

## VARIABLE ABUNDANCE AND ISOTOPIC COMPOSITION OF HYDROGEN INSIDE THE MOON.

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**Introduction:** Water has been detected in samples from the lunar interior ([1], recently reviewed in [2]) and on the surface, remotely (e.g. [3]), in permanently shadowed regions [4], and in glass agglutinate samples [5]. Surface water, particularly ice trapped in permanently shadowed regions near the lunar poles, is a prime target for in situ resource utilization on the Moon, but could the water in the lunar interior or in rocks from the interior be useful as a resource?

Lunar interior water, which accreted with the Moon or was added very early after lunar formation, has now been measured in pyroclastic glasses [1], olivine-hosted melt inclusions [6,7], ferroan anorthosite plagioclase [8], and apatite grains from all major lunar rock types [2, 9-16,18]). The brunt of the analytical effort has focused on lunar glasses/melt inclusions, and apatite.

The overarching goal of these measurements is twofold: to try to constrain the water content of the bulk Moon, and to determine the source(s) of the Moon's water via hydrogen isotopic ratios. Estimating the pre-eruptive water content of a parental magma from glasses and melt inclusions is relatively straightforward, and it was initially thought that similar estimates could be made using OH abundances in apatite [9]. Recent work showing the complexities of volatile partitioning into apatite invalidates the estimates of parental melt water content from apatite [17]. However, apatite data is still a useful recorder of D/H ratios and relative water contents might be discernible among different rock types [2]. This data from lunar apatite (and glasses) indicates there may be multiple reservoirs in the lunar interior.

**Water in the interior:** Fig. 1 summarizes all currently published apatite data, averaged by individual sample and plotted by lithologic type. Several trends are evident. The water content of apatite in the major rock suites varies by 10-50x and seems to be related to rock type. KREEP-rich lithologies have the driest apatite, while mare basalt apatite is much richer in water (Fig.1). Though we cannot estimate the water content of the parental magmas for any of these samples based on the OH abundance measured in the apatite [17], it seems reasonable that samples with drier apatite likely came from drier magmas, and vice versa, if F and Cl contents were roughly similar.

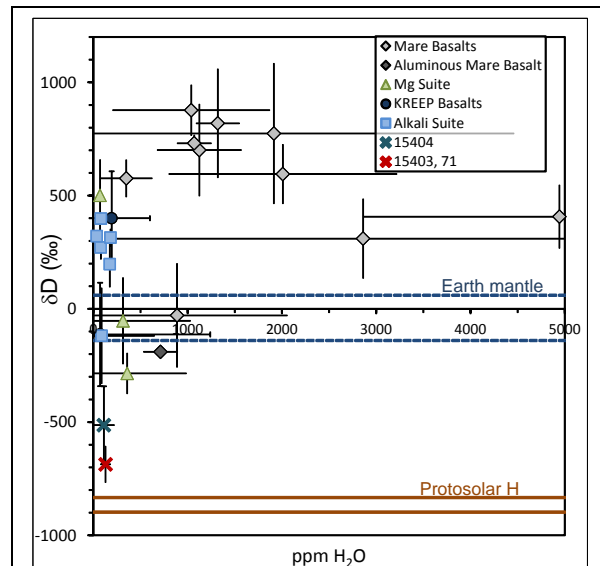


Figure 1. Averages weighted by measurement uncertainty of apatite  $\delta D$  and  $H_2O$  by sample, after [2]. Each point represents a single sample. Error bars denote the range of measured  $\delta D$  or  $H_2O$  in each sample. Data from [2, 12-16, 18, 19, 25]

The  $\delta D$  values of apatite also vary widely. The elevated  $\delta D$  in mare basalts is almost certainly caused by degassing upon eruption from lava flows, when lighter H is lost and heavier D is left in the melt. [13]. The mare basalts likely had an initial  $\delta D$  closer to  $\sim 100\text{‰}$  [13]. Some evolved, intrusive rocks also appear enriched in D ( $+200$  to  $+500\text{‰}$ ), but are not thought to have lost H through degassing as they formed at depth and pressure [2, 14]. There is another cluster of samples that fall in the range of the terrestrial upper mantle ( $-140$  to  $+60\text{‰}$  D, [19]), but due to analytical uncertainties, they might not be completely resolvable from the moderately elevated reservoir.

Our measurements of apatite in quartz monzogabbro 15404, 51 and  $-55$  and 15403, 71 have the lowest  $\delta D$  (down to  $-750\text{‰}$ ) values reported from the Moon so far, indicating a third, low D source inside the Moon (this work, ). Though the range of  $\delta D$  measured in 15404 and 15403 is very similar to the  $\delta D$  observed in agglutinate glasses [5], we do not believe that the low apatite  $\delta D$  reflects solar wind contamination. Soil sample 15400 was taken from on top of impact melt breccia 15405, which has a low exposure age of 11 m.y. [20]. The impact melt breccia itself has no detectable solar wind in it [20, 24]. Addition of solar wind when the clasts were exposed on the lunar sur-

face atop the 15405 boulder is impossible. Solar wind gases do not diffuse in from the outer surface (less than a micron penetration) when a rock sits on the lunar surface. Even if H were to migrate along cracks and came in contact with apatite, the apatite diffusion rate is simply too low at lunar surface temperature. For example, using data from and the interdiffusion coefficient for OH, F, and Cl [26], the total diffusion distance is only  $\sim 10^{-5}$  microns at 100 C (typical lunar surface temperature at noon) in 11 My, the exposure age of 15405 [20]. Thus, contamination with solar wind of clasts exposed on the surface or incorporation into the 15405 impact melt is unlikely. The low  $\delta D$  value may represent a mantle source that contains a primitive component in the lunar interior, similar to low  $\delta D$  melt inclusions in primitive Baffin Island basalts [21].

Analysis of lunar glasses and melt inclusions also provides evidence for multiple water reservoirs in the lunar interior. The picritic glass beads and melt inclusions originated from a magma with  $\sim 1000$  ppm  $H_2O$  [1, 6, 7]. Assuming  $\sim 10\%$  partial melting, the source region for the pyroclastic bead magma would have contained 100ppm  $H_2O$ . In contrast, our measurements of residual quenched glass in KREEP basalt fragments in 15358 contain 58-95 ppm  $H_2O$  [14]. Based on the modal abundances of the glass (15-20%) and accounting for H loss, the initial melt would have contained  $\sim 100$  ppm  $H_2O$ . The KREEP source would have thus contained  $\sim 10$  ppm, an order of magnitude less than the picritic magmas. These calculations are rough, but indicate that there are at least two possible water reservoirs in the lunar interior based on water content.

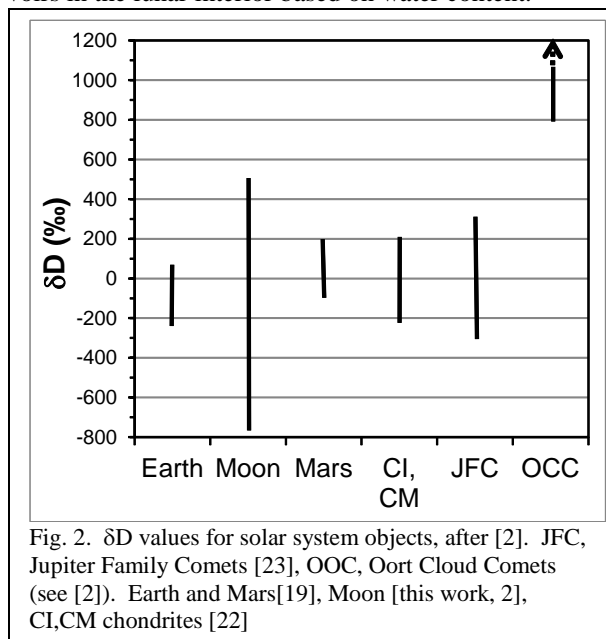


Fig. 2.  $\delta D$  values for solar system objects, after [2]. JFC, Jupiter Family Comets [23], OCC, Oort Cloud Comets (see [2]). Earth and Mars [19], Moon [this work, 2], CI, CM chondrites [22]

**Implications:** The huge range in measured  $\delta D$  in lunar samples makes determining a primordial lunar  $\delta D$  very complicated. It might thus be impossible to determine if a water-bearing deposit in a permanently-shadowed region contained water from the lunar interior or from an external source, at least by D/H ratios alone (Fig. 2). Water is distributed heterogeneously inside the Moon, as shown by  $\delta D$  and water content. The pyroclastic glass source seems to be the most water rich [2,6,7]. However, the Moon is still quite dry. The wettest lunar reservoir yet sampled (represented by olivine hosted melt inclusions in A17 pyroclastic glass beads [6,7]) contains about the same amount of water as depleted MORBs, which are some of the driest rocks on Earth. From a resource exploitation standpoint, it is much more efficient to search for ice, rather than trying to locate water-rich rocks. Examples of potential sites for resource exploration and utilization, such as Amundsen crater, are given by [27].

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