HETEROGENEOUS WATER CONTENTS IN THE LUNAR MARE REGIONS SEEN BY THE MOON MINERALOGY MAPPER (M^3) DATA. S. Li[1], G. J. Taylor[1], K. L. Robinson[2], C. Neish[3] and T. Shea[4]. [1]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i. [2]Albion College. [3]Department of Earth Sciences, University of Western Ontario. [4]Department of Earth Sciences, University of Hawai'i. shuaili@hawaii.edu

Introduction: The analysis of Apollo samples suggests that the water content in the lunar interior is very heterogenous [1]. This is in agreement with magma ocean modeling results that the lunar interior is mostly dry and only a few heterogeneously "wet" spots exist [2]. The Ru and Mo isotopic data indicate that the Moon and Earth may share the same building materials [3], suggesting that the mean abundance of volatiles in the lunar interior may be similar to those in Earth's mantle. Magmas sourced from the interior provide windows to probe the hydration levels of the lunar mantle. In contrast to those >3 Ga Apollo samples, recently returned ~2 Ga old Chang'E 5 samples reveal a dry lunar mantle [4]. This indicates that the hydration level of the lunar interior has evolved through geologic time. Orbital detections of excess hydration features at 10 of 11 large pyroclastic deposits may be indicative of a wet lunar interior [5]. However, those pyroclastic deposits are all dated to >3 Ga. Hydration data for areas with ages < 3 Ga on the lunar surface are needed to further understand the evolution of hydration levels in the lunar interior over time.

Lava flows sourced from the lunar interior in the maria may preserve features of the hydration level of the melt. If any excess water is observed in the mare lavas, in comparison to the surrounding background on the lunar surface, it may be indicative of additional sources of water. Solar wind implantation, impact delivery, and degassing of the lunar interior are thought to be three major contributors to the lunar surface water [6], of which solar wind implantation is the most ubiquitous process on the lunar surface. The impact-delivered hydration can be linked to craters and ejecta formed via impact. If excess hydration is only associated with volcanism (e.g., pyroclastic deposits and lava flows), it may strongly indicate an interior origin.

Data & Methods: We examined the hydration levels of the mare region using the water map derived from the M^3 OP2C data [7]. The OP2C data are 280 m/pixel and were mostly (>90%) acquired near the local noon [8]. Earth-based 12 cm and 70 cm radar data were used to understand the subsurface structure, particle size, and possible chemical variations [9]. The TiO_2 map derived from the LROC WAC data was used [10]. The 15 m/pixel Multiband Imager (MI) data were used to estimate the thickness of lava flows based on the penetration depth of craters in the studied regions.

All M^3 data were thermally corrected with our empirical thermal model that was developed from the spectral features of over 600 Apollo and Luna samples. The model was further validated with the independently measured temperatures by the Diviner radiometer onboard LRO [8].

Water, TiO_2, radar CPR, and age information of mare regions are extracted using the outlines of mare basalt units defined in [11].

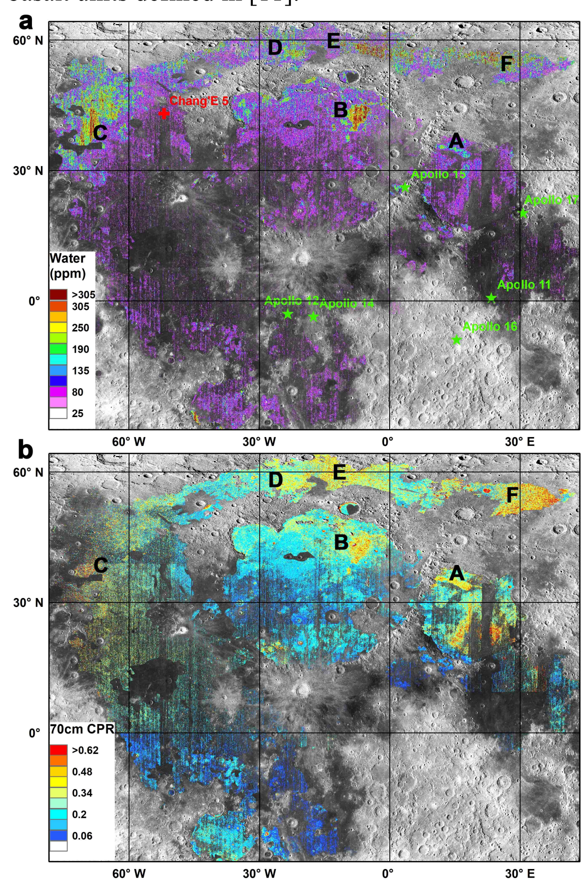

Fig. 1. a. Mapped water contents of basaltic units in the mare region from M^3; sites with returned samples are marked on the map; b. Earth based 70 cm radar CPR maps for the same basaltic units as in a. Letter A-F mark mare units showing water anomalies.

Results: Our global assessment of water anomalies in the lunar mare region suggests that lava flows in the north and center of the mare Serenitatis (A), near Mons Pico in the mare Imbrium (B), northwest of the mare Procellarum (C), and three regions in the mare Frigoris (D-F) all exhibit elevated water contents in comparison to the surrounding background (**Fig. 1a**). However, the LROC WAC albedo map shows no albedo boundaries between high water anomaly regions and their surroundings (the base map in **Fig. 1**). Interestingly, all water anomaly regions exhibit notable elevations in the 70 cm radar CPR map (**Fig. 1b**). We also examined the Earth-based 12 cm radar and Mini-RF CPR maps at these regions and did not find any difference between these regions (A-F in **Fig. 1a**) and their surroundings.

Previous studies suggest that the radar CPR is dominantly affected by wavelength-sized boulders, the element Ti, and rough layer surfaces/interfaces [12]. The TiO_2 map derived from the LROC WAC data at the A-F regions show no notable difference in TiO_2 contents from the surrounding background. However, the water-anomaly regions mostly show very low TiO_2 content. Because other low-TiO_2 regions show no water anomalies, a causal link seems unlikely. The CPR features of the A-F regions are not associated with large impacts and hence are unlikely impact melt flows [13]. A more likely source is from volcanic activity, which would imply that the elevated hydration level could be associated with volcanism.

We also derived the means and standard deviations of the water content at each mare units defined in [11] and plotted them with the age of each mare unit (**Fig. 2**). Heterogenous water contents are seen in mare units with ages from 3 – 4 Ga, while a substantial decline in the water content of mare units younger than 3 Ga is observed (**Fig. 2**) This could be due to the strong degassing of the lunar interior when the flux of volcanic activity was higher before 3 Ga ago. This trend seems consistent with measurements of Apollo samples[4]. However, it is unclear whether the consistency between orbital observations and sample analyses is a true reflection of lunar interior water locked in lava flows or is a coincidence. Future sample returns from these water anomaly regions or rover explorations can help to resolve this question.

Discussion: Previous radar observations suggest that the 70 cm CPR anomaly at regions near north of Serenitatis (A) and Mons Pico (B) could be either due to rugged lava flows or small reduction (~2 wt%) of TiO_2 content that cannot be seen by the 12 cm radar [12, 14]. However, the TiO_2 contents at the A-F regions and their surroundings are all very low (~1 wt%) [10]. Thus, the hypothesis of rugged lava flows in these regions seems favored to explain the 70 cm CPR anomaly.

Lava flows at these regions in Fig. 1a could be similar to pahoehoe or transitional pahoehoe flows on Earth. Inflation of melt during emplacement may have generated rough interfaces that can enhance the radar echo after being broken down by impacts. MI data suggest that the lava flow could be around 15 m thick. The upper few m may have been gardened to fine regolith by impact and consequently cannot be sensed by the 12 cm radar. In contrast, the 70 cm radar can sense 5 – 7 m or even deeper where large chunks of rough lava interfaces may still exist and enhance the 70 cm radar echo.

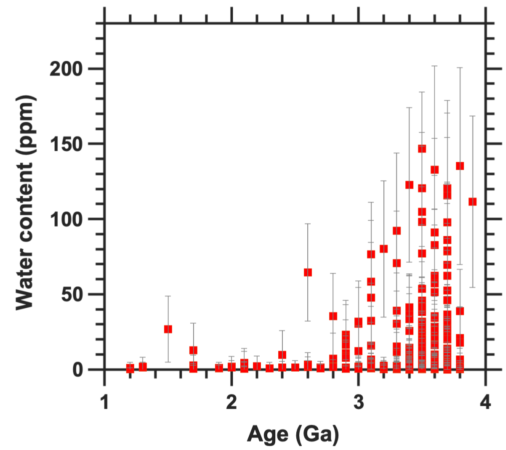

Fig. 2. The relationship between the mean water content and the ages of mare basaltic units in **Fig. 1**.

The observed elevated hydration features in the A-F regions cannot be introduced by thermal correction of M^3 data nor viewing geometry. Unreasonably high temperatures would be required to remove enough thermal components at the surrounding regions to produce similar water absorptions as those of water anomaly regions. This is physically impossible, because all M^3 data across these regions were acquired near local noon. There is no reason to believe that the water anomaly regions should be substantially cooler than the surrounding regions at local noon. All M^3 data from our study regions were photometrically corrected to a standard view geometry to derive their water content. Thus, the water anomalies in A-F cannot be introduced by photometry issues.

Conclusion: Water anomalies observed in several mare regions that may reflect the conditions of lava flow emplacement (as pahoehoe rather than \`a\`a flows). This is consistent with observations on Earth that pahoehoe lavas are normally richer in water content than \`a\`a flows.

References: [1]. Robinson, K.L. and G.J. Taylor. Nat Geosci, 2014. [2]. Elkins-Tanton, L.T. and T.L. Grove. EPSL, 2011. [3]. Worsham, E.A. and T. Kleine. Sci. Adv., 2021. [4]. Hu, S., et al. Nature, 2021. [5]. Milliken, R.E. and S. Li. Nat Geosci, 2017. [6]. Watson, K., et al. JGR, 1961. [7]. Li, S. and R.E. Milliken. 2017. [8]. Li, S. and R.E. Milliken. JGR, 2016. [9]. Campbell, B.A., et al. JGR, 2014. [10]. Sato, H., et al. Icarus, 2017. [11]. Hiesinger, H., et al., 2011, GSA. [12]. Campbell, B.A., et al. GRL, 2009. [13]. Neish, C., et al. Icarus, 2017. [14]. Morgan, G.A., et al. JGR, 2016.