**GEOLOGY EXPLORATION OF LAVA TUBES IN THE LAVA BEDS NATIONAL MONUMENTS.** A. K. Theinat[1*], A. Modiriasari[1], A. Bobet[1], H. J. Melosh[2], S. J. Dyke[1,3], J. Ramirez[1], J. Choi[3], A. Maghareh[1], D. Gomez[1], [1]Lyles School of Civil Engineering, Purdue University, West Lafayette, Indiana 47907, amodiria@purdue.edu; [2]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, Indiana 47907; [3]School of Mechanical Engineering, Purdue University, West Lafayette, Indiana 47907.

**Introduction:** Habitation on planets outside Earth has been gaining the interest of space agencies such as NASA, and industry, e.g. SpaceX. The habitats should function safely and be resilient under different hazards including meteorite impacts, thermal fluctuations, earthquakes, and radiation [1-2]. Recent evidence has indicated the existence of underground openings on the Moon in a form of "lava tubes" that are believed to be formed as the lava channels crust at the surface while the lava underneath flows away; thereby, forming a strong and hard crust thick enough to provide stable, and naturally tunneled-shaped habitats [3-4]. These lava tubes could offer immediate shelter for temporary missions as well as permanent human settlements. Evidence for the presence of the tubes was first provided from careful inspection of data taken from the surface of the moon by JAXA's SElenological and Engineering Explorer (SELENE) spacecraft and NASA's Lunar Reconnaissance Orbiter (LRO), and later from the gravity data from the Gravity Recovery and Interior Laboratory (GRAIL). The data indicated that the width of the lava tubes might be of the order of 1-2 km [5-10].

Several studies investigated the size and stability of these lava tubes under different geometric configurations and material properties. Modiriasari et al. (2018) and Theinat et al. (2018, 2019) provided analytical solutions based on the flow mechanics of the lava, and limit equilibrium methods using the collapsed pits height and size to estimate the dimensions of the lava tubes [11-13]. Terrestrial lava tubes are small (~30 m) compared with the lunar lava tubes [14, 15]. However, understanding lava tubes on Earth should further our understanding of the lava tubes on the Moon. The paper presents the observations of a geological/rock mechanics exploration and interpretation of the terrestrial lava tubes in the Lava Beds National Monuments (LBNM) in Tulelake, CA. 3D model is developed to provide visualization and measurements of the lava tubes (shown in Figure-1). The results of the exploration will be used as data input to evaluate the findings from analytical and numerical simulations in Modiriasari et al. (2018), and Theinat et al. (2018, 2019) [11-13].

**Modiriasari et al. (2018), and Theinat et al. (2018, 2019):** In their study, they assumed that the height to the width ratio of the lava tube is 1:3 as suggested by Blair et al. (2018), and Chappaz et al. (2014a, 2014b) [5, 6, 16]. The slope is taken as 0.01-1.4° as suggested by Hurwitz et al. (2013) [17]. They also used different material properties of basaltic rock with an intact rock strength of 100-250 MPa (estimated for basaltic rock by Marinos and Hoek (2000) [18]). The Geological Strength Index (GSI) was assumed as 50-70, which depends on the surface and the joints conditions of the rock mass and obtained using charts from Marinos and Hoek (2000) [18]. The GSI values were assumed based on the visual examination of images of lava tubes at different locations on Earth.

Figure-1: 3D model of the Valentine Cave.

To define stability, they used the plastic yielding around the lava tube from the simulations as well as the "convergence" defined by the relative displacement between the crown and the invert (top and bottom points at the center of the lava tube). They found that the tensile strength of the rock as well as the overburden thickness govern the structural integrity of the lava tubes. With low tensile strengths and roof thicknesses, yielding around the lava tubes occurs, particularly around the roof, which indicates potential for failures that starts at the crown. In similar manner, they found that the convergence suddenly changes which indicates that the tunnel is being deformed.

**Geology mapping of the lava tubes in the Lava Beds National Monuments:** The data gathered include the geometry of the tubes, gradient, rock description and rock properties, as well as the failure mechanisms responsible for the skylights found in the tubes. More specifically, observations from two caves are presented: Valentine and the Balcony. In the Valentine cave, five sections are chosen (Sections 1 to 5, shown in Figure 2).

**Observations and discussions: 1) Geometry configuration:** The measurements obtained from the exploration show that the typical cross section of the lava tubes explored had a height to width ratio close to 1:3, and a slope of 0.5-1°. These measurements are comparable with the values used in the study by Modiriasari et al. (2018), and Theinat et al. (2018, 2019) of 0.01-1.4°

from Hurwitz et al. (2013) [17]. Note that the ratios for Sections 1, 4, and 5 were 1:3.8, 1:1.7, and 1:1.4, respectively, but are not considered as representative. Section-1 is near the entrance and is exposed to weather conditions; Section-4 is at a location where the lava tube is separated into two; and Section-5 is at a location with a narrow width.

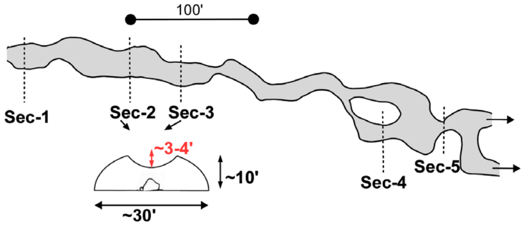
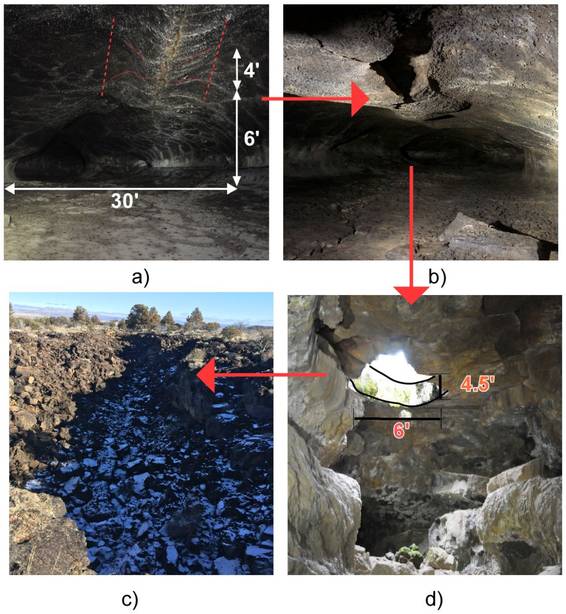


Figure 2: Valentine cave (Section-1 is near the entrance).

**2) Material properties**: The basaltic rock in the lava tube is classified as high strength, following the guidelines from the International Society of Rock Mechanics (ISRM), with an estimated unconfined compression strength in the range of ~150 MPa, estimated in Section-1, to ~250 MPa in Section-5. After careful examining of surface and joints conditions, the Geological Strength Index (GSI) is estimated to be ~60 at Section-1 and gets as high as 85 at Section-5 and beyond. The trend observed was of the rock having a higher strength going deeper in the lava tubes. Based on these findings, the GSI of 50-70 by the study from Modiriasari et al. (2018), and Theinat et al. (2018, 2019) seem to be conservative.

**3) Failure mechanisms and collapse features**: Figure 3 shows four instability patterns identified during the field exploration: 1) sagging of the crown of the tube with a longitudinal tensile crack. The sagging was around ~3-4', as shown in Figure 3-a, and was interpreted as a result of limited tensile strength of the rock, following the results from Modiriasari (2018) and Theinat et al. (2018, 2019). 2) Partial collapse of the crown (Figure 3-b). This is a consequence of further instability of the roof of the tube due to mechanism 1. Further damage to the crown may result in a skylight; that is the rock in the roof collapses and forms a chimney that reaches the surface. This is instability 3. Figure 3-d is a photograph of a skylight and is taken at the Balcony cave. The skylight has a diameter of about 6' and the roof thickness is around 4.5'. Further damage of the rock at the crown of the lava tube causes complete collapse of the rook, which forms a trench, as shown in Figure 3-d. This is instability 4. By examining the rock strength variations and the roof thicknesses changes, we observe that the GSI increases as we go deeper in the lava tube. As a result, we believe that the primary reason of the further instability from sagging in Section-3 (Figure-3a) to the partial collapse at Section-2 in the Valentine cave (Figure-3b) is due to the lower GSI. In Figure-3d, we found that the skylight is mainly formed because the lava tube roof is thinner than the other locations nearby (several measurements were taken before and after the skylight), and the GSI in all these locations appear to be the same which further indicates that the skylight mainly formed due the thin roof thickness. Finally, the collapse in Figure 3-c could be due to one or both reasons.

**Conclusions and Future Work:** The results from the reconnaissance of the lava tubes at LBNM indicate that the cross-section, slope, material properties are consistent with the assumptions used in Modiriasari et al. (2018), and Theinat et al. (2018, 2019). Their stability definitions also seem to reflect the failure mechanisms of the lava tubes. Our future direction is to use the results from the 3D model to provide large sets of data regarding the dimensions of the lava tubes, and the GSIs. Thereby, we can better understand the effect of the size, geometric configuration, and the material properties on the structural integrity of the lava tubes.



a) b) c) d)

Figure 3: Different collapse features: a) sagging (near Section-3 of the Valentine cave, and b) partial collapse (near Sectoin-2 of the Valentine cave, c) skylights (Balcony cave) and, d) long trenches (at different locations).

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