Magmatic Degassing and the Volatile Budget of the Moon

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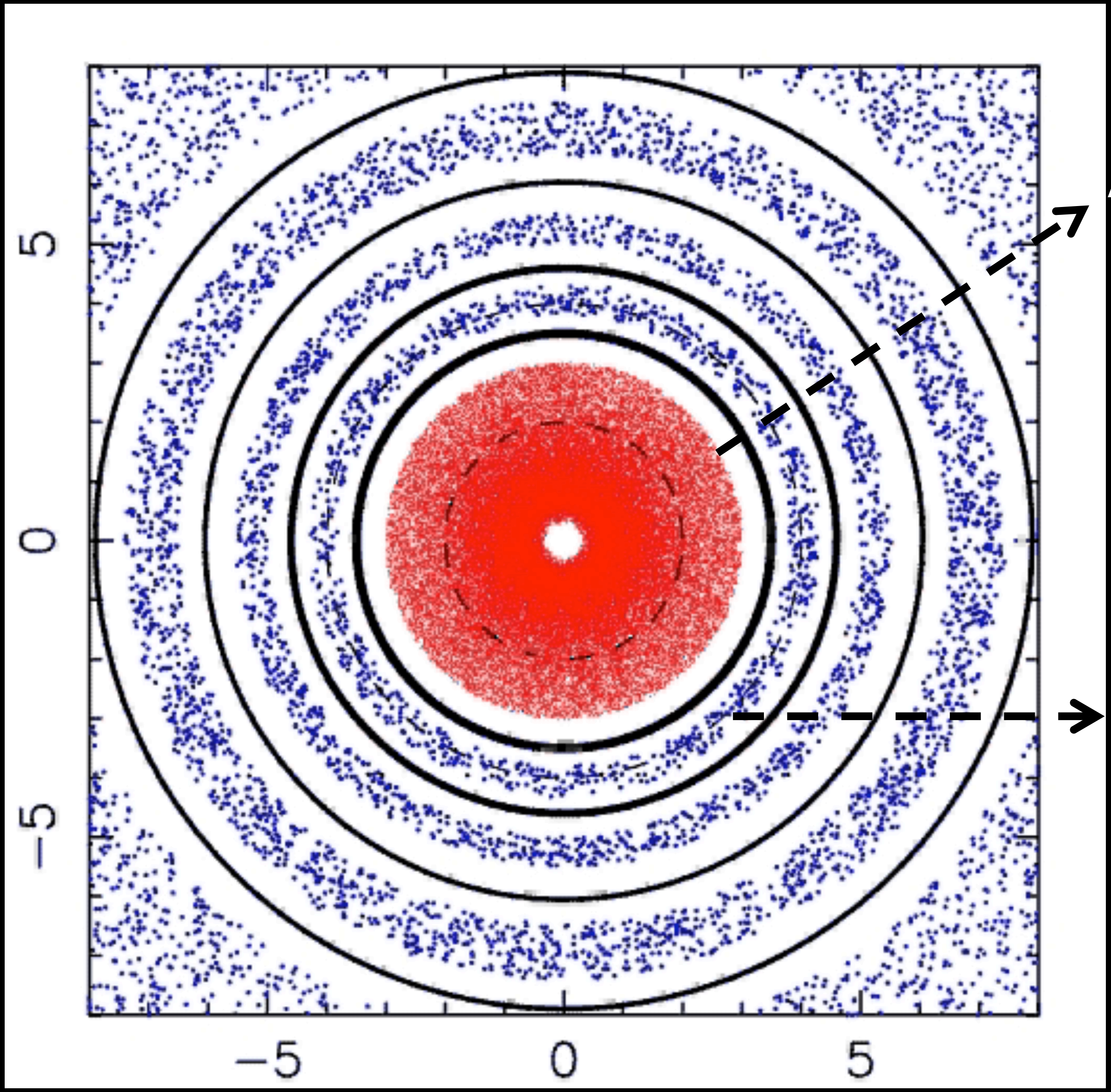
Outline

- Motivation
- Rational for studying the Moon and volatiles
- The “consensus” on the Moon’s Volatile Budget
- Our results and explanation
- Conclusions

The Snow Line (150-175 ^{o}K)



Asteroids type S

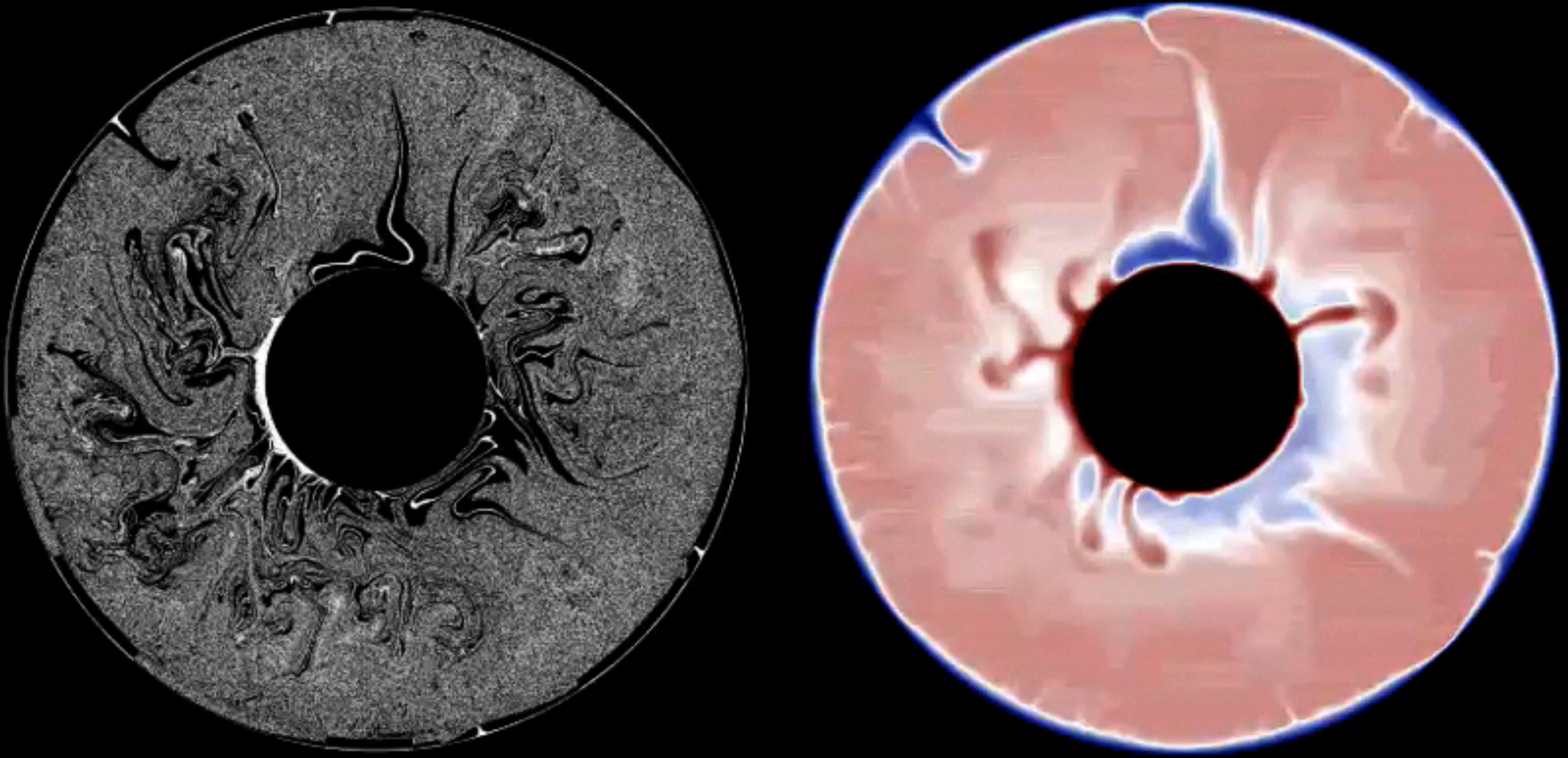
Asteroids type C

Walsh et al., (2011)

But we know the Earth has water

when, how and from where volatiles came to the Earth-Moon system?

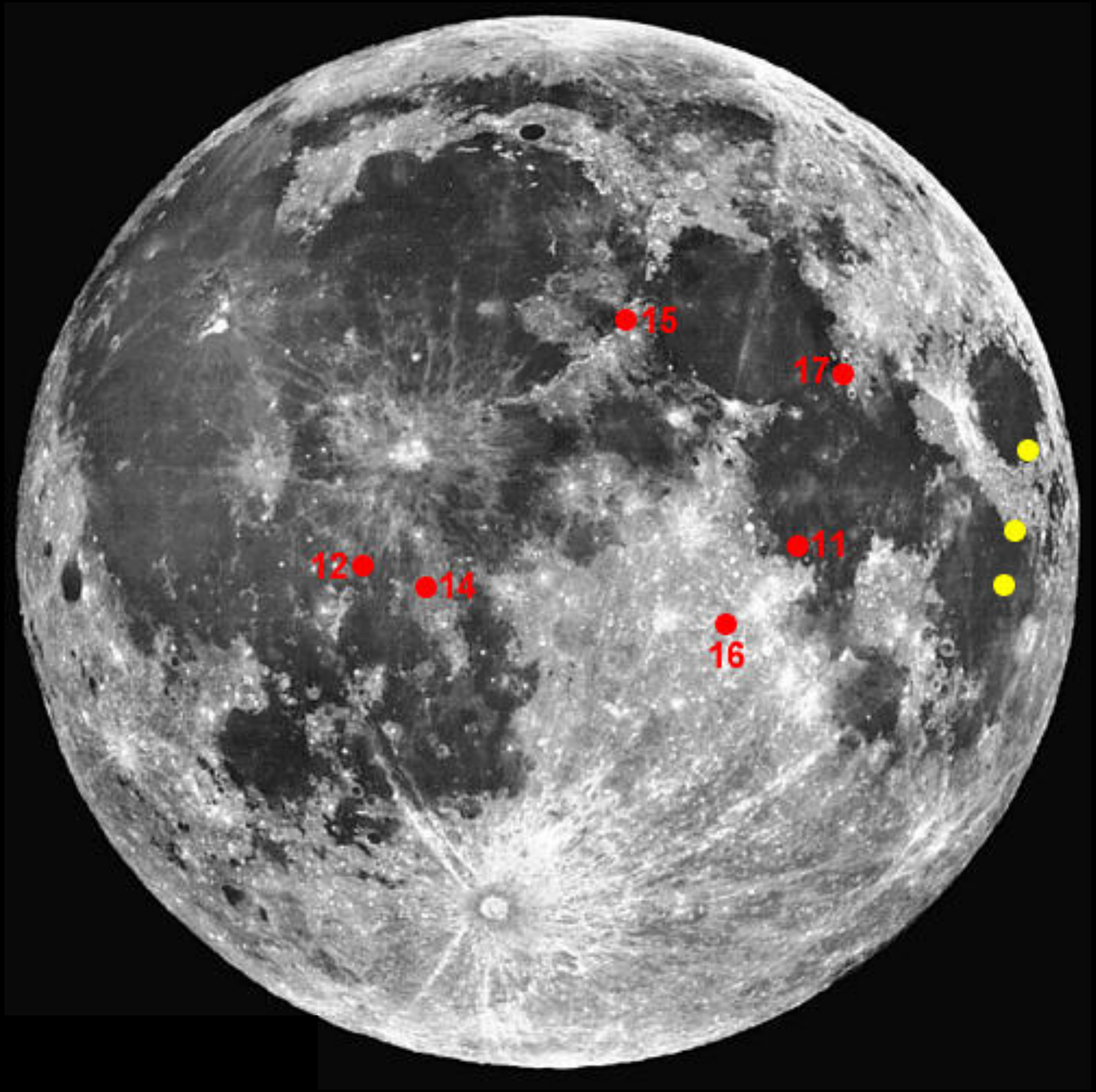
The Dynamic Earth



Cannot provide the answer

Peter van Keken

Why to study the Moon?



The Moon provides a frozen record of the first 200 Ma of Solar System formation.

Why is it important to determine the volatile (H-C) contents of planets?

1) Provides information on the conditions of planet formation.
2) Affects the dynamics of planetary interiors (modifying the mantle and melts viscosities, influencing core segregation and longevity).
3) Decreases the melting point of solids.
4) Affects the mechanism of lava eruption.
5) It is fundamental for the origin of life.

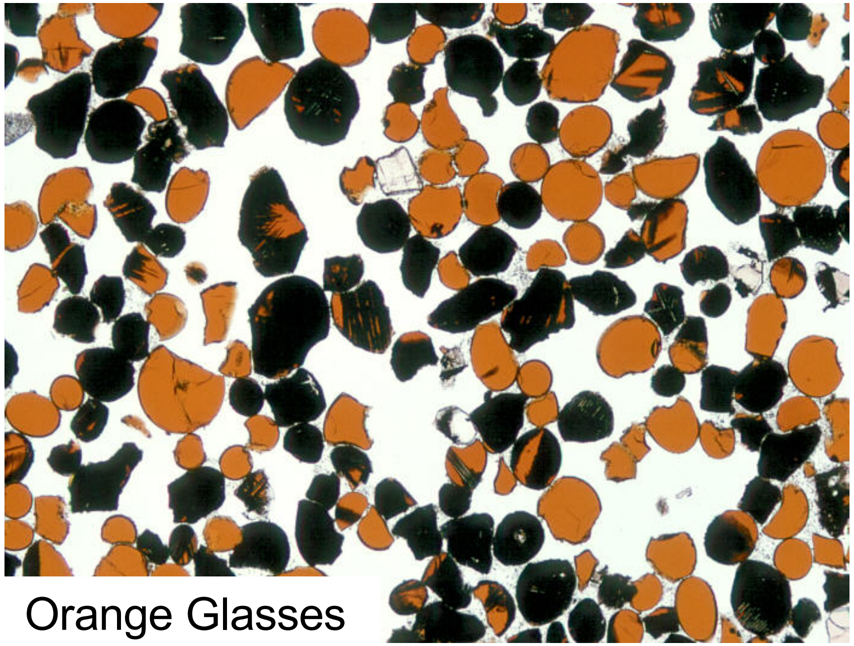
An indirect approach:

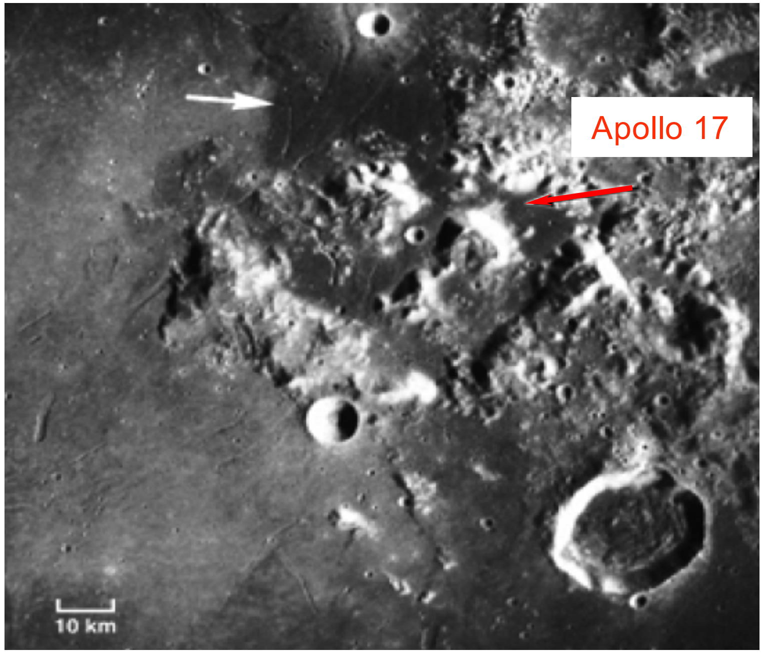
the chemistry of mantle melts

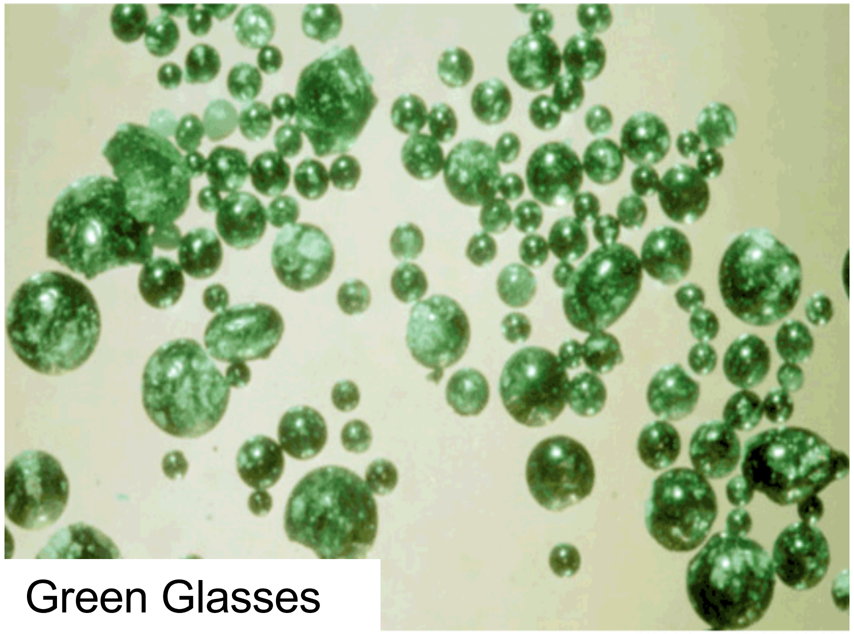
Eruption of Kilauea 1959

Volcanic Glasses

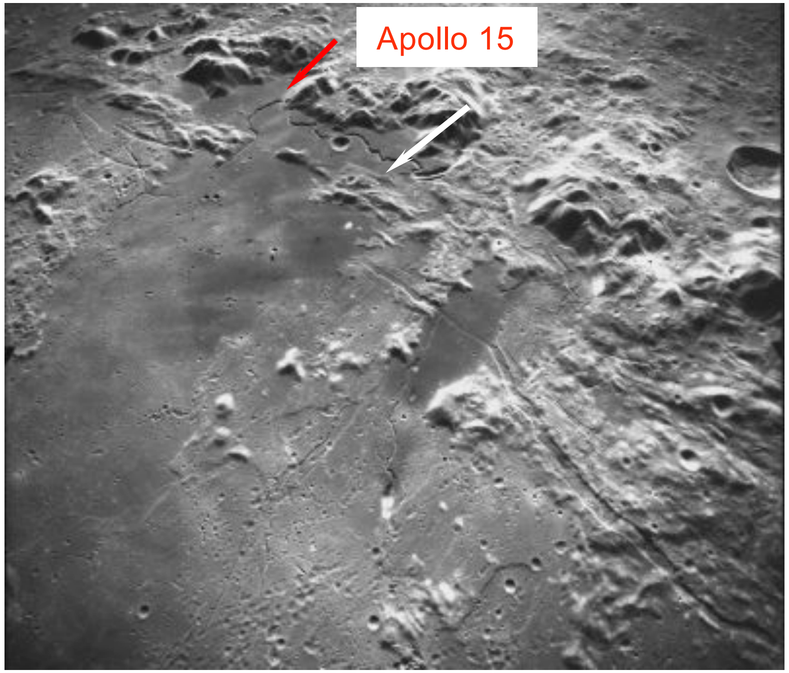
Dark Mantle Deposits


Orange Glasses

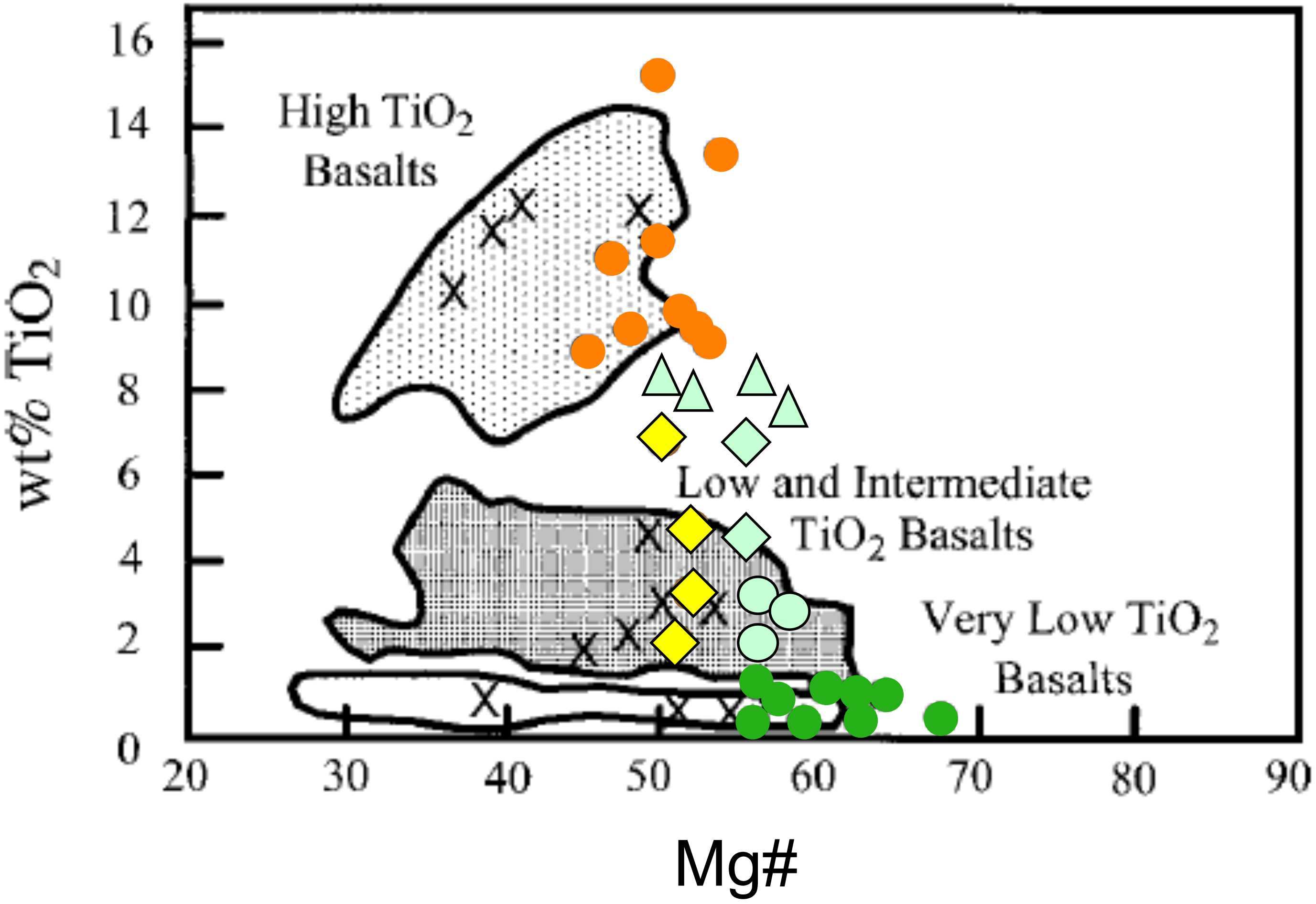



Green Glasses

(NASA Apollo 15, S79-32188.)



The primitive composition of the lunar volcanic glasses



Shearer et al., 2006

(Delano, 1980; 1986; Shearer and Papike, 1993; 1999; Shearer et al., 2006)

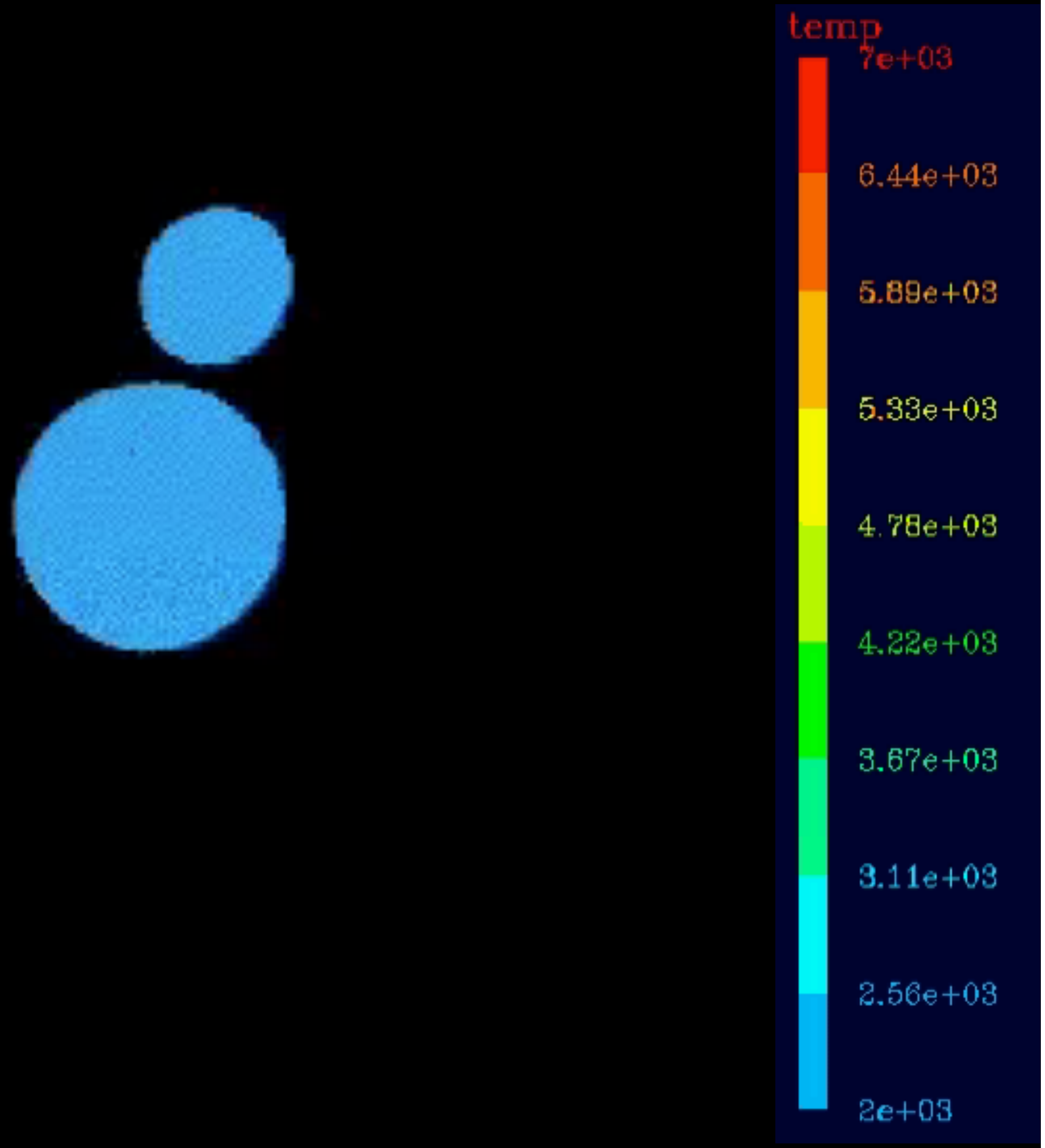
Previous studies on the volatile contents of lunar samples

1) The hydrogen was produced by implantation of solar wind on the surface of the samples.
2) The measured molecular H_2O probably represented terrestrial contamination.
3) The conclusion was that the Moon was “bone dry”

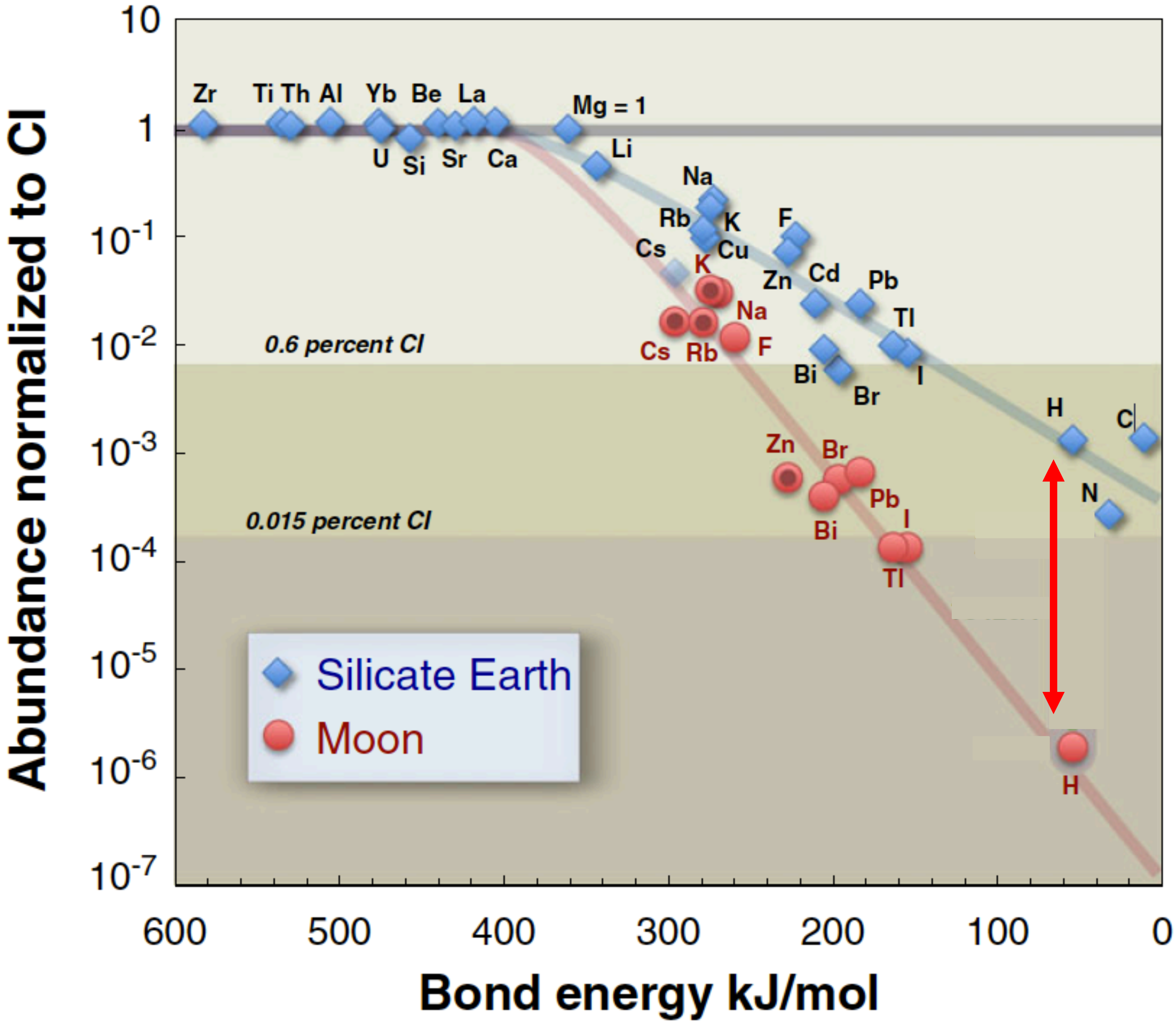
Epstein and Taylor, 1973 and reference therein

For ~ 40 years the evidence for the presence of H_2O in the Moon interior remained elusive. Consistent with the general consensus that the Moon was “bone dry” due to its origin by a Giant impact between the Earth and a Mars-size planet ~ 4.5 Ga.

Simulation of a collision between the Earth and a planet of Mars size (Canup 2004)



The Consensus



Moon volatile depletion
1000 time that of Earth

Albarede et al., 2014

Our work

1.- A little bit of the Analytical Techniques

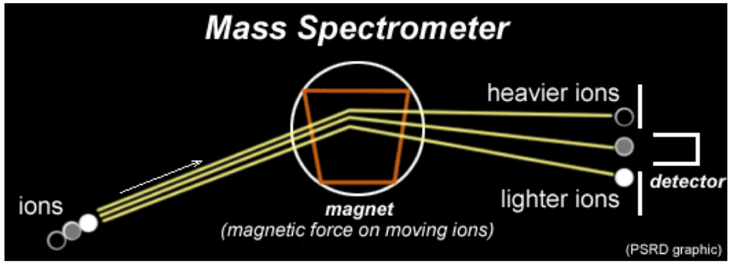
2.- Present the first unequivocal evidence for indigenous lunar water carbon content and confirmation of F, Cl and S in volcanic glasses and melt inclusions.

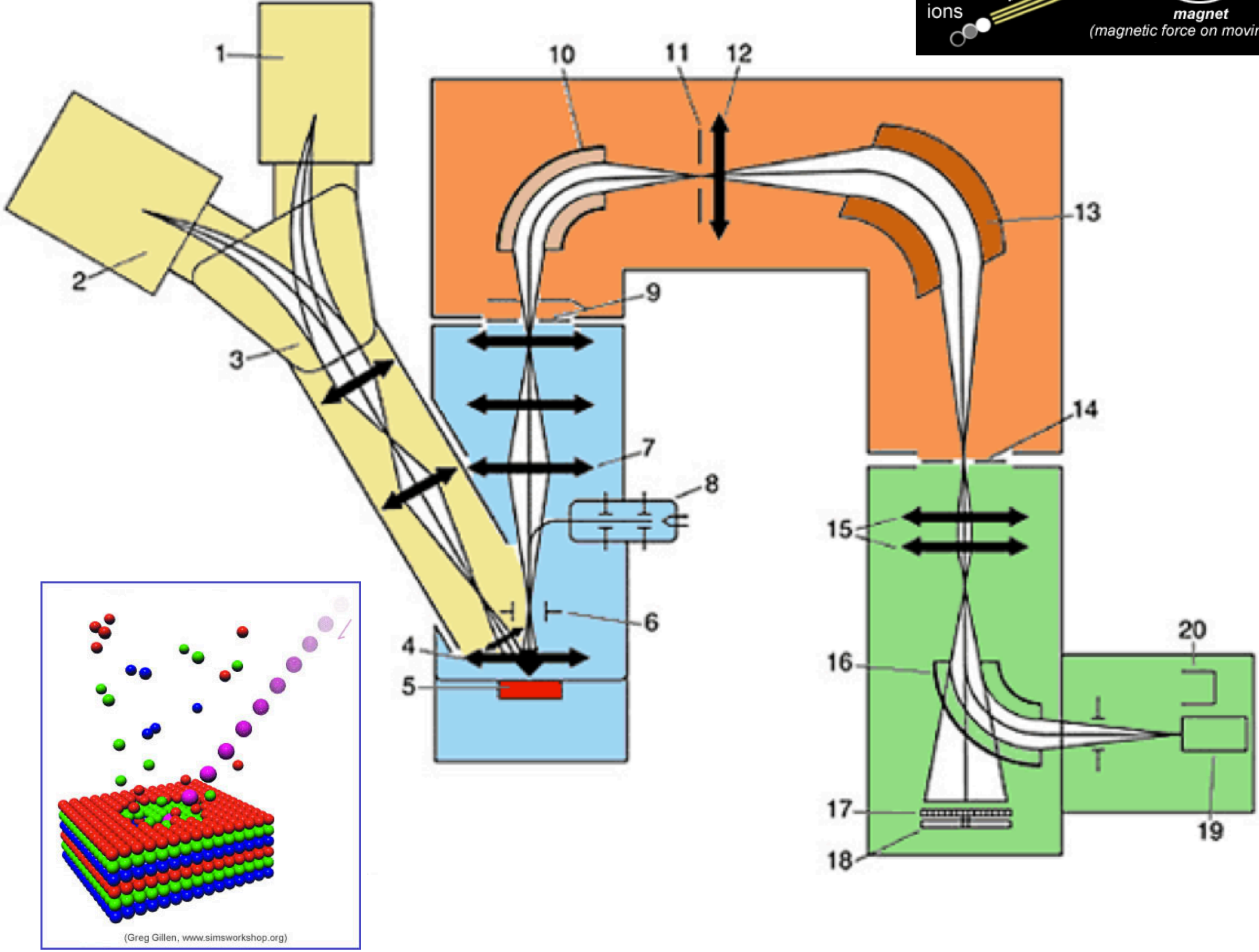
3.- Our Moon volatile budget

4.- Reasons for the discrepancy between our and the consensus Moon’s volatile budget.

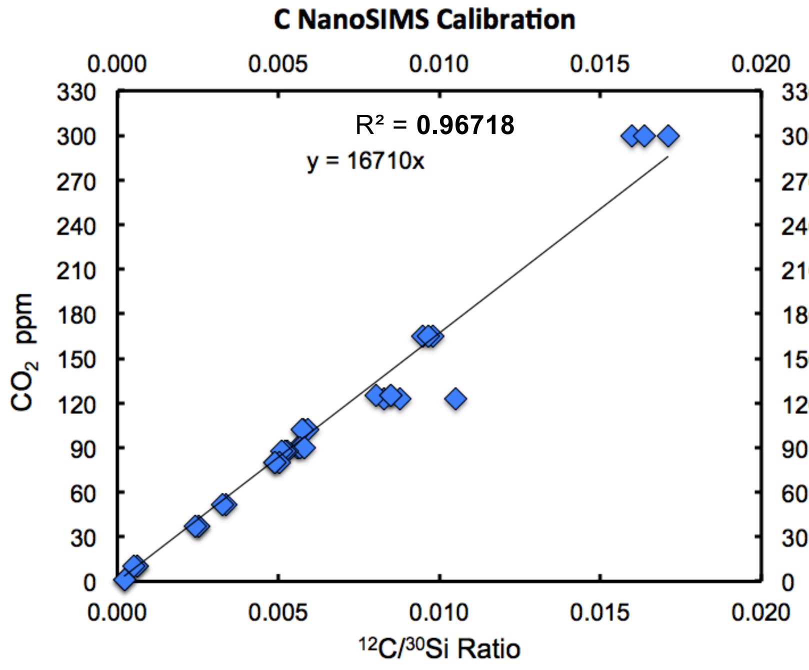
5.- From where, how and when the volatile budge were set in the Earth-Moon system

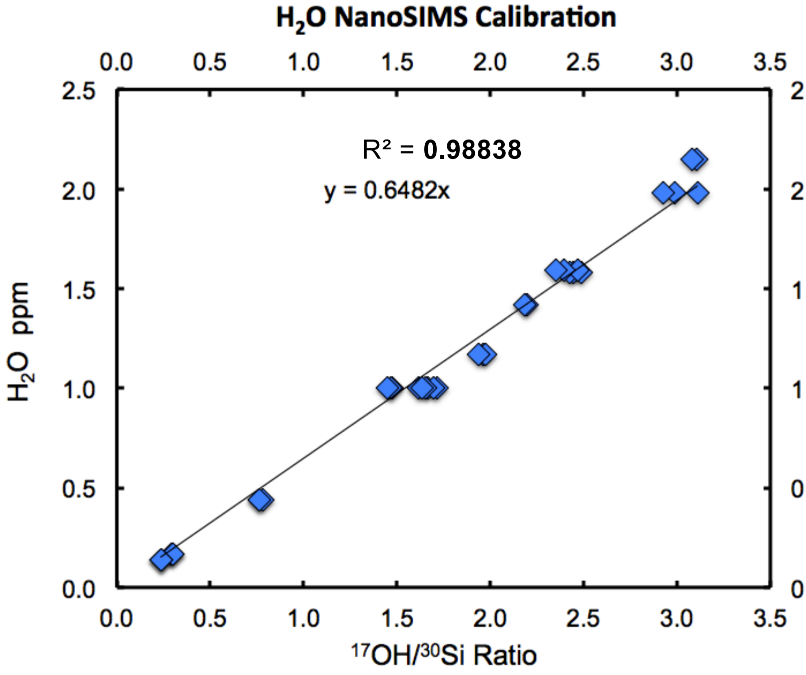
The new SIMS (Secondary Ion Mass Spectrometer)





(Greg Gillen, www.simsworkshop.org)





SIMS data at DTM

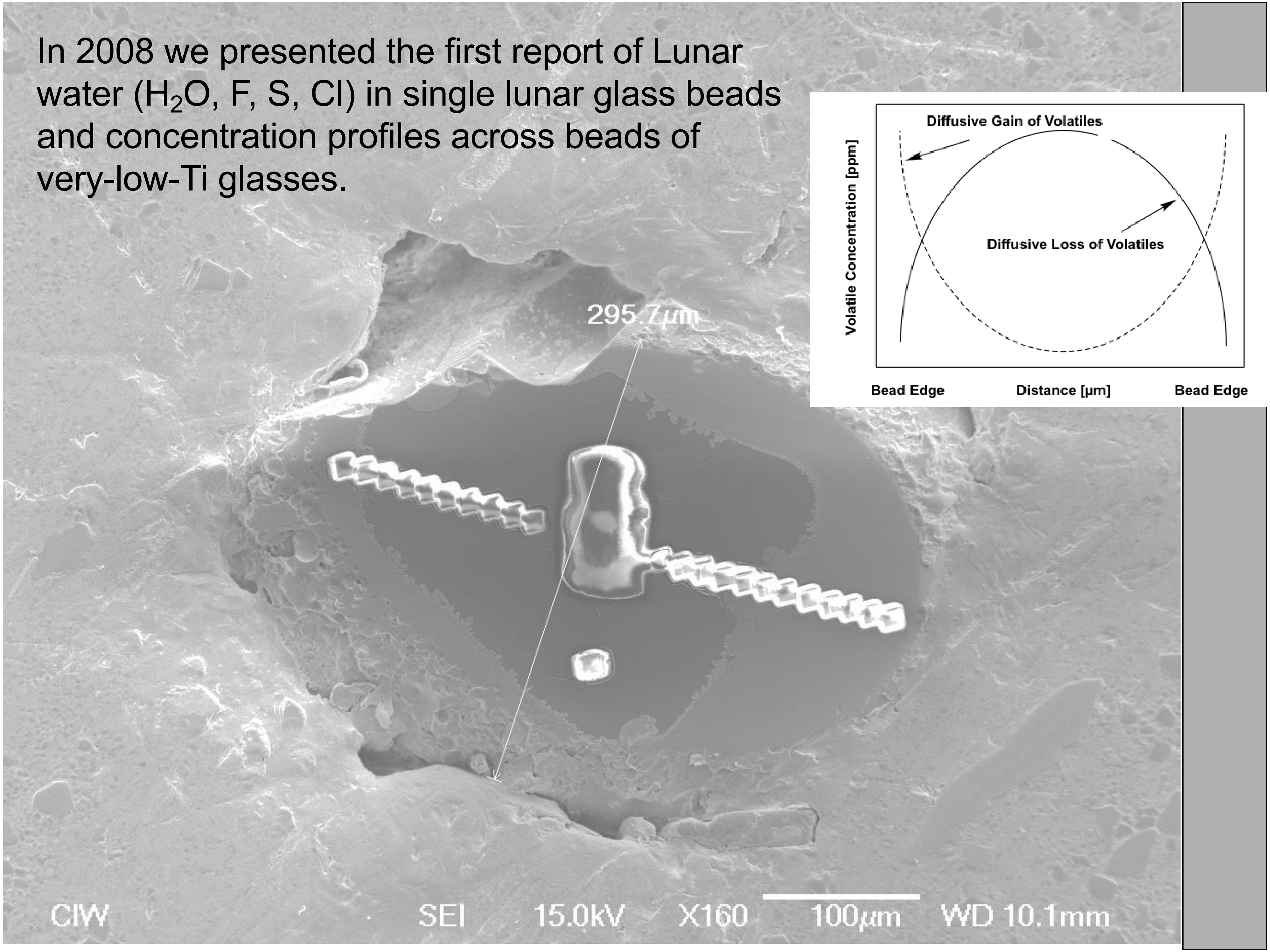
NanoSims : Cs+ beam
3.7µ of 10 µ or 11µ of 30µ
Pre-sputter time 6 min

Detection Limits: C 0.068 ppm and H2O 0.99 ppm; F 0.046 ppm; S 0.064; Cl 0.08 ppm

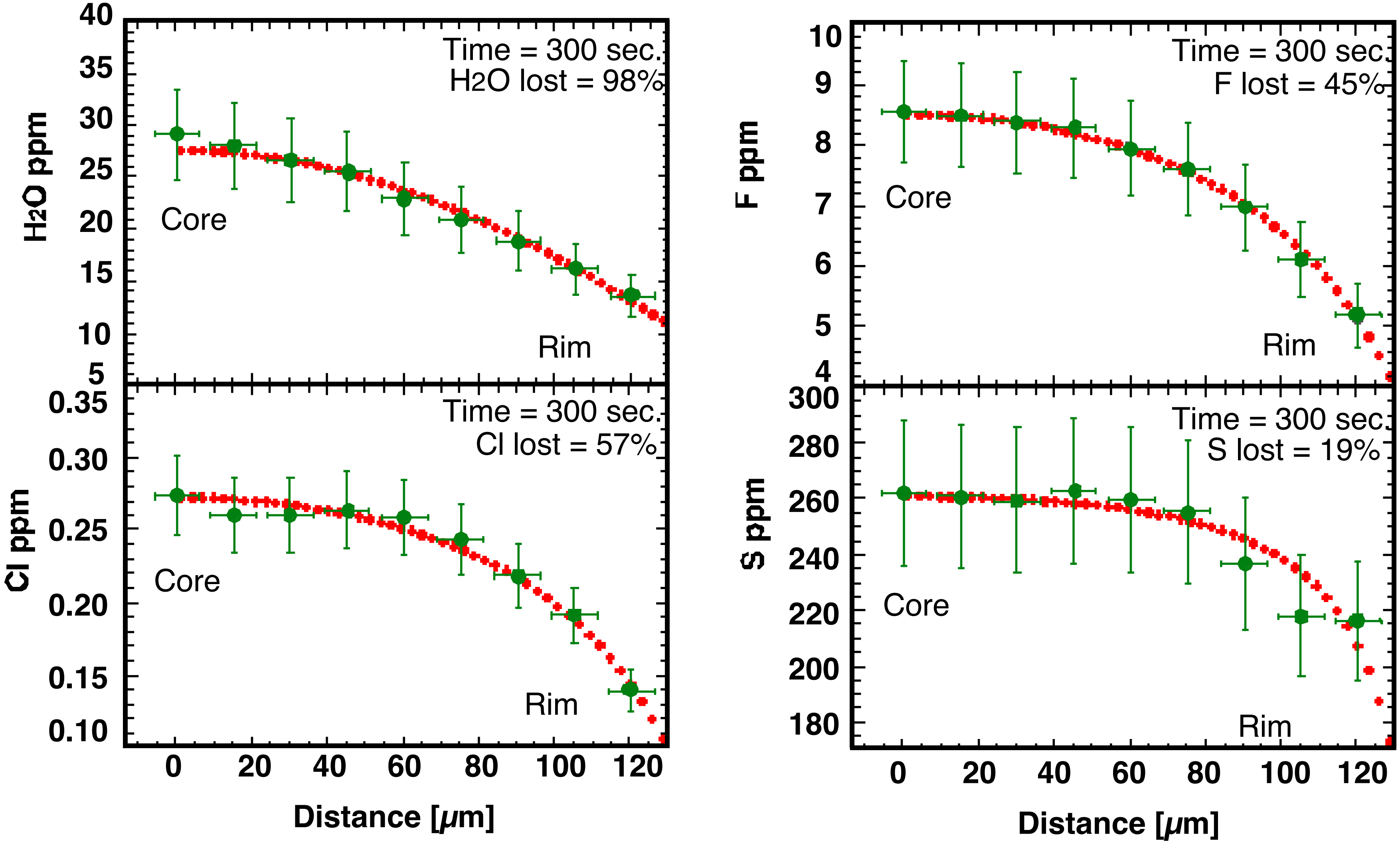
Combined accuracy and reproducibility is 17% for C, 9.3% for H_2O, 13% for F, 6.4% for S, and 29% for Cl.

Hauri et al., unpublished; 2002; 2006; 2011
Koga et al., 2003; Aubaud et al., 2004

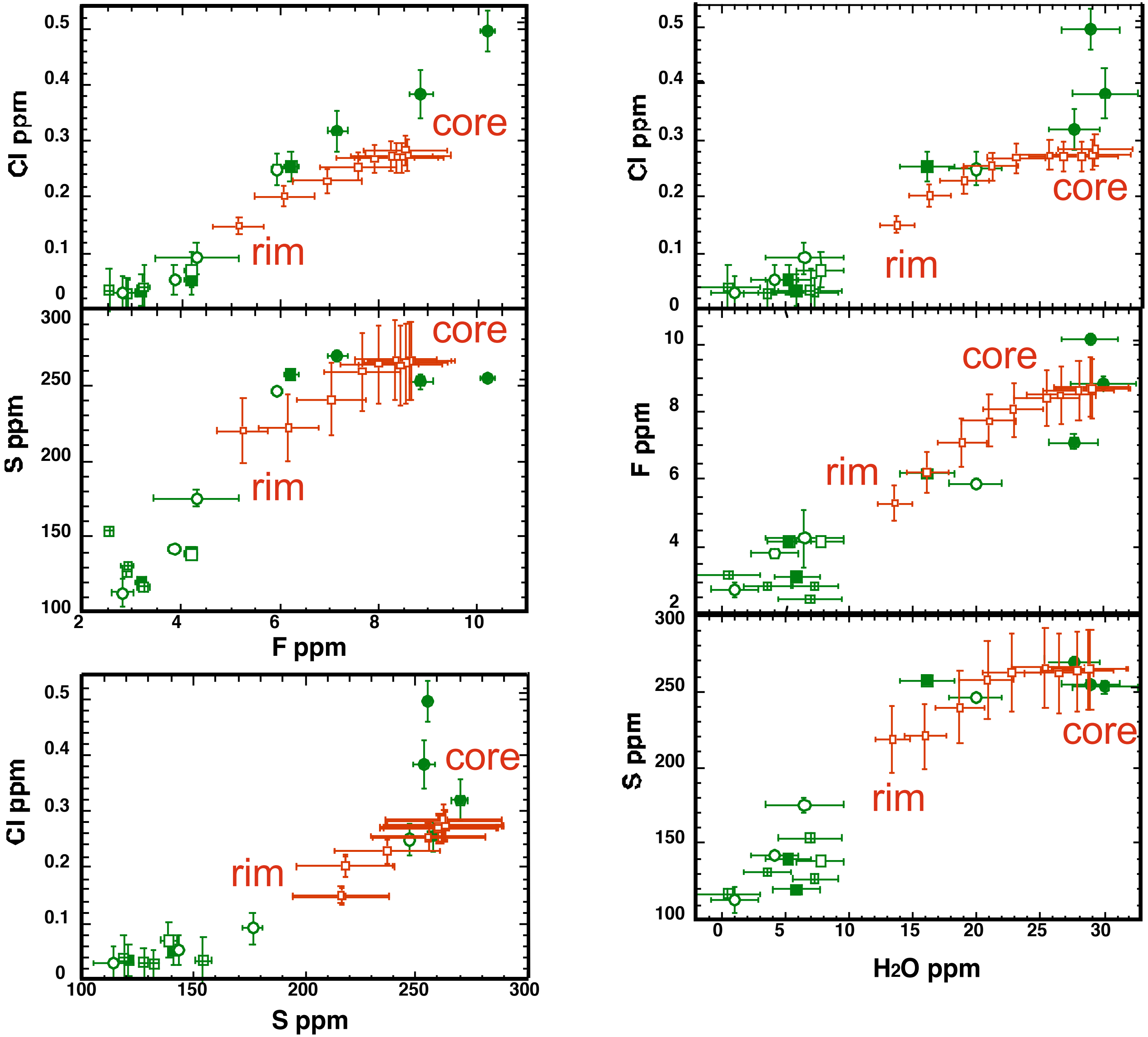
In 2008 we presented the first report of Lunar water (H_2O, F, S, Cl) in single lunar glass beads and concentration profiles across beads of very-low-Ti glasses.



Degassing models with cooling rates of 2°C/sec and 300 sec until the bead is quenched, suggest that the initial water concentration was ~ 750 ppm, with a minimum of 260 ppm at the 95% confidence level.



Concentration profiles in a single bead reproduced the trends defined by all the glasses suggesting the volatile variation is due to degassing processes.



two issues were raised:

what is the primitive (pre-degassing) volatile contents of lunar magmas?

(How much water was in the primitive magmas?)

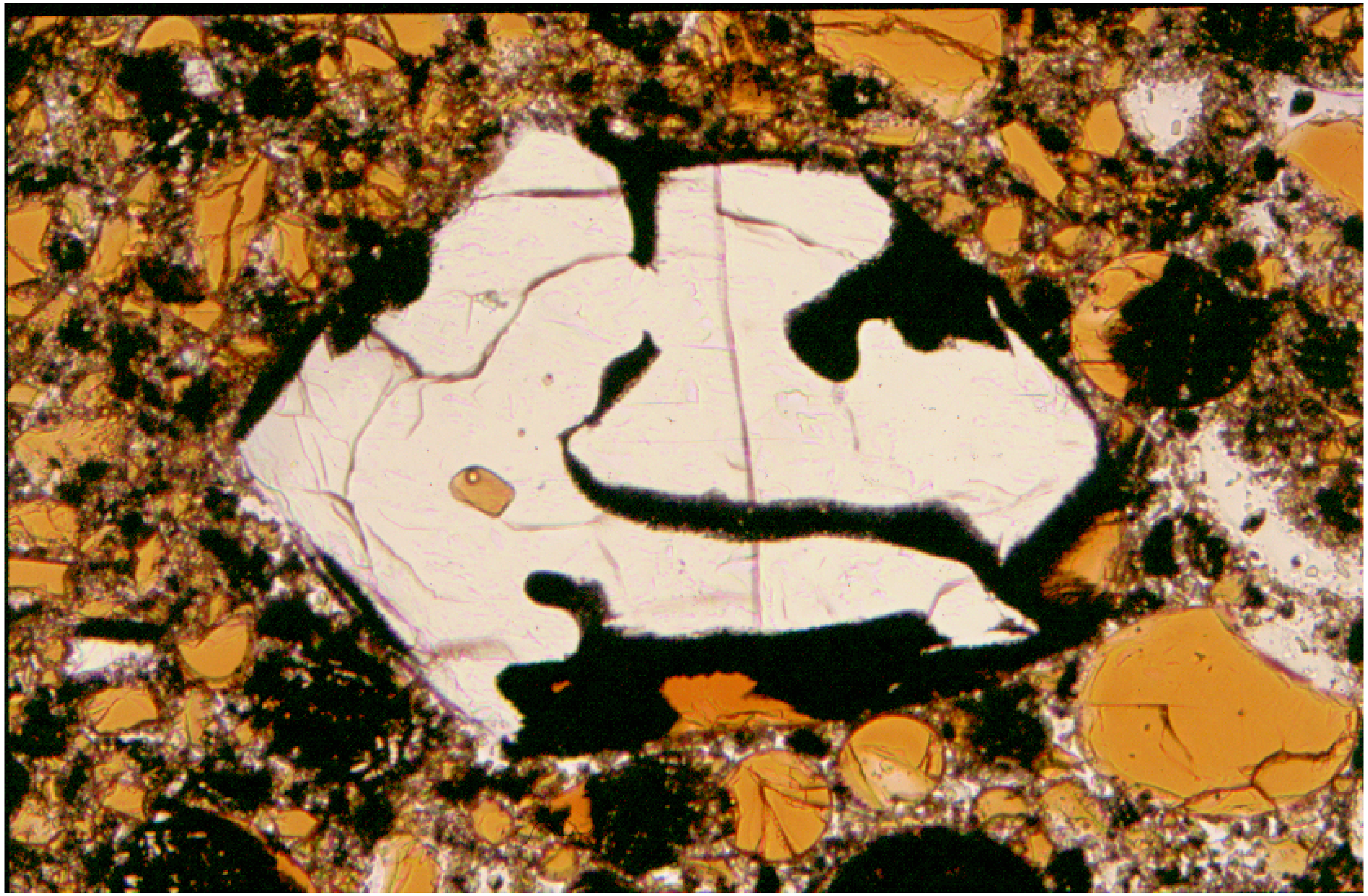
The surface pressure prevailing during eruption of lunar magmas is on the order of 10^{-10} *to* 10^{-15} *bars, ~ one-trillionth the pressure prevailing on Earth's surface (Stern,1999)*

What is the distribution of the volatiles within the Moon (reservoirs)

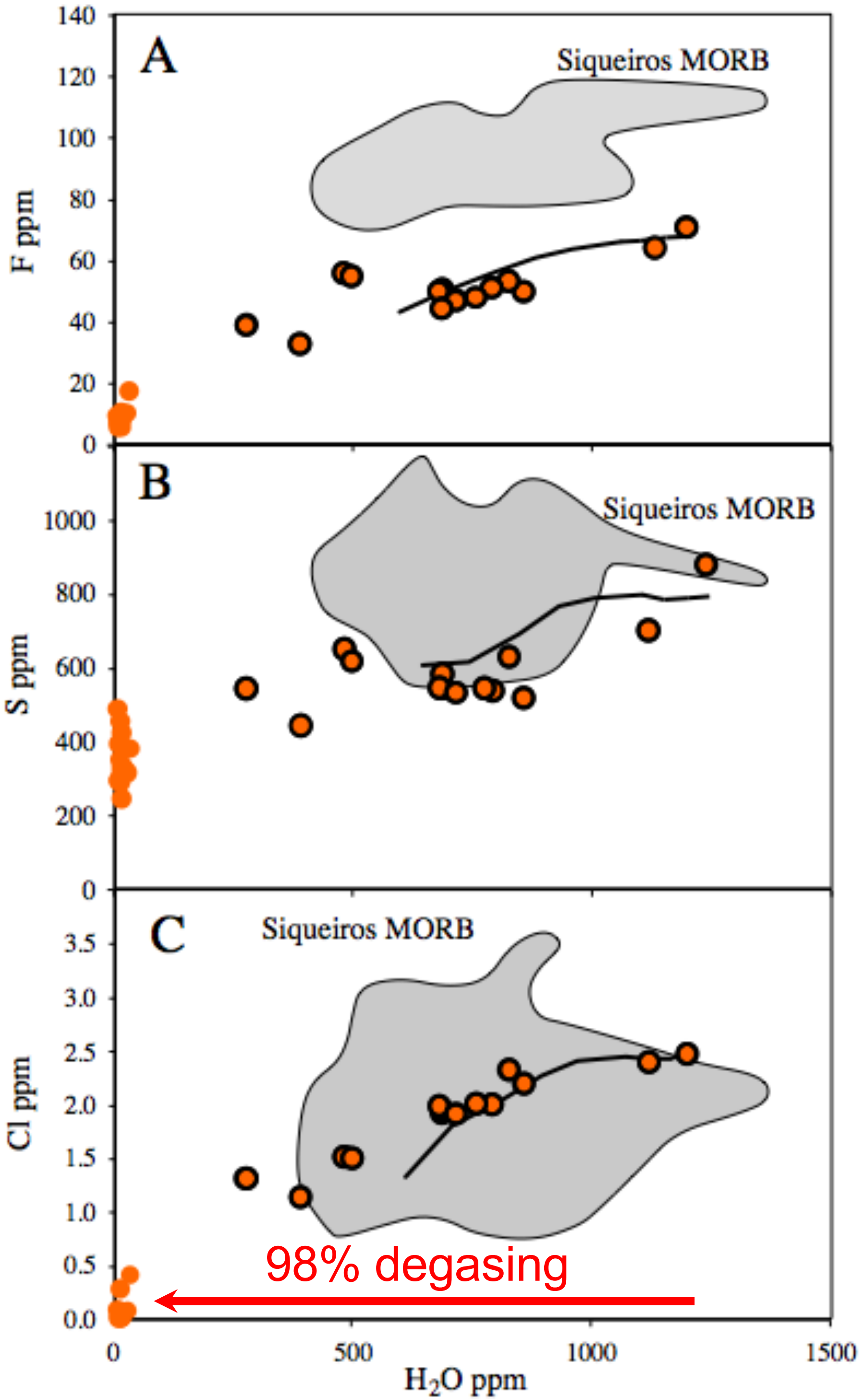
(How representative is our estimation?)

To determine the primitive (pre-degassing) volatile contents

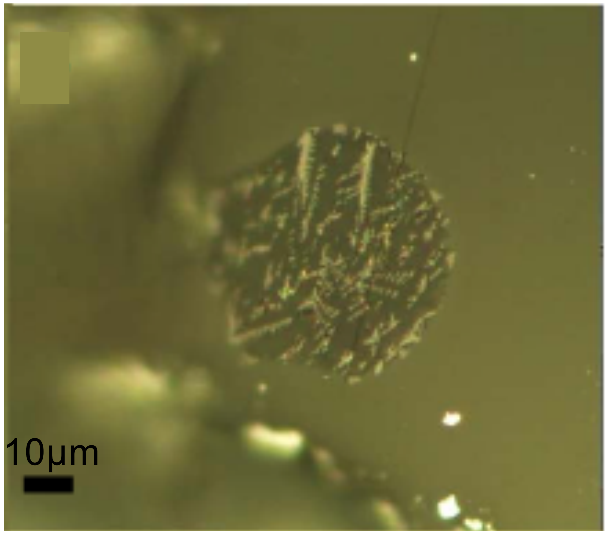
We used melt inclusions



Weitz et al 1999

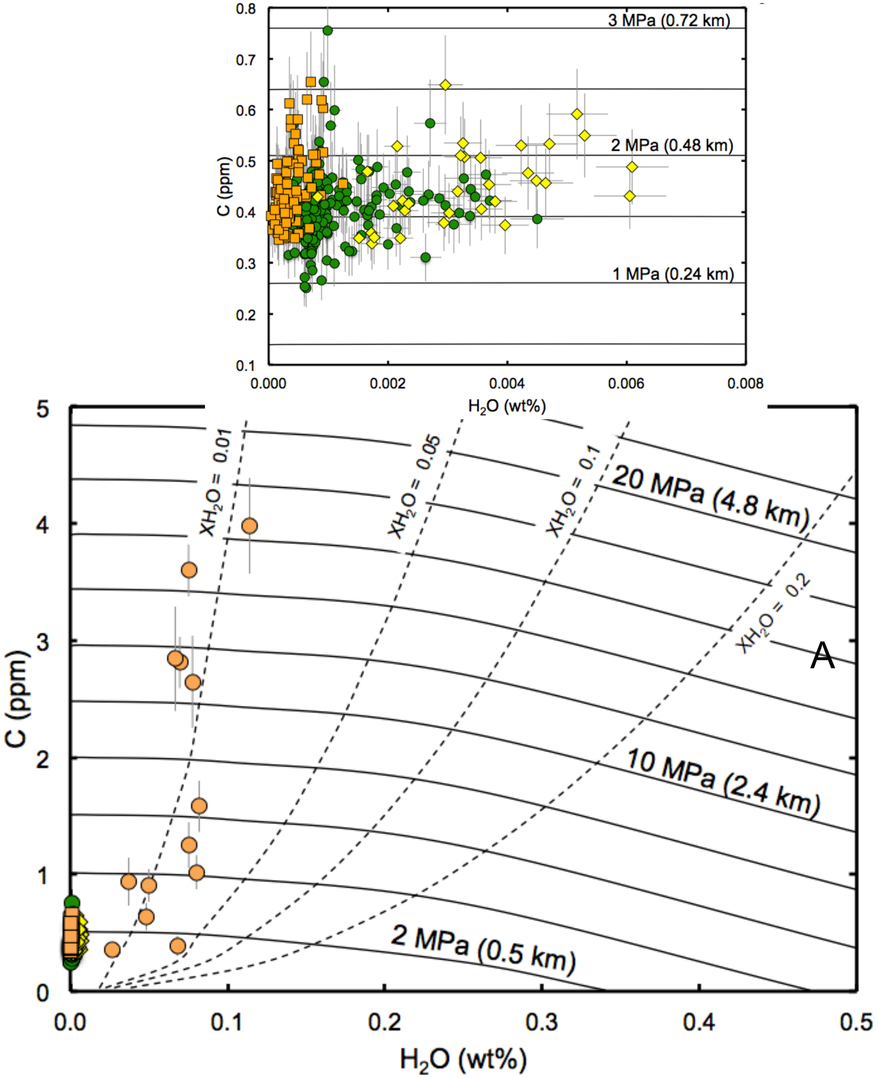


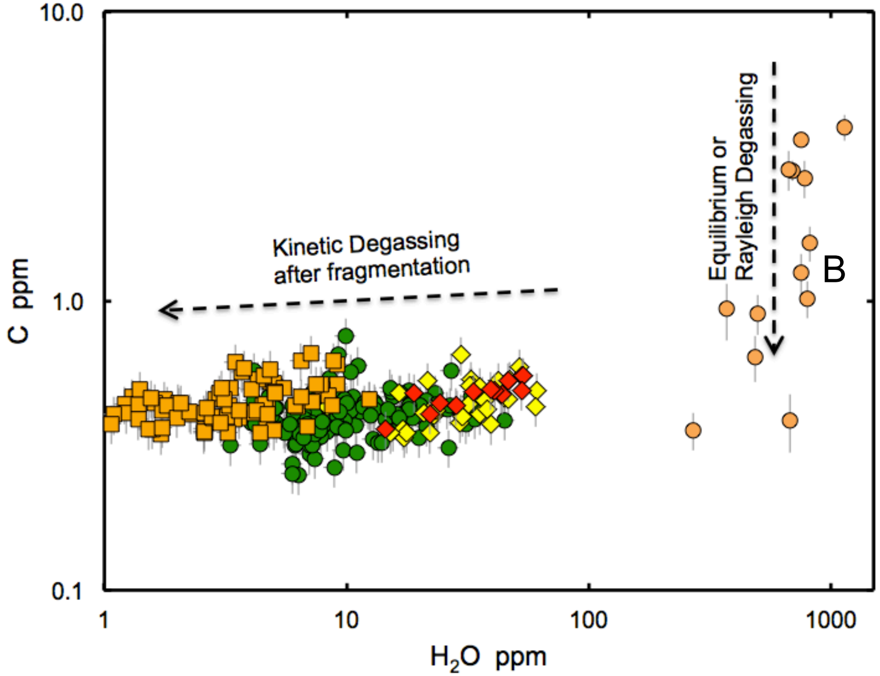
We used olivine-hosted melt inclusions in glass beads from A17 sample.



The new melt inclusion study confirmed our predictions that the volatile contents of the lunar volcanic glasses were equivalent to those found in MORB

The Carbon Content and Magmatic Degassing





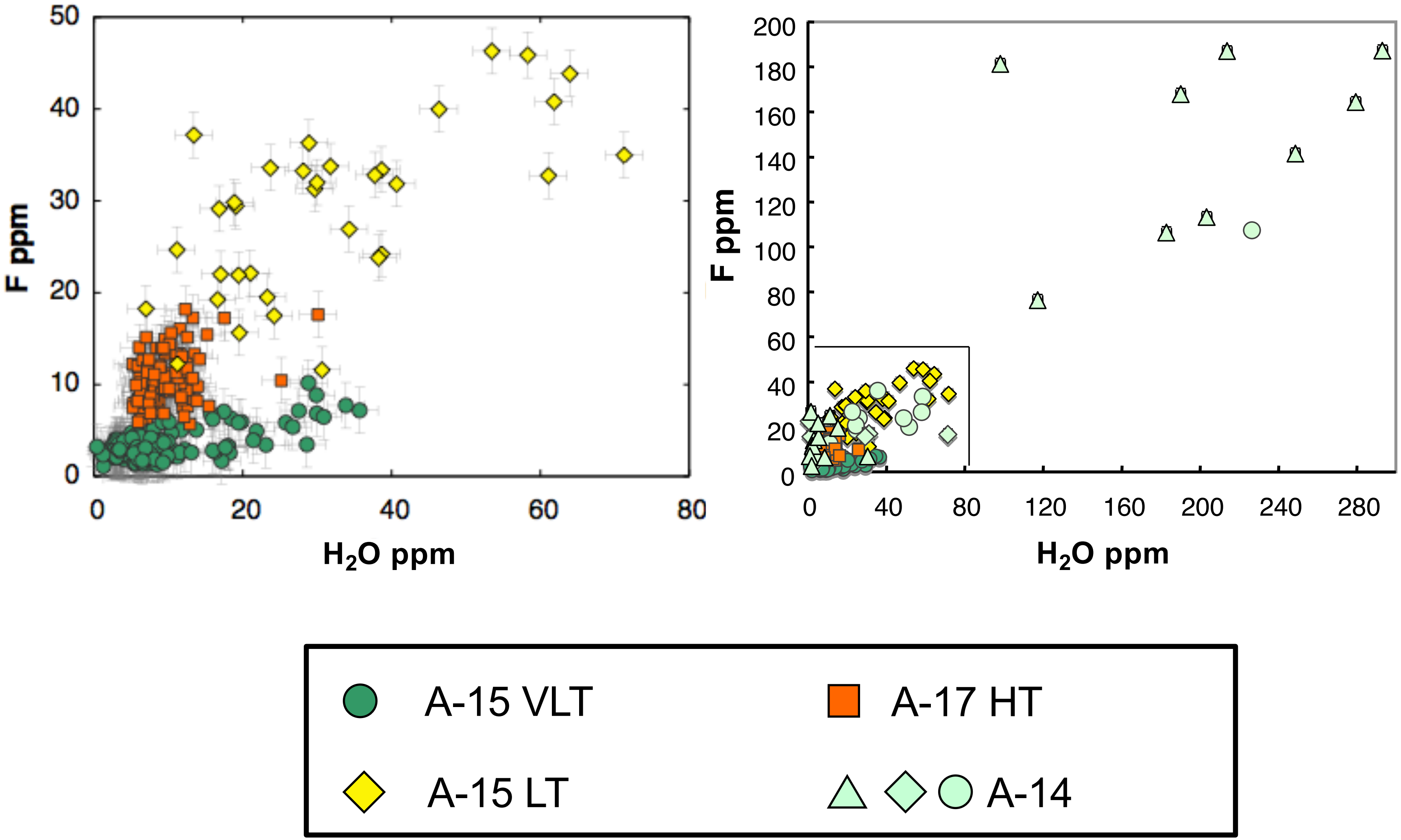
Wetzel et al., 2015

The H/C ratios of the lunar magmas range between 2 and 3, similar to ratios for undegassed terrestrial MORB. And the $\delta^{13}C$ of orange glasses is -7.3‰, similar to that of MORB (6.9±0.9‰).

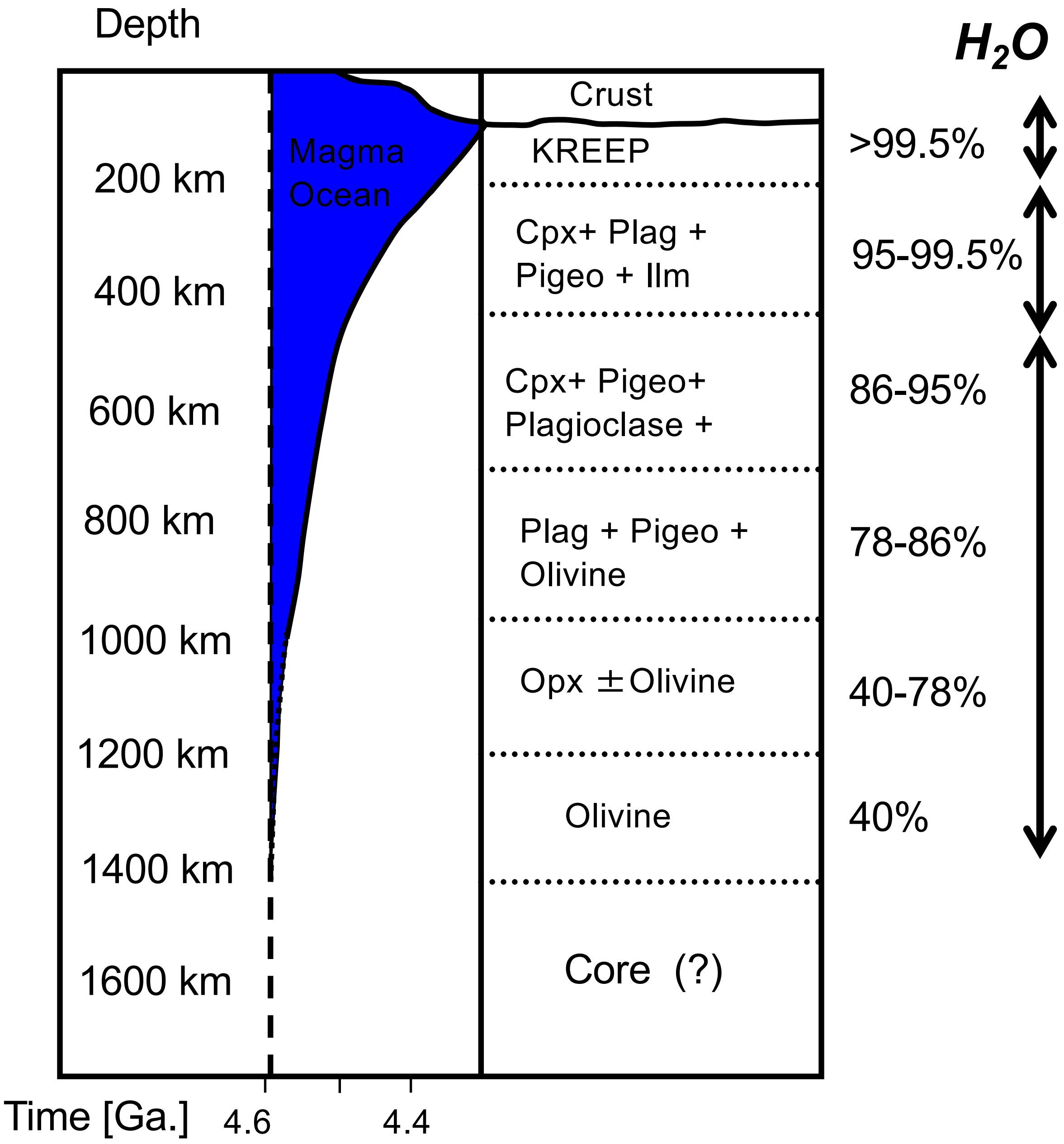
To determine the distribution of the volatiles contents within the Moon

We performed new volatile analyses for more than 360 individual volcanic glasses from A-15, A-17 and A-14 .

F vs H_2O



The evolution of the lunar magma ocean might provide a starting point



Assuming initial concentrations of
H_2O = 100 ppm and Ce = 1.675

H_2O = 23840 ppm and Ce = 236 ppm

H_2O = 140.7 ppm and Ce = 16.7 ppm

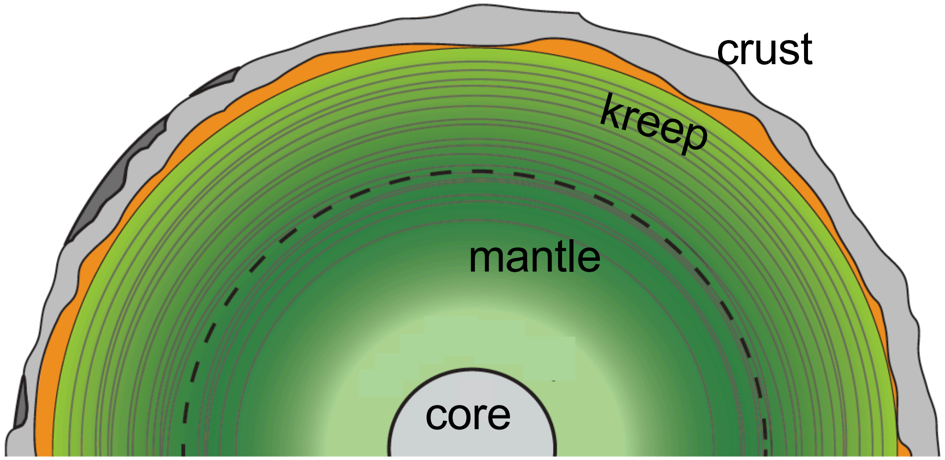
H_2O = 2.4 ppm and Ce = 0.2 ppm

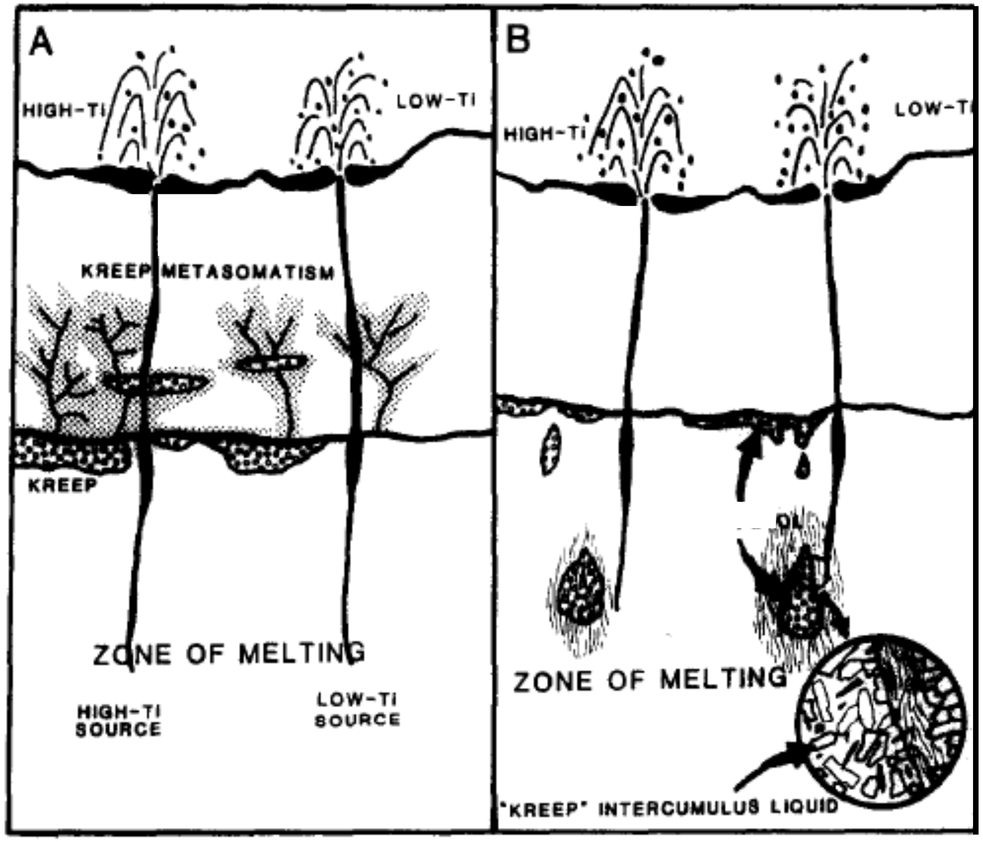
Snyder et al. 1992
Hess and Parmentier, 1995

Two possible scenarios

A) Shallow assimilation of KREEP into primitive melt

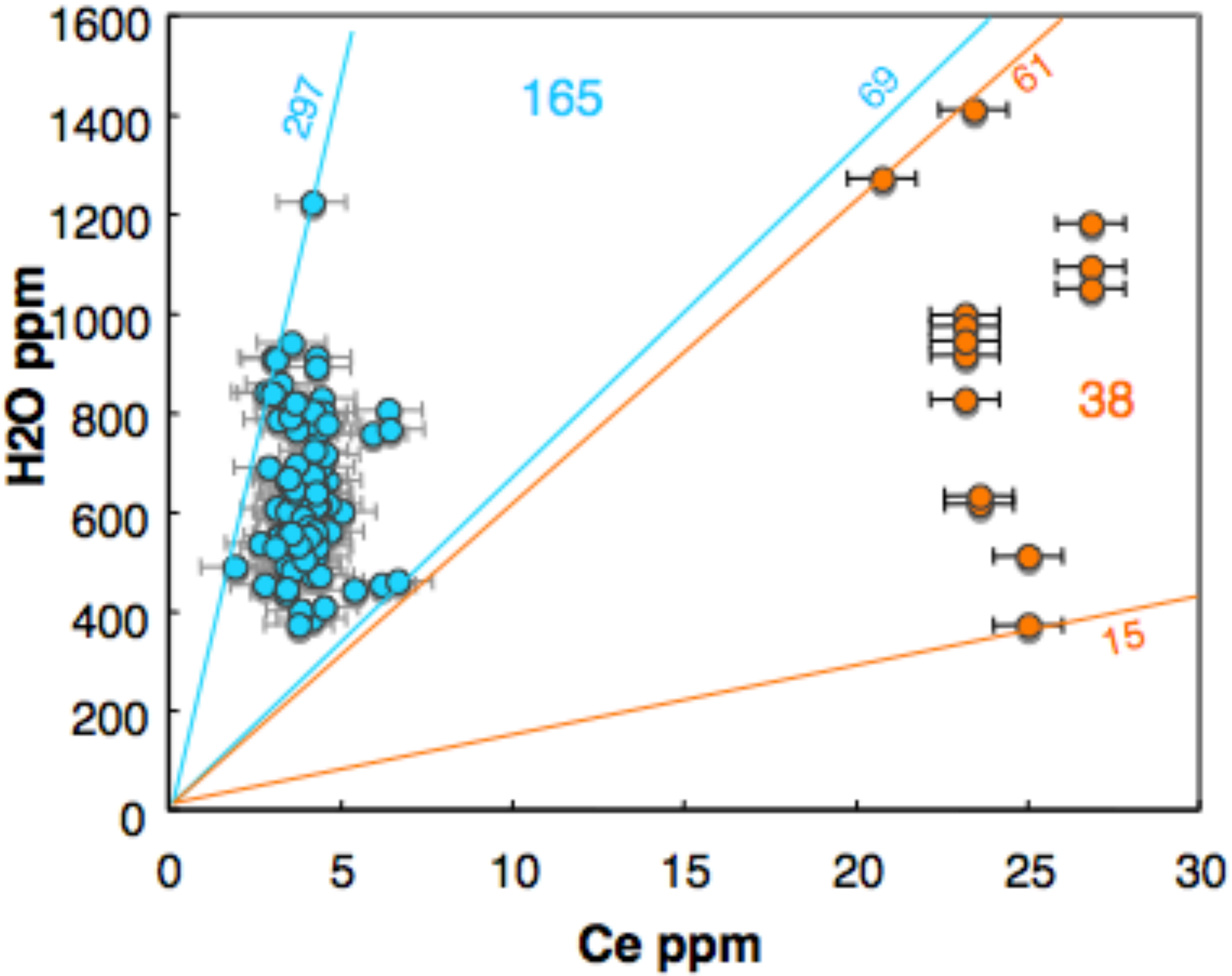
B) Deep hybridization of the lunar mantle source during LMO cumulate overturn



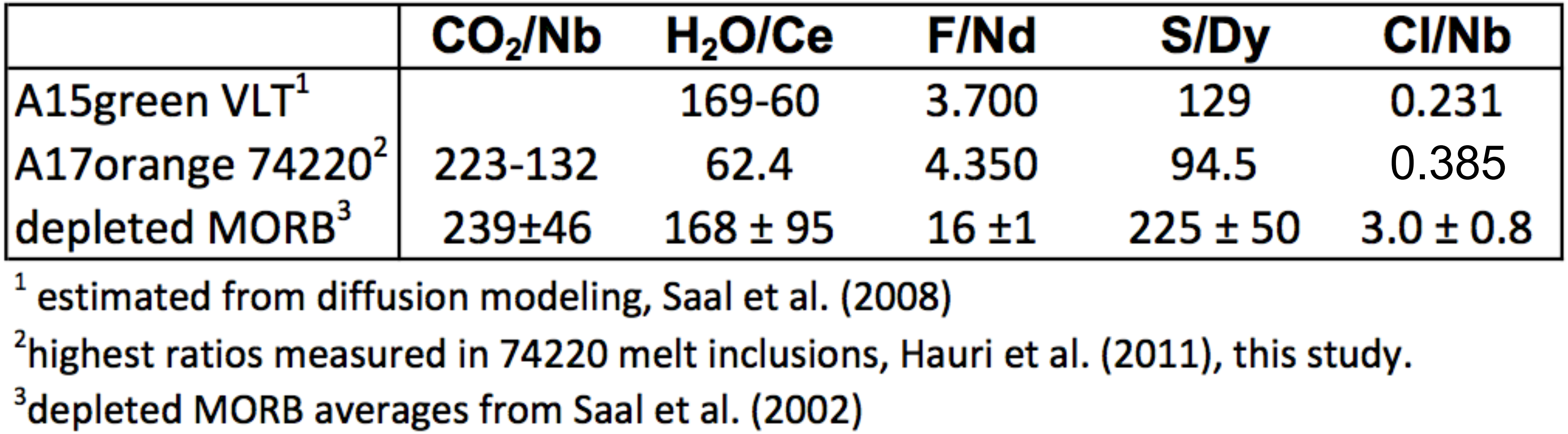


Grove and Krawczynski (2009) Shearer et al. (1990)

Volatile-refractory element ratios in melt inclusions from the Moon and MORB



Volatile/non-volatile ratios for lunar glasses and MORB suggest a factor of <10 rather than 1000 volatile depletion



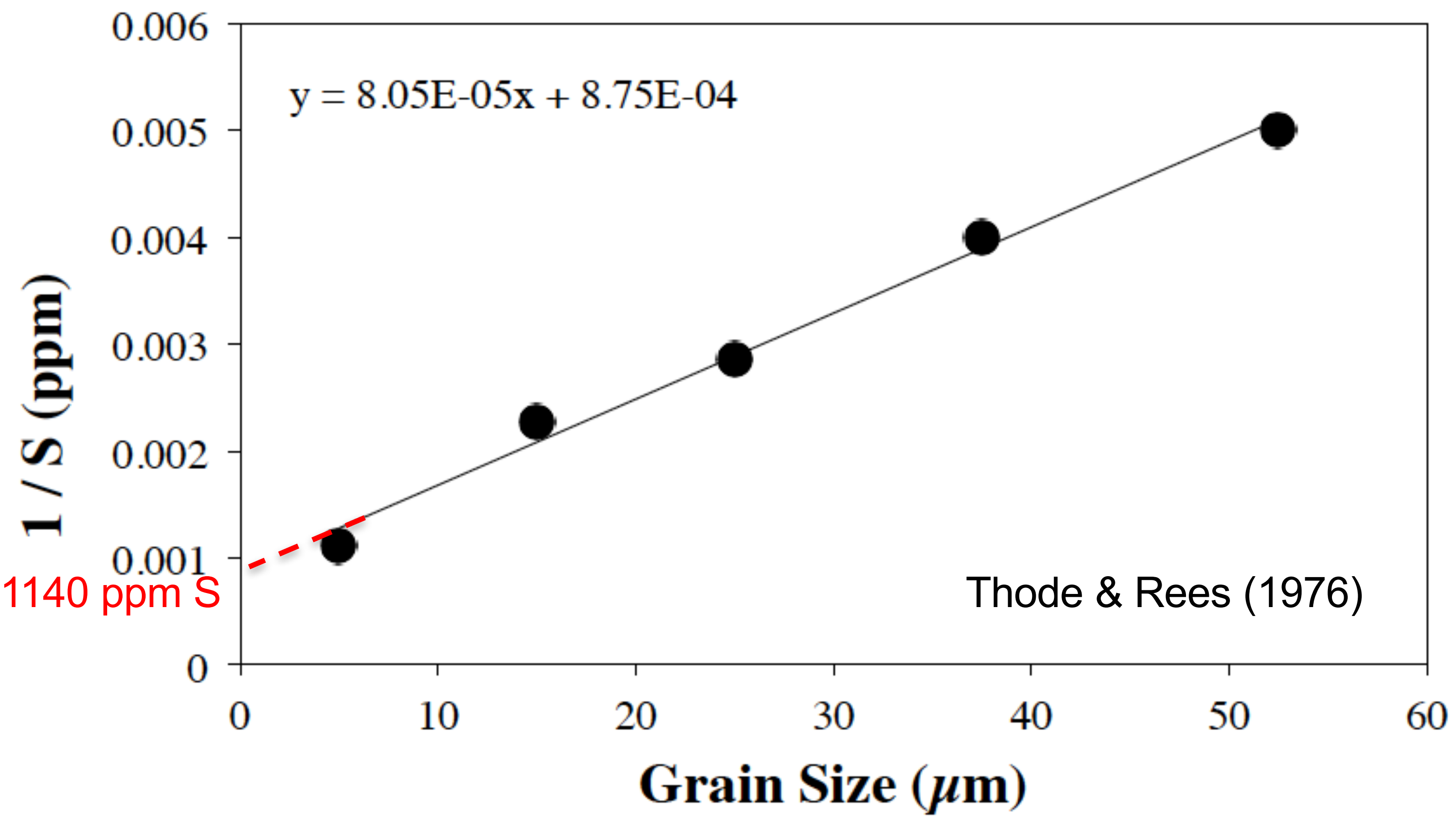
	CO_2/Nb	H_2O/Ce	F/Nd	S/Dy	Cl/Nb
A15green VLT[1]		169-60	3.700	129	0.231
A17orange 74220[2]	223-132	62.4	4.350	94.5	0.385
depleted MORB[3]	239±46	168 ± 95	16 ±1	225 ± 50	3.0 ± 0.8

[1] estimated from diffusion modeling, Saal et al. (2008)

[2] highest ratios measured in 74220 melt inclusions, Hauri et al. (2011), this study.

[3] depleted MORB averages from Saal et al. (2002)

The presence of surface coatings has been widely attributed to their deposition onto bead exteriors during cooling of clouds of volcanic gas



1140 ppm S

Thode & Rees (1976)

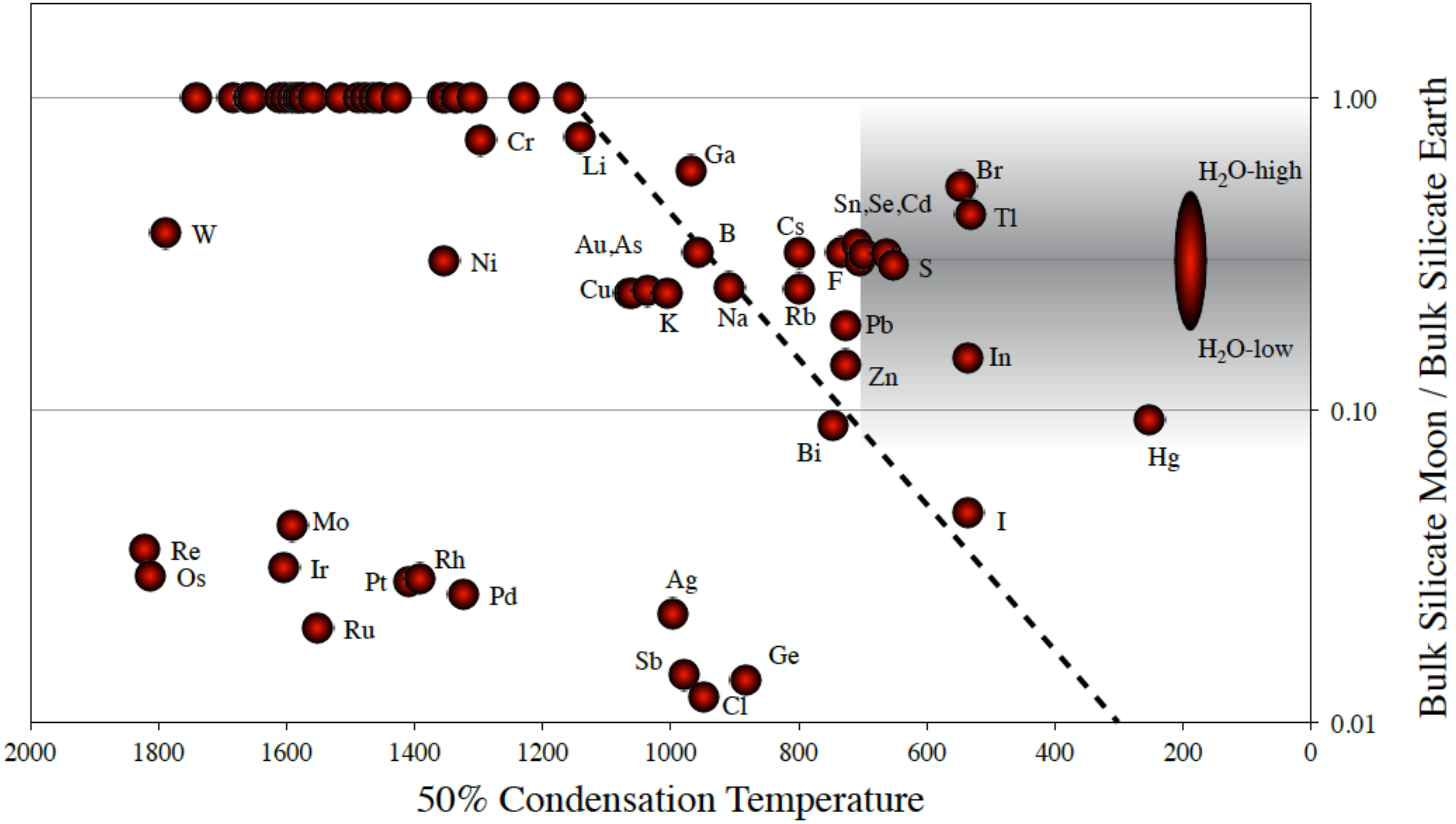
Table 2. Composition of volatile elements in 74220 glass bead coatings, glass bead interiors, and reconstituted pre-eruptive composition (see text).

	S ppm	Na ppm	Zn ppm	Ga ppm	Ge ppb	Cd ppb	In ppb	Te ppb	Hg ppb	Pb ppm
A17orange coating composition	1143	3181	252	19.5	344	267	37.1	93.5	21.3	8.13
A17 orange glass interior composition	325	2137	3.97	*16.7*	0.19	*n.d.*	*n.d.*	*n.d.*	*n.d.*	0.305
A17orange glass reconstituted	884	3692	127	26.3	168	131	18	46	10	4.28
% degassed	63%	42%	97%	36%	100%	*n.d.*	*n.d.*	*n.d.*	*n.d.*	93%

Chou et al. (1975), Wasson et al. (1976), Cirlin et al. (1978) and Krahanbuhl (1980).

The lunar mantle ^{87}Rb/^{86}Sr from Sr isotopes in anorthosites and Mg-suite samples is 0.035 (Carlson et al., 2014) and from a lunar meteorite is 0.044 (Borg et al., 2009), 1/3 and 1/2 of that in the BSE (0.089).

The lunar mantle ^{238}U/^{204}Pb (μ) from Pb isotopes was estimated ~ 30 (Tera and Wasserburg, 1976), 21 (Kita et al., 1995), 18 (Terada et al., 2008), and 10 (Misawa et al., 1993) compared with the BSE value of 8.5. Thus the abundances of Rb (0.245x BSE) and Pb (0.187x BSE) in the BSM

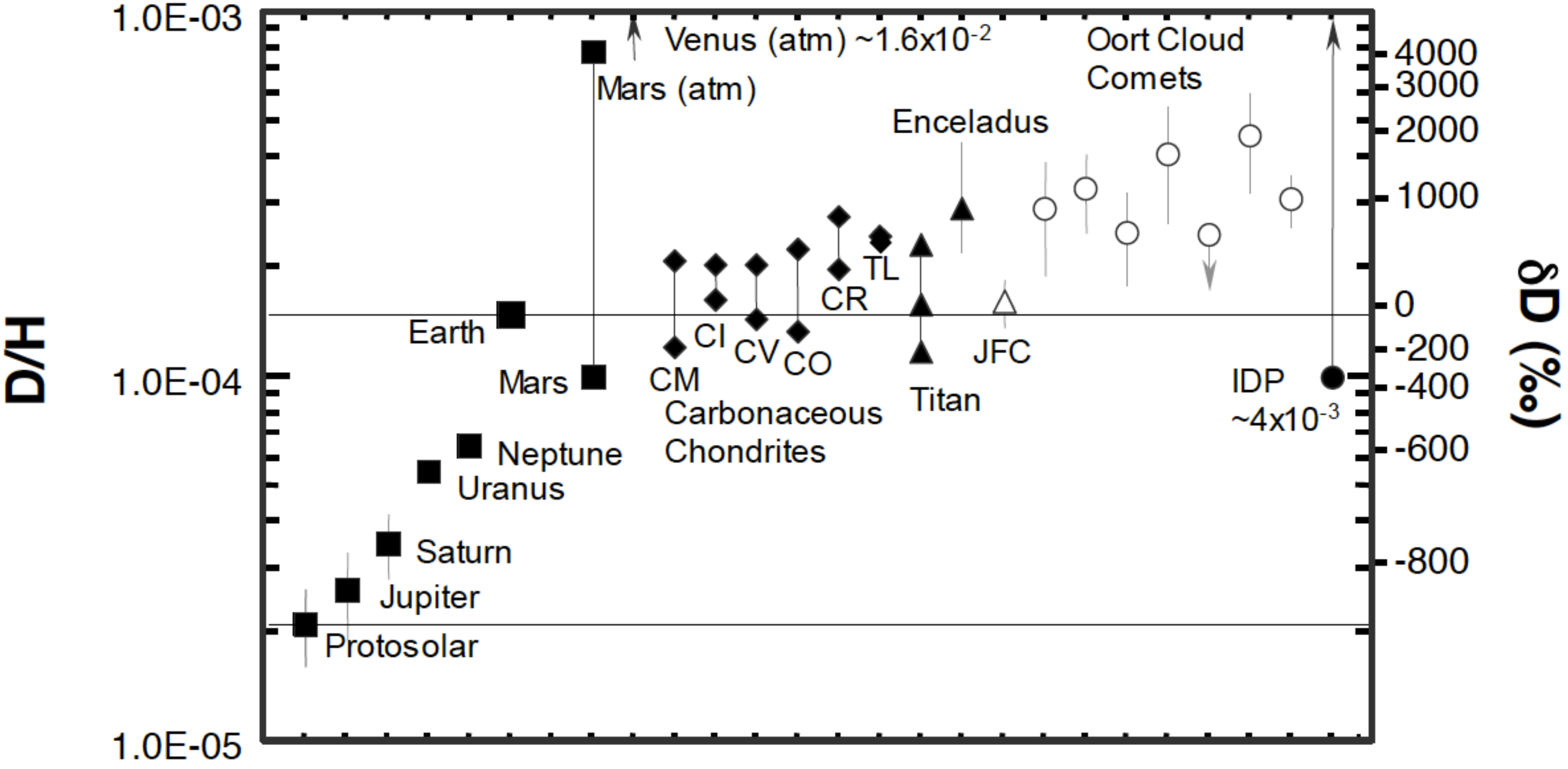


two new issues were raised:

Where did the water came from?

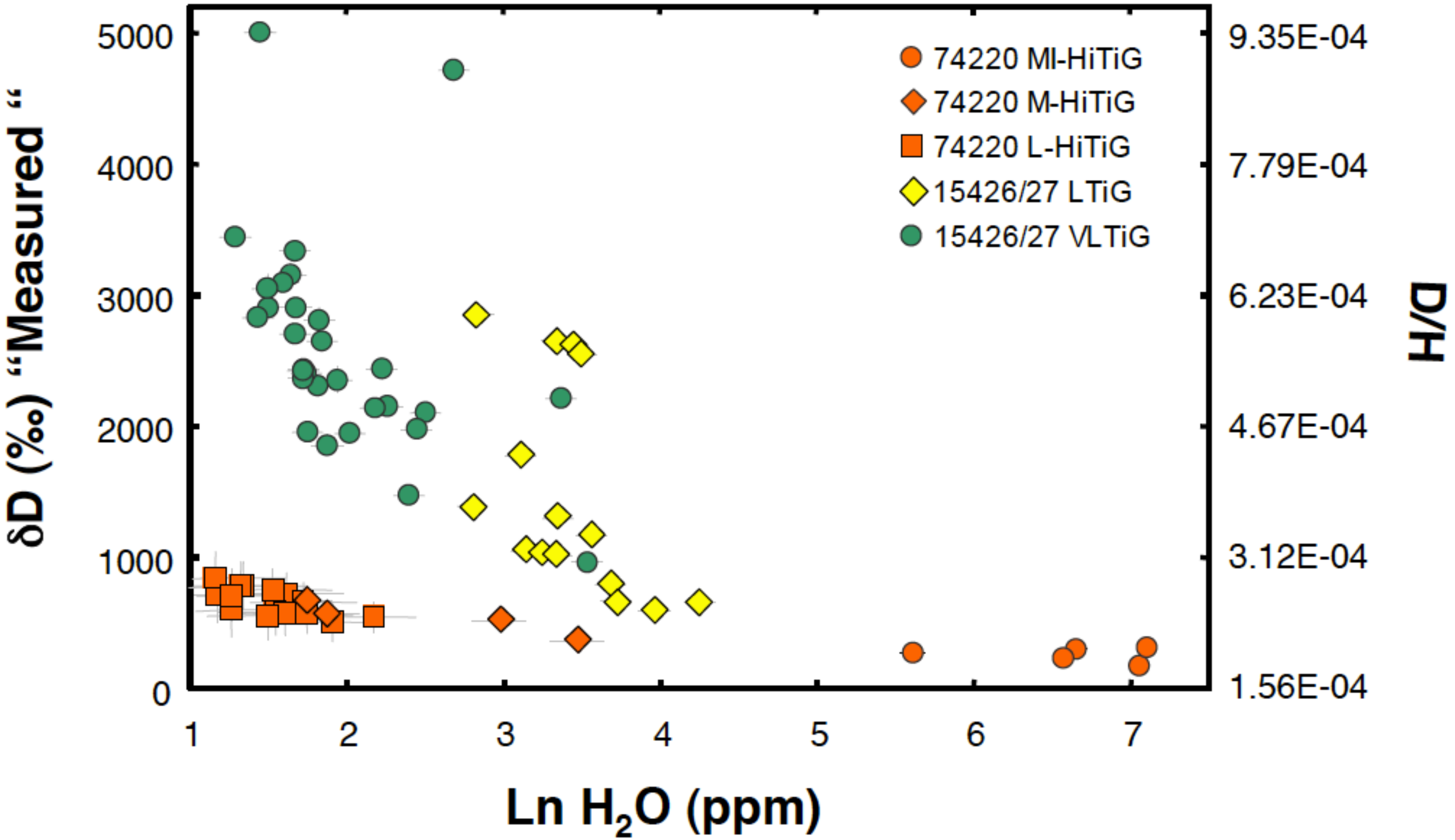
When did the water come to the Moon ?

D/H ratios as a fingerprint for the origin of the lunar water



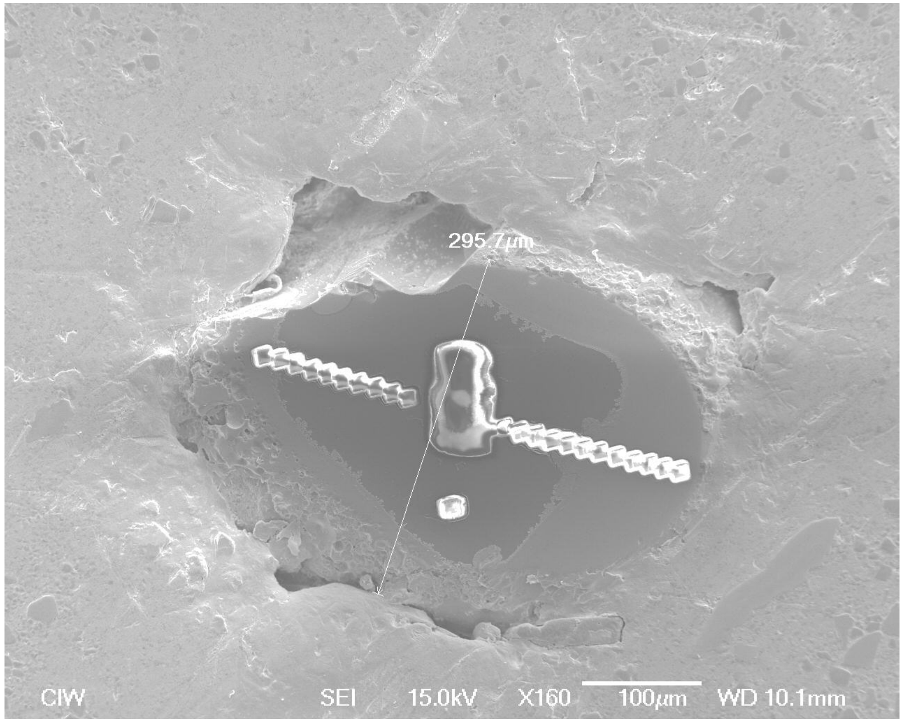
$$\delta D = [(D/H_{sam} / D/H_{SMOW} - 1)*1000]$$

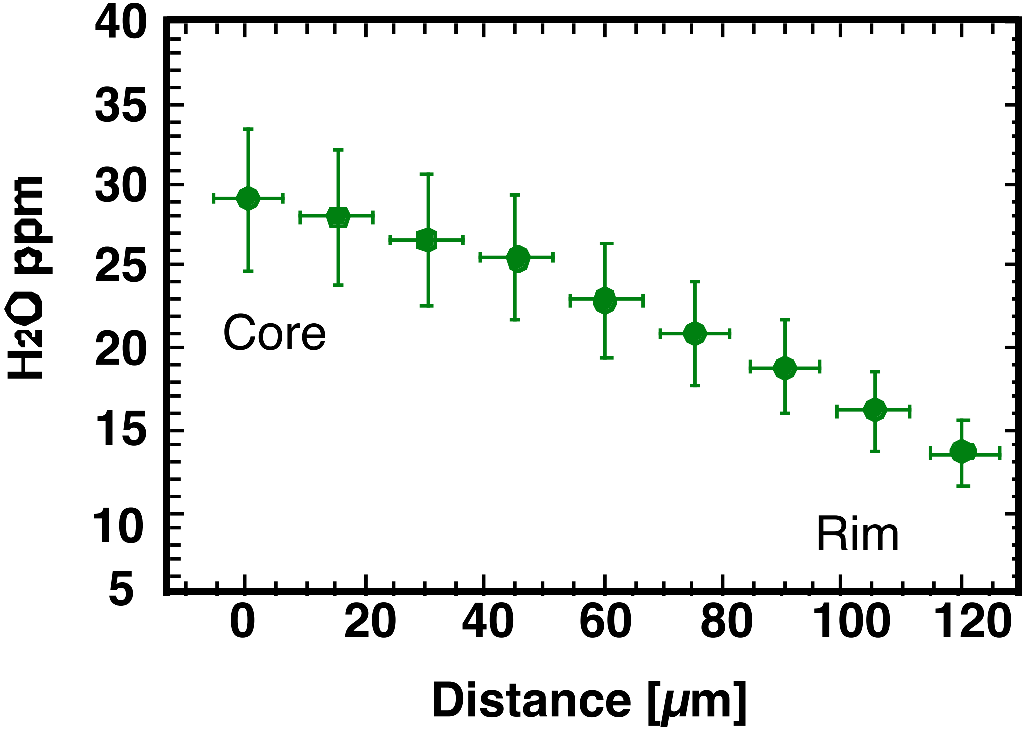
δD measured versus H_2O content in the lunar glasses



We have to consider degassing processes

Equilibrium or Rayleigh Fractionation cannot be applied to the lunar volcanic glasses





Diffusive Degassing:

The mass dependence of diffusion of hydrogen isotopes can be represented as:

$$\frac{D_H}{D_D} = \left(\frac{m_D}{m_H}\right)^{\beta_{H/D}}$$

where β is an empirical exponent that likely depends on hydrogen speciation

Approximate solution of the 1D spherical diffusion equation

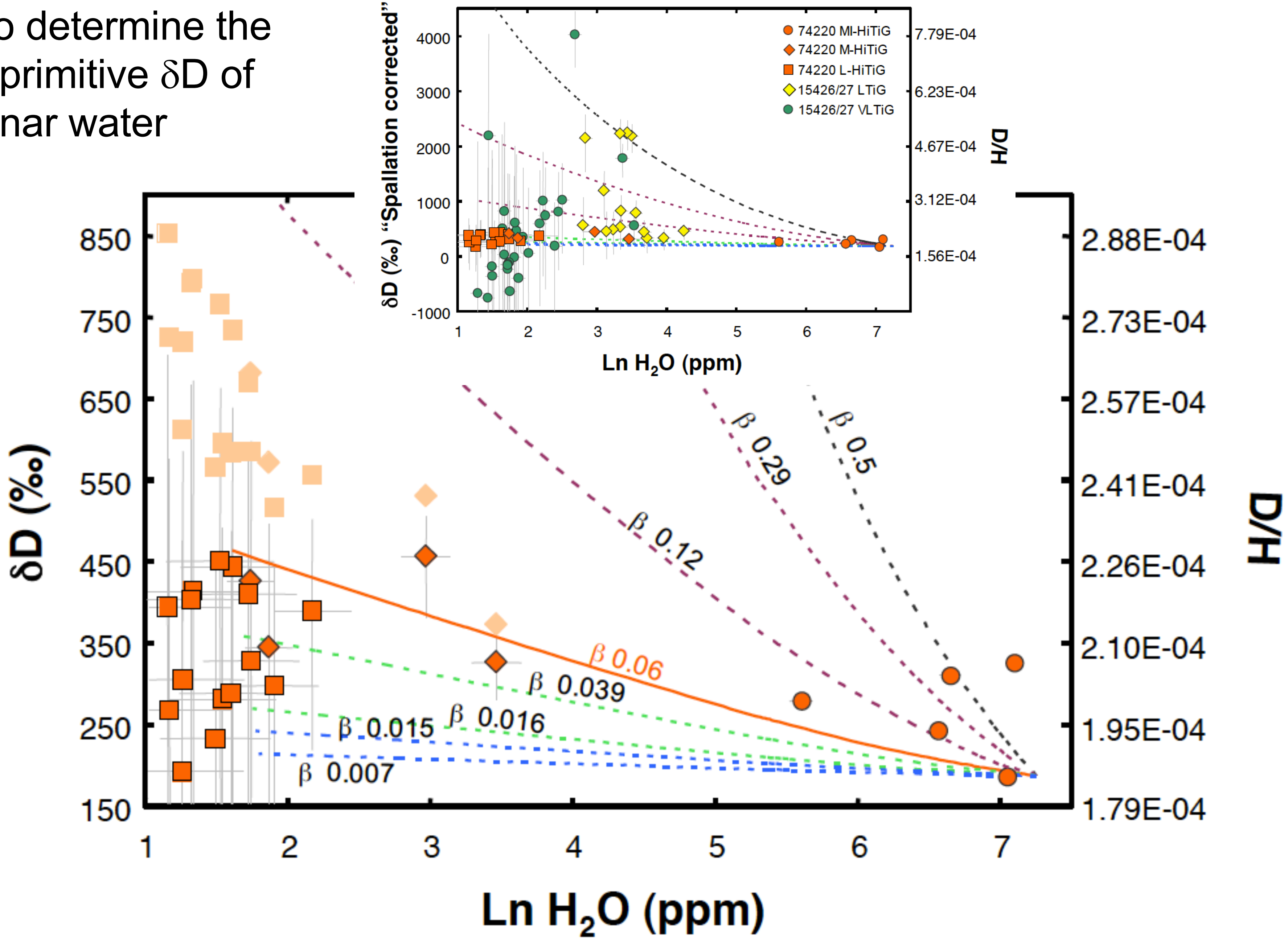
$$0.85 \leqslant f \leqslant 1 \quad f \simeq 1 - (6/\pi^2)\exp(-\pi^2 Dt/a^2)$$

$$0 \leqslant f \leqslant 0.85 \quad f \simeq (6/\pi^{3/2})(\pi^2 Dt/a^2)^{1/2} - (3/\pi^2)(\pi^2 Dt/a^2)$$

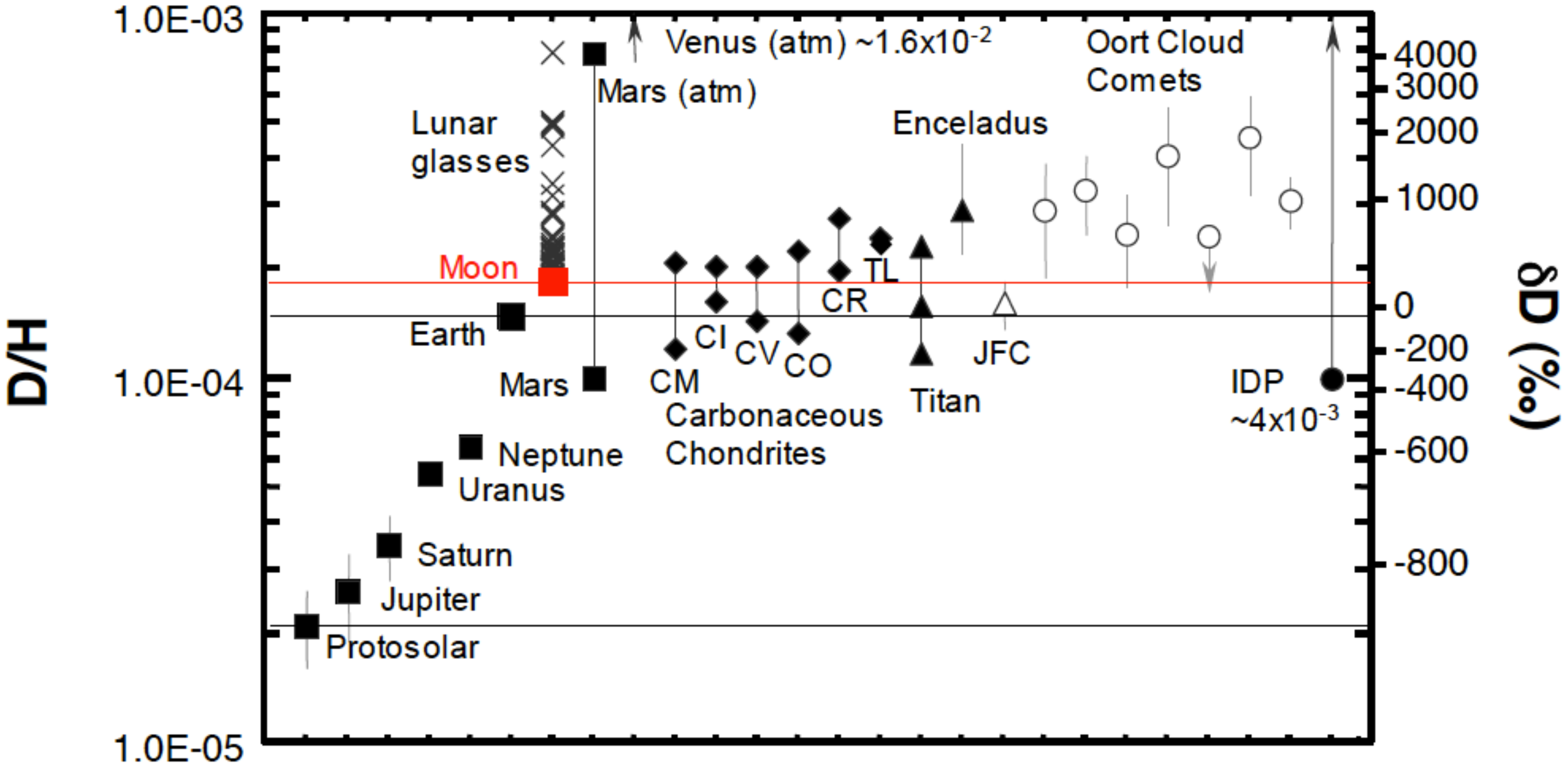
Where “f” is the fraction of H or D lost

McDougall and Harrison (1988)

A17 Melt Inclusions: Key to determine the most primitive δD of the lunar water



The D/H ratios of the lunar melt inclusions indicate that the water in Earth and Moon came from carbonaceous chondrites rather than comets



Halliday (2013), Marty (2012)

Nitrogen isotope confirms the carbonaceous chondrite origin of the volatiles

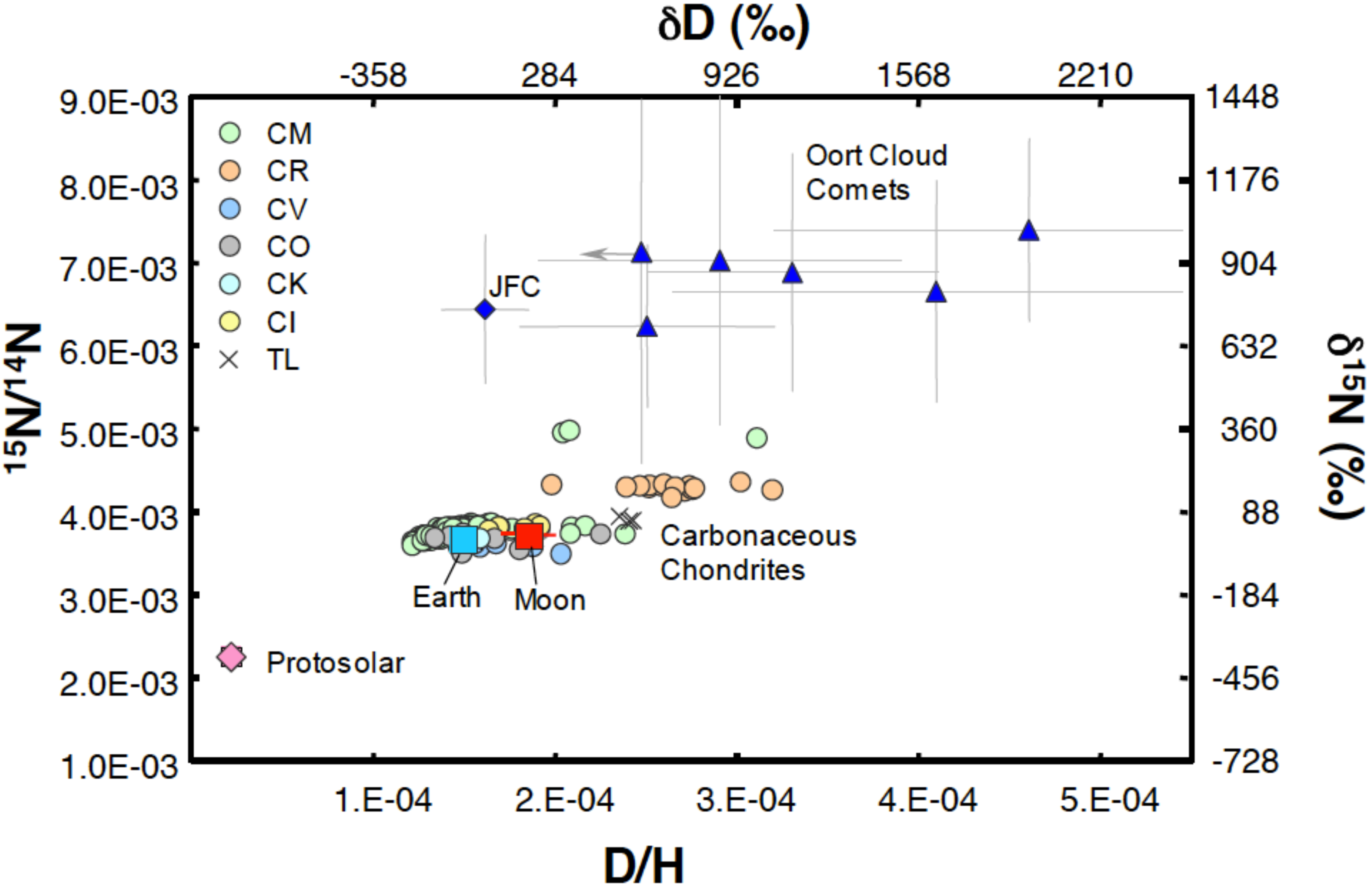


Figure modified from Marty (2012), Marty et al. (2002), Alexander et al.,(2012)

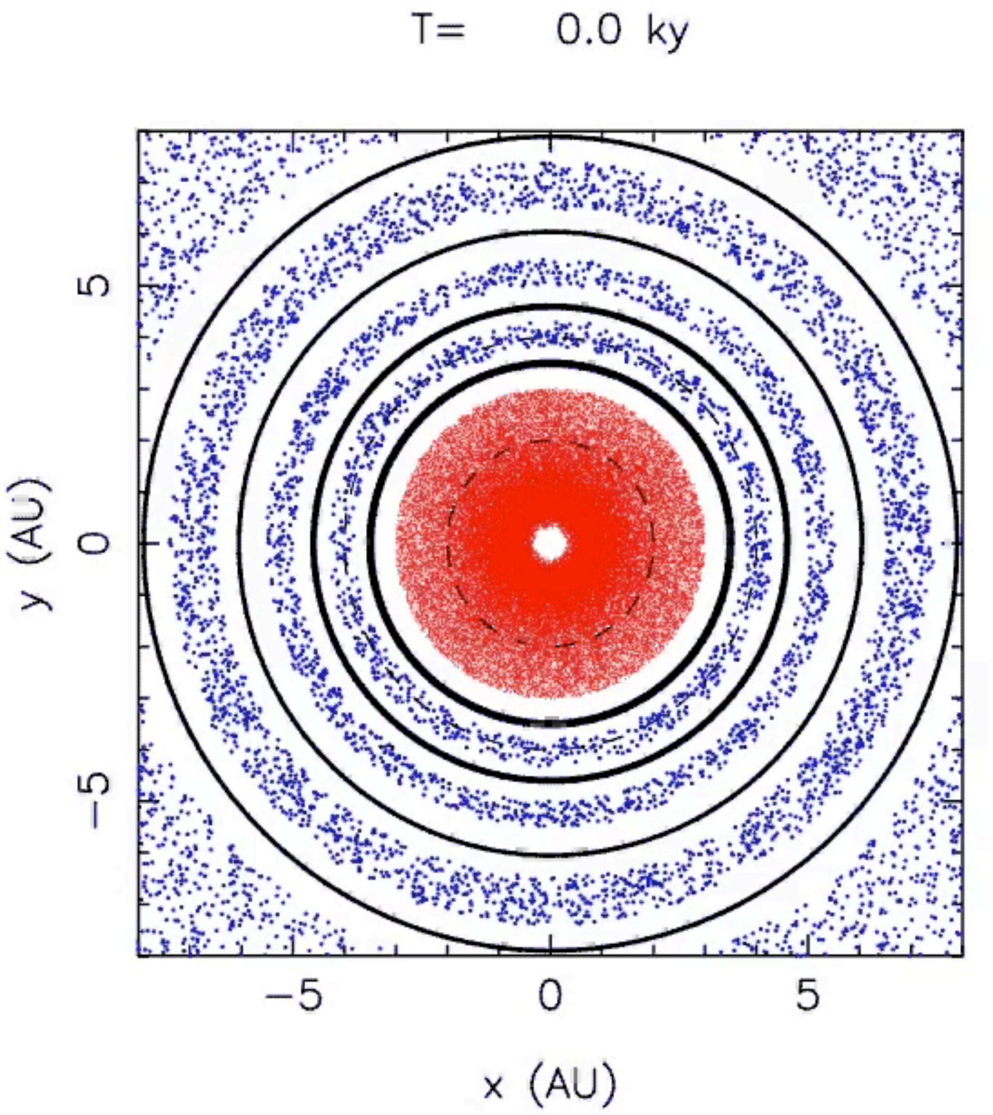
How the volatiles reached the Moon?

The presence of volatiles in lunar volcanic glasses and their δD, $\delta^{15}N$ suggest that either

1) The volatile were added ~ 50-100 Ma after the formation of the Moon during the final stages of accretion: “late veneer of carbonaceous chondrites”.

2) The Earth formed with volatiles and the Giant Impact event did not evaporate all the volatiles away.

The effect of Jupiter migration and Jupiter-Saturn orbital resonance

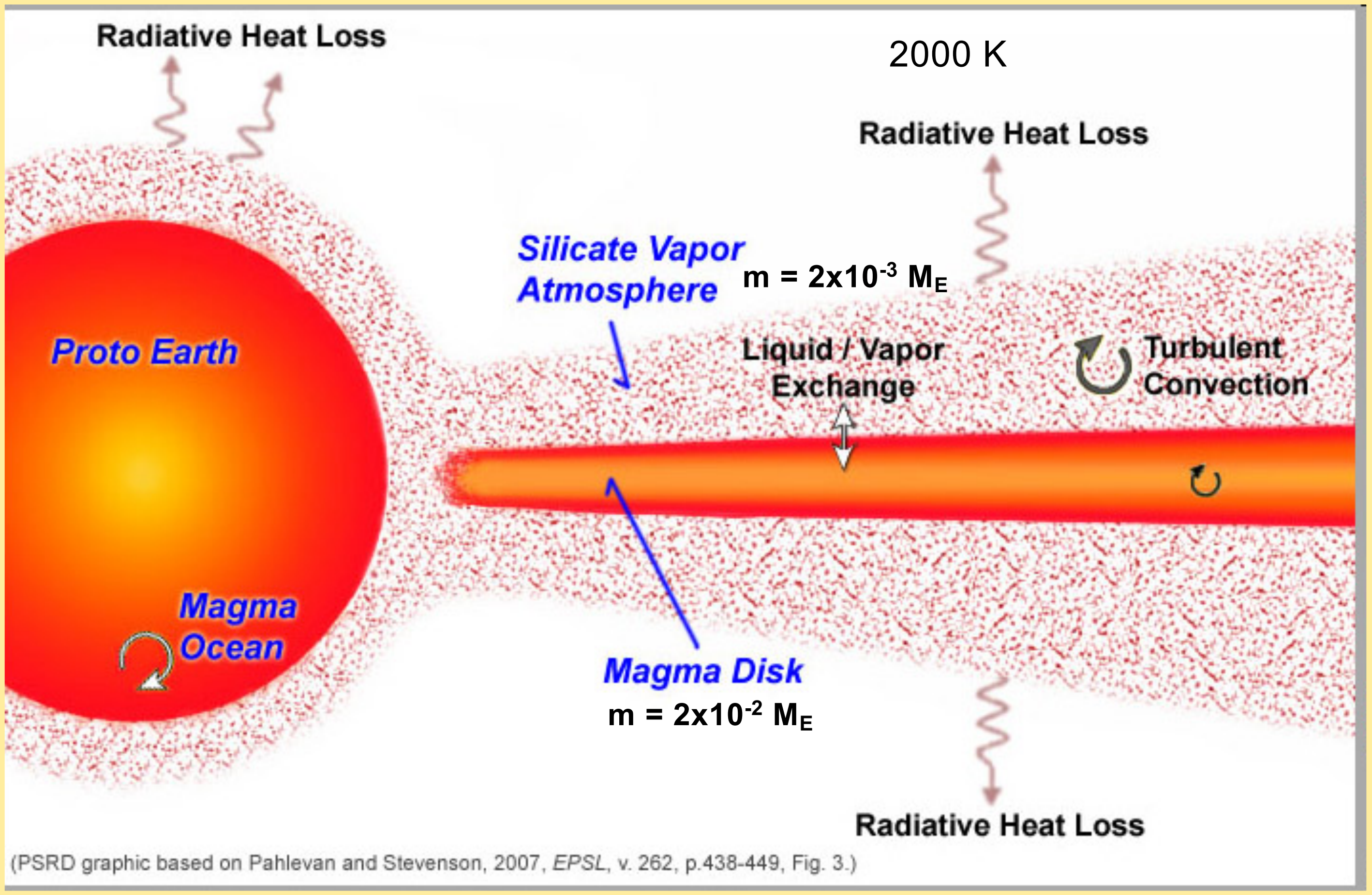


Hydrodynamic simulations provide an explanation for the origin of volatile elements in the Terrestrial Planets

Walsh et al., 2011

How did part of the Hydrogen survive the Giant Impact?

Pahlevan and Stevenson (2007) proposed diffusive equilibration of the silicate vapor atmosphere between the proto-Earth and proto-lunar disk after the giant impact.



(PSRD graphic based on Pahlevan and Stevenson, 2007, *EPSL*, v. 262, p.438-449, Fig. 3.)

Conclusions

1.- We estimated that amount of H, C, F, S and Cl in the lunar volcanic glasses was equivalent to that of MORB.

2.- Volatile/refractory element ratios in the glasses and melt inclusions suggest that the Moon's volatile budget is < 10 time (rather than 1000 times) more depleted that Earth. The reason for the discrepancy is that previous work did not consider magmatic degassing

3.- We showed that the lunar volatiles, as Earth's volatiles, originated from carbonaceous chondrites. The simplest explanation is that Earth had volatiles from its birth (consistent with dynamic models), and either during the giant impact that formed the Moon they were not completely lost or more volatiles were added during the late veneer.