LOFTHELLIR LAVA TUBE ICE CAVE, ICELAND: SUBSURFACE MICRO-GLACIERS, ROCKFALLS, DRONE LIDAR 3D-MAPPING, AND IMPLICATIONS FOR THE EXPLORATION OF POTENTIAL ICE-RICH LAVA TUBES ON THE MOON AND MARS. Pascal Lee[1,2,3], Eirik Kommedal[1,2], Andrew Horchler[4], Eric Amoroso[4], Kerry Snyder[4], and Anton F. Birgisson[5]. [1]SETI Institute, [2]Mars Institute, [3]NASA Ames Research Center, e-mail: pascal.lee@marsinstitute.net, [4]Astrobotic, [5]Geo Travel Iceland.

Summary: The Lofthellir lava tube, Iceland, contains massive ice formations accumulated from meteoric H_2O. We report here on micro-glaciers and rockfalls, as well as the first 3D-mapping of a lava tube and ice-rich cave by drone-borne lidar. Implications for the exploration of potential ice-rich lava tubes on the Moon and Mars are examined.

Introduction: Caves and pits have been identified on the Moon and Mars, many of which are likely lava tubes and their associated skylights, respectively. Candidate impact-melt lava tubes and skylights recently reported at high latitude on the Moon [1], and volcanic lava tubes and skylights identified at high altitude on Mars' giant volcanoes [2], might offer access not only to unique sheltered subsurface environments, but also to potential repositories of subsurface volatiles, in particular H_2O ice.

Given this prospect on the Moon and Mars, understanding the occurrence (origin, distribution, evolution through time) of ice inside lava tubes on Earth is important. While analogies between the Moon or Mars and the Earth regarding ice in lava tubes are not expected to be straightforward, some processes and features associated with ice in such subsurface environments might nevertheless be shared, e.g., the potential role of gravity in cave-ice dynamics (independent of the origin of the ice), or the role of freeze-thaw cycling on cave stability.

In this context, we carried out a field investigation of the occurrence and effects of ice inside a terrestrial lava tube, with focus on characterizing quantitatively the cave's physical environment and its range of ice-related geologic features and processes.

Field Site: We selected the Lofthellir Lava Tube Ice Cave in Iceland, a young (therefore presenting limited weathering degradation) lava cave known to contain a wide variety of massive ice structures in close to pristine condition [3, 4]. Lofthellir is located in the Lake Myvatn region of Iceland, near where Apollo astronaut field geology training took place **(Fig. 1)**. The Lofthellir lava flow is only 3.5 kyr old. The skylight giving access to the cave was first spotted by a local pilot (and perhaps also formed or widened) only in summer 1989 [5] **(Fig. 2)**. The cave and its entrance are on private property. Access is restricted and must be coordinated via authorized private field guides (Saga Travel or Geo Travel Iceland). Our field work in the cave was carried out on 10–11 Oct 2018.

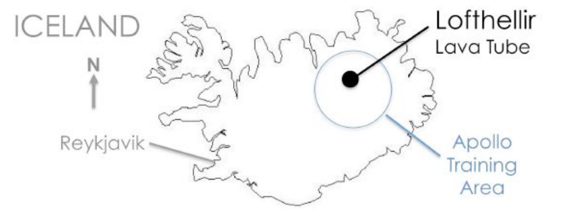

Figure 1. Location of Lofthellir Lava Tube, Iceland.

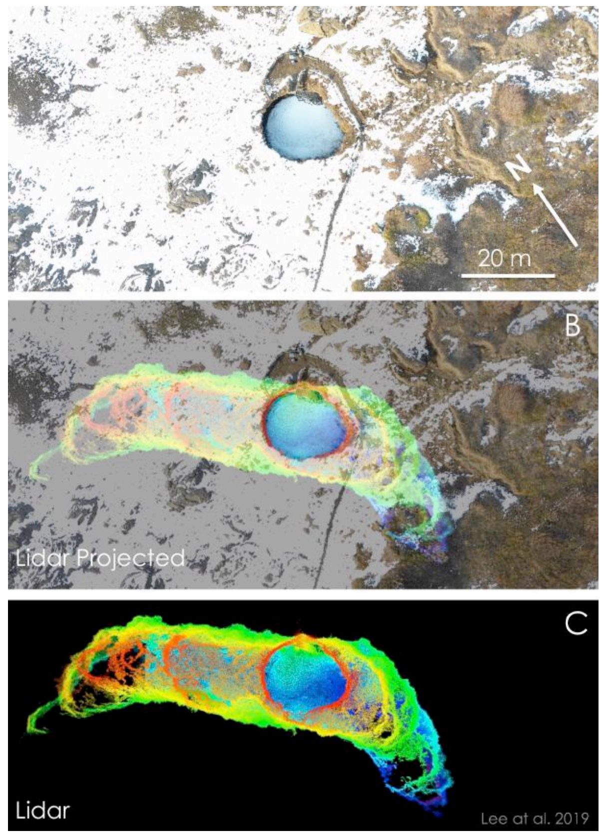

Figure 2. Drone Mapping of Lofthellir Skylight: A) Surface visual with snow dusting; **B)** A with underlying lidar-imaged cave; **C)** Subsurface lidar elevation map (Red: highest elevation; Purple: lowest).

Subsurface Micro-Glaciers: The Lofthellir Lava Tube is on average 10 meters wide. From its skylight entrance, the cave currently extends ~50 m toward the NW and ~120 m toward the SE (main branch), far beyond a lava constriction (1 m wide passage) in the main branch at +20 m **(Fig. 2)**. The floor of the lava tube is almost entirely lined with ice. In the main branch, from +20 m to +60 m, the ice floor rises to the point of constricting passage to a crawl space along the cave's roof. From +60 m to +120 m, the ice floor level drops by ~10 m in a series of wide sub-horizontal steps, revealing the tube's main chamber.

Throughout the length of the lava tube, stalactites and stalagmites of ice occur, in places merged into thick columns, curtains, drapes, and domes of ice. The prevalence of stalactites of ice along the roof of the cave suggests a meteoric origin for most of the H_2O – mainly precipitation at the surface followed by percolation and drip. Isolated wedges of layered ice tucked against nooks in the cave walls are likely relict and suggest earlier episodes of ponding and refreezing and higher past levels of floor ice. Breaks in slope and stark boundaries within the cave ice suggest dynamic interplay between distinct ice masses flowing under gravity via slow creep (viscous flow) with limited mixing or merging. *Subsurface micro-glaciers* are identified for the first time. They are only decameters in scale, but present the requisite accumulation and ablation/melting zones, morainal loads, and lobate flow fronts. The largest example at Lofthellir is "Time Travel Glacier," which descends from the "Castle" ice dome (accumulation zone) **(Figs. 3 and 4)**.

Figure 3. **Lofthellir Subsurface Micro-Glaciers:** Main chamber looking towards "Time Travel Glacier." Astrobotic's 0.7 m-wide hexacopter drone in the foreground at lower left provides scale.

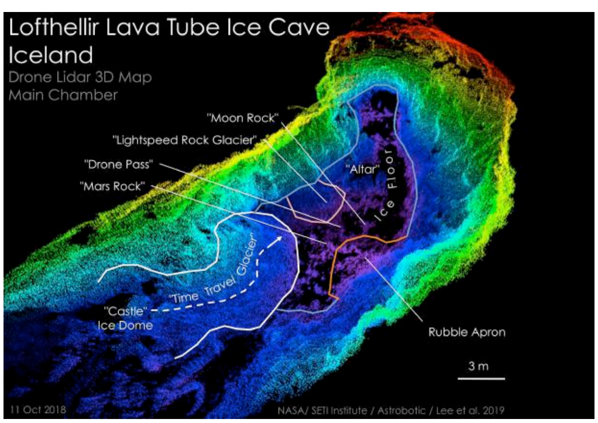

Figure 4. Drone-borne Lidar Map of Lofthellir's Main Chamber: Projected perspective view (Red: highest elevation; Purple: lowest; Black: no coverage).

Rockfalls: There is ample evidence of past and on-going rock fall activity inside Lofthellir, including ice-filled rubble aprons, e.g., "Lightspeed Rock Glacier," and the more recent "Mars Rock" and "Moon Rock" meter-scale drop boulders. Ice-filled joints and fractures throughout the cave suggest gelifraction is a significant process of comminution and desquamation, and thus of cave structural evolution over time.

Drone-borne Lidar 3D-mapping: At Lofthellir we carried out the first drone-borne lidar mapping of an ice-rich lava tube and cave. Astrobotic's GPS-denied mapping and navigation system, AstroNav, gives drones and small free-flying spacecraft the ability to fly in subterranean environments [6]. Both ice and rock cave features were scanned successfully, providing unprecedented precision in mapping the shape and quantifying the dimensions of Lofthellir. Drone-based visible imaging was also performed to capture the Lofthellir skylight and surrounding lava fields.

Implications for Exploring Potential Ice-Rich Lava Tubes on the Moon and Mars: Our physics and geology investigations at Lofthellir highlight the role gravity might play over time, regardless of the source of H_2O, in redistributing ice (by forming ice floors or micro-glaciers) if significant masses of ice build up inside lunar or Martian caves. Gelifraction is also a process that might render exploration, let alone settlement, of ice-rich caves particularly hazardous. Lidar 3D-mapping via propulsive free flying spacecraft (e.g., with cold gas thrusters) could be an efficient way to explore subsurface cavities on the Moon and Mars.

Future Work: Physical environmental sensors installed throughout the Lofthellir Lava Tube and outside it will be retrieved in Oct 2019, after 1 yr of autonomous data logging, to help characterize the thermodynamics of cave conditions.

References: [1] Lee, P. (2018) *49th LPSC*, Abstract #2982. [2] Léveillé, R. & Datta, S. (2014). *Planet. Space Sci.* 58, 592–598. [3] Hróarsson, B. (2006) Islenskir Hellar ISBN9979219726. [4] Waters, E. (2006) *AMCS Bull.* 19. [5] Birgisson, A. F. (2018). *Pers. comm*. [6] Snyder, K. et al. (2017) *ACM/IEEE IPSN*.

Acknowledgments: P. Lee at SETI Institute was supported in part by NASA through Cooperative Agreement NNX14AT27A and by a *Mohammed bin Rashid Space Settlement Challenge* seed grant from the Dubai Future Foundation through the Guaana.com open research platform. Grad. student E. Kommedal was supported in part by a Mars Institute *Fridtjof Nansen Fellowship*. Astrobotic was supported in part by NASA STTR NNX16CK16C. We also thank Baldvin E. Einarsson of Saga Travel, and Julian Watson, Tony Mews, and Daddi Bjarnason of WAG-TV for their help with field logistics.