ACTIVE SEISMIC SUBSURFACE EXPLORATION ON ARTEMIS III: EXPLORATION AND SCIENCE GOALS

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Since the early era of lunar exploration, the Moon's surface was known to be covered with a fine-grained regolith. The regolith is understood to form as a result of billions of years of meteoroid impacts and impact gardening, fracturing and resorting of the lunar surface. The regolith layer is a general feature found on planetary bodies regularly exposed to meteoroid impacts and lacking enough atmosphere to sustain weathering. The regolith layer is the first medium that crewed expeditions will likely encounter, and thus the design and operations of any landed missions need to consider regolith properties.

The Apollo missions established that a megaregolith layer lies beneath the finer grained materials near the surface. The layer is composed of mechanically-disturbed ejecta blankets, impact debris, and highly fractured bedrock. The megaregolith is underlain by intact fractured and nonfractured crystalline rock, although the thickness of the layer is debated, especially as GRAIL results suggest the entire lunar crust may have up to 13% porosity [1]. The shallow sub-surface structure is widely accepted (e.g. [2], Figure 1), especially beneath the Apollo landing sites; however, the detailed variation in lateral structure and stratification of regolith and megaregolith remain unknown, particularly at higher latitudes and at the lunar poles.

Here we propose a suite of geophysical science investigations, specifically active source sounding of the subsurface, that would be enabled by Artemis astronauts and inform on the regolith-megaregolith structure, and provide information on surface evolution of the Moon, lunar bombardment history, and impact processes. The Apollo surface missions demonstrated the capability for detailed investigation of the shallow subsurface structures using astronaut enabled seismic refraction and reflection surveys [3,4], as well as other approaches such as noise correlation techniques [5]. This proposal has high synergy with other seismic experiment focusing on global seismicity (e.g. [6]). The two experiments will provide complementary information and would be good candidates for geophysical packages proposed be deployed on the Moon (e.g. [7,8]).

Science Drivers for Subsurface Seismic Imaging

Seismic reflection and refraction methods in 2D and/or 3D geometries would provide regolith and megaregolith structure around the Artemis III landing site. These methods were used successfully on the Moon by Apollo astronauts who performed active seismic experiments ([3-5;9-12] Figure 2). The resulting velocity models showed the transition between the highly fractured and high porosity regolith layer to an intermediate velocity horizon overlying a more intact bedrock. The resulting velocity models showed the transition between the highly fractured and high porosity regolith layer (~285 m/s) to an intermediate velocity horizon (~580 m/s) overlying a more intact bedrock (~1825 m/s). In impacted terranes, seismic methods can illuminate differences in mechanical disturbance and corresponding elastic properties and can also image or model geological or compositional features (e.g. ice layer, impact melt rock, dike) with contrasting physical properties, dependent upon the experimental design. Given the unique cold trap and thermal evolution histories of the polar regions of the Moon, it is extremely likely that there will be geophysical contrasts within the lunar regolith that vary from the Apollo landing sites. We propose considering multiple observations and outputs such as combining reflection and refraction techniques with more cutting-edge full waveform methods to interpret the new datasets provided by Artemis. Using the same active seismic data, furthermore, the surface wave analysis can be utilized for shallow regolith investigation. Key goals would be to determine physical properties and 2D/3D structure near the landing site. Such data will provide key constraints to integrate with remote sensing data and/or other surface observations completed by the Artemis crew, and will also inform on the site characteristics for the Artemis Base Camp.

Key Questions for Artemis Seismic Imaging

• ***What is the shallow structure of the South Pole and how is this structure related to impact rate and resurfacing process?***

As we see in the case of Apollo (e.g. Figure 2), in situ observations of the lunar subsurface structure are limited to the previous landing sites, which concentrate on the low latitude area of the lunar nearside. Recent global remote sensing observations reveal a large variety of different geological features on the Moon and it was pointed out that observations from Apollo should not be used as a global reference (e.g. [1,13]). It would be of great interest to probe the subsurface structure of the South Pole, which has the potential to be extremely different from equatorially produced regolith and megaregolith. Theoretical investigation implies that the impact rate differs with latitude [14] and thus an active seismic study during Artemis allows investigations as to how the regolith and megaregolith structure differ between the two sites and latitudes.

• ***What is the distribution of ice/volatile bearing layers at the South Pole?***

One of the key scientific questions to be addressed at the lunar South Pole is the existence of ice and volatile materials. Remote sensing observations such as Neutron Spectrometer or Hyper Spectral Imager (e.g. [15,16]) now strongly support the existence of ice at the lunar poles both at depth within the regolith and at the surface. While these observations provide information on its lateral variation, the vertical distribution of ice deposits with depth is not yet resolved. Remote sensing observations have limitations on the depth and spatial resolution that they can probe. In situ measurement of the shallow structure will be informative to how such ice-bearing materials (and their geophysical signature) are distributed within the polar region. Geophysical sounding of subsurface ice will enable future crewed missions to potentially prospect and characterize ice reserves for In Situ Resource Utilization (ISRU). The amount of ice available within an accessible depth will be a strong constraint on the efficiency of ISRU and needs to be understood for realistic and feasible missions. At the same time, it is also important to understand the form of the ice. For example, ice can be present in granular or particle form or it can also serve to cement regolith particles. Such differences will result in predictable changes in elastic properties and thus can be related to observations from 2D and 3D active source seismic observations. Subsurface exploration related to the landing site(s) will open opportunities to examine potential volatile content with depth.

• ***What is the 2D (or 3D) structure of geological features seen at the South Pole?***

Remote sensing data already show that there are characteristic geological features at the South Pole including large impact craters. 2D or 3D imaging of such features will determine the structure of these features, including potential observations at a crater rim, terrace zone, peak ring or central uplift. Detailed structure of any of these crater morphologies would be informative to understand impact processes. Seismic images on Earth represent our only images of complex craters in the third dimension and have demonstrated key aspects of the cratering process such as dynamic collapse and acoustic fluidization of the target [17,18]. Detailed comparisons between craters on Earth and the Moon will serve to constrain impact physics and to provide observations of impact cratering under different gravitational conditions and target rocks. Flat crater floors may also be interesting to understand the 3D structure of basins. Another interesting target will be the imaging of lobate fault scarps, which is viewed as a possible source of shallow moonquakes (see [19] for more details). If the landing site was selected to target specific geological features, we can design observations to uncover the more complete view of the geological feature and its physical properties.

• ***What are the geo-mechanical and geotechnical properties of surface and subsurface layers at the South Pole?***

A goal of the Artemis program is to establish a permanent human presence on the Moon: that goal will require assessing the stability, depth, and geotechnical properties of the lunar regolith to facilitate astronaut safety and structural integrity. Likewise, the Moon could host observatories for physical and astronomical observation (e.g. [20]). Active source seismic investigations are routinely used on Earth to establish site stability before construction starts. As it will be one of the first construction projects to be made on the Moon under different gravitational, atmospheric and radiation environment, an Artemis III active source seismic experiment will provide the pilot data required to enable such construction efforts to begin.

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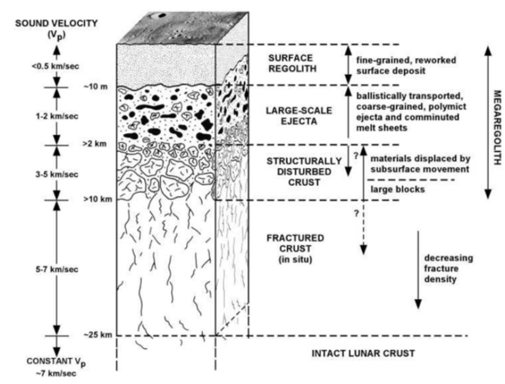

Figure 1. Apollo-based view of the shallow seismic structure of the Moon. Uppermost near-surface layers are highly fractured and continuously impact-gardened, while intact bedrock is expected to be observed at depth (cited from Hiesinger and Head (2006) [2]).

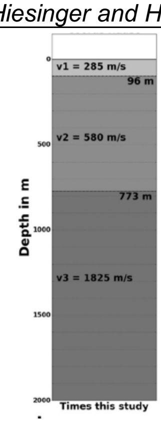

Figure 2. Shallow sub-surface structure obtained from the active seismic experiment of Apollo 17 for the Taurus-Littrow Valley. Low-velocity material, probably rubble and broken rock, is found in the top ~30 m. Below this, higher seismic velocities likely indicate the top of the basaltic layers that are assumed to fill the Taurus-Littrow valley (cited from Heffels et al. (2017) [10]).