LUNAR PITS: SUBLUNAREAN VOIDS AND THE NATURE OF MARE EMPLACEMENT. J. W. Ashley[1], A. K. Boyd[1], H. Hiesinger[2], M. S. Robinson[1], T. Tran[1], C. H. van der Bogert[2], R. V. Wagner[1], and the LROC Science Team. [1]Lunar Reconnaissance Orbiter Camera, School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-3603 (james.ashley@asu.edu); [2]Institut für Planetologie, Westfälische Wilhelms-Universität, Münster, Germany.

Introduction: The possibility for shallow, subsurface lunar voids has existed in the minds of researchers at least as far back as the 1960's, often under the heading of lunar caves [1]. Such voids were anticipated as the straightforward result of lava tube drainage with ceiling failure and subsequent collapse [2]. Any future long-term human presence on the Moon will require reliable protection from surface hazards (radiation, micrometeorites, temperature fluctuations, solar flares, etc.), which can be accomplished effectively using extant lava tube caverns [3-5]. Subsurface void spaces may also preserve unique geologic environments significant to scientific exploration, and pits and/or skylights would naturally serve as points of access to those environments. It is unknown whether these systems are present as intricate "plumbing" networks, or occur as isolated caverns of limited extent. However, it is possible that such caverns could extend for tens or even hundreds of kilometers.

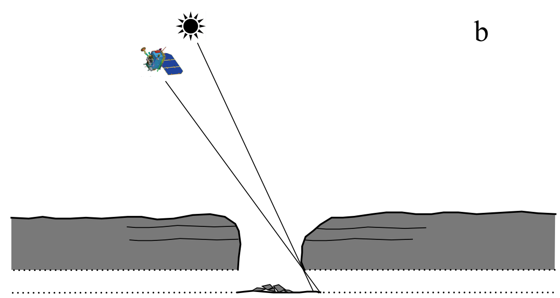
Features described as pit craters, but having a variety of suggested origins have also been observed on Mars [6, 7], Mercury [8], and the Jovian moon system [e.g., 9, 10], with possibilities for larger-scale pit features on Venus [11]. In some sources, however, a distinction is made in discussion between pit craters and skylights, the latter term having an implicit mode of origin as that of lava tube ceiling collapse [12-14].

Location	Image	Depth (m)	Shadow length m	Diameter (m) Max	Diameter (m) Min	Slew angle (°)	Incidence angle (°)
Mare Tranquilitatis	M106662246R	102	60	97	86	0.00	30.52
	M126710873R	106	53	95	85	0.00	26.56
	M137332905R	92	70	98	81	7.05	37.37
	M144395745L	NM	NM	100	NM	-50.46	47.92
Marius Hills	M114328462R	>32*	NM	62	48	6.80	61.38
	M122584310L	36	19	57	46	0.00	28.08
	M133207316L	>8*	NM	76	61	29.13	82.84
	M137929856R	NM	NM	NM	NM	42.86	33.79
Mare Ingenii	M115225180L	>24	NM	146	107	0.00	74.52
	M121124338L	68	87	125	97	0.00	52.00
	M123485893R	47	38	104	68	-5.45	39.05
	M128202846L	76	105	125	68	0.00	54.25
	M136465172L	>47*	NM	110	73	15.51	55.47
	M138819477R	52	42	101	73	0.00	38.91

* depth estimate less certain due to high slew angles
NM not measureable

Table 1. Catalog of images.

Background: The first candidate for such a lunar environment was identified with JAXA's SELenological and Engineering Explorer (SELENE; a.k.a. Kaguya) Terrain Camera and Multi-band Imager at 10 m resolution during an imaging campaign optimized for skylight detection [12]. Nine images (with solar incidence angles ranging from ~ 15° to 73°) were collected by SELENE of a pit feature named Marius Hills Hole by its discoverers, which is located in the Marius Hills region within Oceanus Procellarum at approximately 14.09°N, 303.31°E. The pit was estimated to be ~ 65 m in diameter, and 80-88 ±10 m deep, with a ceiling 40-60 m thick [12]. The SELENE team deduced the formation mechanism for the Marius Hills pit to be partial collapse of a lava tube based on its location within a sinuous rille, and by elimination of other less plausible mechanisms. Direct imaging of cavernous interiors beneath their ceilings is arguably necessary to confirm this interpretation, and requires the combination of optimal solar incidence and high angle slew (off-nadir) imaging.



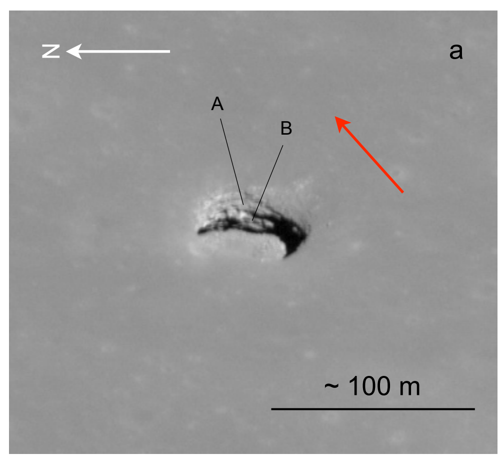


Figure 1a: Marius Hills pit imaged from a slew angle of 43° and a solar incidence angle of 34°. Red arrow shows sun azimuth. N-S pixel scale is 0.55 m; E-W pixel scale is 0.71 m. Note mare bedrock layering in the pit walls. Figure 1b shows the imaging geometry in cross section. Dotted lined zones have not been imaged and are speculative.

Features identified as 'pit-floor craters' have been found on Mercury during the January 14, 2008, flyby of the MEcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft [8]. While these features have a different morphology, scale, and other interpreted modes of origin [e.g., 8] than lava tube skylights, their presence is interpreted to be associated with near-surface magmatic activity, which may increase the odds of finding lava tube systems during higher-resolution surface reconnaissance after MESSENGER achieves orbital insertion in March 2011. In addition, pit features interpreted to be lava tube skylights to subsurface caverns have been found in volcanic regions on Mars [13]. The confirmation of such features within volcanic materials on the Moon lends credibility to these interpretations and possibilities, and encourages their continued exploration.

Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) images have pixel scales up to 0.5 meters at a nominal 50-km altitude over a 2.5 km-wide swath [15], and have been collected for three pits found in lunar mare, including the Marius Hills pit imaged by [12]. Each of these are discussed below.

Marius Hills Pit: LROC NAC was used to re-image the Marius Hills pit under a variety of lighting conditions on four orbits, revealing morphologic details with pixel scales ~ 0.5 m. An oblique (43° slew angle) image reveals portions of the pit floor beyond the nadir view pit perimeter, and beneath the overhanging ceiling rock, thus confirming the 'sublunarean' extension of this pit (Figure 1).

NAC images show pit diameters to range from 60 m to 47 m with a depth of ~ 36 m. The pit outline is elliptical with a faintly trapezoidal modification and walls that exhibit a layered structure.

The sun angle was calculated for both directions using the sub-solar point and the center of the image. The calculation of the height difference between the shadow and the object producing the shadow was then performed in the two orthogonal directions independently and compared for error checking. Figure 1b shows the cross-sectional geometry of the Marius Hills oblique imaging. The vertical Marius Hills pit reveals a multilayered structure of near-surface mare flood basalts. Thickness estimates for the coarser units (highlighted as A and B in Figure 1a have been calculated to be 4 - 8 and 6 - 10 m (± 1 m), respectively.

Mare Ingenii Pit: The Mare Ingenii pit is located at 35.95°S, 166.06°E, and was imaged by the NAC six times with a range in incidence angle of 39° to 75°, and from both nadir and off-nadir positions, allowing for weak stereoscopic viewing. The pit is oblate with a moderately trapezoidal outline and a long axis aligned approximately NNE-SSW. Its dimensions are roughly 101 by 66 m, with a depth of 60 ± 15 m. The pit walls have slopes that range from nearly vertical on the NNW side to approximately 45° on the SSE side. Rubble covers the floor in areas that are illuminated, and rises close to the pit rim, forming a ramp-like structure. The mare terrain surrounding this pit is a level cratered plain, without obvious indications of additional subsurface voids.

Mare Tranquilitatis Pit: In contrast to the Marius Hills and Mare Ingenii pits, the Mare Tranquilitatis pit (8.34°N, 33.22°E) is nearly circular in planform, with diameters ranging from 85 m to 97 m, and a depth of 100 ± 6 m (Figure 2). It was imaged on four orbital passes with a maximum slew angle of -51°. Figure 2a shows approximately 39 percent of the floor in direct sunlight. Figure 2b is a highly oblique view of the pit, showing excellent detail within the subsurface layering and a conspicuous funnel-shaped slope to the rim. An irregular wall profile is suggestive of differential unit strength within the layered materials, possibly resulting from intermittent emplacement of mare deposits with regolith buildup between these events.

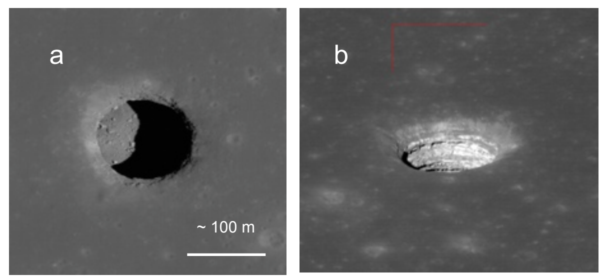


Figure 2. Mare Tranquilitatis pit imaged nadir (0.00°) (2a), and -51° (2b) slew angles; images M126710873R and M144395745L, respectively. Note layering complexity, differentially modified pit wall profile, and funnel-shaped rim in 2b (red scale bars are ~ 100 meters along each length).

Summary: The direct high-resolution imaging of a sublunarean void floor present beneath a sinuous rille, together with additional pit features of similar appearance, provides supporting evidence to their interpretation as collapsed lava tube skylights by confirming a cavernous subsurface, as has been anticipated throughout the literature based on the geomorphology of mare deposits and an understanding of lava flow behavior on Earth, but never directly imaged before.

References: [1] Halliday (1966) *Bull Nat Speleol Soc*, 28,167-170. [2] Kauahikaua et al. (1998) *JGR-Solid Earth*, 103, 27303-27323. [3] Horz et al. (1985) *Lava Tubes: Potential shelter for habitats*, LPSI. [4] De Angelis et al. (2002) *JRR*, 43, S41-S45. [5] Coombs et al. (1992) *NASA-CP-3166*. [6] Wyrick et al. (2004) *JGR-Planets*, 109. [7] Scott et al. (2002) *JGR-Planets,* 107. [8] Gillis-Davis (2009) *Earth and Planetary Sci. Let.*, 285, 243-250. [9] Schenk (1993) *JGR-Planets*, 98, 7475-7498. [10] Croft (1983) *JGR*, 88, B71-B89. [11] Senske et al. (1992) *JGR-Planets*, 97,13395-13420. [12] Haruyama et al. (2009) *JGR, 39.* [13] Cushing et al. (2007) JGR, 34. [14] Witter er al. (2007) *JGR-Solid Earth*, 121. [15] Robinson et al. (2010) *Space Sci. Rev.*, 150, 81-124