Composition and Origin of the Moon II

How to reconcile a giant impact model with geochemical observations?

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Outline

- **Water: evidence for not-so-dry Moon**
- **How to explain the "wet" Moon with a giant impact model?**

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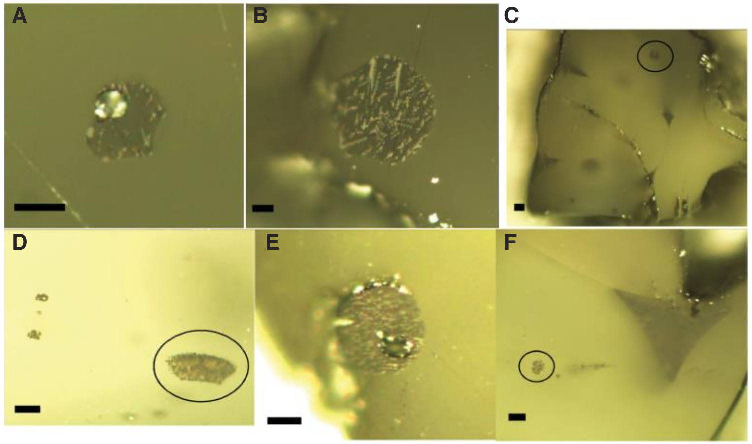
- **Evidence for small difference in isotopic composition (+ large difference in FeO content).**
- **How to explain the isotopic and major element chemistry of the Moon simultaneously?**
  - **Difficulties in the classic giant impact model**
  - **Problems with the recent models: Ćuk-Stewart, Canup**
  - **A new model (magma ocean origin of the Moon)**

Giant impact model and the “dry” Moon paradigm

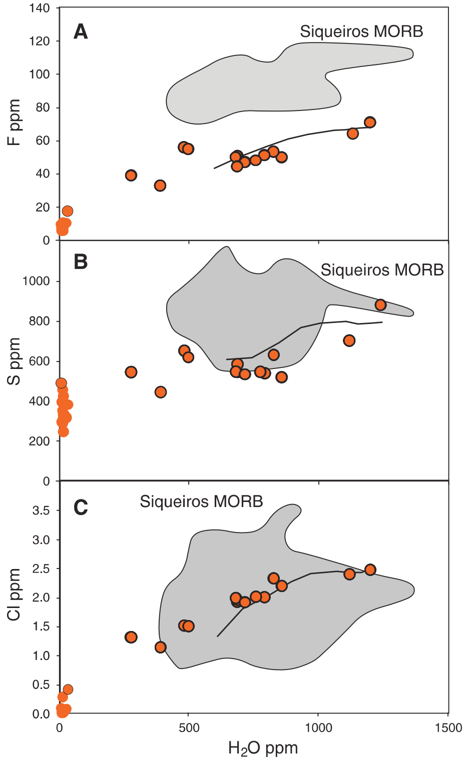
Giant impact → intense heating (→ condensation)
→depletion of volatiles (“dry” Moon paradigm)
→ **How much depletion really?**

New technology allows us to measure the volatile content more precisely → quite different view on the volatile content in the Moon

Geochemical approach
new analysis on old samples → not-so-dry Moon?



Saal et al. (2008, 2013) (olivine)
Hauri et al. (2011) (olivine)
[Greenwood et al. (2011) (apatite)]

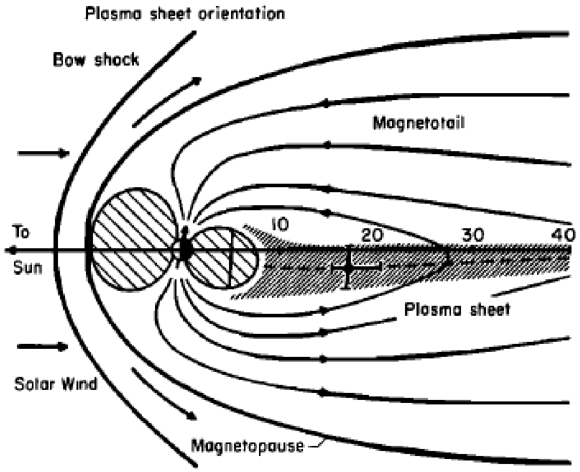


Hauri et al. (2011)

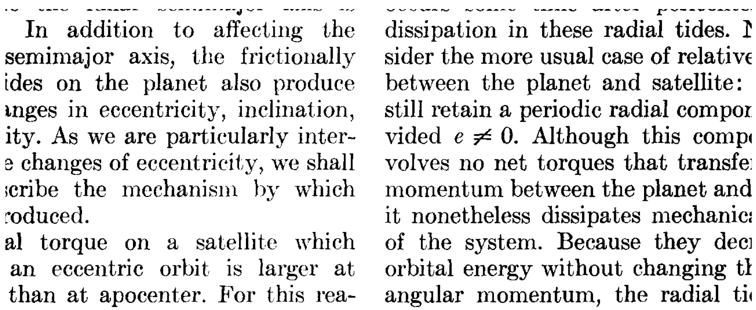
Inclusions in olivine in some lunar rocks show volatile content similar to Earth.
→Lunar **interior** is as wet as Earth's upper mantle (depleted but not-so-dry (~100 ppm wt water)).
→Are these sample representative of the bulk Moon? Aren't they "anomalous"?

How about geophysical observations?

- **Geophysical observations = global (**indirect**)**
- Which observations?
  - Seismic wave velocities
  - Electrical conductivity
  - Tidal Q (viscosity)



Electro-magnetic induction



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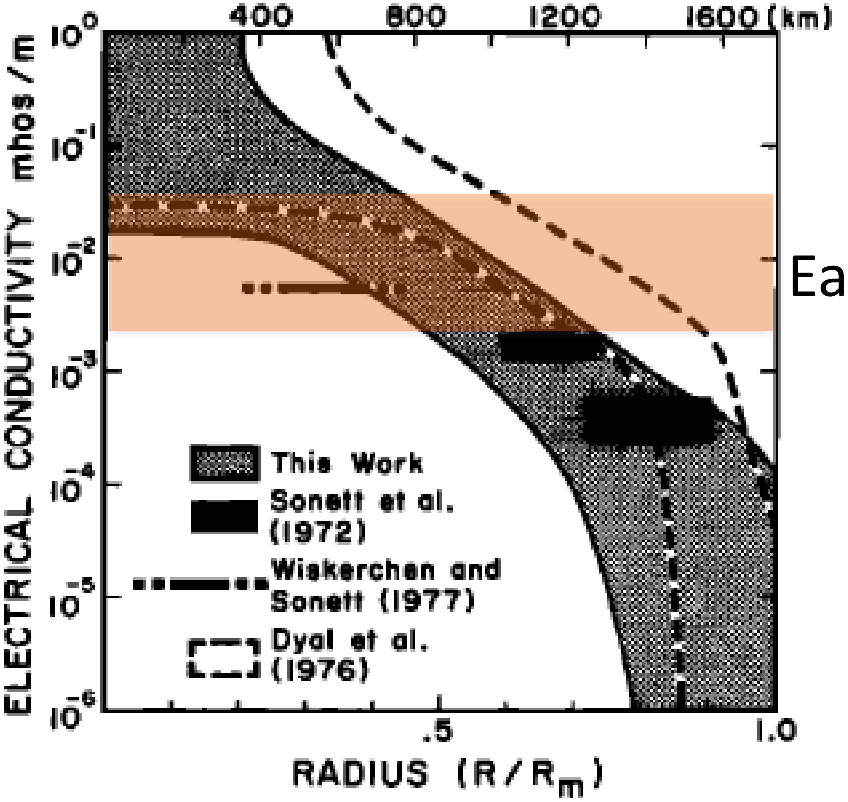
Tidal dissipation

Geophysical observations I:

electrical conductivity



Earth's asthenosphere

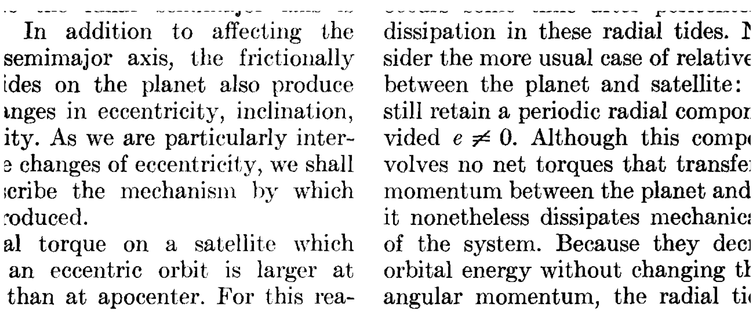
Hood et al. (1982)

Deep lunar mantle has electrical conductivity as high as Earth's asthenosphere ("wet" region?).

Geophysical inference II:
tidal Q

Anelasticity ←→ viscosity (temperature, water content)

Q: **low Q ←→ "soft" materials**



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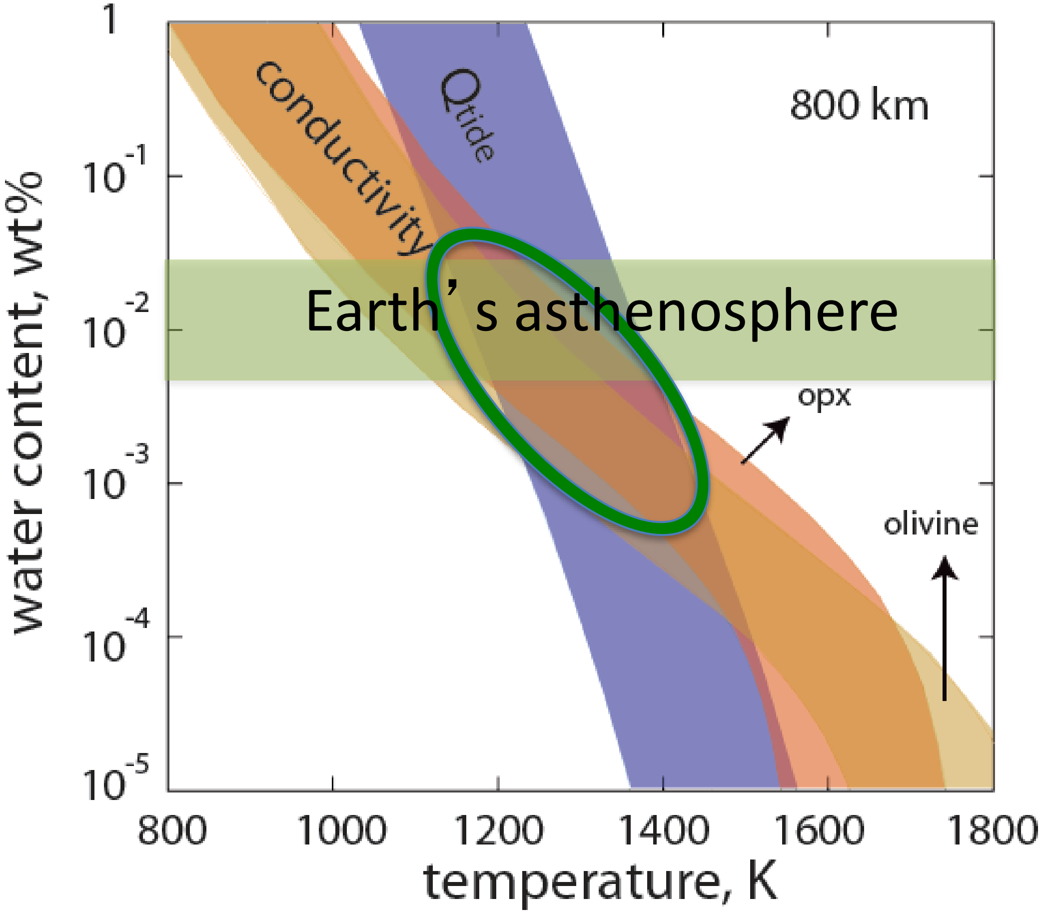
Low tidal Q (37-60 (Williams et al., 2001)))

[tidal Q of solid Earth ~290 (Ray et al., 1996)

Seismic Q of the asthenosphere ~80

Seismic Q of the lower mantle ~300 (Dziewonski-Anderson, 1981)]

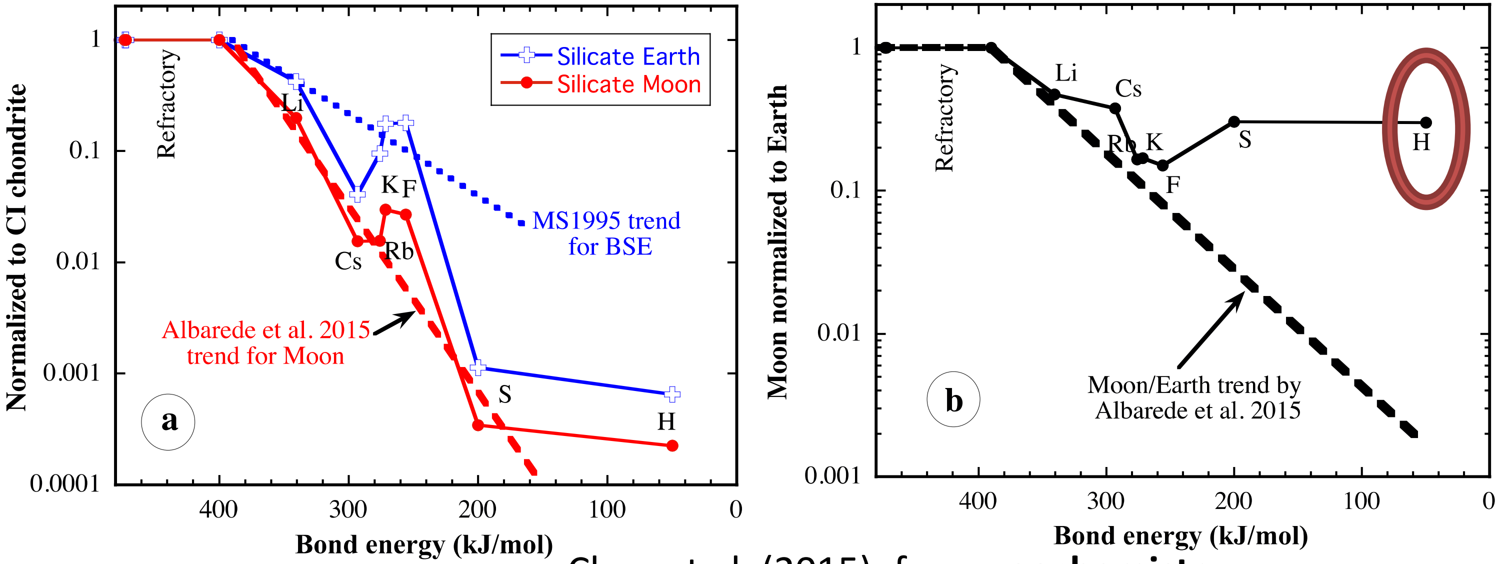
Constraining water content and temperature using both conductivity and tidal Q



Karato (2013)

→Lunar mantle is cooler than Earth's mantle, but its water content is similar to the Earth's asthenosphere (or slightly less).

Volatile depletion in Earth and in the Moon from geochemistry (+ geophysics)



Chen et al. (2015), from **geochemistry**

from geophysics
Karato (2013)

- The Moon and Earth are much depleted with volatiles compared to CI chondrite. (**most volatiles were lost during the formation of Earth**)

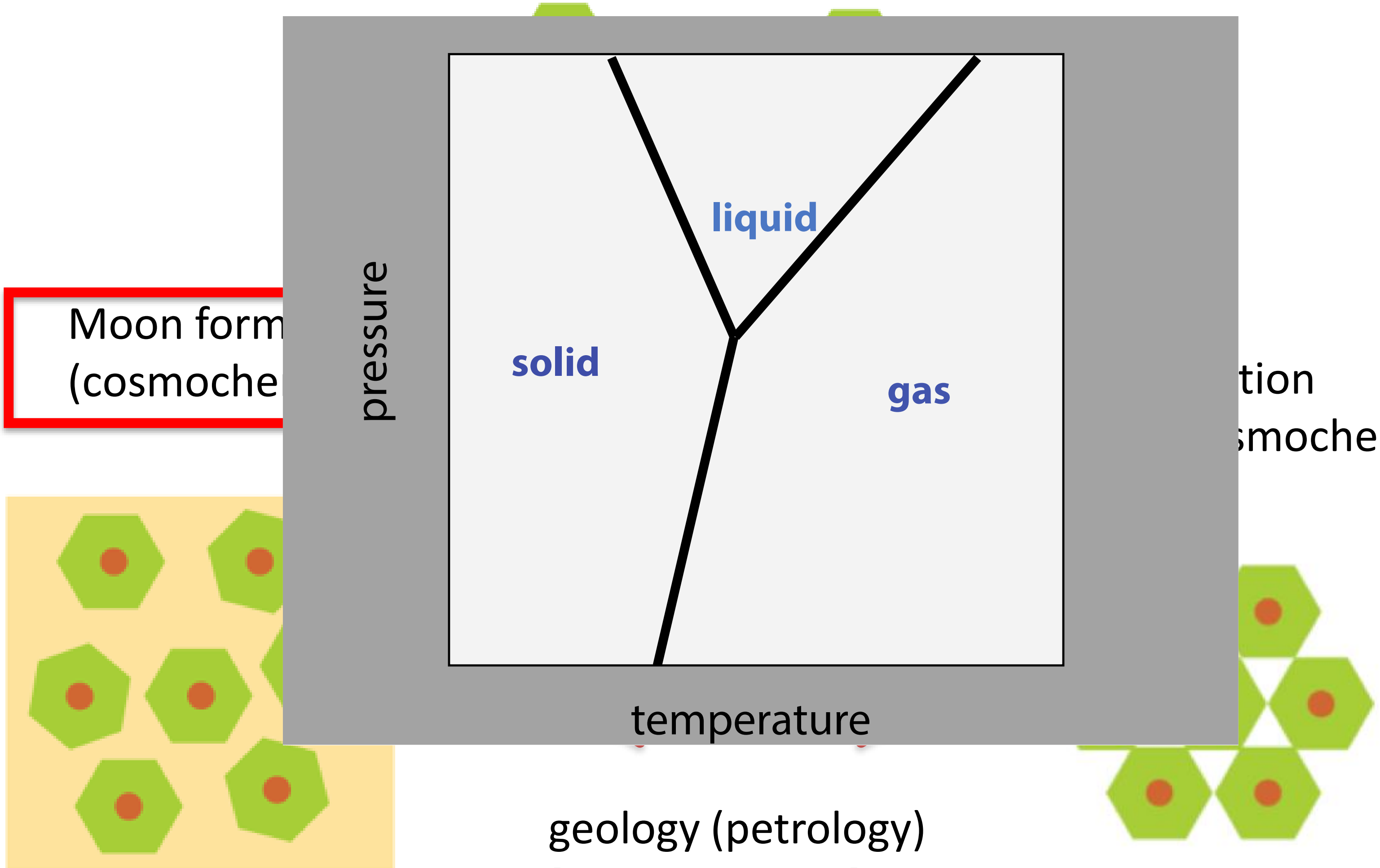
  Volatile loss is controlled by the **bond energy**.

- The Moon is not much depleted with volatiles compared to Earth, and the degree of volatile depletion is insensitive to species (bond energy). (**not much volatile loss during the Moon formation**)

  Volatile loss during the Moon formation is not controlled by the **bond energy**.

- **Why is the nature of volatile loss so different in these two cases?**

How to explain the different degree of volatile loss during planet formation? (back to the basics)



Moon form
(cosme

tion
smochemistry)

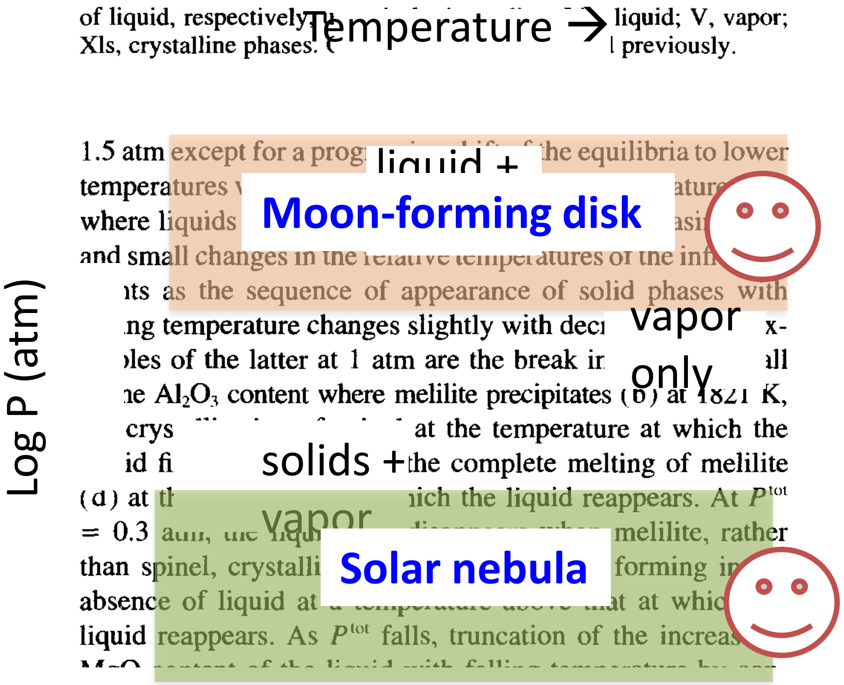
geology (petrology)
[partial melting]

liquid

solid

Why do liquids play an important role for the Moon while solids are important for Earth?

$$P_{disk} \gg \frac{p}{2} G s^{2} \gg \frac{1}{2p} G \frac{M^{2}}{R^{4}}$$

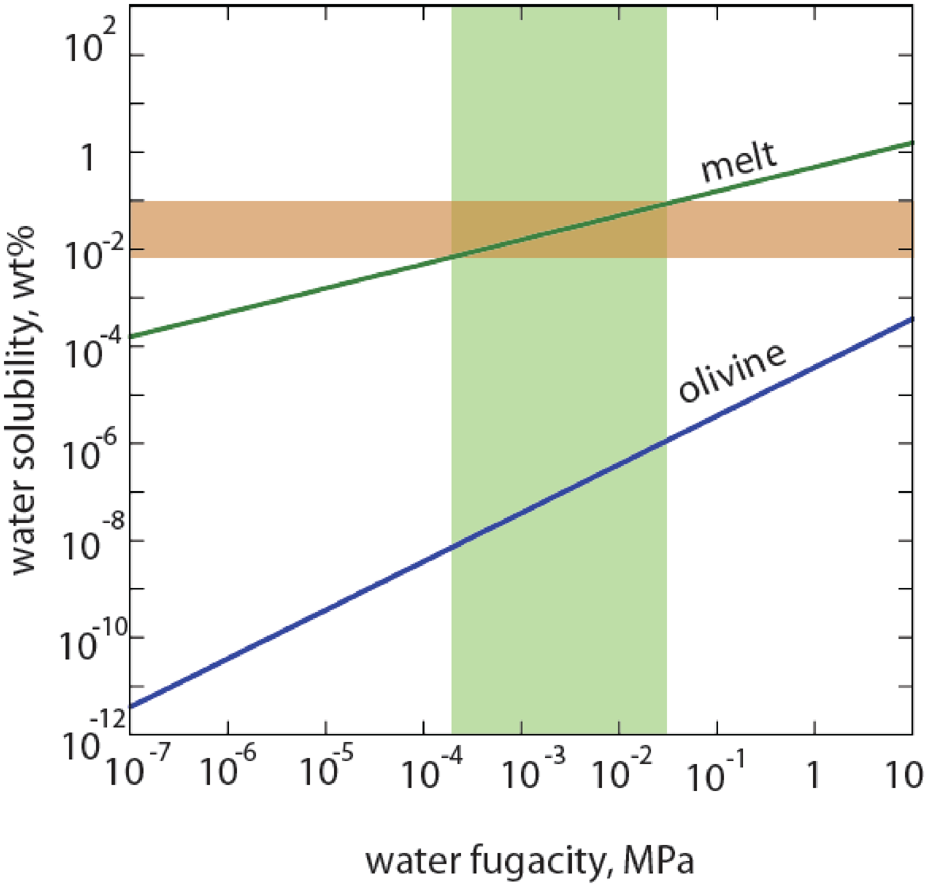


Yoneda-Grossman (1995)

gas → solid: Solar nebula (planet formation) (low P)

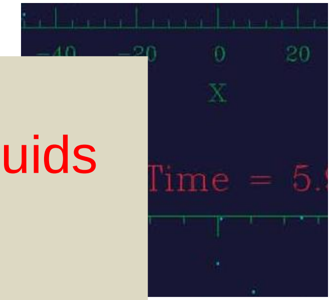
gas → liquid: Moon-forming disk (high P)

Not much water loss due to the condensation to **liquid** (major water loss due to the condensation to solid)



Karato (2013)

Volatiles during the Moon formation after a giant impact



Moon-forming disk

High P (high mass density) → condensation to liquids

and $\tau_{accretion} \leq \tau_{cooling}$

($\tau_{cooling} \approx$ 100 y, $\tau_{acrretion} \approx$ 1-100 y)

→ a large fraction of materials accrete as liquids
→ little depletion in volatiles

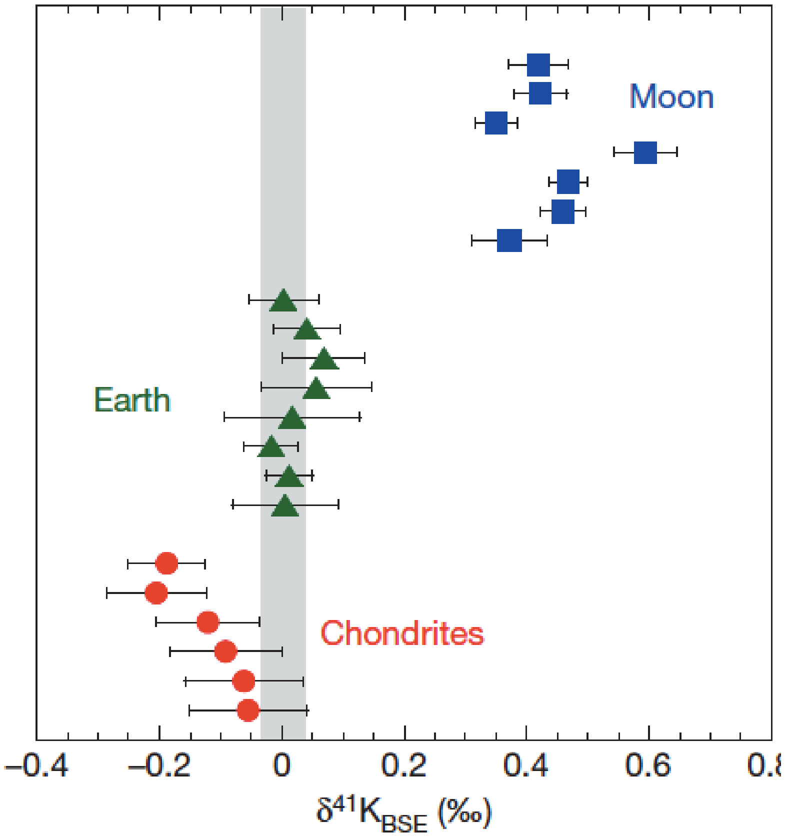
Proto-solar nebula

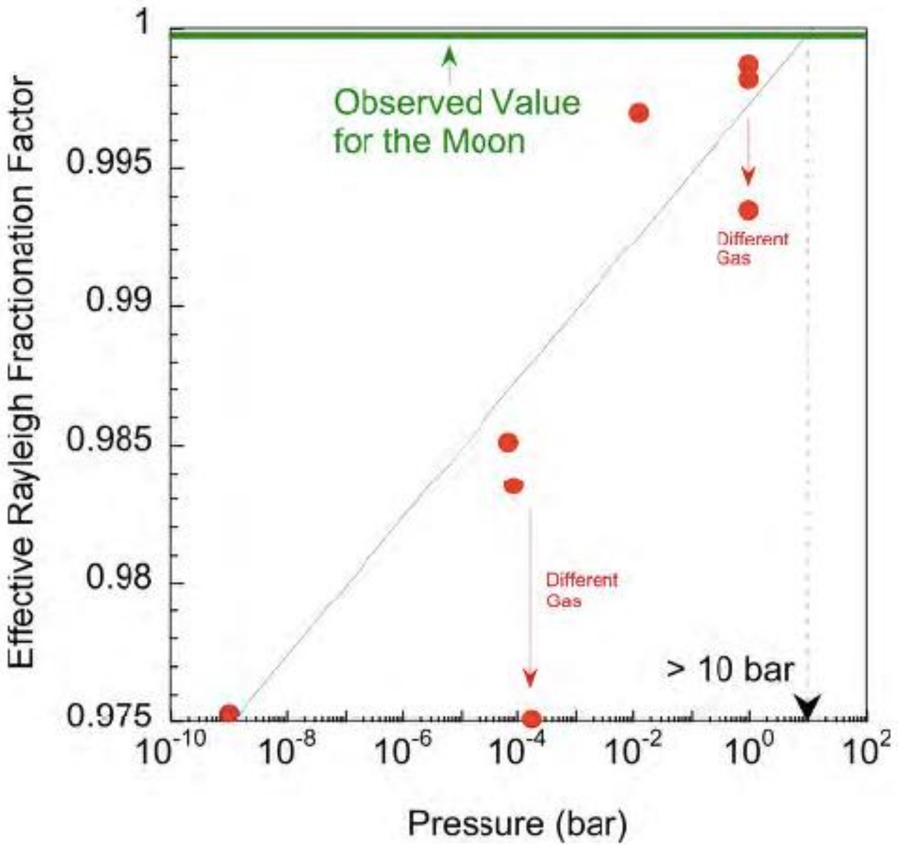
Low P (low mass density) → condensation to solids

[and $\tau_{accretion} \gg \tau_{cooling}$]

→ high degree of depletion in volatiles

Support for high-P condensation: K isotope data





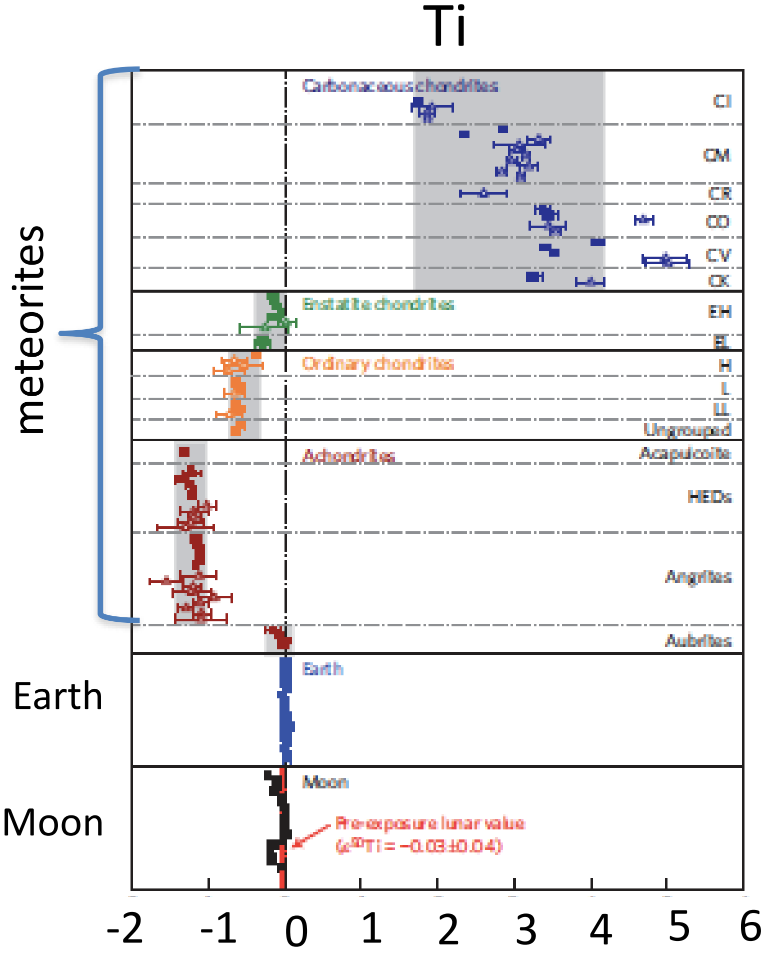
K is a volatile element → large fractionation

Degree of fractionation depends on the pressure → pressure estimate (~10 bar or higher)

Wang-Jacobsen (2016)

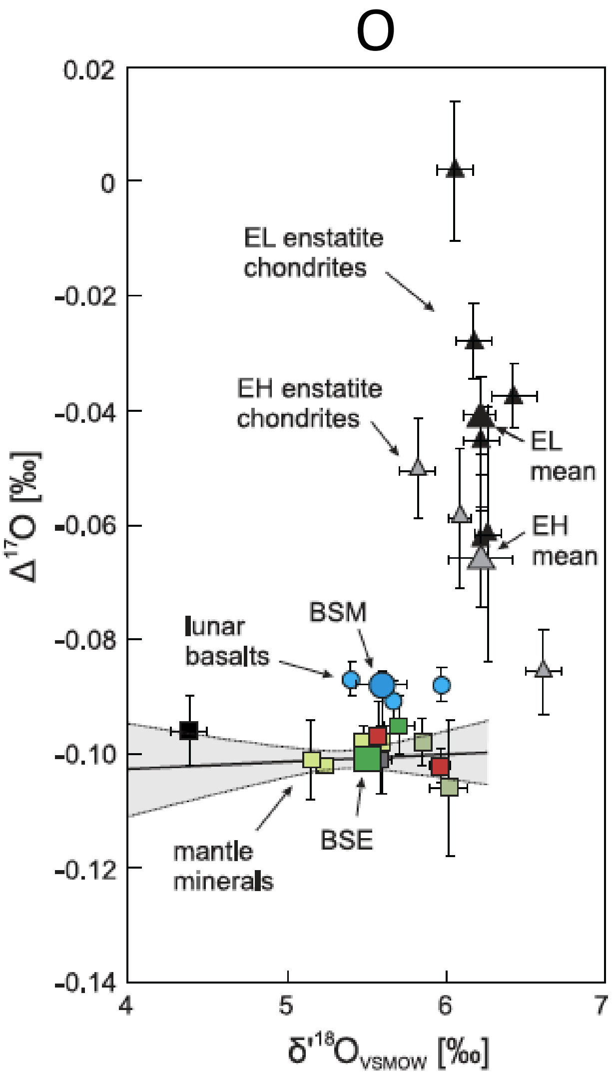
Composition of non-volatile elements I

Small difference in the isotope ratio



$$e^{50}Ti = \left[\left({}^{50}Ti / {}^{47}Ti \right)_{sample} / \left({}^{50}Ti / {}^{47}Ti \right)_{standard} - 1 \right] \times 10^{4}$$

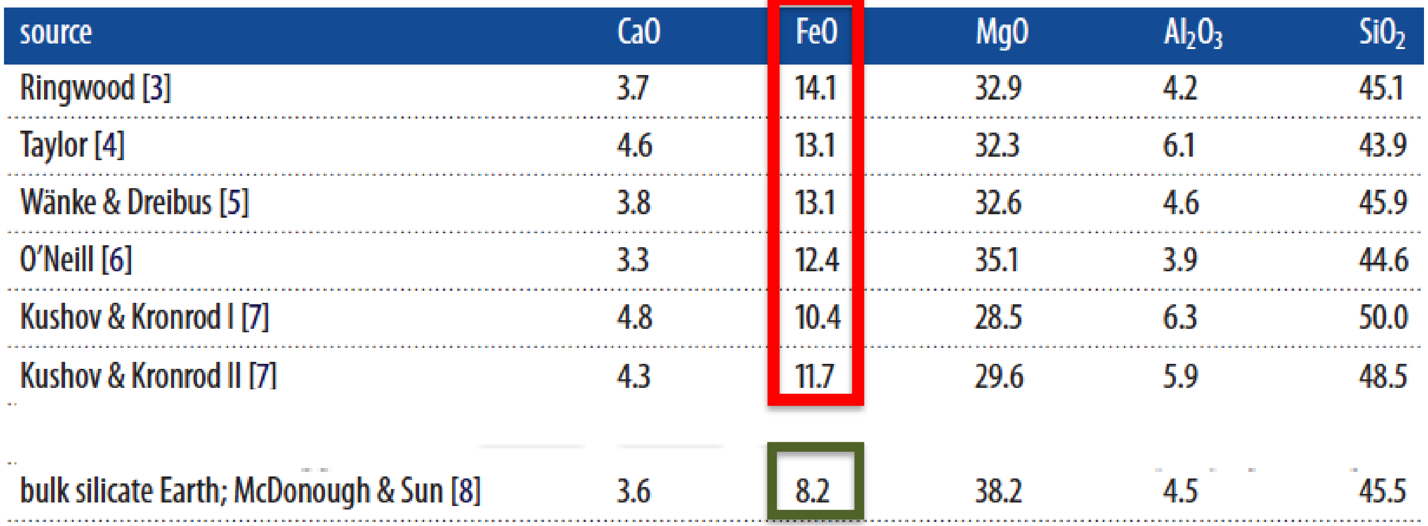
(Zhang et al., 2012)



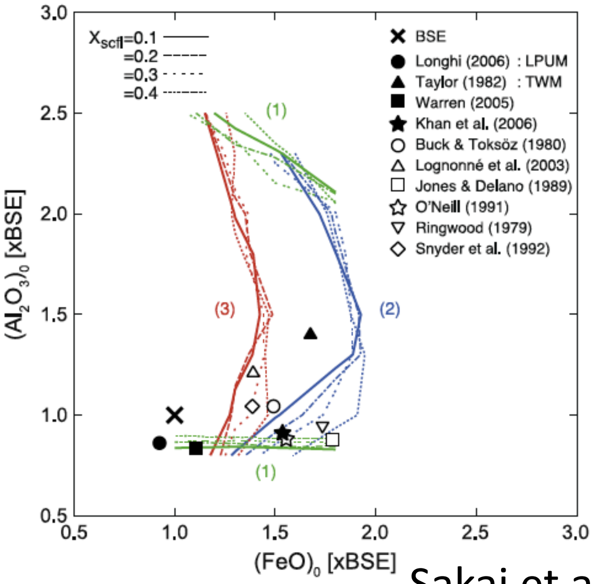
(Herwartz et al., 2014)

Composition of non-volatile elements II

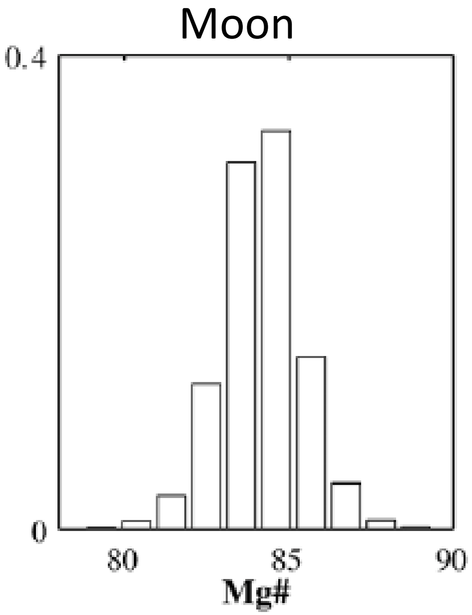
Different FeO/MgO ratio



	source	CaO	FeO	MgO	Al_2O_3	SiO_2
Moon	Ringwood [3]	3.7	14.1	32.9	4.2	45.1
	Taylor [4]	4.6	13.1	32.3	6.1	43.9
	Wänke & Dreibus [5]	3.8	13.1	32.6	4.6	45.9
	O'Neill [6]	3.3	12.4	35.1	3.9	44.6
	Kushov & Kronrod I [7]	4.8	10.4	28.5	6.3	50.0
	Kushov & Kronrod II [7]	4.3	11.7	29.6	5.9	48.5
Earth	bulk silicate Earth; McDonough & Sun [8]	3.6	8.2	38.2	4.5	45.5



Sakai et al. (2014)



Khan et al. (2006)

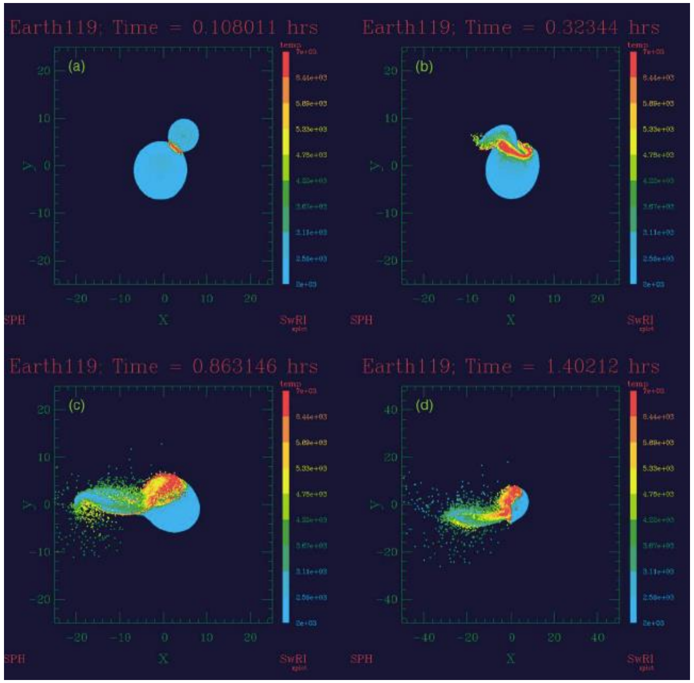
Challenges in developing a model to explain the chemistry of the Moon

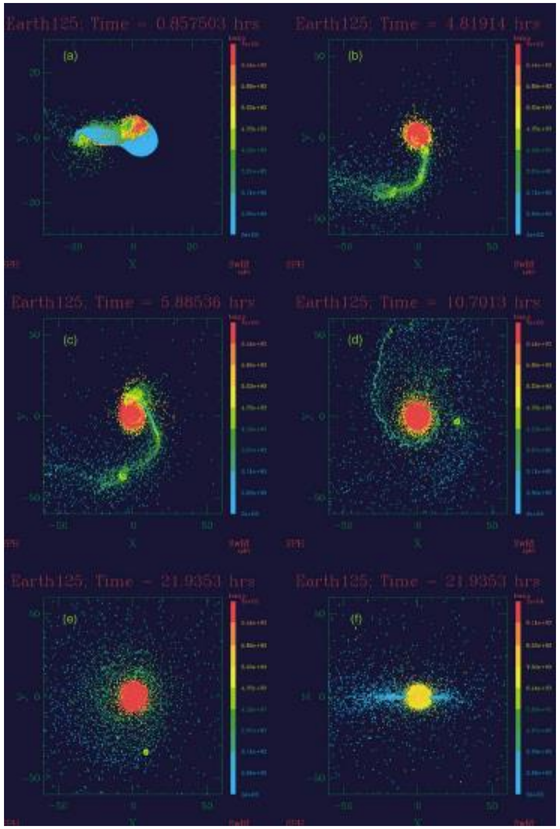
- **Isotope →** the Moon and Earth have very similar composition
- **FeO →** major element chemistry is different

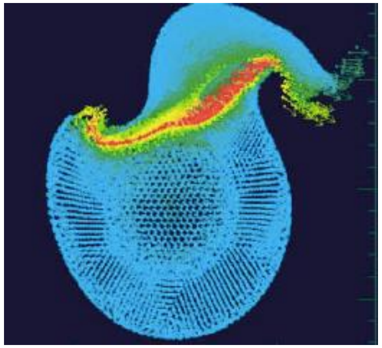
→ If the impactor and the proto-Earth have different composition, what mixing ratio do we need to explain the isotopic similarity?

→ How can we explain the isotopic similarity and the difference in the FeO content?

→ Can these models for composition also explain the large angular momentum?







Canup (2004)

- **A standard model**: oblique collision (← large **angular momentum**) → **shearing** the impactor → **a majority (~80%) of the Moon is made of the impactor materials**

  (inconsistent with the chemistry)

How to explain the similar isotopic compositions and dissimilar FeO?

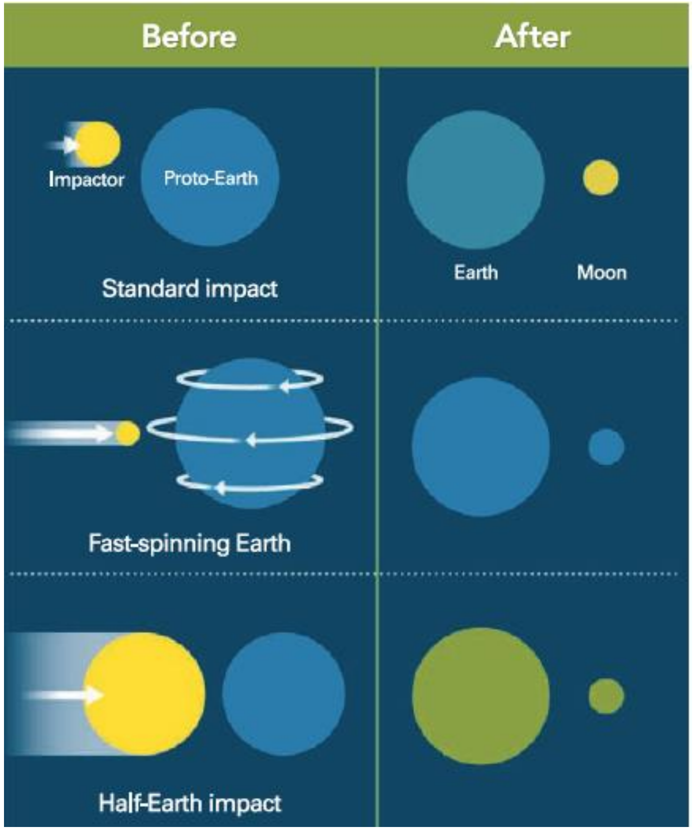
- Well mixing: Pahlevan-Stevenson (2007), Melosh (2014)
  → angular momentum?, how good is the mixing?
- A majority of Moon is from proto-Earth (and the impactor mass was not large): Ćuk-Stewart (2012)
- Same size bodies collided and mixed completely: Canup (2012)

→ **All previous models do not explain dissimilar FeO content. Problems in explaining the large angular momentum.**

→ **A new model: magma-ocean origin of the Moon**

Giant impact and the composition of the Moon

A crisis?

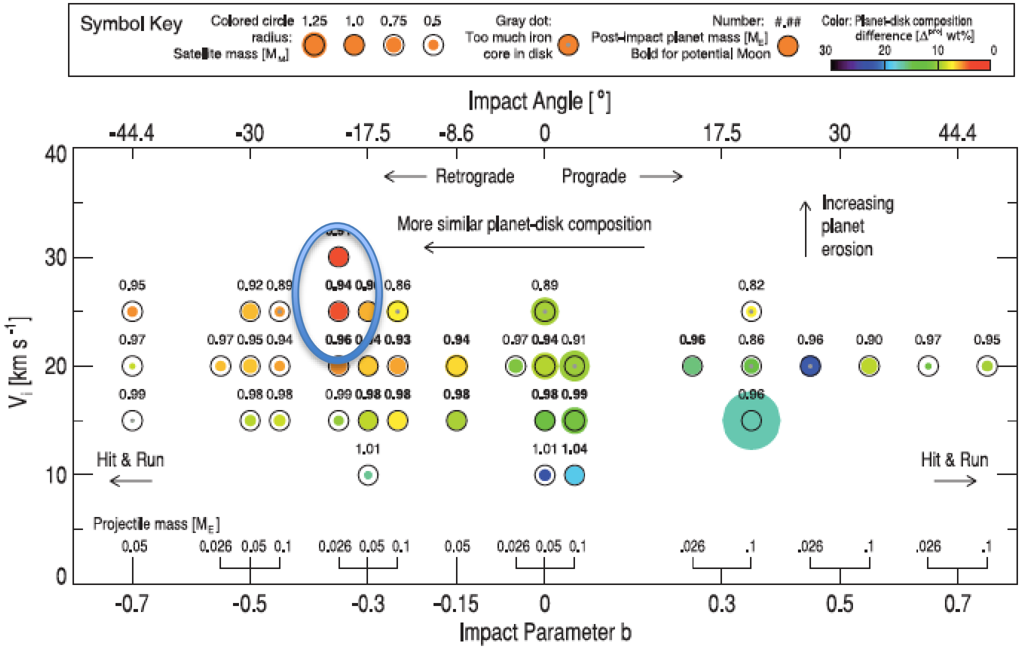


“classic” model
Benz et al. (1986)
Canup (2004)
→ different composition

Ćuk-Stewart (2012)

Canup (2012)

Clery (2013)



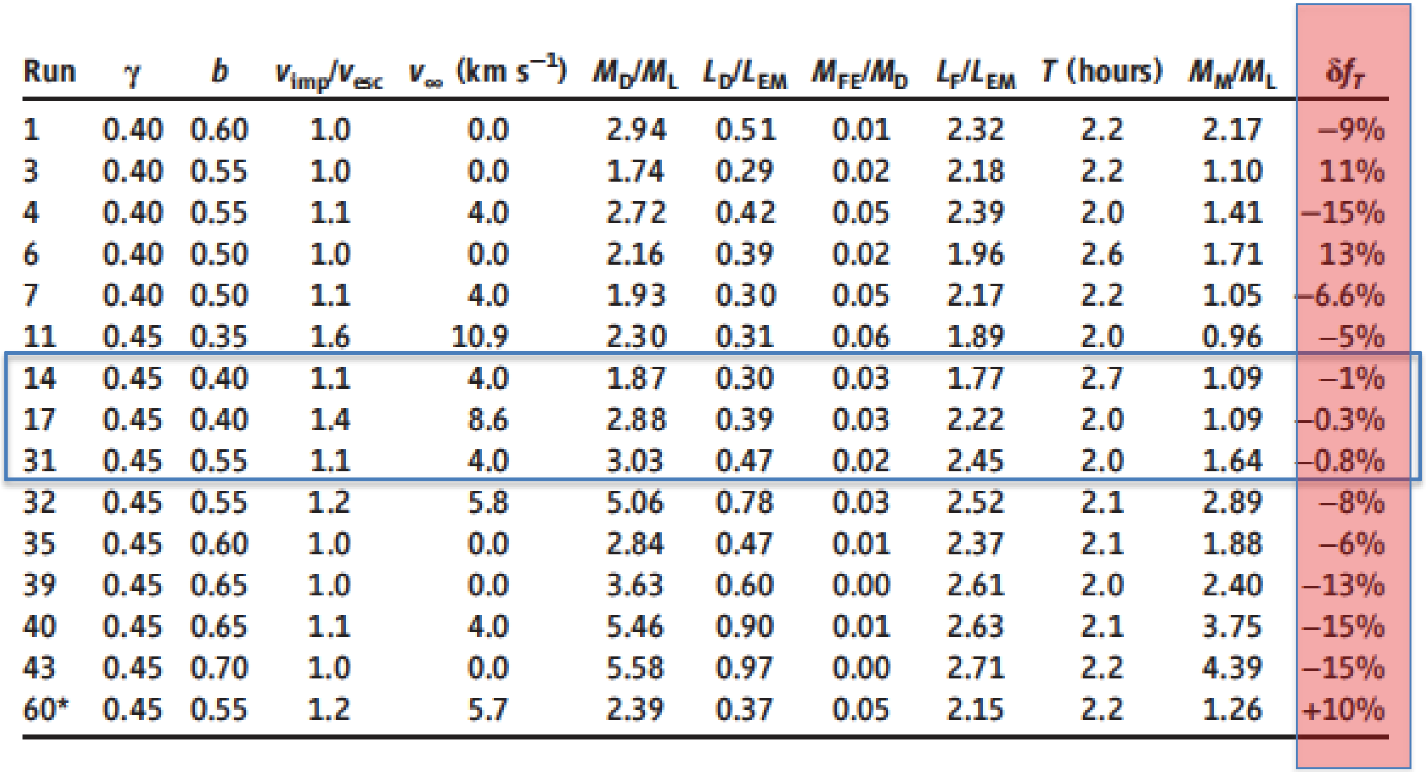
Ćuk-Stewart (2012)

Problems with the Ćuk-Stewart model

1.Only in a small parameter space, can one have the composition similar to Earth (**by chance?**).

2.Predicts a major element composition inconsistent with the observation.

3.Angular momentum?



Run	γ	b	v_{imp}/v_{esc}	v_{∞} (km s^{-1})	M_D/M_L	L_D/L_{EM}	M_{FE}/M_D	L_F/L_{EM}	T (hours)	M_M/M_L	δf_T
1	0.40	0.60	1.0	0.0	2.94	0.51	0.01	2.32	2.2	2.17	−9%
3	0.40	0.55	1.0	0.0	1.74	0.29	0.02	2.18	2.2	1.10	11%
4	0.40	0.55	1.1	4.0	2.72	0.42	0.05	2.39	2.0	1.41	−15%
6	0.40	0.50	1.0	0.0	2.16	0.39	0.02	1.96	2.6	1.71	13%
7	0.40	0.50	1.1	4.0	1.93	0.30	0.05	2.17	2.2	1.05	−6.6%
11	0.45	0.35	1.6	10.9	2.30	0.31	0.06	1.89	2.0	0.96	−5%
14	0.45	0.40	1.1	4.0	1.87	0.30	0.03	1.77	2.7	1.09	−1%
17	0.45	0.40	1.4	8.6	2.88	0.39	0.03	2.22	2.0	1.09	−0.3%
31	0.45	0.55	1.1	4.0	3.03	0.47	0.02	2.45	2.0	1.64	−0.8%
32	0.45	0.55	1.2	5.8	5.06	0.78	0.03	2.52	2.1	2.89	−8%
35	0.45	0.60	1.0	0.0	2.84	0.47	0.01	2.37	2.1	1.88	−6%
39	0.45	0.65	1.0	0.0	3.63	0.60	0.00	2.61	2.0	2.40	−13%
40	0.45	0.65	1.1	4.0	5.46	0.90	0.01	2.63	2.1	3.75	−15%
43	0.45	0.70	1.0	0.0	5.58	0.97	0.00	2.71	2.2	4.39	−15%
60*	0.45	0.55	1.2	5.7	2.39	0.37	0.05	2.15	2.2	1.26	+10%

Canup(2012)

Problems with the Canup (2012) model

1. Only in a small parameter space one can have composition similar to Earth (**by chance?**).
2. Predicts a major element composition inconsistent with the observation.
3. Difficult to explain the large angular momentum

Problems with the Canup, Ćuk-Stewart models

1. Only in a small parameter space, one can obtain composition similar to Earth (**by chance?**).
2. Predicts a major element composition (FeO) that is inconsistent with the observation.
3. Difficult to explain the large angular momentum

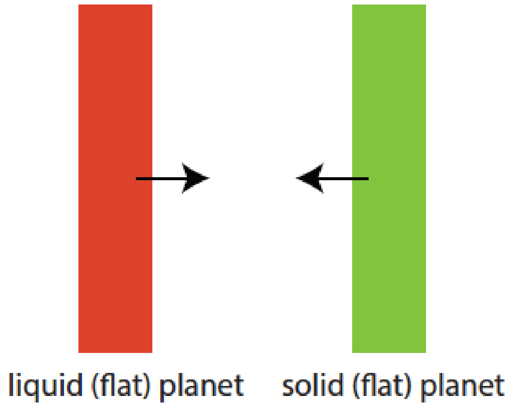
Terrestrial magma ocean origin of the Moon

- Similarity in the isotope composition but higher FeO than Earth → the **Moon from the magma ocean of the proto-Earth**?
- **Is this a physically plausible model?**
  - **Physics of shock heating**

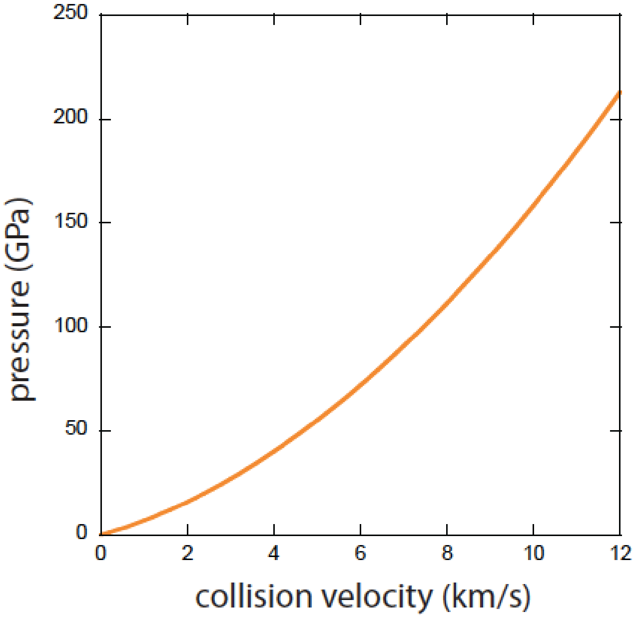
    Proto-Earth likely had a magma ocean, an impactor was likely a solid planet → **heating differently?**
  - Physics of collision/ejection

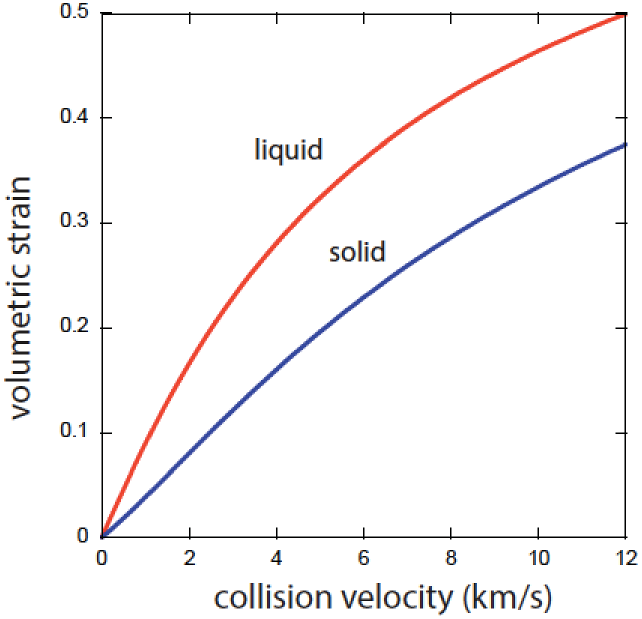
Collision → pressure, volumetric strain

liquid-solid collision leads to a large compression of liquid



The flat Earth Society

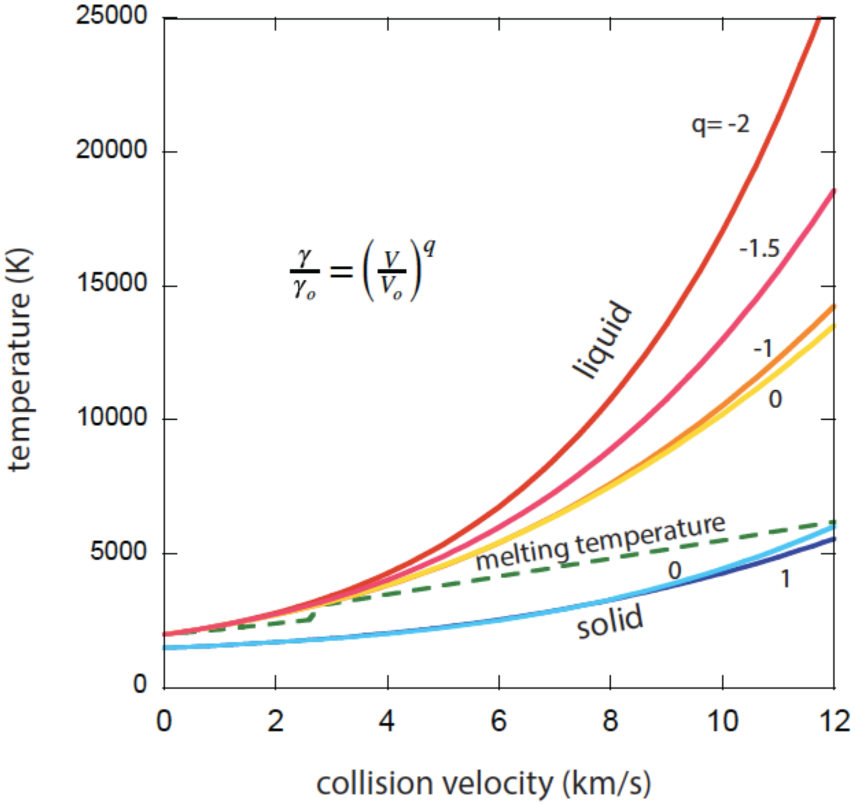




Karato (2014)

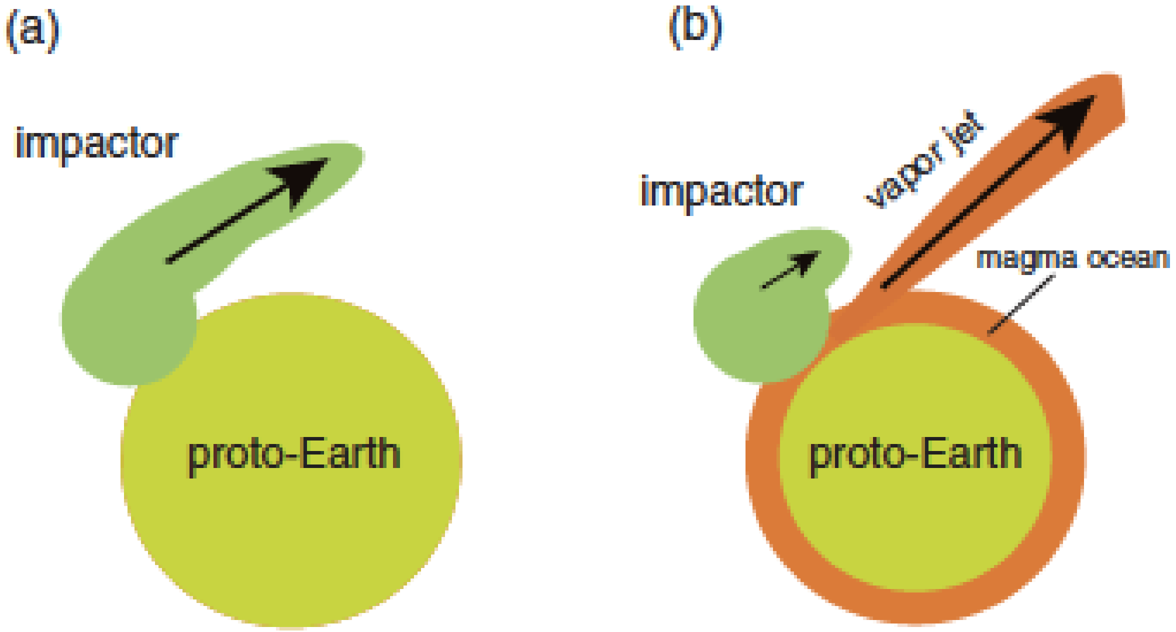
Liquid is more heated than solid

$$dT = \left\{ -\frac{Tg}{V} + \frac{1}{2C_u}\left[\left(P - P_o\right) + \left(V_o - V\right)\frac{dP}{dV} \right] \right\} dV$$



Karato (2014)

Compressional properties of **liquids** are very different from those of **solids** → heating of liquids >> heating of solids → the Moon mainly from the magma ocean of the proto-Earth



If a magma ocean is present in the proto-Earth, a large amount of vaporized materials upon a giant impact (the Moon) is from the magma ocean.

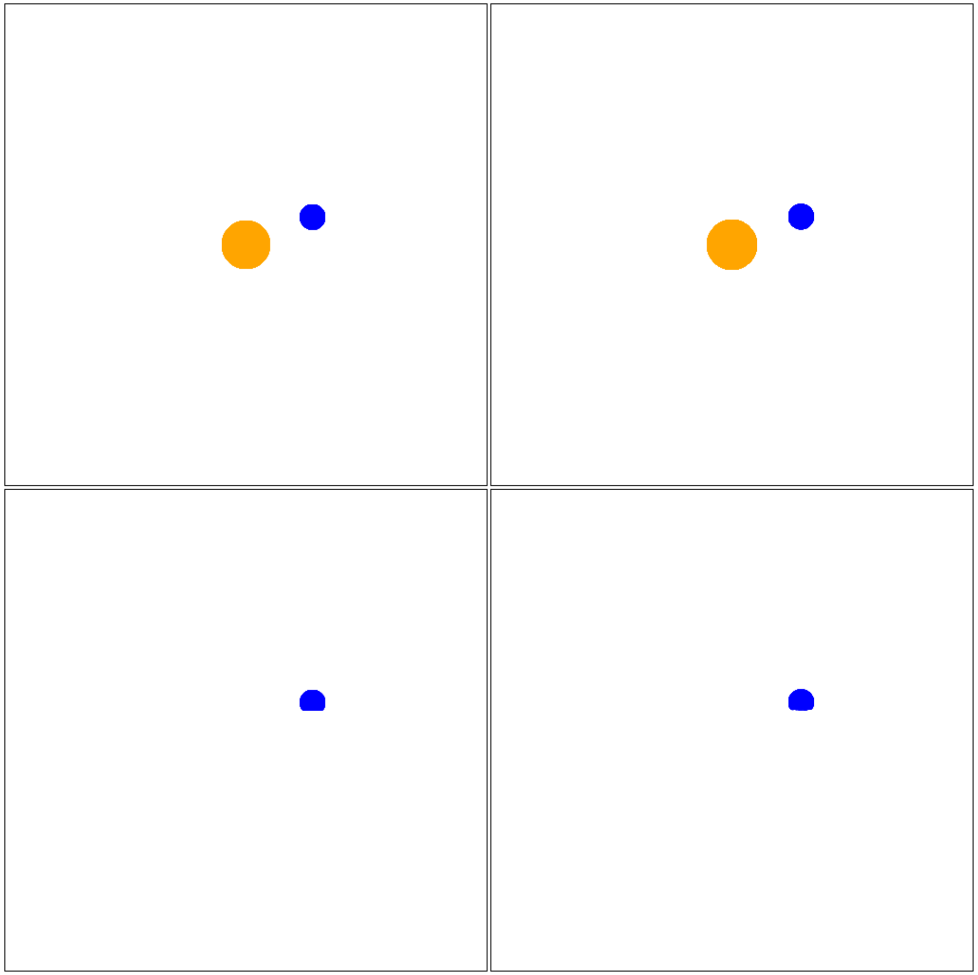
→ **How much materials exchange** (between the proto-Earth and the impactor) do we need to explain the observed chemical composition ?

→ **Mass balance calculation**

A Preliminary Numerical Study

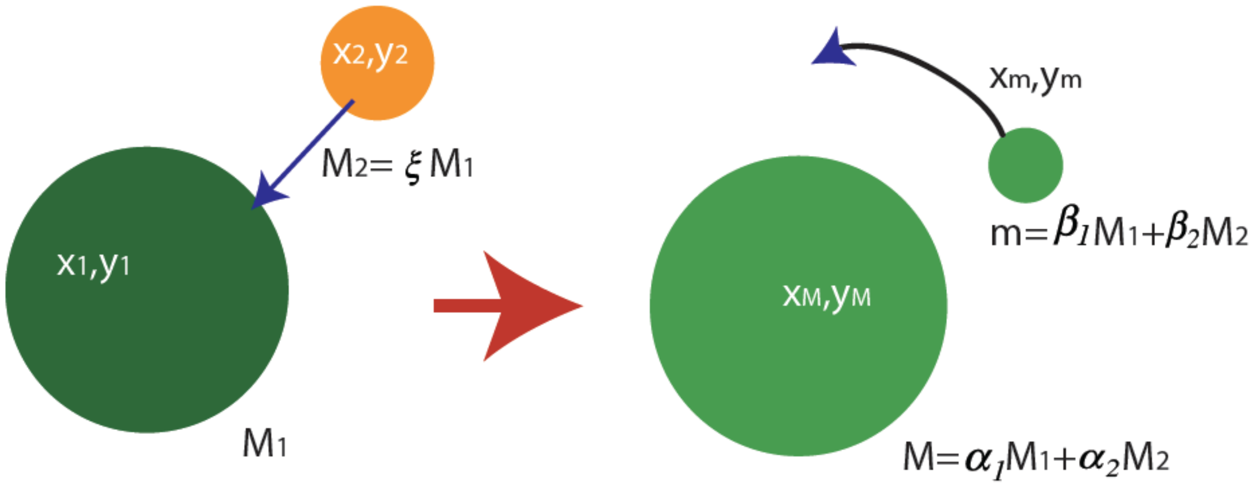
Liquid-Earth
Solid impactor

Solid Earth
Solid impactor



Hosono

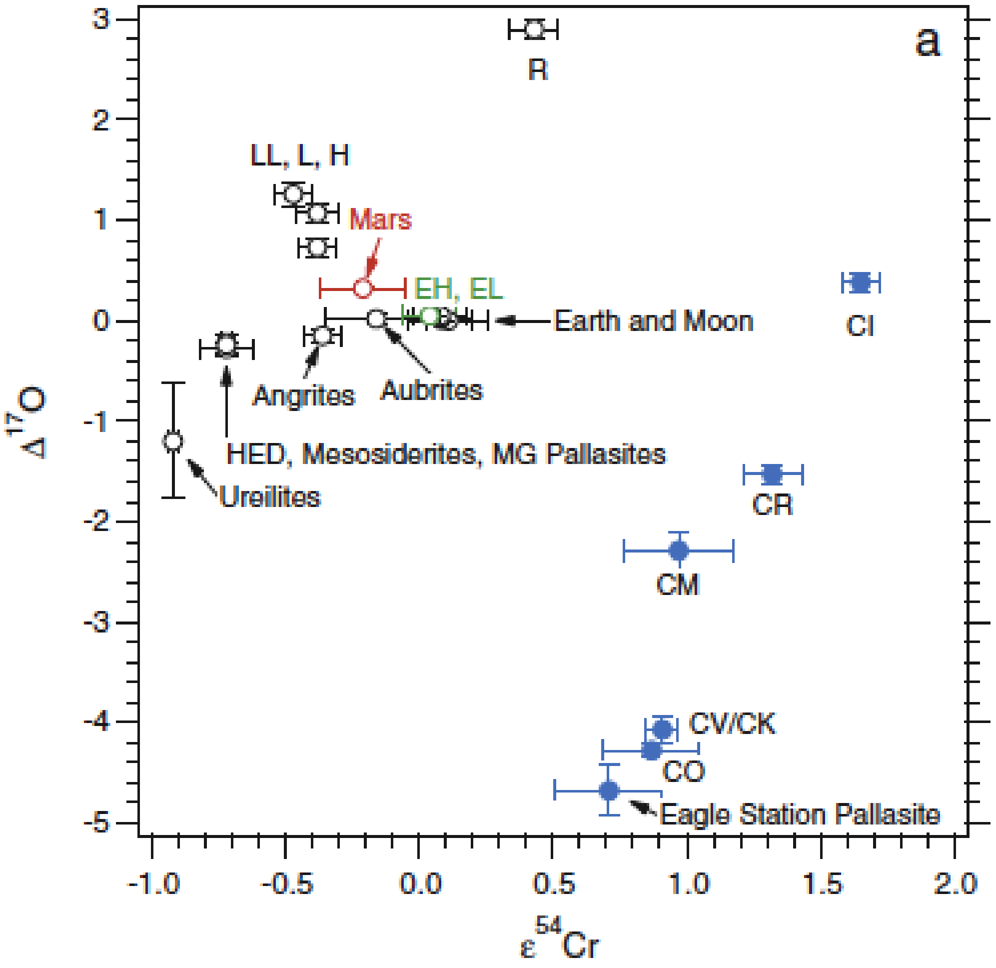
Mass balance and the isotope ratio upon a giant impact

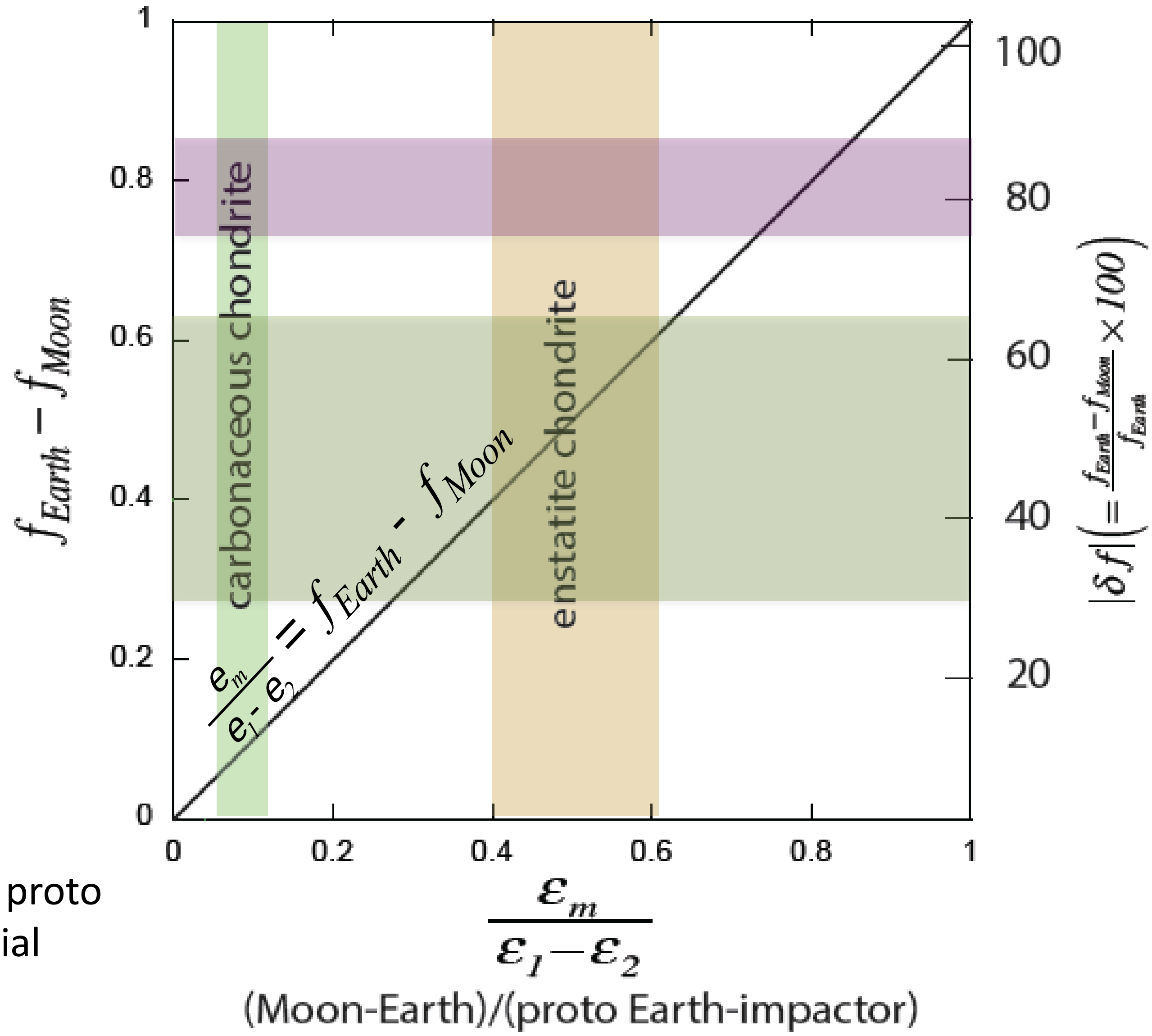


$$\frac{e_m - e_M}{e_1 - e_2} = \boxed{\frac{e_m}{e_1 - e_2} \approx f_{Earth} - f_{Moon}}$$

$$e_i = \frac{\left(\frac{x_i}{y_i}\right)}{\left(\frac{x_M}{y_M}\right)} - 1 \quad i = M, m, 1, 2 \quad \left(e_M \equiv 0\right) \quad f_{Earth,\,Moon} : \frac{\text{proto- Earth mass}}{\text{total mass}} \text{ for Earth, Moon}$$

Isotopic compositions differ among various planetary bodies, meteorites





Classic model

New models

f: fraction of proto
-Earth material

- New models (by us and by others) can explain the isotopic observations if the impactor does not have largely different isotope composition from Earth.
- No successful model can be developed if the impactor is made of carbonaceous chondrite type material.
- Ćuk-Stewart, Canup models: difficult to explain the large angular momentum, cannot explain FeO difference.
- **The magma ocean origin model** explains both the composition and the angular momentum.

[The presence of the magma ocean is a natural consequence of planetary formation.]

Conclusions

Not only geochemistry, mineral physics (+ geophysics) helps understand the composition and the origin of the Moon.

- The water content in the Moon is not so different from Earth.
  - → Moon formation in the dense (high P) gas.
- The isotopic composition of the Moon is only slightly different from Earth, but the Moon-Earth system has large angular momentum and FeO content is different.
  - –Very difficult to explain by previous models
  - **→ the Moon from the magma ocean of the proto-Earth ?**
  - **both isotope obs. and FeO content can be explained** unless the composition of the impactor is very different from Earth
  - **[magma has different degree of heating upon compression, magma has higher FeO content but similar isotopic ratios]**