TOOLBOX FOR RESEARCH AND EXPLORATION (TREX): INVESTIGATIONS OF FINE PARTICULATE MATERIALS ON THE LUNAR SURFACE.

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Introduction: The Toolbox for Research and Exploration (TREX) is a NASA SSERVI (Solar System Exploration Research Virtual Institute) node. TREX (trex.psi.edu) aims to decrease risk to future missions, specifically to the Moon, the Martian moons, and near-Earth asteroids, by improving mission success and assuring the safety of astronauts, their instruments and spacecraft. TREX studies will focus on characteristics of the fine grains that cover the surfaces of these target bodies – their spectral characteristics and the potential resources (such as extractable volatiles) they may harbor. TREX studies are organized into four Themes: Laboratory Studies [1], Moon Studies, Small-bodies Studies [2] and Field Work [3]. Here we focus on lunar studies with an emphasis on investigations of fine-grained materials on the lunar surface.

Moon Studies: The Moon is the only Solar System body humans have visited, and is a likely future human destination. Our investigations, now in the beginning phases, will combine measurements acquired under lunar conditions (vacuum and a range of temperatures) from the Lab Studies theme [1], with lunar spacecraft data and modeling techniques to characterize lunar particle size, mineralogy, thermal attributes, space weathering effects, and correlations with geologic features. Our overarching goals are to expand our understanding of the Moon scientifically, and as a target for future human and robotic exploration [3], and to address ISRU and future instrument development needs.

Investigation of regolith particle sizes on the Moon. We are investigating the influence of particle size on thermally derived surface temperatures and thermal inertia to produce particle size maps of the Moon. An understanding of the distribution of particle sizes in the lunar regolith is an important tool for human mission planning, crew safety, and for identifying strategic areas for ISRU activities. Recent advances in our understanding of the thermophysical properties of the lunar surface, based on data from the Lunar Reconnaissance Orbiter (LRO) Diviner thermal radiometer [e.g. 4-5], have led to a new suite of methods for probing the physical properties of the lunar regolith. For instance, the fact that the two major physical materials present at the lunar surface— large rocks with high thermal inertia and fine materials with low thermal inertia— radiate at different temperatures during the lunar night provides the ability to retrieve the fraction of surface rocks and the temperature of the rock-free regolith [6]. Comparisons between Diviner rock abundance and Earth-based or orbital radar observations, the latter of which are sensitive to wavelength-scale scatterers on the surface and within the upper 1-10 m of regolith, also reveal the presence of buried ejecta from impact craters and constrain the depth of regolith or pyroclastic deposits [e.g., 7-8].

Because thermal conductivity ultimately controls thermal inertia, we are exploring how this quantity depends on particle size via the contact between grains under lunar conditions [9]. Using different estimates for the temperature-dependent behavior of thermal conductivity, we investigate the sensitivity of thermal inertia derived from observed nighttime temperatures to variations in particle size and packing, seeking to determine whether particle size variations produce a recoverable signal in the data, and on what scale. This provides a means of interpreting thermal inertia in terms of particle size. Combining all our results from Diviner rock abundance, radar observations, and interpretations of the calculated thermal inertia, we will produce global particle size maps. We have begun to move the Diviner data set onto the Amazon Elastic Compute Cloud, where parallel disks can be exploited to achieve high throughput for data processing.

Integrating laboratory data and lunar remote sensing spacecraft data. These investigations focus on select lunar targets of interest and incorporate lab results with spacecraft remote sensing data and our results of particle-size characteristics and spatial distributions. For example, we are comparing our lab measurements of lunar samples and minerals with infrared data from the Moon Mineralogy Mapper (M^3) and UV data from the LRO Lyman Alpha Mapping Project (LAMP). Results of this analysis will further our understanding of how the finer fraction of particle sizes affects the spectra over these wavelength ranges, how lab data can improve interpretations of the spacecraft data, the sensitivity of UV wavelengths to space weathering effects in the finest grains, and insight into payloads which would be most beneficial for future spacecraft investigating ISRU potential. Inputs from spacecraft data and lab work are also paired with numerical models to understand the role of impacts in the surface expression of lunar mineralogy. We investigate the nature of and sources of optically immature materials to assess the relationship between optical maturity and particle size. For example, analyses of boulder size-frequency distributions, particularly those relating to rayed lunar craters, incorporated with optical maturity (OMAT) maps, and radar data [e.g. 10] provide new insight into impact processes, illuminate size bias with respect to ejecta maturity, and better characterize changes in lunar soils with time. We also compare LRO LAMP and M^3 data of optically immature and mature regions of similar mineralogy to gain further insights into the processes behind space weathering effects.

The spectral characteristics of various lunar surface features may serve as a probe into the Moon's formational history and, while advancing our understanding of materials available and important for ISRU, can provide insight into scientific questions. For example, we are investigating silicic volcanic features, pyroclastic deposits, and cryptomaria, to inform models of the thermal and volcanic history of the Moon. The vertical mineralogical structure of the lunar crust can be sampled through studying outcrops of olivine, Cr- and Mg-spinel excavated from the crust and mantle of the Moon located in/near large impact crater features [e.g. 11-12]. In addition, photometric measurements of surface features using LRO images, coupled with laboratory spectral analyses, will augment M^3 observations to infer mineralogy at surface locations [13-14]. Elemental data from the Lunar Prospector Gamma Ray and Neutron Spectrometers (LP-GRS/NS) provide additional constraints on mineralogy to characterize regions with anomalous composition. With the LPNS data set we can directly solve for the concentration of specific elements and/or mixing fractions of petrologic end members [15-16]. The elemental data are representative of the bulk regolith to depths of a few decimeters, potentially providing constraining compositional layering.

Lunar ISRU Studies. Future spacecraft will need to conduct in-situ assessment of needed resources [e.g. 17] such as water for spacecraft propellant, water or gases needed to sustain astronauts, geologic materials for building and repair, and other scientific questions. The ability to locate and identify these materials is a critical requirement for in-situ assessments. Employing results from our lab studies and lunar investigations, we are addressing questions such as: How do locations of volatiles (e.g. OH/H_2O) and other resources correlate with particle size and mineralogy and what are the implications? Do fine-grained areas with initial higher porosity mark locations of higher abundances of volatiles/resources?

Though H_2O is known to exist in polar permanently shadowed regions [e.g. 18-19], our TREX studies focus on hydration at lower latitudes that is more accessible for future human missions [e.g. 20-22], but not well understood. We are linking LAMP hydration signatures with geologic features and studying relationships with M^3 data. Far-UV wavelengths are sensitive to the uppermost <~100 nm of the lunar regolith, suggesting that the hydration sensed by LAMP on the lunar dayside is surficial and transient. This has important implications for hydration formation, lifetime, and migration in the regolith.

In addition to studying LRO-measured diurnal hydration variations and comparisons with M^3 measurements, we also compare results with our lab measurements of UV reflectance signatures of lunar minerals with and without ice mixed in, and with monolayers of H_2O injected onto the top of the sample powders. This will be a critical test of the sensitivity of the UV spectral hydration feature to monolayers of material, and could provide evidence for the physics of diurnally varying lunar hydration at the molecular level. There are small areas scattered around the Moon, including some young craters, with enhanced OH/H_2O. We will combine the results of the global maps of [23], made at full M^3 spatial resolution, with the LRO LAMP data [e.g. 22], and our particle size studies, to derive maps of potential resources.

Finer-grained areas are potential locations where higher abundances of volatiles such as OH and H_2O may exist. As they have a larger specific surface area, layers of smaller particles represent a stronger diffusion barrier for buried ice, and they have a larger specific surface area and hence a higher adsorption capacity [24-25]. Therefore, particle size is an important parameter in defining expectations of volatile abundance. Based on thermal inertia maps from the Diviner instrument, we are also producing maps of subsurface ice stability that incorporate particle size in addition to temperature and topography. We incorporate into this effort our understanding of the relation between thermal inertia and particle size, estimates of the amount of adsorbed H_2O, based on the specific particle-size surface areas measured in Apollo samples and on temperature [26], and evaluate the depth to 'stable' ice based on the vapor diffusivity of the surface layer and temperature [4].

References: [1] Lane, M. D. et al. (2018) *this conf.* [2] Domingue, D. L. et al. (2018) *this conf.* [3] Noe Dobrea, E. Z. et al. (2018) *this conf.* [4] Paige, D. A., et al. (2010) *Science*, 330(6003), 479-482. [5] Hayne, P. O., et al. (2017) *JGR*, in press. [6] Bandfield, J. L. et al. (2011) *JGR*, 116, E00H02, doi:10.1029/2011JE003866. [7] Ghent, R. R. et al. (2016) *Icarus*, doi:10.1016/j.icarus.2015.12.014. [8] Carter, L.M. et al. (2015) *AGU*, abstract P51C-2072. [9] Gundlach, B. and Blum, J. (2013) *Icarus*, 223, 479-492. [10] Neish C. et al. (2013) *JGR*, 118, 2247-2261. [11] Tompkins, S., and Pieters, C. M. (1999) *Met. and Plan. Sci.*, 34 (1), 25–41. [12] Wieczorek, M. A., and Zuber, M. T. (2001) *GRL*, 28, 4023–4026. [13] Clegg, R.N. et al. (2014) *Icarus, 227,* 176-194. [14] Clegg-Watkins, R. N. et al. (2016) *Icarus,* 273, 84-95. [15] Prettyman, T. H., et al., (2006) JGR **111**(E12), E12007, doi: 10.1029/2005JE002656. [16] Prettyman, T. H. and McSween Jr., H. Y. (2011) *LPS*, Abstract #2731. [17] Graps, A. et al. (2016) Asteroid Intersections with In-Space Mine Engineering, spaceresources.lu. [18] Gladstone, G. R., et al. (2012) *JGR*, doi:10.1029/2011JE003913. [19] Hayne, P, O. et al. (2015) *Icarus*, 255, 58-69. [20] Vilas, F. et al. (2008) *Earth, Planets, Space*, 60, 67. [21] Clark, R. N. (2009) *Science*, 326, 562–564. [22] Hendrix, A. R. et al. (2012) *JGR,* doi:10.1029/2012JE004252. [23] Clark, R.N. et al. (2016) *LPSC.* [24] Hodges, R. R., Jr. (2002) *JGR*, 107(E2). [25] Cocks, F. et al. (2002) *Icarus*, 160, 386–397. [26] Cadenhead, D. A., & Stetter, J. R. (1974) *LPSC.*