Possible lunar lava tube skylight observed by SELENE cameras

Junichi Haruyama,[1] Kazuyuki Hioki,[2] Motomaro Shirao,[3] Tomokatsu Morota,[1] Harald Hiesinger,[4] Carolyn H. van der Bogert,[4] Hideaki Miyamoto,[5] Akira Iwasaki,[6] Yasuhiro Yokota,[1] Makiko Ohtake,[1] Tsuneo Matsunaga,[7] Seiichi Hara,[2] Shunsuke Nakanotani,[8] and Carle M. Pieters[9]

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[1] We discovered a vertical hole on the Moon, which is a possible lava tube skylight, using data from SELENE's two high-resolution cameras: the Terrain Camera and the Multi-band Imager. The hole is nearly circular, 65 m in diameter, and located in a sinuous rille at the Marius Hills region, a volcanic province on the lunar nearside. We observed the hole at various solar illumination conditions and estimated its depth to be 80 to 88 m. The depth/diameter ratio is much larger than for typical impact craters. There are neither conspicuous deposits indicating volcanic eruptions from the hole, nor are there pit craters adjacent to the hole that could be related to an underlying fault or dike. The area around the hole is covered by a thin (20 to 25 m) lava sheet, which may help protect the lava tube from collapse due to meteorite bombardment. **Citation:** Haruyama, J., et al. (2009), Possible lunar lava tube skylight observed by SELENE cameras, *Geophys. Res. Lett.*, *36*, L21206, doi:10.1029/2009GL040635.

1. Introduction

[2] Lava tubes are common in basalt flows on the Earth, but whether or not they formed on the Moon has been a subject of scientific discussion [*Oberbeck et al.*, 1969; *Greeley*, 1971; *Coombs and Hawke*, 1992]. Numerous workers suggested that sinuous rilles originated as lava-fed channels, some of which formed tube-like structures based on their similarity to terrestrial lava channels and tubes [*Oberbeck et al.*, 1969; *Greeley*, 1971; *Hulme*, 1973; *Cruikshank and Wood*, 1972; *Gornitz*, 1973; *Head*, 1976; *Coombs and Hawke*, 1992]. For example, *Oberbeck et al.* [1969], *Greeley* [1971], and *Cruikshank and Wood* [1972] interpreted some rilles as collapsed or partially collapsed lava tubes, whereas *Coombs and Hawke* [1992] suggested that some exhibited alternating lava channel and tube sections.

[3] Lunar lava tubes are a potentially important location for a future lunar base, whether for local exploration and development, or as an outpost to serve exploration beyond the Moon. Any intact lava tube could serve as a shelter from the severe environment of the lunar surface, with its meteorite impacts, high-energy UV radiation and energetic particles, and extreme diurnal temperature variations [e.g., *Hörz*, 1985; *Coombs and Hawke*, 1992].

[4] Both scientific and exploration factors motivated efforts to search for intact lava tubes in Lunar Orbiter and Apollo images. *Coombs and Hawke* [1992] investigated 67 lava tube candidates within 20 rilles. Four of the locations showed strong evidence for intact tube segments [*Coombs and Hawke*, 1992]. However, their findings remain to be confirmed by higher resolution visible observations, or other techniques such as radar or ground exploration. All previous searches relied on the identification of possible intact lava tube sections adjacent to collapsed sections. No previous work identified small skylights in intact lava tubes on the Moon, probably because of the limited spatial resolution and coverage, or the absence of suitable illumination conditions.

[5] In contrast, based on high resolution data of Mars, *Cushing et al.* [2007] discovered seven small holes on the flanks of Arsia Mons using the Mars Odyssey Thermal Emission Imaging System (THEMIS-IR and VIS), and the Mars Orbiter Camera (MOC) images. Most of these Martian holes, measuring 100 to 225 m in diameter, are either adjacent to pit craters or are associated with pit-crater chains. Although their formation related to faults cannot be excluded, the Martian holes could plausibly be explained as openings to underlying lava tubes.

[6] We undertook a renewed effort to search for intact lava tubes on the Moon, using new global high-resolution lunar image data collected by the Terrain Camera (TC) and the Multi-band Imager (MI) aboard SELENE (nicknamed Kaguya) [*Haruyama et al.*, 2008].

2. Observations and Analysis

[7] SELENE was a Japanese polar orbiter in operation from September 2007 to June 2009. The Terrain Camera (TC) was a panchromatic visible-wavelength push-broom camera (430 to 850 nm) with two ± 15° slant telescopes for stereoscopy. The Multi-band Imager (MI) was a nine-band visible-to-near-infrared push-broom camera with two nadir telescopes. The TC was usually operated at solar elevation angles of <30° and MI at >30°. Pixel resolutions from SELENE's nominal 100 km orbit are 10 m (TC), 20 m (MI visible), and 62 m (MI near-infrared). During the extended mission, cross-track resolutions were twice as high from 50 km altitude.

[8] We searched for evidence for intact lava tubes in a region surrounding the Marius Hills (297 to 315°E, 3 to 24°N, about 500 km × 500 km), a volcanic province

[1]ISAS, JAXA, Sagamihara, Japan.
[2]NTT DATA CCS Corporation, Tokyo, Japan.
[3]Tokyo, Japan.
[4]Institut für Planetologie, Westfälische Wilhelms-Universität, Münster, Germany.
[5]University Museum, University of Tokyo, Tokyo, Japan.
[6]Research Center for Advanced Science and Technology, University of Tokyo, Tokyo, Japan.
[7]Center for Global Environmental Research, NIES, Tsukuba, Japan.
[8]Mitsubishi Space Software Co., Ltd., Tsukuba, Japan.
[9]Department of Geological Sciences, Brown University, Providence, Rhode Island, USA.

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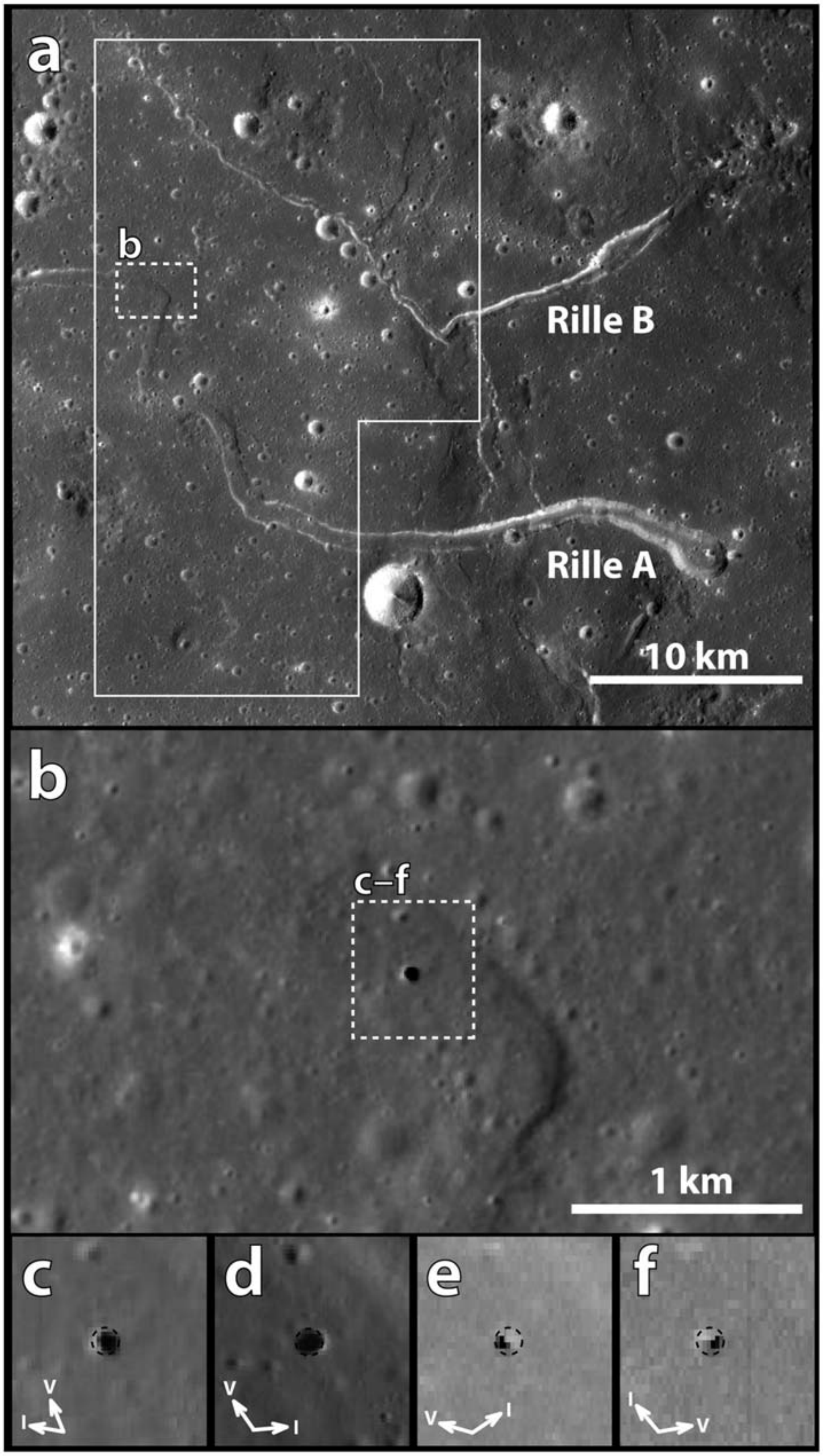

Figure 1. Images of a possible 65 m diameter lunar lava tube skylight in the Marius Hills taken by SELENE Terrain Camera (TC) and Multi-band Imager (MI). (a) Overview of the region (TC, 20 May 2008). The crater counting area is indicated by a solid white polygon. (b) Marius Hills Hole (MHH) at 303.3°E, 14.2°N. (c−f) Enlarged TC and MI images of MHH (Figures 1c and 1d are TC images from 20 May 2008 and 21 January 2009; Figures 1e and 1f are MI images from 17 March 2009 and 13 April 2009). See Table 1 for imaging conditions. Arrows indicate the directions of solar illumination (I) and the view vector from the camera (V).

Table 1. Observations of the Marius Hills Hole by SELENE Cameras

Revolution Number	Date	Incidence Angle (i) (deg)	Emission Angle[a] (e) (deg)	Azimuth Angle[b] (deg)	View Angle[c] (deg)	Spacecraft Altitude (km)	Pixel Resolution[d] (m)	Corresponding Figure
				Terrain Camera (TC) Observation				
2742	20 May 2008	48.0	17.0	100.4	−21.9	108.2	10.8	1a,b,c
3076	17 Jun 2008	73.3	16.8	92.7	15.2	92.0	9.2	
3574	28 Jul 2008	68.2	19.3	264.6	−23.6	121.1	12.1	
5751	21 Jan 2009	72.8	17.7	265.3	−35.4	59.7	6.0	1d
7495	7 Jun 2009	63.0	17.4	96.2	6.7	77.0	7.7	
				Multi-band Imager (MI) Observation				
4242	20 Sep 2008	21.4	1.0	227.8	43.4	123.3	24.7	
4575	18 Oct 2008	19.3	4.3	142.6	86.0	110.4	22.1	
6445	17 Mar 2009	20.9	2.5	236.2	−73.5	49.2	9.8	1e
6794	13 Apr 2009	15.1	4.0	139.9	80.0	57.2	11.4	1f

[a]Emission angle at MHH.
[b]Solar azimuth angle, measured clockwise from the 12:00 position.
[c]The view angle of camera to MHH, projected onto the lunar surface and measured clockwise from the 12:00 position.
[d]Cross-track pixel resolution. Along-track resolutions are 10 m/pixel for TC and 20 m for MI (VIS) independent of spacecraft altitude.

exhibiting many common volcanic structures [*Greeley*, 1971], including the major rilles Rima Marius (250 km long), Rima Suess (200 km long), and Rima Galilei (180 km long). We specifically looked for skylights or cave openings similar to those discovered on Mars. In both TC and MI images, a single skylight candidate was discovered. The hole (Marius Hills Hole, MHH; Figures 1b–1f) is located at 303.3°E, 14.2°N, in a 48 km long sinuous rille ("Rille A" in Figure 1a). Rille A begins in a 3 km-diameter, 270 m-deep volcanic crater. The MHH is ~32 km NW of and at 200 m lower elevation than the center of the source crater. The MHH is in the middle of the sinuous rille, ~250 m from both the eastern and western walls (Figure 1b).

[9] The high-resolution Apollo Metric and Panoramic cameras did not image the MHH area. Lunar Orbiter 5 imaged the upper portion of Rille A (Frame 214 H1–H3) with a ground resolution of ~2.5 m [*Greeley*, 1971], but did not cover the MHH. Lunar Orbiter 4 Frame 157-H2 had the highest spatial resolution (60 m) for this area [*Bowker and Hughes*, 1971]. In this image, the MHH is a small black dot, but cannot be distinguished from regular impact craters.

[10] TC and MI observed the MHH nine times from January 2008 to April 2009 at incidence angles (i) of 48° to 73.3° for TC, and 15.1° to 21.4° for MI, and at solar azimuth angles of 92.7° to 265.3° (Table 1). The MHH is nearly circular, with a diameter of 65 m (Figures 1c–1f). Compared to typical impact craters, the shaded portions of MHH's inner wall appear extremely dark in the images even at an incidence angle of 15° (Figures 1f), so the walls are very steep, even vertical.

[11] When the Sun illuminates the vertical wall of a hole, a minimum depth, d_{sunlit} (sunlit depth), of the hole can be calculated from the hole diameter D and incidence angle i as $D/\tan(i)$ (Figure 2a). This minimum depth should be consistent with an independent estimation of the hole depth from the cross length of the dark portion L of the hole as d_{obs} (observation depth) = $(D - L)/\tan(e)$, where e is the emission angle (Figure 2b). At the smallest incidence angle of TC observations (i = 48°; Figure 1c), a minimum depth d_{sunlit} of the MHH was calculated to be 59 m, consistent with the observation depth d_{obs} of 57 m (±10 m, due to uncertainties caused by the spatial resolution).

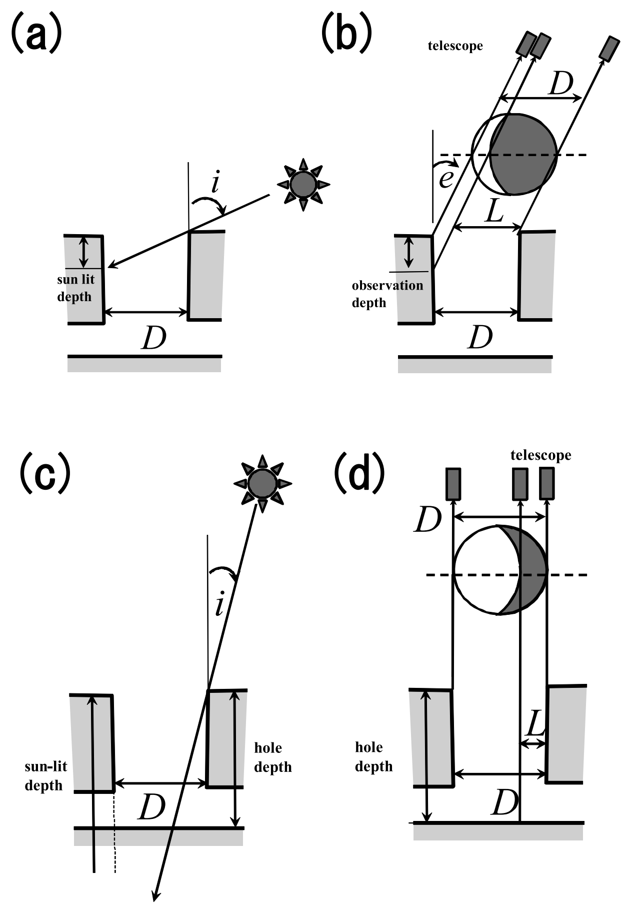

Figure 2. Estimation of the depth of a vertical hole using solar illumination conditions and image data. (a–b) Case A: Sun illuminating the wall of the hole. The d_{sunlit}, at minimum depth, is estimated from the hole diameter D and incidence angle i as D tan i. Alternately, d_{obs} can be independently estimated from the cross length of the dark portion L of the hole as $(D - L)/\tan(e)$, where e is the emission angle. When the Sun illuminates the entire vertical wall of a hole, d_{sunlit} should equal d_{obs}. (c–d) Case B: Sun illuminating the bottom of the hole, where d_{sunlit} would not equal d_{obs}. The hole depth can be estimated by $d_{\mathrm{bottom}} = L/\tan(i)$.

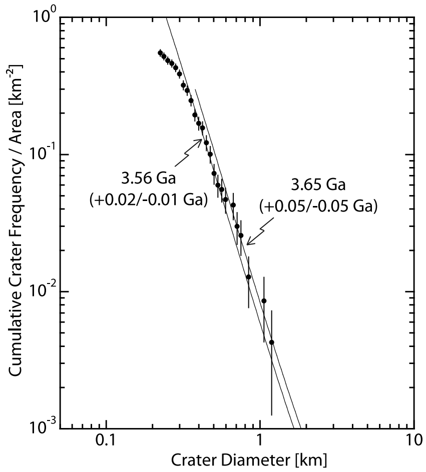

Figure 3. Crater size-frequency distribution (CSFD) and corresponding absolute model ages for the Marius Hills Hole (MHH) region as defined by the solid polygon in Figure 1a (466.7 km^2). Two absolute model ages can be fit to the CSFD, after *Neukum* [1983] and *Neukum and Ivanov* [1994], suggesting that two lavas with distinct ages covered this area. (Error bars are estimated by $(n \pm n^{1/2})/A$, where n is the cumulative number of craters and A is the counting area.)

[12] However, the MI observation at smaller incidence angles (i = 20.9°, 15.1°; Figures 1e and 1f), suggests that d_{obs} is not consistent with d_{sunlit}, indicating that the bottom of the MHH is observed at these incidence angles (Figure 2d). The depth to the bottom from the surface can be calculated by $d_{\mathrm{bottom}} = L/\tan(i)$ (Figure 2d), giving 80 m (i = 20.9°) to 88 m (i = 15.1°); the difference is due to the spatial resolution and/or real differences in the bottom relief. As a result, the depth-to-diameter ratio of the MHH (>1) is much higher than that of a typical impact crater (<0.2 [*Pike*, 1977]).

[13] Assuming that the depth (d_{obs}) of the MHH observed by TC with an incidence angle i of 48° corresponds to the total thickness of the ceiling of the lava tube and any overlying lava flows (∼60 m), we can use the simple single-beam theory [*Oberbeck et al.*, 1969] to estimate the maximum width of the tube to be $(4Sd/3\rho g)^{1/2}$ at lunar gravity (g), where S and ρ are the tensile strength and the density of the ceiling. The estimated maximum width of the tube is 370 m for S = 6.9 MPa, d = 60 m, ρ = 2500 kg/m^3, and g = 1.62 m/s^2 [after *Oberbeck et al.*, 1969], a value that exceeds the MHH diameter and is less than the width of Rille A (∼500 m). Because the depth (d_{obs}) of the MHH observed by TC is a minimum (the vertical walls may extend deeper), the maximum width of an underlying lava tube could be larger. Our estimated lava tube width might also be a minimum, because we are ignoring factors such as structural fracturing, arch mechanics, vertical layering, and differential stress/strain. However, such a simplification is necessary because those factors cannot be derived from available data.

[14] The area around MHH seems to be slightly buried, because the walls of Rille A at that location are less high than at other points along the rille (see Figure 1b). Support for a burial of the rille comes from the model age of the area surrounding MHH, which we derived from crater size-frequency distribution (CSFD) measurements [*Neukum*, 1983]. Because this technique is sensitive to resurfacing events [e.g., *Neukum and Horn*, 1975; *Hiesinger et al.*, 2002], it provides an independent test for the potential burial of the tube by younger lavas. For the solid white polygon (Figure 1a), the CSFD for craters larger than 650 m diameter gives a 3.65 (±0.05) Ga model age (Figure 3). In contrast, craters with 350−550 m diameters, yield a model age of 3.56 (+0.02/−0.01) Ga. For our crater counts, we excluded areas with obvious secondary craters, identified by their morphological characteristics. A reasonable interpretation for the two distinct model ages is that the basalts covering this area formed during at least two eruptions, as observed for other maria on the nearside [*Hiesinger et al.*, 2002, 2003] and farside [*Haruyama et al.*, 2009]. The study area was likely resurfaced by a thin basaltic eruption at 3.56 Ga that did not completely obliterate pre-existing craters on an earlier lava sheet that formed at 3.65 Ga. If we consider that the diameter−to−rim-height ratio of a typical lunar crater of <1 km is <0.05 [*Pike*, 1977], the thickness of the younger lava sheet can be estimated as 20 to 25 m. Thus, the original lava tube ceiling thickness was on the order of 40 meters or more.

3. Formation

[15] We consider several possible origins for the MHH including a local volcanic eruption and collapse. The roofs over many tubes on the Moon may collapse due to meteoroid impacts [e.g., *Coombs and Hawke*, 1992], the withdrawal of lava from the tube, the emplacement of younger lava with its associated additional mass, moonquakes, or tidal forces. All these mechanisms could cause the failure of the roof, particularly at its weakest point near the center of the investigated tube. We exclude a local volcanic eruption as the formation mechanism for the MHH, because there is no conspicuous deposit around the MHH that would indicate eruptions from the hole (Figures 1b−1f), such as albedo or surface roughness differences.

[16] The formation of fault- or dike-related collapse craters by stoping as described by *Okubo and Martel* [1998] for Kilauea pit craters, was suggested for the Martian holes [*Cushing et al.*, 2007]. However, a fault or dike would probably have produced in-line pit craters and/or a graben, but no pit craters are located near the MHH. Additionally, the MHH is in a sinuous rille, not a graben. Indeed, MHH's location within a sinuous rille indicates that the most plausible formation mechanism is the formation of a skylight by collapse of the tube roof. This could occur after limited withdrawal of the lava, by a small random impact onto the tube with a spallation process similar to that described by *Hörz et al.* [1995], or as a result of moonquakes or tidal forces.

4. Conclusion

[17] Using SELENE TC and MI images, we discovered a 65 m diameter vertical hole in the Marius Hills region of the Moon, which we interpret to be a skylight of an intact lava tube, similar to skylights formed on terrestrial and Martian volcanic deposits. Shadow measurements revealed that the hole is at least 80−88 m deep and formed in a lava tube with

a minimum width of ∼370 m. An unsuccessful search for additional skylights along three other sinuous rilles nearby indicates that skylights on the Moon are rare.

[18] Many other workers searched the Marius Hills region for intact lava tubes, because of the large density of sinuous rilles present [e.g., *Greeley*, 1971; *Cruikshank and Wood*, 1972; *Coombs and Hawke*, 1992]. However, to our knowledge, the MHH is the first discovered possible skylight in an intact lava tube on the Moon. This is a potentially important discovery for both studies of lunar volcanology and future human outposts. Lava-tube formation is a significant factor controlling the distribution of volcanic materials on the Moon [e.g., *Greeley*, 1987; *Pinkerton and Wilson*, 1994; *Keszthelyi*, 1995; *Sakimoto et al.*, 1997]. Likewise, the Marius Hills region has long been considered an important and accessible exploration target, both scientifically and technically [e.g., *Coombs and Hawke*, 1992; *Taylor and Spudis*, 1990]. Indeed, the discovery of MHH further supports the importance of the Marius Hills region as a future exploration target.

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References

Bowker, D. E., and J. K. Hughes (1971), Lunar Orbiter photographic atlas of the Moon, *NASA Spec. Publ., NASA SP-206*.

Coombs, C. R., and B. R. Hawke (1992), A search for intact lava tubes on the Moon: Possible lunar base habitats, in *The Second Conference on Lunar Bases and Space Activities of the 21st Century*, *NASA Conf. Publ., NASA CP-3166*, *vol. 1*, 219–229.

Cruikshank, D. P., and C. A. Wood (1972), Lunar rilles and Hawaiian volcanic features: Possible analogues, *Moon*, *3*, 412–447, doi:10.1007/BF00562463.

Cushing, G. E., T. N. Titus, J. J. Wynne, and P. R. Christensen (2007), THEMIS observes possible cave skylights on Mars, *Geophys. Res. Lett.*, *34*, L17201, doi:10.1029/2007GL030709.

Gornitz, V. (1973), The origin of sinuous rilles, *Moon*, *6*, 337–356, doi:10.1007/BF00562210.

Greeley, R. (1971), Lava tubes and channels in the lunar Marius Hills, *Moon*, *3*, 289–314, doi:10.1007/BF00561842.

Greeley, R. (1987), The role of lava tubes in Hawaiian volcanoes, *U.S. Geol. Surv. Prof. Pap.*, *1350*, 1589–1602.

Haruyama, J., T. Matsunaga, M. Ohtake, T. Morota, C. Honda, Y. Yokota, M. Torii, Y. Ogawa, and LISM Working Group (2008), Global lunar-surface mapping experiment using the Lunar Imager/Spectrometer on SELENE, *Earth Planets Space*, *60*, 243–256.

Haruyama, J., et al. (2009), Long-lived volcanism on the lunar farside revealed by SELENE Terrain Camera, *Science*, *323*, 905–908, doi:10.1126/science.1163382.

Head, J. W. (1976), Lunar volcanism in space and time, *Rev. Geophys. Space Phys.*, *14*, 265–300, doi:10.1029/RG014i002p00265.

Hiesinger, H., J. W. Head III, U. Wolfe, R. Jaumann, and G. Neukum (2002), Lunar mare basalt flow units: Thickness determined from crater size-frequency distributions, *Geophys. Res. Lett.*, *29*(8), 1248, doi:10.1029/2002GL014847.

Hiesinger, H., J. W. Head III, U. Wolf, R. Jaumann, and G. Neukum (2003), Ages and stratigraphy of mare basalts in Oceanus Procellarum, Mare Nubium, Mare Cognitum, and Mare Insularum, *J. Geophys. Res.*, *108*(E7), 5065, doi:10.1029/2002JE001985.

Hörz, F. (1985), Lava tubes: Potential shelters for habitats, in *Lunar Bases and Space Activities of the 21st Century*, edited by W. W. Mendell, pp. 405–412, Lunar Planet. Inst., Houston, Tex.

Hörz, F., M. J. Cintala, R. P. Bernhard, and T. H. See (1995), Cratering penetration experiments in Teflon targets at velocities from 1 to 7 km/s, *Int. J. Impact Eng.*, *17*, 419–430, doi:10.1016/0734-743X(95)99867-Q.

Hulme, G. (1973), Turbulent lava flow and the formation of lunar sinuous rilles, *Mod. Geol.*, *4*, 107–117.

Keszthelyi, L. (1995), A preliminary thermal budget for lava tubes on the Earth and planets, *J. Geophys. Res.*, *100*, 20,411–20,420.

Neukum, G. (1983), *Meteoritenbombardement und Datierung planetarer Oberflachen*, Habilitationsschrift, Ludwig Maximilians Univ., Munich, Germany.

Neukum, G., and P. Horn (1975), Effects of lava flows on lunar crater population, *Moon*, *15*, 205–222, doi:10.1007/BF00562238.

Neukum, G., and B. A. Ivanov (1994), Cratering size distributions and impact probabilities on Earth from lunar, terrestrial planet, and asteroid cratering data, in *Hazards Due to Comet and Asteroids*, edited by T. Gehrels, pp. 359–416, Univ. of Arizona Press, Tucson.

Oberbeck, V. R., L. Q. Willam, and R. Greeley (1969), On the origin of lunar sinuous rilles, *Mod. Geol.*, *1*, 75–80.

Okubo, C. H., and S. J. Martel (1998), Pit crater formation on Kilauea volcano, Hawaii, *J. Volcanol. Geotherm. Res.*, *86*, 1–18, doi:10.1016/S0377-0273(98)00070-5.

Pike, R. J. (1977), Size-dependence in the shape of fresh impact craters on the Moon, in *Impact and Explosion Cratering*, edited by D. J. Roddy, R. O. Pepin, and R. B. Merrill, pp. 489–510, Pergamon, New York.

Pinkerton, H., and L. Wilson (1994), Factors controlling the length of channel-fed lava flows, *Bull. Volcanol.*, *56*, 108–120.

Sakimoto, S. E. H., J. Crisp, and S. M. Baloga (1997), Eruption constraints on tube-fed planetary lava flows, *J. Geophys. Res.*, *102*, 6597–6613, doi:10.1029/97JE00069.

Taylor, G. J., and P. D. Spudis (Eds.) (1990), Geoscience and a lunar base: A comprehensive plan for lunar exploration, *NASA Conf. Publ., NASA CP-3070*.

S. Hara and K. Hioki, NTT DATA CCS Corporation, Tokyo 136-0071, Japan.

J. Haruyama, T. Morota, M. Ohtake, and Y. Yokota, ISAS, JAXA, Sagamihara 229-8510, Japan. (haruyama.junichi@jaxa.jp)

H. Hiesinger and C. H. van der Bogert, Institut für Planetologie, Westfälische Wilhelms-Universität, D-48149 Münster, Germany.

A. Iwasaki, Research Center for Advanced Science and Technology, University of Tokyo, Tokyo 153-8904, Japan.

T. Matsunaga, Center for Global Environmental Research, NIES, Tsukuba 305-8506, Japan.

H. Miyamoto, University Museum, University of Tokyo, Tokyo 113-0033, Japan.

S. Nakanotani, Mitsubishi Space Software Co., Ltd., Tsukuba 305-0032, Japan.

C. M. Pieters, Department of Geological Sciences, Brown University, Providence, RI 02912, USA.

M. Shirao,1-3-11, Nishi-Asakusa, Taito-ku, Tokyo 111-0035, Japan.