VOIDS IN LUNAR MARE AND IMPACT MELT DEPOSITS — A COMMON-SENSE EXPEDIENT TO THE EXPANSION OF HUMANS INTO SPACE.

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Introduction: Apollo exploration of the Moon was a high-risk enterprise that only the courageous would dare undertake. While the extravehicular activities of Apollo operations regarded radiation, micrometeorites, solar wind, temperature extremes, and the vacuum of space as acceptable occupational hazards, any long-term human presence on the Moon will require a more active risk mitigation posture. Fortunately, protection from most surface hazards may be found naturally and inexpensively inside accessible subsurface voids (i.e. caverns) when shielding from a few meters of ceiling rock is present [e.g., 1]. Long regarded as possibilities [2-5], candidates for subsurface planetary voids and their systems have been appearing in new high-resolution imagery of both the Moon [6-8] and Mars [9], and have become a topic of general interest [e.g., 10]. While Mars candidate voids have an astrobiological component to their attraction, lunar speleology is motivated more by what subsurface voids represent to 1) basic lunar science, and 2) lunar engineering.

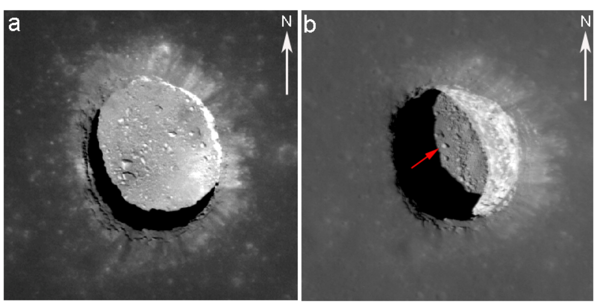

Figure 1. The 90 meter-diameter Tranquillitatis pit; 1a shows a nadir view, NAC frame M155016845R, image is ~175m wide; 1b is an oblique image (M152662021R; emission angle 26°) revealing a minimum of 20 meters of subsurface floor space (surface east of three conspicuous rocks at shadow's edge, red arrow).

Basic Lunar Science: Open voids provide access to the subsurface and therefore represent exploration potential of high value to science. Lava tubes likely contain records of magma source compositions, evolution, and flow morphologies, protect delicate minerals, and afford access to paleo-regolith layers (which could preserve ancient samples of implanted solar wind). However, geothermal temperatures [11,12] within cavernous environments should hold constant and probably exceed the sublimation temperatures of most likely volatiles. Voids located near surface features of high scientific interest could serve as convenient bases of operation for their exploration. Two types of subsurface voids, one in mare deposits and the other in ponded impact melt deposits, were identified from lunar orbit [6,13]. Preliminary studies suggest that visible openings in both types are the result of ceiling collapse. However, precise modes of deposit emplacement, cavern formation, entrance formation, lateral extent and subsurface connectivity remain speculative without further evaluation. Depending on the type of void under consideration, improved insights into volcanic or impact melt emplacement processes are anticipated from their exploration.

Lunar Engineering: In addition to surface hazard protection, subsurface environments would conserve resources and reduce engineering costs by providing "ready-made" structures requiring a minimum of retrofitting to become useful as habitations or caching supply depots. Indeed when considering facilities suitable for the long-term habitation and exploration of the Moon, such natural voids would be difficult to improve upon.

Voids in mare deposits: To date eight pits have been identified in Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) [14] images within mare deposits having the potential for subsurface access. These are located in Mare Tranquillitatis, Oceanus Procellarum (Marius Hills area), Schlüter crater, Lacus Mortis, Mare Ingenii, and Mare Fecunditatis [13]. Most pits are well-removed from mare margins, and many show fine layering in their walls that could provide valuable insights on the nature of mare emplacement. Oblique NAC frames of the two features in the Marius Hills and Mare Tranquillitatis confirm subsurface extents of at least 12 and 20 meters from the pit margins, respectively. Additional passage is considered likely if the voids are lava tubes.

Lunar rilles form either by surface erosion or by tube collapse [e.g., 15]. The Marius Hills pit is located within a lunar rille and so currently represents the best candidate for a true skylight (collapsed lava tube ceiling) on the Moon. Other rilles or pit crater chains have been found to be linear but discontinuous [16]. The space between such features likely represents uncollapsed tube. Obvious entrances to these structures have yet to be confirmed. While gaining access to this type of underground environment may be difficult, an inventory is appropriate for any comprehensive considerations of subsurface exploration/exploitation, and is in preparation.

Voids in impact melt: While lava tubes with collapsed ceilings (skylights) represent the most commonly visualized mechanism of lunar speleogenesis [e.g., 6,8], new evidence suggests that some lunar caves may result from internal adjustments during cooling within impact melt accumulations associated with large, complex craters [7]. More than 170 of these melt pond pits, of various shapes and sizes, were identified in NAC images associated with twenty-eight impact craters across the Moon [13]. Most of these pits appear to be the result of collapse into subsurface voids. For example, the bridge spanning the negative relief feature in Figure 2a would not be possible if the pits were caused by extension. Additional negative relief features occur as trench-like valleys and canyons ranging in length from less than 5 to 2,000 m (Figure 3). Their outlines may be sharply defined or subdued, with 1) irregular margins, 2) pinching terminations, 3) bridging across portions of their widths, and 4) suggestions of continuation (topographic lows in sinuous patterns) beneath adjacent surfaces.

Site selection for landed assets will rely on orbital data in the early stages of planning. Whenever feasible, preliminary considerations for any cave investigation should include 1) cross-sectional and lateral cave passage dimensions, 2) accessibility and trafficability estimates, 3) structural integrity determinations, 4) determining whether the floor surface is smooth or rocky; if rocky, size-frequency distribution and rock-arrangement determinations, and 5) whether there are one or multiple levels to the cave.

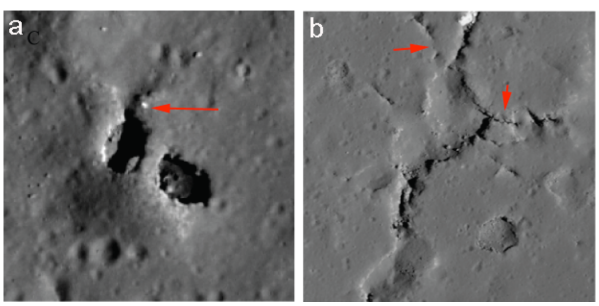

Figure 2. Examples of pit morphologies in impact melt deposits. 2a (175 m wide) and 2b (200 m wide) are in Al-Tusi pond, associated with King crater on the lunar farside. More than 170 such features have been found to date. North is up in all images. Note shadow to the west of the bridge on the pit floor in 2a. Red arrow indicates possible overhang or uncollapsed portion. 2b shows a region of collapse with several branching avenues, some of which may contain roofs or existing voids (red arrows).

Summary: Two types of lunar negative relief feature have different speleological implications — one that involves a cavernous void (collapse; found in both mare and impact melt), and another which may or may not be associated with a subsurface void space (extensional fracturing; found in impact melt). In the latter case, a subsurface system of networked voids can be visualized, but remains hypothetical. Separating the features involving possible extension from those resulting from melt withdrawal and collapse is being conducted by [13]. Continuing the assessment of known and future subsurface void discoveries will provide insights into the details of lunar speleogenesis, impact melt emplacement, mare deposit emplacement, and enhance applied exploration science. The practicability of using the lunar subsurface either for temporary or long-term habitation, or as resource caching facilities for surface exploration, is straightforward, and has been an anticipated chapter of lunar science for more than 130 years [5].

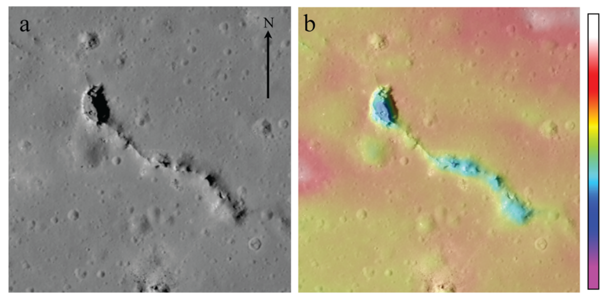

Figure 3. 3a presents a sinuous pit in the King crater Al-Tusi impact melt; NAC frame M136756054R. A number of bridged or "roofed-over" portions are apparent in this image. Figure 3b includes the complimentary NAC DEM data, the color scale for which ranges across 60 meters of topographic relief. Images are 0.5 km wide.

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