PLANETARY EXPLORATION OF LAVA TUBES WITH LIDAR AT CRATERS OF THE MOON, IDAHO.

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Introduction: We completed a lidar survey of lava tubes in Idaho as an analog to the exploration of pits on the Moon **[1-3]** and Mars **[4,5]**. Pits are exploration targets for future missions because they provide both lucrative science and possible shelter **[6,7]**. Exploration at these sites will require innovative engineering to access the interiors **[8,9]**. We present findings that demonstrate the scientific and operational potential of lidar within such challenging environments, and discuss our results for Indian Tunnel, the largest tube we surveyed **(Fig. 1).**

Background: Airborne (ALS) and terrestrial (TLS) laser scanners have been widely used to study remote volcanic terrains **[10]**, but have not been used to study lava tubes in detail. However, limestone cave systems have been surveyed with TLS for over a decade **[11]**. Investigations in Idaho **[12]** and Hawai‘i **[13]** are some of the first scientific studies to use lidar to document long sections of lava tubes and have implications for using lidar to explore pits on the Moon or Mars.

Data: The SSERVI FINESSE team (Field Investigations to Enable Solar System Science and Exploration) surveyed Indian Tunnel at Craters of the Moon National Monument and Preserve, ID between 2014-2016.

Lidar instrument. We used a Riegl Vz-400 TLS which is a near-infrared, vertical line scanner with a nominal range up to 450 m. We used two preset 360° scanning profiles (PAN20 and PAN40) on the TLS to yield horizontal point spacing of 4 mm and 7 mm at a distance of 100 m, respectively, with a precision of 3 mm and accuracy of 5 mm. A Nikon D800 camera for true color overlay and a Trimble R8 differential global positioning system (DGPS) receiver for precise positioning outside the tube are mounted on top of the TLS.

Data processing. The lidar scans were processed in RiSCAN PRO 2.3 software. Interior scans with no DGPS positioning were matched to surface scans using the coarse adjustment tool. The multi-station adjustment tool was then used to make fine-scale (cm to mm) corrections to the orientation of each scan. We combined 46 scans of the interior (29 scans) and surface (17 scans) to create the point cloud (898 million points) **(Fig. 2)**.

Observations: Indian Tunnel (43.44° N, 113.53° W) is part of the ~2 ka Blue Dragon Flow **[14]**. The flow texture on the surface above the tube is dominated by pāhoehoe. Six collapse pits mark the axis of the tube along a subtle topographic high. Ropey pāhoehoe textures extend radially away from the collapse pits, an indication these were active skylights during the eruption.

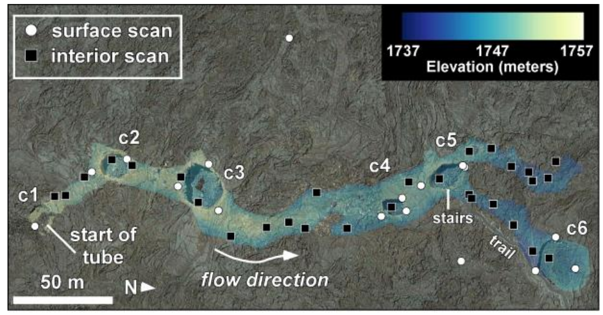

Figure 1. Point cloud of Indian Tunnel overlain on a satellite image (Google Earth) to show relationship of lava tube to the surface. Collapse features labeled c1-c6.

Morphology. Indian Tunnel is ~250 m long, 6 to 22 m wide, 2 to12 m high, and the roof thickness is 0.5 to 6.0 m. The cross-sectional shape of the tube changes along its length, but mostly resembles a semicircle to A-shape. The primary tube bifurcates at the fifth collapse pit **(c5** in **Figs. 1-3).** The eastern limb is aligned with other collapse pits in the local area and was likely the preferred conduit for lava flowing from Indian Tunnel.

Interior. Ropey pāhoehoe textures are preserved on the floor, but very few flow textures are preserved on the tube walls. Cupolas are also present in several locations on the ceiling **(Figs. 2,3).** Rubble piles occur below each pit indicating the skylights have expanded by collapse. Side tubes in the upper walls of two collapse pits indicate localized paths in overflow at the skylight rims **(Fig. 3)**. The floor of the tube drops ~7 m over the 250 m length that we scanned for a slope of -0.028 (θ = -1.6°). The software program MeshLab was used to find that the volume of the tube interior is 27,947 m^3.

Discussion: The start of the lava tube is adjacent to a broad depression (not shown) that may be a portion of the Blue Dragon flow that drained out through Indian Tunnel. No additional collapse pits are observed to the south of this topographic depression in remote sensing imagery, but a series of collapse pits can be traced to the north past Indian Tunnel. Additional fieldwork is needed to confirm the source area of Indian Tunnel.

Exploration. Lidar has multiple applications to mission and science operations for exploring planetary surfaces including hazard avoidance and traverse planning. This type of instrument can be mounted to rovers and UAVs to rapidly collect high-resolution topographic

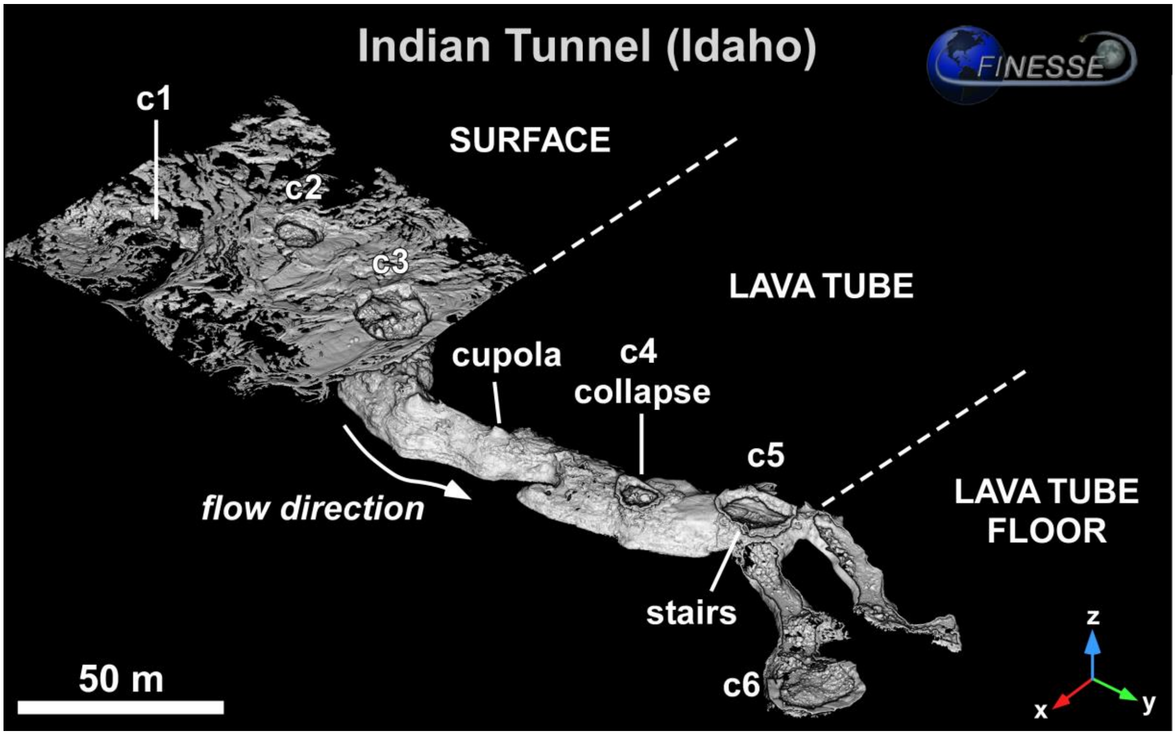

Figure 2. Point cloud showing the surface with selected sections removed to reveal only the lava tube and floor.

data with mm-scale accuracy and precision. During surface reconnaissance at a pit, lidar can scan into shadowed regions beneath the pit rim and compare results with ground penetrating radar (GPR) **[15]** and/or gravimetric data **[16,17]** to confirm the presence, dimensions, and position of a tube. Lidar is the optimal instrument for surveying on the pit floor and inside a tube or cave, if present, as lidar is an active system that does not rely on sunlight and can reveal the physical structure 10s to 100s of meters away. The possible size of lunar tubes **[18]** may drive instrument and mission requirements.

Summary: Lidar captures broad-scale morphologic relationships and finer-scale textures within a single data set, revealing unique morphologies of lava tubes. Applied to planetary exploration, mountable/portable lidar instruments can effectively increase our situational awareness and decrease decision making risk through its data output. This will be important when exploring the shadowed interiors of pits on the Moon and Mars.

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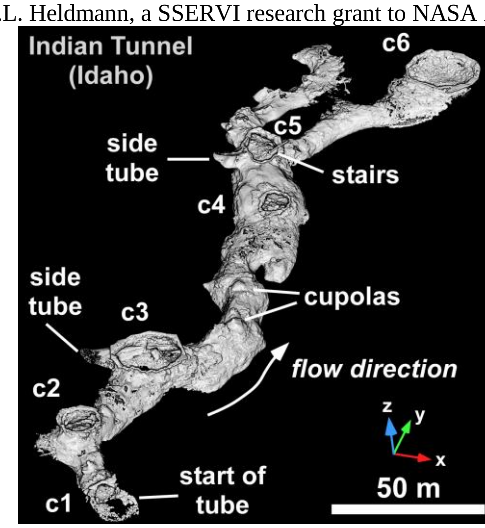

Figure 3. Morphology of Indian Tunnel lava tube.