INVESTIGATIONS OF YOUNG TECTONIC STRUCTURES: DATA COLLECTION TO ASSESS RESOURCE POTENTIAL AND SEISMIC HAZARD CHARACTERIZATION. M. E. Banks[1], R. N. Watkins[2], J. A. Grier[2], L. S. Schleicher[3], T. R. Watters[4], N. C. Schmerr[5], M. Bensi[5], R. C. Weber[6], C. H. van der Bogert[7], J. T. S. Cahill[8], M. Lemelin[9], T. M. Hahn Jr.[10], J. D. Clark[10], N. R. Williams[11], and H. Hiesinger[7]. [1]NASA Goddard Space Flight Center, Greenbelt, MD, USA, maria.e.banks@nasa.gov [2]Planetary Science Institute, Tucson, AZ, USA, [3]Independent Researcher, lisaschleicher.org, [4]Smithsonian Institution, National Air and Space Museum, Washington, DC, USA, [5]University of Maryland, College Park, MD 20742, USA, [6]NASA Marshall Space Flight Center, Huntsville AL, USA, [7]Institut für Planetologie, Münster, Germany, [8]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, [9]Dept. Géomatique appliquée, Université de Sherbrooke, Sherbrooke, Canada, [10]School of Earth and Space Exploration, Arizona State University, AZ, USA, [11]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA USA.

Introduction: Lunar lobate scarps (Fig. 1), or thrust fault scarps, are widespread across the lunar surface. They are among the youngest landforms on the Moon, with some likely still active today [1-4]. The relatively young age of the lunar scarps is supported by their pristine morphology and cross-cutting relationships with small diameter craters [3, 5]. Absolute ages estimated from infilling rates for small-scale back-scarp graben [6], and from the size-frequency distributions of impact craters proximal to the scarps, show that most studied scarps were active in the late Copernican (<400 Ma), and that fault activity caused surface renewal and disturbance (erasure of craters <~20-100m in diameter) up to kilometers from the scarp trace itself [7, 8]. Additionally, a recent study connected lobate scarp thrust faults with revised epicenter locations for shallow moonquakes detected by seismometers emplaced during Apollo missions [9]. Preliminary results from investigations of lobate scarps using multiple data sets (i.e., Optical Maturity Index (OMAT), Lunar Reconnaissance Orbiter (LRO) photometry) revealed no distinctive signatures for the scarps or surrounding surfaces in OMAT images, but distinct differences immediately on or proximal to the scarp faces in photometric parameter maps [10]. Evaluated together, these differences in photometric values may indicate variations in maturity and/or backscattering characteristics, and therefore differences in physical properties (i.e., increased surface roughness, redistributed regolith particulates, and/or altered grain sizes and shapes due to particles breaking apart during seismic shaking from slip events) between surface materials on the scarp and on the surroundings [11, 12].

These findings have important implications for future human and robotic exploration in highlighting lobate scarps as: 1) unique structures of scientific interest, 2) locations that may host resources (for example, fresh/redistributed regolith particles with large surface areas that may preferentially sequester volatiles, such as OH), and 3) possible hazards due to potentially ongoing seismic activity. The Artemis lunar exploration program will explore the region surrounding the lunar south pole with robotic and human surface operations. Figure 1 shows an example of a lobate scarp (unofficially named Shoemaker, 86.28ºS, 54.68ºE) [13] in this region. The Shoemaker fault scarp is also located within kilometers of several permanently shadowed regions (PSRs), which are also high priority landing sites due to their potential to harbor resources. Studies have shown the PSRs in Fig. 1 to be accessible and to have confirmed water ice in Moon Mineralogy Mapper data [14].

Here we present several surface investigations aimed at: increasing our scientific understanding of these scarps, collecting valuable data to inform models to evaluate the seismic hazard, and characterizing surface and near-surface materials that have been disturbed by ground motion from coseismic slip events to assess how they might inform and benefit future surface activities. Site-specific estimates of the shear-wave velocity in the lunar south polar region are essential for producing accurate seismic hazard evaluations that will be important for designing safety-related structures, systems, and components for a future lunar operating environment.

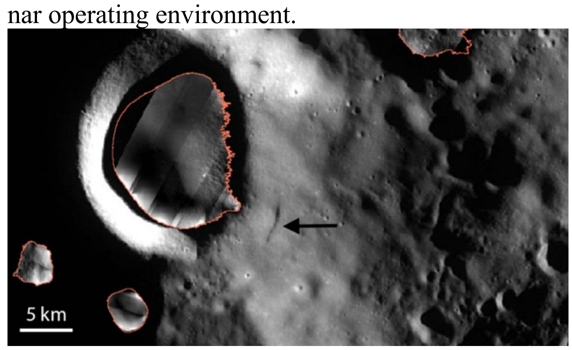

Figure 1. *LRO camera (LROC) mosaics showing Shoemaker lobate scarp (black arrow, 86.28ºS, 54.68ºE) [13] and nearby PSRs (outlined in orange).*

Surface Investigations: *Characterization of surface and near-surface materials:* Lunar lobate scarps often display a deficit of small craters in their immediate vicinity and are distinct from surrounding terrain in photometric investigations, but show no distinctive differences in OMAT [7, 8, 10]. It is not yet unknown what mechanisms are responsible for this. Seismic waves attenuate less rapidly on the Moon compared to the Earth. This likely moves and shakes particles, perhaps in some way akin to acoustic fluidization, breaking them apart and potentially increasing surface roughness, and perhaps resulting in softening and erasure of small craters. If seismic shaking is sorting the upper regolith in a way similar to the 'desert pavement' phenomenon, dust could also be sequestered between grains which may benefit surface operations.

We propose surface investigations to characterize the size-frequency distribution of particles in the very near surface. This could be done by using a tool to dig one or several distributed shallow trenches, a shallow regolith drill to obtain core samples from a few centimeters to a meter or so depth, or by repeating pounded core experiments similar to those done by the Apollo astronauts. Detailed analysis of layers in trenches or core samples (that ideally could be returned to a lab for detailed analysis), will provide insight into the sorting of fines, distribution of dust, layer depth and thickness, and variations in particle size and characteristics (cohesion, petrography, density/porosity, particle shapes, etc.) with depth and along and distal to the scarp face. These soil properties would need to be compared with measurements/cores made at a reference site away from a scarp, which could also serve as a reference for any cores taken in PSRs. Additionally, the spectra on the scarp face could be measured and used to estimate the degree of space weathering. This could then be compared with more distal surroundings to estimate the rate of optical maturation at these sites.

In the vicinity of the lobate scarp, we also propose use of instruments designed to measure the volatile content in the lunar soil (via rover or astronaut) and to demonstrate the possibility for extraction. The bulk hydrogen of the regolith on the surface of the scarps and immediately surrounding the scarps could be measured using a neutron spectrometer. Water and hydroxyl content could be evaluated with a near-IR spectrometer. The vertical distribution of volatiles could be obtained from samples retrieved from a variety of depths, potentially using the same core samples as used to assess particle sorting with depth.

Seismic hazard characterization: To assess lobate scarps as seismic hazards, we propose surface operations to inform a preliminary probabilistic seismic hazard analysis (PSHA) for the Moon. A PSHA consists of 3 components: Seismic Source Model, Ground Motion Model, and Site Response Model [15, 16]. We propose Artemis astronauts deploy instruments, including seismometers and a geophone array (similar to what is deployed in the field on Earth) on a south polar fault scarp (such as Shoemaker; Fig. 1), perform an active source survey of the fault in the subsurface, and leave a passive monitoring instrument to determine the seismicity and associated ground motion that might occur in the vicinity of the fault. For the active source survey, we propose an approach similar to the Active Seismic Experiments used in Apollo, including astronaut deployed devises similar to the "thumpers", or explosive charges or small mortars to be detonated after the astronauts and/or rover have departed the site.

Results from these field investigations would provide valuable information on fault dip angle, dip direction, fault geometry (i.e., planar or listric), and depth of faulting. This data is essential for constraining fault parameters for modeling the source. A traverse with a GPR with a frequency range down to about 100 MHz (via astronaut or rover) might reveal the near-surface part of the thrust fault and its geometry. Ideally a seismic survey would enable imaging of the fault to even greater depths and support estimation of ground motions.

If a lobate scarp is not directly accessible to astronauts or a rover, we propose simply deploying a single seismometer at sites of interest to acquire horizontal-to-vertical spectral ratios [e.g., 17, 18]. Seismic observations collected in any typical south polar terrain would enable comparison with the near-side terrains where the Apollo-era seismometers were located (three in mare and one in highlands terrain) and preliminary information on the fundamental resonance of the site needed to produce an accurate site response analysis. An array of seismometers deployed at any sites visited across the south polar region would provide valuable data for informing ground motion models. Seismometers could also be deployed traversing crater walls, (such as the crater hosting a PSR in Fig. 1), to provide key information regarding topographic amplification [19] which can significantly enhance quake ground motions. This is essential for seismic hazard characterizations for sites located on crater rims near PSRs to understand surface-wave affects common in basins.

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References: [1] Watters T. R. and Johnson C. L.(2010) in *Planetary Tectonics*, Cambridge Univ. Press, 121–182. [2] Binder A. B. (1982) *Earth, Moon, and Planets, 26*, 117–133. [3] Binder A. B. and Gunga H.-C. (1985) *Icarus, 63*, 421-441. [4] Schultz P. H. (1976) University of Texas Press, Austin, TX. [5] Watters T. R. et al., (2010) *Science*, 936-940. [6] Watters T. R. et al. (2012) *Nature Geoscience*, DOI: 10.1038/NGEO1387. [7] van der Bogert C. H. et al. (2018) *Icarus*, *306*, 225-242. [8] Clark J. D. et al. (2015) *LPSC XLVI*, Abstract #1730. [9] Watters T. R. et al., (2019) *Nature Geoscience,* DOI:10.1038/s41561-019-0362-2. [10] Banks M. E. et al., (2019) *LPSC L*, Abstract #2577. [11] Sato et al. (2014) *JGR*, *119*, 1775-1805. [12] Hapke B. (2012) *Icarus, 221,* 1079-1083. [13] Watters T. R. et al., (2015) *Geology*, 43, 851–854. [14] Lemelin M. (2020) *LPSC LI*, Abstract #1197. [15] Nuclear Regulatory Commission, Regulatory Guide 1.208 (2007). [16] Schleicher et al., (2019) *LPSC LI*, abstract 3064. [17] Nakamura, Y. (1989) *Q. Rep. Railway Tech. Res. Inst*. 30, 25–33. [18] Kawase, H. et al., (2019) *Soil Dynamics and Earthquake Engineering*, doi: 10.1016/j.soildyn.2018.01.049. [19] Stolte A. C. et al., (2017) *Bulletin of the Seismological Society of America*, *107*, 1386-1401.