MORPHOLOGY OF PIT CRATERS ON MERCURY FROM STEREO-DERIVED TOPOGRAPHY AND IMPLICATIONS FOR PIT CRATER FORMATION. Klaus Gwinner[1], James W. Head[2], Jürgen Oberst[1], Jeffrey J. Gillis-Davis[3], Zhiyong Xiao[4, 5], Robert G. Strom[4], Frank Preusker[1], Sean C. Solomon[6]. [1]DLR Institute of Planetary Research, Berlin, Germany (Klaus.Gwinner@dlr.de); [2]Department of Geological Sciences, Brown University, Providence, RI 02912; [3]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i, Honolulu, HI 96822; [4]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85719; [5]China University of Geosciences (Wuhan), Wuhan, Hubei, P. R. China, 430074.[6]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015

Introduction: During the flybys of Mercury by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft [1], the widespread contribution of volcanic processes to the surface evolution of Mercury became recognized [2]. Among the relevant features observed were irregularly shaped, rimless pit craters occurring on the floors of several ("pit-floor") craters and interpreted to originate from subsurface drainage of magma [3]. Candidate pyroclastic deposits identified from spectral and morphological characteristics were also related to irregularly shaped craters observed at the centers of many of these deposits [4-8]. Because pit-floor craters apparently lacked similar deposits and because high-resolution images and detailed topographic data were not available, the relationships between the two types of depressions remained unclear. Here we report on the occurrence and morphology of pit craters inferred from digital terrain models (DTMs) produced from stereo images obtained with the Mercury Dual Imaging System (MDIS) narrow-angle camera (NAC) and wide-angle camera (WAC) [9], acquired following the insertion of MESSENGER into orbit around Mercury. We also discuss implications of the morphological characteristics for modes of formation and evolution.

Datasets and Methods: Systematic stereo coverage by MDIS is currently in progress (as of the second Mercury solar day of the primary mission orbit, beginning in September 2011). Although first DTMs based on large continuous image blocks are just being completed [10], we were able to exploit a number of additional local stereo datasets acquired during the first Mercury solar day for surface reconstruction and characterization of 40 pit craters, of which 7 have diameters >20 km. As suggested by an updated compilation [11], these numbers are related to current coverage rather than to the actual size distribution of pit craters on Mercury. Stereo analysis is based on block adjustment as applied to data from the Mercury flybys [12,13], and on the approach for surface reconstruction documented in [14]. Derived height values are recorded on regular grids spaced at ~1.5 times the image ground resolution (for the current dataset: 410 m > grid spacing > 200 m for most models, and several high resolution datasets led to grid spacing as small as 25 m). We measured the depth and the largest and smallest horizontal diameters of each pit crater from vertical sections. Slope angles were determined on sections and slope maps. We used orthoimages for localizing profiles and supporting further interpretation.

Since many pit craters are small compared to the DTM grid spacing (few tens of grid samples), resolution effects have to be considered carefully. Applying image orientation at sub-pixel three-dimensional point precision [13] and sub-pixel image matching, the main limiting factors for deriving unbiased heights and slopes at scales close to the ground resolution of the images are local terrain curvature, sample spacing and the filter characteristics of the applied methods for image correlation and height interpolation. Given the methodology [14] and the applied parameter setting for distance-weighted interpolation, grid heights depend on stereo-measured point heights within a radius equivalent to the grid spacing. Slope values derived on typical length scales of 2 DTM pixels are not biased by interpolation if the surface is approximately planar on a length scale of 1 km for a 0.2 km height raster (2 km for the data set with the lowest resolution in this study). Systematic low-pass effects on height values related to area-based image correlation are possible for terrain patches with marked curvature on length scales <3.4 km (for grid spacing of 0.2 km and 17×17 matching windows). Such effects are limited, however, to curvatures that cause variation of stereo disparity according to polynomial degree 4 and higher within the matching windows, i.e. to terrain very rough at the scale of image ground resolution. Considering the specific geometry of pit craters (potentially short slopes, slope breaks at the flank limits), we decided to report flank slopes only for features with smallest diameters >10 km.

Results: ***General Characteristics.*** The depth of pit craters on Mercury can attain considerably high values. The two deepest pits in our dataset display a rim-to-floor depth of 3.3 km. However, depths as small as 0.07 km are observed. The average diameter of the pits ranges from 4 to 27 km. The depth/width ratio shows an overall variation between 0.03 and 0.17. Most pits show evidence of clustering to some degree, i.e., superimposition of two or more individual depressions, resulting in several depth maxima separated by elevated septae and embayments of rims and floors. These are characteristics typical of summit calderas and pits of shield volcanoes on Mars and the Earth. Since pit clusters can show a preferred alignment direction, the depth/width ratios for the short axis of clusters or elongated pits (0.03-0.24) may be more meaningful. Our measurements confirm the earlier observation that the diameters of crater-hosted pits are not related to the diameter of the host [3]. In addition, our data show that the depths of the pits are apparently unrelated to the diameter of the host.

Characteristic occurrence types. Pit craters on Mercury are seen in various types of terrain. We distinguish the following characteristic types of occurence: (1) center of host craters (2) concentric structures of craters and basins, such as rims, walls and peak rings (3) crater floor positions other than types 1 or 2 (4) intercrater terrain. According to average morphometric parameter values (Table 1), central floor pits (type 1) and intercrater pits tend to be deeper and show higher depth/width ratios than the two other classes. Structure-aligned pits and general floor pits tend to be both narrower and less deep, but differ among each other in the average 2:1 horizontal aspect ratio of the former. In contrast, central pits display more equant rim shapes than those in all other locations. All floor pits of the dataset are superimposed on smooth deposits, whereas intercrater pits usually are not but are always found close to such deposits. Structure-aligned pits show both associations.

Slope characteristics. Most vertical sections of the pit craters show straight inner flanks with rounded slope breaks at the rim and floors. Floors are usually convex downward but flat floor portions do occur. Along the rims, shallow outward-sloping outer flanks or small radially-aligned ridges are seen in some cases. These might represent proximal pyroclastic or effusive deposits or remnants of collapsed peaks. All observed central craters show maximum slope values of about 34°, as do two of the three structure-aligned and general floor pits with available slope maps. Values of up to ~40° are seen rarely and occur in small areas, in agreement with the absence of major visible scarps or layer contrasts at the scale of the current image coverage. Conversely, intercrater pits show smaller maximum slope (20°-30°), in agreement with a subdued, smoothed appearance, suggesting draping or higher degradation. Similarly, a number of relatively younger pits that embay their neighbors show steeper flanks.

Maximum slope angle shows a positive correlation with pit depth, suggesting that the equilibrium slopes of the deeper pits are less easily obliterated by deposits from post-collapse eruptions or external sources. Positive evidence for infill products (e.g., paucity of impacts, difference in reflectance, flooding markers, floor deposit onlapping the walls) is observed also in most cases when flat floor segments are present.

Discussion and Conclusions: Degradation might provide an explanation for the fact that no pyroclastic deposits (most likely easily erodible) unrelated to craters or basins have been identified to date from spectral properties [8,15], whereas our data suggest that intercrater pit characteristics are compatible in terms of depth and depth/width ratio with those pyroclastic vents included in both an earlier compilation [8] and the present study. Furthermore, we note that pit embayments not only affect the walls, but also involve further floor deepening. This result suggests they are not only related to shallow slope processes, but rather can indicate a multi-stage subsidence history for the respective pit craters (or clusters).

In summary, several lines of new evidence – similar characteristics of pits in intercrater and impact-related settings, occurrence commonly within clusters, multi-stage evolution, and, last but not least, their great depths – enforce the hypothesis that the origin of pit craters on Mercury is related to magmatic processes [2,3]. When compared with terrestrial calderas and related analogue experiments, the apparent absence of peripheral extensional structures around pit craters on Mercury is striking. Very narrow, near-vertical and thus inherently unstable extensional belts are associated with funnel-type collapse at large ratios (>1) of roof thickness to reservoir width [16], as frequently observed for terrestrial summit pit craters. This mode of caldera collapse would constrain the minimum depth of associated crustal reservoirs to few kilometers according to the smallest pit craters, and a minimum depth of ~20 km according to the largest pit craters in the dataset. Alternatively, a regular involvement of explosive activity could contribute to concealing the peripheral caldera structure

References: [1] S.C. Solomon *et al.* (2008), *Science* **321**:59. [2] J.W. Head *et al.* (2008), *Science* **321**:69. [3] J.J. Gillis-Davis *et al.* (2009), *EPSL* **285**:243. [4] S.L. Murchie *et al.* (2008) *Science* **321**:73 [5] M.S. Robinson *et al.* (2008), *Science* **321**:66. [6] D.T. Blewett *et al.* (2009), *EPSL* **285**:263. [7] L. Kerber *et al.* (2009), *EPSL* **285**:263. [8] L. Kerber *et al.* (2011), *PSS* **59**:1895. [9] S.E. Hawkins, II, *et al.* (2007), *Space Sci. Rev.* **131**:247. [10] F. Preusker *et al.*, (2012), LPS **43**, this mtg. [11] J.J. Gillis-Davis *et al.* (2012), LPS **43**, this mtg. [12] J. Oberst *et al.* (2010), *Icarus* **209**:230. [13] F. Preusker et al. (2011), *PSS* **59**:1910 [14] K. Gwinner *et al.* (2009), *PERS* **75(9)**:1127. [15] T.A. Goudge *et al.* (2012), LPS 43, this mtg. [16] O. Roche *et al.* (2000), *JGR* **105**:395.

Table 1. Average morphometric parameters of pit craters for different occurence types and the overall dataset. W_{avg}, W_{min}, and W_{max} are the average, smallest, and largest diameter for a given pit crater. A_w is the horizontal aspect ratio W_{min}/W_{max}.

Location Type	Pit Diam. W_{avg} [km]	Aspect A_w [ ]	Depth D [km]	D/W_{avg} [ ]	D/W_{min} [ ]
Central Floor Position	17.7	0.87	2.21	0.12	0.13
Crater and Basin Structures	14.0	0.50	0.94	0.06	0.10
General Floor Position	9.3	0.68	0.72	0.08	0.09
Intercrater Terrain	20.1	0.71	1.73	0.10	0.12
All	14.0	0.69	1.31	0.09	0.11