NEW DISCOVERIES OF LUNAR HOLES IN MARE TRANQUILLTATIS AND MARE INGENII. Junichi Haruyama[1], Seiichi Hara[2], Kazuyuki Hioki[2], Tomokatsu Morota[1], Yasuhiro Yokota[1], Motomaro Shirao[3], Harald Hiesinger[4], Carolyn H. van der Bogert[4], Hideaki Miyamoto[5], Akira Iwasaki[5], Makiko Ohtake[1], Yoshifumi Saito[1], Tsuneo Matsunaga[6], Shunsuke Nakanotani[7], Carle M. Pieters[8], and Paul G. Lucey[9], [1]ISAS, JAXA, Japan (Haruyama.junichi@jaxa.jp), [2]NTT DATA CCS CORPORATION, Japan, [3]Taito-ku, Tokyo 111-0035, Japan, [4]Westfälische Wilhelms-Universität, Germany, [5]The University of Tokyo, Japan, [6]NIES, Japan, [7]Mitsubishi Space Software Co., Ltd., Japan, [8]Brown University, USA, [9]University of Hawaii, USA.

Introduction: We recently reported the discovery of a vertical hole on the Moon [1] in data acquired by the Terrain Camera (TC) and Multiband Imager (MI) on the Japanese lunar orbiter Selenological and Engineering Explorer (SELENE) [2], (nicknamed Kaguya). The 65 m-diameter hole is located at 303.3 °E, 14.2 °N in the Marius Hills region in Oceanus Procellarum on the near side of the Moon. The Marius Hills Hole (MHH) is probably a skylight in a lava tube. Here, we report the discovery of two additional nearly circular deep shafts.

Hole Search Methodology: SELENE TC and MI achieved almost 100% coverage of the Moon during the twenty-one month SELENE mission. To find vertical holes similar to MHH, we extracted the TC data of higher solar elevation angles (SEAs) of > 40° (Fig. 1). At these sun angles, the shadowed portions of these vertical shafts receive less sunlight reflected off of their walls than typical shallow lunar craters causing their shadows to be darker than typical craters. Because TC's sensitivity is very high, we can detect this difference. We searched for the lowest radiances in the data set and found two new holes in Mare Tranquillitatis and Mare Ingenii.

Mare Tranquillitatis Hole: The hole in Mare Tranquillitatis (MTH) is located at 33.2 °E, 8.3 °N (Fig. 1), 350 km from the Apollo 11 landing site. It is nearly twice the diameter of the MHH, and is roughly circular with a short axis length of 110 m (east-west) and a long axis length 120 m (north-south) (Fig. 2). The east rim is about 50 m higher than the west rim. MTH was observed eight times by TC and twice by MI. From the higher SEA data (49.6° in TC observations and 75.6° and 82.8° in MI), we estimate the hole to be 180m deep from the east rim. Unlike the Marius Hills Hole (MHH), MTH is not in or near a sinuous rille. There are numerous craters near MTH, but no other holes are present at the resolution of TC (10 m).

Mare Ingenii Hole: Using the same search for low radiance data, we discovered a hole in Mare Ingenii (MIH) at 166.0 °E, 35.6 °S, near a prominent swirl feature on the far side of the Moon (Fig. 1). It has a slightly irregular shape (rounded triangle) with a long axis length of 140 m (east-west) and a short axis length of 110 m (north-south) (Fig. 3). Its northwest rim is a few tens of meters higher than the other portions of the rim. TC observed MIH six times and MI observed it once. Because we could not detect the bottom of MIH, even at the highest SEA (47.4° with TC), we can only place a lower limit on the depth of 90 meters. Like that in Mare Tranquillitatis, this hole is not located on or near a rille.

Interior Temperatures of Underlying Lava Tubes: The temperatures of these cavities are of interest for lunar resources and as special lunar microenvironments. Based on a thermal equilibrium calculation for the shallow lunar interior, we estimated the temperature at the bottoms of the holes. For the surface albedos around the lunar holes, we used radiance data acquired by TC. Assuming a diffuse (Lambertian) surface, the albedos are 3.6%, for the surfaces around MHH, 3.7% around MTH, and 5.2% around MIH (Table 1). The interior temperatures of any lava tubes possibly connected to MHH, MTH, and MIH are estimated to be 18, 19, and 4 °C (Table 1). These temperatures may be overestimated because we used the radiance data obtained at SEA < 50°, and thus the opposition effect has been ignored. The estimated temperatures inside the tubes using 7 and 10% albedos are listed in Table 1.

Table 1. Interior Temperatures of Lunar Holes

	FromTC Radiance data (albedo)	Albedo 7%	Albedo 10%
MHH	18 °C (3.6%)	15°C	14°C
MTH	19°C (3.7%)	16°C	13°C
MIH	4 °C (5.2 %)	3°C	0°C

Hydrogen Accumulation in lava tubes exposed by skylights: The lunar surface is continuously showered by solar wind protons. Although a small fraction of the protons are implanted into the lunar surface, most protons escape into space. However, the deep holes and their possible connected lava tubes might effectively trap solar wind protons. The surface ages surrounding MHH, MTH, and MIH are 3.5 Gyr [1], 3.7 Gyr [3], and 3.2 Gyr [4]. If the holes opened simultaneously with or just after the formation of surrounding surfaces and the solar proton flux was similar to the current flux: 4×10^8 /cm^2/sec [5], the integrated amount of the protons inside MHH, MIH, and MIH and their connected lava tubes would be 3×10^3, 1×10^4, and 9×10^3 tons, which correspond to water of 3×10^4, 9×10^4, and 8×10^4 tons (Table 2). While these abundances are not entirely protected from loss, the vertical shafts and especially any connected lava tubes are protected from loss mechanisms such as sputtering and UV radiation, while preserving local low temperatures.

Observations By Other Missions: Although SELENE impacted on the Moon and ended its mission in June 2009, the Lunar Reconnaissance Orbiter (LRO) is currently observing the lunar surface with a variety of instruments. The observations acquired by LRO instruments will provide much additional information on these lunar holes. For example, the Lunar Reconnaissance Orbiter Camera (LROC) will reveal the detailed structure of the holes, Diviner can investigate the thermal conditions of the holes, and Chandrayaan and Change'1 data will also hopefully provide additional data for these holes. Of critical importance, is to investigate and understand the geological setting of each of the holes, to determine whether they are associated with lava tubes, like MHH, or have another origin.

Table 2. Possible Proton and Corresponding Water Concentrations in Lunar Holes

	Size (m x m)	Age (Gyr)	Proton Concentration [ton]	Corresponding Water concentration [ton]
MHH	65 x 65	3.5	3.0×10^3	2.7×10^4
MTH	110 x 120	3.7	1.0×10^4	9.0×10^4
MIH	140 x 110	3.2	8.5×10^3	7.7×10^4

References:

[1] Haruyama J. et al. (2009) *GRL*, 36, L21206, doi:10.1029/2009GL040635. [2] Haruyama J. et al. (2008) *Earth Planets and Space*, 60, 243-255. [3] Hiesinger H. et al. (2000), *JGR*, 105(E12), 29239-29276. [4] Haruyama J. et al. (2008) *Science*, 322, 938-939. [5] Starukhina L. V. and Shkuratov Y. G. (2000) *Icarus* 147, 585–587.

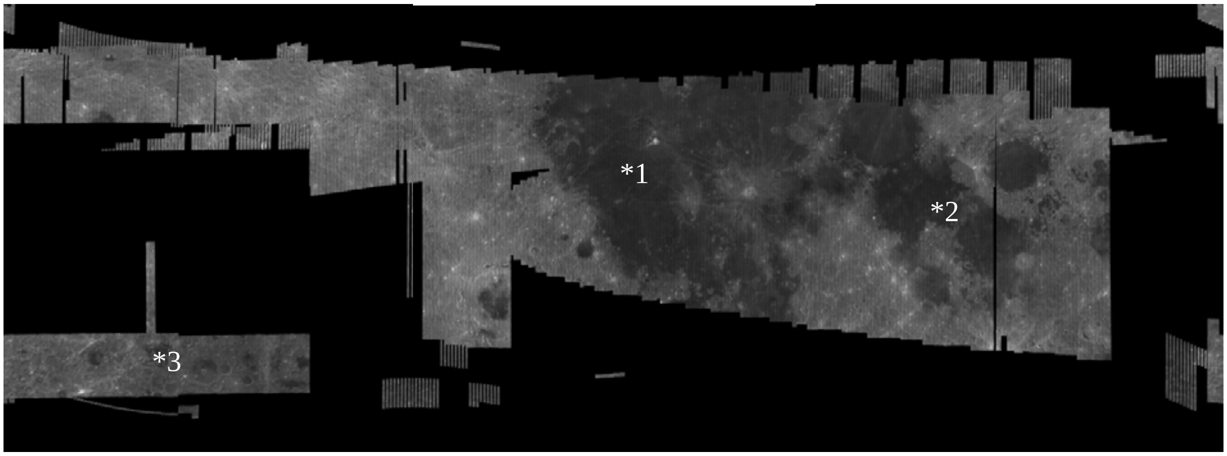

Figure1. SELENE Terrain Camera observation coverage at solar elevation angles > 40°. Marius Hills Hole and newly discovered holes in Mare Tranquillitatis and Mare Ingenii are indicated by *1 (303.3 °E, 14.2 °N), *2(33.2 °E, 8.3 °N), and *3(35.6 °S, 166.0 °E).

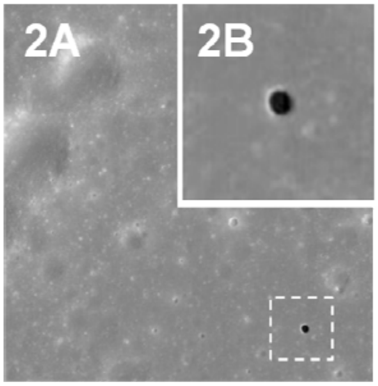

Figure 2. Enlarged TC images of Mare Tranquillitatis Hole, nearly circular with a short axis length of 110 m (east-west) and a long axis length 120 m (north-south).

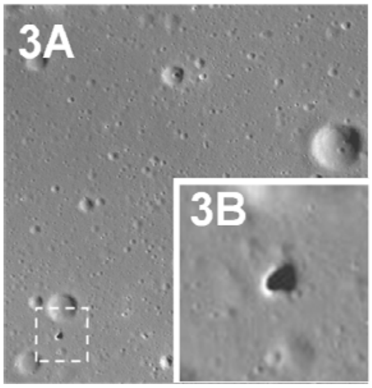

Figure 3. Enlarged TC images of Mare Ingenii Hole, a slightly irregular shape (rounded triangle) with a long axis length of 140 m (east-west) and a short axis of 110 m (north-south).