LUNAR CAVES IN MARE DEPOSITS IMAGED BY THE LROC NARROW ANGLE CAMERAS

J. W. Ashley[1], M.S. Robinson[1], B. Ray Hawke[2], A. K. Boyd[1], R. V. Wagner[1], E. J. Speyerer[1], H. Hiesinger[3,4], C. H. van der Bogert[3]; [1]Lunar Reconnaissance Orbiter Camera, School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-3603 (james.ashley@asu.edu); [2]Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI; [3]Institut für Planetologie, Westfälische Wilhelms-Universität, Münster, Germany; [4]Brown University, Providence, RI, USA.

Introduction: Any long-term human presence on the Moon will require reliable protection from surface hazards (radiation, micrometeorites, temperature cycling), which can be facilitated using existing caves [1-4]. Such voids could also provide access to a diversity of pristine geologic formations. Depending on the type of cavern, these formations may include delicate sublimate minerals, paleo-regolith layers (which could preserve ancient samples of implanted solar wind), records of magma source region compositional evolution [e.g., 5,6], and/or surface flow morphologies.

Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) [7] images are revealing potential opportunities for such exploration and habitation beneath the lunar surface at a variety of locations and geologic environments across the Moon. NAC imaging currently confirms the existence of sublunarean voids associated with two of three pits in mare deposits, and has revealed more than 140 negative relief features formed in impact melt deposits, some of which are likely to be the result of collapse into subsurface void spaces. The possibility for additional spaces beneath intact ceilings in both types of settings is plausible, if not likely.

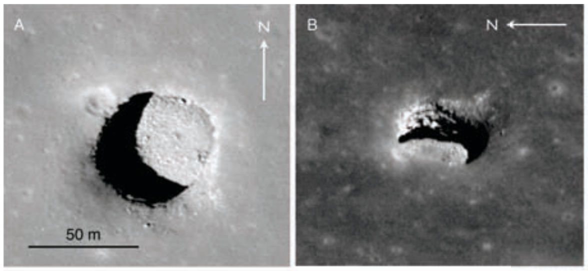

Figure 1. Marius Hills pit (A) near-nadir (emission angle 0.5°) image (M122584310L) showing pit outline and rubble-strewn floor (incidence angle 25°); image is approximately 140 m wide. (B) Pit imaged (M137929856R) with a 34° incidence angle and a 45° emission angle, showing ~12 m of illuminated floor beneath cavern ceiling. Note layering in pit walls; image is approximately 250 m wide.

The lunar pits were located using SELenological and ENgineering Explorer (SELENE) Terrain Camera (TC) images [4,8], and confirmed as cavernous using LROC NAC images [9]. These pits are located in the Marius Hills region of Oceanus Procellarum at 14.2°N, 303.3°E (Figure 1), and within Mare Tranquillitatis at 8.3°N, 33.2°E (Figure 2). A third pit was identified within Mare Ingenii at 35.6°S, 166.0°E [8], but an associated subsurface void has yet to be confirmed for this pit. All three pits also show fine layering in their walls that speak volumes on the nature of mare emplacement (Figures 1B & 2D-F) [9].

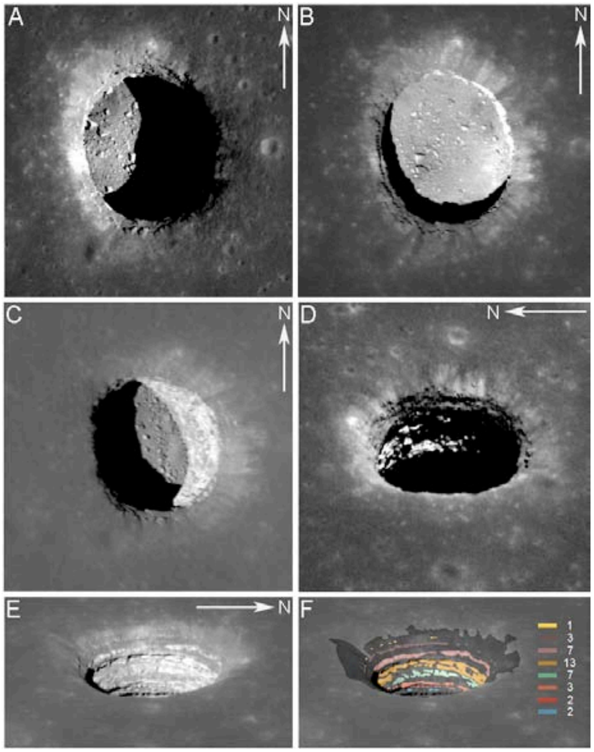

Figure 2. Mare Tranquillitatis pit; (A) near-nadir image (M126710873R) and (B) 7° emission angle image (M155016845R), collectively reveal more than 90 percent of the floor, both images are approximately 175 m wide. (C) Oblique view (26° emission angle; M152662021R), a significant portion of the illuminated area is beneath overhanging mare. Layering is revealed in D, E, & F (M155023632R and M144395745L, respectively). Outcropping bedrock layer thickness estimates are presented in F in meters, ± 1 m.

The Marius Hills pit outline is slightly elliptical, with diameters ranging from 48 to 57 m (Figure 1). From the southwest rim to one third of the floor diameter (from southwest to northeast), shadow measurements show a maximum depth of 45 ± 2 m (M122584310L). Our stereo-derived digital terrain model (using NAC pair M155607349, M155614137) shows the pit floor to be 45 m below the sharp rim and

52 m below the surrounding flat mare surface. The floor of the Marius Hills pit is littered with meter-scale blocks with no resolvable impact craters. Forty-six of 93 blocks measured within the illuminated area are larger than 2 m, with the largest block having a maximum length of 5 m. The standard deviation of reflectance values of the pit floor is four times higher than that of the reflectance of the surrounding mare, indicating a blockier surface (M122584310L).

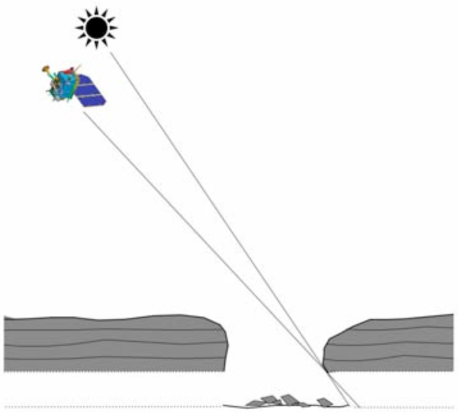

Figure 3. Schematic showing Marius Hills cave in cross-section with viewing geometry for direct observing under the surrounding mare seen in Figure 1B. A similar situation is shown in Figure 2C for the cave in Mare Tranquillitatis. The dotted lined portion of this void space is speculative.

An oblique (43° emission angle) NAC image that was closely aligned with the incidence vector captured illuminated portions of the pit floor beyond the nadir-view pit perimeter, and beneath ceiling rock, revealing the cavernous nature of the pit in Marius Hills (Figure 3). The distance imaged along the floor into the cavern (beneath the ceiling) is ~12 m, and the height of the ceiling above the floor is ~17 m. How far the void extends beyond the shadow edge is unknown. This oblique image also reveals eight layers in the pit wall that range in thickness from 4 to 12 ± 1 m, with an average thickness of 6 m.

The Mare Tranquillitatis pit diameters range from 84 to 99 m, with a maximum depth from shadow measures of ~107 m (Fig. 2A, B). Several large, angular blocks, ranging in size from 3 to 8 m are sparsely distributed across the floor, and likely represent detritus from the pit walls or collapsed roof materials. The standard deviation of the integrated floor reflectance is seven times that of the surrounding mare, while the smooth area between the boulders is only three times higher. These values show the floor to be significantly rougher than the mare surface. An oblique view (26° emission angle) of the pit in Mare Tranquillitatis shows ~20 m of floor extending beneath a ceiling, and thus confirms a second subsurface void (Figures 2C & 3). Subtracting the thickness of the visible ledge (~47 m) from the depth of the pit indicates an approximately 60-meter high opening to the cave. The oblique images (Figure 2D, E) also shows a funnel-shaped slope at the rim, and reveal fine layering in the walls.

As the Marius Hills cave is located within a sinuous rille, the pit feature is likely a skylight resulting from ceiling collapse into an unfilled lava tube [4,8,9]. Similar explanations are reasonable for the Tranquillitatis and Ingenii pits, although these features are not associated with obvious rilles in their respective mare. LROC NAC targeting of all three features remains ongoing.

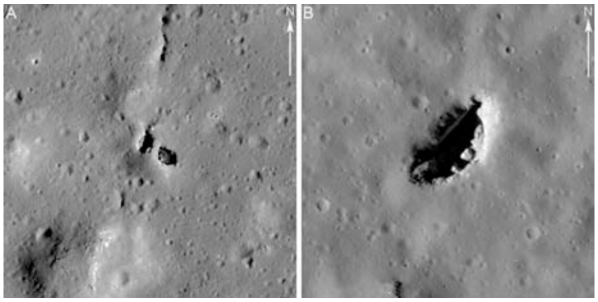

Figure 4. (A) Natural bridge traversing a subsurface void in large impact melt pond north-northwest of King crater (M113168034R; incidence angle = 48°, emission angle = 1°); image is approximately 350 m wide. (B) Negative relief feature (approximately 20 m deep) in Copernicus crater melt deposit (M135317661R; incidence angle = 58°, emission angle = 17°); image is approximately 290 m wide).

Negative relief features within impact melt deposits present a range of morphologies that include linear canyons and sinuous valleys interpretable as extensional cracks. Others are probably the result of melt withdrawal and collapse (Figure 4), suggesting the possibility for extant caves beneath the surfaces immediately adjacent to these, or elsewhere within the ponded melt volume.

Summary: Collapse features over probable lava tubes within mare (skylights) may provide points of ingress to larger "trunk" cave passages. Collapse features over areas of melt pond drainage suggest additional sublunarean voids. Both types of cave offer intriguing exploration and habitation opportunities.

References: [1] Horz et al. (1985) *Lava Tubes: Potential shelter for habitats*, LPSI. [2] Coombs et al. (1992) *NASA-CP-3166*. [3] De Angelis, et al., (2002) *J. Radiat. Res.*, *43*, S41-S45. [4] Haruyama et al., (2009) *JGR, 39.* [5] Weider et al., (2010) *Icarus*, *209*(2), 323-336. [6] Crawford et al., (2007) *Astron. and Geophys.*, *48*, 3.18-3.21. [7] Robinson et al. (2010) *Space Sci. Rev.*, 150, 81-124. [8] Haruyama et al., (2010) *LPSC XLI*, Abs. #1285. [9] Robinson et al., *JGR* (in review).