ICE-RICH CAVES ON THE MOON AND MARS: PROSPECTS AND PRAGMATIC RECOMMENDATIONS FOR EXPLORATION.

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Summary: We synthesize lessons learned from our recent studies of lava pits and caves on the Earth, Moon and Mars, and of promising technologies to explore these, and offer recommendations for the future.

Pits/Caves & Lava Tubes on the Moon & Mars: Over 300 pits have been identified on the Moon [17,35,36]. The USGS' Mars Global Cave Catalog lists over a thousand pits and candidate caves [12]. The vast majority of planetary pits are associated with lava cavities, mostly volcanic or impact melt lava tubes. Some pits on Mars are of volcano-tectonic origin [9,11]. None are likely from speleogenesis in karst.

Most pits and caves identified on the Moon are within 60° of the equator, a biased distribution reflecting an inherent limitation in the automated approach used to identify lunar pits [35]. While still geologically interesting, low latitude pits/caves are not expected to be cold enough to cold-trap H_2O ice, mainly because their warm sunlit floors would radiate substantial heat into adjacent cave volume. However, we recently identified candidate impact melt lava tube skylights on the floor of Philolaus Crater (D~70km, 72.1°N,32.4°W), 800 km from the lunar North Pole [23,24]. If confirmed, these skylights would be high enough in latitude to have permanently shadowed floors as cold as the poles' Permanently Shadowed Regions (PSR).

Terrestrial Analogs: Lava tubes on Earth, including collapsed ones, are analogs for *sinuous rilles* and *pit crater chains* on the Moon and Mars [33,14,8,24]. To understand better if and where H_2O ice might occur inside lava tubes on the Moon and Mars, and how it might be explored, we investigated the Lofthellir Lava Tube Ice Cave, Iceland, and mapped it in 3D with a drone-borne LiDAR [25,26] **(Fig. 1).**

Water Ice in Lava Tubes: Because subsurface cavities on planetary bodies offer shelter from ionizing radiation, meteoritic bombardment, drastic diurnal temperature variations, and surface dust transport, they represent environments radically different from the surface. Caves on Earth may be repositories of perennial H_2O ice even if external conditions preclude stable surface ice year-round [1,16]. Analogously, some caves on the Moon and Mars might be volatile-rich.

Building on previous studies of thermal conditions inside planetary lava tubes [21], we find that for high latitude skylights on the Moon with permanently shadowed floors, the portion of the cave immediately below the skylight achieves the coldest temperatures (T~40-60K), as the open sky overhead maximizes radiative heat loss. If H_2O is available in sufficient amounts, H_2O ice will accrete immediately below the pit, forming a cap of ice over any existing debris pile on the pit floor **(Fig.2).** Over time, with continued H_2O supply, cold-trapping of ice would expand laterally into the subsurface cavity beyond the skylight area.

At Lofthellir, where most of the H_2O ice is exogenic, derived from atmospheric H_2O either as water vapor or by meteoric precipitation followed by infiltration [25,26], there is ample supply of H_2O, and large ice masses occupy the cave. Our field study revealed that this ice is dynamic, forming micro-glaciers with accumulation, flow and ablation/melt zones, and moraines. The rockfall debris loads carried by some micro-glaciers qualify them as *micro- rock glaciers*.

On the Moon, it remains unknown if sufficient H_2O ice mass would accumulate inside high-latitude lava tubes to allow it to creep under its own weight given the extremely low temperatures. The candidate pits in Philolaus and associated rilles are narrow (<50m across), implying small lava tube volumes and limited ice masses per unit section [25,26].

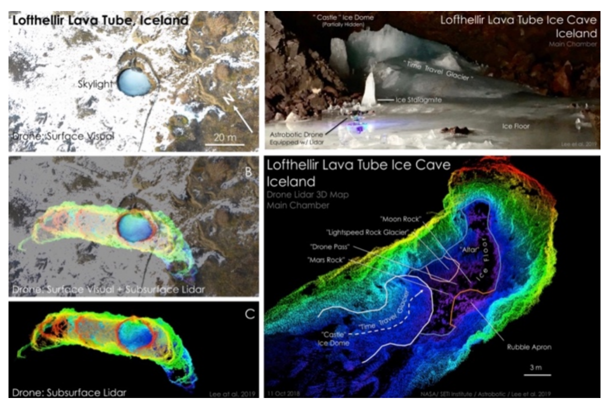

Fig. 1: Lofthellir Lava Tube Ice Cave, Iceland. **L**: Drone + LiDAR 3D mapping of skylight area. **R: Top**: Micro-glaciers. **Bot**: Main chamber LiDAR map [25,26].

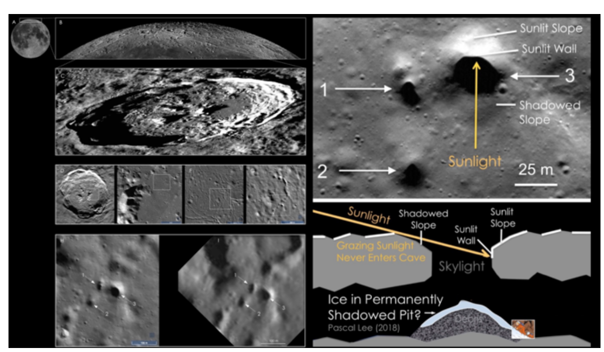

Fig. 2. Candidate permanently shadowed impact melt lava tube pits (skylights) in Philolaus Crater near the North Pole of the Moon. [23,24].

On Mars, the possibility of ice caves has also been proposed [e.g.37]. Because Mars has a substantial, H_2O-saturated atmosphere that provides an exogenous source of H_2O [e.g.,22,2,3,30], and because its giant volcanoes might still be active and release endogenic H_2O [e.g.,30], lava tubes on Mars, even at high altitude, are likely to harbor H_2O ice. The protracted history of glaciation on Mars, including on Tharsis volcanoes, further raises chances that some Martian lava tubes may be long-term repositories of ice [18,32,34].

Astrobiology Potential: Lava tubes on Mars have significant astrobiological potential [e.g.,15,4,10,29]. The likely association of volatiles with these caves strengthens their potential for harboring biosignatures, including of extant life. Given the biocidal agents acting on Mars at present, the Martian surface is likely sterile, and the sheltered, warmer, wetter subsurface is a more likely place where extant life might be found. Finding extant life, more so than fossils, is critical to deciding whether any biosignature found is alien or not, as analysis of fresh genetic material must be performed in order to establish alien phylogeny. While lower mass and cost deep drilling technologies might one day be deployed on Mars [20], caves offer immediate ways of exploring the subsurface for alien life.

Resources & Habitability of Lava Tubes: The exploration of lava tubes should also be of high priority in the context of human exploration. Lunar circumpolar caves cold enough to cold-trap H_2O ice would offer a valuable non-polar option for H_2O ice ISRU.

Lava tubes have also been proposed as "ready-made" safe havens that humans could occupy for habitation and settlement [e.g.,19,7]. However, this prospect is likely not as realistic - because not as necessary -, as often assumed. On Earth, while humans have a long history of inhabiting caves, most caves used were in karst, not lava tubes. Lava tubes have rarely been used for extended stays, for three main reasons: i) There is often no source of liquid water nearby, in contrast to karst caves which, by definition, form *by* liquid water flow; ii) Lava tubes are significantly more hazardous than karst caves, as they are more prone to rockfalls, mainly because the formation of lava tubes involves drastic cooling and contraction of initially molten rock, which produce highly fractured walls and ceilings. Susceptibility to collapse is exacerbated by the fact that volcanic regions are generally also seismically active; iii) Because of their history of collapse, lava tube surfaces are often extremely rough and their floors difficult to traffic. Lava tubes with smooth, glassy walls, are uncommon.

The above three issues would persist on the Moon and Mars, where meteoritic impacts are an extra cause of continual fracturing and instability. If ice is present, a valuable resource would be on hand, but as we observed in Iceland, ice accretion increases gelifraction, which then promotes rockfalls. For ice-rich caves on Mars, acute planetary protection concerns also arise. More importantly, the main advantages of a planetary cave (shielding from ionizing radiation [13] and temperature swings) are easily and safely achieved by burial of habitat structures under regolith "sand bags".

Robotic and Human Exploration: Access and exploration of pits on the Moon and Mars pose an exciting challenge. Classical robotic mobility systems proposed for pit and cave exploration, such as autonomous rovers and walkers, direct landers, tethered robots, and danglebots, all involve substantial complexity and risk, including the need to interact carefully, and thus slowly, with ground and wall obstacles. Slow is not good, as access to lasting power and comms while caving are limited. Drones have been proposed (gas thrustered flyers or rotorcraft) as they offer the key advantages of being nimble, quick, and touchless [26]. However, as drones would still risk stirring up considerable dust, another promising approach is proposed with JPL's GlobeTrotter universal soft hopper concept [27,28] **(Fig.3)**. Given the multitude of caves on the Moon, Mars, and beyond, such a universal, low cost, robust robotic approach to exploring caves, with human follow-up as required, is recommended.

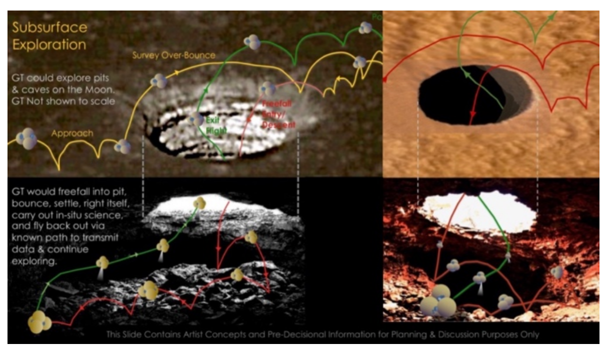

Fig.3: GlobeTrotter Soft Hopper Cave Explorer Concept.

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