

**ABUNDANCE, DISTRIBUTION, AND ISOTOPIC COMPOSITION OF WATER IN THE MOON AS REVEALED BY BASALTIC LUNAR METEORITES.** M. Anand<sup>1,2</sup>, R. Tartèse<sup>1</sup>, J. J. Barnes<sup>1</sup>, N. A. Starkey<sup>1</sup>, I. A. Franchi<sup>1</sup>, and S. S. Russell<sup>2</sup>. <sup>1</sup>Planetary and Space Sciences, The Open University, Milton Keynes, MK7 6AA, UK. <sup>2</sup>Dept. of Earth Sciences, The Natural History Museum, London, SW7 5BD, UK (Mahesh.Anand@open.ac.uk).

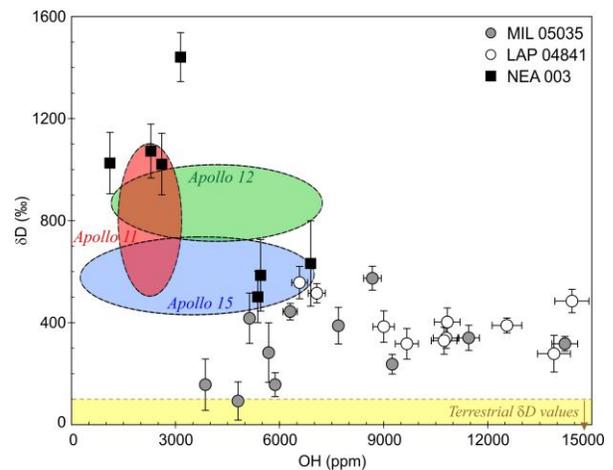
**Introduction:** Lunar meteorites arguably provide a wider sampling of the lunar surface compared to the samples collected during the Apollo and Luna Missions. Apatite is the main hydroxyl-bearing (proxy for water) mineral in lunar samples, especially in basaltic rocks. The ages of lunar basaltic meteorites also span a larger range compared to basaltic samples collected during Apollo and Luna missions. Thus, by determining the H-content and the H isotopic composition of apatites from lunar basaltic meteorites of different ages it is possible to investigate the abundance, distribution and isotopic composition of water in the lunar interior.

In the context of recent developments in our understanding of the history of water on the Moon, currently there is less disagreement over the presence of water in the lunar interior [1-10] but uncertainties exist regarding the abundance, distribution, and the source(s) of this lunar water. In addition, it is also not known if the water content of the lunar interior has changed through time [11]. Firstly, the giant-impact origin of the Moon is thought to have involved a lunar magma ocean (LMO) phase. Much of any water present during the accretion of the Moon would presumably have been lost to space because of high-temperatures but some primordial water may have been sequestered in minerals and rocks formed by LMO solidification [12]. Secondly, if the LMO phase did not involve whole-Moon melting, a more volatile-rich, primitive mantle, could still exist deep inside the Moon. Finally, there is also a possibility that some additional water was accreted to the Moon after the LMO solidification through impacts of chondritic materials [13-15].

Mare basalts (and volcanic glasses) derived by partial melting of the lunar mantle have erupted episodically onto the lunar surface. Any evidence for the presence of water in the lunar mantle is likely to be preserved in mare basalts as water behaves incompatibly during mantle partial-melting and is thus partitioned preferably into the melt. The Apollo and Luna missions collected a range of lunar samples including those of primary LMO products (e.g., anorthosites, Mg-suite rocks etc.) and a variety of mare basalts with crystallization ages predominantly ranging from ~ 3.9 to ~ 3.1 Ga [16]. In contrast, there are a number of basaltic lunar meteorites ranging in age from 4.35 Ga to ~ 2.8 Ga [16]. Thus, by measuring the H-content and H isotopic composition of water contained in apatites in

these lunar meteorites, we can investigate any secular changes in the water content of the lunar interior.

**Samples and Methods:** We have selected four lunar basaltic meteorites (LAP 04841 (paired with LAP 02205 - 3.1 Ga [17]), NEA 003 – ~ 3.1 Ga [18], MIL 05035 – ~ 3.9 Ga [19] and Kalahari 009 – 4.35 Ga [20]), covering nearly the entire age-range of basaltic lunar meteorites that have been age-dated in terrestrial laboratories using various radiometric techniques. Kalahari 009 and MIL 05035 samples belong to the very-low-Ti lunar basaltic samples whereas NEA 003 and LAP 04841 belong to the low-Ti group.



**Fig 1. OH contents and D/H ratio measured in apatites from the three basaltic lunar meteorites. The shaded regions represent the OH- $\delta$ D dataset for Apollo mare basalts taken from [21]**

We have measured the OH contents and D/H ratios in apatites using a Cameca NanoSIMS 50L located at the Open University. So far, we have analysed apatites from NEA 003, LAP 04841, and MIL 05035. The analytical conditions involved a large Cs<sup>+</sup> primary beam of ~ 270 pA current, which was rastered over a 10  $\mu$ m  $\times$  10  $\mu$ m area. Mass resolving power was set at ~ 4000 and secondary ions <sup>1</sup>H, <sup>2</sup>D, <sup>12</sup>C, and <sup>18</sup>O were collected from the central 5  $\mu$ m  $\times$  5  $\mu$ m area. Analysis times were typically 20 minutes, including a 3 minute pre-sputter (12  $\mu$ m  $\times$  12  $\mu$ m). OH contents were calibrated using the measured <sup>1</sup>H/<sup>18</sup>O ratio and calibrations calculated for reference apatites with known OH contents, which were also used to correct D/H ratios for instrumental mass fractionation (details in [10]). OH con-

tents and D/H ratios, given in the  $\delta$  notation, are reported in Fig. 1 with their  $2\sigma$  uncertainties derived from the reproducibility of associated sets of standard analyses and the internal precision of each analysis.

**Terrestrial contamination:** All lunar meteorites in worldwide collections are finds. No lunar meteorite has yet been witnessed as a fall. Therefore, inevitably all lunar meteorites contain products of terrestrial contamination which often poses an additional challenge in interpreting the geochemical data in terms of parent body processes. In case of lunar meteorites selected for this study, two were found in Antarctica and the other two were recovered from deserts of Africa. In addition, the terrestrial ages of these four meteorites vary from recent (Kalahari 009) to several tens of thousands of years (LAP 02205). Finally, MIL and LAP are crystalline basalts where NEA and Kalahari are brecciated samples. Therefore, the terrestrial alteration history of each sample needs to be looked at on a case by case basis taking into account the petrological characteristics of each meteorite. For our OH and D/H measurements, clean and crack-free areas within each apatite grain were first selected on the basis of optical and BSE images of the polished sections prior to NanoSIMS work. Secondary ion images of  $^1\text{H}$  and  $^{12}\text{C}$  were then monitored during pre-sputtering to further ensure that the analysed areas were free of any surficial contamination, cracks and hotspots. However, hidden cracks sometimes appeared during analyses. In such cases, only portions of the secondary ions signal corresponding to analysis of pristine material were considered using the NanoSIMS DataEditor software developed by Frank Gyngard (Washington University).

**Results:** For NEA 003, the OH contents and H isotope composition obtained from 7 analyses, carried out on 4 separate grains, range between  $\sim 1000$  and  $7000$  ppm and  $\sim 500$  and  $1400$  ‰, respectively. For MIL 05035, the OH contents and H isotope composition obtained from 11 analyses, carried out on 4 separate grains, range from  $\sim 4000$  to  $14000$  ppm and  $\sim 100$  to  $570$  ‰, respectively. For LAP 04841 the OH contents and H isotope composition obtained from 10 analyses, carried out on 5 separate grains, range from  $\sim 6500$  to  $14500$  ppm and  $\sim 280$  to  $560$  ‰, respectively.

**Discussion:** There are a number of features that are apparent in Fig 1. For example: 1) The OH contents of apatites from lunar meteorites span a larger range compared to those from Apollo mare basalts. 2) The  $\delta\text{D}$  values measured in the three lunar meteorites are outside the terrestrial range, show some overlap with data from Apollo mare basalts but they expand considerably

the lower and upper bounds for  $\delta\text{D}$  values reported previously for lunar basalts. 3) Apatites from MIL and LAP meteorites show the largest range in OH contents at relatively restricted (and lower)  $\delta\text{D}$  values compared to apatites from NEA 003 which show large variations in  $\delta\text{D}$  values at relatively restricted OH contents. The OH- $\delta\text{D}$  data for MIL is consistent with previously reported data by [22]. The variation in OH- $\delta\text{D}$  dataset for the three lunar meteorites cannot be ascribed to terrestrial contamination. These variations mirror OH- $\delta\text{D}$  trends seen for Apollo mare basalts suggesting that lunar meteorites analysed in this study have faithfully preserved their geochemical history acquired on the Moon. There appears to be no obvious correlation with the age of the sample and its OH- $\delta\text{D}$  characteristics. However, we are in the process of acquiring data on additional samples which will help address this issue.

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