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Pascal Lee

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Pascal Lee
SETI Institute

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Habitability of Lava Tubes on the Moon and Mars: Lessons From Earth

Pascal Lee
SETI Institute, 189 Bernardo Ave, Mountain View, CA 94043, USA
Mars Institute, NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035-1000, USA

Executive Summary

Background. Lava tubes are caves that form when the surface of a lava flow cools and solidifies, while molten rock underneath continues to flow and eventually drains away: a tube-shaped underground cave is then created. Lava tubes are known to exist on the Moon and Mars where they may form in either volcanic or large impact crater settings.

Motivation. Lava tubes on the Moon and Mars are of interest for space settlement because caves have been proposed as natural shelters that future human explorers could occupy. Caves would in principle protect dwellers from surface radiation, wide temperature swings, micrometeorite impacts, and rocket exhaust blast. Some lava tubes on the Moon and Mars might also be cold enough to trap water ice, which, if water ice is actually present, might offer access to an important resource, and in the case of Mars, also to potential underground habitats for microbial life.

Goal and Objectives. The main goal of our study was to begin to learn more about the physical and geological reality of lava tubes on Earth, specifically with respect to their habitability. Our objectives focus on two issues of central relevance to assessing the potential habitability of lava tubes on Earth, and by extension on the Moon and Mars: **1)** Geotechnical characteristics: How accessible and safe are lava tubes? What makes some lava tubes experience collapse? **2)** Relation to ice: Why, when and how does ice occur and evolve in lava tubes?

Approach and Findings. 1) To begin surveying the geotechnical characteristics of lava tubes, we carried out a review of the published technical literature on the topic. Our finding is that while there is an abundance of archaeological and historical reports and maps documenting the access, exploration, investigation, use, and occupation of lava tubes, including many anecdotal mentions of collapse features inside lava tubes, there are essentially no published quantitative studies of the geotechnical properties of lava tubes using modern standard geotechnical metrics. **2)** To begin examining the relationship between lava tubes and ice, we carried out a field investigation of the Lofthellir Lava Tube Ice Cave in Iceland in which massive ice is known to exist. Our field observations suggest that the ice inside Lofthellir is predominantly *meteoric* in origin (water from atmospheric precipitation or condensation) rather than from volcanic venting. In other words, the water inside the cave came mostly, if not exclusively, from "above", not "below". We also report two important new findings: **a)** *Underground micro-glaciers* are recognized for the first time; they form in the lave tube as a result of accumulation, slow movement, and loss of water and massive ice under the effect of gravity; **b)** *Gelifraction*, the fracturing of rocks by freezing of water trapped in joints, is an important cause of breakup and collapse inside this ice-rich lava tube.

Conclusions. 1) Our literature survey indicates that we still have little quantitative knowledge about the geotechnical properties of lava tubes on Earth, and therefore limited understanding of the factors that influence their evolution on our planet, let alone on the Moon or Mars; **2)** Our field study of an ice-rich lava tube in Iceland suggests that, if ice were able to accumulate inside lava tubes on the Moon or Mars - regardless of its origin -, **a)** *gravity* might produce underground micro-glaciers, while **b)** *gelifraction* might increase the risks of rock fall and collapse (compared to ice-free caves).

Next Steps. The following is recommended: **A)** Carry out detailed geotechnical assays of a series of lava tubes on Earth that captures their diversity in composition, size, shape, age, and weathering history, to understand better the key factors that might control the evolution of lava tubes on the Moon and Mars; **B)** Further investigate Lofthellir and other ice-rich lava tubes on Earth to understand better if and how ice might occur and evolve inside lava tubes on the Moon and Mars; **C)** Identify, design, and test robotic systems and astronaut hardware that will enable safe and productive exploration of lava tubes on the Moon and Mars.

Additional Accomplishments: Our project also enabled, and benefitted from, other research and outreach activities that collectively help advance the human exploration and settlement of space: **i)** By combining resources from other research projects funded by NASA and other partners, we carried out at Lofthellir the first successful flight of, and 3D-mapping by, a lidar-equipped drone inside a lava tube and ice-rich cave; **ii)** our fieldwork at Lofthellir was filmed and will be featured in an upcoming episode of *What on Earth?* (Season 6), the award-winning TV documentary series and most-watched program on the US Science Channel; **iii)** Results of our research will be presented at the upcoming 50th Lunar and Planetary Science Conference in Houston, TX (18-22 March 2019) (Lee et al. 2019).

Main Results or Outputs

Background

Lava tubes are caves that form when the surface of a lava flow cools and solidifies, while molten rock underneath continues to flow and eventually drains away: a tube-shaped underground cave is then created. Lava tubes are known to exist on the Moon and Mars where they may form in either volcanic lava flows (volcanic lava tubes) or in large impact structures (impact melt lava tubes) (Wagner & Robinson 2014, Léveillé & Datta 2014, Lee 2018a,b).

Motivation

Lava tubes on the Moon and Mars are of interest to space settlement because caves have been proposed as natural shelters that future human explorers could occupy (e.g., Von Ehrenfried 2019 and references therein). Caves would in principle protect dwellers from surface ionizing radiation, wide temperature swings, micrometeorite impacts, and rocket exhaust blast.

Some lava tubes on the Moon and Mars might also be cold enough to trap water ice, which, if water ice is actually present, might offer access to an important resource. Access to water on the Moon and Mars is considered key to sustainable long-term human settlement. Water serves as a life-critical hydration fluid and solvent, and also as coolant and fuel source (Hydrogen H_2 and oxygen O_2 are rocket fuels that may be derived from H_2O). Access to extractable water will likley drive the location and site selection of settlements on the Moon and Mars. In the case of Mars, any water or ice in caves might also represent potential underground habitats for microbial life.

To date, over 300 pits and caves have been identified on the Moon, all at latitudes less than about 50^o N or S. (Robinson and Wagner 2014, Wagner 2018). In addition, a few *candidate* pits were recently reported inside Philolaus Crater near the North Pole of the Moon, and interpreted as possible impact melt lava tube skylights (Lee 2018). (A *skylight* is a usually round opening above a lava tube resulting from the collapse of a limited section of the lava tube's roof). If confirmed, the lava tubes in Philolaus Crater would be at such high latitude (~72^oN) that sunlight would never enter the caves to heat up the rocks below their skylights. As a result, portions of these caves could be cold enough for H_2O ice, if present, to accumulate and remain trapped and stable on timescales of millions to possibly hundreds of millions of years **(Fig. 1).** In the case of Mars, most lava tubes and their associated skylights or pit craters are found on the flanks of the planet's giant volcanoes, and therefore at relatively high altitude. The interiors of these caves could also be cold enough to trap H_2O ice on similar geologic timescales **(Fig. 2).**

In spite of the *a priori* promising prospects offered by lava tubes on the Moon and Mars for human exploration and habitation **(Fig. 3)**, it remains unclear if settling lava tubes would be practical. Many lava tubes on Earth are difficult to access and/or present awkward geometries to move through, and like all caves, may be subject to dangerous rock falls and collapse. It is also unclear how H_2O ice, if present, might build up and evolve over time inside lava tubes on the Moon and Mars.

Goal and Objectives

The main goal of our study was to begin to learn more about the physical and geological reality of lava tubes on Earth, specifically the factors that affect their habitability, in order to establish a rigorously informed basis for assessing the potential habitability of lava tubes on the Moon and Mars. Our objectives focused on two issues of central relevance to assessing the habitability of lava tubes on Earth, and by (cautious) extension, on the Moon and Mars:

Objective 1: Geotechnical characteristics: How accessible and safe are lava tubes? What makes some lava tubes experience collapse?

Our Objective 1 was to understand the geotechnical characteristics of lava tubes on Earth, the factors that determine these, and potential implications for the habitability of lava tubes on the Moon and Mars. We aimed to identify, in the case of terrestrial lava tubes, the range of variation in the geometry, scale, internal surface roughness (of floors, ceilings and walls), insulation (as affected by fractures, fissures, and diffusive exchanges with the surface), and stability (as measured by ceiling and wall collapses and their frequency), and the factors that determine these.

Objective 2: Relation to ice: Why, when and how does ice occur and evolve in lava tubes?

Our Objective 2 was to understand why, when and how H_2O ice occurs in lava tubes on Earth, and potential implications for H_2O ice in lava tubes on the Moon and Mars. We aimed to identify, in the case of

terrestrial lava tubes in cold regions, the conditions under which, and the forms in which, H_2O ice occurs inside lava tubes. Source(s) for the H_2O ice, whether exogenic (*meteoric*, *i.e.,* from “above”) or endogenic (volcanic, *i.e.,* from “below”), would need to be identified as well.

Approach (Methods and Processes)

Geotechnical Properties of Lava Tubes

Lava tubes on Earth are expected to display significant variations in geotechnical properties. They present a wide range in geometry and scale, in internal surface roughness (floors, ceilings, and walls), in the insulation they offer (many are fractured, fissured, and/or in diffusive contact with the surface environment), and in their stability (many experience collapse). Although lava tubes have been widely studied, their geotechnical properties and the factors that determine these, have yet to be analyzed systematically and synthesized into a coherent understanding. To begin surveying the geotechnical characteristics of lava tubes, we carried out a systematic review of the published scientific and technical literature on the topic.

Ice in Lava Tubes

Little is known about the conditions under which lava tubes may harbor water ice, the form(s) in which ice is found (distributed vs massive), and the origin(s) of the ice. The relative contributions of exogenous sources (meteoric, *i.e.,* atmospheric precipitation or condensation) and endogenous sources (volcanic volatile release) have not been studied systematically. Chemical alteration and devitrification of volcanic glass in contact with water in lava tubes may also trap water in hydrated minerals on geological time scales. To begin examining the relationship between lava tubes and ice, we carried out a field investigation of the Lofthellir Lava Tube Ice Cave in Iceland, one of few ice-rich lava tube systems (with massive ice) known on Earth, and one associated with a currently active volcanic region. We focused our field investigation on the geology, hydrology, and cryology of Lofthellir, and installed a series of environmental data loggers to monitor atmospheric pressure, temperature, lighting, and relative humidity, both outside and inside the cave for an entire year, to characterize the thermodynamics of the cave system.

Findings and Results

Geotechnical Properties of Lava Tubes: A Review

Regarding the geotechnical properties of lava tubes and the factors that determine these, our finding is that while there is an abundance of archaeological and historical publications and maps documenting the access, exploration, investigation, occupation, and use of lava tubes on Earth, including many anecdotal mentions of collapse features inside lava tubes, there are as yet no published quantitative studies of the *geotechnical* properties of lava tubes using modern standard geotechnical metrics.

A recent review of the archaeology and history of human (*Homo sapiens*) occupation of lava tubes since prehistoric times can be found in Von Ehrenfried’s (2019) monograph, *From Cave Man to Cave Martian*. But it is difficult to extract from the many original accounts consistent geotechnical information.

To illustrate the challenge, we examine here the example of published studies on the human occupation of lava tubes in Iceland. Of the approximately 500 lava tubes known in Iceland, 200 present evidence of former human occupation. The oldest record is the case of the *Surtshellir* and *Vigishellir* lava tube system (Patel 2017). At *Surtshellir* (“Blackener’s Cave”), there are ruins of a 4.5 m tall human-made wall spanning the 12 m width of the cave, made of cave collapse blocks weighing up to 4 metric tons each. This wall is the largest known Viking Age stone structure in Iceland. In adjacent *Vigishellir* (“Fortress Cave”), a smaller and older lava tube branching off of *Surtshellir*, there is a 6.7 m x 3.3 m oval shaped stone wall considered the oldest standing Viking structure. Radiocarbon dating of animal bone remains at the site yield dates ranging from 890 to 930 A.D., *i.e.,* shortly after the arrival of the first Norse migrants, Iceland’s earliest long-term settlers. In spite of these clear signs of human use, there is no evidence for long-term occupation of the lava tubes, possibly because of the ongoing danger presented by rock fall from the roof and walls of the caves, the lack of running water nearby, and/or the extremely rugged terrain outside the caves which would have made hunting or raising livestock difficult. Indeed, most lava caves in Iceland with evidence of human occupation usually show signs of only brief, transient use (Patel 2017). A potential lesson here for Moon and Mars exploration and settlement might be that, in spite of the availability of natural shelters such as caves, what ultimately might determine the location of a habitat for early settlers is safety/reliability of the shelter, *and* accessibility to local resources (water in particular).

Reports of lava tube rock falls and collapse often imply that they are/were the result of seismic activity and weathering (chemical and/or physical). As a result of our fieldwork for Objective 2, we now show that *gelifraction* (rock fracturing by freezing of water) may also be a significant factor in rock falls and collapse in lava tubes under cold climate regimes (see next section).

Ice in Lava Tubes

Investigation of the Lofthellir Lava Tube Ice Cave, Iceland: A Field Report

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 (Hróarsson 2006, Waters 2006). Lofthellir is located in the Lake Myvatn region of Iceland, near where Apollo astronaut field geology training took place **(Fig. 4)**. More information on Apollo era training in Iceland can be found here: http://bit.ly/2IVGJM8. The Lofthellir lava flow is only about 3,500 years old. The skylight giving access to the cave was first spotted by a local pilot (and perhaps also formed or widened) in summer 1989 (A. F. Birgisson, *pers. comm*.). The cave and its skylight entrance are on private property **(Fig. 5).** Access is restricted and protected, and must be coordinated via authorized private field guides. Our fieldwork in the cave was carried out on 10–11 Oct 2018.

Geometry. 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 **(Figs. 5 and 7)**. 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 **(Fig. 14).**

Ice. 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 **(Figs. 8 and 9).** 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 **(Fig. 9 - Left)**. In places, the textured surface of ice deposits suggests repeated episodes of partial thawing and refreezing **(Fig. 9 – Right).** Isolated wedges of layered ice tucked against elevated nooks in the cave walls are likely relict and suggest earlier episodes of ponding and refreezing and higher past levels of floor ice **(Fig. 10).** 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" (a name our field team proposed), which descends from the "Castle" ice dome (accumulation zone) **(Fig. 11)**.

Rock Falls. There is ample evidence of past and ongoing rock fall activity inside Lofthellir, including ice-filled rubble aprons, e.g., "Lightspeed Rock Glacier" (a name our field team proposed) **(Fig. 12),** ice-free rubble aprons **(Fig. 13),** and the more recent "Mars Rock" and "Moon Rock" meter-scale drop boulders (names our field team proposed) **(Figs. 15 and 17).** 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 **(Fig. 13).**

Drone Mapping. At Lofthellir, we also 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 (Snyder et al. 2017) **(Fig. 16).** Both ice and rock cave features were scanned successfully, providing unprecedented precision in mapping the shape and quantifying the geometry and dimensions of Lofthellir's skylight entrance area **(Fig. 7)** and main chamber **(Fig. 17).** Drone-based visible imaging outside the lava tube also captured the Lofthellir skylight in surrounding lava fields **(Fig. 7 - A).**

Environmental Monitoring. A total of 10 Onset HOBO environmental data loggers were installed inside and outside Lofthellir, of which 7 were installed inside the cave at a variety of locations: lava tube ceilings, walls, and floors, on and off interior ice, and along and away from fractures and fissures **(Fig. 15).** These loggers will be retrieved after 1 year of environmental monitoring (in Oct 2019, c/o our field guide A. F. Birgisson), and their data processed then to fully complete the current study.

In summary, our field observations suggest that the ice inside the Lofthellir Lava Tube Ice Cave is predominantly *meteoric* in origin (water from atmospheric precipitation or condensation) rather than from volcanic venting. In other words, the water inside the cave came mostly, if not exclusively, from "above", not "below". We also report two significant new findings:

a) *Underground micro-glaciers* are recognized for the first time; they form in the lave tube as a result of accumulation, slow movement, and loss of water and massive ice under the effect of gravity;

b) *Gelifraction*, the fracturing of rocks by freezing of water trapped in joints, is an important cause of breakup and collapse inside this ice-rich lava tube.

Obstacles or Changes in Direction During the Project

Review of Geotechnical Properties

Given the dearth of scientific or technical literature on the geotechnical properties of lava tubes revealed by our publication survey, we elected to reduce the scope we had originally planned to place on a detailed review and synthesis of the existing literature, and increased instead the scope of our field investigations at the Lofthellir Lava Tube Ice Cave in Iceland to include detailed in-situ observations of the cave's structural geology, and rock fall and collapse history. In addition, we "joined forces" with separate ongoing research projects on planetary drone science exploration operations supported by NASA and other industry and non-profit partners (Astrobotic, Mars Institute, SETI Institute) to carry out together the first field tests of a lidar-equipped drone at Lofthellir **(Figs. 6 and 16).** As a result of this collaborative approach, our research project was significantly enhanced by producing the first drone-acquired 3-D map of the interior of a lava tube or of any ice-rich cave. The 3-D maps of Lofthellir have in turn allowed us to gain a much clearer understanding of the geometry and dimensions of the lava tube, and of many of its structural features **(Figs. 7 and 17).**

Environmental Data Loggers.

Our original intent was to carry a short-term environmental characterization of the Lofthellir Lava Tube Ice Cave - to acquire essentially a snapshot of environmental conditions inside and outside the cave at the time of our visit. To that effect, the data loggers would have been installed and moved every 2 days over a period of 14 days to investigate different domains of the ice-rich lava tube complex.

Once we defined our field plans in more detail, however, and realized the challenge and cost of accessing the lava tube multiple times over a period of 2 weeks, and also recognizing the much greater scientific value of carrying out a longer term environmental monitoring study of the cave, we opted to install our data loggers just once and to leave them behind and allow them to operate autonomously for an entire year **(Fig. 15).** Although this meant that no environmental data would be available for immediate analysis following our field deployment, arrangements were made with our local field guide (A. F. Birgisson) to retrieve our data loggers in 1 year and to ship them back to our lab for analysis. At that time, an entire year of environmental data will be available, which will be of great value for helping us understand the thermodynamics of this ice-rich lava tube system. The anticipated data will take more time to acquire, but it will be far more valuable scientifically and will have cost much less to obtain.

Potential Impact and Opportunities for implementation of the Results

Aside from many anecdotal accounts of rock fall and collapse features observed inside lava tubes, our survey of the scientific and technical literature for quantitative studies of the geotechnical properties of lava tubes shows that this is an area of research that has, as yet, received very little attention. This is not necessarily surprising, as lava tubes have generally not been used on Earth for long-term human settlement. While there is a long history of human exploration and use of lava tubes, occupation of these caves appears to have been mostly short-term, intermittent or transient (e.g., Patel 2017). A hypothesis as to why this short-term interest has been the general case might be found in the combined facts that many lava tubes are inherently challenging to access and move through, prone to dangerous rock falls and collapse, located (by their very nature) in seismically active areas which promotes structural instability, surrounded by rough terrain and topography, and not necessarily close to sources of water (unlike karst caves which were formed *in association with* water). This does not imply that lava tubes on the Moon and Mars should be dropped from consideration for exploration and settlement. Rather, it indicates that detailed studies of the geotechnical properties of lava tubes on Earth and of the factors that influence these must be undertaken first in order to establish the rigorous framework needed to assess the promise and risks of lava tubes on the Moon and Mars. As well, pits and caves on the Moon and Mars should be explored robotically starting now to gain as early as possible first hand understanding of their physical and geologic reality.

Meanwhile, our field investigation of the ice-rich Lofthellir Lava Tube Ice Cave opens the exciting prospect of potentially finding, *if* H_2O ice does occur and accumulate inside (some) lava tubes on the Moon and Mars – regardless of the H_2O's origin -, underground micro-glaciers and rock glaciers, the result of viscous creep of ice over time under the effect of gravity, even reduced gravity. The presence of ice inside a cave, however, would also be expected to be accompanied by *gelifraction*, which would promote rock falls and collapse. Icy caves on the Moon or Mars might therefore likely be rough.

In summary, lava tubes on the Moon and Mars would be very exciting to explore, but whether or not any would be safe/reliable enough for long-term settlement remains to be investigated, starting with terrestrial lava tubes first to establish a rigorous basis for comparisons.

Conclusions and Next Steps

Conclusions

1) Geotechnical Properties of Lava Tubes. Our survey to date of the scientific and technical literature on the geotechnical properties of lava tubes on Earth has not yielded any published study using modern geotechnical metrics. Although substantial literature exists documenting the archaeology and history of human exploration, investigation, occupation, and use of lava tubes, the references provide only anecdotal accounts of geotechnically-relevant features, not quantitative data that would allow understanding the factors that influence the geotechnical properties of lava tubes and how they affect these properties.

2) Ice in Lava Tubes. Our field investigation of the ice-rich Lofthellir LavaTube Ice Cave in Iceland has allowed detailed documentation of a wide range of ice related features and structures inside the cave. Our observations suggest that the massive ice formations found inside the cave are predominantly due to H_2O of *meteoric* origin (from atmospheric precipitation at the surface and atmospheric condensation inside the cave), as opposed to H_2O produced by volcanic venting. In addition, two new findings were made:

a) *Underground micro-glaciers* are recognized for the first time; they form in the lave tube as a result of accumulation, slow movement, and loss of water and massive ice under the effect of gravity;

b) *Gelifraction*, the fracturing of rocks by freezing of water trapped in joints, is an important cause of breakup and collapse or rock inside this ice-rich lava tube.

These two findings are of significance because of their potential relevance to the Moon and Mars. If massive H_2O ice does occur inside lava tubes or other caves there, we predict that gravity, even if reduced, would act over time to mobilize the ice via viscous creep and produce micro-glaciers and rock glaciers. Gelifraction, however, would also be expected to operate and promote rock falls and collapse.

3) Additional Achievements

Our project also enabled, and benefitted from, other research and outreach activities that collectively help advance the human exploration and settlement of space:

i) By combining resources from other ongoing research projects funded by NASA and other partners, we carried out together with these projects at Lofthellir the first successful flight of, and 3D-mapping by, a lidar-equipped drone inside a lava tube and ice-rich cave (Lee et al. 2019). This success should encourage further design and development work on propulsive free flying robotic spacecraft systems for the exploration of pits and caves on the Moon and Mars.

ii) Our fieldwork at Lofthellir was filmed and will be featured in an upcoming episode of *What on Earth?* (Season 6)*,* the award-winning TV documentary series and most-watched program on the US Science Channel.

iii) Results of our research will be presented at the upcoming 50th Lunar and Planetary Science Conference in Houston, TX (18-22 March 2019) (Lee et al. 2019).

The lessons learned to date maybe considered transformative in that they provide key new insights, gained from practical field experience, into some of the potential wonders (underground micro-glaciers!), and also possible dangers (rock fall, collapse), that await us in the exploration of lava tubes on the Moon and Mars.

Next Steps

As next steps in this research, we recommend, and would propose, the following follow-up work:

Geotechnical Field Survey: A campaign of detailed geotechnical investigations of a select *series* of lava tubes on Earth, capturing their diversity in composition, size, shape, age, weathering history, and ice content, to understand the key factors that influence their geotechnical properties and evolution, and by (cautious) extension, the geotechnical properties and evolution of lava tubes on the Moon and Mars.

Global Study of Ice-Rich Lava Tubes: A broadened global survey of ice-rich lava tubes to investigate the origin, mode of occurrence, diversity, effects, evolution through time, and microbiology of ice in lava tubes, and potential implications for ice in lava tubes on the Moon and Mars.

Human & Robotic Exploration of Lava Tubes: Given the special importance lava tubes will likely have in the human exploration of the Moon and Mars, identify and design robotic and astronaut hardware systems that would enable and maximize safe and productive lava tube exploration **(e.g., Fig. 18).**

Figures

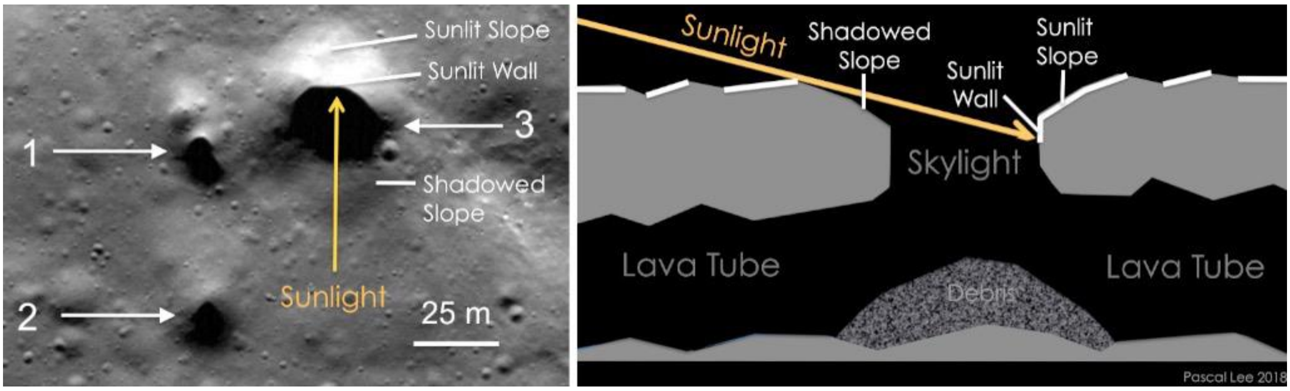

Figure 1. Lava Tube Skylights Near North Pole of the Moon? Left: Shadowed depressions on the floor of Philolaus Crater near the North Pole of the Moon interpreted as candidate impact melt lava tube entrances or *skylights* (NASA LRO). **Right**: These lava tubes would be as such high latitude that sunlight would never enter them. Temperatures in the caves could be so low that H_2O ice, were it present, could be stable for eons (Lee 2018b).

Figure 2: Lava Tubes and Skylights on Mars. Left: Collapsed lava tubes on the flanks of the Pavonis Mons volcano on Mars (ESA MEX). **Center:** A pit (D~200 m) interpreted as a possible lava tube skylight on Pavonis Mons volcano, Mars (NASA MRO). **Right**: The "Jeanne" pit crater (D~150 m) on Arsia Mons volcano, Mars (NASA MRO).

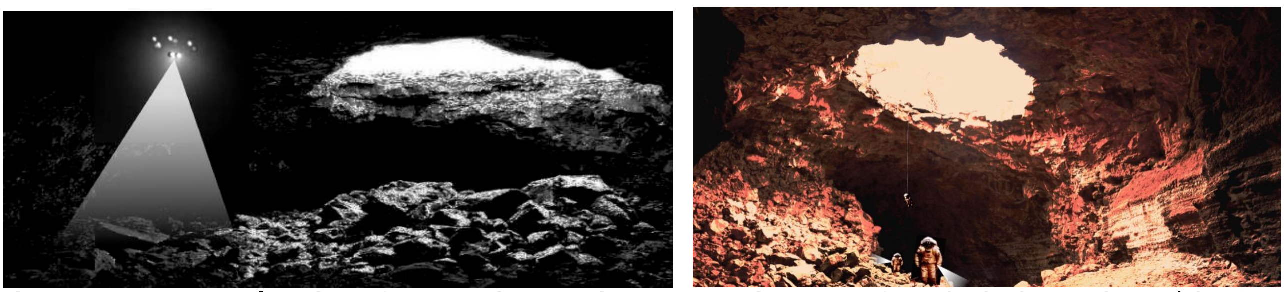

Figure 3: Future Exploration of Lava Tubes on the Moon and Mars. Left: Robotic drones (propulsive free flying spacecraft) could be used in the reconnaissance/mapping of caves on the Moon and Mars. **Right:** Humans would follow for in-depth exploration and, potentially, habitation and settlement (Lee 2018b).

Figure 4. Iceland Map, Lofthellir Lava Tube Ice Cave, and Astronaut Training. The Lofthellir Lava Tube Ice Cave is located in North Central Iceland, in the general region in which most of the Apollo astronaut field geology training in Iceland took place. Lofthellir was not known at the time. Given the lava tube's relevance to the Moon and Mars, this lava tube should be added to any future training curriculum in Iceland for Moon or Mars-bound astronauts. (**Left:** Map base by Georelief. Annotations by P. Lee; **Right:** Lee et al. 2019).

Figure 5. Lofthellir Lava Tube Ice Cave Skylight Entrance. Left: Outside view from ground level. **Right:** View from the twilight zone inside the lava tube's northwest branch. At far left is the ladder that was used by the field team to descend into the lava tube through the skylight.

Figure 6: Astrobotic's Lidar-Equipped Drone: The 0.7 m wide hexacopter drone is seen here descending into the skylight of the Lofthellir Lava Tube Ice Cave.

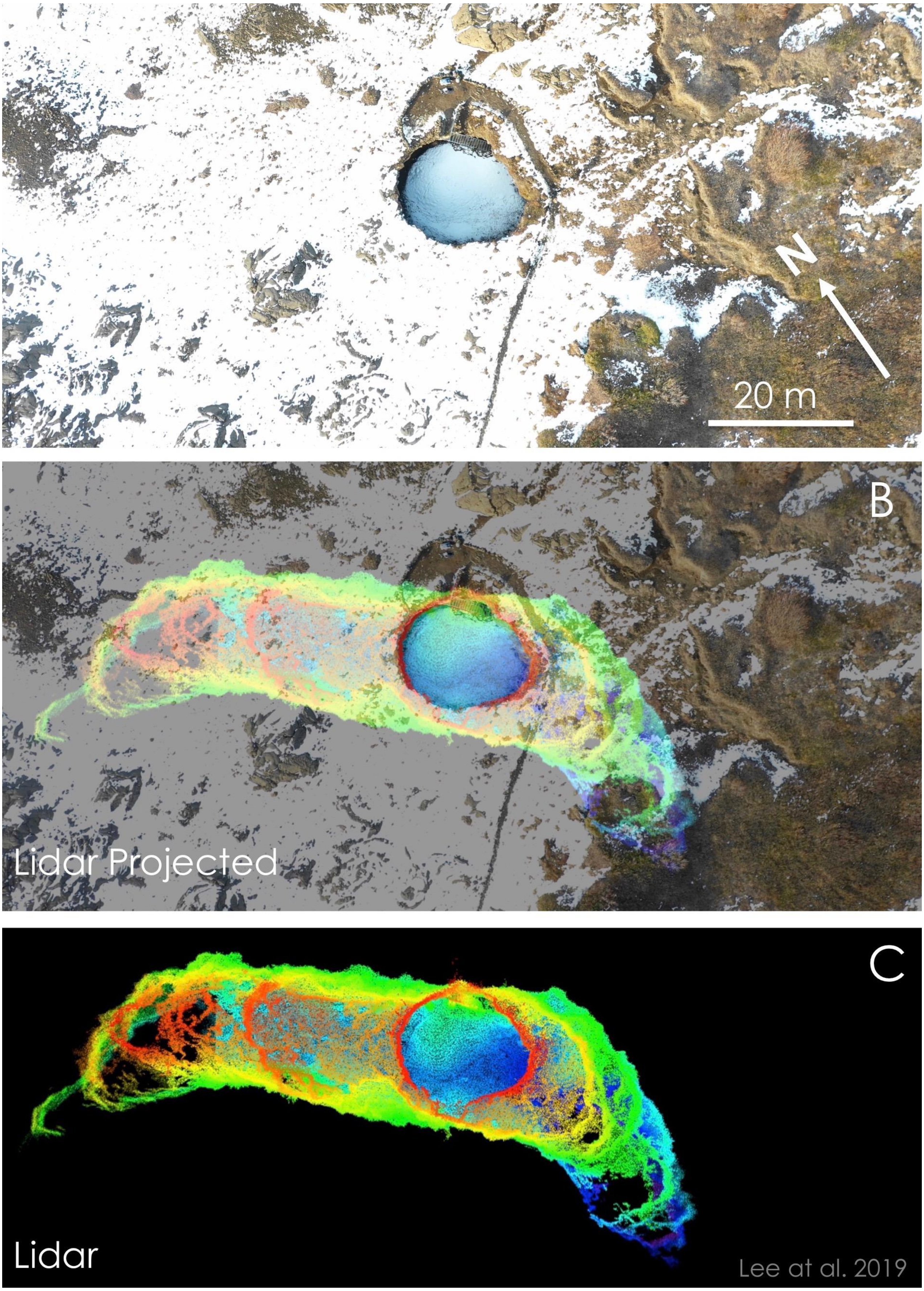

Figure 7: Drone Mapping of Lofthellir Lava Tube Ice Cave Skylight Entrance: **A:** Surface visual imaging with snow dusting on ground, including at the bottom of the skylight; **B:** A with underlying lidar-imaged cave; **C:** Subsurface lidar elevation map (Red: highest elevation; Purple: lowest) (Lee et al. 2019).

Figure 8. Massive Ice in the Lofthellir Lava Tube Ice Cave. Left: The icy floor of the lava tube presents several merged domes of ice connected to – and clearly fed from – the roof via ice stalactites. **Right:** Rocky debris along the walls of the cave – individual boulders or rock piles – may become encased in massive ice.

Figure 9. Growth and Metamorphism of Ice Stalagmites and Ice Domes. Left: The "Altar' is a cluster of ice stalagmites in Lofthellir's Main Chamber. Near the center of the image, meltwater dripping from the cave ceiling produces a splash of liquid water from a small meltwater pool at the top of an ice stalagmite, forming a distinct ejecta pattern. **Insert:** Close-up of the splash ejecta pattern. The ejected meltwater partially refreezes upon contact with colder ice near the base of the ice mass and the floor of the cave. The wide reach of the meltwater ejecta allows massive, wide-based stalagmite clusters to form. **Right:** The surface of mature ice stalagmites and ice domes presents disruption textures such as polygonal patterns with cells of lower albedo clear ice surrounded by rims of brighter rough ice. These are interpreted as being due to repeated cycles of thawing and freezing of the ice mass' surface zone (over a depth of a few cm).

Figure 10. Old Layered sIce. Isolated remnants of horizontally layered ice hanging above the current elevation of the cave's ice floor attest to earlier higher levels of the floor ice. The left arm of a caver in a yellow jacket in the background provides scale.

Figure 11: Lofthellir Subsurface Micro-Glaciers. View of the main chamber looking towards "Time Travel Glacier". Astrobotic's 0.7 m-wide hexacopter drone at lower left provides scale. (Lee et al. 2019).

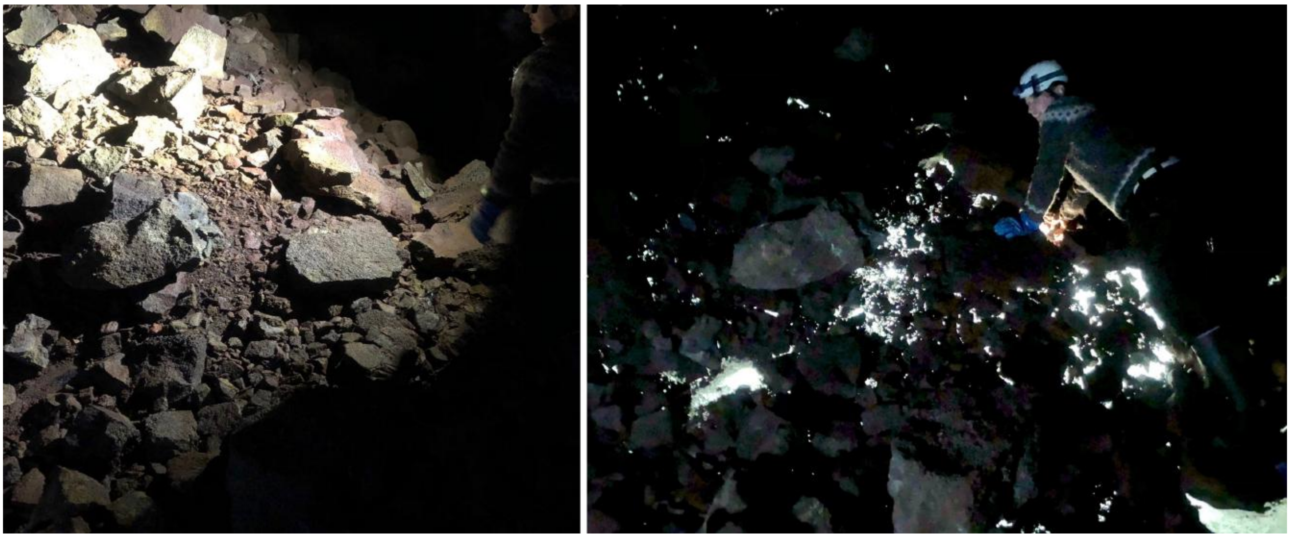

Figure 12: Lofthellir "Lightspeed Rock Glacier", a Subsurface Rock Micro-Glacier. Left: In reflected light. **Right:** Same view with transmitted light. The rock component visible on the apron is a thin veneer of rocky debris resulting from recent falls and slides. The material lying immediately underneath is massive clear ice. Deeper inside the debris and ice apron, there might be other ice-rich and rock debris layers.

Figure 13: Gelifraction and Collapse. Ceiling and wall collapse is an active modification process in the Lofthellir Lava Tube Ice Cave. **Left:** Gelifraction – the fracturing of rock by freezing of water along joints – contributes to comminution (breakdown in size) and desquamation (flaking) of rocks. **Right:** A recent collapse along a 5 m section of the cave. A curtain of merged ice stalactites near the far end of the debris apron suggests gelifraction played a role in fracturing the ceiling and wall rocks, leading to collapse.

Fig. 14. Lofthellir Lava Tube Ice Cave 3D Sketch Map. Perspective sketch map of the Lofthellir Lava Tube Ice Cave sketched on 10 Oct 2018 as the field team investigated the cave along progressively deeper sections. Ice deposits were colorized in blue later. The length shown is approximately 130 meters of the total 200+ meters. The entrance skylight would be to the right (not shown). The Astrobotic lidar-mapping drone was flown in the Main Chamber at far left.

Figure 15. Rock Falls and Environmental Sensors. Rock fall debris aprons incorporating varying amounts of ice create the V-shaped narrow seen here across the Main Chamber of the Lofthellir Lava Tube Ice Cave. “Moon Rock”, a 1 meter wide boulder seen here sitting in the dark on the cave’s icy floor appeared recently as a result of a single mass rock fall (A. F. Birgisson, *pers. comm.*). Environmental data loggers were installed at different locations inside and outside the cave to collect 1 full year of recordings of variations in lighting (from cave visits), temperature, atmospheric pressure, and relative humidity.

Figure 16: Drone in Flight Inside the Lofthellir Lava Tube Ice Cave. The hexacopter drone with integrated lidar developed by Astrobotic is seen here in flight inside Lofthellir's Main Chamber. This was the first time a drone equipped with a lidar mapped a lava tube, and a cave with ice.

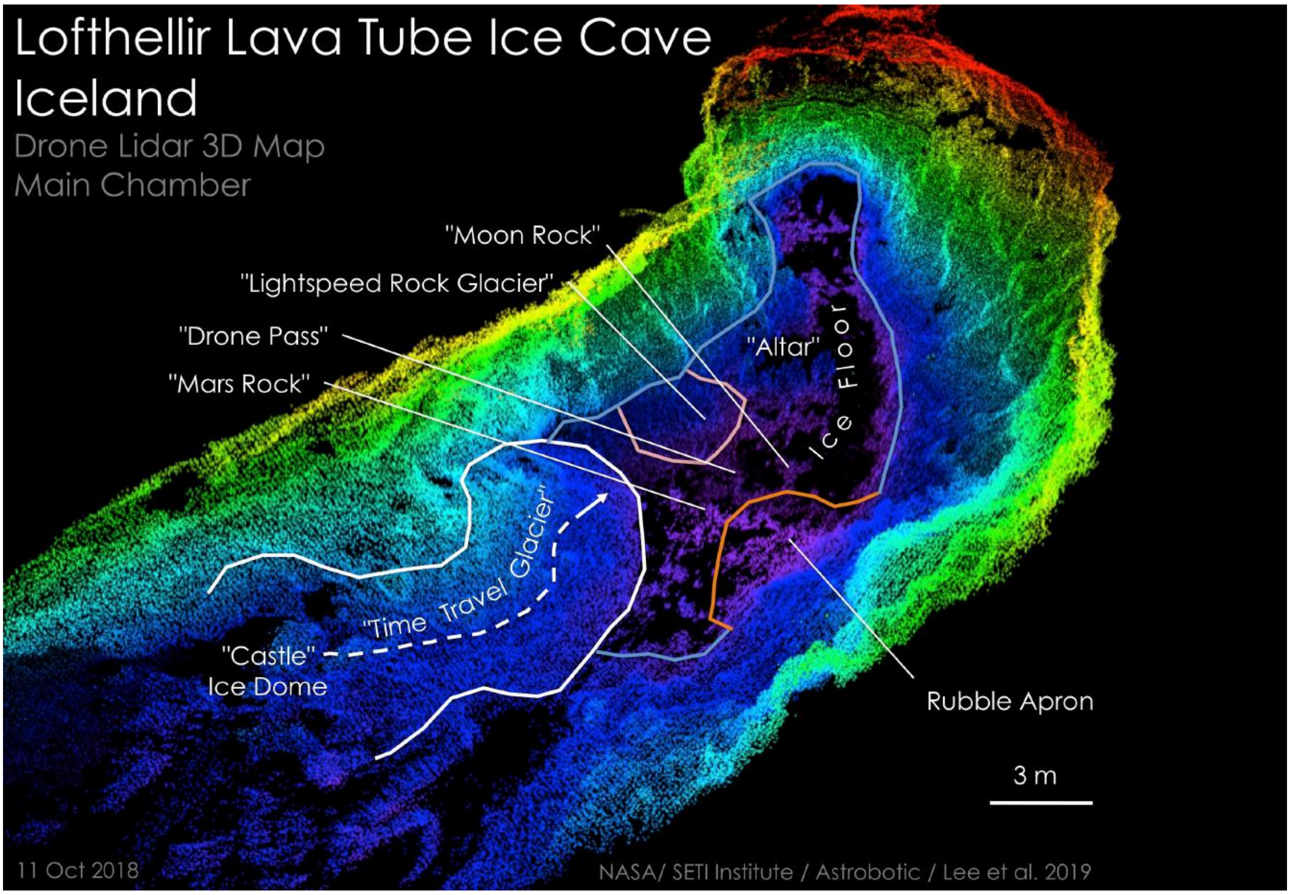

Figure 17: Drone-Borne Lidar Map of the Lofthellir Lava Tube Ice Cave's Main Chamber. Drone map produced by Astrobotic's drone-borne lidar. Projected perspective view. (Red: highest elevation; Purple: lowest; Black: no coverage. The main geologic features referred to in this report are indicated in this rendering (Lee et al. 2019).

A B C D

Figure 18. EVA Boot Sole Design for Icy Surface Exploration. A: Tintin explores an icy cave on the Moon but loses traction (Note his tread-less and cleat-less soles) (Herge/Moulinsart); **B:** Apollo Moon boot overshoes (Smithsonian); **C:** Treaded but cleat-less sole of Apollo Moon boot overshoe (NASA/Smithsonian); **D:** Rubber boot with treads and cleats used by our field team at Lofthellir Lava Tube Ice Cave, Iceland. The design of future planetary EVA boot shoe soles should include options with cleats and crampons to ensure safe traction on eventual icy surfaces.

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Figure 19: Field Team that investigated the Lofthellir Lava Tube Ice Cave, Iceland.

Abbreviations

DFF	Dubai Future Foundation
ESA	European Space Agency (ESA Member Countries)
HMP	Haughton-Mars Project
JAXA	Japan Aerospace Exploration Agency (Japan)
Lidar	Light Detection and Ranging
LRO	Lunar Reconnaissance Orbiter
MBR	Mohammed Bin Rashid
MEX	Mars Express
MRO	Mars Reconnaissance Orbiter
NASA	National Aeronautics and Space Administration (USA)
Rannis	Rannsóknamiðstöð Íslands (Icelandic Centre for Research) (Iceland)
STTR	Small business Technology TRansfer
UAE	United Arab Emirates
UAESA	United Arab Emirates Space Agency (UAE)

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