Composition and origin of the Moon

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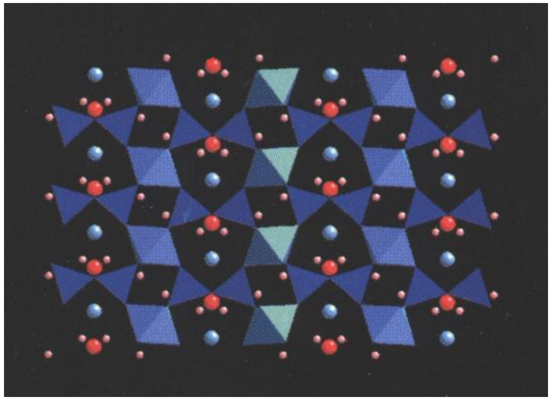
Why the Moon?

- **Giant impact model ←** **chemistry** and angular momentum
- **Giant impact model is questioned.**
  - **Unexpected observations**: "wet" Moon?
  - **Very close agreement in isotope composition (+ different FeO content):** hard to explain with a classic giant impact model

Outline

- **Is there water in the Moon as much as in the Earth?: Geophysical evidence for the "wet" (not-so-dry) Moon**
- **How to explain the "wet" Moon with a giant impact model?**

- **How to explain the isotopic and major element chemistry of the Moon simultaneously?**

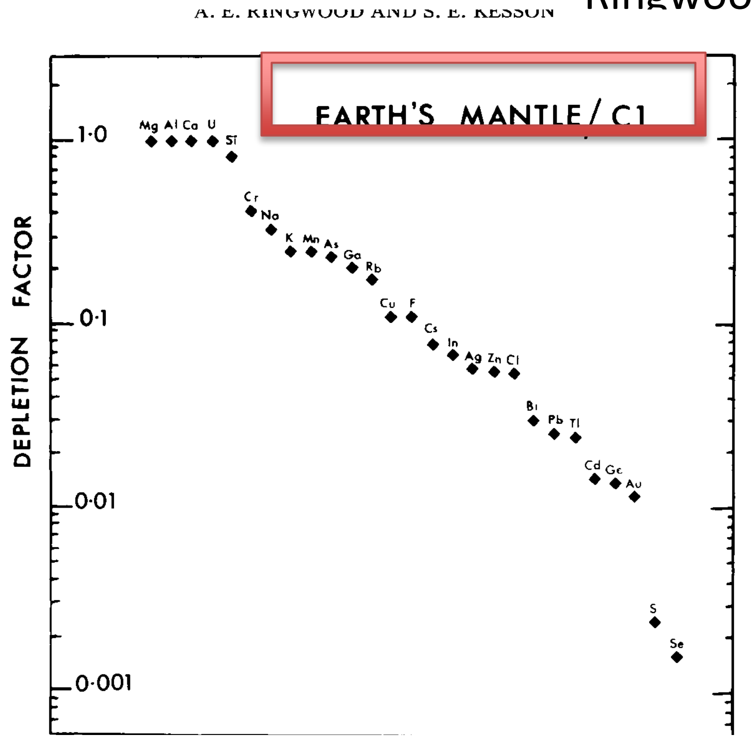


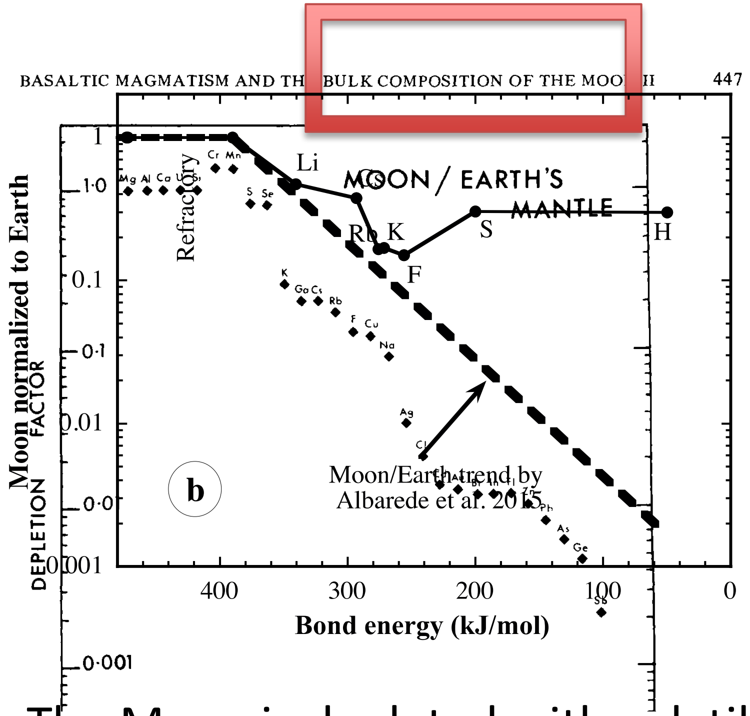
Mineral Physics
+
Planetary formation

“dry” Moon paradigm

Ted Ringwood (1930-1993)

Ringwood-Kessen (1977)





Earth is depleted with volatiles (“dry”) relative to the primitive materials (CI).

The Moon is depleted with volatiles relative to Earth. → very “dry” Moon

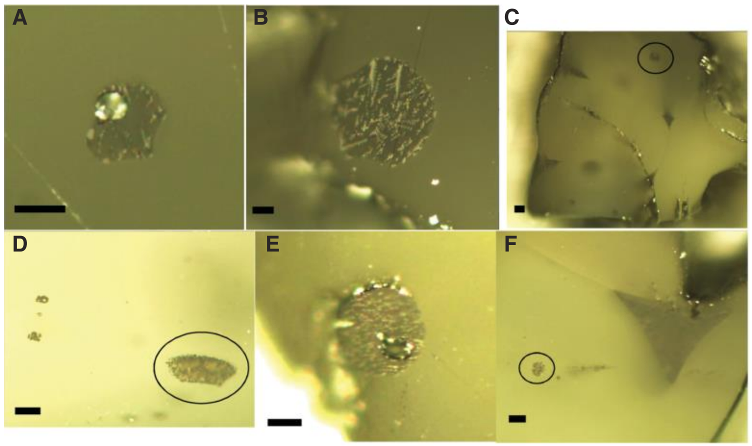
Results with modern technology revised the volatile depletion pattern (to be explained)

Giant impact model and the "dry" Moon paradigm

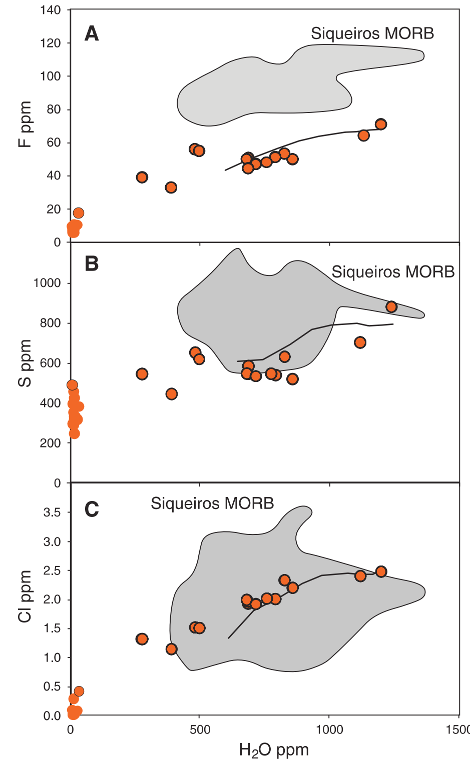
Giant impact → intense heating (→ condensation)
→depletion of volatiles ("dry" Moon paradigm)
→ **How much depletion really?**

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

Geochemical approach I:
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)]

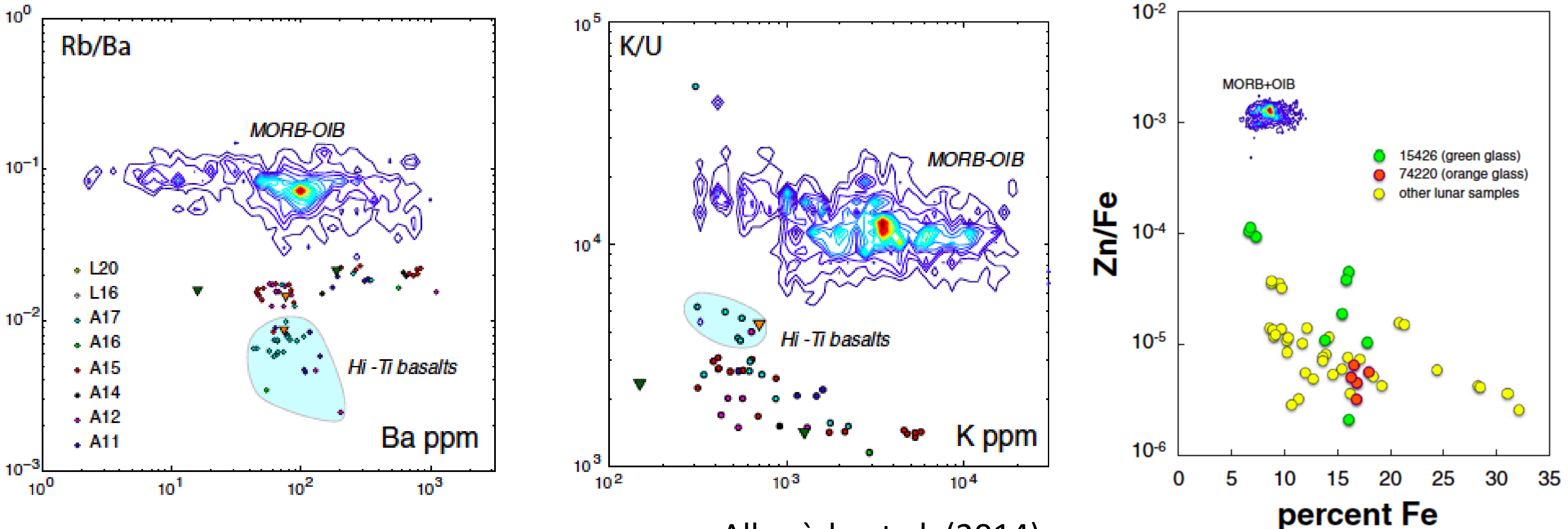


Hauri et al. (2011)

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)).

Geochemical approach II:

An argument against the not-so-dry Moon
(Albarède, 2009; Albarède et al., 2014)



Albarède et al. (2014)

The bulk of the Moon is substantially more depleted in volatile elements than Earth. (strong emphasis on Zn)

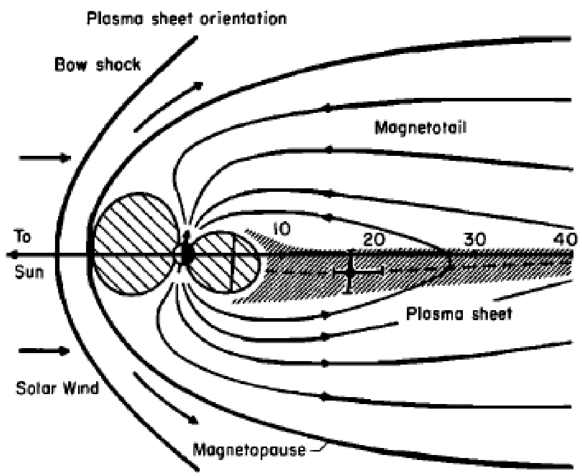
→ **Not-so-dry rocks are not representative (anomalous samples)?**

"Typical" lunar interior is dry (less than 1 ppm wt water).

→ **How about the geophysical observations?**

How about geophysical observations?

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



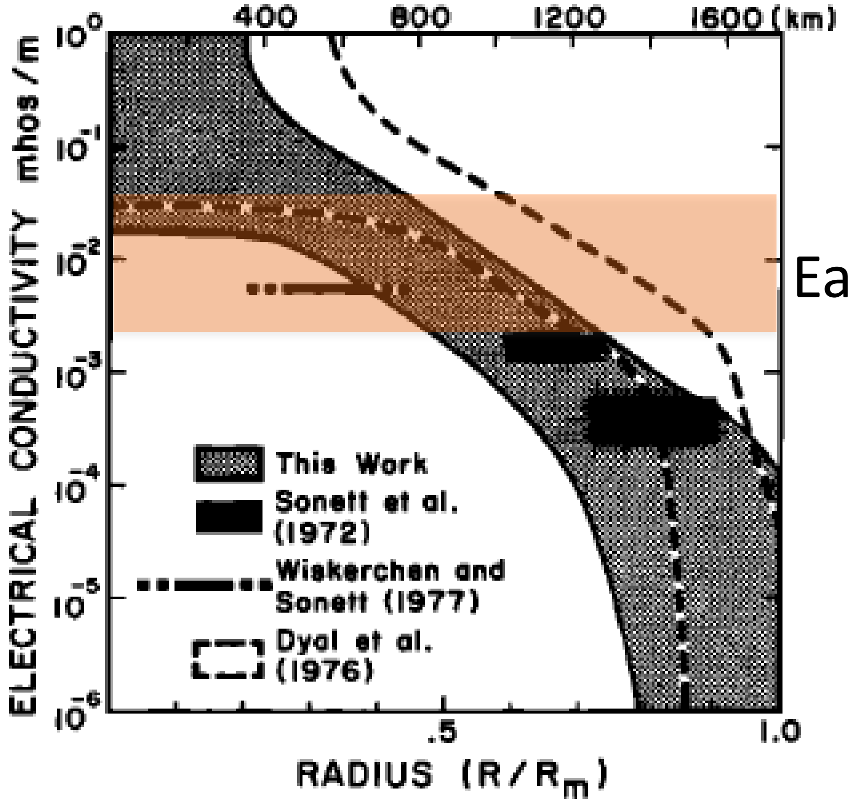
Electro-magnetic induction

In addition to affecting the semimajor axis, the frictionally ides on the planet also produce inges in eccentricity, inclination, ity. As we are particularly inter- e changes of eccentricity, we shall scribe the mechanism by which roduced.
al torque on a satellite which an eccentric orbit is larger at than at apocenter. For this rea-

dissipation in these radial tides. I sider the more usual case of relative between the planet and satellite: still retain a periodic radial compor vided $e \neq 0$. Although this comp volves no net torques that transfe momentum between the planet and it nonetheless dissipates mechanic of the system. Because they dec orbital energy without changing th angular momentum, the radial ti

Tidal dissipation

Geophysical observations I:
electrical conductivity

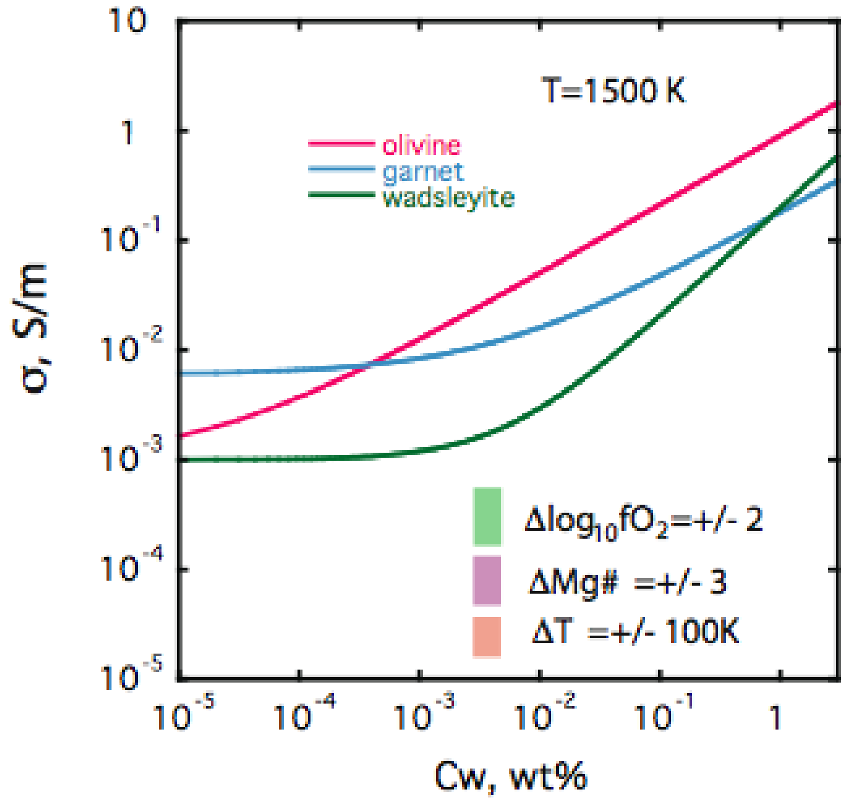


Hood et al. (1982)

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

Water (hydrogen) enhances electrical conductivity.

$$\sigma = \sigma_{o1}\left(\frac{f_{O2}}{f_{O2,o}}\right)^{q_1}\exp\left(-\frac{H^*_{\sigma 1}}{RT}\right) + \sigma_{o2}\left(\frac{C_W}{C_{Wo}}\right)^{r_\sigma}\left(\frac{f_{O2}}{f_{O2,o}}\right)^{q_2}\exp\left(-\frac{H^*_{\sigma 2}}{RT}\right)$$

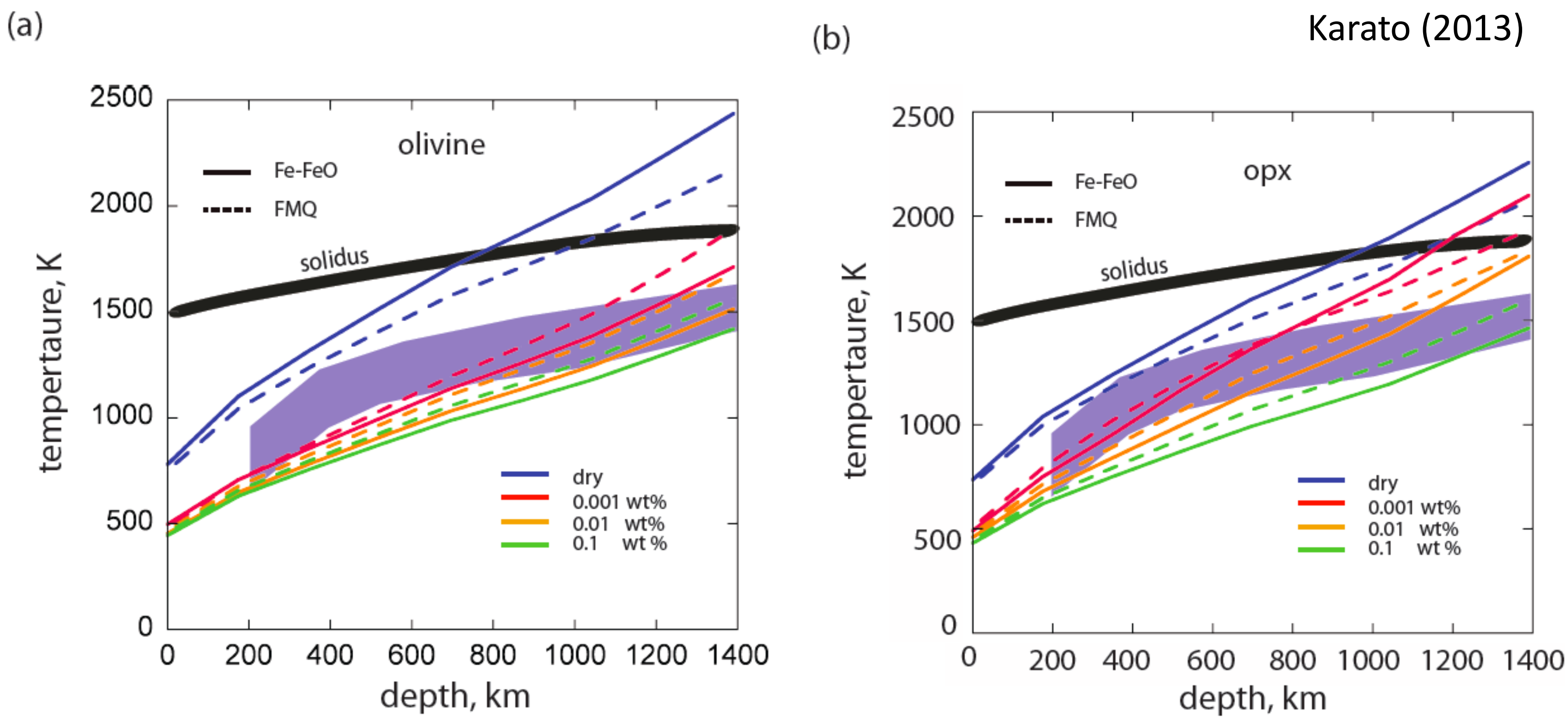


Karato (2011)

→ Useful water sensor

Temperature and water content in the Moon from electrical conductivity

Karato (2013)



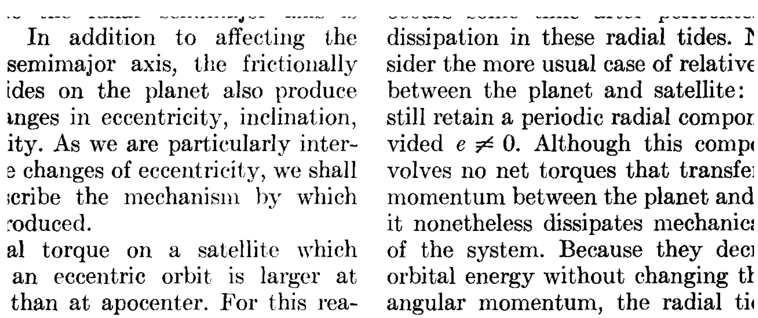
"Dry" Moon predicts very high T → Some water ??

But no unique solution from conductivity alone because of the temperature-water trade-off

Geophysical inference II:
tidal Q

Anelasticity ←→ viscosity (temperature, water content)

Q: **low Q ←→ "soft" materials**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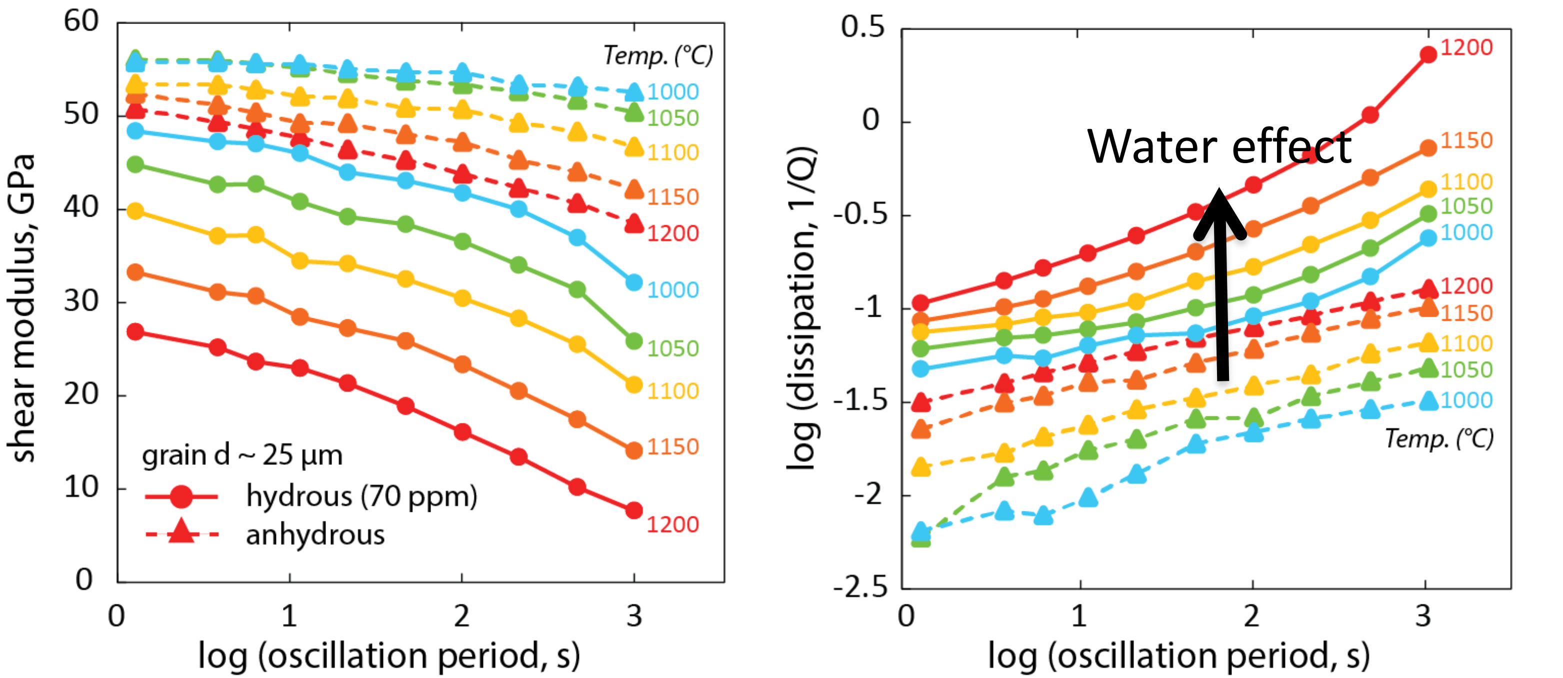
Low tidal Q (37-60 (Williams et al., 2001)))

[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)]

Water (hydrogen) enhances anelasticity (tidal dissipation).

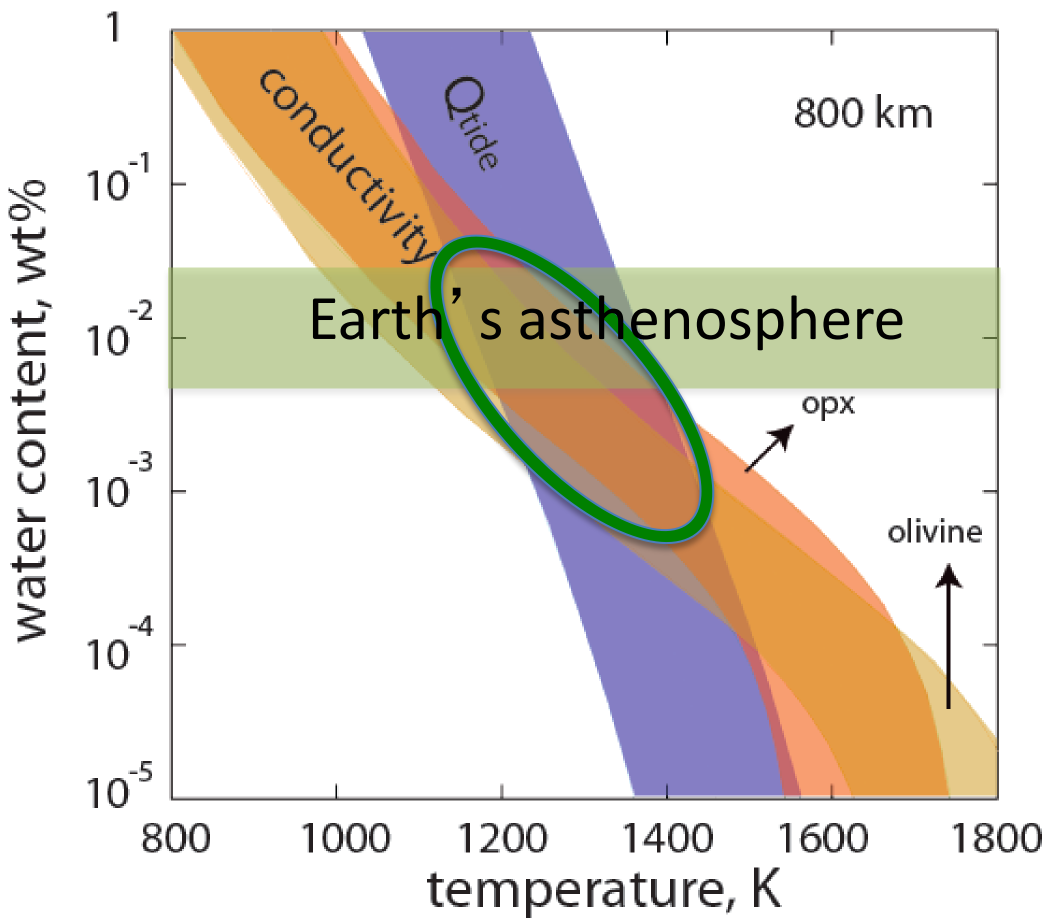


David, Cline II, Jackson, Faul and Berry, In preparation (2016)

$$\frac{Q^{-1}(C_W,T;x)}{Q_o^{-1}(C_{Wo},T_o;x)} = \left(\frac{w}{w_o}\right)^{-a} \frac{\left[1+\left(\frac{C_W}{C_{Wtr}}\right)^{rQ}\right]}{\left[1+\left(\frac{C_{Wo}}{C_{Wtr}}\right)^{rQ}\right]} \exp\left[-\frac{H_Q^*}{R}\left(\frac{1}{T}-\frac{1}{T_o}\right)\right]$$

→ Another useful water sensor (needs some models on frequency and depth dependence)

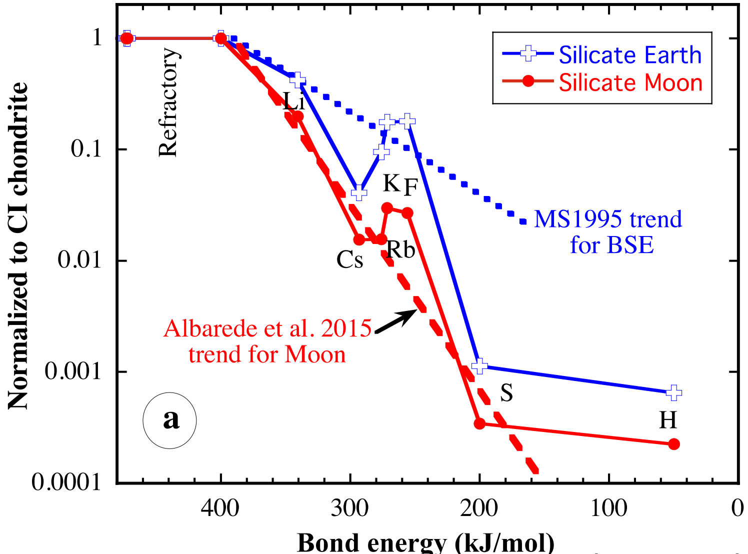
Constraining water content and temperature
using both conductivity and tidal Q

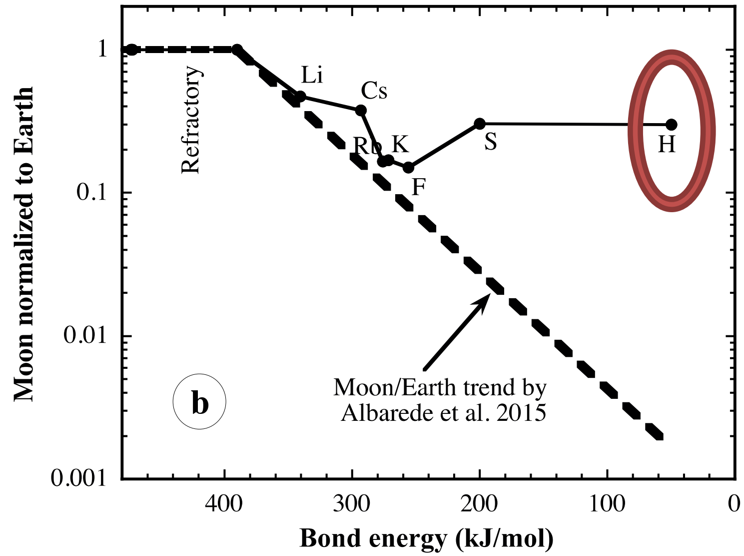


Karato (2013)

→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)





from **geophysics**
Karato (2013)

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

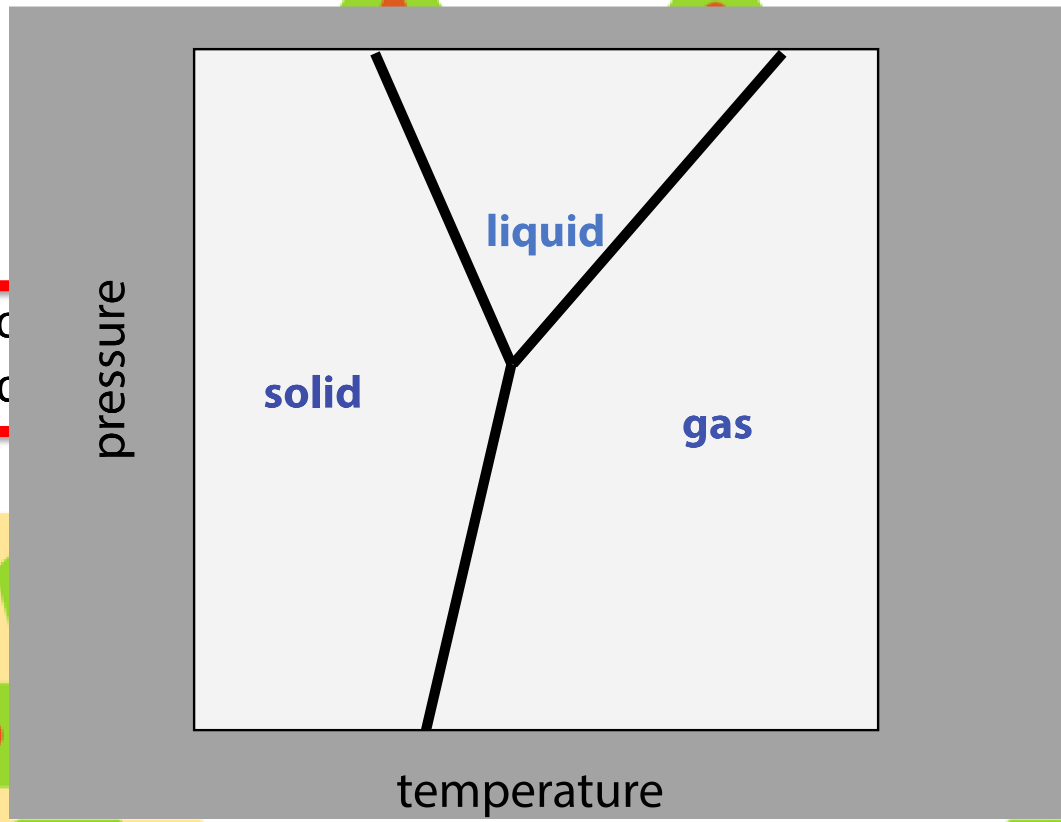
- The Moon and Earth are much depleted with volatiles compared to CI chondrite. (**most volatiles were lost during the formation of Earth**)

  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?**

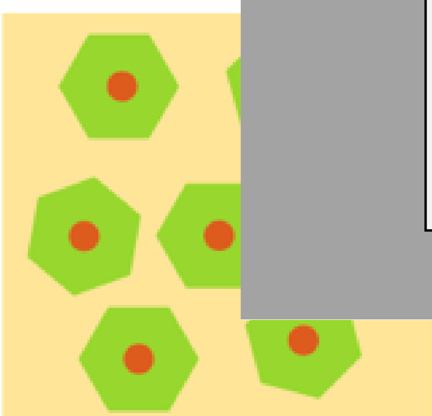
How to explain the different degree of volatile loss during planet formation? (back to the basics)

Moon fo
(cosmoc

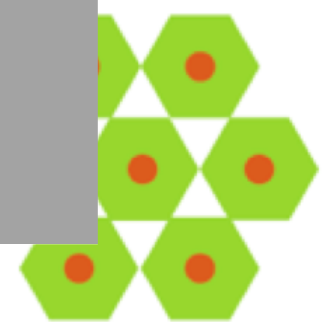


)
emistry

geology (petrology)
[partial melting]



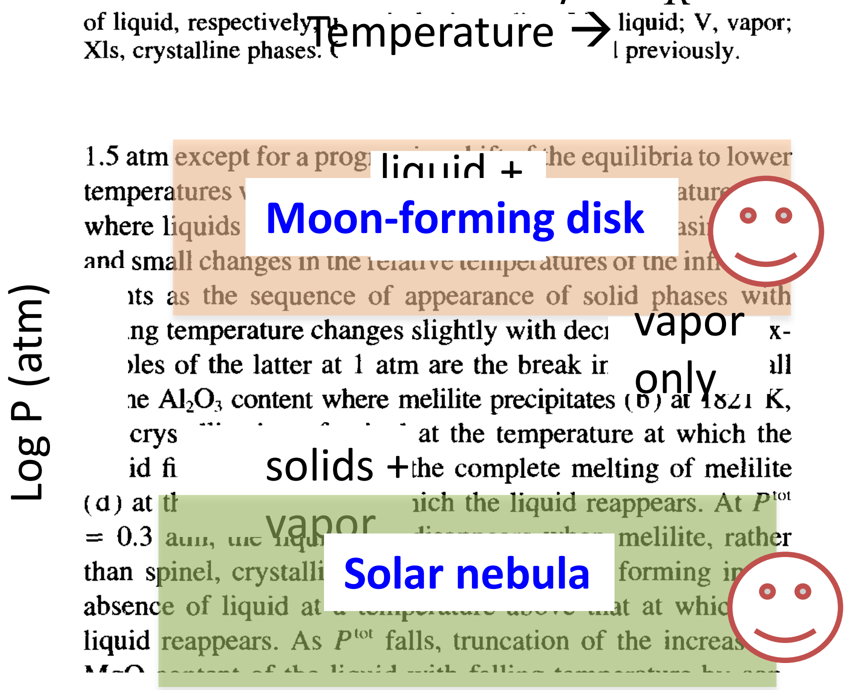
liquid



solid

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

$$P_{disk} \approx \frac{\pi}{2} G \sigma^2 \approx \frac{1}{2\pi} G \frac{M^2}{R^4}$$

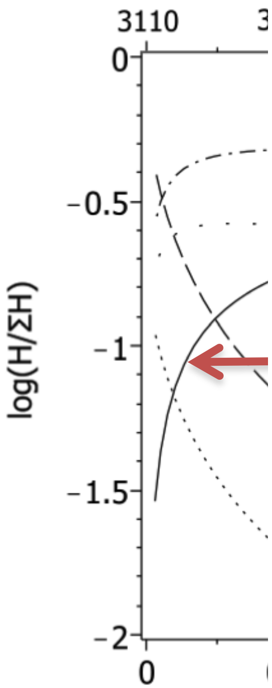


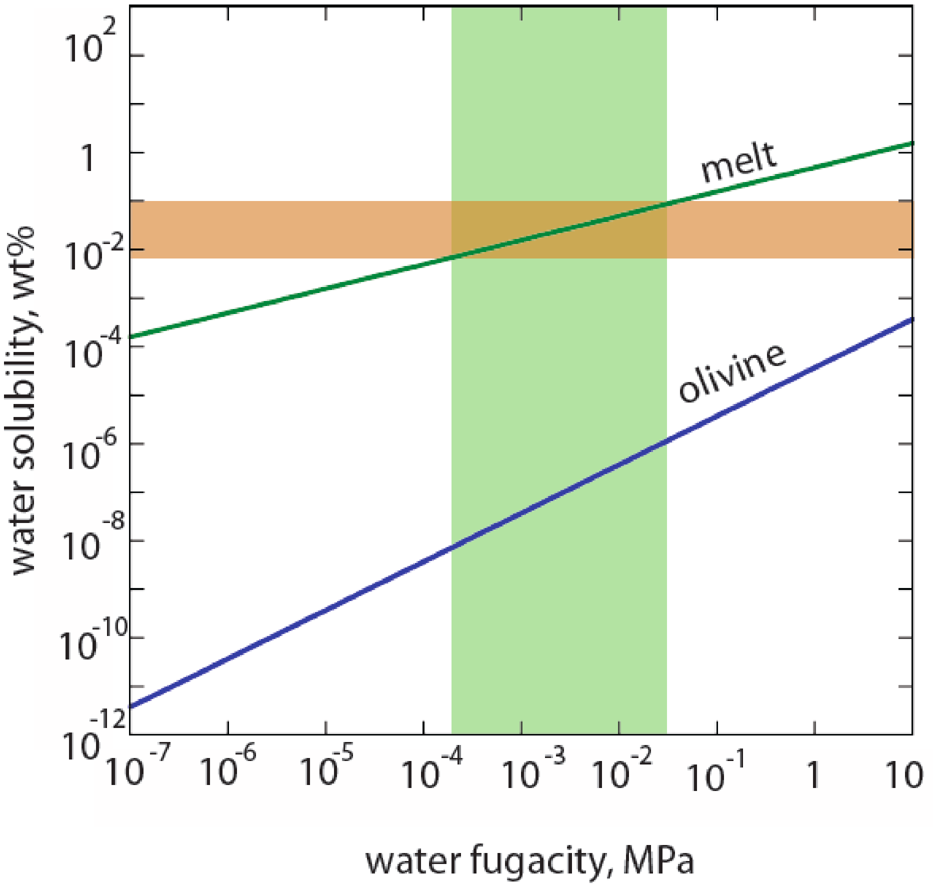
Yoneda-Grossman (1995)

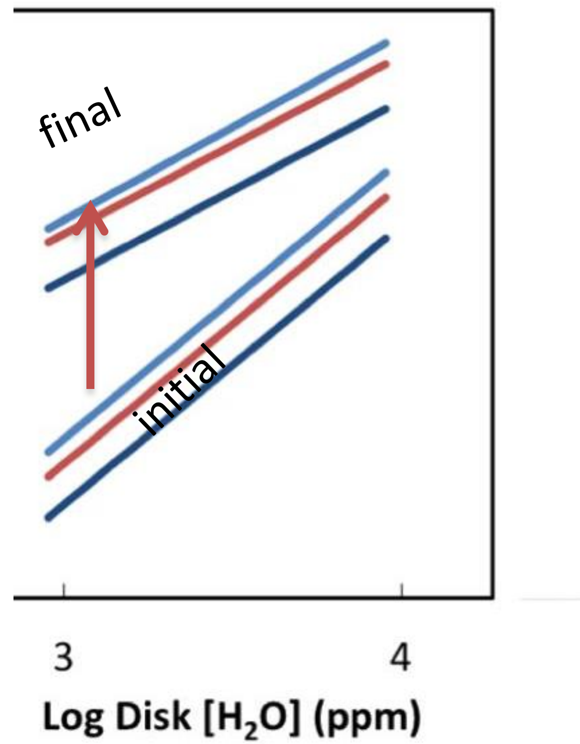
gas → solid: Solar nebula (low P)

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

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







Karato (2013)

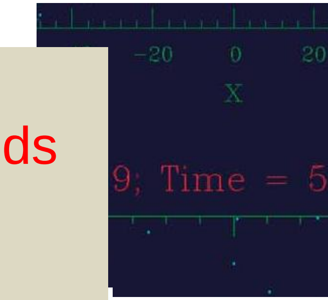
ato and Fegley (submitted)

model: N

only small degree of water depletion by condensation to liquid

(amorphous materials can also dissolve a large amount of water)

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

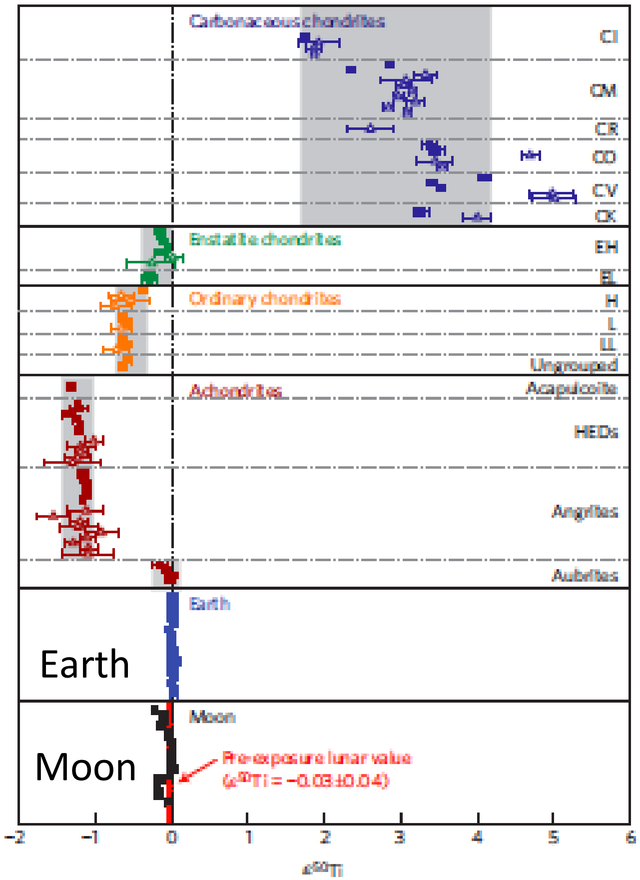
Proto-solar nebula

Low P (low mass density) → condensation to solids

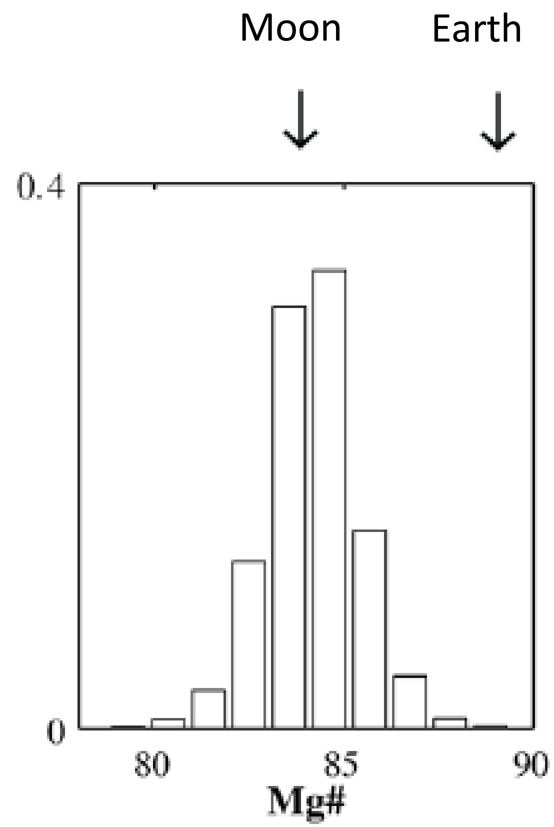
[and $\tau_{accretion} \gg \tau_{cooling}$]

→ high degree of depletion in volatiles

How ca Isotope, major element chemistry mposition and the different major element chemistry ?



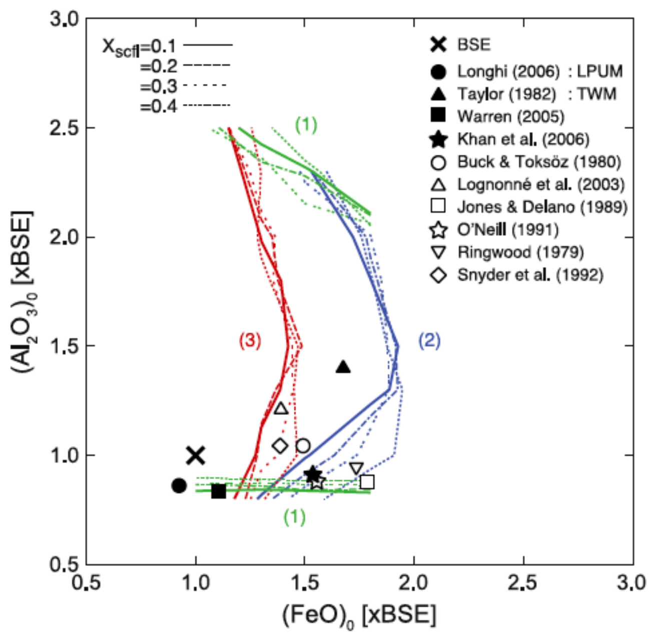
Very similar **Ti isotope composition**
(Zhang et al., 2012)



Different Fe/(Fe+Mg) (higher FeO content in the Moon)
(Khan et al., 2006; Kuskov-Kronrod, 1998)

	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

Melosh (2014)



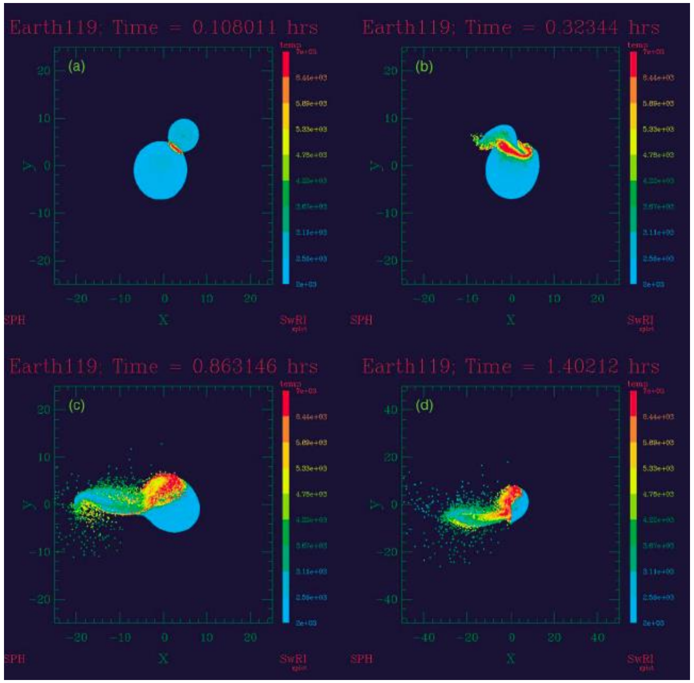
Sakai et al. (2014)

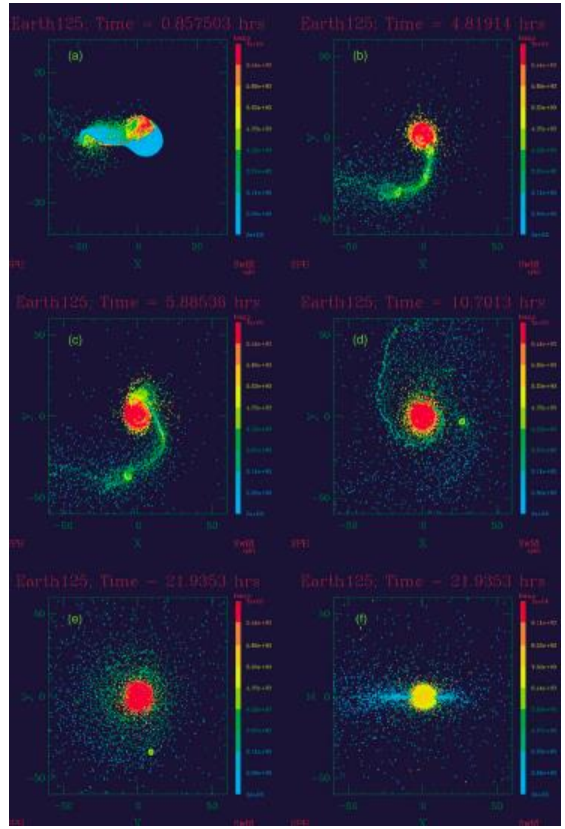
Challenges in developing a model to explain the chemistry of the Moon

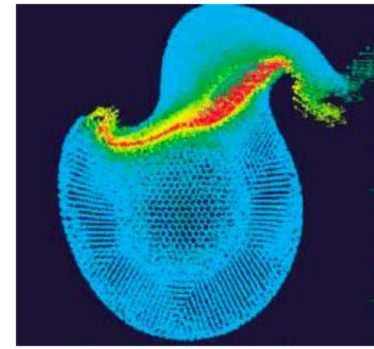
- **Isotope →** the Moon and Earth have very similar composition
- **FeO →** major element chemistry is different

→ How could the Moon be formed mostly from the proto-Earth materials?

→ If the Moon was formed from proto-Earth, then why FeO composition is so different between the Moon and Earth?







Canup (2004)

- **A standard model**: oblique collision (← large **angular momentum**) → **shearing** the impactor → **a majority (~70%) of the Moon is made of the impactor materials**

  (inconsistent with the chemistry)

How to explain the similar isotopic compositions and dissimilar FeO?

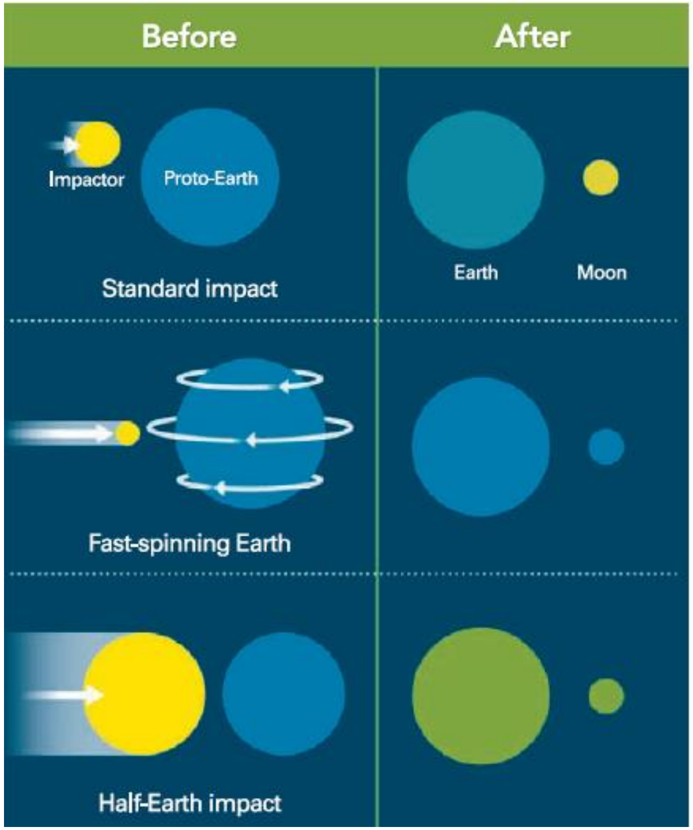
- Well mixing: Pahlevan-Stevenson (2007), Melosh (2014)
  → angular momentum?, how good is the mixing?
- A majority of Moon is from Earth (and the impactor mass was not large): Cuk-Stewart (2012)
- Same size bodies collided and mixed completely: Canup (2012)

→ **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?

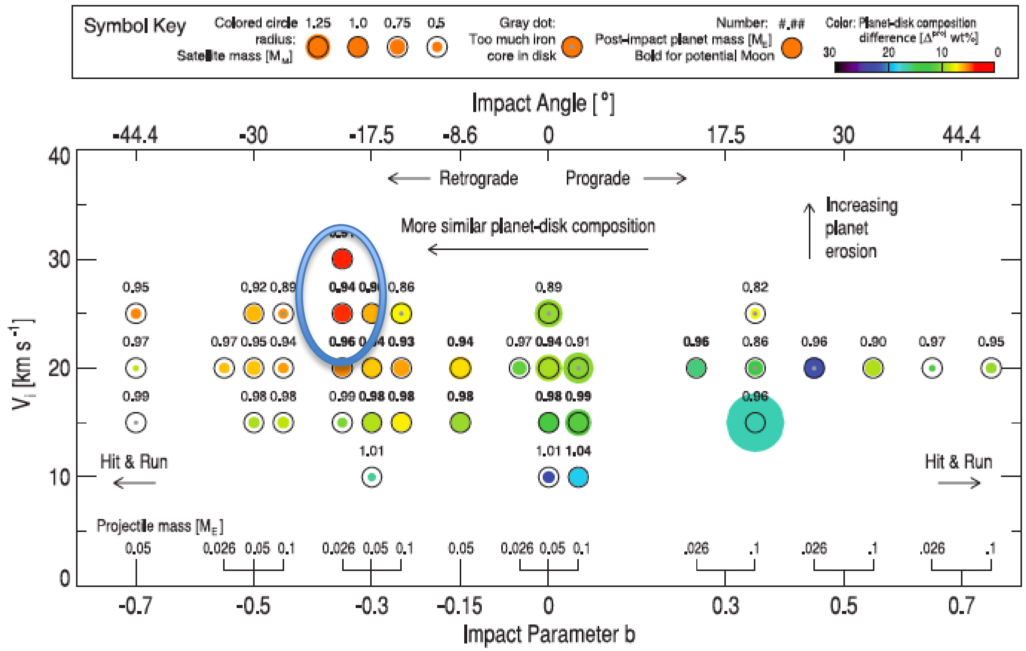
Clery (2013)



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

Cuk-Stewart (2012)

Canup (2012)



Cuk-Stewart (2012)

Problems with the Cuk-Stewart model

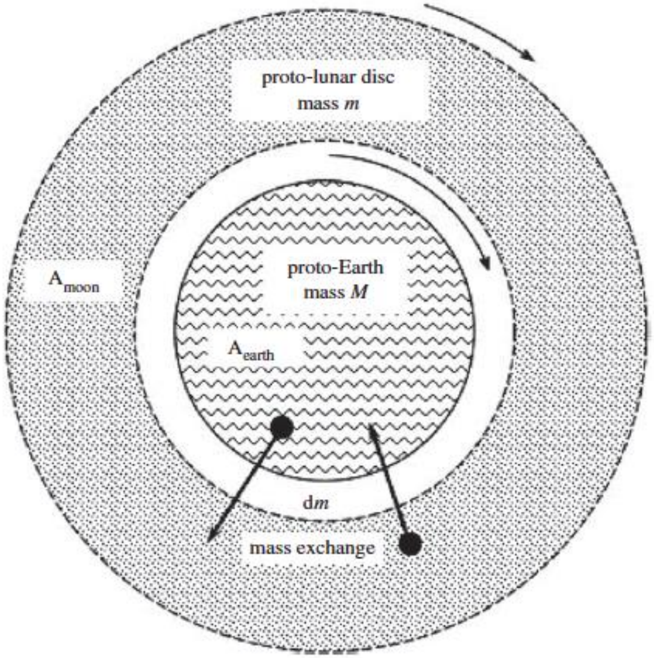
1. Only in a small parameter space one can have composition similar to Earth (**by chance?**).
2. Predicts a major element composition inconsistent with the observation.

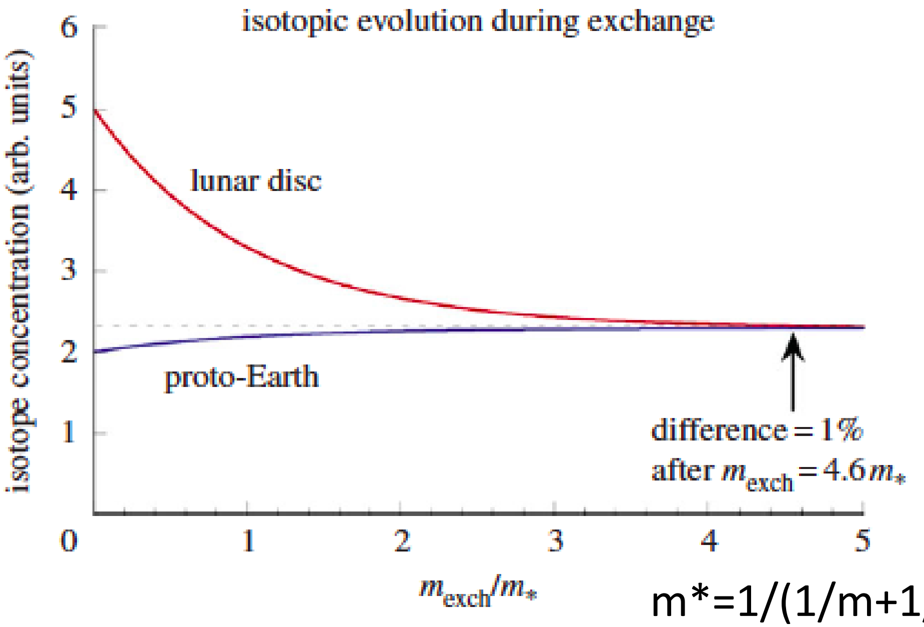
Problems with the Canup, Cuk-Stewart models

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

A mixing model

(Melosh, 2014)





$m^*=1/(1/m+1/M)\sim m$

→Very extensive mixing must occur to explain a similar composition.

→Hard to explain the angular momentum (large mass exchange → large momentum exchange → reduce the angular momentum of the Moon → a serious problem!?

Also this model does not explain the difference in FeO.

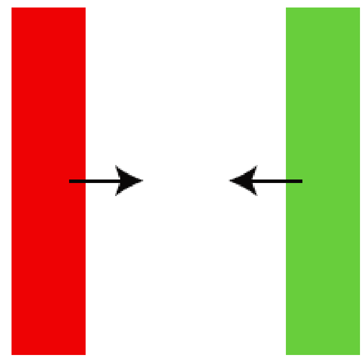
Terrestrial magma ocean origin of the Moon

- 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**

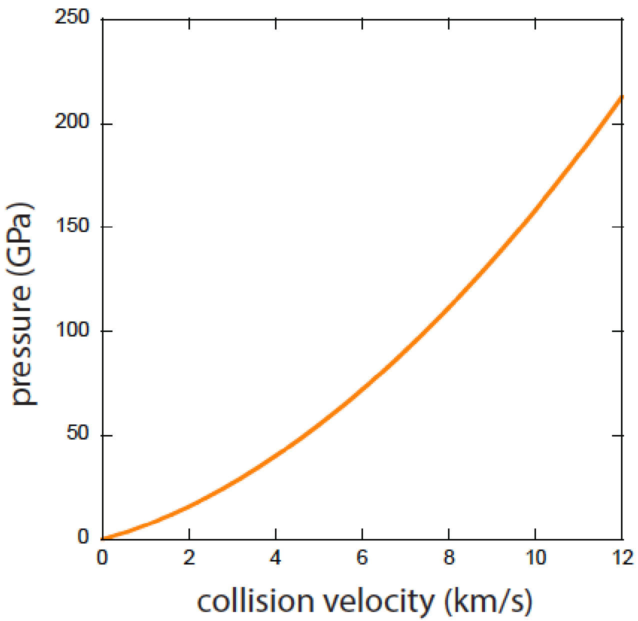
    Proto-Earth likely had a magma ocean, an impactor was likely a solid planet → **heating differently?**
  - Physics of collision/ejection

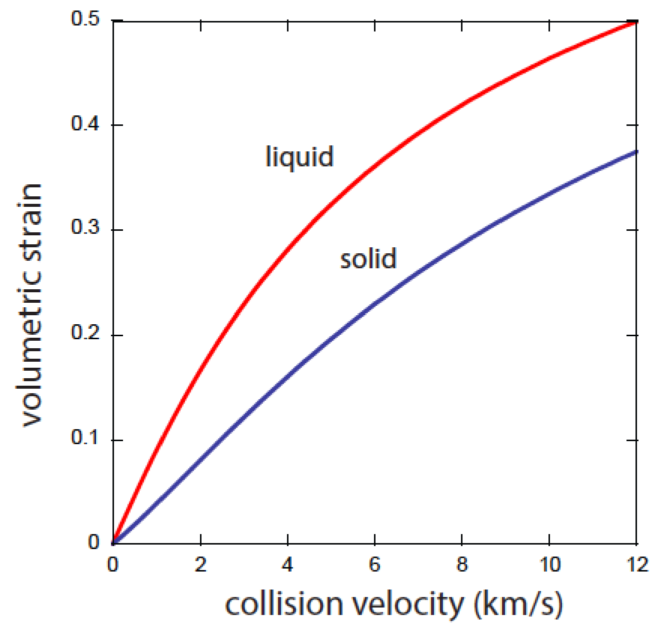
Collision → pressure, volumetric strain

liquid-solid collision leads to a large compression of liquid



The flat Earth Society

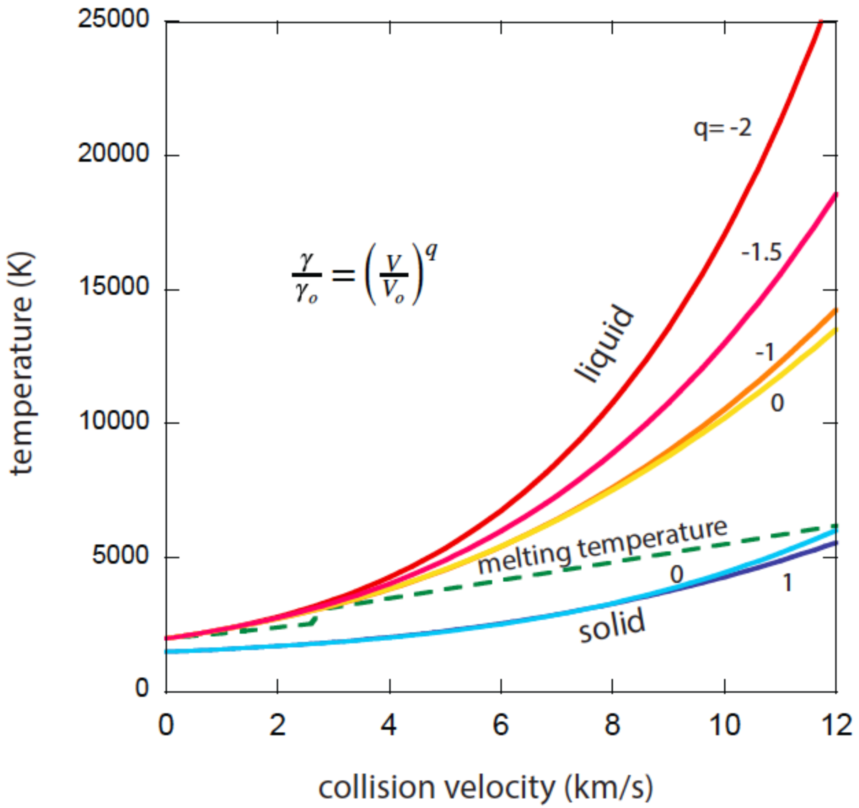




Karato (2014)

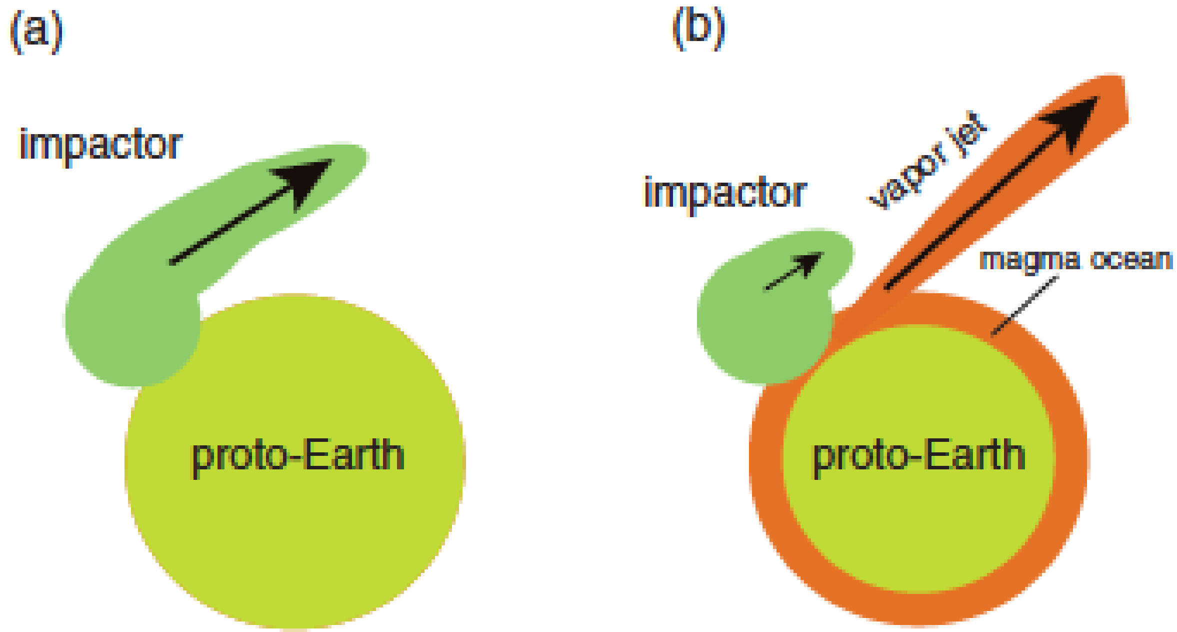
Liquid is more heated than solid

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



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.

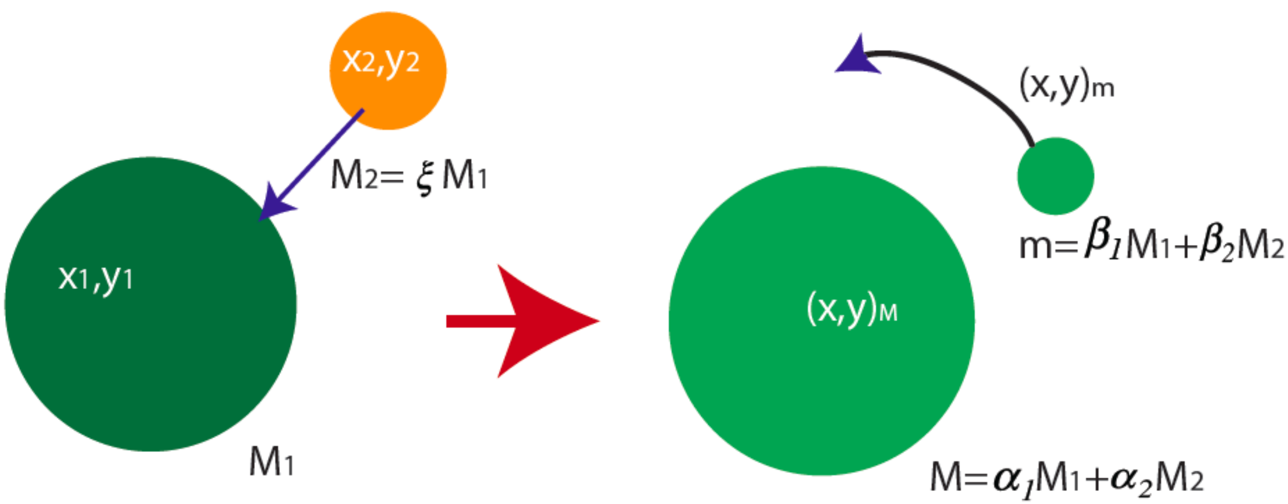
→**How much materials exchange** (between the proto-Earth and the impactor) do we need to explain the observed chemical composition ?

→ **Mass balance calculation**

Mass balance and the isotope ratio upon a giant impact

$$e_m = \frac{\left(\frac{x}{y}\right)_m}{\left(\frac{x}{y}\right)_M} - 1 = \frac{x\left(\frac{a_1}{a_2} - \frac{b_1}{b_2}\right)(e_1 - e_2)}{\left[\frac{b_1}{b_2}\left(\frac{\frac{x_2}{y_2}}{\left(\frac{x}{y}\right)_M}\right) + x\right]\left[\frac{a_1}{a_2}\left(\frac{\frac{x_1}{y_1}}{\left(\frac{x}{y}\right)_M}\right) + x\right]} \approx \frac{x\left(\frac{a_1}{a_2} - \frac{b_1}{b_2}\right)}{\left(\frac{b_1}{b_2} + x\right)\left(\frac{a_1}{a_2} + x\right)}\left(e_1 - e_2\right)$$

$$e_{1,2} = \frac{\left(\frac{x_{1,2}}{y_{1,2}}\right)}{\left(\frac{x}{y}\right)_M} - 1$$



→ If a large amount of the Moon is from the **proto-Earth**, the correction factor will be small enough to explain the isotope and FeO composition.
[Without magma ocean, ~70% of the Moon would be from the **impactor**]

Terrestrial magma ocean origin of the Moon

- Magma ocean (melting)
  - different major element chemistry
  - no or little change in (the heavy) isotope composition

→ Similarity in the isotopic composition

→ Dissimilarity in the major element chemistry

- Explains the chemistry of the Moon as a "natural" consequence of planetary formation

Conclusions

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

- Water content in the lunar mantle
  - Geophysical obs. + mineral physics
  - → **the Moon is as "wet" as (or slightly less wet than) Earth**
  - → Condensation of liquid phases + quick accretion compared to cooling time-scale (due to the **small space** in which the Moon was formed)
- Collisional heating
  - Mineral physics + thermodynamics → heating the pre-existing magma ocean, not much heating on the solid part
  - → **the Moon from the magma ocean of the proto-Earth ?**

  both isotope obs. and FeO content can be explained.

  [if more than ~70% of mass is from Earth, isotope obs. can be explained]

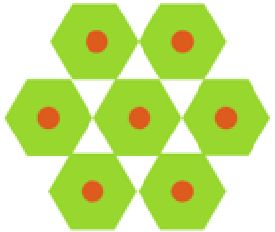
  → **Need numerical modeling is needed : work in progress in collaboration with Hosono and Makino at Riken, Kobe, Japan)**

Liquids and solids have different thermodynamic properties.

Condensation temperature Tc:

$$\mu_i^{gas}\left[=\mu_{i,o}^{gas}+RT_c\,log(1-a)\frac{f_i}{P_o}\right]=\boxed{\mu_i^{solid,liquid}}$$

solid



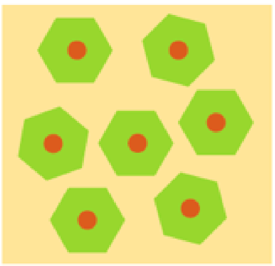
gas → **solid**

→ **internal energy** dominates

→ strong effect of chemical bonding

→ **sensitive to species**

liquid



gas → **liquid**

→ **configurational entropy** dominates (Jing-Karato, 2011)

[**hard sphere model** (~van der Waals model)]

→ little effect of chemical bonding

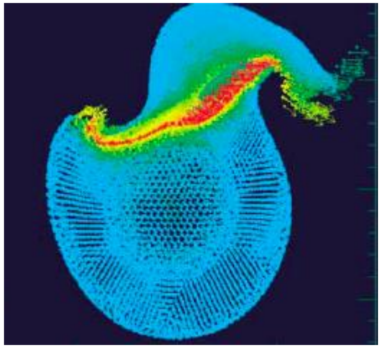
→ **insensitive to species**

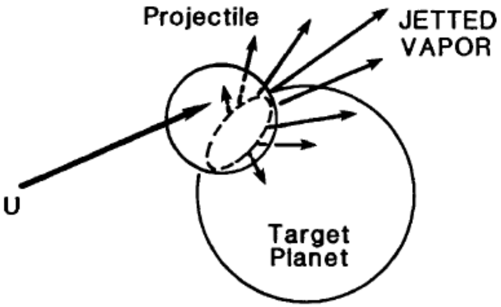
Liquid ←→ solid contrast explains the difference in the abundance pattern of volatiles between Earth and Moon.

Many questions
are unanswerable.
Many answers are questionable.

Shearing versus vapor jets

(impactor versus magma ocean)





$$\text{shear: } f_{shear} \approx \frac{\Delta(\rho v)}{\Delta t}, \qquad \text{jets: } f_{jet} \approx \frac{\Delta P}{\Delta L}$$

$$\frac{f_{jet}}{f_{shear}} \approx \frac{\Delta P}{\Delta L}\frac{\Delta t}{\Delta(\rho v)} \approx 10^{-2}\Delta t$$

$\Delta t \approx 10^3$ (sec): Canup (2004) → jet dominates?

Outline/Summary

- **The Moon is not-so-dry.**

  Water content of the Moon can be inferred not only from the direct geochemical method but also indirectly from the geophysical method. → slightly less water than Earth

- **Not-so-dry Moon can be explained by a model of Moon formation in the small space (giant impact).**

  Liquids play a key role.

  → conventional **volatility scaling** (based on the gas to **solid** condensation) does not work for the Moon.

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?**).

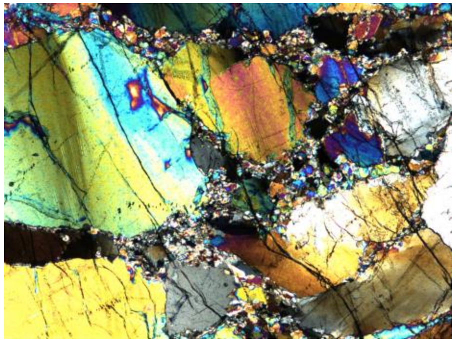
2.Predicts a major element composition inconsistent with the observation.

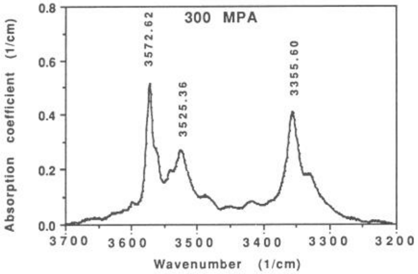
3.Difficult to explain the large angular momentum

How do we infer the water content in a planet?

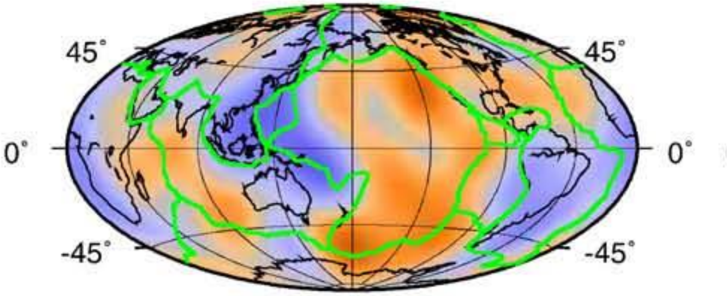
Geological (geochemical) obs.
(direct, limited regions and depth)

a

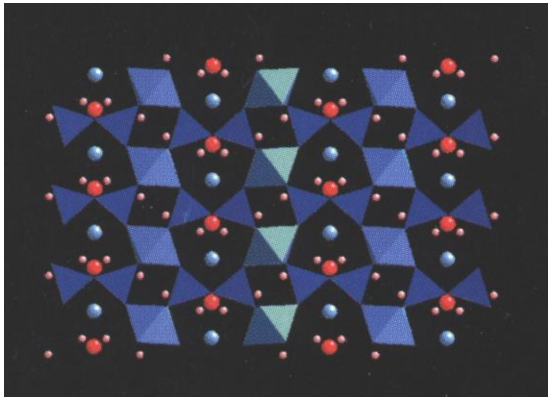




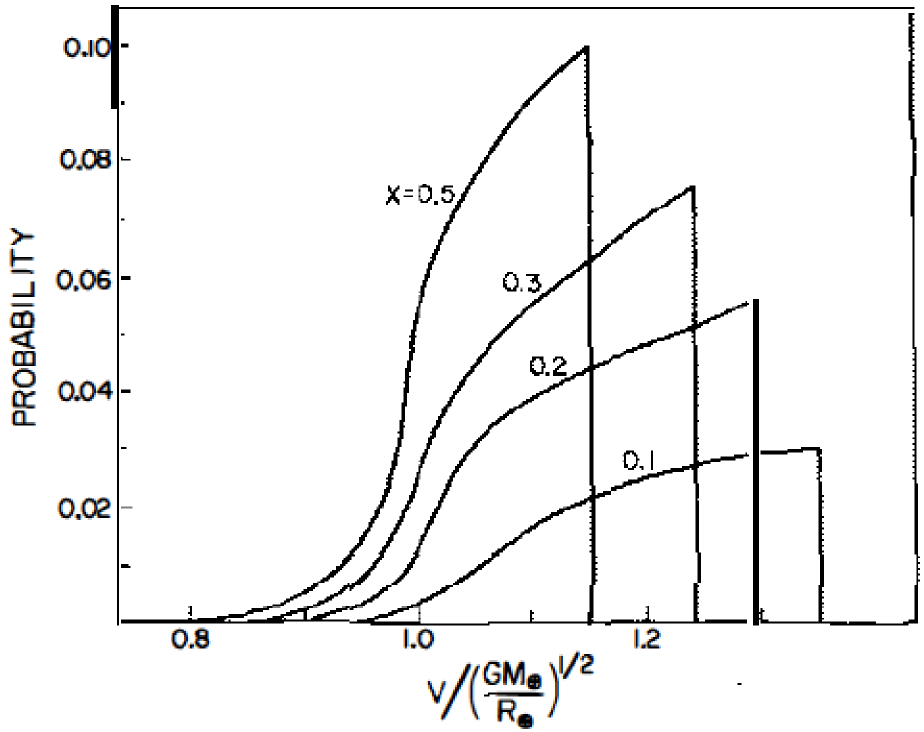
Geophysical obs.
(global, indirect)



Need a microscopic model (theory) based on **mineral physics**



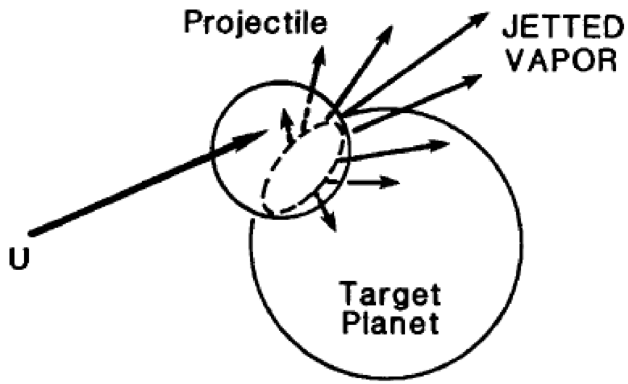
Probability of ejected materials to go to the proto-Earth surrounding orbit (case B)

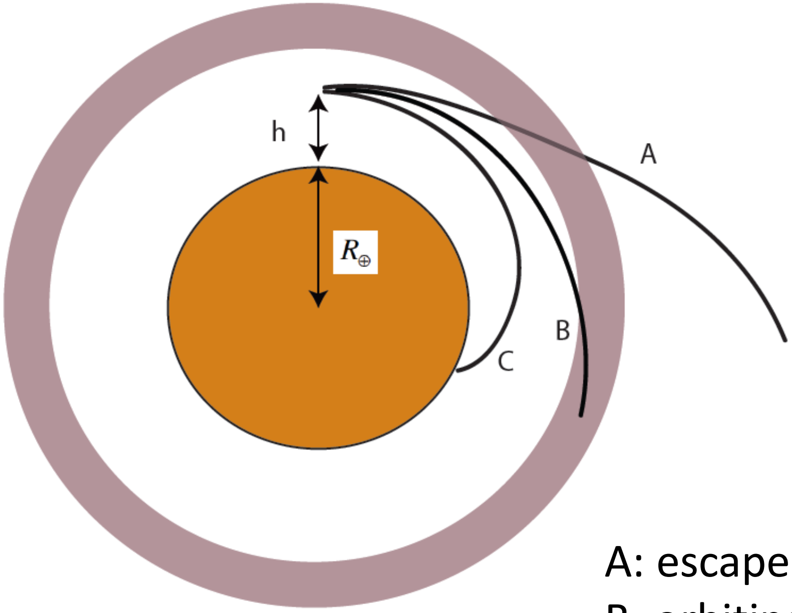


Stevenson (1987)

Gaseous phase expands (large $x = \frac{h}{R_\oplus}$)
→more chance to get into the proto-Earth surrounding orbit (in previous studies, materials going to the orbit were mostly from the impactor)

Is the Moon formed mostly from the impactor or from the proto-Earth?





A: escape
B: orbiting Earth → Moon
C: re-impact

Collision ejects materials → materials that are ejected to a **certain height** and velocity could become the Moon