PREPARING FOR GEOPHYSICAL SCIENCE ENABLED BY CREWED AND ROBOTIC MISSIONS ON THE SURFACE OF THE MOON N. Schmerr[1], J. Richardson[1,4], R. Ghent[2], M. Siegler[3], K. Young[4], M. Wasser[4], P. Whelley[1,4], D. Buczkowski[5], L. Carter[6], C. Connor[7], L. Connor[7], J. Bleacher[4], M. Fouch[8], D. Baker[4], T. Hurford[4], L. Jozwiak[5], S. Kruse[7], V. Lekic[1], A. Naids[10], R. Porter[11], L. Montesi[1], D. C. Richardson[1], E. Rumpf[12], N. Schorghofer[3], J. Sunshine[1], S. Goossens[4,18], N. Whelley[1,4], D. Wyrick[9], W. Zhu[1], E. Bell[1], J. DeMartini[1], D. Coan[10], D. Akin[1], B. Cohen[4], E. Mazarico[4], C. Neal[13], M. Panning[14], N. Petro[4], B. Strauss[4], R. Weber[15], T. Glotch[16], A. Hendrix[3], A. Parker[17], and S. Wright[3], [1]University of Maryland, College Park, MD, USA (nschmerr@umd.edu), [2]University of Toronto, Toronto, Canada, [3]Planetary Science Institute, Tucson, USA, [4]Goddard Space Flight Center, Greenbelt, USA, [5]Johns Hopkins Applied Physics Laboratory, Laurel, USA, [6]University of Arizona, Tucson, USA, [7]University of South Florida, Tampa, USA, [8]Samara/Data, Washington DC, USA, [9]Southwest Research Institute, San Antonio, USA, [10]NASA Johnson Space Center, Houston, USA, [11]Northern Arizona University, Flagstaff, USA, [12]USGS, Flagstaff, USA, [13]Univerity of Notre Dame, Notre Dame, USA, [14]Jet Propulsion Laboratory, Pasadena, USA, [15]NASA Marshall Space Flight Center, Huntsville, USA, [16]Stony Brook University, Stony Brook, USA, [17]Southwest Research Institute, Boulder, USA. [18]University of Maryland Baltimore County, USA.

Introduction: Geophysical methods have been incredibly successful in identifying resources on Earth as they provide a means of characterizing and mapping the sub-surface using data gathered on and above the target structures. **Geophysics on the Moon will be an important tool for identifying key targets for geological prospecting, scientific sampling, assessing hazards and risks to crew and infrastructure, and determining the near subsurface and deeper workings of the lunar interior.** Our team, Geophysical Exploration of the Dynamics and Evolution of the Solar System (GEODES), is exploring natural resources on the Moon through a suite of multidisciplinary geophysical investigations that would be enabled by crewed Artemis and/or robotic Commercial Lander Payload Service (CLPS) missions to the lunar surface, or a future Lunar Geophysical Network (LGN).

Geophysics, which provides for the remote sensing of planetary interiors, has defined and imaged planet Earth's global structure, from crust to core, with progressively increasing resolution since the early 20th century. Beginning in the 1960s, geophysics played a pivotal role in the development of plate-tectonic theory and has been central in identifying natural resources for our civilization. In the past, planetary science has been dominated by orbital or fly-by spacecraft, and therefore most of our geophysical information on extraterrestrial interiors comes from gravitational, magnetic, and electromagnetic fields. Until recently, landed missions have focused on geochemical analysis and geologic observations. However, the six US Apollo missions performed a host of geophysics experiments on the surface of the Moon, including passive and active seismology [1], heat flow [2], magnetometry [3], retroreflectors for lunar ranging [4], and surface gravity measurements [5]. More recently, the geophysical properties of the Moon were explored from orbit with the Gravity Recovery and Interior Laboratory (GRAIL)

Figure 1. Left: Apollo 14 astronaut Edgar Mitchell operates the Thumper for the Active Seismic Experiment. Right: Astronaut Don Pettit prepares for an active source seismic shot in the SFVF. GEODES builds upon a rich heritage of analog research in planetary exploration. Image Credits. NASA, J. Richardson

[6]. Since Apollo, the only ground-based geophysics were executed by China's Chang'e 3 and 4, which both acquired ground-penetrating radar (GPR) data from lunar rovers [7].

From both orbit and the surface, geophysics has provided a tantalizing glimpse of the Moon's structure from crust to core [e.g., 8, 9], its internal temperature and global thermal evolution, as well as information on locations to prospect for possible in-situ resources. The Moon has served as a proven, comprehensive testbed for extraterrestrial geophysics, which has set the stage for surface geophysical experiments on other worlds, notably the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission to Mars [10]. InSight successfully landed at Elysium Planitia on Mars in November 2018 and is now the first ground-based geophysics-focused mission in the Solar System. Despite these advances, key geophysical questions remain unanswered about the near-surface resources of the Moon. Artemis and CLPS missions provide a new opportunity to investigate near surface and deep interior structure on the Moon.

As humans journey further into space, access to critical supplies needed to sustain themselves including food, air, water, shelter, rocket fuel, and spare parts will be essential. It is of paramount importance for future explorers to be able to efficiently identify and utilize resources found in the environments around them. Geophysics is a powerful tool for sounding the subsurface for the presence of potential *in situ* resource utilization (IRSU) materials and has been and remains essential for resource identification on Earth.

For the Moon, we identify four essential resources that will enable future human space exploration and ISRU: I) Lava tubes and void spaces, capable of hosting people and infra-structure; II) Subsurface ice deposits, that can be used for volatile extraction; III) Regolith, which covers the surface of all target bodies, potentially serving as a building material but also presents a hazard to human and robotic operations and health; and IV) Magma-tectonic Systems, which mobilize, concentrate, and trap volatiles, unique rocks, and ore minerals. These geophysical targets are available at many potential landing sites across the surface of the Moon.

Approach: We aim to provide maximum insight by integrating multiple geophysical methods. The interpretation of geophysical methods is often non-unique or uncertain. This can be overcome by combining diverse methods that are sensitive to complementary material properties [11]. The combination of integrated field observations and process-based modeling links insights from Earth-based geophysical analogs to the environments present beyond Earth (**Figure 1**). In combining techniques, we also aim to develop best practices and instrument requirements for future surface geophysics exploration of ISRU targets at the Moon.

Furthermore, to enable ISRU and lunar science, future crewed exploration of the lunar surface must include long lived monitoring equipment (seismometers, heat flow experiments, retroreflectors, EM soundings, etc.), ideally deployed in networks across the surface of the Moon. Also, there is a need for near-surface active geophysical surveys to characterize the detailed geological subsurface (ground penetrating radar, active source seismics, active EM soundings, potential fields surveys). The GEODES team seeks to enable these activities by investigating a suite of Earth-based field analogs that address the science and exploration goals of Artemis and CLPS mission deployments.

Analog Sites: Our team has identified three field sites on Earth that provide access and opportunities to: 1) validate models of near-surface structure in analog geologic settings (*e.g.*, lava flows, lava tubes, cinder cones), 2) test data collection methods in order to develop instrument and mission architecture recommendations, 3) determine the optimal scales of measurements to characterize resources, and 4) identify the observational overlap between outcrop-scale and orbital geophysical measurements. Upcoming 2020-2025 GEODES field expeditions will be to Lava Beds National Monument, northern California; the San Francisco Volcanic Field (SFVF), Flagstaff, Arizona; the East Snake River Plain, southern Idaho; and targets in Hawaii and Iceland. We invite members of the community interested in geophysical science to join us in these field campaigns with both their instrumentation and expertise.

Future Outlook: The Moon will serve as a comprehensive testbed for extraterrestrial geophysics by explicitly integrating across different existing datasets and by assessing the improvements to subsurface exploration and geological interpretation that would be enabled by human presence. Furthermore, interest and opportunities for the next generation of geophysical experiments on the Moon are at an all-time high, including forthcoming NASA partnerships with commercial missions deploying equipment on the lunar surface, and the New Frontiers competition in which the Lunar Geophysical Network is a strong candidate [12]. Extending lessons learned from the human exploration of the Moon to near-Earth asteroids and the moons of Mars is also of interest, as astronaut exploration of these bodies will be complementary to a future human presence on Mars.

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References: [1] Latham, G. V. *et al.* (1969) *Trans-Am Geophys Union* v. 50, 679. [2] Grodzka, P. G. *et al.* (1972) *Science* 176, 506 10.1126/science.176.4034.506. [3] Dyal, P. *et al.* (1970) *Science* 169, 762 10.1126/science. 169.3947.762. [4] Bender, P. L. *et al.* (1973) *Science* 182, 229 10.1126/science.182.4109.229. [5] Talwani, M. *et al.* (1973). Apollo 17 Prel. Sci. Report vol. 330 pp. 13. [6] Zuber, M. T. *et al.* (2012) *Science*, 10.1126/science.1231507. [7] Gou, S. *et al.* (2019) *Earth and Plan Sci Lett* 528, 10.1016/j.epsl.2019.115829. [8] Weber, R. C. *et al.* (2011) *Science* 331, 309 10.1126/science.1199375. [9] Wieczorek, M. A. *et al.* (2013) *Science* 339, 671. [10] http://insight.jpl.nasa.gov/ [11] Green, P. J. (1995) *Biometrika* 82, 711. [12] Neal, C. *et al.* (2019). Proceedings of the 50th LPSC vol. 50.