TESTING THE POSSIBLITY OF A VOLATILE-ENRICHED ORIGIN FOR SAMPLE 74220. Peng. Ni* and Youxue Zhang, Department of Earth and Environmental Sciences, the University of Michigan, Ann Arbor, MI 48109-1005, USA. (*Currently at Geophysical Laboratory, Carnegie Institute of Washington, Washington DC 20015, USA. Email: pni@carnegiescience.edu)

Introduction: Volatiles on the Moon have profound implications for the model of Moon formation. Since 2008, our view of a dry Moon has been greatly changed with the discovery of H_2O in volcanic glass beads [1], apatites [2-6], anorthosites [7], and melt inclusions (MIs) [8,9]. In particular, "MORB-like" abundances of H_2O, F, Cl, and S have been reported for MIs from 74220 [8,9].

Study on MIs from lunar basalt samples, however, show that their H_2O/Ce ratios could be lower by almost two orders of magnitude compared to MIs from 74220 [9]. Since some authors argue that sample 74220 is a local heterogeneity unrepresentative of the lunar mantle [10], interpretation of the relatively high H_2O/Ce ratio for 74220 requires a better understanding of its relationship with other lunar samples.

To test the possibility of 74220 being originated from a volatile-enriched origin inside the lunar mantle, here we compare MIs in 74220 to a larger set of mare basalt samples in terms of their volatile (H_2O, F, Cl, and S) and moderately volatile element (Li, Na, K, Cu, Zn, Ga, Ge, Rb, Cs, and Pb) abundances.

Samples and methods: Olivine-hosted melt inclusions in three low-Ti basalts (12040,199, 15016, 47, and 15647, 22) and two high-Ti basalts (10020, 49 and 74235, 22) are analyzed for their major elements by a CAMECA SX-100 electron microprobe at the University of Michigan. Their volatile (H_2O, F, Cl, and S) and non-volatile trace element (Li, Na, K, Sr, Y, Zr, Nb, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) concentrations are measured using a CAMECA IMS 7-f GEO SIMS at Caltech. Among these five mare basalt samples, partially glassy MIs are found in 10020 and 74235, which are directly polished for analyses. Crystalline MIs found in 12040, 15016 and 15647 are homogenized in a vertical furnace under a constant flow of high-purity N_2 before preparation into an indium mount for analyses.

In addition, one MI, one glassy embayment, and one glass bead from 74220 are analyzed for their moderately volatile element (Li, Na, Cu, Zn, Ga, Ge, Rb, Cs, and Pb) concentrations by LA-ICP-MS at the University of Windsor using a PhotonMachines Analyte Exicte 193 nm laser system coupled with an Agilent 7900, quadrupole ICP-MS [11].

MPI-DING glasses [12] and NIST glass standards are used for the reduction of SIMS and LA-ICP-MS data.

H_2O/Ce ratios in the lunar MIs: After removing H_2O-Ce data from homogenized MIs that are <45 µm in diameter, the effect of diffusive H loss on these MIs can be minimized to <20% [13]. The H_2O/Ce ratios, however, still vary significantly from ~50 for 74220, to ~9 for 10020, ~3 for 74235, and ~1 for other samples with homogenized MIs (Fig. 1).

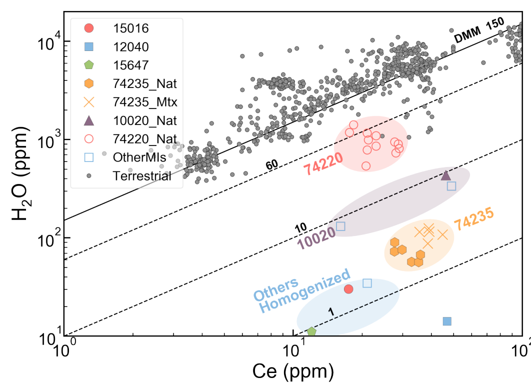

Figure 1. H_2O versus Ce plot for lunar and terrestrial melt inclusions. Open symbols represent literature data from [9], [13] and [14].

One observation is that, the variation in H_2O/Ce ratios is correlated with the apparent cooling rate for the samples. For the sample with the highest H_2O/Ce ratio (74220), most MIs found in the sample are glassy. For samples with intermediate H_2O/Ce ratios (10020, 74235), a small number of partially glassy MIs are found. While for samples with the lowest H_2O/Ce ratios, no glassy MIs are found so far. Therefore, we interpret the variation in H_2O/Ce across different lunar samples are at least partially due to various degrees of H_2O loss during cooling on the lunar surface.

Other volatiles (F, Cl, and S): Most of the lunar MIs studied so far have consistent F/Nd ratios between 1 and 4, with those from 74220 falling into the same range. MIs from 12040, however, are found to have F/Nd ratios of ~20. Since this is currently the only sample that has different F/Nd ratios in the melt inclusions, a more likely explanation is that 12040 experienced F enrichment due to secondary processes.

All lunar MIs, including those from 74220, show similar Cl/K ratios between a narrow range of 0.0035 and 0.015, with a geometric average of ~0.008.

S/Dy ratios show large variations in MIs within individual samples, likely due to the effect of sulfide segregation or degassing loss. After reducing the effects by adopting the highest S/Dy ratio in each individual sample, 74220 shows similar S/Dy ratio (95) compared to other high-Ti mare basalts (78 for 74235 and 94 for 10020). The low-Ti basalts show slightly higher S/Dy ratios (118 to 179) compared to the high-Ti basalts, but the difference is relatively small.

Moderately volatile elements: By comparing moderately volatile element concentrations in the MI and the glass bead from 74220, we found that ~80% of Cu and Zn in the glass bead are lost during eruption. The effect of degassing loss is relatively small for other moderately volatile elements: ~40% for Cs and Ga, 20% to 30% for Pb and Rb, and 10% or lower for Na, K, Li and Ge.

To better compare moderately volatile element abundances in 74220 and in other lunar samples, they are coupled with refractory elements with similar degrees of incompatibility, and the ratios for MIs from 74220, MIs from other lunar basalts, lunar glass beads [14], and lunar basalt bulk measurements (from "Mare Basalt and Glass Database" compiled by Clive R. Neal) are plotted in Fig. 2.

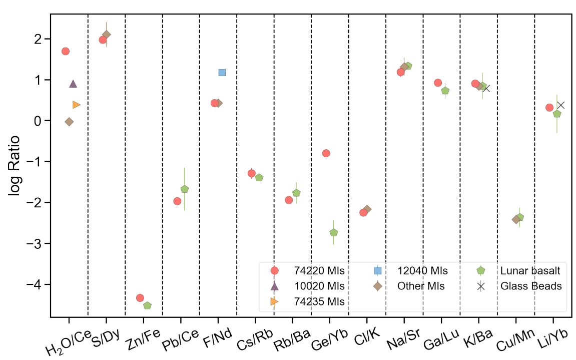

Figure 2. Comparing volatile and moderately volatile elements in 74220 to other lunar samples.

Is 74220 a local heterogeneity? As can be seen from Fig. 2, 74220 has consistant F/Nd, S/Dy, Zn/FeO, Pb/Ce, Cs/Rb, Rb/Ba, Cl/K, Na/Sr, Ga/Lu, K/Ba and Li/Yb ratios compared to other lunar basalt samples studied so far. Given this similarity, it is unlikely that the high H_2O/Ce ratios in 74220 are due to a volatile-enriched origin in the lunar mantle for 74220. Therefore, a straightforward explanation to the large variations in H_2O/Ce ratios is that 74220 is able to better preserve the primitive H_2O signature of the lunar mantle compared to other lunar samples. Based on a H_2O/Ce ratio of ~50 for 74220 and a BSE abundance of 1.675 ppm for Ce [15] in the primitive lunar mantle, the lunar mantle is estimated to contain ~84 ppm H_2O, slightly lower than the result of ~110 ppm as previously reported in [9].

Volatile depletion trend on the Moon: By comparing volatile and moderately volatile element abundances in the lunar mantle and in BSE [15], the volatile depletion trend on the Moon can be estimated (Fig. 3).

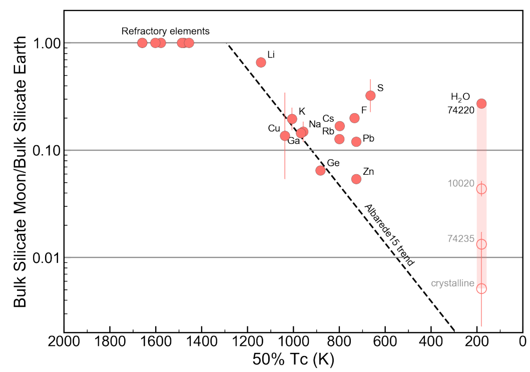

Figure 3. Estimated volatile depletion trend on the Moon based on lunar melt inclusion data.

The estimated volatile depletion trend for the Moon does not correlated well with the half condensation temperatures [16] for the elements. The most distinct feature is that the Moon is not very depleted in volatile elements with 50% Tc < 700K, similar to the observation in [14]. Our estimated depletion trend for the Moon provides important constrains on the model of Moon formation, requiring volatiles to be partially preserved through the giant impact, or delivered to the lunar magma ocean before it fully solidified.

References: [1] Saal A. E. et al. (2008) *Nature*, *454*, 192-196. [2] Boyce J. W. et al. (2010) *Nature*, *466*, 466-469. [3] Boyce J. W. et al. (2014) *Science*, *344*, 400-402. [4] McCubbin F. M. et al. (2010) *PNAS*, *107*, 11223-11228. [5] Barnes J. J. et al. (2014) *EPSL*, *390*, 244-252. [6] Tartese R. et al. (2014) *MPS*, *49*, 2266-2289. [7] Hui H. et al. (2013) *Nat. Geosci.*, *6*, 177-180. [8] Hauri E. H. et al. (2011) *Science*, *333*, 213-215. [9] Chen Y. et al. (2015) *EPSL*, 427, 37-46. [10] Albarede F. et al. (2015) *MPS*, *Nr 4*, 568-577. [11] Ni P. et al. (submitted) *GCA*. [12] Jochum et al. (2006) G^3, *7*, 1525-2027. [13] Ni P. et al. (2017) *EPSL*, *478*, 214-224. [14] Hauri E. H. et al. (2015) *EPSL*, *409*, 252-264. [15] McDonough W. F. et al. (1995) *Chemical Geology*, *120*, 223-253. [16] Lodders (2003), *Astrophys. J.*, *591*, 1220-1247.