CHARACTERIZATION OF LAVA TUBES WITH MAGNETOMETRY. E. Bell[1], N. Schmerr[1], K. Young[2], P. Whelley[3], W. Brent Garry[3], S. Kruse[4], S. Esmaeili[4], S. Jazayeri[4], [1]University of Maryland, Department of Geology, College Park, MD 20742 ebell1@umd.edu, nschmerr@umd.edu; [2]UTEP/Jacobs JETS Contract at NASA Johnson Space Center, Houston, TX 77058; [3]NASA Goddard Spaceflight Center, Greenbelt, MD 20771; [4]University of South Florida, School of Geosciences, Tampa, FL 33620.

Introduction: Lunar exploration will likely lead to permanent human occupation of the surface. Apparent skylights to lava tubes have been located around the Moon [1, 2]. Lunar lava tubes could be ideal locations to afford human bases protection from radiation, extreme temperatures, and meteor impacts [3, 4]. Per a study by Blair, lunar lava tube diameters could extend orders of magnitude beyond terrestrial analogs, up to the same scale as lunar sinuous rilles [5].

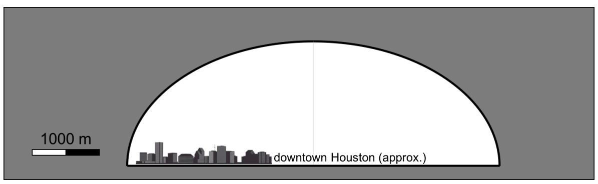

Figure 1: Depiction of theoretical structurally feasible 5 kilometer diameter lunar lava tube [5].

However, the question remains as to how to provide a relatively simple first order approximation of the location and morphology of lunar lava tubes using either orbital or surface sensors. The answer to this question can be used to select locations on the Moon likely containing lava tubes for both scientific analysis as well as operational needs, such as determining those likely suitable for human occupation.

Magnetometry is useful for mapping of rock units with sufficient magnetic signature [6]. Magnetic mapping has adequate resolution to locate subsurface volcanic features, such as dikes, within the upper several hundred meters [7] of the Earth's crust.

To date, minimal research has been completed on the correlation of magnetic anomalies produced by lava tubes to their locations or to geomorphic characteristics of the tubes themselves. Studies have included validating the use of magnetometry for determining the presence of a lava tube void under a roadway within Lava Beds National Monument (LBNM) [8], as well as attempts to track flows within active lava tubes [9].

This study aims to map and catalog the magnetic anomalies produced by lava tubes with varying morphologic characteristics. The hypothesis is that the variation in magnetic signature of lava tubes can be correlated to a combination of tube size, depth, and interior features (e.g. rubble, roughness, and fractures).

Study Region: The LBNM field site encompasses a multitude of lava tubes, lava beds, and cinder cone volcanos that are associated with the Medicine Lake shield volcano on the border of California and Oregon. This is the largest volcano in the region, consisting of over 30 major lava flows, 200 vents, and likely multiple magma chambers, with eruptions occurring over the past 500,000 years [10].

This area contains the greatest number of lava tubes, over 200, within the continental United States. They range in length from just a few meters to approximately 7000 meters. Their complexity varies from single segregated tubes, to multiple levels, and interwoven branches [10, 11]. Many of the lava tubes are from basaltic flows that occurred between 40,000 and 30,000 years ago. The tubes surveyed for this study formed approximately 11,000 years ago.

Approach: In May of 2017, as part of the NASA TubeX lava tube exploration study [12], four lava tubes of varying complexity were surveyed in LBNM. The lava tubes surveyed were Valentine Cave, Skull Cave, Hercules Cave, and Indian Well Cave. Data were obtained by surface magnetic surveys, using parallel lines at 2 to 3 meter intervals running perpendicular to the length of the lava tubes such as in the survey of Skull Cave in figure 2. The magnetometer system continuously acquires the total magnetic field strength

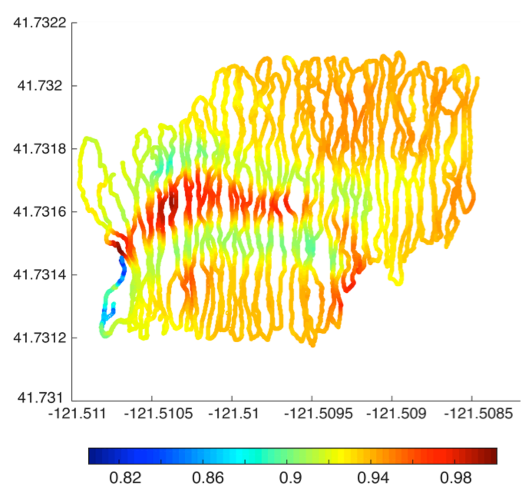

Figure 2: Results of surface magnetic survey of Skull Cave normalized to maximum recorded value. Cave location is magnetic high (red).

and GPS location. Additionally, Light Detection and Ranging (LiDAR) surveys of both the interior and surface of the lava tubes were conducted. These data capture high resolution surface details of the interiors, and in conjunction with differential GPS exact distances from the surface to any feature of interest.

Initial analysis is being performed on transects of Valentine Cave, an approximately 11,000 year old tube that is about 365 meters in length with about a 2 m thick roof. It's generally humid environment results in bands of water-deposited minerals along the ceiling. It contains several pillars, and multiple branching and reconnecting tubes of various diameters. The ceiling and walls of this tube are covered with lavacicles and dripstone formations [11, 13]. Figure 3 shows interpolated results of the magnetic survey of Valentine Cave.

The analysis of these transects will be used to catalog the correlation of the magnetic surface signatures with the underlying tube morphology. These results will then be adjusted for the scale and remanent signatures expected for lunar lava tubes, and used to identify potential tube sites on the Moon, as well as enveloping their morphology. These results can be used to select locations for scientific analysis as well as operational needs, including suitability for human occupation.

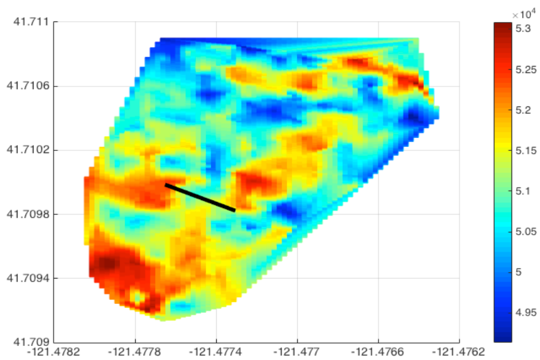

Figure 3: Lat/Long plot of interpolated magnetic survey of Valentine Cave system. Black line indicates cross-section shown in Figure 4. Units are nanoTesla.

Analysis: From these data sets, a catalog of lava tube cross-section models correlating the recorded surface magnetic signature with various lava tube magnetic and morphologic characteristics, as seen in Figure 4, is being created. The characteristics include modelled magnetic susceptibility and remanent magnetization; tube height, width, and depth; overall cross-sectional profile, and possibly other internal features. Additionally, the magnetic cross-sectional models envelop the range of potential tube depth and cross-section producing a given surface magnetic signature.

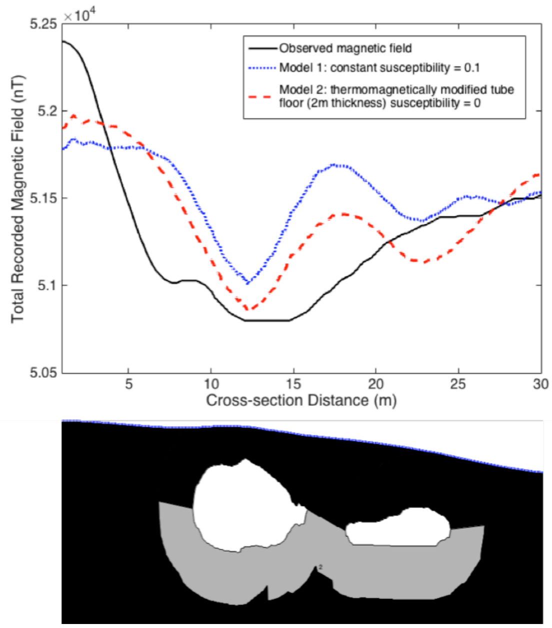

Figure 4: Top: example model of total magnetic field of Valentine Lava Tube cross-section (assumed 51500 nT field, dec=14.3°, inc=64.7°). Bottom: cross-section model (*white*: lava tubes; *black & gray*: basaltic lava; *gray*: Model 2, thermomagnetically modified floor).

Conclusion: The analysis of surface magnetic surveys of terrestrial lava tubes will provide a baseline correlation between the morphology of lava tubes and their resulting magnetic signature.

These results are expected to lead to the use of lunar magnetic data as an initial search method for lunar lava tubes. This is expected to provide an analytically and financially low overhead method to use as a first order exploration for lava tubes, and to narrow the search for those having potential for habitation.

Additionally, the magnetic signatures acquired within this study have potential to help define instrument requirements for lava tube searches and studies on other planetary bodies.

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