YOUNG THRUST FAULT SCARPS AS TARGETS OF OPPORTUNITY FOR EXPLORATION AND SEISMIC HAZARD CHARACTERIZATION. T. R. Watters[1], M. E. Banks[2], L. S. Schleicher[3], N. C. Schmerr[4], M. T. Bensi[4], R. C. Weber[5], C. R. Neal[6], C. L. Johnson[7,8], Y. Nakamura[9], M. S. Robinson[10], and others. [1]Smithsonian Institution, Washington, DC, USA, watterst@si.edu, [2]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [3]Independent Geophysicist, now at the USGS, Menlo Park, CA, USA, [4]Univ. of Maryland, College Park, MD, USA, [5]NASA Marshall Space Flight Center, Huntsville, AL, USA, [6]Univ. of Notre Dame, Notre Dame, IN, USA, [7]Univ. of British Columbia, Vancouver, BC, [8]Planetary Science Institute, Tucson, AZ, [9]Univ. of Texas at Austin, Austin, TX, USA, [10]Arizona State Univ., Tempe, AZ, USA.

Introduction: In 1972, Apollo 17 astronauts Harrison (Jack) Schmitt and Eugene Cernan were the first humans to make a field examination of a fault scarp on another planetary body. Although the Lee-Lincoln scarp (~20.2°N, 30.6°E) is not an imposing feature in the Taurus-Littrow valley landscape, when Cernan and Schmitt attempted to drive straight up the scarp face with the Lunar Roving Vehicle (LRV), the wheels lost traction and they had to steer across-slope to reach the top of the ~80 m high fault scarp.

Lobate scarps (Fig. 1) are the result of thrust faulting; i.e., contractional faults that displace crustal materials up and over adjacent terrains [1-3]. It is now known that these faults are broadly distributed throughout the lunar highlands [3-5], are forming some of the youngest landforms on the Moon, and are likely still tectonically active today [5]. There are at least three clusters and two individual fault scarps in the Artemis III landing site area within 6° of the south pole, with additional fault scarps likely in permanently shadowed regions (PSRs).

The relatively young age of the lunar scarps is supported by their size, pristine morphology, and cross-cutting relationships with small diameter craters [3]. 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 <~20-100 m in diameter) up to kilometers from the scarp trace itself [7, 8].

Lunar seismicity was recorded by four seismometers placed at the Apollo 12, 14, 15 and 16 landing sites. These seismometers recorded 28 shallow moonquakes (SMQs) [9]. A recent study connected lobate scarp thrust faults with clusters of relocated epicenters of SMQs [5]. One of the strongest SMQs recorded occurred in 1973 with a body wave magnitude >5.6 and an epicenter near the south pole (84°S, 134°W) [9, 10]. Relocated epicenters of this event with surface solutions fall within 6° of the south pole [5].

Evidence of recent coseismic slip events may be expressed by disturbed regolith from downslope creep or landslides that exposed fresh material with a higher albedo than the surrounding mature regolith (darkened by space weathering [5, 11]). Fresh boulder fields in relatively high albedo patches may also be evidence of recent changes resulting from seismic shaking [5]. Boulder movements or falls expressed by tracks in the regolith are common near lobate scarps, likely triggered by coseismic slip events on related thrust faults [3, 5, 12].

Human exploration of lobate thrust fault scarps offers the opportunity to: 1) make measurements and detect secondary structures that provide insight in the kinematics of scarp formation, 2) sample rocks and materials transported from depth by thrust faults, 3) sample recently exposed fresh or redistributed rocks and regolith, 4) evaluate possible hazards due to potentially ongoing seismic activity, and 5) deploy a geophysical station near a scarp. Depending on the location of the landing site, the Artemis III astronauts may have the opportunity to explore a possibly active lunar fault formed by a combination of global contraction and tidal forces.

Here we offer suggestions for the investigation of young fault scarps that will increase our scientific understanding of these landforms, allow collection of fault-related samples of exhumed and disturbed rocks and regolith, and obtain critical data necessary to evaluate lunar seismic hazards. Both modeled and direct measurement of magnitudes of SMQs from coseismic slip events on the thrust faults are important for designing shake-tolerant structures, systems, components, and instruments employed in a future lunar operating environment.

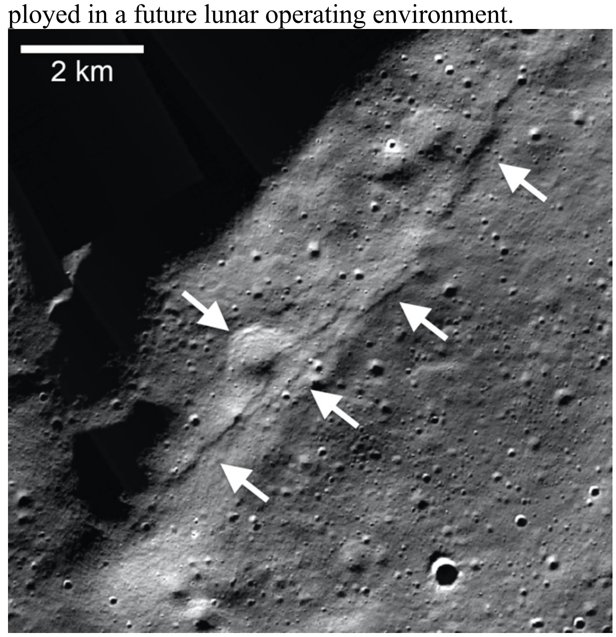

***Figure 1**. Lunar Reconnaissance Orbiter Camera (LROC), Narrow Angle Camera (NAC) mosaic of the Wiechert cluster of lobate scarp (left pointing arrows) near the south pole. A scarp crosscuts an ~1 km degraded crater (right pointing arrow).*

Exploration of Lunar Fault Scarps: Several south polar lobate scarps, occur on or near large areas with very low slopes. The Wiechert cluster, located at ~86.7°S, 146.7°E, consists of at least five individual fault scarps (Fig. 1). These scarps have a maximum relief of ~10 m. The maximum slopes on the scarps in this cluster are estimated to be ~10°. The Ibn Bajja cluster, located at ~86.6°S, 81.1°W, has four individual fault scarps with a maximum relief of ~20 m. The maximum slope on the scarps in this cluster are estimated to be <15°. The maximum slopes on scarps in these clusters are lower than those on the Lee-Lincoln scarp that reach >20° in some locations. The Wiechert cluster has an advantage when solar illumination is considered; simulations show the area of the scarps is estimated to be illuminated >50% of a year [see 13].

Survey of a Fault Scarp: Artemis astronauts could conduct a walking survey of a lobate scarp. Measurements of slope of the scarp face could be made for use in forward mechanical modeling to constrain the fault geometry and depth of faulting. Examination of the back-scarp terrain could reveal secondary, small-scale structures undetected in LROC NAC images, which may provide additional insight into the kinematics and mechanical properties of the deformed materials. Shallow trenches in the scarp face at its base could reveal the fault, allowing direct measurement of the geometry of the uppermost segment of the thrust fault. The geometry of the near-surface fault could be more completely characterized by a walking traverse of a scarp with a ground penetrating radar (GPR) instrument using a frequency range down to about 100 MHz. An active seismic survey would enable imaging of the fault and host stratigraphy to even greater depths [see 14].

Sampling of Fault Scarp Related materials: Surface breaking thrust faults can provide a means to sample material transported from some depth. This depth depends on the fault-plane angle, the cumulative slip, and the depth of faulting. Forward mechanical modeling shows the depth of faulting is shallow [5, 15] and the cumulative slip for low relief scarps is typically <50 m [15]. Thus, rocks and regolith exposed by faults are expected to be from depths of a few to at most tens of meters. Astronauts could sample such materials along the base of the scarp face at or just below the surface. Shallow buried rocks could be retrieved using a tool to dig shallow trenches. Cosmic ray exposure ages of collected rocks and lithic fragments could be used to date recent activity on the fault.

Lobate fault scarps often display a deficit of small craters in their immediate vicinity [7, 8] and are distinct from surrounding terrain in photometric and optical maturity (OMAT) investigations [11]. 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. Samples collected from one or several distributed shallow trenches, or a shallow regolith drill or pounded core, could be used to characterize the size-frequency distribution of particles. Detailed analysis of layers in trenches or core samples (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 (e.g., cohesion, petrography, density/porosity, particle shapes) with depth and along and distal to the scarp face. Additionally, magnetic and near-IR spectral measurements could be used to estimate the degree of space weathering (rate of maturation), and water and hydroxyl content.

Seismic Hazard Characterization: Coseismic slip events on active thrust faults present a hazard to long-term habitations on the Moon as well as to scientific instruments. To assess the seismic hazard of the young thrust faults, astronauts could perform surface operations to inform a preliminary probabilistic seismic hazard analysis (PSHA) for the Moon. A PSHA consists of three components: Seismic Source Model, Ground Motion Model, and Site Response Model [16, 17]. Astronauts could deploy a geophysical package near a lobate scarp that includes seismometers (long period and short period) capable of detecting small magnitude SMQs, and acquiring horizontal and vertical components of ground motion [see 18, 19]. Seismometer data can be used to derive magnitude and location of SMQs, augmenting data from the 28 recorded events, and to inform seismic source models.

Seismic observations collected in typical south polar terrain could enable comparison with the near-side terrains where the Apollo-era seismometers were located and offer preliminary information on the fundamental resonance of the site needed to produce an accurate site response analysis. Seismometers deployed at sites near a fault scarp in the south polar region could provide valuable data for informing ground motion models, including key information regarding topographic amplification [20], which can significantly enhance quake ground motions. These data are 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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