PORTABLE MAGNETIC SURVEYS AT THE LUNAR SURFACE DURING ARTEMIS. J. A. Richardson[1,2], J. R. Espley[1], D. A. Sheppard[1], E. Bell[2], B. E. Strauss[1,3], N. C. Schmerr[2], and K. E. Young[1]. [1]NASA Goddard Space Flight Center, Greenbelt MD 20771 (jacob.a.richardson@nasa.gov), [2]University of Maryland, College Park MD 20742, [3]National Institute of Standards and Technology, Gaithersburg MD 20899.

Magnetic measurements are a key part of understanding the history of the Moon. They also can reveal subsurface features of scientific and exploration interest (e.g., iron-bearing igneous deposits, buried meteorites, and subsurface voids). Many objectives of magnetic investigations will require local-scale measurements done by portable magnetometers (e.g. a small backpack worn by an astronaut or rover).

Background: When iron-rich igneous rocks, such as basalt and some impact melt deposits, cool in the presence of a magnetic field, they often preserve records of the intensity and orientation of that field. Some lunar basalts retrieved from the Moon's surface during the Apollo missions hold records of an ancient lunar dynamo field at least as strong as that of the present-day Earth [1]. The igneous rock population at the surface of the Moon spans virtually the entire history of the satellite (100 Ma to 4.5 Ga) and mare volcanism was primarily emplaced between 3-4 Ga [2,3]—overlapping in time with a strong 78 ± 43 µT lunar dynamo (~3.9-3.6 Ga) and a transition from that strong field to a weaker (~5 µT by 3 Ga) dynamo [1,4] (Fig. 1). Improved characterization of magnetized rocks of a variety of ages at the lunar surface would enable the creation of more rigorous timelines and dynamic models of the lunar dynamo. The geologic record of basalt emplacement on the Moon is more complete than that on Earth, making the Moon a natural laboratory to study the magnetic field of a terrestrial body. Thus understanding the history of the lunar dynamo directly informs the overall history of the Moon and Earth.

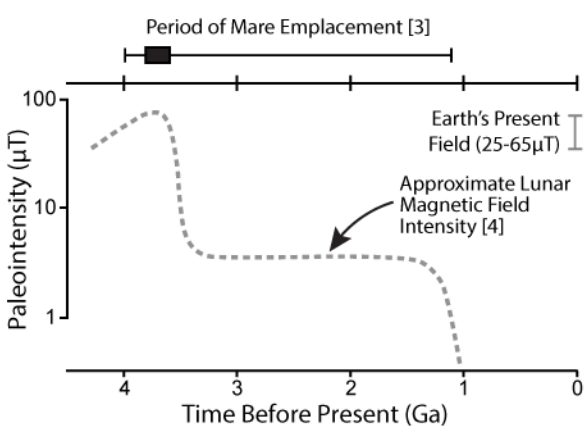

Figure 1. The lunar magnetic field has varied in intensity over lunar history. Magnetic investigations at the lunar south pole (3.6+ Ga in age [7]) will inform paleointensity reconstruction at a period when the lunar dynamo might have been very strong.

Downward continuation of orbital magnetic data has not led to a perfect replication of these measurements generally underestimate the magnetic field at the surface [6]. This is likely due to the fact that many magnetic anomalies have a limited spatial extent and are therefore are too "low wavelength" (<60 km) to be seen by 30 km resolution magnetic maps produced by orbital investigations. Still, from orbit much of the lunar surface is known to have average field strengths of ≥1 nT, including the lunar south pole [6]. Surface investigations are needed to better understand the source and configuration of lunar magnetic anomalies.

Magnetic Surveys During Artemis Missions: In addition to stationary magnetometers on the Moon, which are currently expected payloads on Commercial Lunar Payload Service (CLPS) missions, portable magnetometers are a high-science impact tool to include in Artemis Missions because their frequent use and stage of development in terrestrial geophysical exploration minimizes challenges to their use and maximizes the utility of returned data. Mapping magnetized rocks on the lunar surface can help prospect for exploration-enabling resources (ore deposits and void spaces) and can be used as a tool to better understand the emplacement history of igneous rocks as some buried geologic units are expected to create magnetic anomalies.

The lunar south pole is an excellent location to investigate the history of the ancient lunar dynamo. Orbital data identifies the south pole as having a detectable, ≥1 nT magnetic field at the surface [6]. While this seems small, it is comparable to the Apollo 16 landing site's orbit-derived strength of 3.5 nT [6], though at the surface the *minimum* magnetic field strength recorded over the entire site was 112±5 nT [5]. The age of the south pole also preserves an ancient surface that might have been formed during a period of a strong active dynamo: the crater Shackleton is likely 3.6 Ga in age [7], placing its formation near the apparent waning of the lunar dynamo observed in Apollo samples (Figure 1). Remanent magnetism measurements within iron-bearing rocks at this site can immediately constrain dynamo strength at this mysterious epoch of lunar magnetism.

A portable magnetometer can be used to map subsurface units that can be of importance both scientifically and in regards to ISRU. Figure 2 illustrates magnetic anomalies that would be measured of a buried lava flow on the Moon using information (depth, remanent magnetism [8]) gathered from Apollo 17 (which

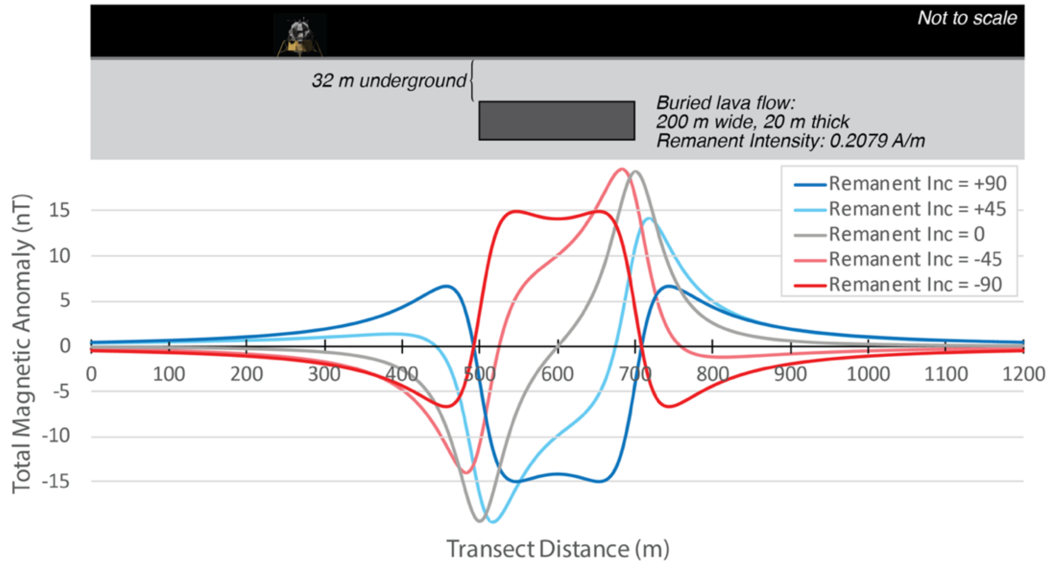

Figure 2. Modeled surface magnetic fields (below) from a buried Apollo 17-informed [8] lava flow (above). These anomalies would be detectable be traverses at a landing site and have a shape dependent on the inclination of magnetization of the unit. A similar model of a buried decimeter-sized, 50 kg meteorite at 1 m depth predicts 2 nT magnetic anomalies over the buried body.

lacked a portable magnetometer). If a transect is walked across the surface over this buried unit, measured anomalies would reach or exceed 15 nT. The shape of the anomaly is intrinsically linked to the inclination of the remanent magnetism (the different colors in Figure 2), which, for in-place igneous units, is a preserved response to the orientation of the magnetizing field. **Identifying coherent bedrock layers with magnetometers can also provide maximum depths of regolith**, which would have an net zero magnetic signal if its clasts are randomly oriented.

A portable magnetometer can help to identify regions of significant magnetic field strength to sample for more in-depth paleomagnetic investigations that are currently only possible in laboratories on Earth. Magnetic investigations of returned samples have been critical to reconstructing the history of the lunar dynamo field. Portable magnetometers can enable high-grading samples or sample locations if magnetic strength is reported in real time.

Portable Magnetometer Requirements: Successful magnetic investigations on Artemis will require magnetometer instruments to be able to measure the surface accurately and often. Our team has developed requirements for such an instrument to address the science questions posed above, namely: *What is the history of the lunar dynamo? What is the buried stratigraphy and structure at the Artemis mission site?*

We find that for large units (e.g., Figure 2, impact melts), measurements will be required to have 10 nT precision with readings at 1 m spatial separation or better. Absolute geolocation is required within several meters. For smaller, decimeter- to meter-sized objects (e.g., buried meteorites, blocks of ejecta), 2 nT precision field readings at 20 cm spatial separation is required, with similar geolocation requirements. Regularized grid surveys would provide additional science return for all sizes/shapes of expected magnetic anomalies.

Our team recommends that magnetometers that can meet these requirements be able to continuously collect data during Artemis EVA without constant astronaut intervention. Traversing with a magnetometer will require a light instrument, which can be aided if power and data telemetry are handled external to the magnetometer (i.e. by an attached rover or suit). Fluxgate magnetometers that can meet the science requirements have been developed at NASA Goddard Space Flight Center for previous space missions and are already very light (30 g, <0.5W). While these magnetometers can easily achieve 2-10 nT precision in magnetically quiet field environments, it is imperative that the Artemis Mission works to characterize the magnetic signals of mission infrastructure (suits, rovers, landers), similar to Apollo studies [9], to achieve these precisions in a mission setting.

Acknowledgments: The NASA SSERVI GEODES grant #80NSSC19M0216 supported this work.

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