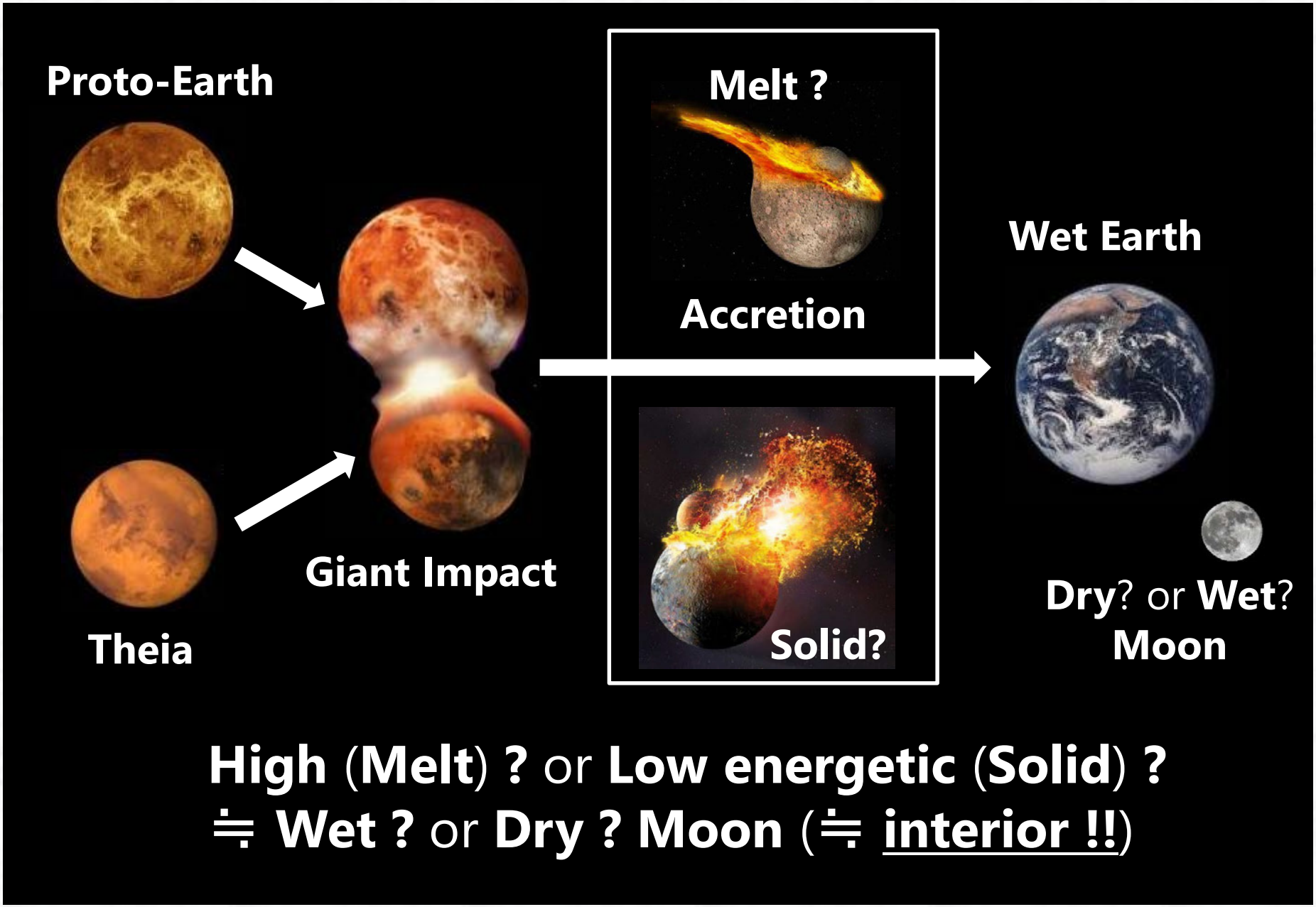
A new vision of water in the Moon

Masahiro Kayama[1, 2]

[1]Department of Earth and Planetary Materials Science, Tohoku University

[2]Creative Interdisciplinary Research Division, Frontier Research Institute for Interdisciplinary Sciences, Tohoku University

Introduction – Giant impact –



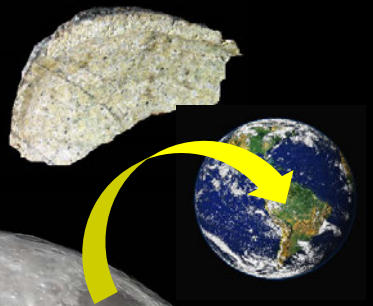
High (Melt) ? or **Low energetic (Solid) ?**
≒ **Wet ?** or **Dry ? Moon** (≒ **interior !!**)

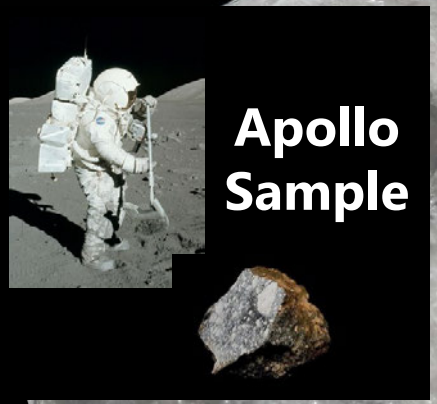
Introduction – Water of the Moon –

- **Surface** = Dry, but…

Spacecraft

Meteorite





Apollo Sample

Calculation

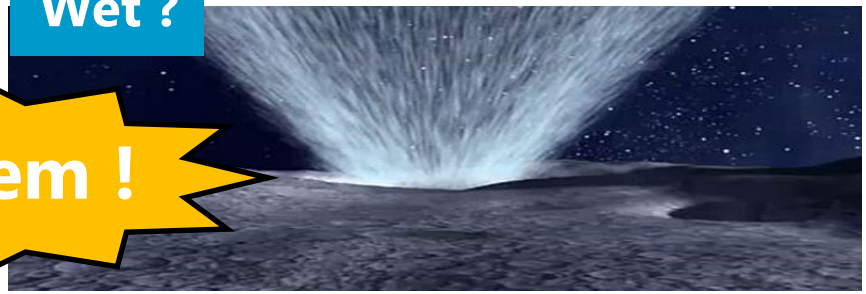
- **Interior** = Wet? Dry?

Previously dry, but recently…

- **Water-rich minerals**
- **Wet simulation model**

Introduction – Water: the key to Moon's history –

Dry ?



Wet ?

Problem !

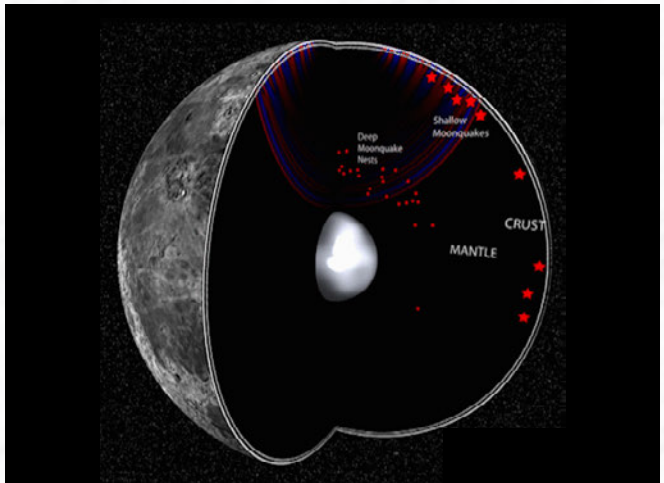
Contribution to the history

Giant Impact

→ High or Low energetic ?

Differentiation

→ Overturn ? Melt ?

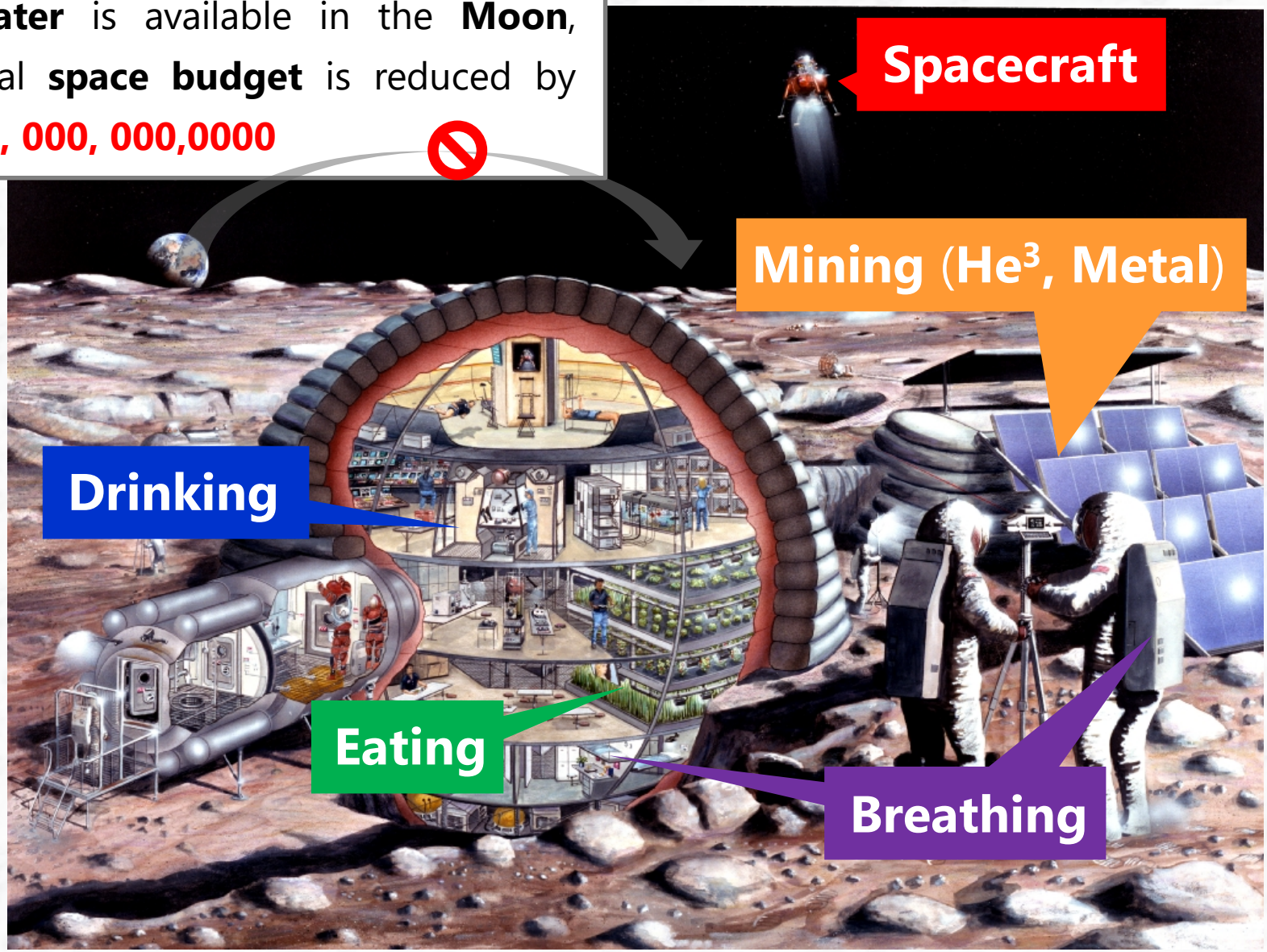


Deep Moonquake

→ Heat ? Fluid (water) ?

Introduction – Water resource –

If **water** is available in the **Moon**, annual **space budget** is reduced by **$121, 000, 000,0000**



The purpose of this study

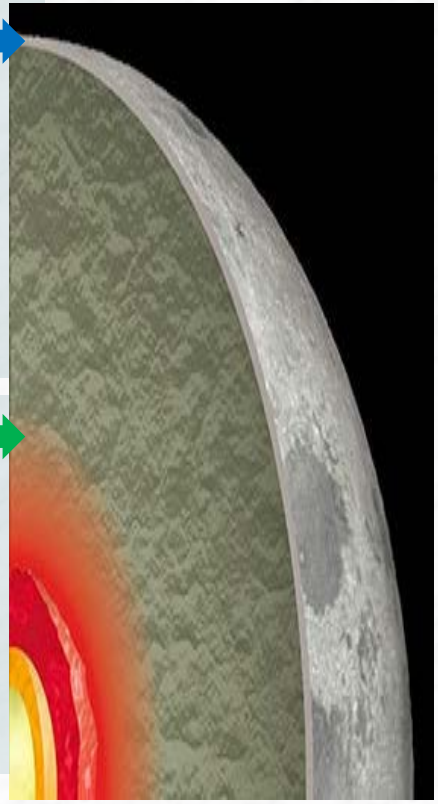
Introducing our and previous studies of lunar water:

Surface to Subsurface

- **Water** near the **poles** and in the **subsurface**
- **Solar wind-induced OH** on the **regolith soil**
- **OH** in the **old anorthosite crust**

Shallow to Deep Mantle

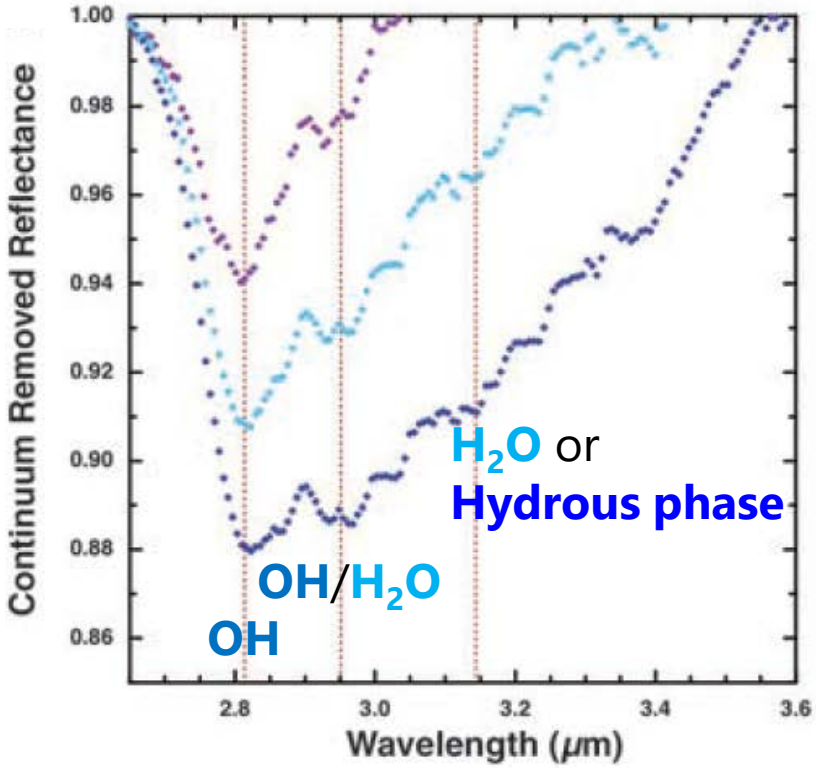
- **OH** in the shallow to deep **mantle**
- **OH** and **H_2O** in the shallow **KREEP-rich mantle**
- **Fluid** in the **low seismic velocity zone**



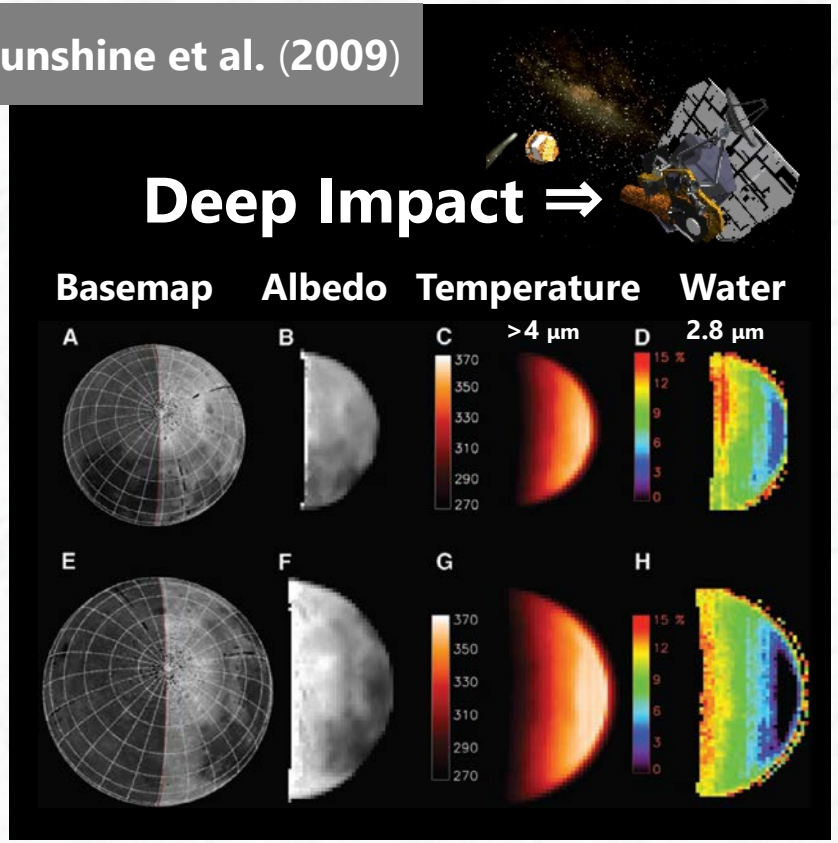
With a discussion of the Moon's history

With the future plans (Sample return, Seismic and Neutrino)

Surface water – The Deep Impact Spacecraft –



Sunshine et al. (2009)

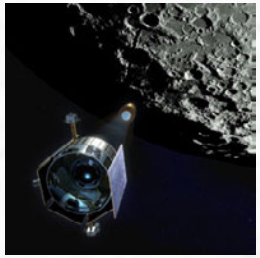


Near Infrared (**NIR**) **spectrometer** detected the **water bands**

- **2.8-3.1 μm**: **OH**, **H_2O** and **hydrous phase**

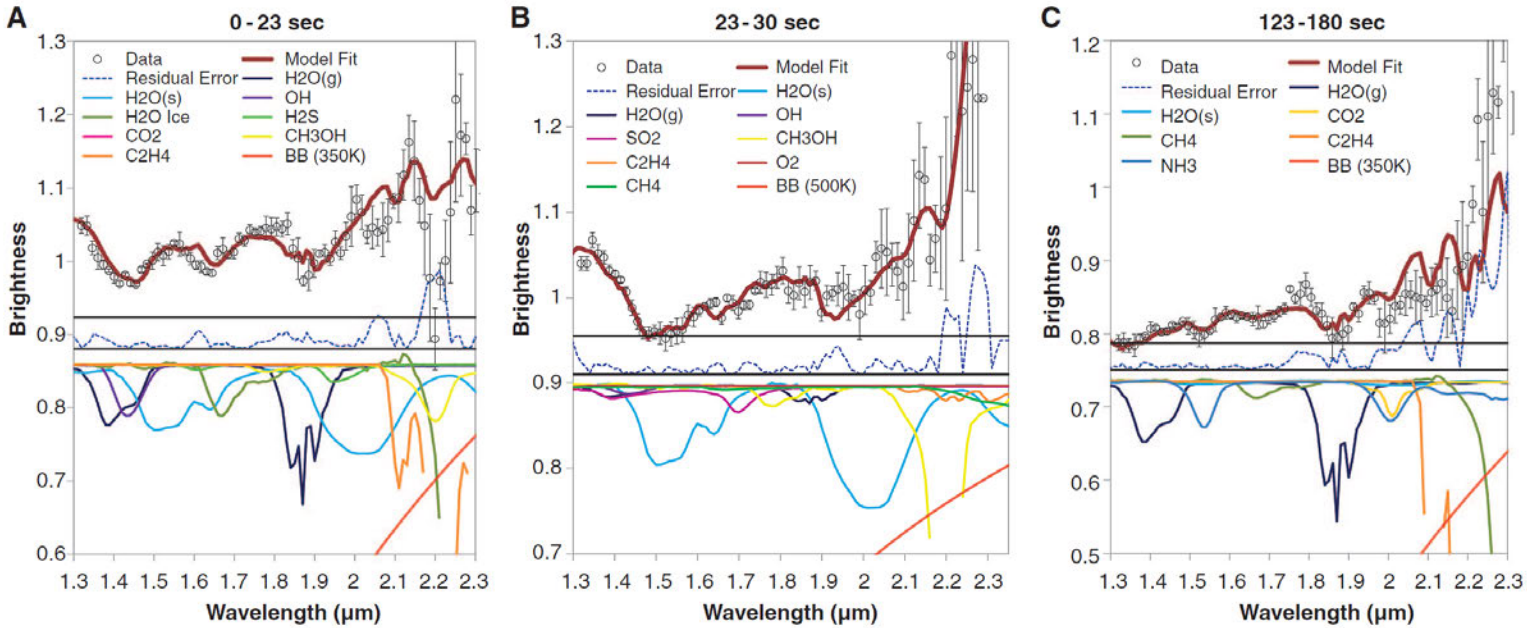
→ **Bulk water content of the soil: 0.3 wt.%** (Volatility: **0.5 wt.%**)

Surface water – LCROSS Spacecraft –



⇐ LCROSS spacecraft

Colaprete et al. (2010)



Near Infrared (**NIR**) **spectrometer** found the **water bands**

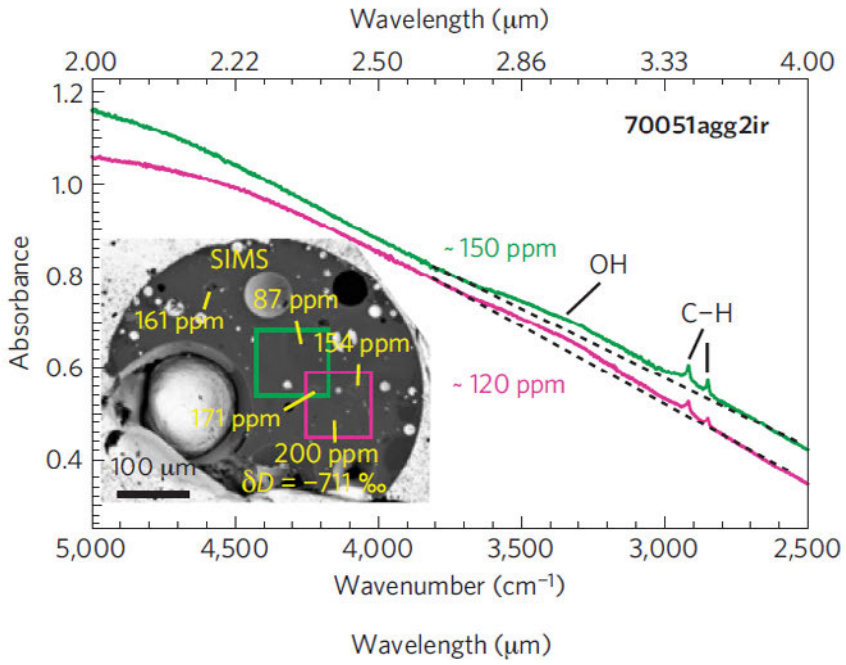
- **2.2**, **1.9**, **1.4 μm**: **OH**, **H_2O** and **Ice** in the **surface** (**~0.7 m** depth)
- Mainly **Asteroid**/**Comet**, Slightly **Solar Wind** origins

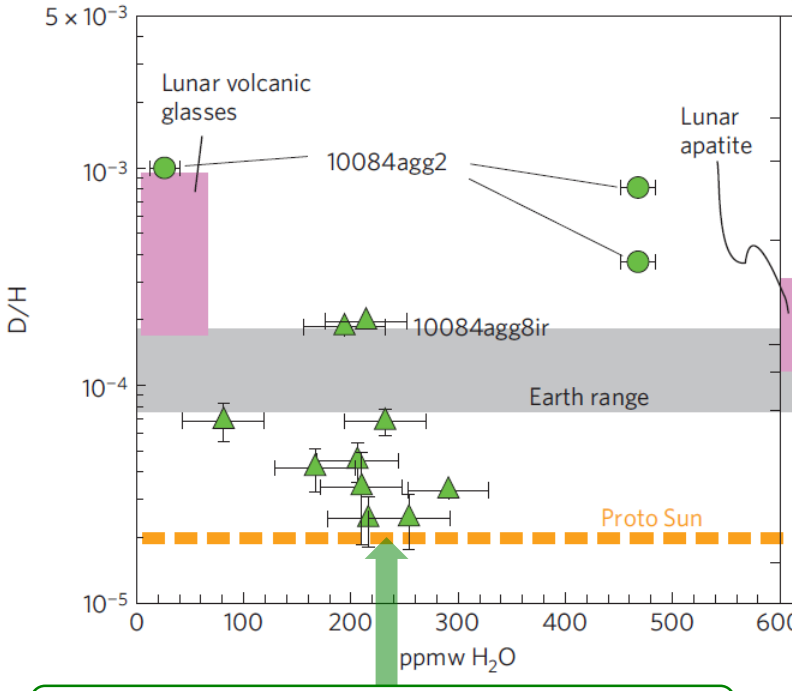
155 ± 12 kg = **5.6 ± 2.9 wt.%** **OH** & **H_2O** near the **South Pole**

Surface water – Apollo samples –

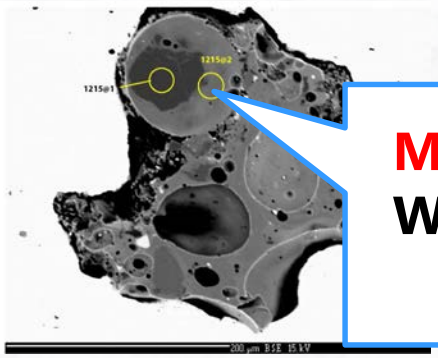
Hydroxyl in the regolith agglutinate

Liu et al. (2010)





H implantation by **the solar wind**



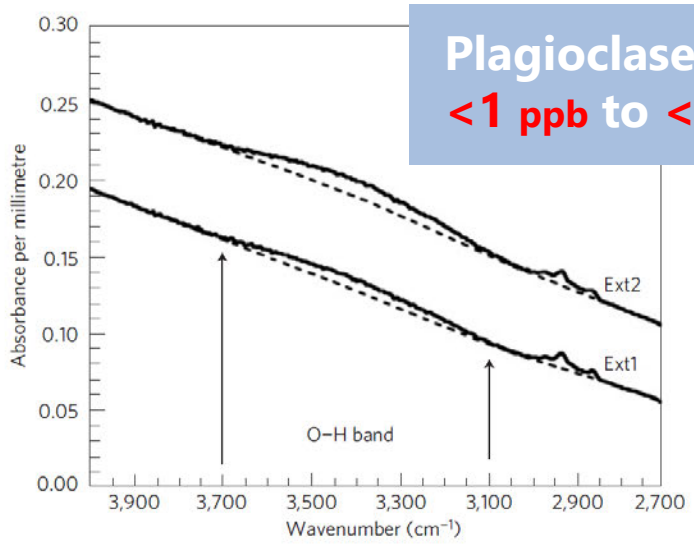
Maximum 70 ppm

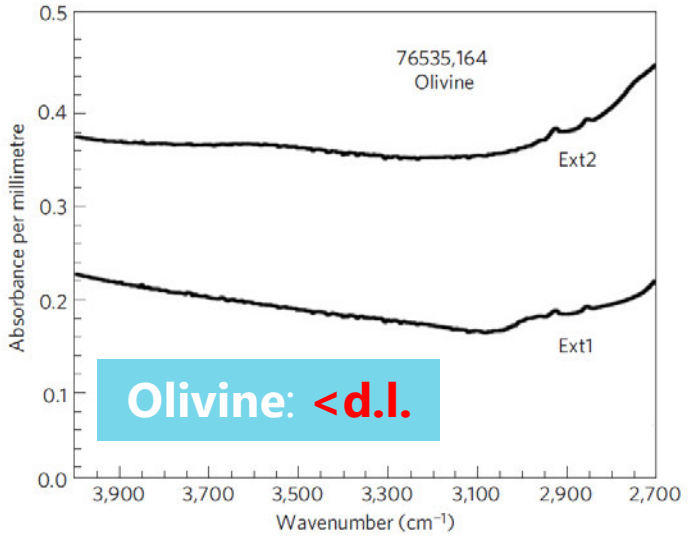
Water-rich regolith → **Solar-wind** induced **hydroxyl** in the agglutination

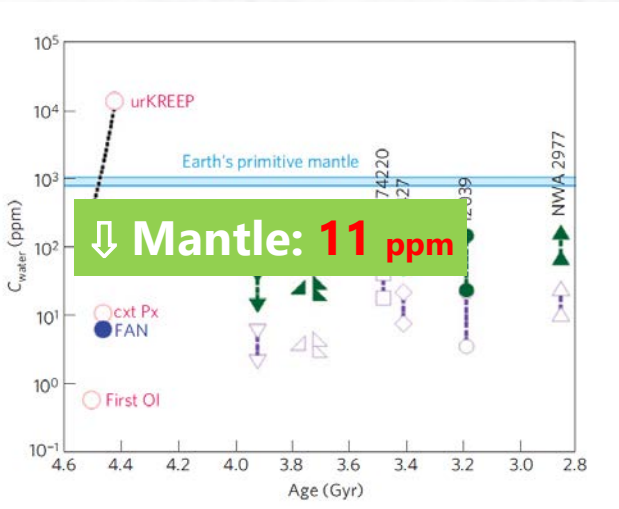
Surface water – Apollo samples –

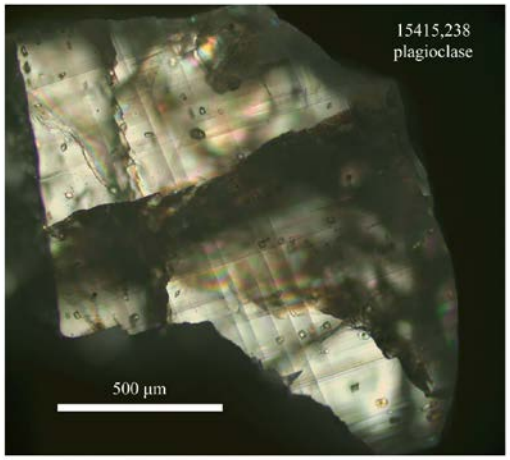
Hydroxyl in the old lunar anorthosite crusts

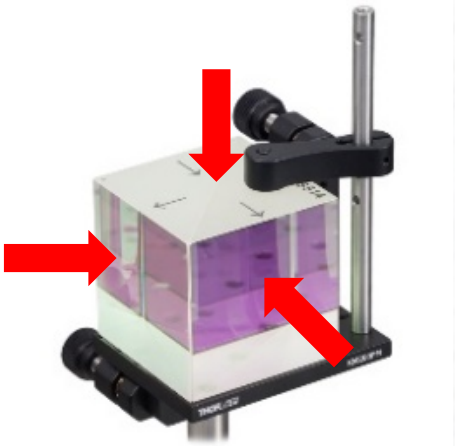
Hui et al. (2010)





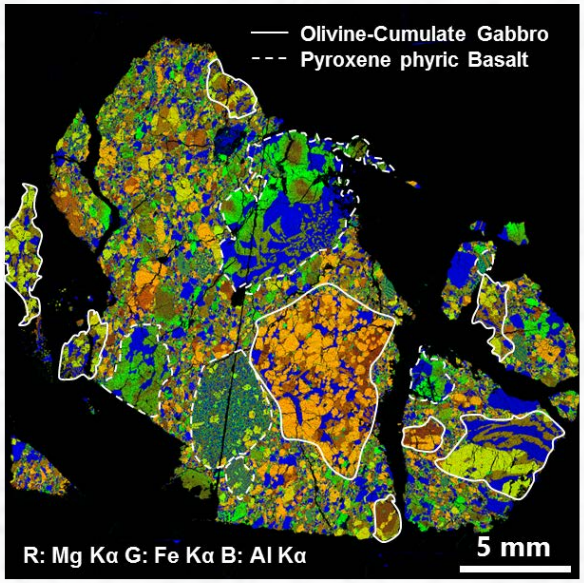


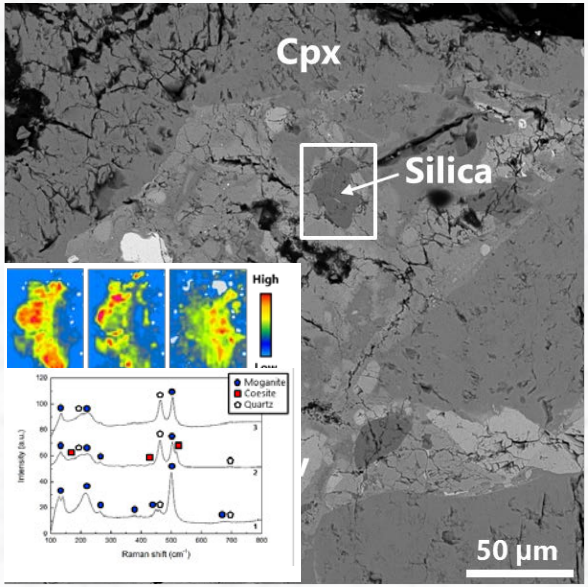




Subsurface water – Lunar meteorite –

Hydroxyl/molecular water in lunar meteorite (Kayama et al. in submitted)





- SiO_2 (*s*) + $2H_2O$ ↔ H_4SiO_4 (*aq*)

(**Moganite**) (Water) (Silicic acid)

>76 ppm **>46 ppm**

➡ **Sunlit surface**: Fluid predicated moganite

➡ **Subsurface**: Fluid can cold-trapped as **water ice**

Bulk water content

- **Spacecraft** (the **poles**)

Lunar prospector: **0.1 wt.%**?

Deep Impact: **0.3 wt.%**

LCROSS: **5.6 wt.%**

Chandrayaan-1: **80 ppm**

- **Lunar rocks** (the **PKT**)

Basalt: **<1 ppb**?

Anorthosite: **<1 ppb** to **<6.4 ppm**

Regolith: **<70 ppm**

Subsurface breccia: **>46 ppm**

⇒ **Most water-rich pole**
Slight water from **surface** to **subsurface** in the **whole Moon**

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We will introduce our and previous studies of lunar water:

Surface to Subsurface

- **Water ice** near the **poles** and in the **subsurface**
- **Solar wind-induced OH** on the **regolith soil**
- **OH** in the **old anorthosite crust**

Shallow to Deep Mantle

- **OH** in the shallow to deep **mantle**
- **OH** and **H_2O** in the shallow **KREEP-rich mantle**
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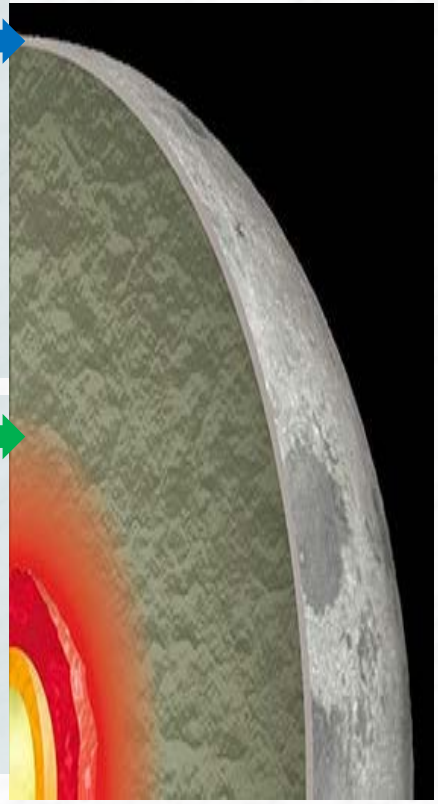
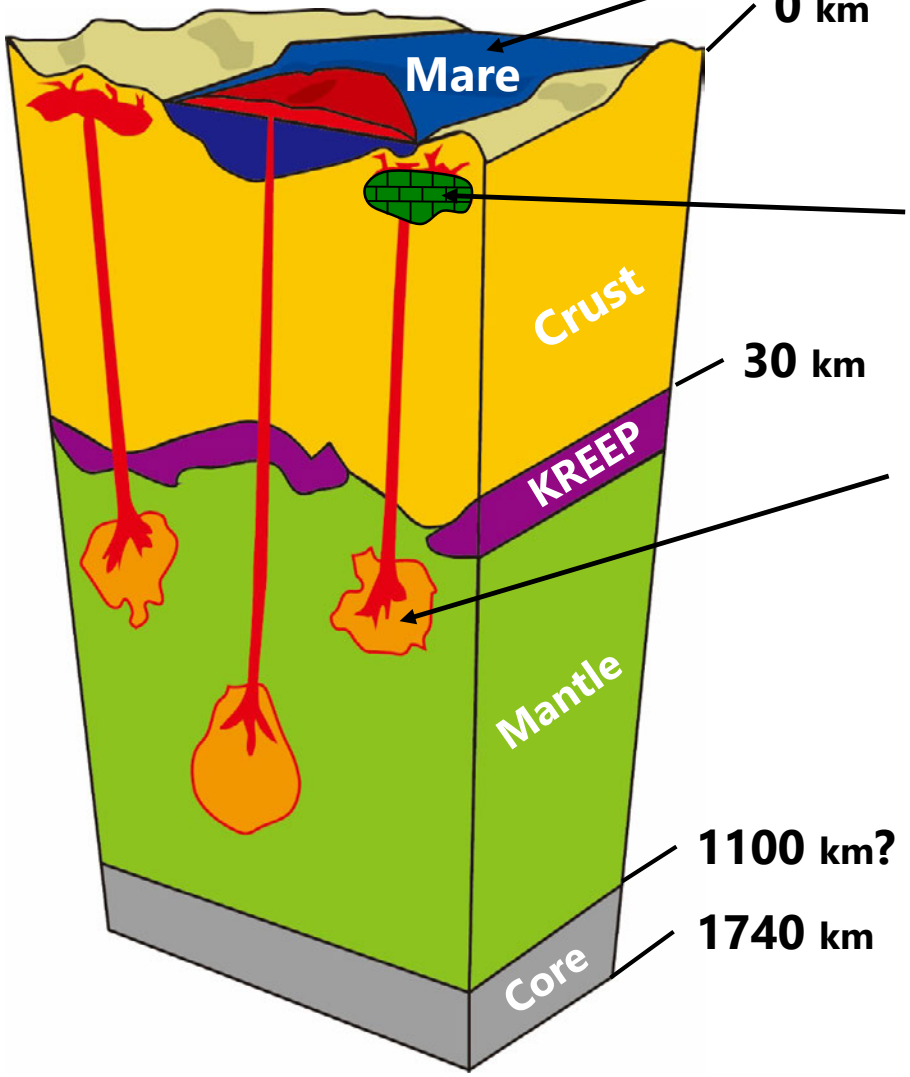


With a discussion of the Moon's history

With the future plans (Sample return, Seismic and Neutrino)

Traces of water in the mantle

Procellarum Basin



Mare Basin

- **Basaltic magma**
  Apatite, **Plagioclase**] **SIMS** & **FTIR** (+**EPMA**)

Magma chamber

- **Gabbro** (**Mg-suite**)
  Olv, Pyx, Plg → **SIMS** & **FTIR**

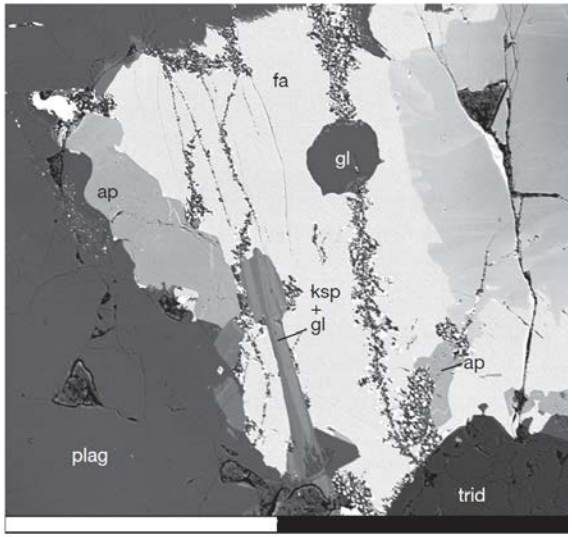
Partial Melting

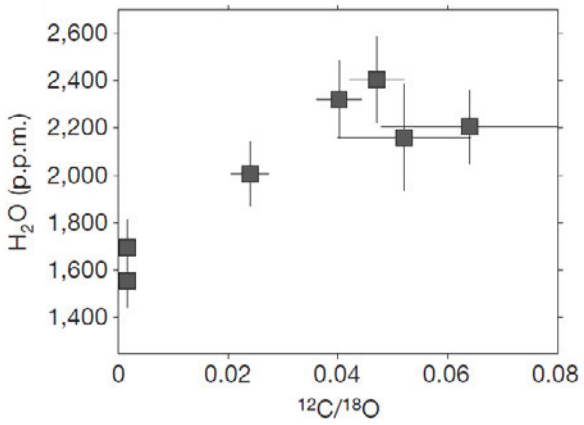
- **Melt**
  Melt inclusion (Olivine-hosted)
  → **SIMS** & **FTIR**

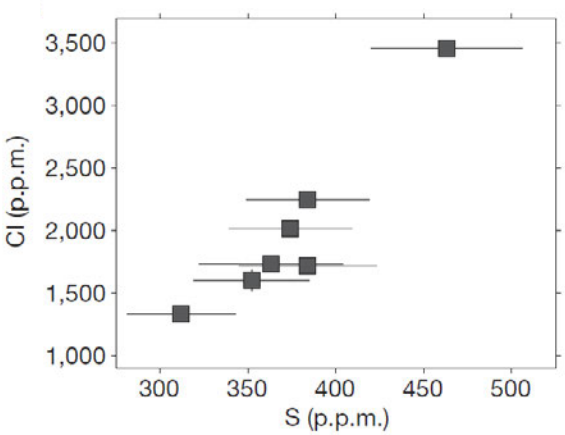
Water in the Mantle – Apollo samples –

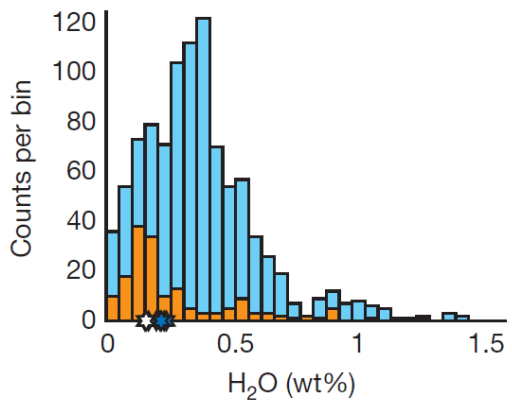
Lunar apatite with abundant volatilities

Boyce et al. (2010)









- **Apatite** in **KREEP-rich basalt**
- **No correlation** of **H** with **Cl-S**
- Assuming **partition coefficient**, **melting rate**, **NAMs %**, **degassing degree** of the **Earth**

➡ **Apatite**: up to **4000 ppm OH**

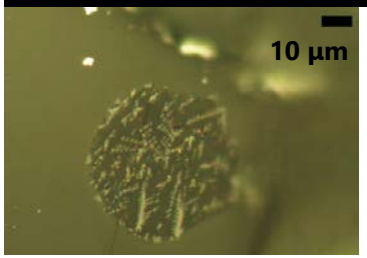
➡ **Mantle**: **6-30 ppm Water**

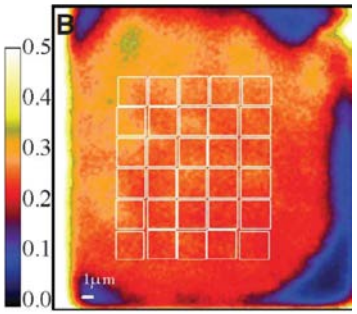
Water in the Mantle – Apollo samples –

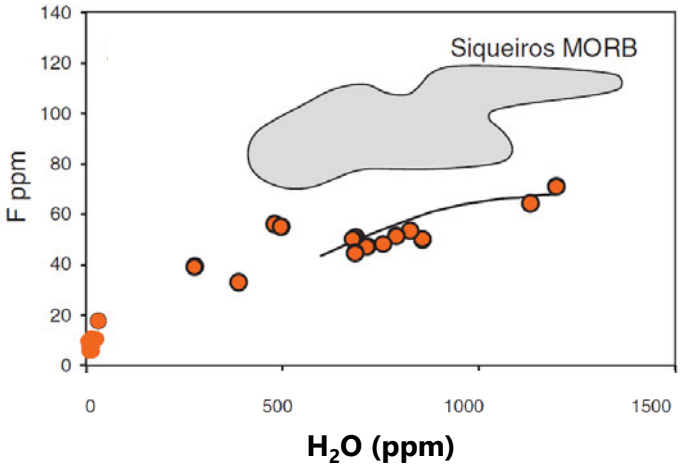
High Pre-Eruptive Water-rich Melt Inclusions

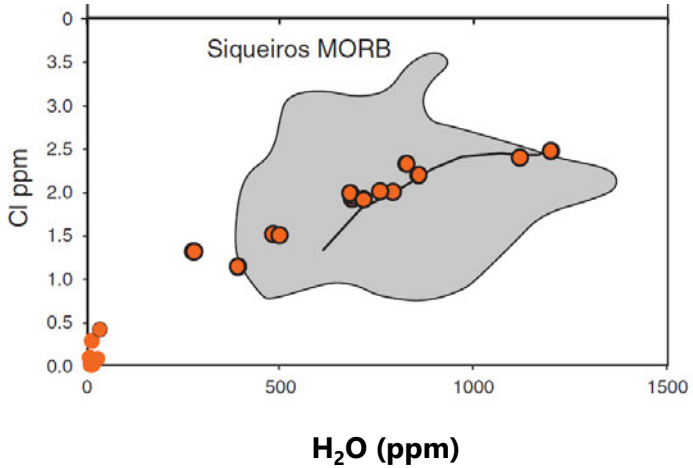
Hauri et al. (2011)

Melt inclusion in olivine of High-Ti volcanic glass bead









- **Olivine-hosted melt inclusions** without **magmatic degassing**
- **Abundant volatilities** (**H**, **F**, **S**, **Cl**) similar to **MORB**

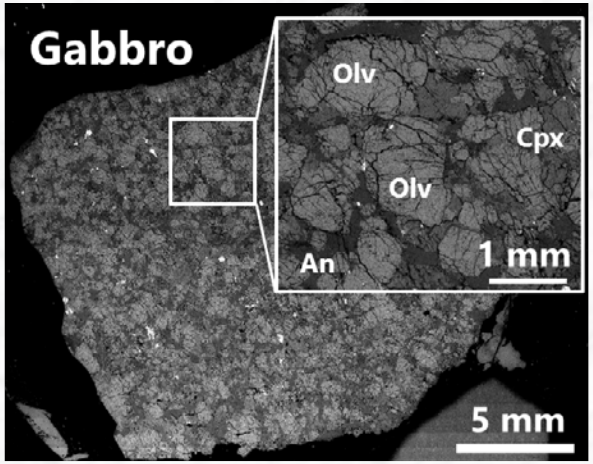
➡ **Mantle**: **79-409 ppm Water**

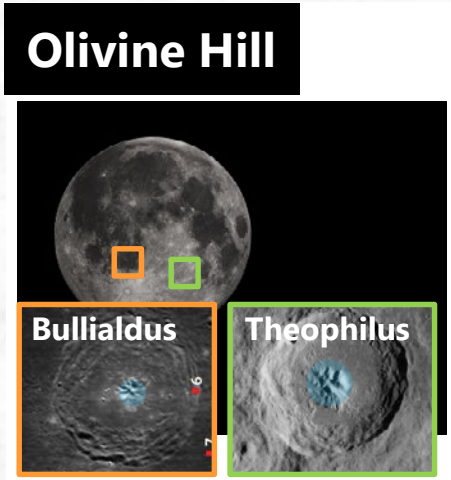
*Assuming **partition coefficient**, **melting rate** of the **Earth**

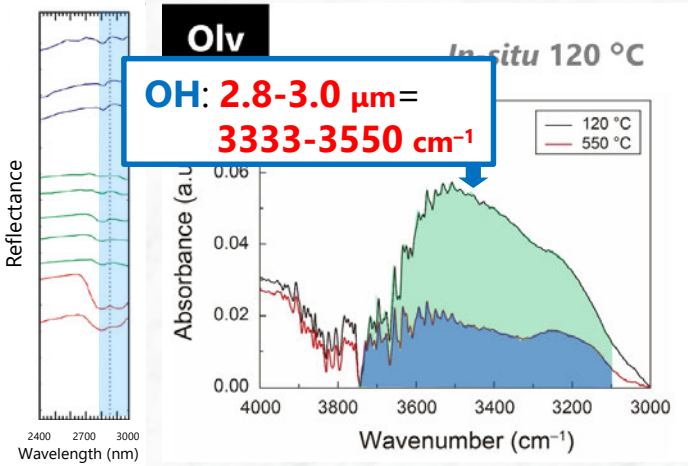
***Degassing degree**: **0 %** (**95-99 %** for Apatite)

Water in the Mantle – Lunar meteorite –

Water-rich gabbro and wet upper mantle beneath the PKT lunar meteorite (Kayama et al. in submitted)



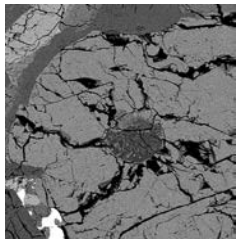




Mineral	Mode (vol.%)	Content (ppm)
Olivine	51.0	**238**
Clinopyroxene	41.1	**198**
Plagioclase	7.1	**85**
Others	0.8	**0**

Bulk content (ppm)

➡ **Mantle**: **>210 ± 88** ⇐ no assumptions

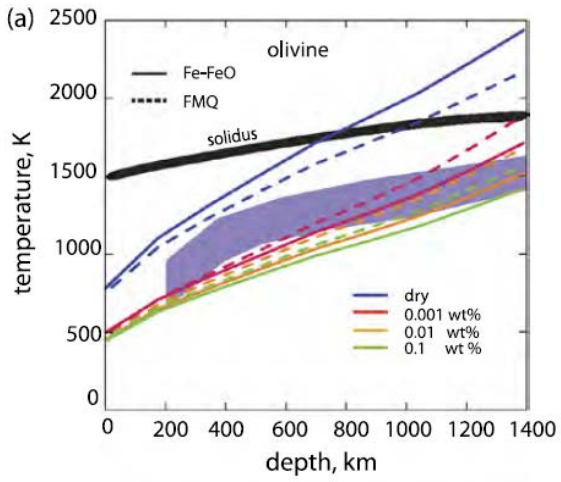


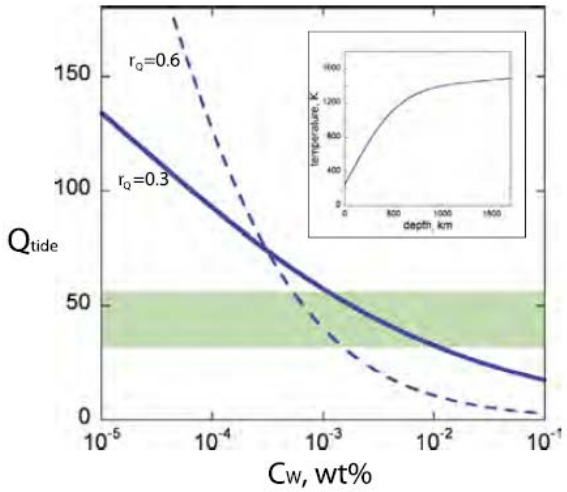
- **Melt inclusion**
- **Olivine**
- **Clinopyroxene**

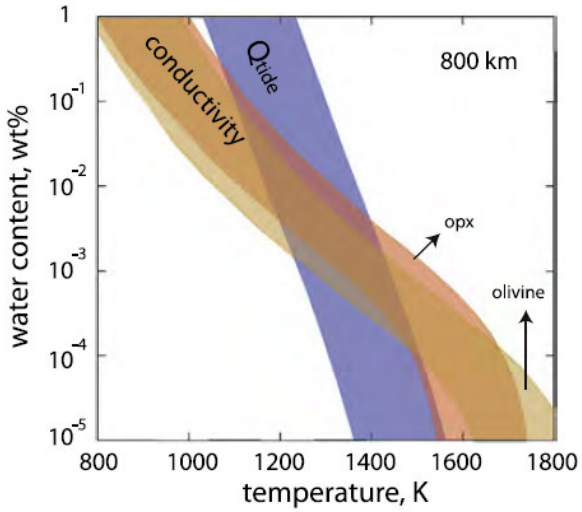
⇒ **SIMS analysis**

Wet Mantle

Geophysical constraints on water content of the mantle







- **Layered water distribution** of the **lunar magma ocean**
- **Water estimation** of the **Mantle** by **Electric conductivity** and **Tidal Q**

  ***Olv** & Opx, <4.5 GPa, Low/High f, r_Q=0.3-0.6

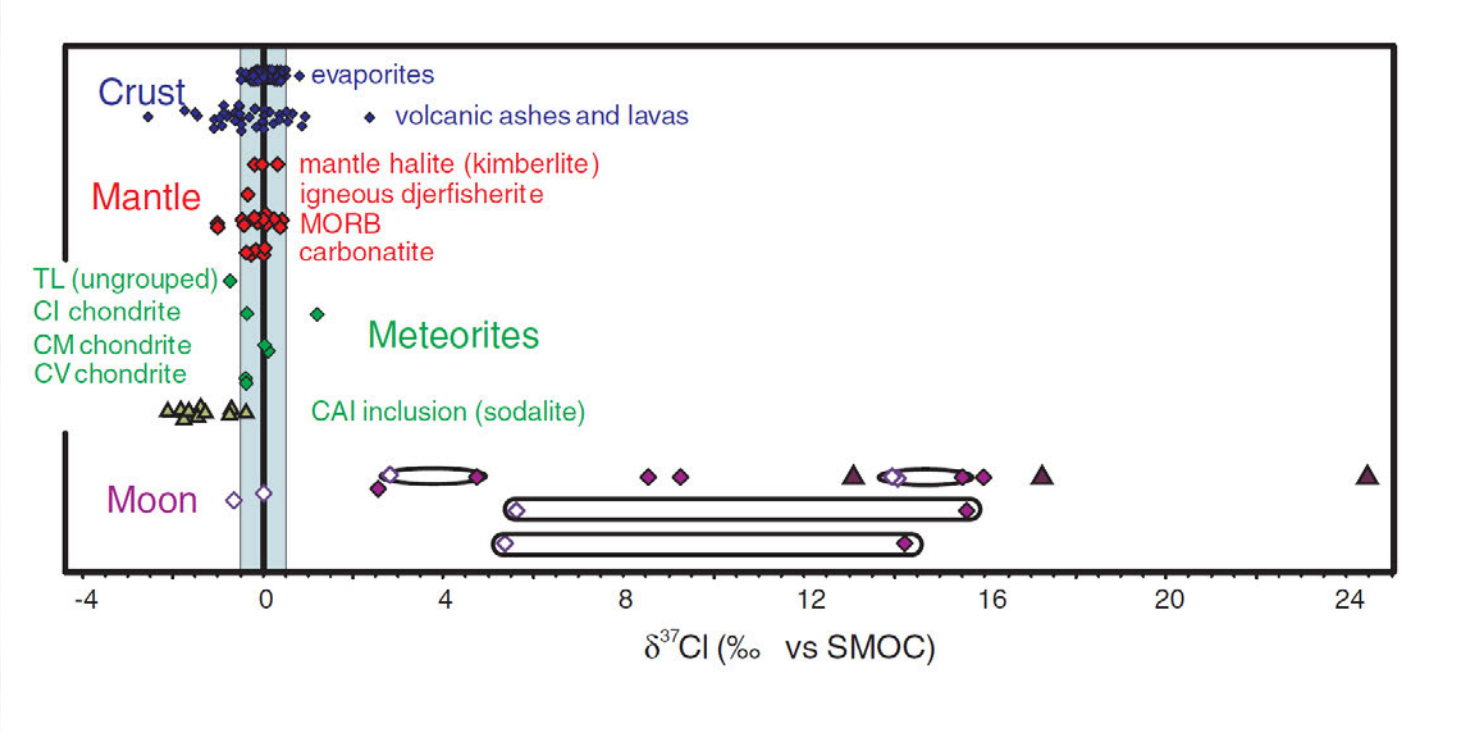
  ➡ **Water content** of the **Mantle**: **0.1-0.01 wt.%**

  ➡ **Quicker accretion** of the fragment than **cooling** after **Giant Impact**

Dry Mantle

Dry Mantle based on chlorine isotope

Sharp et al. (2010)



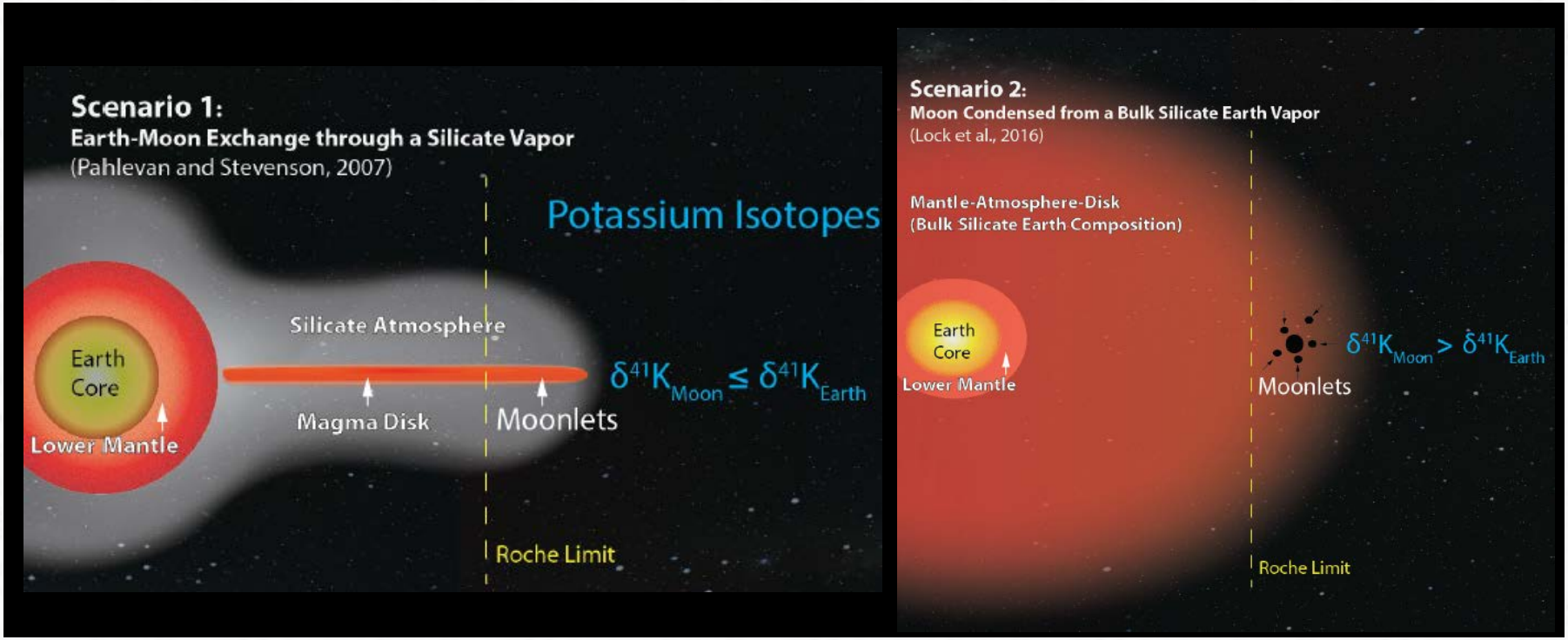
- **Chlorine isotope** of the **Apollo basalt**, **volcanic glass** and **apatite**
- **δ^{37}Cl** in **Lunar rocks**: **-1-+24 ‰** *in Earth's rocks: **0-1.6 ‰**
- Inferred **mantle water content**: **<10 ppb H**, based on **δ^{37}Cl**

➡ **Mostly Dry**, but **rarely Wet Mantle** view?

Dry Mantle

High energetic Giant Impact model

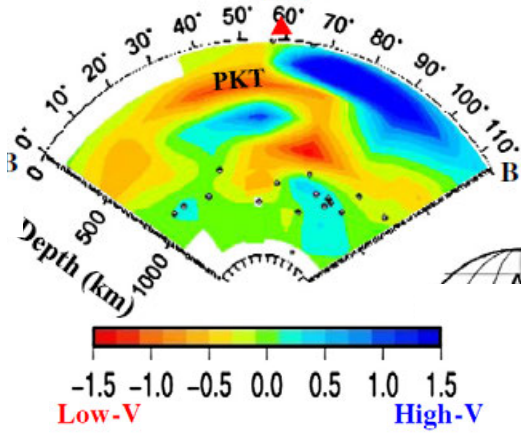
Wang and Jocobsen (2016)



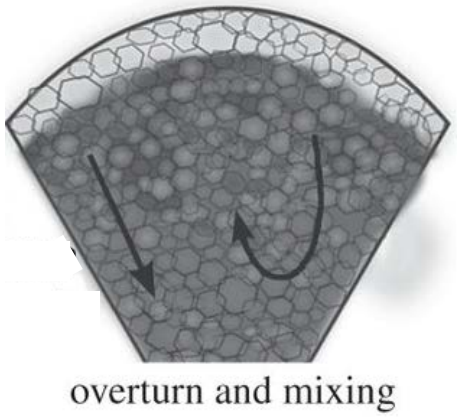
- **Water-heterogeneous** view of the **Mantle**, but…
- **Overall Wet**? (**11-409 ppm**) or **Dry**? (**<1-10 ppb**)
- **Close relationship** with the **Giant Impact model** !!

In the future plan

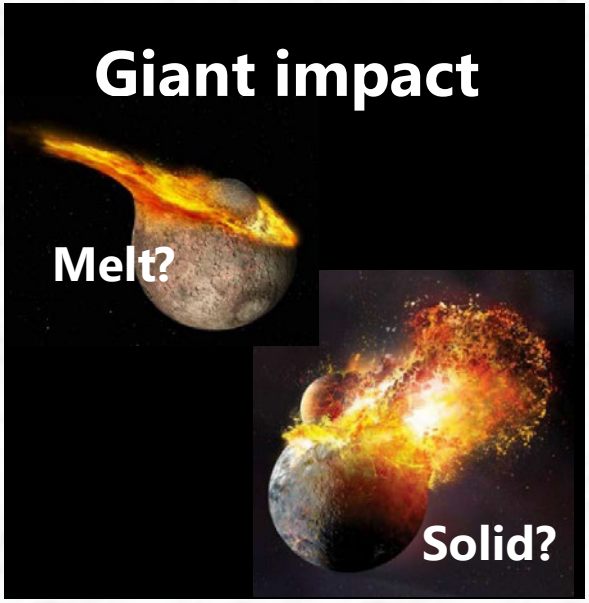
Seismic tomography



Mantle overturn

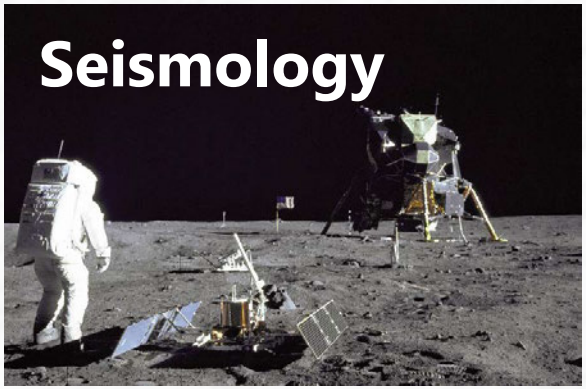


Giant impact

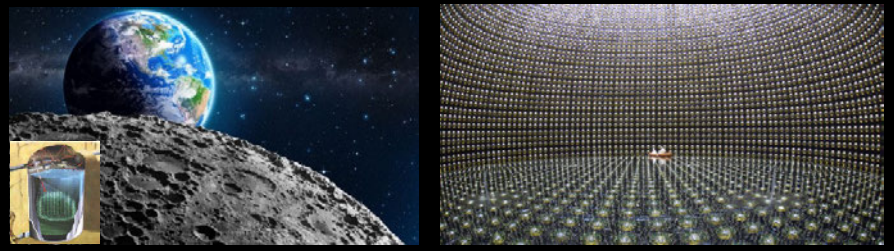


Interpreted by a comparison of **water distribution** of the **Moon's** with **thermal gradient**

Seismology



Neutrino Geophysics




Thank you for your attention !!