FORMATION SCENARIO OF CONTINUOUS SLOPES ASSOCIATED WITH LUNAR MARE PIT/HOLE STRUCTURES.

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Introduction: Number of the discovered pit/hole structures (D=~10–100 m orders) in lunar mare is continuously increasing since 2009 [1–6]. Additionally, we find 2 mare hole structures at Compton crater (a crater with mare patches inside) and West part of Marius Hills region. The total number of the pit/holes we know in lunar mare becomes 15. Remarkably, 5 of 15 mare holes exhibit a long slope which continuing from the lunar surface to the floor of the hole. We tentatively call these slopes as 'continuous slopes'. We are motivated by the existence of these slopes. Subject of this study is to present a feasible scenario about the continuous slope formation.

New mare pit/holes: *Compton crater hole.* A hole structure (56.23°N, 106.20°E) (Figure 1A,B) is located in the lava deposit inside Compton crater (*D*=162 km) (Figure 1C,D). Since ordinary craters also have shadows at local noon time around this latitude, this region was excluded in the previous image surveys [2, 4]. In Figure 1B, an overhang cliff is seen at north east direction. South part of the hole was not directly illuminated by the sun light, but the enhanced images can show the outline of the cliff. A continuous slope exists at northwest side of the hole (direction b in Figure 1A).

West Marius Hills hole. A hole structure (13.55°N, 301.83°E) (Figure 2A,B) locates at west part of the Marius Hills region (Figure 2D). This place is 44.62 km apart from the known Marius Hills hole [1,3] in the west-southwest direction. To avoid confusion, we call this new place as the 'West Marius Hills' hole. At the time of this work, only one NAC image (Figure 2A,B) is available for this hole. Due to the high sun elevation angle (76.77°) of the image, the whole places around here show no shadow, except for the cliff. A continuous slope lies at south-west direction of the pit.

Shape analysis: Based on the outlook, we classify 15 mare holes into three types: (a) Basic-type (6 members), (b) Slope-type (5 members), and (3) Wide-types (4 members). At the basic-type holes, complete periphery of the holes are surrounded by steep walls. The slope-type holes exhibit 'continuous slope'. Since the rest of the mare pits/holes seem to have small amount of wall and overhang, we classify them into the wide-type holes. Although the wide-type holes are not direct scope of this paper, there is a possibility that the basic-type and slope-type holes will become wide-type holes by the impact erosion of micro-meteoroids after a long time.

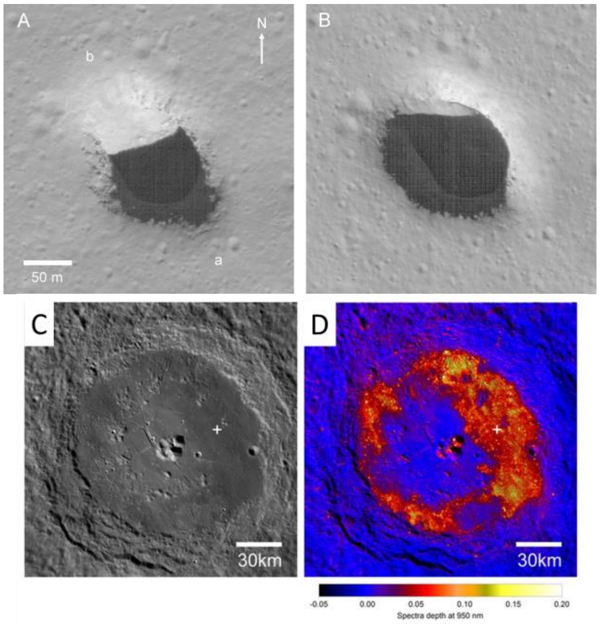

Figure 1. (A) Compton crater hole. LROC NAC [7] image (M110892182R) is enhanced to see inside the shadow. (B) Enhanced NAC M152194772R. (C) Context map of Compton crater. Kaguya Terrain Camera (TC) [8] mosaic. White cross indicates the location of the hole. (D) Depth of reflectance spectra at 950 nm band (Kaguya Multiband Imager [9] data). Red-yellow color region corresponds to mare deposit.

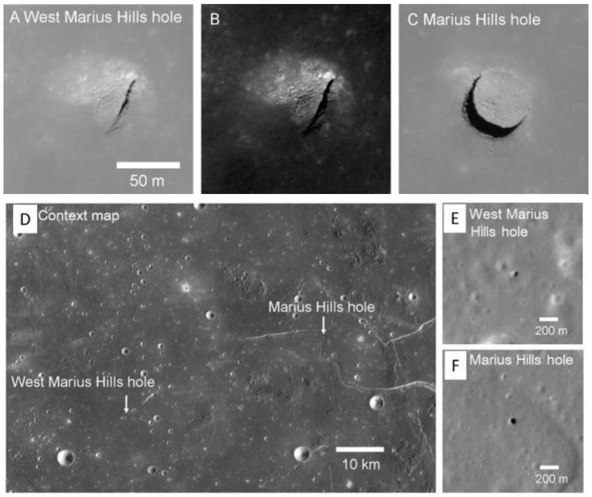

Figure 2. (A) West Marius Hills hole (NAC M124952951R). (B) Panel A is enhanced to see details. (C) The Marius Hills hole is shown in same scale for comparison (NAC M155607349R). Solar phase angle is 15°. (D–F) TC mosaic of Marius Hills region.

To understand character of the slope-type holes, we fit ellipses to the inner pit cliff outlines (determined by human eyes) of the 11 mare holes including the basic-type and slope-type holes, using the LROC NAC images [7] with a fitting method of [10]. As a result, it is found that the inner pit shape of a slope-type hole tends to have two features: (1) high flattening (Figure 3), and (2) coincidence of the slope azimuth and the major-axis azimuth (Figure 4). These features suggest that the formation of the continuous slopes may be linked to the the initial formation of the hole.

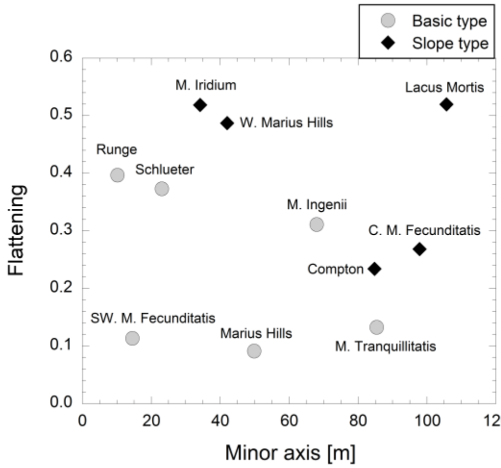

Figure 3. Derived flattening *f* is shown as the function of minor axis. The flattening *f* is defined as $f=(a-b)/a$ (a: semi-major axis; b: semi-minor axis).

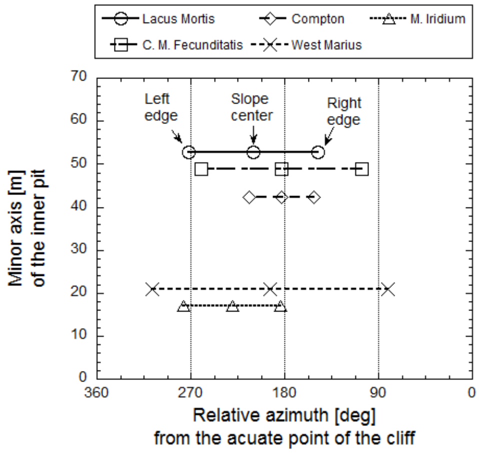

Figure 4. Relative azimuths of the continuous slopes.

Volume of the debris to construct a slope: Surfaces of the continuous slopes are generally covered by smooth regolith. It suggests an existence of the erosion effect caused by micro-meteoroid impacts after the initial formation of the hole. Is it possible to construct a continuous slope by erosion effect alone? As a thought experiment, we assume that a continuous slope has been developed from a vertical cliff with total depth *d*, due to the long-time impact erosion (Figure 5A). Based on a simple cross-section geometry calculation, we estimate that the retreat length l~$0.68d$ is required to construct a continuous slope. However, this value does not suit current depth and semi-minor axis of the slope-type holes. For example, we measured the depth of the Lacus Mortis hole [4] as ~125 m, and the required retreat length becomes ~85 m. On the other hand, the current semi-minor axis is 53 m. It is unnatural to assume such large retreat length. This thought experiment suggests that the impact erosion mechanism alone is not enough to construct the observed continuous slopes.

If the initial condition of the wall is a sloped wall instead a vertical wall, the required volume of the debris become much smaller. Therefore, we propose an alternate hypothesis (Figure 5B) that an impact occurred on the edge of a void might made an inclined crater or a half collapsed cliff, and it might be grown to a continuous slope with later erosion.

This impact-on-edge scenario may also explain the high flattening of the ellipse and the coincidence between the slope azimuth and the major-axis azimuth. However, there is not experimental evidence to support this hypothesis yet. A laboratory impact experiment and/or a computer simulation are important to test the scenario.

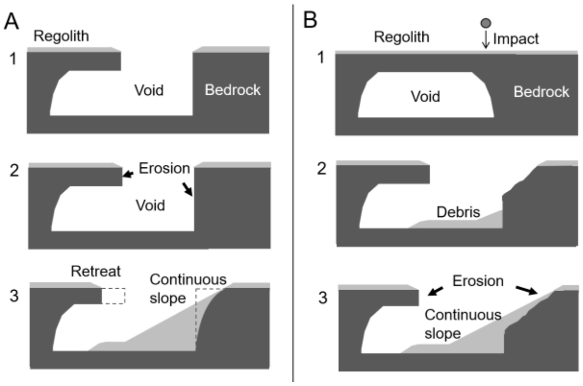

Figure 5. (A) Hypothetical vertical cliff scenario. (B) Impact-on-edge scenario.

References: [1] Haruyama J. et al. (2009) *GRL, 36*, L21206. [2] Haruyama J. et al. (2010) *LPS 41st*, Abstruct #1285. [3] Robinson M. S. e al. (2012) *Planetary & Space Sci., 69*. [4] Wagner R.V. and Robinson M. S. (2014) *Icarus, 237*, 52–60. [5] Wagner R.V. and Robinson M. S. (2015) *The 2nd International Planetary Caves Conf.*, Abstract #9021, [6] Wagner R. V. et al. (2017) *LPS 48th*, Abstract #1201. [7] Robinson M. S. et al. (2010) *Space Sci. Rev., 150*, 81–124. [8] Haruyama J. et al. (2008) *Earth Planets Space, 60*, 243–255. [9] Ohtake M. et al. (2008) *Earth Planets Space, 60*, 257–264. [10] Fitzgibbon A.W. et al. (1999) *IEEE Trans. on Pattern Analysis and Machine Intelligence, 21(5)*, 476–480.