**MAGNETIC SURVEYS TO PROBE THE LUNAR SUBSURFACE.** J. A. Richardson[1,2], E. Bell[2], N. C. Schmerr[2], J. R. Espley[1], D. A. Sheppard[1], C. B. Connor[3], P. L. Whelley[1,2], B. E. Strauss[1,4] 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]University of South Florida, Tampa, FL 33620 [4]National Institute of Standards and Technology, Gaithersburg MD 20899.

**Introduction:** 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.

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. Indeed, magnetic field strengths measured *in situ* at Apollo sites range from 3-327 nT [5]. While downward continuation of orbital magnetic data has not led to a perfect replication of these measurements, unexplored surface regions of the Moon have been identified that are much more magnetic [6].

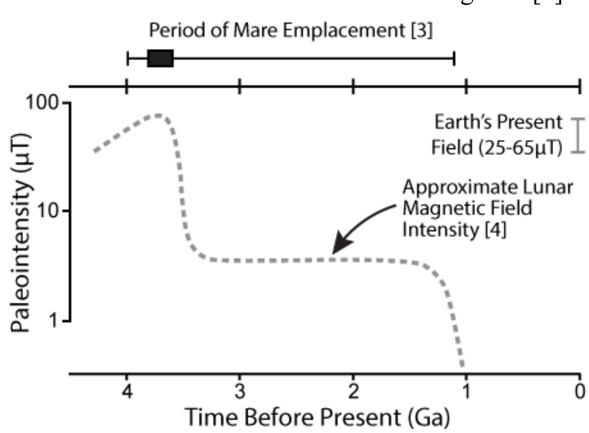


Figure 1. The lunar magnetic field has varied in intensity over lunar history. Times of change should be recorded by igneous rocks that erupted from 1.2-4 Ga.

***In situ* Magnetic mapping of lava flows:** Magnetic surveys of lava flows are often carried out on Earth with a magnetometer sensor placed 1-2 meters above a walking researcher on a non-magnetic pole or suspended multiple meters below an aircraft. In the walked method, analogous to a lunar surface EVA, measurements are taken at a 1-5 Hz rate and georeferenced.

*Field analogs*. Using a proton precession magnetometer carried 2-3 m over basalt lavas with little to no sediment cover, Bell *et al.* [7] mapped magnetic anomalies of >3000 nT created by the lava flow itself. Surveys by George *et al.* [8] using a similar, Cesium-vapor magnetometer, found that lava flows buried 150 m by non-magnetic alluvial material can produce surface anomalies of >400 nT.

We have also performed a vertical survey of lava flow units in Mauna Loa (Hawaii, USA) (Fig. 2). Such a survey would provide valuable measurements during descent along a lunar cliff face with outcropping bedrock. We find that, at ~1 m from exposed basalt magnetic field strength varies by 1000s nT in each spatial dimension as measurements are taken across several subhorizontal lava flow units.

**Magnetic mapping of void spaces:**

Lava tubes and other subsurface void spaces (e.g. impact melt sheet cracks) are potential resources for shelter and investigating pristine lunar surfaces [7]. Collapse pits are evidence of tubes on the Moon and the presence of lunar swirls is evidence that tubes or similar buried features have remnant magnetic signatures that alter the magnetic field at the lunar surface [9].

*Field analog.* Our team has carried out magnetic surveys over accessible lava tubes in Lava Beds National Monument (LBNM, Northern California, USA) and Mauna Loa (Hawaii, USA). LBNM lava tubes are situated within post-glacial basalt lava flows (<13 ka, [10]) and Mauna Loa lava tubes are <1 ka [11], and were emplaced in a magnetic field of similar intensity to the present field. We find that the ability to recognize magnetic anomalies of tubes with <20 m of overburden rock is dependent on tube interior size and shape. Large caverns ~20 m in diameter are easily identifiable within the non-uniform magnetic anomalies produced by basalt flows (Fig. 3) [7]. Smaller cavities are less clear and might require advanced processing techniques or complementary evidence (e.g. an adjacent collapse pit) to identify.

**Magnetometer instrument requirements on the lunar surface:** Magnetic anomalies on the lunar surface

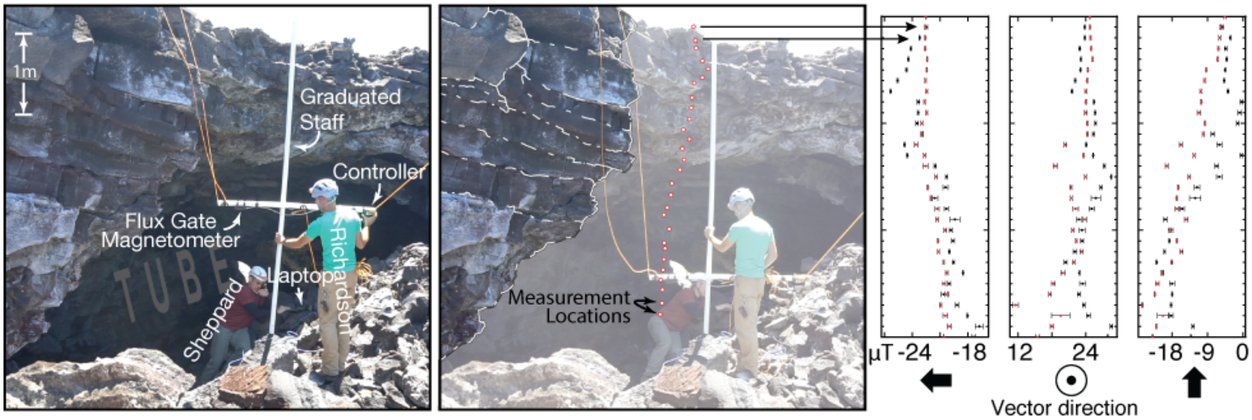


Figure 2. We used a 3-axis fluxgate magnetometer to survey a vertical lava flow cliff on Mauna Loa, Hawaii. A similar investigation on the Moon will enable examination of magnetic properties of different lava flow layers.

might be similar in amplitude to anomalies detected in volcanic terrains on earth (100s to 1000s of nT) though in these cases the primary source of the magnetic field will be magnetized rocks in the absence of an ambient dynamo field, so the total magnetic field strength will also be 1000 nT or less in most areas on the Moon. Fluxgate magnetometers are ideal for lunar geophysics exploration because of their ability to measure a larger range of magnetic field values than typical scalar field magnetometers. These magnetometers can also have a precision of ~0.1 nT, which is adequate to map magnetic anomalies from near surface igneous rocks on Earth.

Care will have to be taken to provide as magnetically quiet an environment as possible, potentially by following the terrestrial field example of hoisting the magnetic sensor meters above a suited astronaut during EVA. Additionally, common georeferencing capabilities available on the Earth (*e.g.* GPS) are not currently available on the Moon. This can be partially mitigated by careful use of relative positioning techniques (inertial reference units, etc.) but georeferencing infrastructure at the Moon would be beneficial for the science discussed here. A prototype hand-held fluxgate magnetometer with georeferencing capability has been recently developed by the Goddard magnetometry group; a flight version of this would leverage Goddard's high-heritage fluxgate instruments.

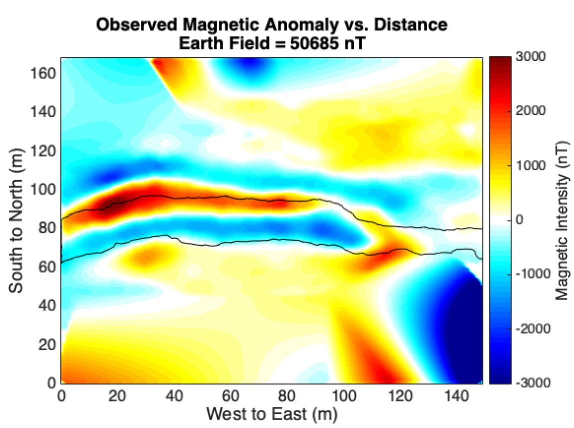


Figure 3. Magnetic anomaly maps can help identify buried structures like lava tubes. Skull cave (LBNM) produces a negative anomaly. The gradient of the magnetic field helps identify cave boundaries.

*Susceptibility.* Susceptibility measurements of iron-bearing rocks on the Moon can further constrain lava and magma flow direction [13], deformation of magnetized units from faulting [13], and generally discriminate lithologic units [14]. This measurement records how magnetized a sample becomes in the presence of an applied (*i.e.,* instrument-generated) magnetic field. This measurement should be practical on the Moon where the current exogenous magnetic field strength is ~1 nT. Susceptibility measurements have been made of retrieved lunar samples and indicate that basalts, breccias, and anorthosites have different mean susceptibilities that vary by orders of magnitude [14]. Handheld susceptibility meters, similar to commercial-grade field instruments, would enable similar *in situ* measurements on the Moon.

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