ORBITAL EVIDENCE FOR WATER IN PYROCLASTICS AT TAURUS-LITTROW AND OTHER DARK MANTLE DEPOSITS ON THE MOON: ABUNDANCE, RESOURCE IMPLICATIONS, AND FUTURE DIRECTIONS. R. E. Milliken[1], S. Li[2], C. Huber[1]. [1]Dept. Earth, Environmental & Planetary Sciences, Brown University, Providence, RI 02912 Ralph_Milliken@brown.edu, [2]Hawai'i Institute of Geophys. & Planetology, Univ. of Hawai'i at Manoa, Honolulu, HI 96822.

Introduction: One of the most exciting areas of research in lunar science over the past decade has been the recognition and quantification of water (hereafter used to include OH and H_2O) in returned lunar samples [1-4 and refs. therein]. Though not without controversy, such results can place important constraints on the formation conditions and magmatic evolution of the Moon, all of which highlight the importance of *in situ* exploration and sample return. Water has been measured in a range of lunar materials, including basalt, anorthosite, agglutinate, and volcanic glasses [3]. For the latter, orange glass beads from Apollo 17 and olivine-hosted melt inclusions within those beads have been particularly informative for constraining post- and pre-eruptive water contents in a high-Ti lunar magma [1,4].

Though critical for piecing together the history of the Moon, the returned Apollo and Luna samples represent only a small fraction of the lunar surface. In addition, glass beads from the central regions of the numerous lunar dark mantle deposits (DMDs) [5] have not been sampled directly in place. These larger DMDs may be more representative of lunar pyroclastic eruption processes on the Moon as a whole. Fortunately, there exist a variety of global datasets acquired by orbiting spacecraft, and remotely sensed compositional information for large scale pyroclastic deposits (DMDs) may provide a link to lab measurements of volcanic glasses in the Apollo collection.

It has been previously shown that near-infrared (NIR) reflectance spectra of the lunar surface exhibit absorptions in the ~2.65-4 μm wavelength region that are diagnostic of OH/H_2O [6-9]. At a global scale, these spectral signatures are largely consistent with formation of OH due to solar wind interactions with the lunar regolith [6-9], consistent with direct measurements of water in agglutinitic glass that is formed during lunar space weathering [10]. However, recent analyses of NIR data acquired by the Moon Mineralogy Mapper (M^3) instrument have revealed the presence of water absorptions in nearly all previously mapped DMDs, including those at Taurus-Littrow [11].

Here we present an overview of water in lunar pyroclastic deposits as derived from M^3 data, with a focus on deposits at Taurus-Littrow and links to Apollo 17 samples. We discuss estimates of water content based on the spectral data and ongoing efforts to refine such estimates in order to bridge the gap between orbital data and 'ground truth' from returned samples.

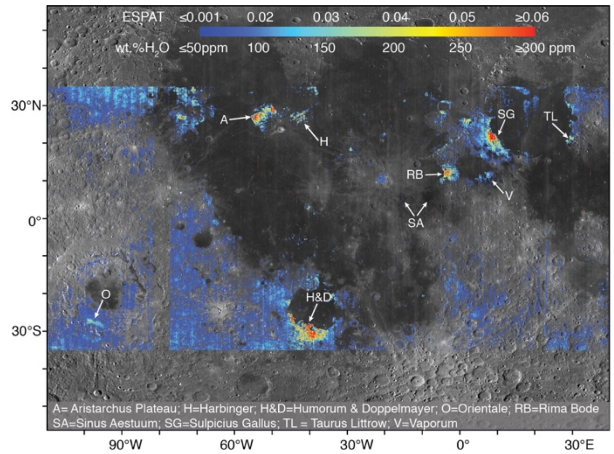

Figure 1. Water content of the lunar surface derived from M^3 data and as reported in [11]. Large DMDs are labeled and exhibit higher water contents compared with adjacent terrains.

Methods: A critical step in order to assess the presence and strength of water absorptions in M^3 data is the removal of thermally emitted radiation at wavelengths >2 μm in order to isolate solar radiation reflected by the surface. Our analysis uses the thermal correction method of [12], and the thermally corrected M^3 reflectance spectra are converted to single scattering albedo using the model of Hapke, which accounts for photometric variations due to differences in viewing geometry and reduces effects of multiple scattering.

Lab spectral measurements have shown that water absorption strengths calculated based on single scattering albedo are linearly related to water content for a wide variety of hydrated phases, including water-bearing glasses of lunar composition [11]. We use this lab-based trend to convert water absorptions in M^3 data to estimates of water content for DMDs and the Taurus-Littrow region (Fig. 1-2). A similar linear relationship to water content does not commonly exist when using 'band depth' values calculated from reflectance spectra; those values often exhibit false correlations with albedo. Use of single scattering albedo in order to avoid this effect is particularly important to consider for lunar DMDs, which are commonly darker than other lunar materials.

Results: As reported in [11], nearly all previously mapped DMDs exhibit a distinct increase in water absorption strength compared with their surrounding terrains. This is true for regional/large pyroclastic deposits that have been studied for decades as well as some potential smaller DMDs that have been identified in more recent LRO images [13]. After subtracting a potential 100 ppm water due to solar wind implantation, estimated water contents for DMDs have average values of ~50-150 ppm, with local enhancements of ~300-400 ppm near potential vent regions (Fig. 1) [11].

Though spectra of most lunar pyroclastic deposits exhibit water absorptions that are clearly stronger than adjacent terrains, converting absorption strengths to estimates of absolute water content requires knowledge or assumption of particle size. In this work we assume DMDs are dominated by particles ~6-80 µm in diameter, similar to measured mean values for Apollo soils enriched in glass beads. Despite uncertainties associated with this assumption, estimated water content values for pyroclastic deposits closest to Taurus-Littrow and the A17 site are predominantly <150 ppm, and many pixels exhibit water contents <50 ppm water (Fig. 2). For comparison, up to ~30-50 ppm water has been directly measured for A17 orange glass beads [14]. Higher water contents have been measured for olivine-hosted melt inclusions in orange glasses from A17 [4], but such features are too small to be resolved by means of remote sensing.

Implications & Future Directions: Water contents for DMDs estimated from M^3 data are commonly higher than values that have been directly measured in the Apollo volcanic glasses. Several factors can affect the amount of water that is present in a glass bead, including degassing history and the volatile content in the original magma source region. For the NIR spectra, the largest source of uncertainty in estimates of water content is the uncertainty in the particle size distribution of DMDs. Despite what appears to be an intriguing overlap in the range of water contents estimated from M^3 data of pyroclastics closest to Taurus-Littrow and lab measurements of A17 orange glasses, it remains difficult to ascertain if this is serendipity or actual agreement between methods of fundamentally different spatial scale.

Higher water contents estimated from M^3 data may indicate that some lunar pyroclastic deposits are less degassed than glasses in the Apollo collection, perhaps retaining water contents that are closer to values of magma source regions. Or, observed differences in water content between DMDs may reflect variations in water content of magma source regions and thus the lunar mantle. Though the data are sparse, interpreted high-Ti pyroclastic deposits (such as those at Taurus-Littrow) yield higher water content values in the M^3 analysis than interpreted lower-Ti deposits [11]. If true, such a trend would be consistent with either differences in degassing history or water content of magma source regions.

Alternatively, water contents based on M^3 data may be overestimated due to imperfect knowledge of particle sizes within the DMDs. Ongoing work is focused on integrating parameters derived from remotely sensed data (M^3) with magma ascent and eruption models [15] to further constrain particle size in these deposits. In effect, the observed distribution of volcanic glass around a vent and initial estimates of water content can be used to solve the eruption model inversely, which then leads to a new estimate of glass distribution, particle size, and water content (accounting for diffusion). The process can be iterated until acceptable agreement is achieved between the parameters predicted by the eruption model and the observed distribution of volcanic glass based on M^3 data.

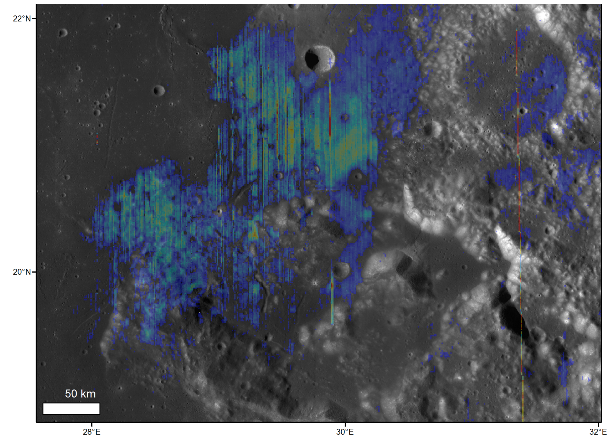

Figure 2. Close-up water map of DMD at Taurus-Littrow region. Color scale is same as in Fig. 1

Because the most glass-rich portions of DMDs have not yet been directly sampled, it is difficult to determine which, if any, of the complicating factors discussed above (degassing, heterogeneity in magma source regions, particle size), can be ruled out. This highlights the need for continued *in situ* exploration of the Moon and for the return of glass-rich samples from a more central region of a large pyroclastic deposit. Water observed in the Apollo 17 glasses and corresponding orbital data also raise questions about whether or not pyroclastic deposits may provide a viable source of water for a sustained human presence on the lunar surface. Perhaps fittingly, samples from what was the final Apollo expedition may thus hold some of the answers as to why and how to return to the Moon for longer duration.

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