Composition of the Moon and Implications for Its Origin

with some discussions on scientific methodology

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My first encounter with “Kumazawa”

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地球内部物理学

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Shimazu (1967)

“The Kumazawa principles”
(as I understand them)

- Do what anyone else does not do.
- Develop your own method (methodology).
- Challenge the big problems.

→ **history (+ “philosophy” (methodology))**

Bragg’s principles (1938) (from Dyson (1970)):
(1)Don’t try to revive past glories.
(2)Don’t do things just because they are fashionable.
(3)Don’t be afraid of the scorn of theoreticians.

Composition and Origin of the Moon

Motivation

- **A challenge to the "dry" Moon paradigm**

  "Wet" Moon from geochemistry (Saal et al., 2008; Hauri et al. 2011)

  → How about the lunar interior?

  → Why wasn't water lost by a giant impact?

- A giant impact model has difficulties in explaining lunar chemistry.

  (according to numerical modeling (Canup, 2004), the Moon is formed mostly from the impactor, not from the proto-Earth)

→ **Use (geo)physics to address these questions**

Water in the Moon from geophysical observations

Physics and chemistry of Moon formation processes

Composition and Origin of the Moon

Conclusions

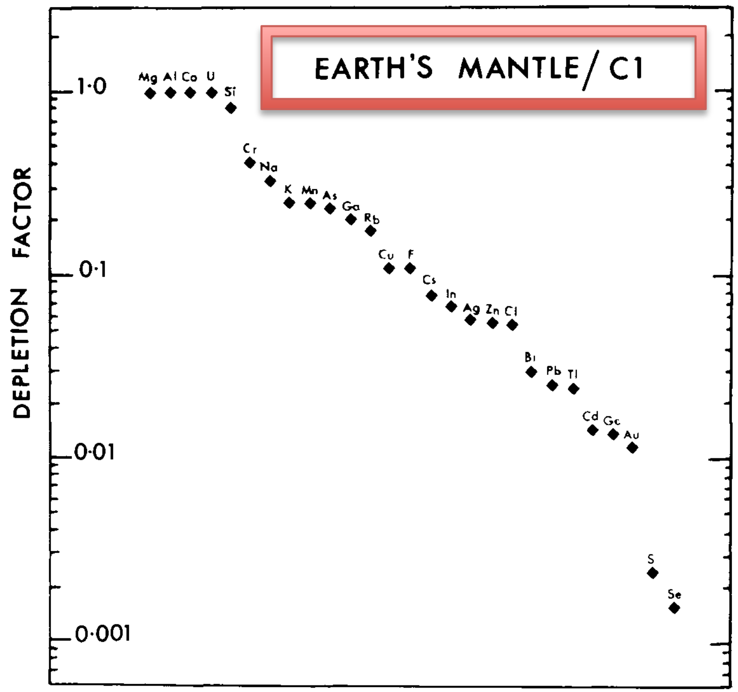
- **Geophysical observations** show that the lunar mantle is as “wet” as the Earth’s upper mantle.
    - A majority of water could be acquired to the Moon if accretion occurs quickly compared to the cooling time-scale.
- **The Moon was formed from the magma ocean of the proto-Earth.**
    - A giant impact heats and vaporizes the pre-existing magma ocean on the proto-Earth but not the solid impactor.

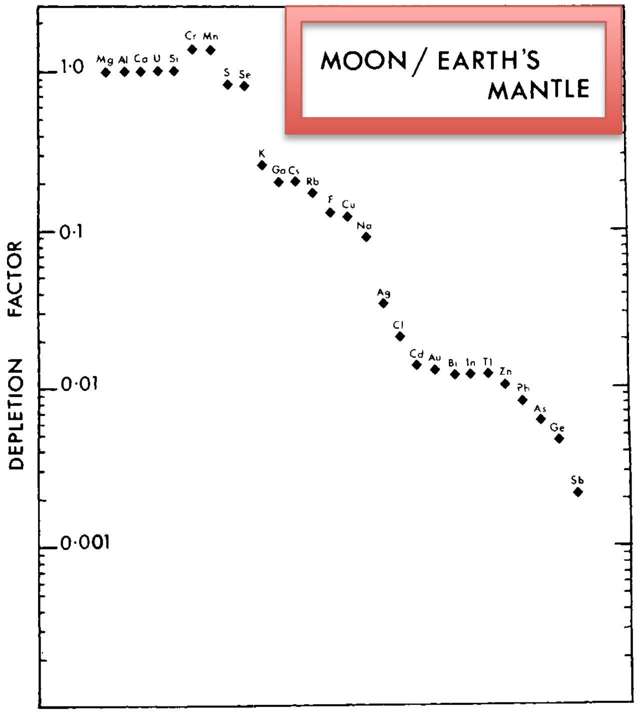
- **Many aspects of lunar composition can be interpreted as a natural consequence of planetary formation** (if one applies **(geo)physics** properly) **as opposed to by processes controlled by chance.**

“dry” Moon paradigm

Ted Ringwood (1930-1993)

Ringwood-Kessen (1977)





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

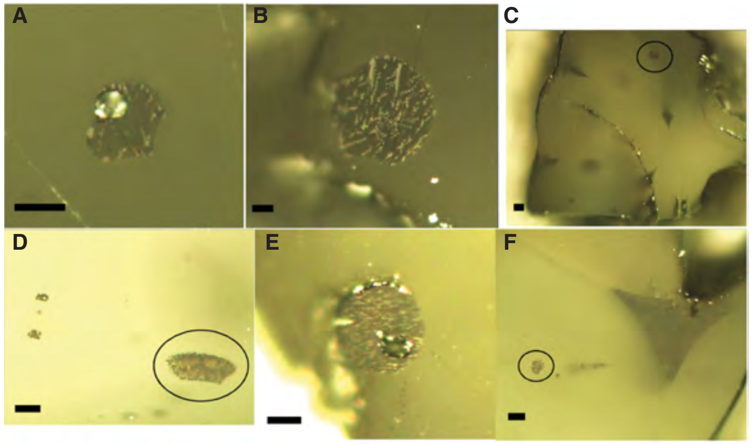
The Moon is depleted with volatiles relative to Earth. → “dry” Moon

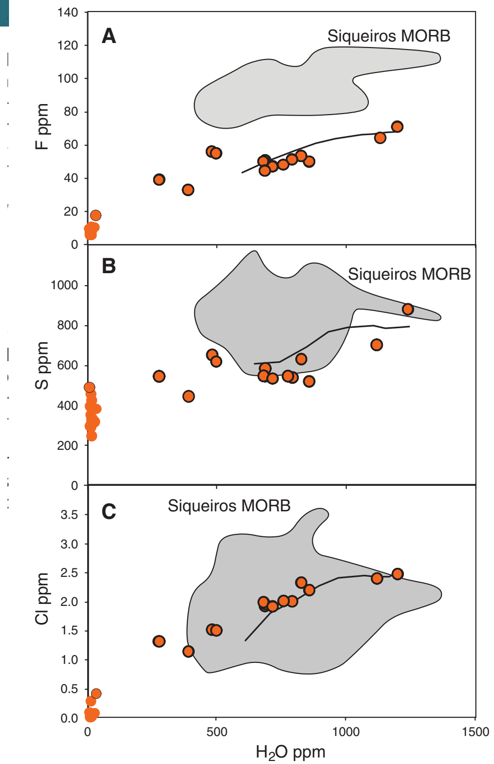
A giant impact model

giant impact → intensive heating → volatile loss
Are all the volatile elements depleted in the Moon?

(similarities and differences in composition between Earth and the Moon →
How can this model explain them?)

Not-so-dry Moon!





Saal et al. (2008)
Hauri et al. (2011)

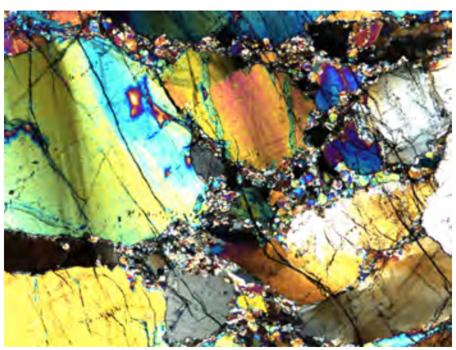
Some lunar samples (inclusions in olivine) contain water (+ other volatile elements) similar to Earth's upper mantle (depleted but not-so-dry).

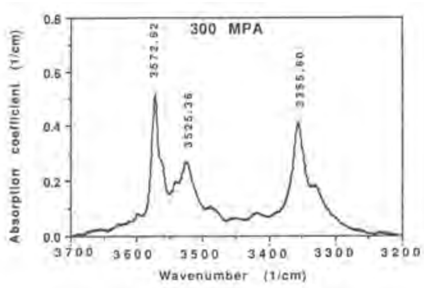
But does this imply globally "wet (not-so-dry)" Moon?

How do we study the water content?

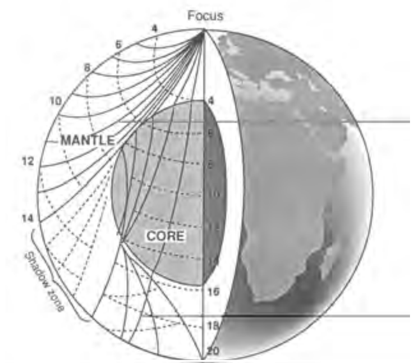
Geological (geochemical) obs.
(direct, limited regions and depth)

a

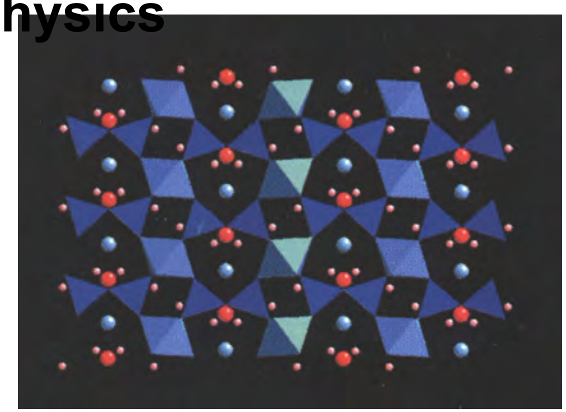




Geophysical obs.
(global, indirect)

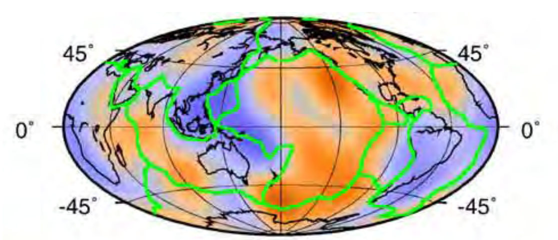


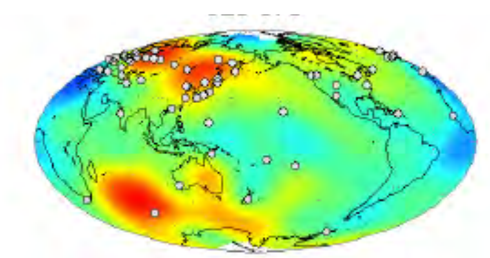
Need a microscopic model (theory) based on **mineral physics**



Geophysical approach

- Deep interior (spatial distribution)
- Which observations?
  - Seismic wave velocities
  - Electrical conductivity
  - Seismic wave attenuation, tidal dissipation (Q)





Strategy

Some water sensitive geophysical observables

$X(C_W, T; \xi)$

C_W : water content, T: temperature

ξ : something else (major element chemistry)

(1) infer ξ

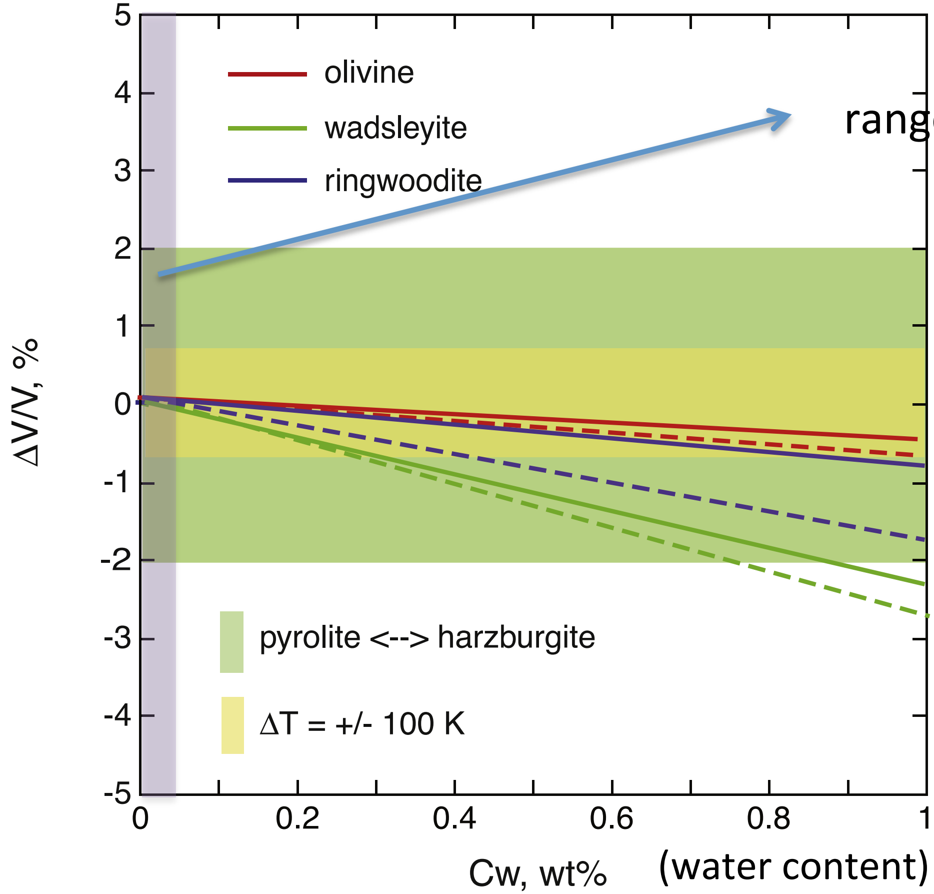
(2) infer (C_W, T)

(3) infer T and C_W

from one observable

from two observables

Seismic wave velocity depends weakly on water content but strongly on the major element chemistry and T



range of typical water content

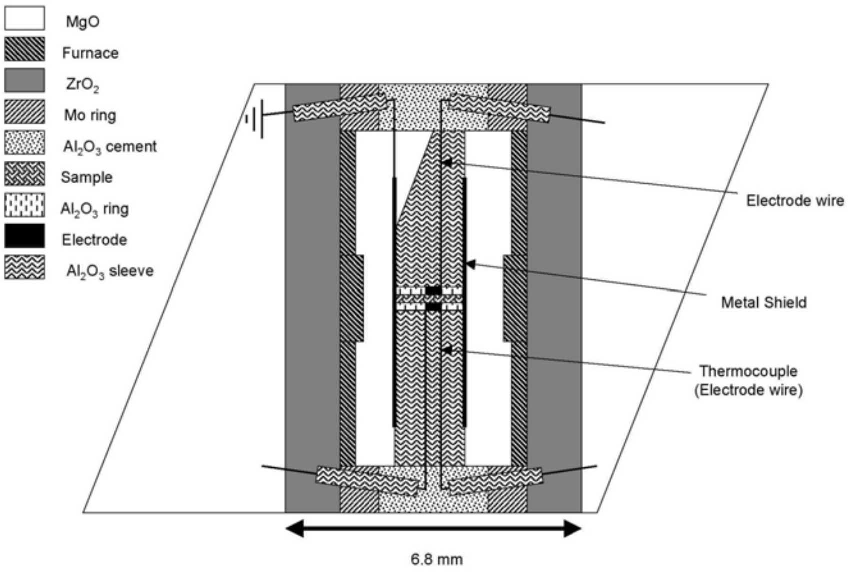
(water content)

Karato (2011)

→Useful for inferring major element composition

→But water effect is too small to be detected.

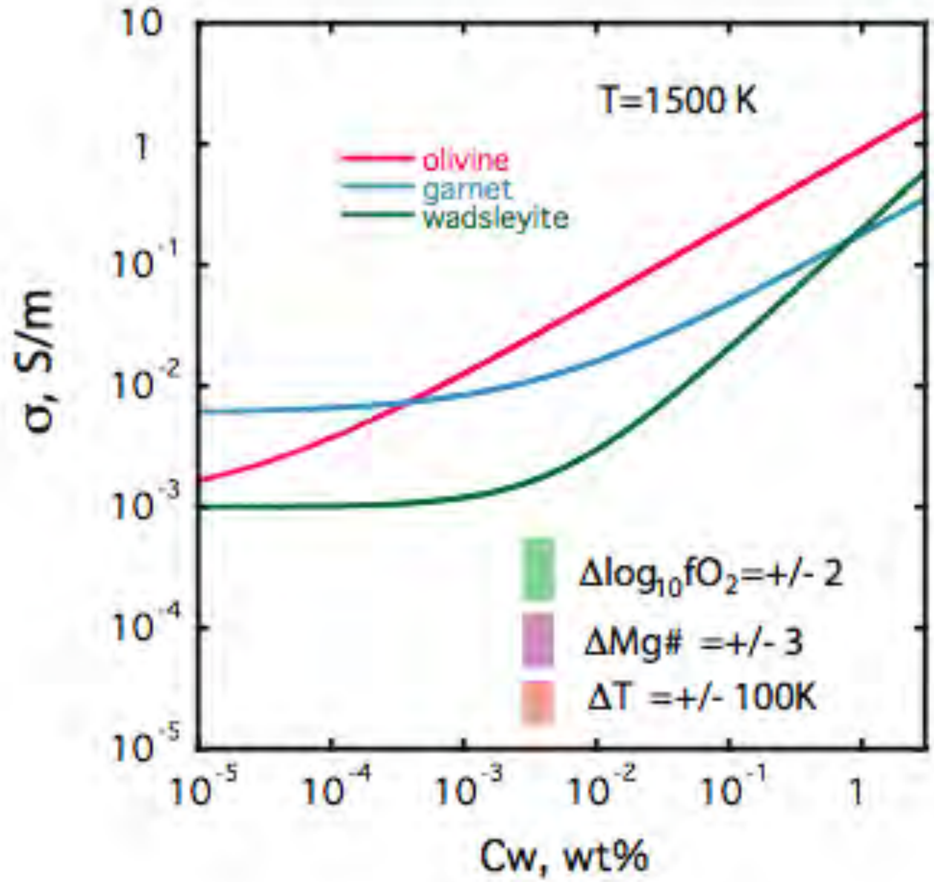
An experimental set-up for conductivity measurements



Electrical conductivity depends strongly on water content

(relatively weakly depends on T and other factors)

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

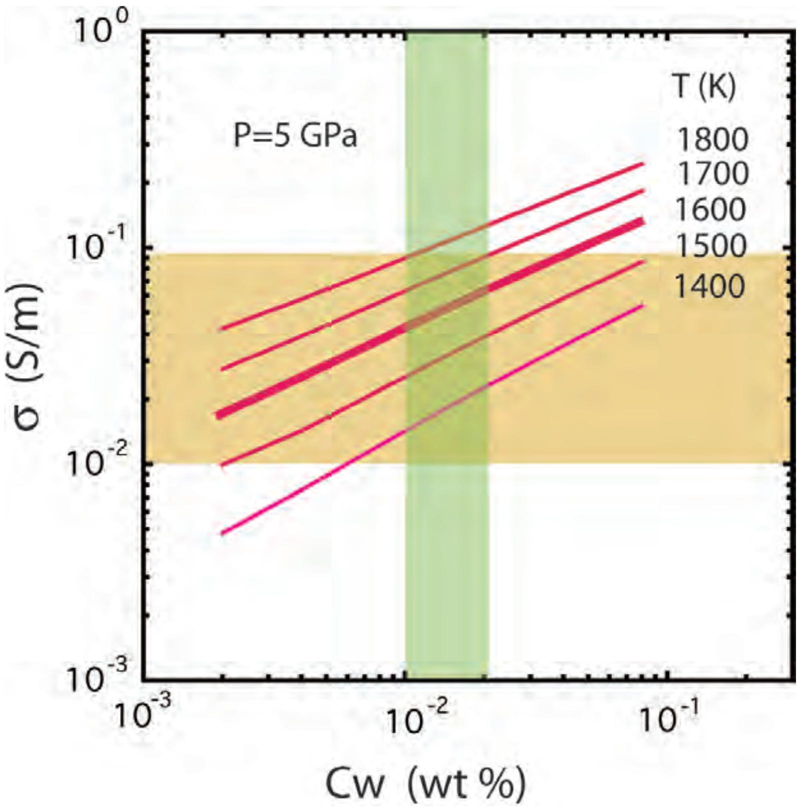


Karato (2011)

→ Useful for inferring water content

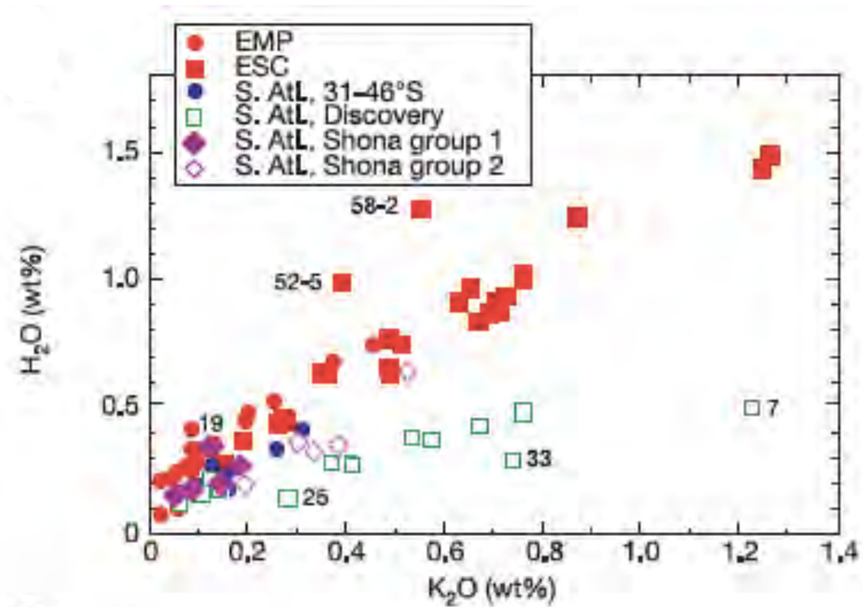
Testing the method

Geophysics (mineral physics)



electrical conductivity → ~0.01 wt%
(Dai-Karato, 2009)

Geochemistry



MORB chemistry → ~0.01 wt%
Dixon et al. (2002)

Some water sensitive geophysical observables

$X(C_W, T; \xi)$ **X: electrical conductivity, Q**

C_W : water content, *T*: temperature

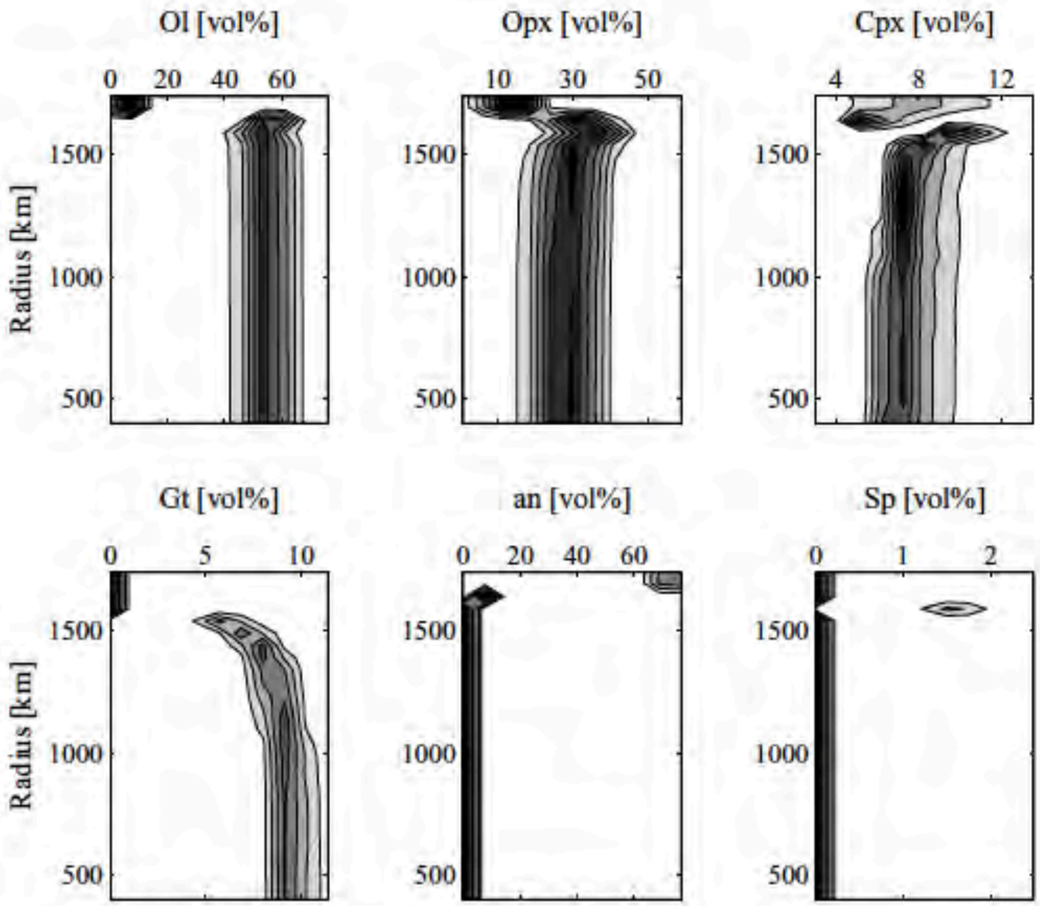
ξ : something else (major element chemistry)

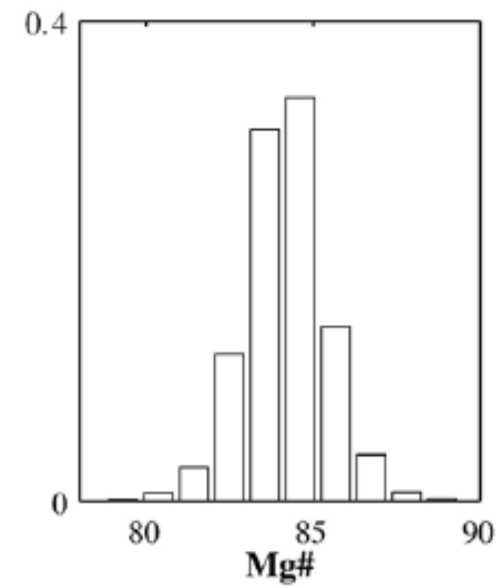
(1) infer ξ **(from seismology)**

(2) infer (C_W, T) from one observable

(3) infer *T* and C_W from two observables

ξ Bulk composition from seismology (after Khan)

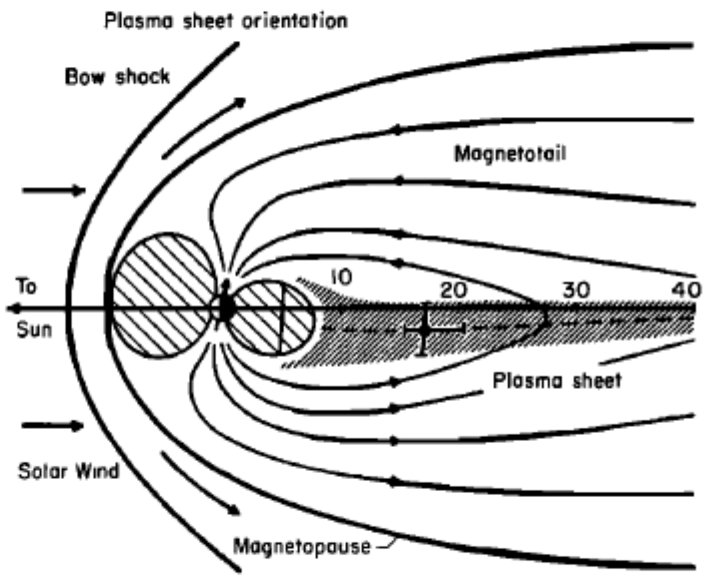




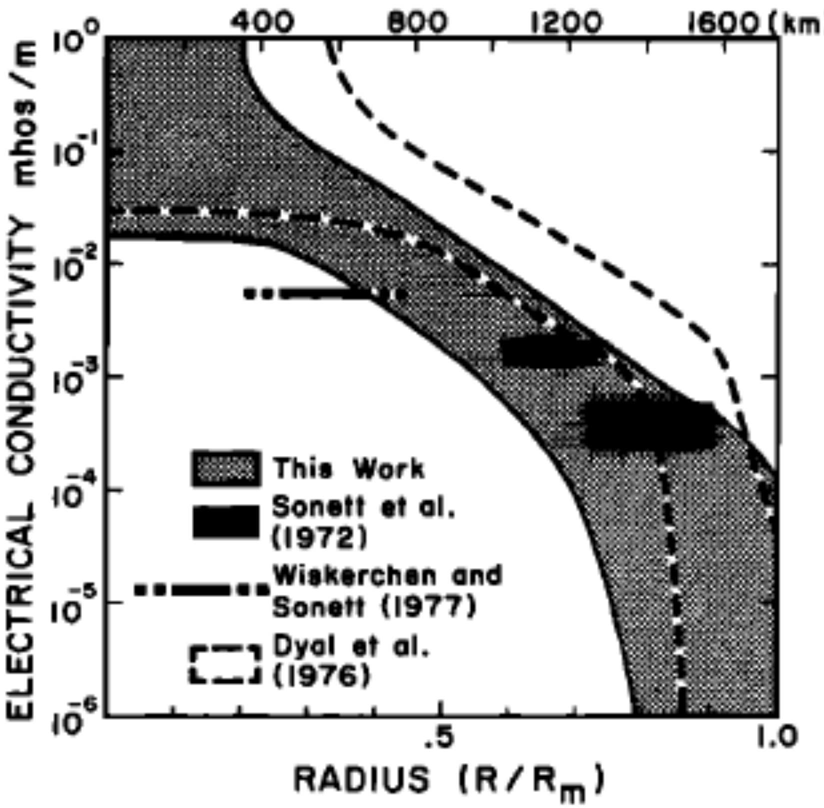
Mg#=100xMgO/(MgO+FeO)

The Moon has a higher FeO content than Earth.

Geophysical observations I: electrical conductivity



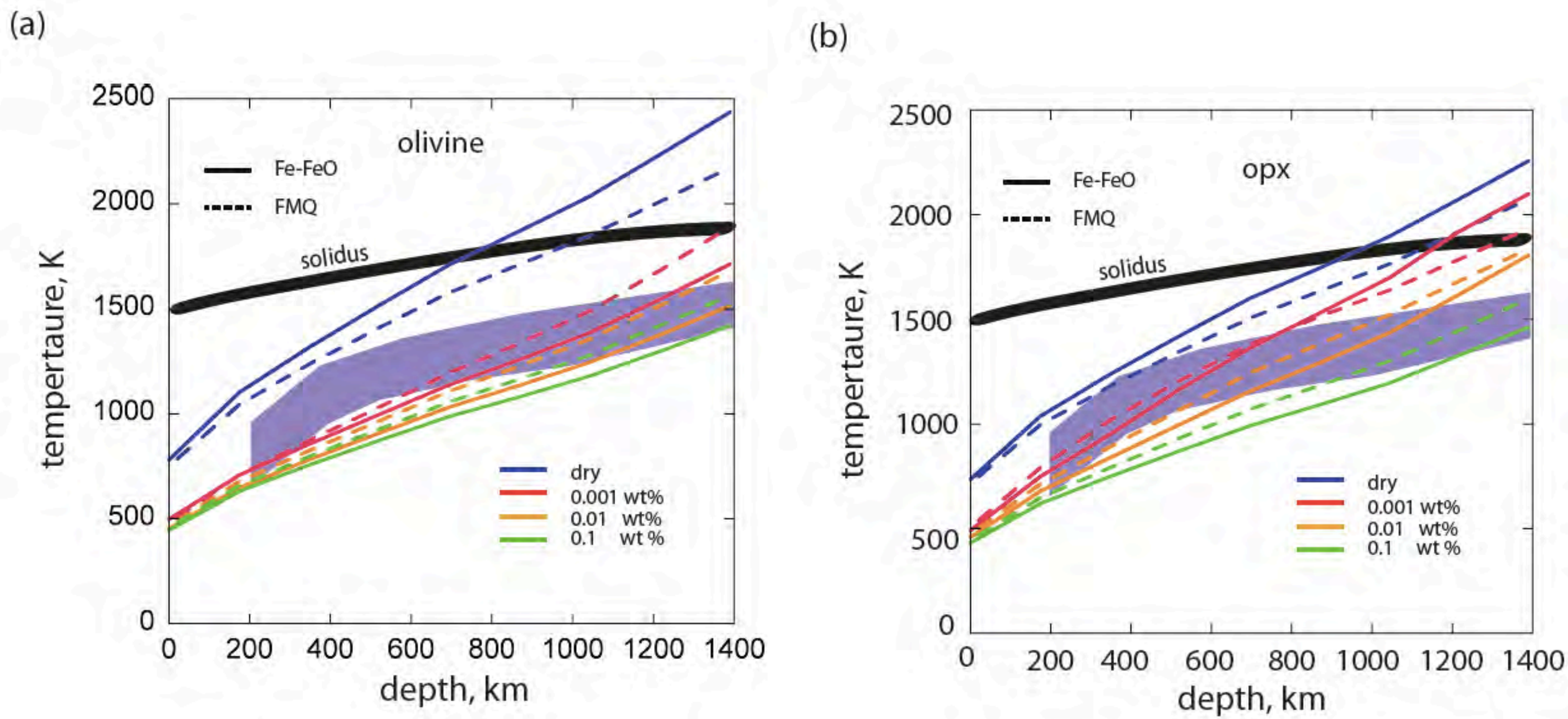
Sonett (1982)



the Moon
(Hood et al., 1982)

Temperature and water content in the Moon

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



→ "Dry" Moon predicts very high T

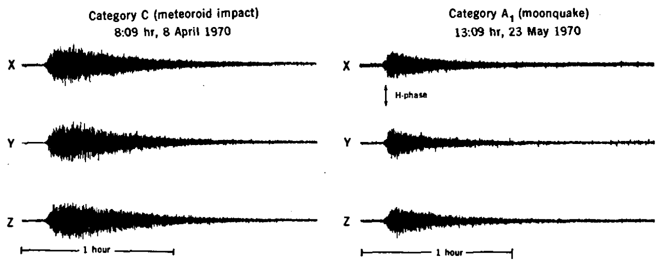
→ Some water ??

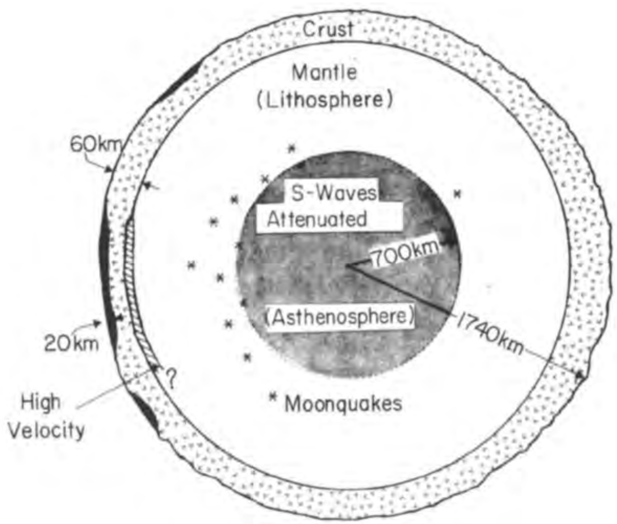
[**no unique solution from conductivity alone**]

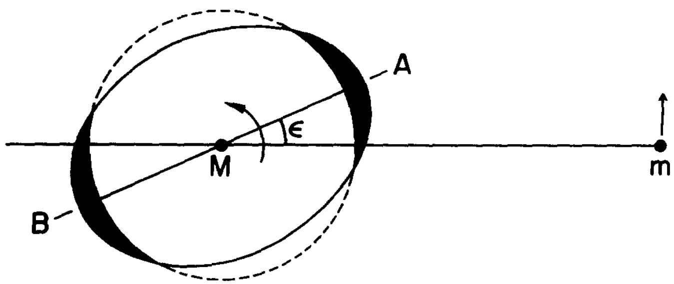
Geophysical observations II: Anelasticity

Anelasticity ←→ viscosity (temperature, water content)

Q: low Q → high energy dissipation (high degree of anelasticity)







$$Q_{tide}^{-1} = \tan 2\varepsilon$$

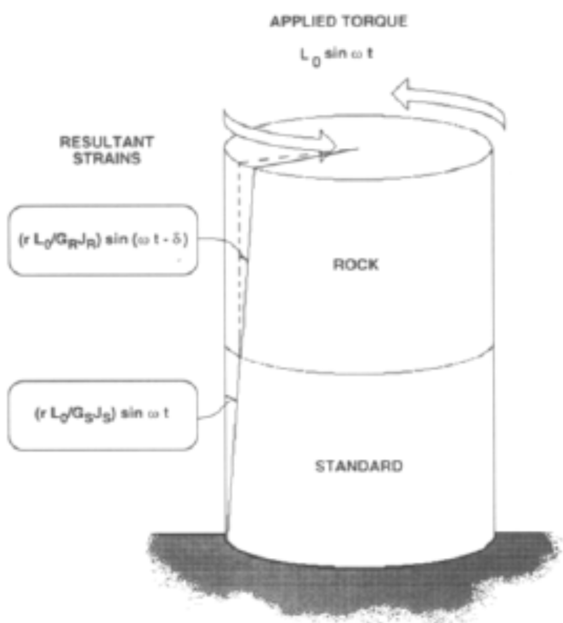
High seismic Q (large errors)

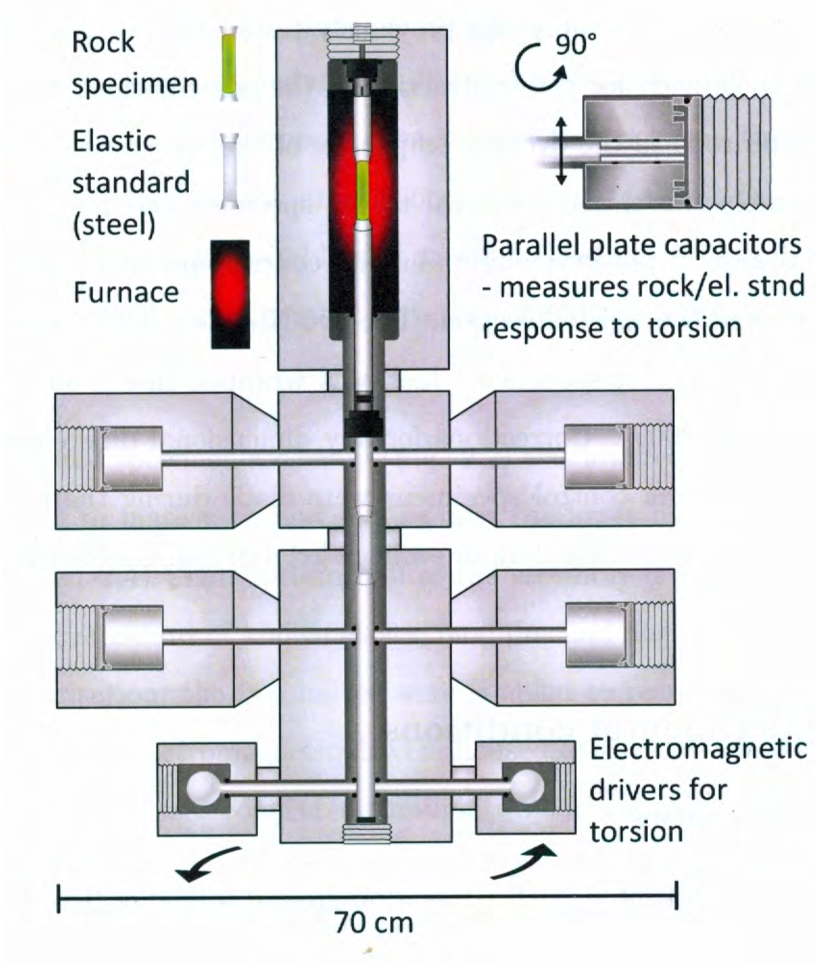
Low tidal Q (37-60: **small errors**)

Toksöz (1974), Nakamura-Koyama (1982)

Tidal Q (Williams et al. (2001))

Experimental studies





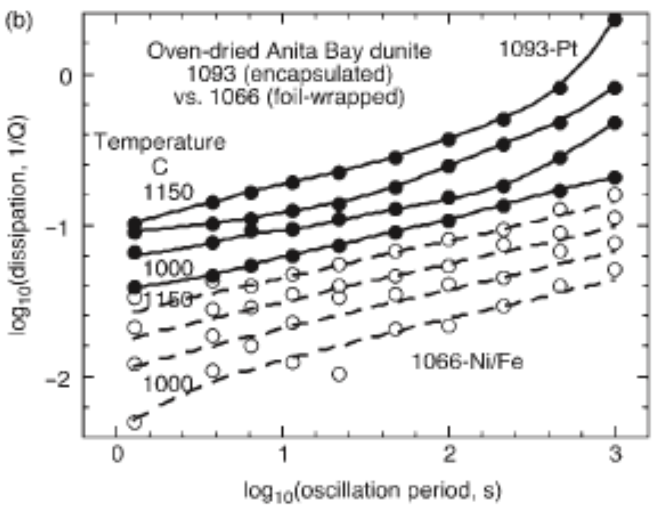
Jackson (2009)

Anelasticity (Q) and water

$$Q^{-1} \sim (\omega\tau)^{-\alpha} \propto \tau^{-\alpha}$$

$$\tau \propto \eta \propto \frac{1}{C_W^r} \text{ (for most cases), } C_W \text{ : water content}$$

$$\rightarrow \quad \boxed{Q^{-1} \propto C_W^{\alpha r} = C_W^{r_Q}}$$



"wet"

"dry"

Aizawa et al. (2008)

Formulation based on micro-physics of Q

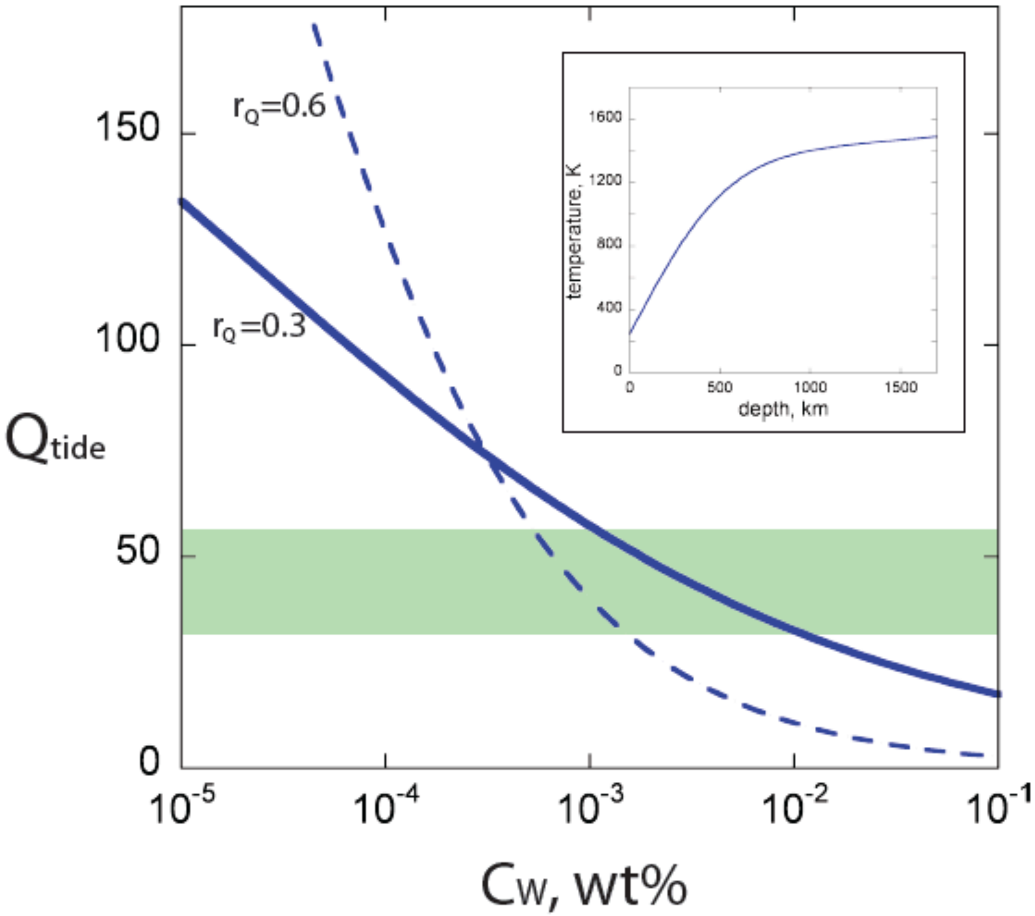
- "Power law" $Q^{-1} \propto \omega^{-\alpha}$
- Maxwell time scaling $Q^{-1} \propto (\omega\tau)^{-\alpha} \propto \eta^{-\alpha}$
  - analogy with creep (Karato (1995, 2003), McCarthy et al. (2011))
  - experimental support (Jackson (Faul, Aizawa); Takei; Cooper)
- "anchored value approach"

$$\frac{Q^{-1}(C_W, T; \xi)}{Q_o^{-1}(C_{Wo}, T_o; \xi)} = \left(\frac{\omega}{\omega_o}\right)^{-\alpha} \frac{\left[1+\left(\frac{C_W}{C_{Wtr}}\right)^{rQ}\right]}{\left[1+\left(\frac{C_{Wo}}{C_{Wtr}}\right)^{rQ}\right]} \exp\left[-\frac{H_Q^*}{R}\left(\frac{1}{T}-\frac{1}{T_o}\right)\right]$$

Q_o $(=80)$: Q of the Earth's asthenosphere

Q(z)→ Qtide (for a given T-z)

$$Q_{tide}^{-1} = \int Q^{-1}(z) \cdot W(z)\,dz$$

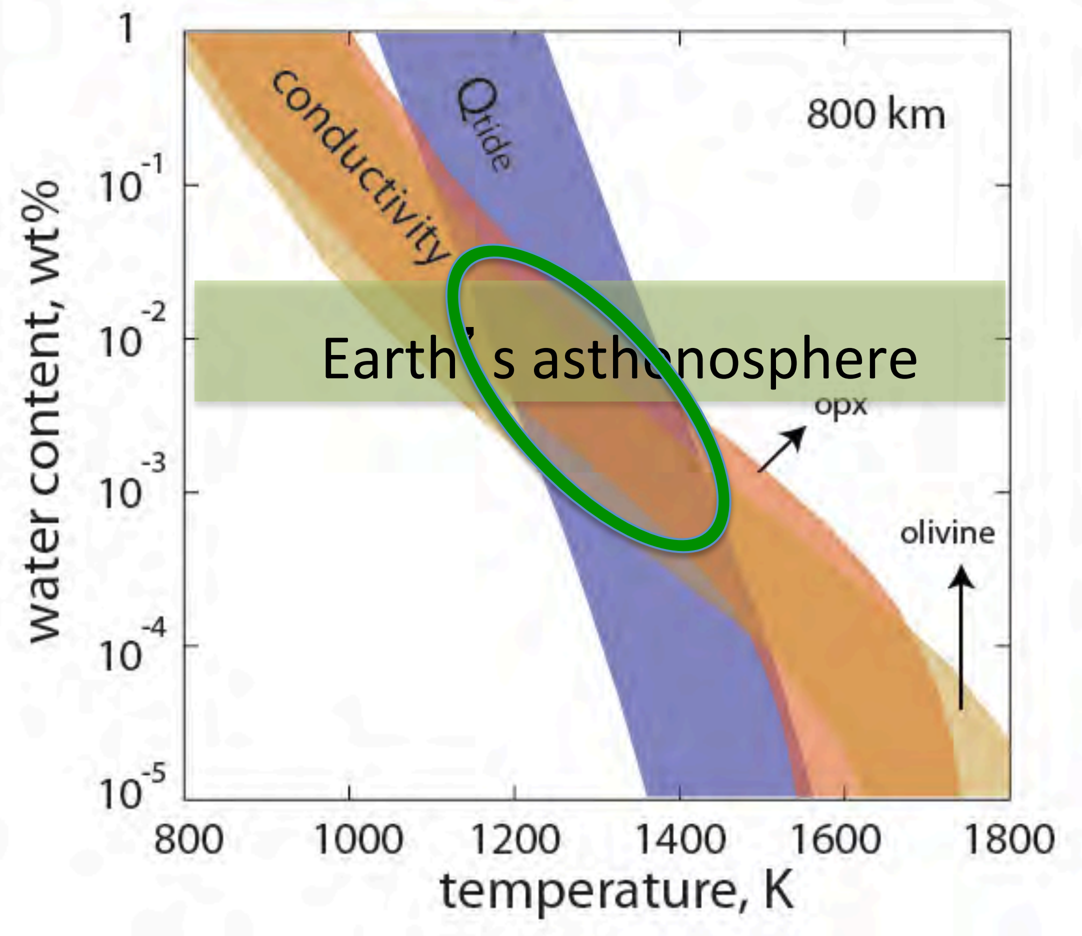


$$Q \propto C_W^{-r_Q}$$

Tidal Q suggests lunar interior has some water (similar to Earth's asthenosphere).

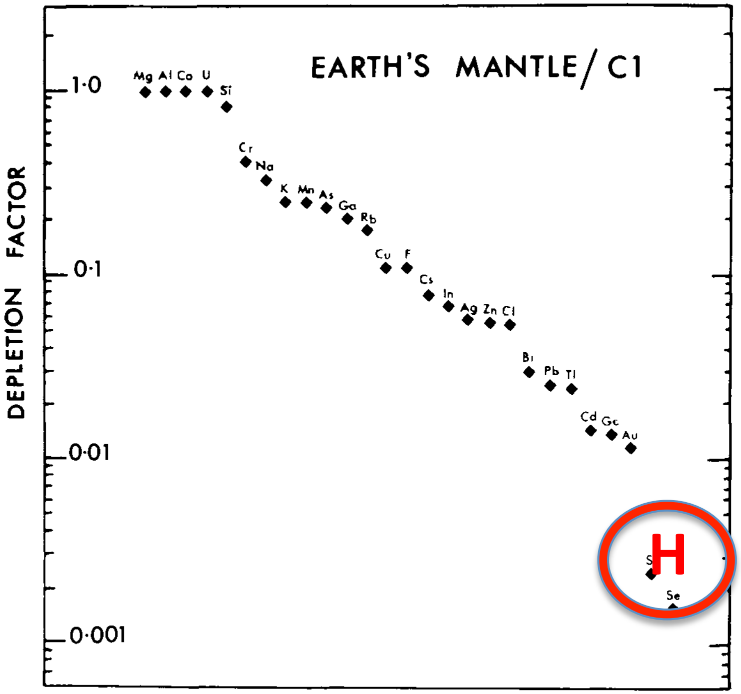
But the results depend on the assumed T (z) (no unique solution).

Constraining water content and temperature using both conductivity and Q

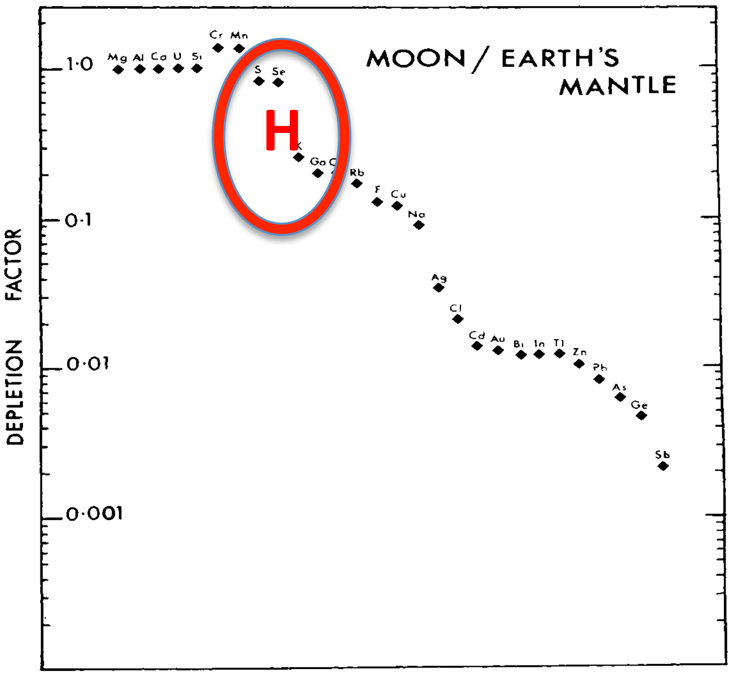


→Lunar mantle is cooler than Earth's mantle,
but contains water similar to the Earth's asthenosphere.

"not-so-dry" Moon



Hydrogen is depleted in Earth (relative to CI chondrite).



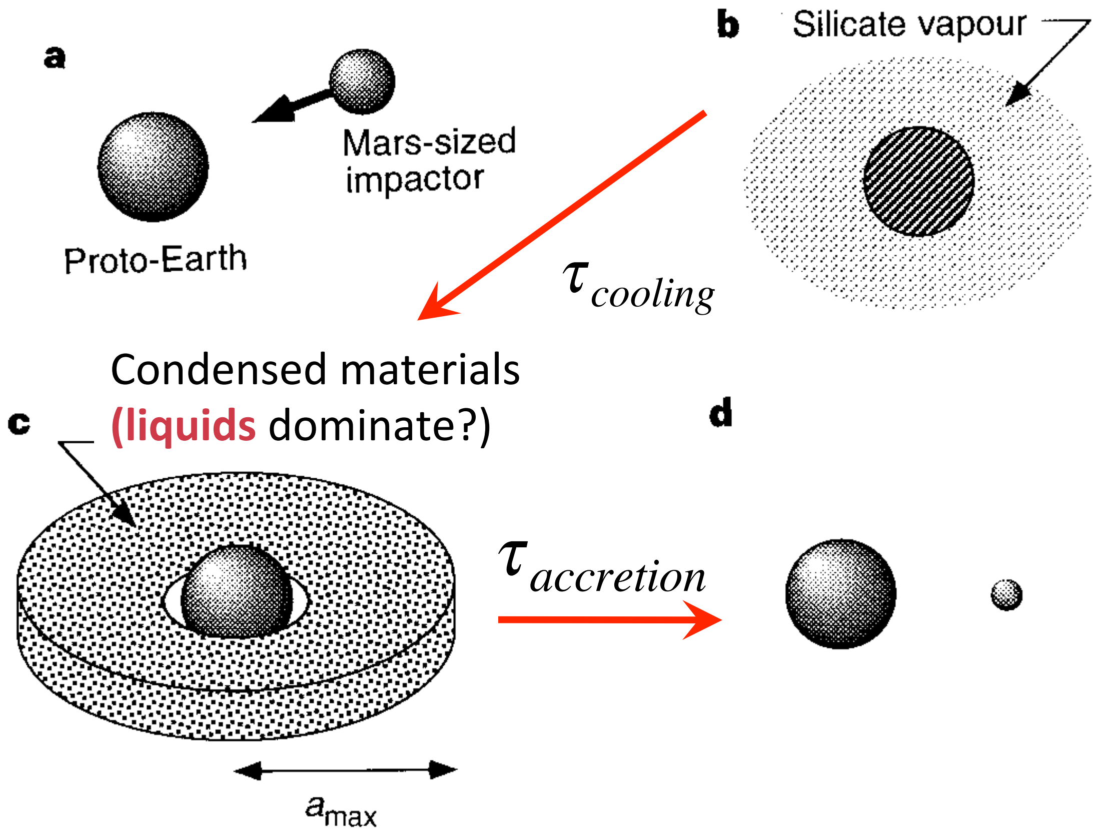
Hydrogen is not much depleted in the Moon relative to Earth.

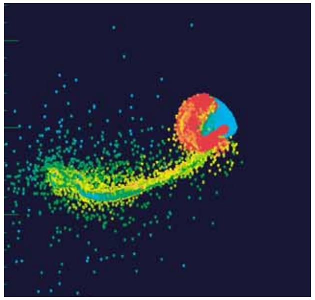
→Moon formation process did not remove much water

(although much of water was lost during Earth formation)

→ Why? (what is the difference between Moon and Earth formation?)

Why wasn't much water lost during the Moon formation (although much water was lost during Earth formation)?

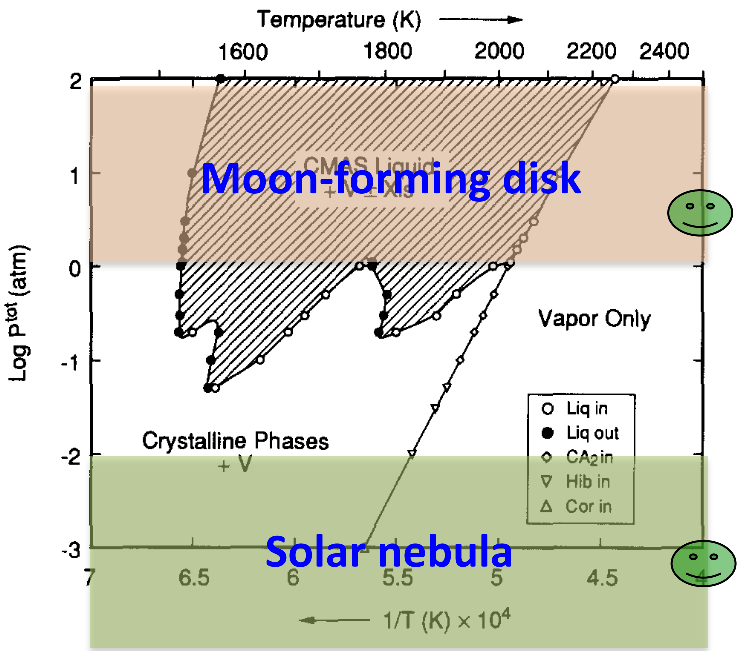


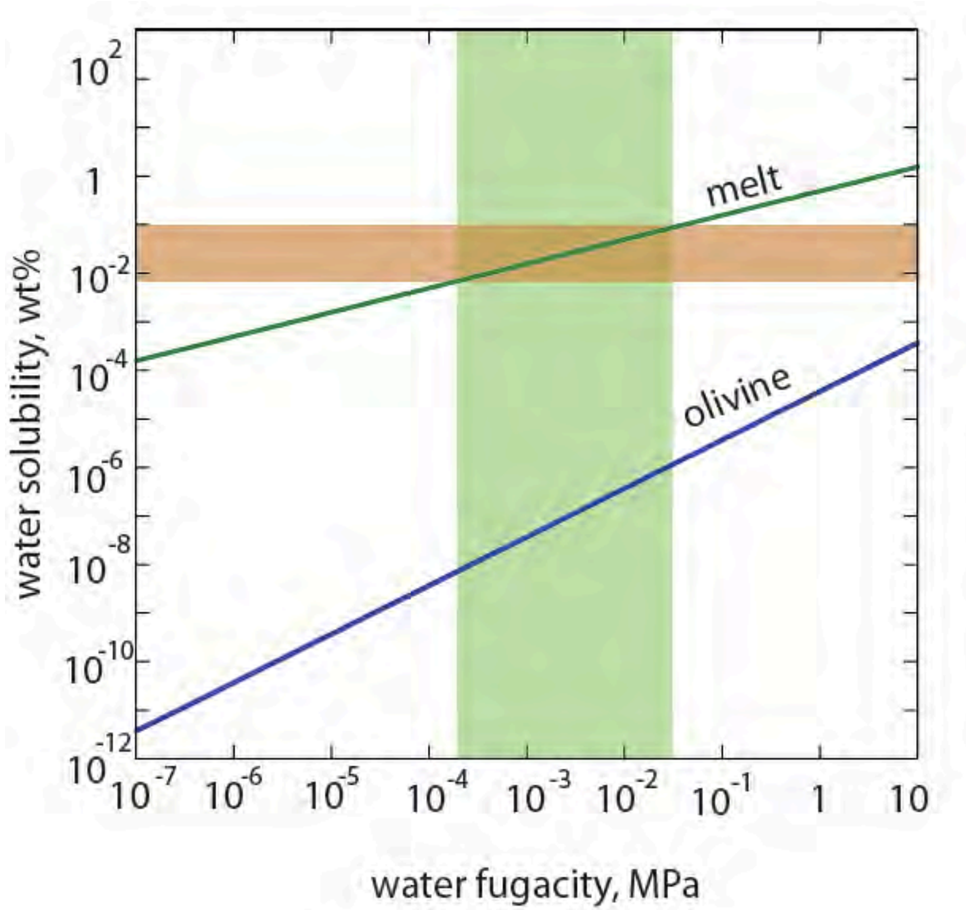


Formation of the Moon occurred in the **much smaller space** than the formation of Earth in the solar nebula.

→ **high-pressure vapor (liquid condensation?), short accretion time**

Moon-forming disk was at high-P → liquid phase
Liquids can dissolve a substantial amount of water





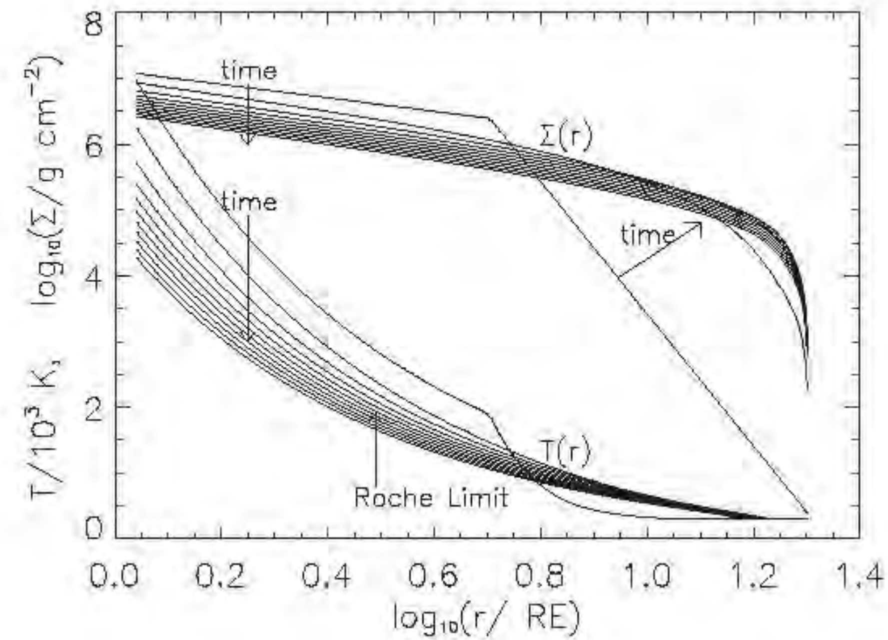
Yoneda-Grossman (1995)

Cooling and accretion time scale
(in order to keep water, accretion must be quick)

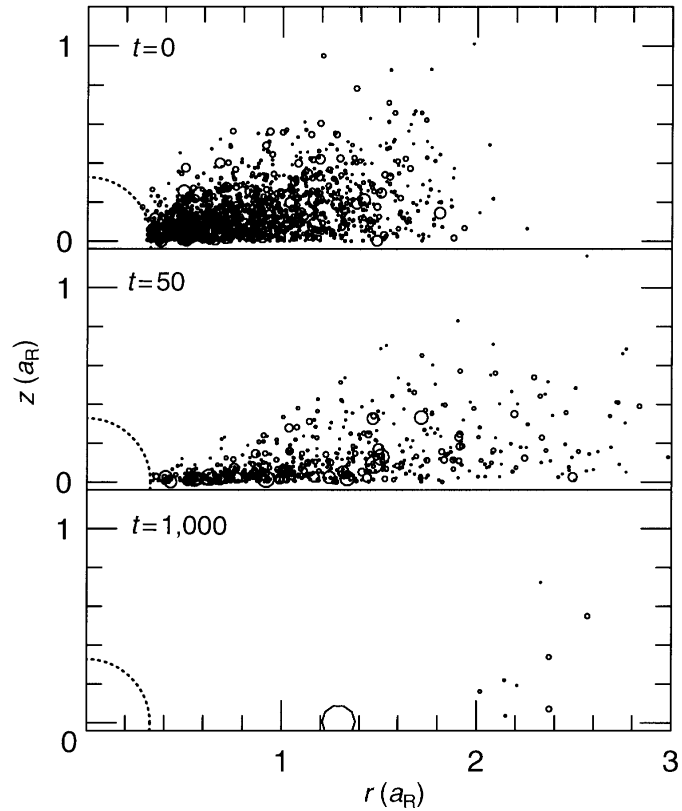
$$\tau_{cooling} \sim \frac{M_D \cdot C}{2\pi R^2 \sigma_{SB} T^3} \sim 300\,(\text{years}) \left(\frac{1500}{T}\right)^3 \sim 100\,(\text{year})$$

$$\tau_{accretion} \sim 2 \Sigma_d^{-1} M_D^{1/3} \rho_s^{2/3} \left(\frac{v_{ran}}{v_{esc}}\right)^2 \Omega_K^{-1}$$

$$\sim 10^7\,(\text{year}) \left(\frac{M_D}{M_\oplus}\right)^{1/3} \left(\frac{R}{1\,\text{AU}}\right)^3 \left(\frac{M_\oplus}{M_\odot}\right)^{-1/2} \sim 1\,(\text{year})$$



Cooling time-scale~ 30 year
(Desch-Taylor, 2011)



t=1000~1 year
(Ida et al. , 1997)

→ Cooling time scale is longer than accretion time scale

→ **Accreted materials are mostly liquids**

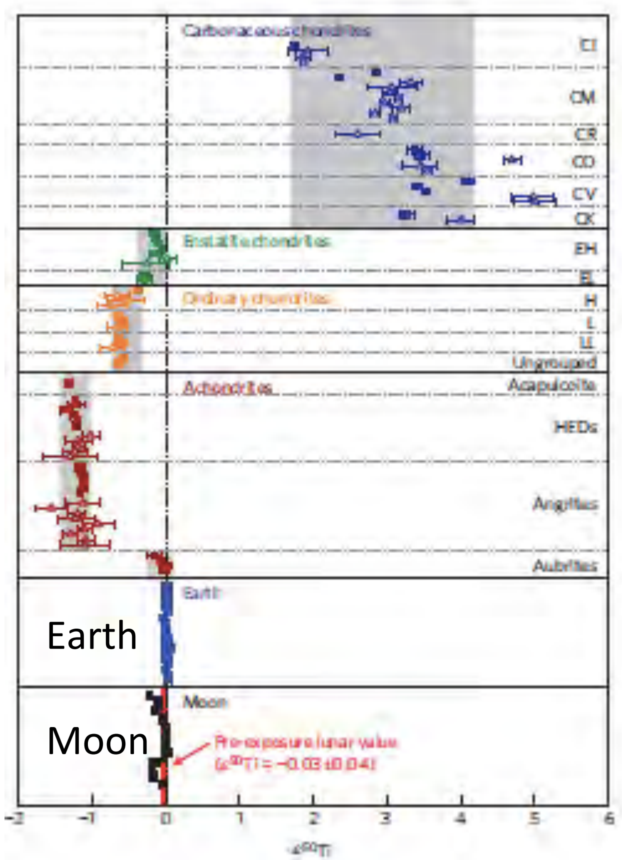
→ Initial materials for the Moon are “wet” (not so “dry”).

“Not-so-dry” Moon could be explained by a quick accretion model in the small space.

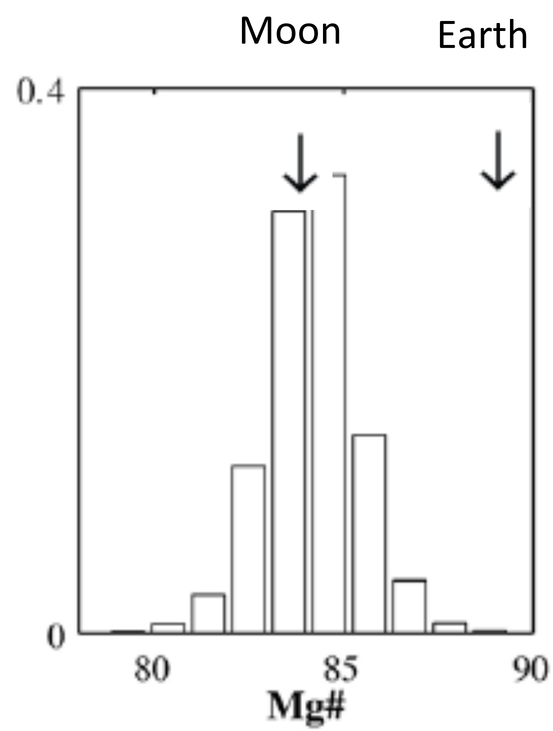
Can a giant impact model also explain other major geochemical features?

Isotopic composition is **very similar** between the Moon and Earth → from the same materials
Major element composition is not similar → some fractionation (without isotopic fractionation)

How can we explain these two apparently conflicting observations?

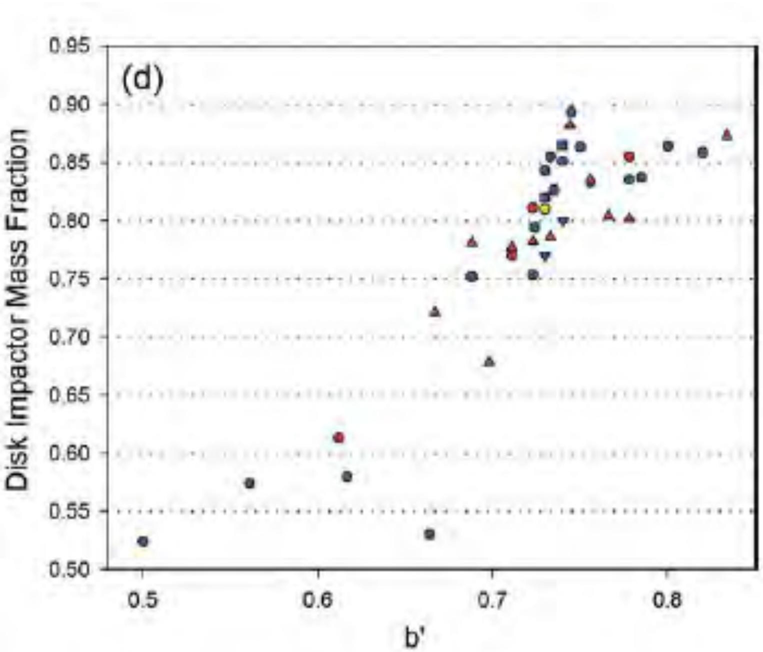


Very similar Ti isotope composition
(Zhang et al., 2012)

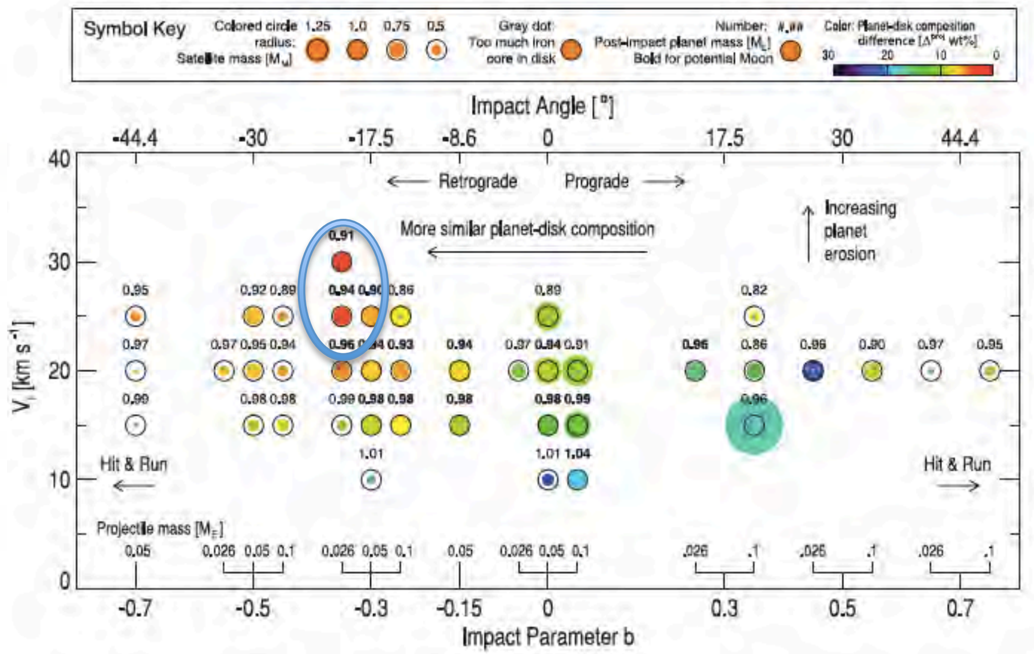


Different Fe/(Fe+Mg) (higher Fe content in the Moon)
(Khan et al., 2006; Kuskov-Kronrod, 1998)

Giant impact and the composition of the Moon



Canup (2004)



Cuk-Stewart (2012)

Problems with previous models

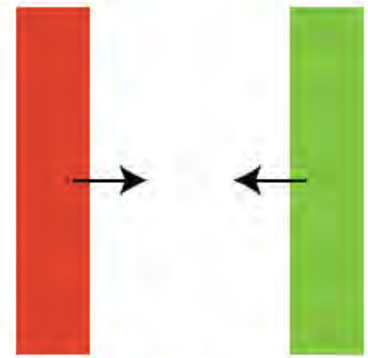
1. Most of materials are from the impactor. Only in a small parameter space (with unreasonably high impact velocity) one can have composition similar to Earth (**by chance?**).
2. Does not explain difference in the major element composition.

Terrestrial magma ocean origin of the Moon?

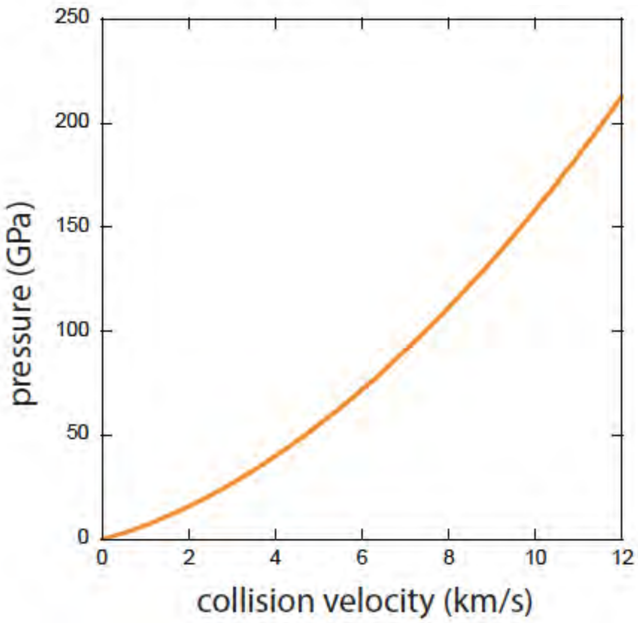
- Similarity in isotope composition but lower Mg# (higher FeO) than Earth → Moon from the magma ocean of the proto-Earth?
- Is this a physically plausible model?
  - **Physics of shock heating**

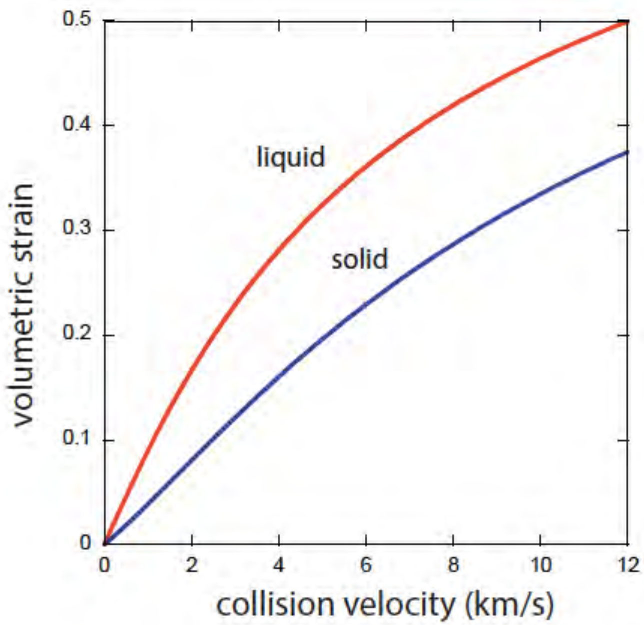
Collision → pressure, volumetric strain

liquid-solid collision leads to the large compression of liquid



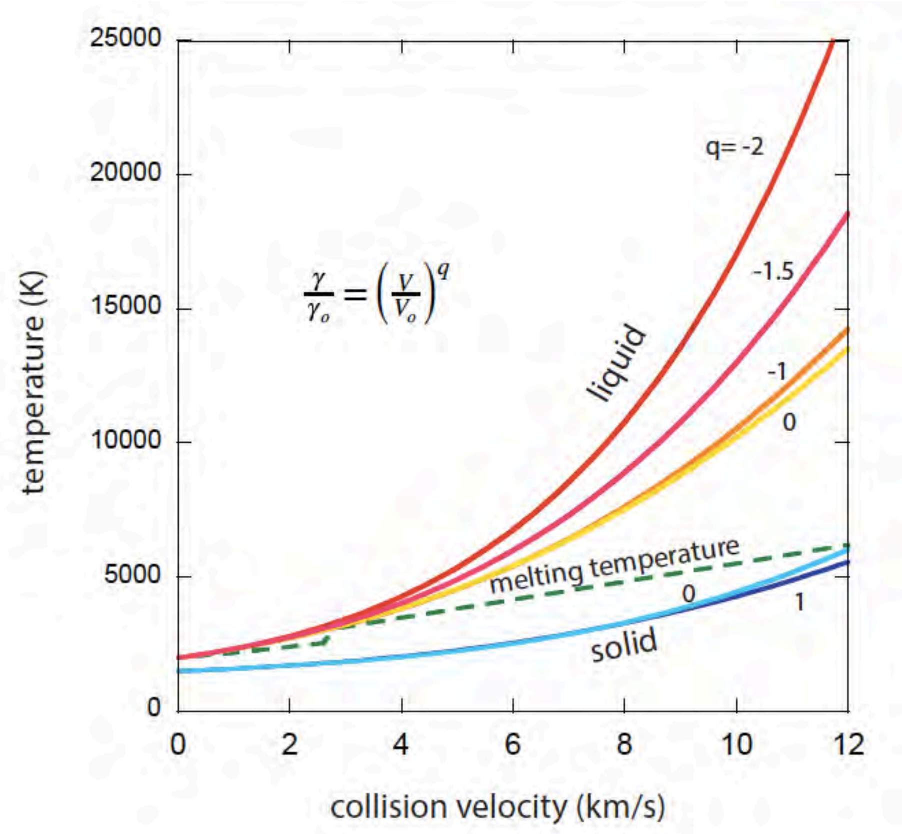
liquid (flat) planet solid (flat) planet





Liquid is more heated than solid

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

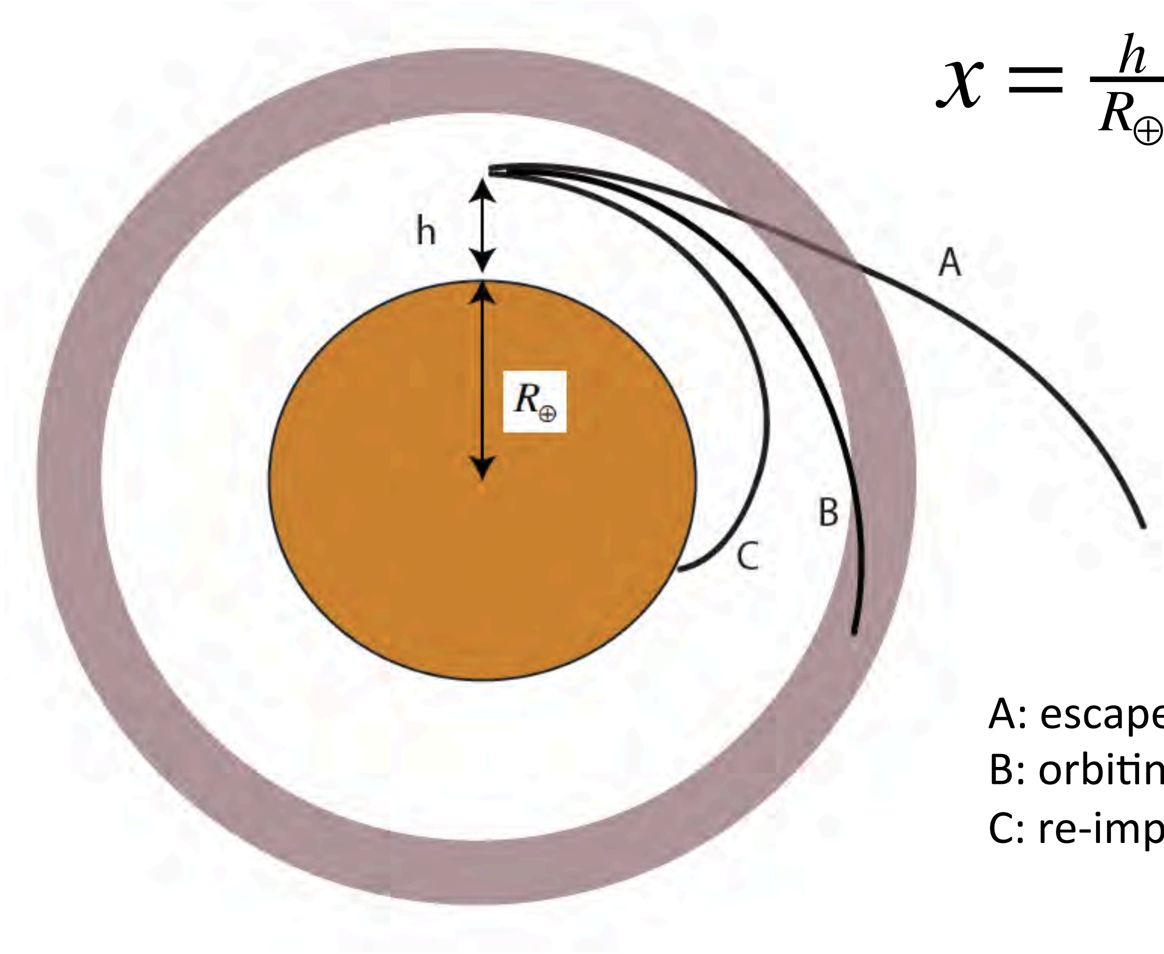


Large volumetric strain

Negative q (the Grüneisen parameter becomes large at high compression).

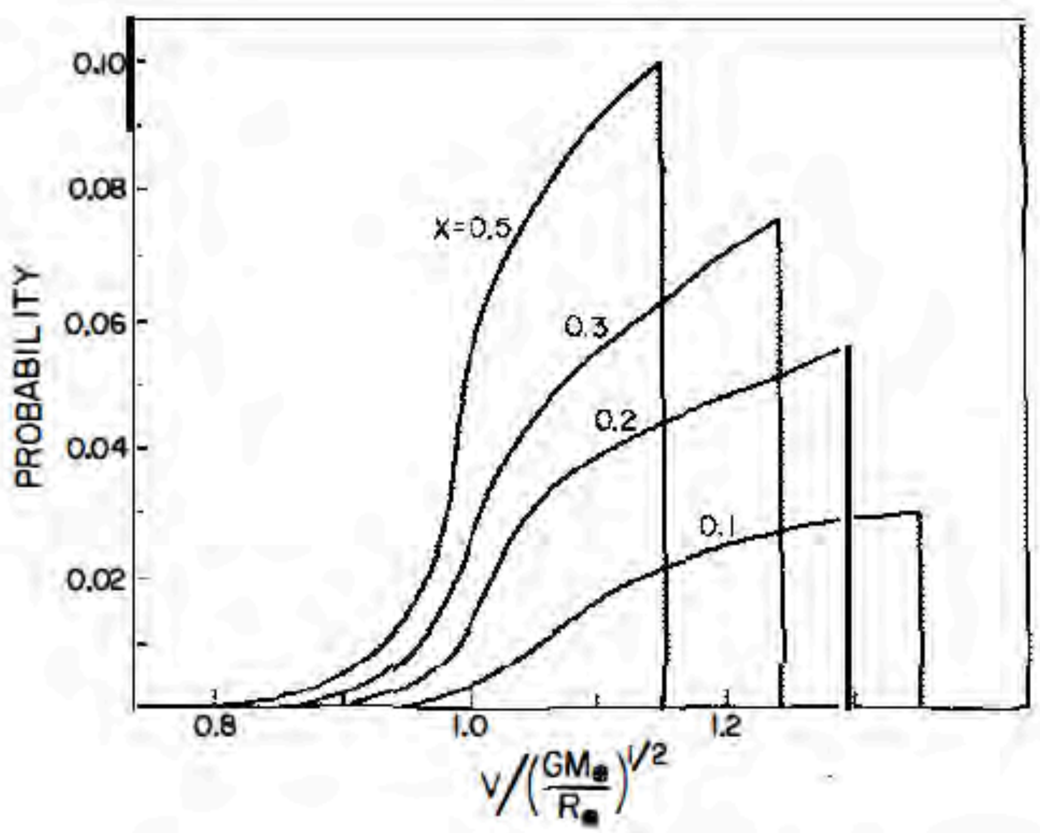
Fate of ejected materials

$$x = \frac{h}{R_{\oplus}}$$



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

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

Conclusions

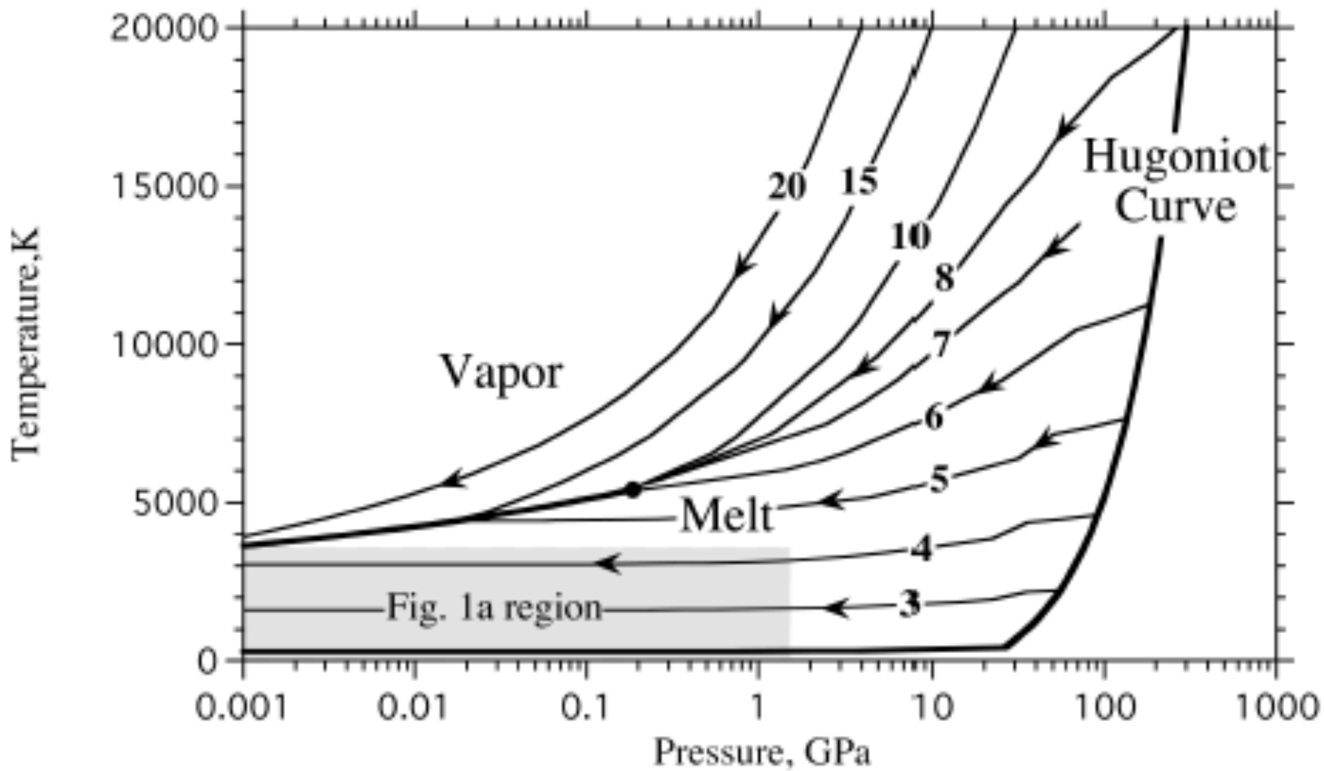
- **Mineral physics (+ geophysics) helps understand the composition and the origin of the Moon.**
- Water content in the lunar mantle
  - Geophysical obs. + mineral physics

  → **the Moon is as “wet” as Earth**

  → quick accretion compared to cooling time-scale
- Collisional heating
  - Mineral physics + thermodynamics → heating the pre-existing magma ocean, not much heating on solid part

  → **the Moon from the magma ocean of the proto-Earth ?**

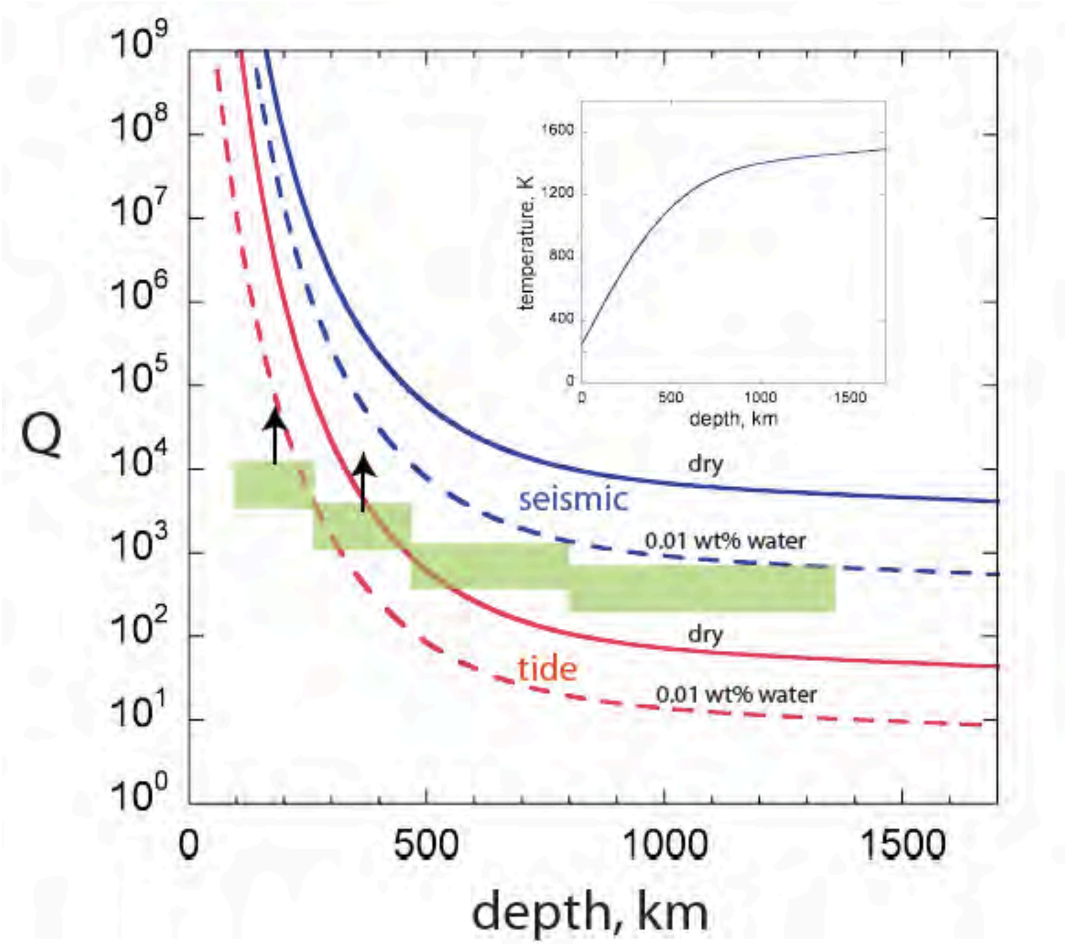
After a giant impact, pre-existing magma ocean vaporized → volume expansion



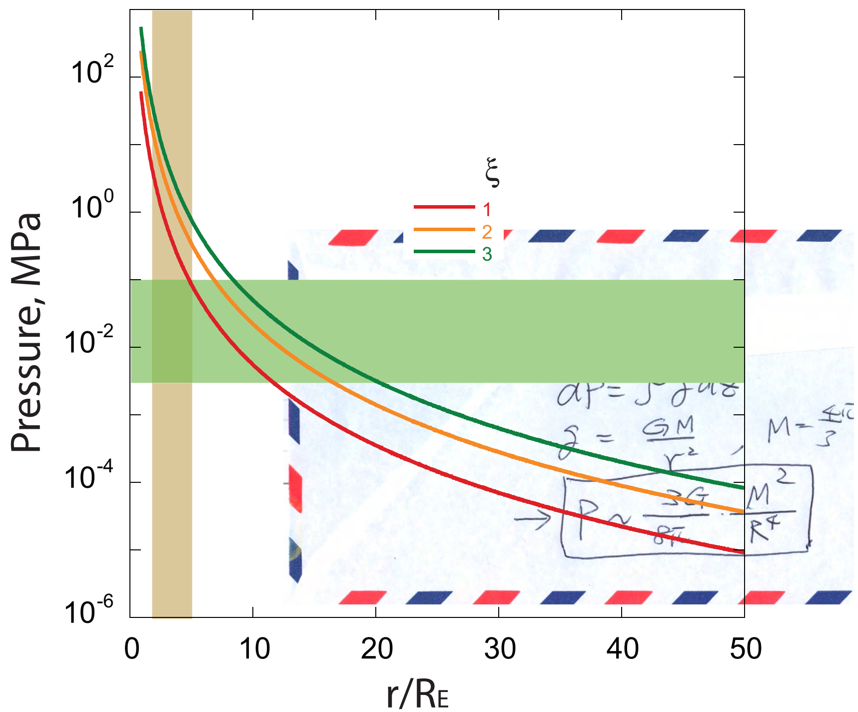
Melosh (2007)


Someone lost a key in the dark---
Why don't you look around
any other places with your own torch?
Its so dark
elsewhere
?

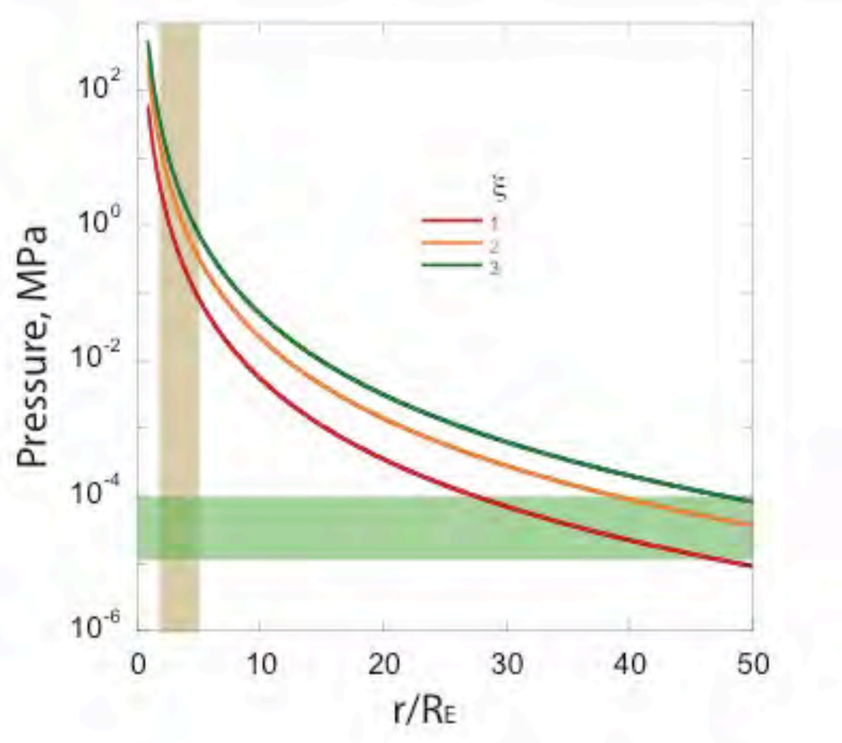
Q-z models for a given T-z



Initially condensed materials will be liquid phase if P is high → how high is the pressure of the Moon forming disk?



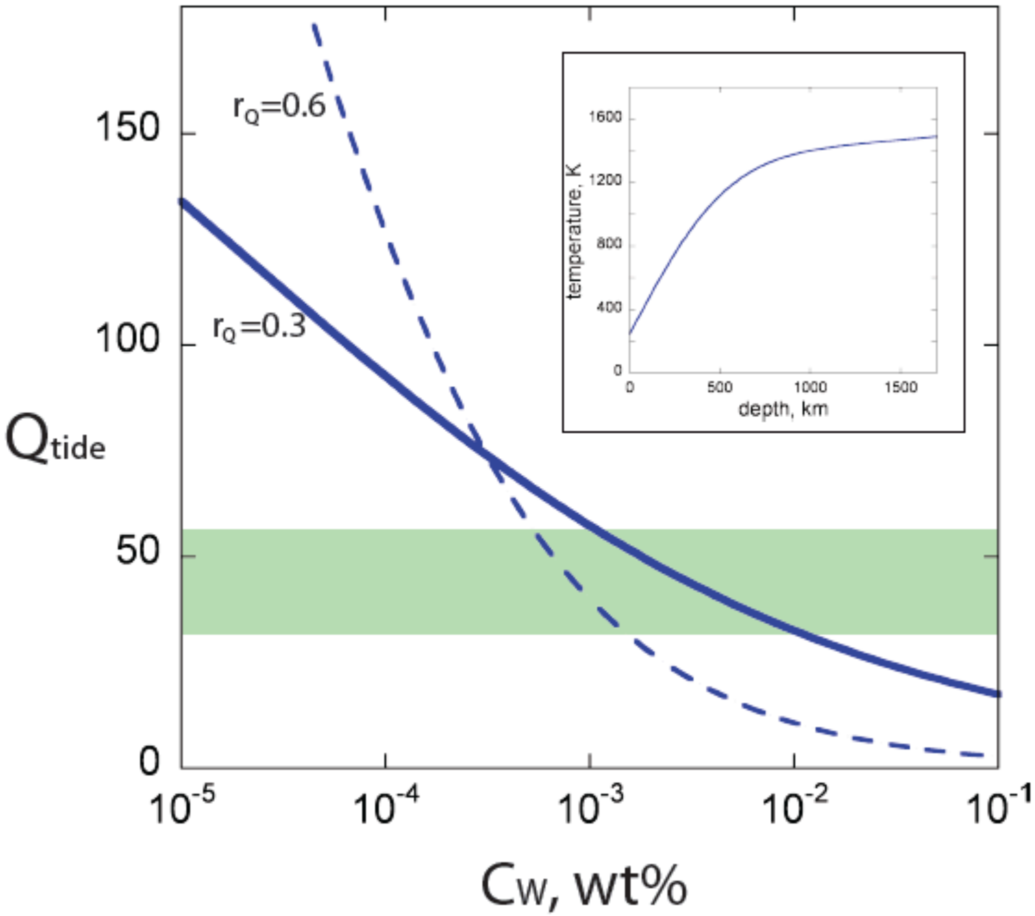
No H_2



H_2-rich gas

→ Liquid stability region expands with hydrogen

Q(z)→ Qtide (for a given T-z) $Q_{tide}^{-1} = \int Q^{-1}(z) \cdot W(z) dz$



$Q \propto C_W^{-r_Q}$

Tidal Q suggests lunar interior has some water (similar to Earth's asthenosphere).

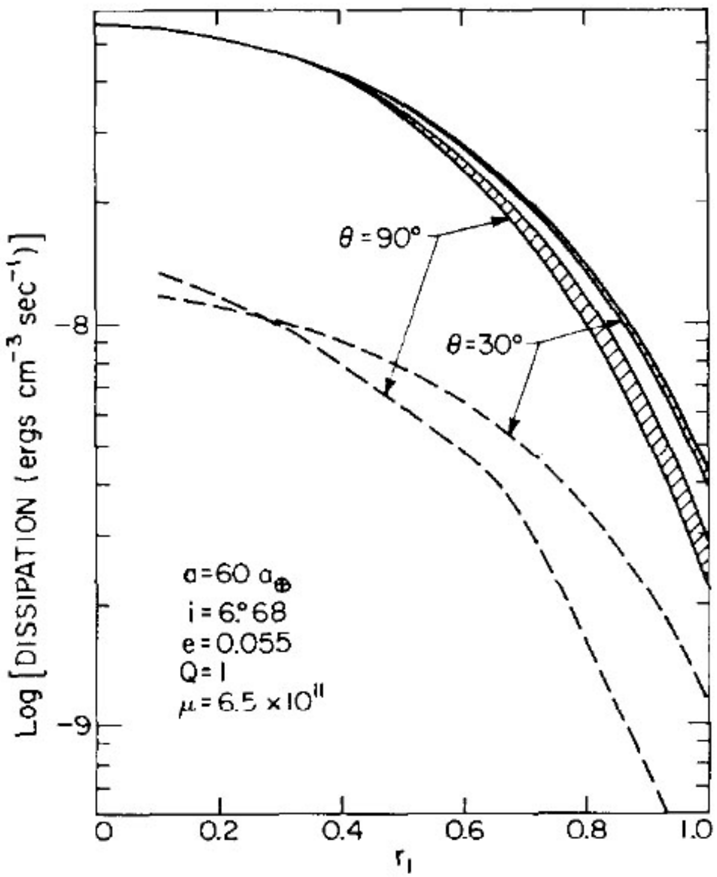
But the results depend on the assumed T (z) (no unique solution).

My encounter with Kumazawa-san

- From the book by Shimazu (1967)
- Meeting in Nagoya (1974?)
- Meetings in Tokyo (mid 1980's)
  – Discussions on high-P deformation apparatus
- At Albany (2008)
  – At Miyashiro's home with Shige Maruyama

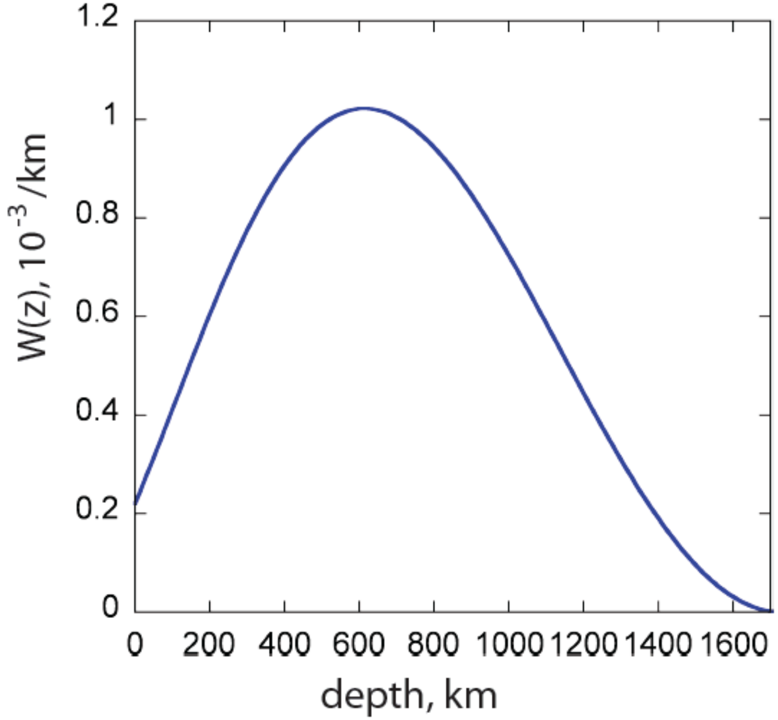
Tidal dissipation and depth-dependent Q

tidal Q is sensitive to mid-mantle properties



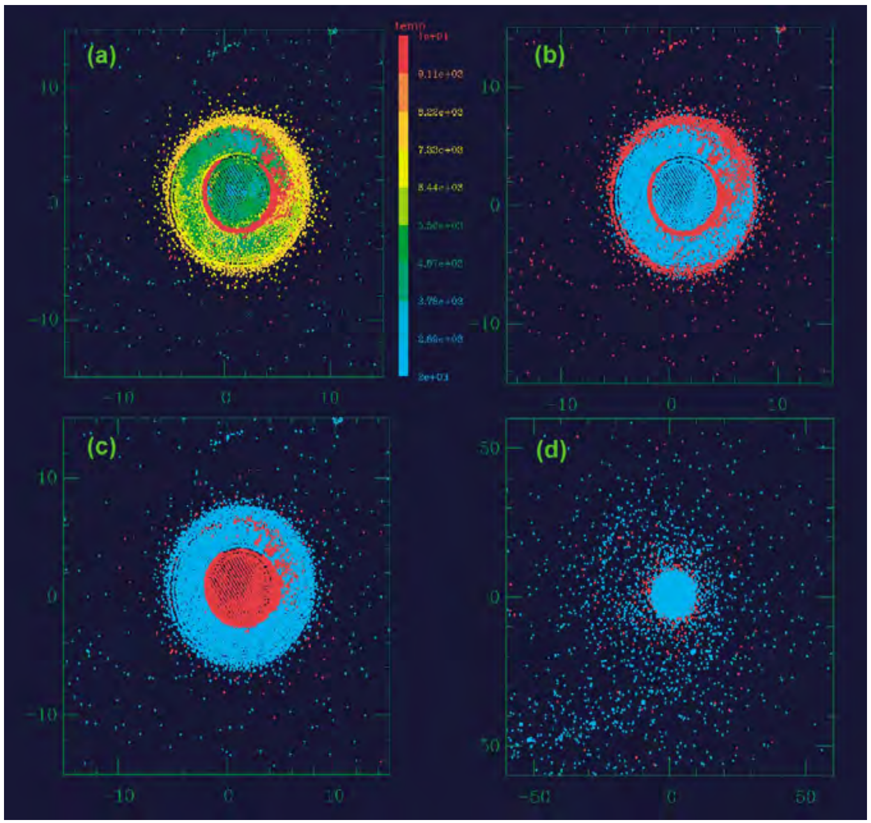
Peale-Cassen (1978)

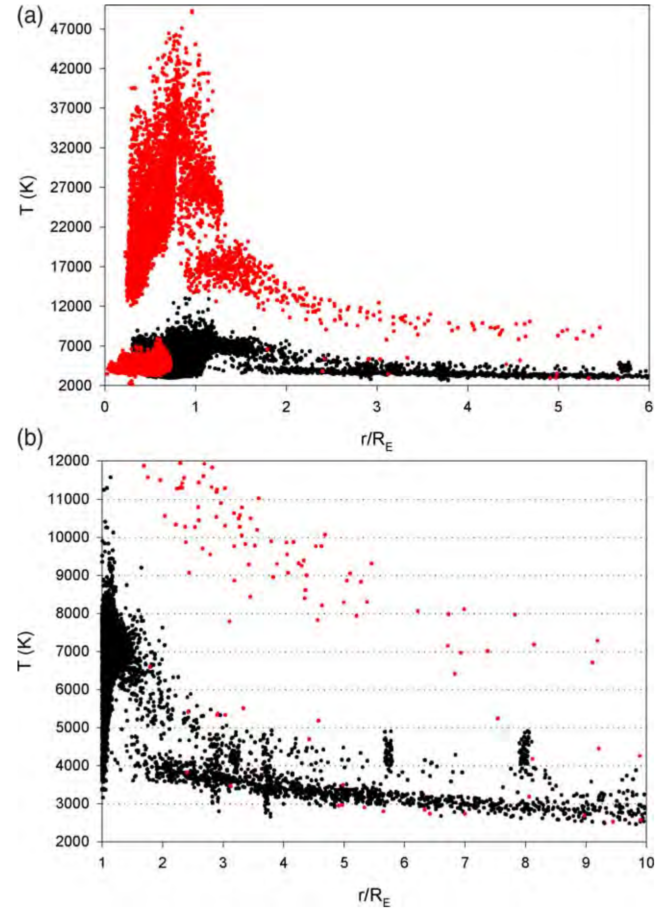
Weighting function



$$Q_{tide}^{-1} = \int Q^{-1}(z) \cdot W(z)\,dz$$

weighting function = (strain energy)*(volume)


(a)
(b)
(c)
(d)
temp


(a)
T (K)
47000
42000
37000
32000
27000
22000
17000
12000
7000
2000
0 1 2 3 4 5 6
r/R_E
(b)
T (K)
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1 2 3 4 5 6 7 8 9 10
r/R_E

Canup (2004)

Conclusions

- Water content in the lunar mantle can be inferred from geophysical observations.
- **Water content in the lunar mantle is similar to that of the Earth's upper mantle** (~$10^{-2 +/- 1}$ wt%).
- Not much water was lost during a giant impact because of the **small volume** in which impact-induced materials were ejected.

→ High P nebula (disk) → **liquid phase** condensation

→ fast accretion → accretion of liquids (**with water**)

Implications

- The Moon was formed from the magma ocean of the proto-Earth. → similarity of isotopic composition, dissimilarity of the major element chemistry (e.g., Mg#)
- The condensation in the Moon-forming disk was gas → liquid (not gas → solid).
- The Moon was formed before a majority of liquid solidified.