Title:

Knob Heights within Circum-Caloris Geologic Units on Mercury: Interpretations of the Geologic History of the Region

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Abstract:

The circum-Caloris geologic units show morphology consistent with ejecta-derived formation, however crater counts suggest the units formed after the basin. To determine if the surrounding units are directly related to basin formation or products of later volcanic resurfacing events, we measured the heights and densities of knobs in 22 study regions to the east of the Caloris basin in three geologic units circumferential to the basin: the Odin Formation, the Van Eyck Formation, and the Smooth Plains Formation. In these study regions the size and concentration of ejecta blocks generally decrease away from the crater rim. The morphology that superposes the knobs and the distribution of knob heights within each study region suggests that the knobs were deposited as ejecta and later embayed by one or multiple volcanic events. The distribution of knob height and concentration indicates that the knobs within the circum-Caloris units are related to the formation of the basin.

Keywords: Mercury, Caloris Group, Caloris Basin, Ejecta, Knobs

1. Introduction and Background

The Caloris basin on Mercury was first recognized in 1974 during the Mariner 10 flybys, although images revealed less than half of the basin. It was not until 2008 when the MErcury Surface, Space ENvironment, GEOchemistry, and Ranging (MESSENGER) spacecraft [Solomon *et al.*, 2008] conducted its first flyby of the planet that the basin was seen in its entirety [Murchie *et al.*, 2008; Fassett *et al.*, 2009; Watters *et al.*, 2009]. Caloris is the largest recognized impact basin on the planet with a 1,550 km diameter [Murchie *et al.*, 2008] and is surrounded by a variety of geologic units. Units distributed circumferentially around the basin are known as the

Caloris Group: the Caloris Montes, the Nervo Formation, the Odin Formation, and the Van Eyck Formation and were first mapped using Mariner 10 images (Figure 1) [Schaber and McCauley, 1980; McCauley *et al.*, 1981; Guest and Greeley, 1983]. Circum-basin geologic units have long been used to derive the stratigraphic history of a planet, in particular the Moon [e.g., Shoemaker and Hackman, 1962; McCauley, 1967; Wilhelms, 1972]. Caloris is the youngest and largest impact basin on the innermost planet, so understanding the origin of the circum-Caloris geologic units will help constrain the geologic history of this planet and give insight on how large impacts have modified its surface. Early geologic mapping suggests the Caloris circumferential geologic units are related to the basin [Trask and Guest, 1975; McCauley *et al.*, 1981; Guest and Greeley, 1983; Spudis, 1993]. However, crater counts indicate that some of the geologic units (e.g. the Odin Formation) comprising this surficial unit solidified long after the Caloris impact [Murray *et al.*, 1975; Strom *et al.*, 2008; Fassett *et al.*, 2009; Denevi *et al.*, 2013]. In this paper, we investigate the heights and densities of knobs within the hummocky terrains of the Odin and Van Eyck Formations, as well as the Smooth Plains Formation, which is a volcanic unit not associated with the Caloris Group. Studying this terrain gives insight into the geologic history of the region and helps determine whether these units are derived from impact or volcanic processes.

The Odin Formation contains extensive patches of hummocky plains that extend as far as 800 km from the rim of the Caloris basin [Guest and Greeley, 1983]. Geomorphologic characteristics (e.g. hummocky terrain and smooth plains) and similarities between the Odin and Smooth Plains Formations suggests the Odin Formation was partially flooded by the Smooth Plains unit [Guest and Greeley, 1983]. More recent studies have identified two dominant terrains in the Odin formation: the knobby Odin-type terrain and the smooth Odin-type plains [Fassett *et*

al., 2009; Denevi et al., 2013]. The knobs within the hummocky terrain have been interpreted to
 be ejecta blocks that were deposited during the formation of Caloris [Trask and Guest, 1975;
 McCauley et al., 1981; Guest and Greeley, 1983; Spudis, 1993]. A previous study found that
 knobs within the Odin Formation are roughly 2 km in length and decrease in density with
 distance from the rim [Fassett et al., 2009]. This decrease in density away from the rim supports
 the hypothesis that the knobs are related to basin formation based on the mechanics of ejecta
 emplacement due to ballistic sedimentation—where large (in respect to both size and amount)
 fragments of ejecta, hereinafter referred to as blocks, are deposited closer to the rim and smaller
 sized and amounts of blocks are deposited farther away from the rim [Oberbeck, 1975]. Analysis
 of MESSENGER Mercury Dual Imaging System (MDIS; [Hawkins et al., 2007]) data shows the
 Odin Formation does not differ dramatically in color from the Caloris rim material [Denevi et al.,
 2013]. The knobby terrain and smooth plains within the Caloris units also do not differ
 markedly in color [Denevi et al., 2013]. If the Odin Formation, or the smooth component of the
 Odin Formation were volcanic, then these units would likely exhibit a distinct change in color
 from the Caloris rim. Crater counts (crater sizes ~10 – 100 km in diameter) within this region
 also indicate that the Odin-type plains are younger than the basin [Fassett et al., 2009; Denevi et
 al., 2013]. These studies suggest that the knobs constitute elevated terrain that was subsequently
 embayed or buried by the Smooth Plains or another volcanic unit [Murray et al., 1975; Strom et
 al., 2008; Fassett et al., 2009; Denevi et al., 2013].

Similar to the Odin Formation, the Van Eyck Formation also hosts extensive patches of
 hummocky plains [Guest and Greeley, 1983]. However, the Van Eyck Formation mantles
 preexisting terrain that extends almost 300 km further than the Odin Formation, and has been
 embayed only slightly by Smooth Plains material [Guest and Greeley, 1983]. The Van Eyck

Formation consists of plains-filled depressions thought to have formed by secondary cratering and crater chains from the Caloris-forming impact [McCauley *et al.*, 1981]. Crater counts by Fassett *et al.* [2009] suggest that the age of the Van Eyck Formation is similar to the age of large blocks surrounding the Caloris rim (also known as the Caloris Montes unit) and both were emplaced during the Late Heavy Bombardment (~4 Ga years ago). These ages indicate that the Van Eyck and Caloris Montes formations are dominated by ejecta generated in the Caloris impact.

The Smooth Plains Formation surrounding Caloris was initially interpreted to be either shock-melt deposits or lava flows characterized by lobate ridges that overlay older terrain [Greeley and Guest, 1983]. More recent crater size-frequency distributions have shown that the Smooth Plains surrounding Caloris were emplaced after the Caloris interior smooth plains and thus are subsequent volcanic deposits [Strom *et al.*, 2008]. A more recent study by Murchie *et al.*, [2015] shows that the Caloris interior and exterior plains are spectrally distinct from each other in the MESSENGER MDIS eight-color map. Caloris exterior plains units, the circum-Caloris smooth plains and smooth Odin-type plains, mapped by Denevi *et al.* [2013] using MESSENGER MDIS data are spectrally similar at the 430-1020 nm range [Denevi *et al.*, 2013]. This suggests that both plains materials exterior to the basin may have been derived from the same source. It is proposed that the smooth Odin-type plains were embayed by relatively thin deposits of volcanic material, resulting in a gradational change between the two units [Denevi *et al.*, 2013]. Kilometer-scale knobs are also seen in the Smooth Plains Formation in the northern portion outside the basin rim [Oberst *et al.*, 2010; Denevi *et al.*, 2013].

The morphologies described above have been observed in lunar basins and their associated ejecta [e.g. Wilhelms, 1987; Denevi *et al.*, 2013]. The concentration and relationship

between the plains and basin ejecta near Imbrium basin on the Moon imply an impact-derived origin for the plains unit (i.e., impact melt) [Wilhelms, 1987]. The lineated and hummocky ejecta surrounding Imbrium are partially buried by plains deposits and are most likely related to the basin as well [McCauley, 1977]. In addition to what is seen at Imbrium, a distinct gradient between ejecta-derived massifs and knobs can be seen at Oriental basin [McCauley, 1977]. While these relationships at Caloris are less developed, the lunar examples serve as an analog for the circum-Caloris units. If the knobs near Caloris are ejecta blocks, they should be consistent with models of ballistic ejecta emplacement, where both the height and normalized density (number of knobs divided by the area) decrease with distance from the Caloris rim [Oberbeck, 1975]. If the distribution of knob heights and densities are random, the knobs could instead represent: 1) materials produced in a resurfacing event, which may include Caloris impact melt or 2) ejecta of surrounding craters that superpose the volcanic terrain. Here, we analyze the height and densities of knobs around the Caloris basin to determine if the knobs are ejecta blocks derived from the Caloris impact.

2. Methodology

Using ArcMap in ArcGIS 10.1, a morphologic map of the terrain surrounding the Caloris Basin was constructed, with the goals of determining the formation mechanisms and constraining the ages of the Caloris Group units. We used the MESSENGER MDIS global mosaic (Planetary Data System version 9; 250 meters/pixel) as a basemap. The Greeley and Guest [1983] and Schaber and McCauley [1980] geologic maps of the Shakespeare and Tolstoj Quadrangles, respectively, covered parts of the Caloris basin and were also utilized as references for mapped unit boundaries. We selected 22 areas of interest east of the Caloris basin ranging ~100 – 600 km

from the rim of the basin for our analysis (Figure 2). This region was chosen because the Odin-type terrain with the roughest texture and highest density of knobs is located in this region [Denevi *et al.*, 2013].

Knob structures were classified as features that are roughly circular topographic highs. Knob-like structures arranged in semi-circular patterns were assumed to be the remnants of degraded impact craters, and were not included in the analysis. Because topographic highs and lows illuminate differently in images showing morphology, we identified features utilizing shadow direction.

We measured the heights of knobs identified within each of these regions, grouped within the three geologic units of interest defined by Guest and Greeley [1983]: the Van Eyck Formation, the Odin Formation (focusing on the knobby Odin-type terrain), and the Smooth Plains Formation. We also calculated the density of the knobs within each region and normalized the results by dividing the number of knobs by the area of the study region, similar to the methods in McBeck and Buczkowski [2013]. In this work, we subdivided our study regions into sections based on their distance from the rim of Caloris, where each section is 100 km in width.

We used photoclinometry to measure the height of the knobs rather than Mercury Laser Altimeter (MLA) data [Zuber *et al.*, 2012], because the latter has sparse coverage at the latitudes of our study region and the knobs are small relative to MLA data resolution. This technique has been used successfully in many instances to make topographic measurements on Mercury [Oberst *et al.*, 2010; Preusker *et al.*, 2011; Barnouin *et al.*, 2012]. Individual MDIS wide-angle camera (WAC; ranging from ~200 – 350 meters/pixel) images with high incidence angles (>65 degrees; [Barnouin *et al.*, 2012]) were used to measure the height of the knobs. Where available, both MDIS narrow-angle camera (NAC; ranging from ~30 – 40 meters/pixel) and WAC images

were used to evaluate the height of knobs. The image identification name, center sample resolution, emission angle, and incidence angle for each WAC image used are presented in Table 1. We calculated knob heights (h) using:

$$(1) \quad h = \frac{l_s}{\tan(i) \pm \tan(e)}$$

as detailed by *Chappelow and Sharpton* [2002] and *Barnouin et al.* [2012], where l_s is the measured length of the knob shadow, i is the incidence angle (in radians), and e is the emission angle (in radians) which is positive when the sun is in front of the spacecraft and negative when it is behind. The reported errors (e) are similarly calculated:

$$(2) \quad e = \frac{\text{center sample resolution}}{\tan(i) \pm \tan(e)}$$

where the +/- used in Equation 2 is the same as the +/- used in Equation 1 for consistency. Equation 2 calculates the “height” of a shadow that covers an entire pixel within a given image. Because shadows are sometimes only a portion of a single pixel within an image, we use Equation 2 to add or subtract length from the measured shadow, depending on the angle of the sun.

It is important to note that calculations with high incidence and emission angles provide almost identical results to calculations with lower incidence and emission angles [*Barnouin et al.*, 2012]. We therefore did not constrain an upper limit on either the incidence or emission angles. Images were processed using ISIS3 (Integrated System for Imagers and Spectrometers, version 3—a United States Geological Survey image processing software package) [*Anderson et al.*, 2004] at the United States Geological Survey in Flagstaff using Projection on the Web [*Hare et al.*, 2013] and then imported the images into ArcMap where the measurements were taken.

3. Results

We found that the arithmetic mean height of the knobs within each study region ranges from 0.06 – 0.32km (Table 2). The knob heights are generally tallest closest to the basin rim and decrease with distance (Figure 5a; Table 3). However, there is a large spike in the Smooth Plains knob heights between 301 – 400 km from the rim of the basin, which results from study regions Smooth(1) and Smooth(2) (Figure 1, 2, and 5a). Because both of these study regions are to the northeast of the basin, it is unclear whether the knobs are locally high in that area or regionally high throughout the entirety of the 301 – 400 km distance bin.

While conducting the height study, we found knobs in one region that were in alignment with lineations mapped within the Van Eyck Formation by Guest and Greeley [1983] but contained within the Smooth Plains Formation. We propose a change in the contact around this region as shown in Figure 4. Due to these observations, we therefore termed this region the Anomalous Area.

To assess consistency with our knob height measurements, the knob density distribution was also assessed. We see an increase in the number of knobs in the Van Eyck Formation with distance from the basin rim (Figure 5b; Table 3). However, there is a significant increase in density 201 – 300 km from the basin rim. Both the Odin and the Smooth Plains Formation also follow roughly the same density pattern. The increase in densities from 201 – 300 km is seen in study regions surrounding the basin, not just localized to a specific azimuth. Note that the tallest knobs do not decrease in density with distance from the Caloris rim and the shorter knobs do not increase in density with distance from the rim (Figure 5c). We also find that the Smooth Plains formation has an overall greater number of knobs than the Odin formation (Table 2).

Two regions (Odin (1) and Anomalous Area) are covered by both NAC and WAC images. We found that NAC images produced heights consistent with measurements from WAC

images (Table 2). These two study regions were the only areas with NAC coverage available in the PDS and thus we could not conduct a full study of possible height differences between the two data resolutions. With this case study, we show that our WAC findings are within error of calculations that use higher resolution data.

4. Discussion

Our knob height measurement results follow trends predicted by current models of ballistic emplacement i.e., larger deposits occur near the rim and smaller deposits occur farther away [Oberbeck, 1975]. The height measurements therefore suggest that the knobs are ejecta blocks. However, the knob densities do not agree with predicted models of ballistic ejecta emplacement [Oberbeck, 1975], because density increases with distance away from the rim. The distribution of height and concentration of knobs suggest the knobs may be 1) pre-existing terrain left behind from a resurfacing event (including Caloris ejecta blocks that were embayed by either Caloris impact melt or volcanics not related to the basin) or 2) ejecta from surrounding craters that superpose volcanic terrain.

Because the interpretations of the knobs' origin rely on the results for both the heights and the densities, it is important to consider the formation interpretations for both together. Our knob height results suggest that the knobs have an impact origin, and we therefore assume this interpretation throughout our discussion of knob densities. Interpretation 1 for the knob densities postulates that the knobs are Caloris ejecta and the plains surrounding the knobs are either Caloris impact melt or volcanic smooth plains material. The subsequent embayment would have affected knob densities by covering up shorter blocks, leaving only taller/larger blocks behind. Knobs that may have been “flooded” (covered by deep embaying material) are closer to the rim,

showing that the Odin-type plains are more likely impact melt than lava. In addition, embayed knobs could be caused by a thick continuous ejecta field. To examine the possible origins of the embaying units, we can look at crater populations as well as morphology, particularly in the Odin Formation. Crater population statistics are currently the best way to derive relative ages for a planetary surface. The crater population of the Odin formation corresponds to surfaces that are young in age [Fassett *et al.*, 2009; Denevi *et al.*, 2013], in contrast to the older relative ages of the Caloris rim and Van Eyck Formation, which indicate a volcanic resurfacing event post-basin formation [Murray *et al.*, 1975; Strom *et al.*, 2008; Fassett *et al.*, 2009; Denevi *et al.*, 2013]. However, it has been suggested that current crater populations around Caloris may not be statistically significant due to peculiarities in secondary crater formation [Denevi *et al.*, 2013] and thus the ages of the Odin-type plains should be reevaluated. In terms of morphology, Denevi *et al.* [2013] suggests the Odin-type knobby plains are consistent with an origin as Caloris ejecta due to their knobby and hummocky textures that are similar to what is seen on lunar basins [Wilhelms, 1987] as well as stratigraphic relationships between hummocky terrain and smooth plains [Fassett *et al.*, 2009]. The current study supports interpretation 1 based on the knob height results.

Interpretation 2 postulates that the knobs are ejecta, but not ejecta derived from the Caloris basin. Instead the blocks could have derived from large craters surrounding Caloris (Verdi—145 km diameter, Brahms—96 km diameter, Van Eyck—250 km diameter, etc.). While this is a possible situation, it is unlikely for two reasons. The first is the size of the ejecta blocks. Heights ranging from 50 – 300 meters with diameters of roughly 2 km [Fassett *et al.*, 2009] suggest the blocks formed from an impact that was quite large, perhaps larger than the aforementioned craters. While this is still very unconstrained, using equations from Lee *et al.*,

[1996], the “maximum block size” of Caloris could be anywhere from 5 to greater than 30 km across. The second is that this interpretation does not explain why we see knobs in the southeastern portion of the study region, where large impacts are missing but blocks are still present.

Overall, our findings support the formation event presented by Interpretation 1. We note that the knobs within the Anomalous Area are interpreted to initially be a part of the Van Eyck Formation and later embayed by the Smooth Plains Formation, which is consistent with the Greeley and Guest [1983] mapping; however, we propose a new contact for this unit (Figure 4). The density findings reported here are consistent with the work conducted by McBeck and Buczkowski [2013] who also suggest that the knobs may be ejecta blocks. If our interpretation is correct, the stratigraphy of the units would be as follows: the Van Eyck Formation would represent Caloris ejecta that has not been significantly modified, the Odin Formation would contain Caloris ejecta that is intermediately embayed by volcanic material and/or Caloris impact melt, and the Smooth Plains Formation would contain lava flows that would have almost completely embayed the pre-existing Caloris ejecta blocks.

5. Conclusion

Geomorphic and spectral evidence suggests that the circum-Caloris units are dominated by ejecta blocks created in the Caloris event, whereas relative ages derived from crater size-frequency distributions indicate that the surface of this unit is younger than Caloris, and thus likely volcanic. To help differentiate the age and origin of the circum-Caloris geologic units, we used photoclinometry measurements to quantify the distribution of the height and densities of knobs within the Odin, Van Eyck, and Smooth Plains Formations. The measured circum-Caloris

knob heights are consistent with the interpretation that the ejecta blocks were ballistically emplaced [*Oberbeck, 1975*] and later embayed by secondary geologic processes such as volcanic flows and/or impact melt. However, the density of the knobs are not consistent with this interpretation due to their increase in density away from the rim. This inconsistency may imply that the knobs within the Odin, Van Eyck, and Smooth Plains Formations derived from the formation of the Caloris basin and were later embayed.

Key objectives for future work and extending our findings consist of an in-depth study of the Caloris knobs at different radial distances around the entire circumference of the basin. To do this, we will use our current methods as well as additional datasets (adding compositional information) and crater population statistics to add further constraints on the interpretations. Analog knob studies of lunar basins would also be beneficial to compare and contrast knobby plains surrounding large impact basins (e.g. Imbrium and Orientale).

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References:

- Anderson, J. A., S. C. Sides, D. L. Soltesz, T. L. Sucharski, and K. J. Becker (2004), Modernization of the Integrated Software for Imagers and Spectrometers, vol. 35, p. 2039.
- Barnouin, O. S., M. T. Zuber, D. E. Smith, G. A. Neumann, R. R. Herrick, J. E. Chappelow, S. L. Murchie, and L. M. Prockter (2012), The morphology of craters on Mercury: Results from MESSENGER flybys, *Icarus*, 219, 414–427, doi:10.1016/j.icarus.2012.02.029.
- Chappelow, J. E., and V. L. Sharpton (2002), An improved shadow measurement technique for constraining the morphometry of simple impact craters, *Meteorit. Planet. Sci.*, 37, 479–486, doi:10.1111/j.1945-5100.2002.tb00834.x.
- Denevi, B. W. et al. (2013), The distribution and origin of smooth plains on Mercury, *J. Geophys. Res. Planets*, 118, 891–907, doi:10.1002/jgre.20075.
- Ernst, C. M. et al. (2015), Stratigraphy of the Caloris basin, Mercury: Implications for volcanic history and basin impact melt, *Icarus*, 250, 413–429, doi:10.1016/j.icarus.2014.11.003.
- Fassett, C. I., J. W. Head, D. T. Blewett, C. R. Chapman, J. L. Dickson, S. L. Murchie, S. C. Solomon, and T. R. Watters (2009), Caloris impact basin: Exterior geomorphology, stratigraphy, morphometry, radial sculpture, and smooth plains deposits, *Earth Planet. Sci. Lett.*, 285, 297–308, doi:10.1016/j.epsl.2009.05.022.
- Guest, J. E., and R. Greeley (1983), Geologic Map of the Shakespeare Quadrangle of Mercury, *Atlas Mercury, 1 : 5,000,000 Geologic Series*(Shakespeare Quadrangle), H 5M 45, I35 G.1983, I–1408 (H–3).
- Hare, T. M., S. W. Akins, R. M. Sucharski, M. S. Bailen, and J. A. Anderson (2013), Map Projection Web Service for PDS Images, vol. 44, p. 2068.
- Hawkins, S. E. et al. (2007), The Mercury Dual Imaging System on the MESSENGER Spacecraft, *Space Sci. Rev.*, 131, 247–338, doi:10.1007/s11214-007-9266-3.
- Lee, P., J. Veverka, P. C. Thomas, P. Helfenstein, M. J. S. Belton, C. R. Chapman, R. Greeley, R. T. Pappalardo, R. Sullivan, and J. W. Head III (1996), Ejecta Blocks on 243 Ida and on Other Asteroids, *Icarus*, 120, 87–105, doi:10.1006/icar.1996.0039.
- McBeck, J., and D. Buczkowski (2013), Detailed Geomorphic Mapping of the Odin Formation, Caloris Basin, Mercury, *Geol. Soc. Am. Annu. Meet., Abstract No. 383-6*(Geological Society of America), Denver, Colorado.
- McCauley, J. F. (1967), The nature of the lunar surface as determined by systematic geologic mapping, p. 431.
- McCauley, J. F. (1977), Orientale and Caloris, *Phys. Earth Planet. Inter.*, 15(2–3), 220–250, doi:10.1016/0031-9201(77)90033-4.

- McCauley, J. F., J. E. Guest, G. G. Schaber, N. J. Trask, and R. Greeley (1981), Stratigraphy of the Caloris basin, Mercury, *Icarus*, 47, 184–202, doi:10.1016/0019-1035(81)90166-4.
- Murchie, S. L. et al. (2008), Geology of the Caloris Basin, Mercury: A View from MESSENGER, *Science*, 321, 73, doi:10.1126/science.1159261.
- Murchie, S. L. et al. (2015), Orbital Multispectral Mapping of Mercury by MESSENGER: Evidence for the Origins of Plains Units and Low-Reflectance Material, vol. 46, p. 1606.
- Murray, B. C., R. G. Strom, N. J. Trask, and D. E. Gault (1975), Surface history of Mercury - Implications for terrestrial planets, *J. Geophys. Res.*, 80, 2508–2514, doi:10.1029/JB080i017p02508.
- Oberbeck, V. R. (1975), The role of ballistic erosion and sedimentation in lunar stratigraphy, *Rev. Geophys. Space Phys.*, 13, 337–362, doi:10.1029/RG013i002p00337.
- Oberst, J., F. Preusker, R. J. Phillips, T. R. Watters, J. W. Head, M. T. Zuber, and S. C. Solomon (2010), The morphology of Mercury's Caloris basin as seen in MESSENGER stereo topographic models, *Icarus*, 209(1), 230–238, doi:10.1016/j.icarus.2010.03.009.
- Preusker, F., J. Oberst, J. W. Head, T. R. Watters, M. S. Robinson, M. T. Zuber, and S. C. Solomon (2011), Stereo topographic models of Mercury after three MESSENGER flybys, *Planet. Space Sci.*, 59(15), 1910–1917, doi:10.1016/j.pss.2011.07.005.
- Schaber, G. G., and J. F. McCauley (1980), Geologic Map of the Tolostoj Quadrangle of Mercury (H-8), *U. S. Geol. Surv.*, Map I-1195.
- Shoemaker, E. M., and R. J. Hackman (1962), Stratigraphic Basis for a Lunar Time Scale, vol. 14, pp. 289–300.
- Solomon, S. C. et al. (2008), Return to Mercury: A Global Perspective on MESSENGER's First Mercury Flyby, *Science*, 321, 59, doi:10.1126/science.1159706.
- Spudis, P. D. (1993), *The Geology of Multi-ring Impact Basins*.
- Strom, R. G., C. R. Chapman, W. J. Merline, S. C. Solomon, and J. W. Head (2008), Mercury Cratering Record Viewed from MESSENGER's First Flyby, *Science*, 321, 79, doi:10.1126/science.1159317.
- Trask, N. J., and J. E. Guest (1975), Preliminary geologic terrain map of Mercury, *J. Geophys. Res.*, 80, 2461–2477, doi:10.1029/JB080i017p02461.
- Watters, T. R., J. W. Head, S. C. Solomon, M. S. Robinson, C. R. Chapman, B. W. Denevi, C. I. Fassett, S. L. Murchie, and R. G. Strom (2009), Evolution of the Rembrandt Impact Basin on Mercury, *Science*, 324, 618, doi:10.1126/science.1172109.
- Wilhelms, D. E. (1972), Preliminary Geologic Map of the Region around the Candidate Proclus Apollo Landing Site, vol. 289, p. 72.

345 Wilhelms, D. E. (1987), The Geologic History of the Moon, *Prof Pap. 1348, United States*
346 *Geological Survey*(United States Government Printing Office), Washington, D.C.
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Figure 1. Mosaic of monochrome MESSENGER MDIS NAC and WAC images at 250 meters/pixel (available on the Planetary Data System) showing the eastern section of the Caloris basin with both the Greeley and Guest [1983] and the Schaber and McCauley [1980] geologic maps at a 50% transparency; Study regions and correlating geologic units are also shown.

Figure 2. Separation of study regions for ballistic emplacement comparison; The basin center is shown in red and located at 31.5°N and 162.7°E as stated by [Ernst *et al.*, 2015]; Basin rim is indicated by a white circle with a 1,550 km diameter [Murchie *et al.*, 2008]; The subsequent rings are at 100 km intervals; Basemap data is a mosaic of monochrome MESSENGER MDIS NAC and WAC images at 250 meters/pixel (available on the Planetary Data System). Our study regions are shown in the context of these rings.

366 **Figure 3.** The range of knobs within the Odin, Van Eyck, and Smooth Plains Formations in a
367 Lambert Conformal Conic projection centered on the given latitude and longitude. Differences in
368 illumination patterns due to incidence angle can also be seen where shadows formed by knobs
369 are indicated in red arrows and shadows produced by craters are shown in blue arrows. (a)
370 Example of knobs within the Odin Formation in MDIS WAC image EW0250134169G (166°W,
371 17°N). (b) Example of knobs within the Van Eyck Formation in MDIS WAC image
372 EW0212633165G (166°W, 45°N). (c) Example of knobs within the Smooth Plains Formation in
373 MDIS WAC image EW0212676855G (169°W, 51°N).

a.

b.

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Figure 4. (a) Lambert Conformal Conic projection showing regional context for proposed Van Eyck Formation contact with both the Greeley and Guest [1983] and the Schaber and McCauley [1980] geologic maps at a 50% transparency. Basemap data is a mosaic of monochrome MESSENGER MDIS NAC and WAC images at 250 meters/pixel (available on the Planetary Data System). Black box denotes the Anomalous Area study region. Red dotted line includes our proposed inclusion of the Van Eyck Formation. Note: all knobs within the Anomalous Area are within our proposed contact. (b) Equirectangular projection showing the proposed inclusion in the white box and Anomalous Area in the black box. The region right of the white line is not included in Figure 4.a but is shown here for another example of the Van Eyck lineations that have been embayed by Smooth Plains material. Red arrows show the example Van Eyck lineations.

a. **b.** **c.**

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Figure 5. (a) Knob heights and (b) densities versus distance from the crater rim calculated from data in Table 3. Odin formation calculations are shown in grey, Van Eyck formation calculations are shown in black (with the Anomalous Area included), and Smooth Plains formation calculations are shown in white. Associated error bars are included. (c) Knob density versus distance from the crater rim binned by knob heights. Knob heights between 0-0.1 km are shown in black, 0.11-0.2 km in white, 0.21-0.3 km in grey, and 0.31+ km in beige.

MDIS Images*	Center Sample Resolution (m/pixel)	Incidence Angle (degrees)	Emission Angle (degrees)	Associated Study Region(s)
EW0212720211G	242.04	79.63	1.94	Odin (1) Anomalous Area Smooth (2)
EW0212763775G	215.15	80.44	2.29	Odin (2) Van Eyck (4)
EW0212763671G	241.61	80.32	2.50	Odin (3)
EW0212676623G	276.14	78.672	1.70	Odin (4)
EW0213024520G	223.86	79.86	18.72	Odin (5)
EW0212676461G	319.90	78.54	1.86	Odin (6) Van Eyck (5)
EW0227768922G	270.40	78.36	8.89	Odin (7)
EW0250134169G	228.26	88.82	53.24	Odin (8)
EW0250278179G	214.67	86.97	47.89	Odin (9)
EW0212589543G	320.32	76.65	1.25	Odin (10)
EW0212720084G	275.41	79.50	2.10	Van Eyck (1)
EW0212633165G	276.09	77.81	1.39	Van Eyck (2)
EW0212763862G	193.82	80.58	2.10	Van Eyck (3) Smooth (3)
EW0212676855G	216.04	79.09	1.46	Smooth (1)
EW0212633396G	216.25	78.37	1.23	Smooth (4)
EW0250335978G	274.93	82.77	51.58	Smooth (5) Smooth (6)
EN0228240116M	34.87	71.54	48.062	Odin (1)
EN0228326549M	37.63	68.58	58.22	Anomalous Area

397 **Table 1.** MESSENGER MDIS images used in this study showing center sample resolution,
398 incidence angle, emission angle, and associated study regions.

399

400 *NAC images have an image identification name beginning with 'EN'; WAC images have an
401 image identification name beginning with 'EW.'

402

Study Region	Number of Knobs	Arithmetic mean Knob Height (km)	Calculated Error ($\pm$ km)	Area of Study Region (km^2)	Arithmetic mean Knob Density (knobs/km^2)
Odin (1)	8	0.26	0.04	1.02×10^6	7.83×10^{-6}
Odin (1)*	8	0.25	0.01	1.02×10^6	7.83×10^{-6}
Odin (2)	18	0.23	0.04	9.66×10^6	1.86×10^{-6}
Odin (3)	34	0.18	0.04	6.06×10^6	5.61×10^{-6}
Odin (4)	32	0.20	0.06	3.06×10^6	1.05×10^{-5}
Odin (5)	84	0.31	0.04	1.35×10^7	6.24×10^{-6}
Odin (6)	31	0.32	0.06	7.68×10^6	4.04×10^{-6}
Odin (7)	29	0.25	0.05	6.07×10^6	4.78×10^{-6}
Odin (8)	110	0.06	0.01	2.81×10^7	3.92×10^{-6}
Odin (9)	53	0.29	0.01	2.92×10^7	1.82×10^{-6}
Odin (10)	25	0.31	0.08	2.77×10^6	9.02×10^{-6}
Anomalous Area	3	0.25	0.04	3.33×10^5	9.02×10^{-6}
Anomalous Area*	3	0.28	0.01	3.33×10^5	9.02×10^{-6}
Van Eyck (1)	15	0.30	0.05	5.97×10^6	2.51×10^{-6}
Van Eyck (2)	8	0.22	0.06	2.00×10^6	4.01×10^{-6}
Van Eyck (3)	20	0.13	0.03	1.84×10^6	1.08×10^{-5}
Van Eyck (4)	15	0.23	0.04	1.10×10^6	1.36×10^{-6}
Van Eyck (5)	22	0.26	0.06	2.69×10^6	8.18×10^{-6}
Smooth (1)	18	0.26	0.04	4.31×10^6	4.18×10^{-6}
Smooth (2)	2	0.30	0.04	3.51×10^6	5.70×10^{-7}
Smooth (3)	3	0.14	0.03	2.07×10^6	1.45×10^{-6}
Smooth (4)	7	0.21	0.04	2.00×10^6	3.50×10^{-6}
Smooth (5)	88	0.21	0.03	8.00×10^6	1.10×10^{-5}
Smooth (6)	28	0.30	0.04	4.99×10^6	5.61×10^{-6}

403

404 **Table 2.** Arithmetic mean height and density of knobs per study region accompanied by the
405 number of knobs contained in each study region. Data is derived from the WAC images unless
406 noted with an asterisk. See Figure 1 for locations.

407

408 *Denotes data derived from NAC images

409

Distance from rim (km)	Study Region	Arithmetic mean* Height (km)	Arithmetic mean Density (knobs/km ²)	Arithmetic mean Height Per Formation	Arithmetic mean Density Per Formation
100 – 200	Odin (9) Smooth (6)	0.29 ± 0.03	3.71 x 10 ⁻⁶	<i>Odin</i> 0.29 ± 0.01	<i>Odin</i> 1.82 x 10 ⁻⁶
				<i>Smooth</i> 0.30 ± 0.04	<i>Smooth</i> 5.61 x 10 ⁻⁶
201 – 300	Odin (1)	0.26 ± 0.05	6.97 x 10 ⁻⁶	<i>Odin</i> 0.26 ± 0.05	<i>Odin</i> 6.86 x 10 ⁻⁶
	Odin (3)				
	Odin (4)				
	Odin (5)				
	Odin (6)			<i>Van Eyck</i> 0.28 ± 0.06	<i>Van Eyck</i> 5.35 x 10 ⁻⁶
	Odin (7)				
	Odin (10)				
301 – 400	Van Eyck (1)	0.22 ± 0.04	3.93 x 10 ⁻⁶	<i>Smooth</i> 0.21 ± 0.03	<i>Smooth</i> 1.10 x 10 ⁻⁵
	Van Eyck (5)				
	Smooth (5)				
	Odin (2)			<i>Odin</i> 0.14 ± 0.02	<i>Odin</i> 2.89 x 10 ⁻⁶
	Odin (8)				
401 – 500	Anomalous Area	0.19 ± 0.03	6.20 x 10 ⁻⁶	<i>Van Eyck</i> 0.23 ± 0.05	<i>Van Eyck</i> 6.51 x 10 ⁻⁶
	Van Eyck (2)				
	Smooth (1)				
501 – 600	Smooth (2)	0.13 ± 0.03	1.08 x 10 ⁻⁵	<i>Smooth</i> 0.28 ± 0.04	<i>Smooth</i> 2.37 x 10 ⁻⁶
	Van Eyck (4)			<i>Van Eyck</i> 0.23 ± 0.04	<i>Van Eyck</i> 1.36 x 10 ⁻⁵
401 – 500	Smooth (3)	0.17 ± 0.03	2.47 x 10 ⁻⁶	<i>Smooth</i> 0.17 ± 0.03	<i>Smooth</i> 2.47 x 10 ⁻⁶
	Smooth (4)				
501 – 600	Van Eyck (3)	0.13 ± 0.03	1.08 x 10 ⁻⁵	<i>Van Eyck</i> 0.13 ± 0.03	<i>Van Eyck</i> 1.08 x 10 ⁻⁵

410

411 **Table 3.** Knob measurements statistics at different crater radii from the Caloris rim as shown in

412 Figure 2. All data is derived from WAC image measurements.

413

414 *Arithmetic mean is calculated by taking an average of the mean heights/densities within each

415 study region.