartoon of models for the origin of the Moon.*



# *Origin of the Moon*

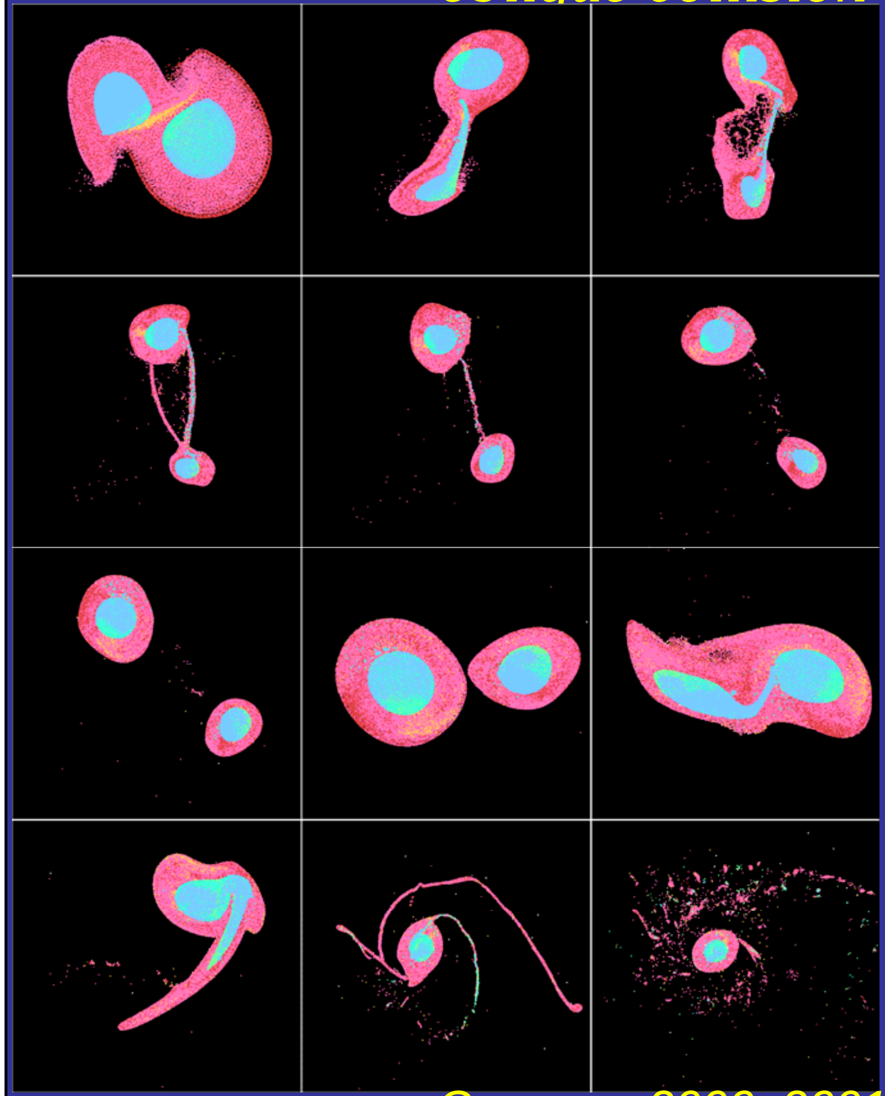
| *theory* | *problems* |
|---|---|
| 1) capture | plausibility, Fe depletion |
| 2) fission | angular momentum, resulting lunar comp. |
| 3) co-accretion | angular momentum, Fe depletion,<br>5 ° inclination |
| 4) giant impact | ? many uncertainties ? |

Summarized from Wood (1985)

# “Giant Impact” Hypothesis

*Hartmann and Davis (1975); Cameron and Ward (1976)*

*Moon forms from debris ejected when early Earth suffered an oblique collision with another protoplanet*



Cameron 2000, 2001

•Extremely high energy impact late in Earth’s formation

•Coupled origin of the Earth and Moon

•Evidence of impact events believed typical of late stage terrestrial accretion

**Key constraints**:

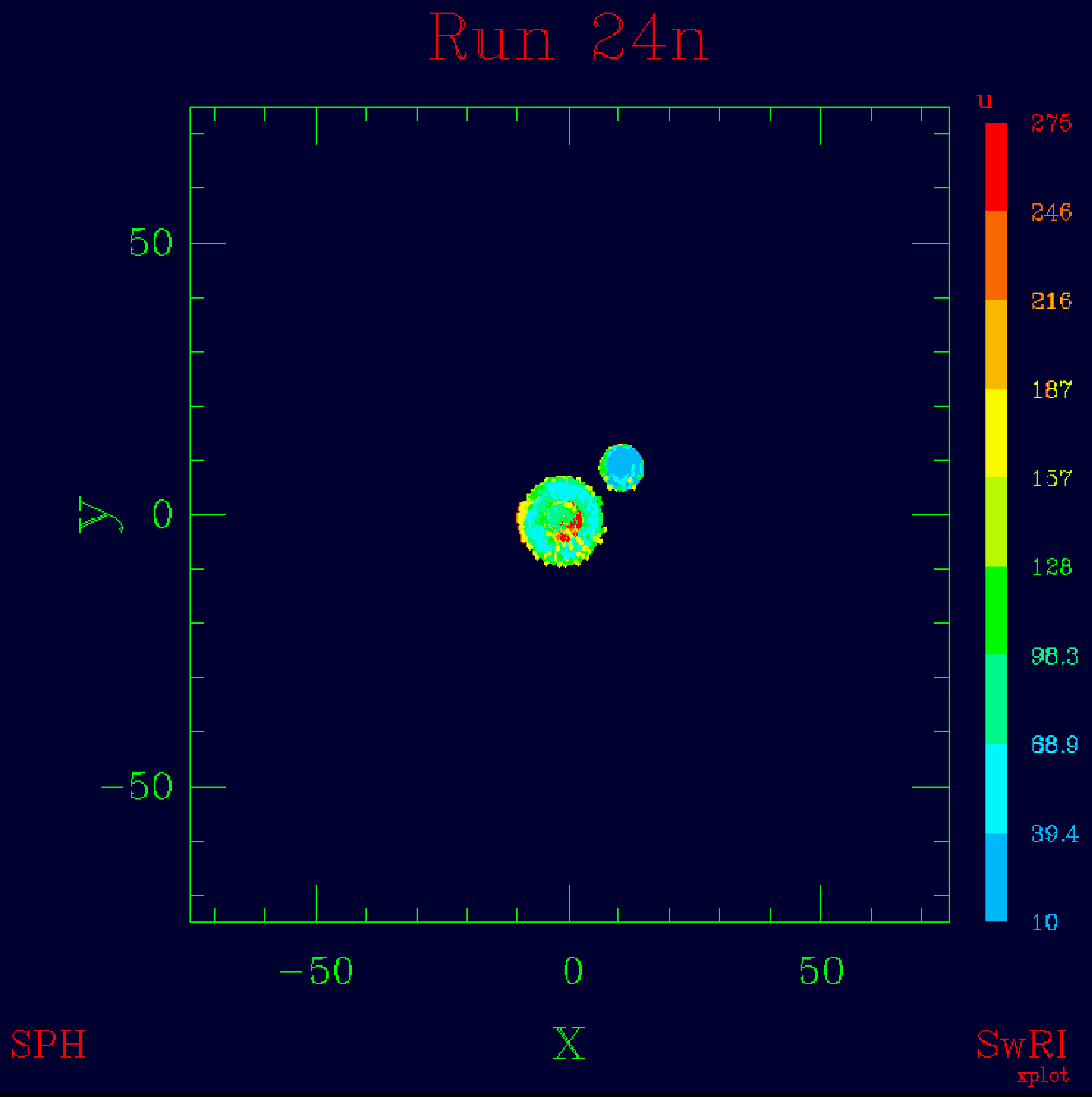
Sufficient orbiting material to form Moon beyond Roche limit

$$M_D \geq 1.5 - 2\ M_L$$

- Iron-depleted protolunar material
  Lunar core ≤ 0.03 $M_L$
- Earth-Moon system angular momentum

# **Recent work**: Late impact/smaller impactor

*(Canup & Asphaug 2001)*



$M_{Imp}: M_{Tar} = 1:9$

- $M_{Tot} = 1.02 M_{\oplus}$
- $L_{Imp} = 1.2\ L_{\oplus\text{-M}}$
- $v_{Imp} = v_{esc}$

- $M_D = 1.7 M_L$
- $M_{FE}/M_D = 0.02$

- Color scales with internal energy

# Some implications

- Impactor:
  Impact velocity 1 – 1.1 $v_{esc}$
  $v_{Inf} \leq$ 3-4 km/sec
  Impactor had orbit close to that of Earth, with $\Delta a < 0.1$-$0.2$ AU

- Protolunar debris:
  Mostly from impactor, with target contribution up to 10-20% by mass
  Temperatures: ~ 2000 – 3000 K
  Large intact clumps?

- Post-impact Earth:
  Predicted temperatures ~ 4000 – $10^4$ K
  Acquired > 90% of its final mass

# ***Summary***

- Wide variety of oblique, low-velocity impacts can produce satellites

- Class of impacts does exist that can account for final masses and angular momentum of Earth & Moon (least restrictive impact scenario is a late impact of ~$0.1M_\oplus$ object)

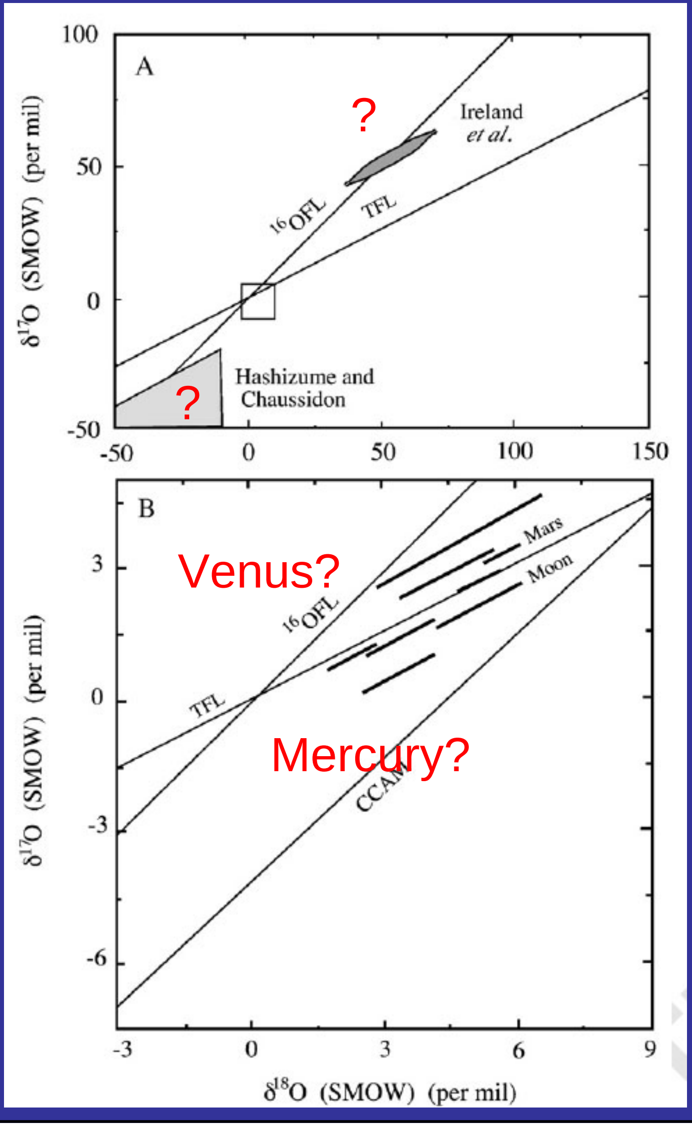
- Terrestrial feeding zones are narrow early (0.01 to 0.04 a.u.), but become wider later (mixing between inner and outer parts if inner solar system).

# *Outstanding problems*

- O isotopes – significance?
- Earth-Moon compositional characteristics
- Volatile element depletion of the Moon
- no known chondrite can match Earth bulk composition
    - Allegre – carbonaceous chondrite
    - Javoy – enstatite chondrite

***Earth is difficult to understand compared to Mars, Vesta***

# a) oxygen diagnostic for inner solar system?



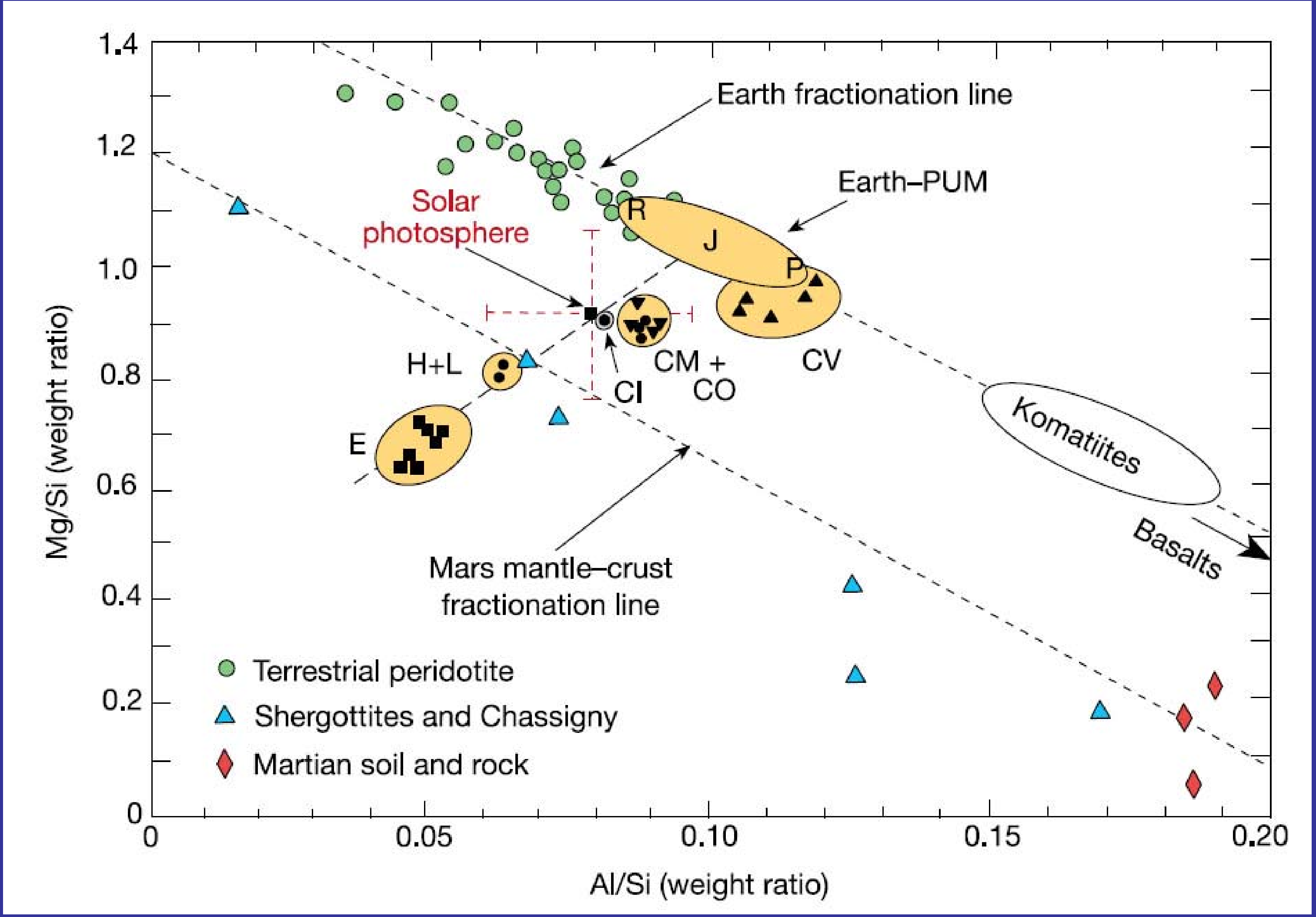
Maybe not.

Solar Wind debate
(Genesis)

Mercury, Venus unknown

# b) Earth-Moon compositional characteristics

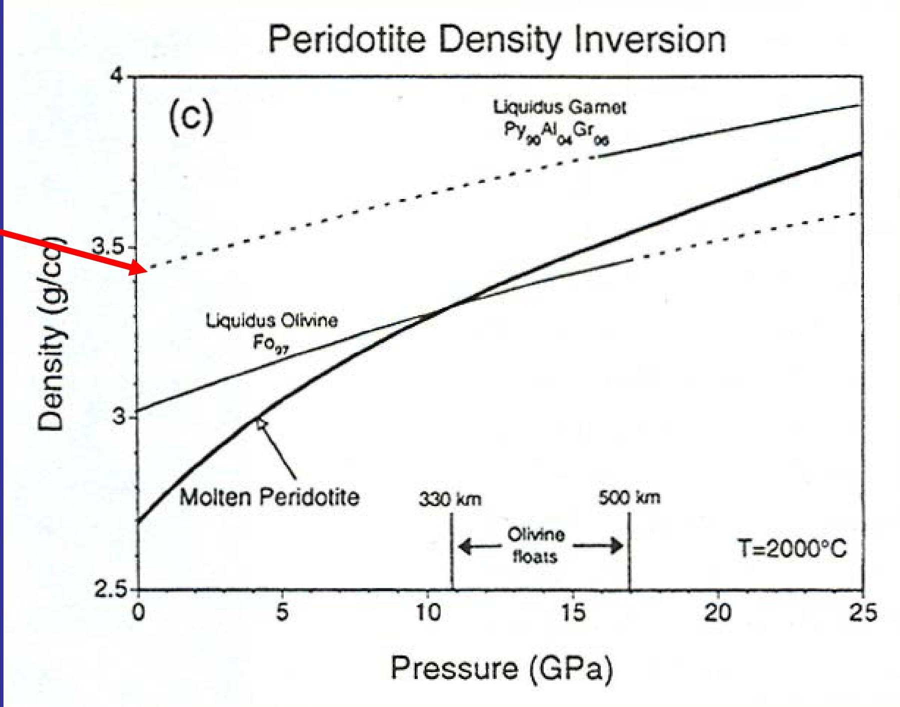
## Mg/Si of Earth's upper mantle



# b) Earth-Moon compositional characteristics

## How to explain Earth’s super-chondritic Mg/Si ?

*Olivine flotation?*



*Upper mantle different from lower mantle?*

Geophysical models predict mostly the same UM - LM

*Si in core ?*

(but requires very reducing conditions that would produce depletions of Ga, P, Nb, and Ta that are not observed)

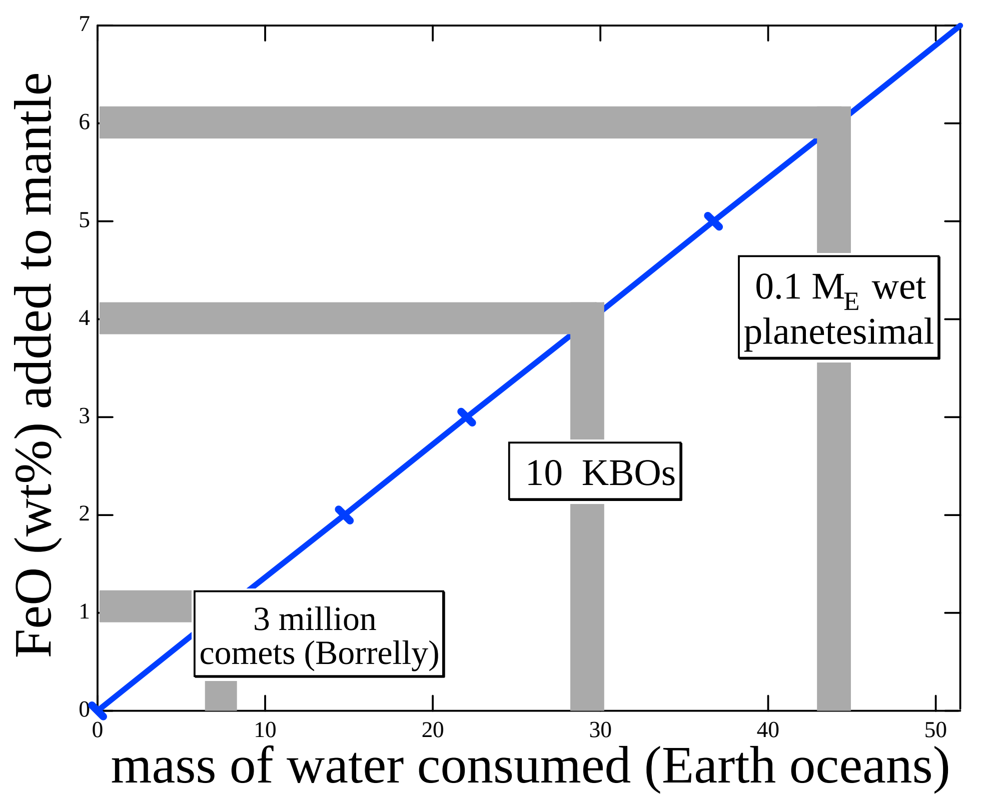
Conclusion: maybe Earth = non-chondritic

# EH chondrite Earth?

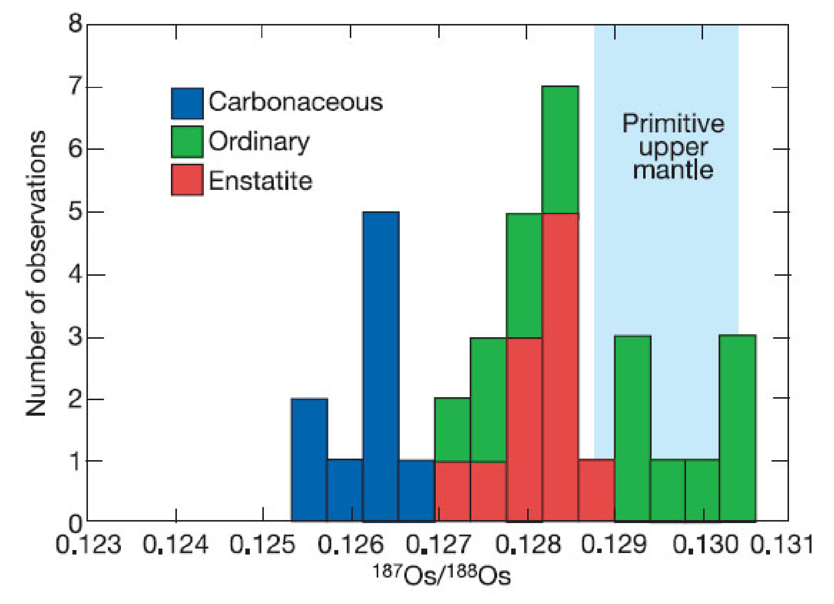
Satisfies oxygen, Fe-FeO balance, and Os isotopes

But not tested for trace elements, or phase equilibria

## Water consumed vs. FeO added



From Righter et al. (2006)

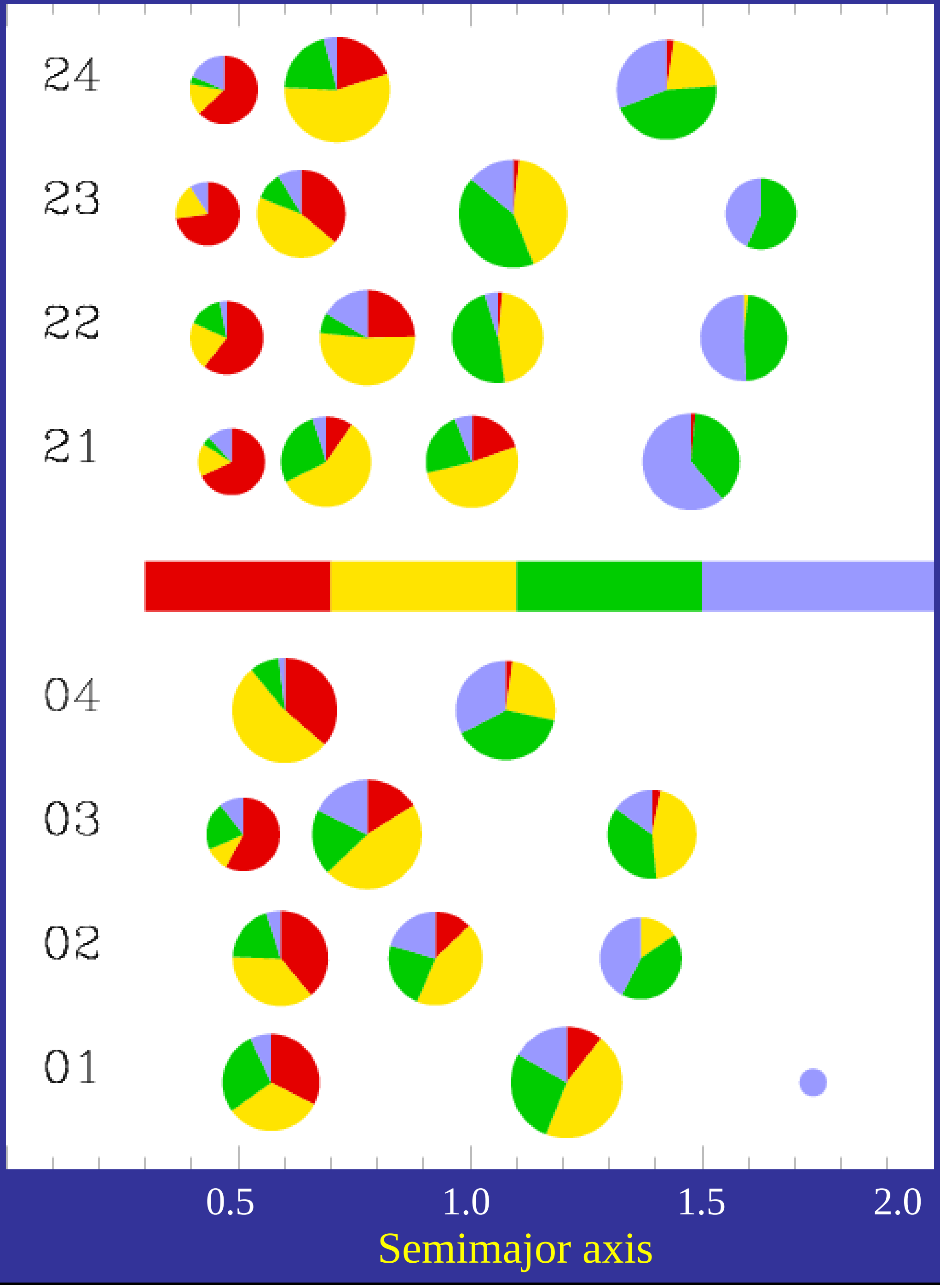


From Drake and Righter (2002)

# *Material provenance*

**Local or mixing ?**

Although early in process accretion occurs in narrow feeding zones,
mixing between inner and outer inner solar system becomes common and extensive

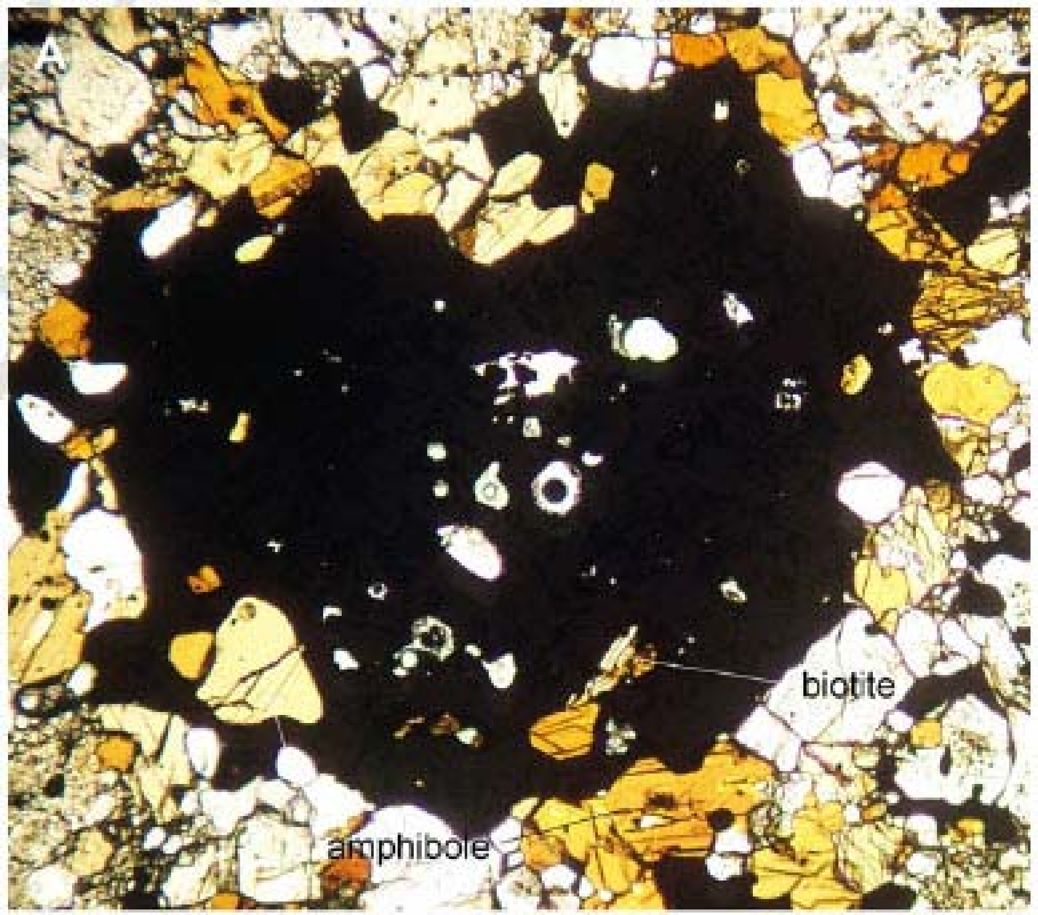


(from Chambers 2001)

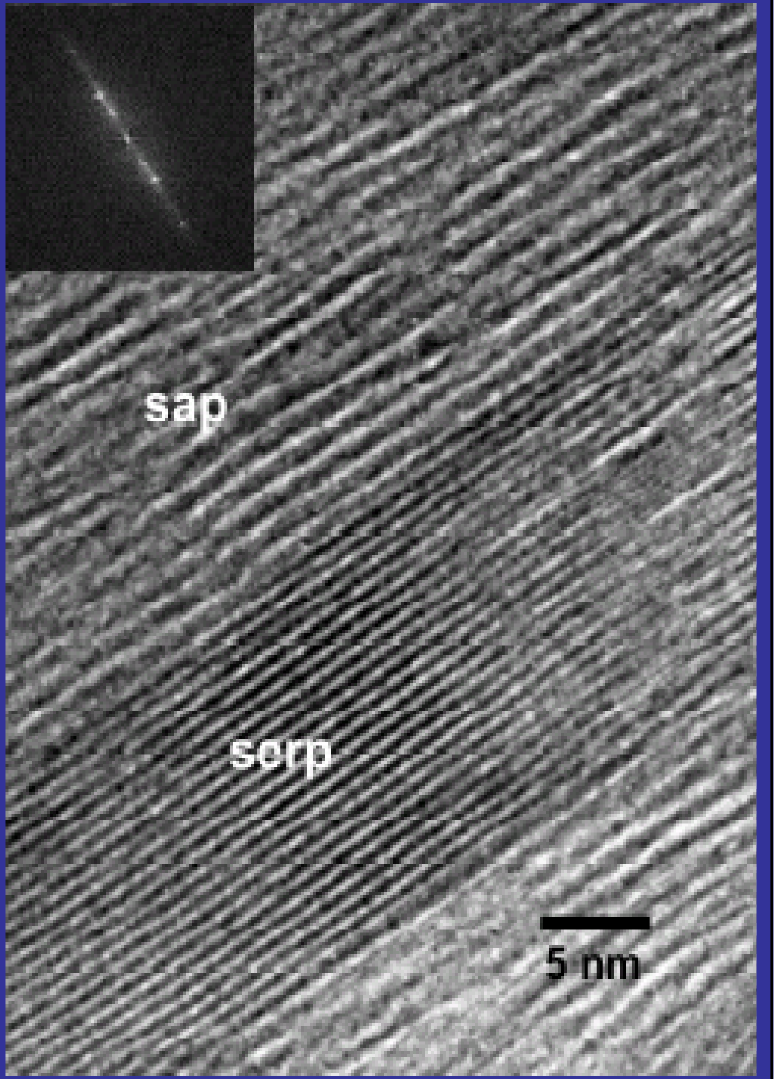
# How did Earth get its water?

## Asteroidal ?

LAP 04840



Tagish Lake

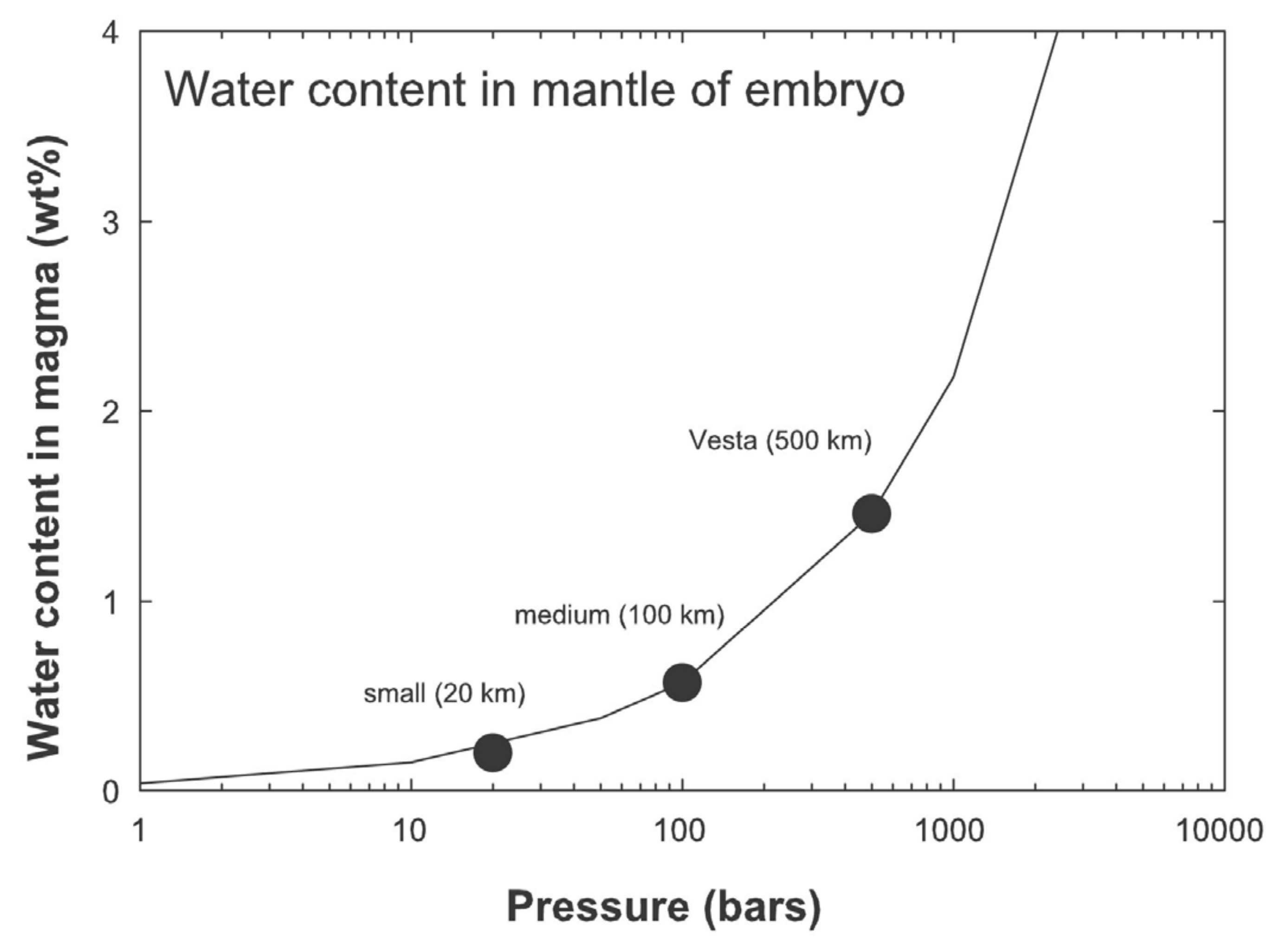


from Righter and Neff (2007)

from Keller and Flynn (2001)

# How did Earth get its water?

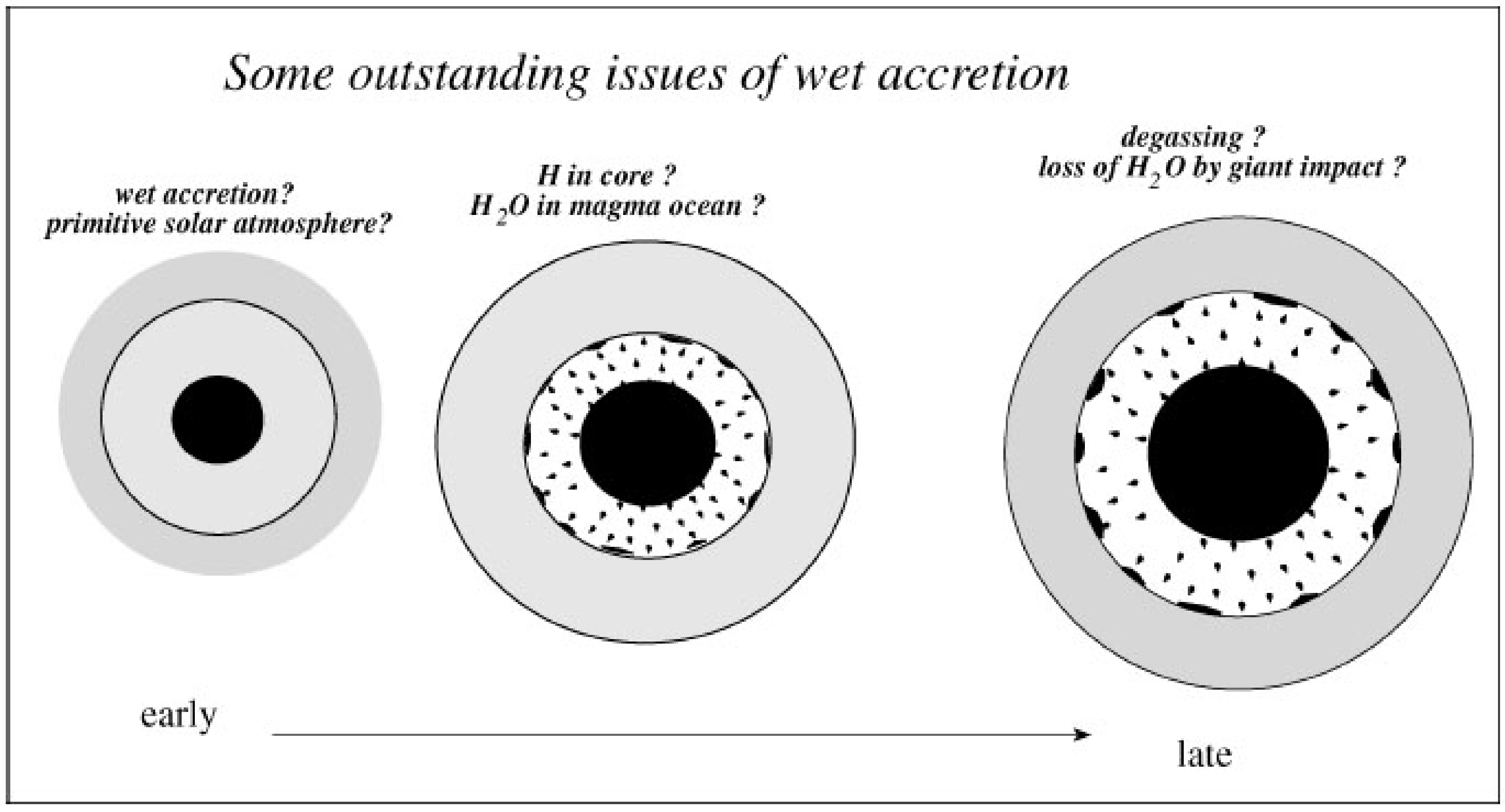
Even small molten asteroids can hold several wt% water



From Righter et al. (2006)

# How did Earth get its water?

## What happens to Earth's water during acccretion?



# Summary

- Vesta can be made from known meteorites, but volatile element depletion remains unresolved
- Mars can also be made from some known meteorites, but uncertainties of large core composition make it somewhat problematic
- It is thought that Earth cannot be made from known meteorite groups, and may have been made from distinct material not in our collections

- sample return from Mercury, Venus, Moon, Mars, comets, asteroids
- Continued analysis of existing samples (Genesis) new experiments, measurements
- Integrating modelling with observations