Rembrandt impact basin: Distinguishing between volcanic and impact-produced plains on Mercury

Jennifer L. Whitten a,⇑, James W. Head b

a Center for Earth and Planetary Studies, Smithsonian Institution, Washington, DC 20004, USA
b Department of Geological Sciences, Brown University, Providence, RI 02912, USA

Article history:
Received 28 October 2014
Revised 21 May 2015
Accepted 16 June 2015
Available online 20 June 2015

Keywords:
Mercury
Mercury, surface
Volcanism
Cratering

ABSTRACT

The surface of Mercury has been heavily modified by impact cratering and volcanic plains since the initial formation of its lithosphere and crust. As in the case of the Moon, the origin of early plains deposits has been difficult to determine because ponded impact basin ejecta and impact melt deposits can mimic the topography and texture of extrusive volcanic plains. In order to understand better the role that impact basins play in resurfacing on Mercury, we used MESSENGER Mercury Dual Imaging System (MDIS) data to map the distribution of plains deposits within and around the relatively young Rembrandt impact basin (~720 km in diameter). There are two different Rembrandt plains units: (1) high-reflectance interior and exterior plains, and (2) low-reflectance exterior plains. The morphology, crater size–frequency distribution, and N(20) crater density values were analyzed for each deposit. Observations of the two high-reflectance plains deposits are consistent with previous studies of volcanically produced smooth plains on Mercury. The low-reflectance exterior plains are older than the other high-reflectance plains and comparable in age to the Rembrandt basin impact event. On the basis of age, areal distribution, and albedo relationships with basin materials, the low-reflectance plains are interpreted as basin impact melt deposits. The large areal extent of the low-reflectance plains suggests that basin impact melt deposits may have played an important role in resurfacing Mercury, especially during the early geologic history of the planet when impact rates were higher.

1. Introduction

The process controlling the formation of smooth plains deposits on the terrestrial planetary bodies has been strongly debated, with two major formation hypotheses: (1) formation as volcanic flows (Murray et al., 1974, 1975; Strom, 1977; Kiefer and Murray, 1987; Spudis and Guest, 1988) and (2) formation by the emplacement of fluidized impact ejecta, an origin similar to that hypothesized for the Cayley plains on the Moon (Trask and Guest, 1975; Wilhelms, 1976; Oberbeck et al., 1977). For the Moon it is known that low-albedo smooth plains (lunar maria) are produced by volcanic eruptions. Persuasive evidence has been presented by many workers that the majority of the high-albedo smooth plains surrounding large impact basins, especially Orientale and Imbrium, are the result of ejecta-related cratering processes (e.g., Eggleton and Schaber, 1972; Oberbeck et al., 1973, 1975; Chao, 1974; Moore et al., 1974), and that only a small percentage of these lunar light plains represent cryptomaria, extrusive volcanic deposits buried by veneers of basin ejecta (Schultz and Spudis, 1979; Antonenko et al., 1995; Giguere et al., 2003; Whitten and Head, 2015a, b). Detection of lunar cryptomaria is assisted by the availability of high spatial and spectral resolution data which enables the identification of distinctive spectral and albedo contrasts. However, distinct albedo differences between young, mare-equivalent volcanic plains and the surrounding uplands do not exist on Mercury, further complicating the distinction between volcanic and impact-related plains deposits.

Most scientists involved in the geological mapping of Mercury from Mariner 10 data interpreted the smooth plains deposits to be of volcanic origin on the basis of their textural similarity to the lunar maria, stratigraphic relationships with smaller flooded craters in basin interiors, their location within many large impact craters and basins, the large volume of smooth plains deposits contained within topographic depressions, and minor spectral and albedo variations between the smooth plains and the surrounding terrain (e.g., Hapke et al., 1975; Strom et al., 1975). Reanalysis of the Mariner 10 color data led Robinson and Lucey (1997) to conclude that the locations of boundaries between distinct color units provided further evidence for an effusive volcanic origin of smooth
plain deposits within individual impact craters ≤ 200 km diameter (Head et al., 2009, 2011). However, impact melt scaling laws (e.g., Cintala and Grieve, 1998) suggest that substantially more impact melt should be produced on Mercury compared with the Moon. Impact melt production is dominated by the magnitude of an impact event that, in turn, is controlled by the impactor density, size and velocity, impact angle, and the target density. Predicted impact velocities for the terrestrial planets indicate that Mercury has the highest average velocity, 42.5 km/s compared with 19.4 km/s for the Moon (Le Feuvre and Wieczorek, 2008). Expected total melt volumes for basin-sized impact events (diameters >300 km) on Mercury and the Moon are estimated to be in the order of >10^6 km^3 (Eqs. (5), (7a), and (8) from Cintala and Grieve, 1998; Eqs. (9) and (12) from Abramov et al., 2012). The proportion of impact melt ejected from impact craters and basins decreases with larger transient crater diameters (Cintala and Grieve, 1998), so that large impact basins could eject <40% of the impact melt produced. This percentage suggests that approximately 5 × 10^3 km^3 of impact melt could be deposited exterior to a Rembrandt-sized basin, a volume comparable to that of the Columbia River Basalt Group (Tolan et al., 1989); such a large volume of ejected melt should be observable around the youngest mercurian impact basins especially if the impact melt is not ejected until the later modification stage of crater evolution, as suggested by recent models of impact ejecta emplacement (Ooblinski et al., 2011).

Several young impact basins on Mercury contain extensive smooth plains both within and exterior to the basin rim. While the interior deposits are generally thought to be volcanic on the basis of spectral differences (Murchie et al., 2008; Fassett et al., 2009; Denevi et al., 2009, 2013; Prockter et al., 2010; Marchi et al., 2011), the basin exterior plains have a more uncertain origin. For instance, Caloris (~1550 km in diameter; Fassett et al., 2012) has extensive smooth plains deposits interior and exterior to the entire basin (Denevi et al., 2013). The Caloris interior smooth plains have spectral properties consistent with the high-reflectance red plains (HRP) MDIS color unit (Denevi et al., 2009), which has been linked to a volcanic origin. The morphology, tectonics, and superposed crater population of the interior smooth plains are also consistent with a volcanic origin (e.g., Murchie et al., 2008; Watters et al., 2009b). On the other hand, the low–reflectance, color properties (Rava and Hapke, 1987; Robinson et al., 2008; Denevi et al., 2009), morphology, and stratigraphic relationship between the Caloris exterior plains and the basin rim are consistent with these exterior smooth plains being associated with the impact basin formation (Fassett et al., 2009; Denevi et al., 2013). The size–frequency distribution of superposed impact craters, however, indicates that emplacement of the Caloris exterior smooth plains occurred well after the basin-forming event (Strom et al., 2008; Fassett et al., 2009; Denevi et al., 2013). Either the crater size–frequency distributions do indicate real differences in the ages of the Caloris smooth plains, or one of several things has to be true: (1) the variations in the crater populations are not statistically significant, (2) the physical strength of the Caloris exterior plains is different from the interior plains leading to variations in crater diameter for the same-sized projectile, or (3) the rim of Caloris experienced self-secondary cratering which artificially increased the age of the basin impact event (Denevi et al., 2013).

Rembrandt basin (~720 km in diameter; Fassett et al., 2012) has similar morphologic units to Caloris, including interior and exterior smooth plains deposits that can be used to evaluate these three different possibilities and elucidate the distribution of impact basin melt and ejecta on Mercury. Rembrandt was discovered during the MESSENGER spacecraft’s second flyby of Mercury (Watters et al., 2009a) in the southern hemisphere (32.8°S, 87.5°E). It is the second largest, well-preserved impact basin on Mercury that formed at approximately the same time as Caloris (Watters et al., 2009a). While Rembrandt is noteworthy for its successive phases of contractional and extensional deformation, the interior and exterior plains provide an interesting case study for understanding better the distribution of basin ejecta and melt deposits and the relationship between basin formation and the emplacement of volcanic deposits on Mercury.

Similar to Caloris, the color properties of the Rembrandt basin plains vary between the basin interior deposits and the exterior plains deposits. Unsupervised cluster analyses conducted with MESSENGER’s Mercury Atmospheric and Surface Composition Spectrometer (MASCS) data support the observation of different MDIS color units interior and exterior to Rembrandt basin (Helbert et al., 2013). The MASCS unsupervised cluster analysis results suggest that the Rembrandt interior plains are spectrally similar to the northern smooth plains while the exterior plains are similar to the surrounding terrain. Supervised classification of MASCS data from 300 to 1450 nm (Izenberg et al., 2014) also showed that the plains around Rembrandt have a spectral signature distinct from the interior plains. These spectral measurements support the hypothesis that the Rembrandt interior and exterior plains have different formation processes.

The plains around Rembrandt will be analyzed to determine whether impact basins on Mercury have extensive exterior impact melt deposits or whether these plains are dominantly volcanic in origin. The majority of circum-Caloris smooth plains are thought to have been formed volcanically (Fassett et al., 2009; Denevi et al., 2013); however, there are lingering questions about whether a certain circum-Caloris unit (the Odin formation) is impact basin ejecta. This study will specifically address the following questions: (1) Are there different types of smooth plains deposits around Rembrandt basin? and (2) What is the formation mechanism responsible for the emplacement of these plains deposits? Through this research, we use the Rembrandt deposits to address larger outstanding questions regarding the distribution of different plains, what they reveal about the relationship between impact basins and volcanism, and what the Rembrandt plains deposits reveal about the generation of basin impact melt on Mercury.

2. Methods

The primary data for this study are images derived from the MESSENGER Mercury Dual Imaging System (MDIS) instrument (Hawkins et al., 2007). Other supplemental datasets include stereo photogrammetric topography data (Gaskell et al., 2008; Edmundson et al., 2011; Becker et al., 2012) derived from MDIS images and the MDIS color data. A region approximately 1700 km × 1400 km in size, centered over Rembrandt basin, was selected for detailed mapping of plains deposits. Smooth plains, referred to as high-reflectance plains (PrH) in this study, were mapped according to previously developed identification criteria (e.g., Trask and Guest, 1975; Denevi et al., 2013), which includes surfaces that are sparsely cratered, are flat to gently undulating,
and have a smooth surface texture. Other plains deposits noted in this region were most easily identified by a lower reflectance, a greater population of superposed craters, and a rougher texture compared with the PrH smooth plains. Initially, in order to distinguish between PrH and low-reflectance smooth plains (PrL), only an MDIS 750 nm mosaic was used for mapping. Then, a high incidence angle image of the same region was used to ensure that all smooth plains deposits had been mapped. Images taken at a high incidence angle, having longer shadows, effectively capture the morphology of a surface. Subtle features, such as wrinkle ridges and smooth textures, are easier to identify using images taken at a high incidence angle. The high incidence map was most useful when mapping the PrL plains; the lower surface reflectance of this unit made it difficult to discern the morphology in some locations. Only smooth plains deposits >20 km in diameter were included in the mapping.

The average reflectance of each areally extensive plains deposit was measured using an MDIS 8-band color mosaic (~670 m/pixel). The 1000 nm band, the longest MDIS wavelength, was chosen for analysis because MDIS color units (Denevi et al., 2009) have the largest variation in surface reflectance at longer wavelengths due to variations in spectral slope. To ensure that the reflectance values derived from the Rembrandt plains units can be compared with MDIS color units, the average reflectance values for representative MDIS color units were also measured (Table 1). Low-reflectance material (LRM) is the darkest MDIS color unit followed by MDIS color units were also measured (Table 1). Low-reflectance material (LRM) is the darkest MDIS color unit followed by MDIS color units were also measured (Table 1). Low-reflectance material (LRM) is the darkest MDIS color unit followed by MDIS color units were also measured (Table 1). Low-reflectance material (LRM) is the darkest MDIS color unit followed by MDIS color units were also measured (Table 1).

The Tolstoj basin rim and surrounding plains materials (16.2°C176 N, 195.3°C176 E), plains SW of Moody crater (16.4°C176 N, 125.9°C176 E) and the Firdousi–Faulkner plains (5.0°C176 N, 162.3°C176 E) were measured to derive an average HRP value while the Borealis plains (70.4°N, 277.2°E), Caloris interior (32.6°N, 162.3°E), and the Firdousi–Faulkner plains (5.0°N, 72.9°E) were used to derive the average reflectance for the HRP unit.

To estimate the ages and determine the stratigraphic relationships between the different plains units within and surrounding Rembrandt basin we measured the superposed crater populations. An MDIS 250 m/pixel image mosaic was used to identify all superposed craters >5 km in diameter. Obvious secondary craters (e.g., elongated rim, herringbone pattern, location in a chain or cluster) were excluded from our counts because these craters can make a planetary surface appear artificially older (e.g., McEwen and Bierhaus, 2006; Strom et al., 2011). Crater size–frequency distributions and crater density values (Table 2) were determined for each exposure of mapped plains (Fig. 1) to assess relative ages and compare them to observed stratigraphic relationships. In order to compare the areal density of impact craters and relative ages of the geologic units, N(20) and N(10) values are calculated for each study region, where N(D) is the number of craters with diameter ≥ D (in km) per 106 km2 area within a study region. Crape density measurements are determined for craters ≥10 km and ≥20 km in diameter in order to minimize the effects of secondary impact craters (which dominate at diameters <15 km on Mercury (Strom et al., 2011)) on a stratigraphic reconstruction of the smooth plains at Rembrandt basin. Confidence intervals for each data point are reported as 1σ, which are estimated as the square root of the number of craters per diameter bin (Crater Analysis Techniques Working Group, 1979).

Embayed craters were used to estimate the volume of each exterior plains unit. To be considered embayed, a crater (a) must be almost completely filled with smooth plains so that only its rim is visible, or (b) must lack an identifiable secondary crater field and its proximal ejecta deposits appear embayed. One to two

### Table 1

1000 nm surface reflectance of global MDIS color units and Rembrandt plains deposits.

<table>
<thead>
<tr>
<th>Unit</th>
<th>1000 nm reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low reflectance material</strong></td>
<td></td>
</tr>
<tr>
<td>Tolstoj rim</td>
<td>0.071</td>
</tr>
<tr>
<td>Neruda</td>
<td>0.065</td>
</tr>
<tr>
<td>Atget</td>
<td>0.075</td>
</tr>
<tr>
<td>Circum-Tolstoj plains</td>
<td>0.074</td>
</tr>
<tr>
<td>Plaines SW of Moody crater</td>
<td>0.072</td>
</tr>
<tr>
<td>Average LRM</td>
<td>0.071</td>
</tr>
<tr>
<td><strong>Low-reflectance blue plains</strong></td>
<td></td>
</tr>
<tr>
<td>Circum-Caloris plains</td>
<td>0.085</td>
</tr>
<tr>
<td>Plains E of Grainger crater</td>
<td>0.077</td>
</tr>
<tr>
<td>Average LBP</td>
<td>0.081</td>
</tr>
<tr>
<td><strong>Intermediate plains</strong></td>
<td></td>
</tr>
<tr>
<td>Global average</td>
<td>0.096</td>
</tr>
<tr>
<td><strong>High-reflectance red plains</strong></td>
<td></td>
</tr>
<tr>
<td>Borealis plains</td>
<td>0.119</td>
</tr>
<tr>
<td>Caloris interior</td>
<td>0.107</td>
</tr>
<tr>
<td>Firdousi–Faulkner plains</td>
<td>0.123</td>
</tr>
<tr>
<td>Average HRP</td>
<td>0.116</td>
</tr>
<tr>
<td><strong>Rembrandt plains</strong></td>
<td></td>
</tr>
<tr>
<td>Unit 1</td>
<td>0.101</td>
</tr>
<tr>
<td>Rembrandt interior</td>
<td>0.110</td>
</tr>
<tr>
<td>Average PrH</td>
<td>0.106</td>
</tr>
<tr>
<td>Hummocky plains</td>
<td>0.082</td>
</tr>
<tr>
<td>Unit 2</td>
<td>0.084</td>
</tr>
<tr>
<td>Unit 3</td>
<td>0.082</td>
</tr>
<tr>
<td>Unit 4</td>
<td>0.095</td>
</tr>
<tr>
<td>Unit 5</td>
<td>0.091</td>
</tr>
<tr>
<td>Average PrL</td>
<td>0.088</td>
</tr>
</tbody>
</table>

* Listed “Units” correspond to those labeled in Fig. 1a.
* The PrH average was computed using Unit 1 and Rembrandt interior values.
* The PrL average was computed using Units 2–5.

### Table 2

Crate density ages for Rembrandt, Caloris, and smooth plains deposits.

<table>
<thead>
<tr>
<th>Unit</th>
<th>N(20) ± 1σ</th>
<th>N(10) ± 1σ</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rembrandt deposits</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All PrL</td>
<td>10 ± 7</td>
<td>39 ± 14</td>
<td>This study</td>
</tr>
<tr>
<td>(1) PrH</td>
<td>11 ± 11</td>
<td>22 ± 16</td>
<td>This study</td>
</tr>
<tr>
<td>(2) PrL</td>
<td>53 ± 11</td>
<td>115 ± 16</td>
<td>This study</td>
</tr>
<tr>
<td>(3) PrL</td>
<td>63 ± 16</td>
<td>121 ± 22</td>
<td>This study</td>
</tr>
<tr>
<td>(4) PrL</td>
<td>29 ± 21</td>
<td>88 ± 36</td>
<td>This study</td>
</tr>
<tr>
<td>(5) PrL</td>
<td>42 ± 21</td>
<td>116 ± 35</td>
<td>This study</td>
</tr>
<tr>
<td>Rim material</td>
<td>58 ± 14</td>
<td>117 ± 48</td>
<td>This study</td>
</tr>
<tr>
<td>Interior</td>
<td>45 ± 15</td>
<td>85 ± 21</td>
<td>This study</td>
</tr>
<tr>
<td>Interior</td>
<td>45 ± 12</td>
<td>103 ± 19</td>
<td>Denevi et al. (2013)</td>
</tr>
<tr>
<td><strong>Caloris deposits</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rim material</td>
<td>54 ± 12</td>
<td>–</td>
<td>Watters et al. (2009)</td>
</tr>
<tr>
<td>Basin ejecta</td>
<td>58 ± 13</td>
<td>–</td>
<td>Fassett et al. (2009)</td>
</tr>
<tr>
<td>Interior</td>
<td>23 ± 4</td>
<td>75 ± 7</td>
<td>Fassett et al. (2009)</td>
</tr>
<tr>
<td>Interior</td>
<td>26 ± 4</td>
<td>80 ± 7</td>
<td>Denevi et al. (2013)</td>
</tr>
<tr>
<td>South of Caloris</td>
<td>32 ± 9</td>
<td>92 ± 16</td>
<td>Denevi et al. (2013)</td>
</tr>
<tr>
<td>East of Caloris</td>
<td>25 ± 8</td>
<td>91 ± 15</td>
<td>Denevi et al. (2013)</td>
</tr>
<tr>
<td>Tolstoj basin</td>
<td>19 ± 9</td>
<td>56 ± 16</td>
<td>Denevi et al. (2013)</td>
</tr>
<tr>
<td>Basin ejecta</td>
<td>93 ± 16</td>
<td>173 ± 22</td>
<td>Whitten et al. (2014)</td>
</tr>
</tbody>
</table>

* Numbers listed next to certain units denote their location in Fig. 1a.
embayed craters were identified in each plains deposit (deposits 1–5, Fig. 1a) between 8 and 40 km in diameter (Table 3). Morphologic relationships for mercurian craters derived by Pike (1988), which have been confirmed by MESSENGER altimetric data (Barnouin et al., 2012), were used to estimate the expected rim heights of these embayed craters. It was assumed that the craters were morphologically fresh at the time of embayment and that the predicted crater rim height accurately estimated the buried crater rim height. If the impact craters were degraded prior to embayment, then the Pike (1988) and Barnouin et al. (2012) relationships will overestimate the rim height. Stereo photogrammetric topographic data (Gaskell et al., 2008; Edmundson et al., 2011; Becker et al., 2012) were used to produce topographic profiles across the selected embayed craters in order to determine current rim heights. Measured rim heights were determined from five stereo topographic profiles taken from each crater. From the ten rim height measurements made for each crater, the three largest values were averaged together to produce the final measured rim height value. Each stereo topographic profile was analyzed in conjunction with MDIS images to ensure measurements reflected only rim heights; for example, rim height estimates from certain sections of a crater rim were not used in the analysis if a fresh impact crater obscured or destroyed the embayed crater rim. The predicted and actual rim heights were then compared to produce an estimate of the plains deposit thickness. If more than one embayed crater was identified in a plains unit, then the estimated thickness of the plains was determined by averaging the two thickness estimates (Table 4).

3. Plains identification and mapping

Many plains deposits can be identified within and around Rembrandt basin, most of which are not contained within pre-existing or post-basin formation impact structures. Two different plains units were identified during geologic mapping (Fig. 1a, Table 5): (1) the high-reflectance plains (PrH), which can be subdivided into interior and exterior deposits, and (2) the low-reflectance (PrL) exterior plains. The PrL surface is more textured than either type of PrH deposit. MDIS 250 m/pixel mosaic. Lambert azimuthal equal area projection centered on Rembrandt basin. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
PrL are predominantly confined to the Rembrandt basin exterior as contiguous areally extensive deposits. The albedo of this unit varies across the map area, but is consistently lower than that of the PrH (cf. Fig. 1b–d). The current topographic distribution of the PrL is markedly different from the PrH. PrL are not confined to topographic lows; instead, each deposit of PrL traverses both high and low-standing topography (Fig. 2). For instance, Units 4 and 5 (Fig. 1a) overlap with Enterprise Rupes and thus have rapid and substantial changes in topography, on the order of 1.7 km and 2.8 km, respectively, due to elevation variations along the fault scarp. Compared with the PrH, the PrL have a larger population of superposed craters and appear to be more modified by impact and tectonic processes. For instance, the PrL are heavily modified by wrinkle ridges and lobate scarps, especially to the northeast of the basin (Fig. 3a). This dense region of wrinkle ridges and lobate scarps coincides with the most well-preserved exposures of Rembrandt basin sculpture (Fig. 3b), lineated terrain oriented radial to the basin center. Lineations are expressed as a series of ridges and troughs (4–25 km wide), formed from basin ejecta that scoured the surface or by the coalescence of individual crater rims in secondary chains. The PrL do not show any morphologic evidence of basin ejecta modification, such as coalesced secondary crater chains or basin-radial scoured terrain that form basin sculpture. Instead, the PrL fill in the topographically low regions within lineated terrain and embay it, so that only the sculpture “rims” are visible above the plains (arrows, Fig. 3b).

4. Surface reflectance values

Average reflectance values for each of the areally extensive plains units (Fig. 1a) were derived using MDIS color data at 1000 nm. The LRM, LBP, IP, and HRP units have surface reflectance...
values of 0.071, 0.081, 0.096, and 0.116, respectively (Fig. 4; Table 1). Both the interior and exterior PrH around Rembrandt basin have average reflectance values of 0.110 and 0.101, consistent with the MDIS HRP unit (Table 1). The Rembrandt PrL 1000 nm surface reflectance of 0.088 is much lower than either of the PrH units. Reflectance measurements of a hummocky plains deposit in the northern interior of the basin (Fig. 1a, dashed white outline), interpreted to represent original basin materials (Watters et al., 2009a; Ernst et al., 2015), have a surface reflectance of 0.082. The hummocky basin unit and the PrL exterior plains have reflectance values that are most consistent with the MDIS LBP unit. Rembrandt exterior PrL have a comparatively higher reflectance.
than the other LBP units, but this is possibly due to contamination from the deposition of bright fresh crater ejecta onto the eastern deposits of PrL (i.e., Unit 2; Fig. 1a) (Fig. 5a).

5. Impact crater size–frequency distribution data

The size–frequency distributions of superposed crater populations were determined for each of the plains units mapped within and around Rembrandt basin (Fig. 6). A cumulative frequency plot shows the Rembrandt interior PrL, the exterior PrL, and the exterior PrL (Fig. 6a). The superposed crater populations of all of the PrL units were combined to improve statistics because these plains have similar morphologies, suggesting that the PrL represent a single geologic unit. A cumulative size–frequency plot of the individual PrL displays a similar density of craters in each diameter bin (Fig. 6b), supporting the interpretation that these plains were deposited contemporaneously and can be analyzed as a single unit. The PrL exterior plains have a higher density of superposed craters at all diameters compared with the exterior PrL, and only a slightly higher density than the interior PrL at diameters <30 km (Fig. 6a). Of the two PrL units, the exterior plains have a lower density of craters compared with the interior plains (Table 2).

The cumulative crater size–frequency distributions for the exterior PrL and the interior PrH overlap at diameters >30 km (Fig. 6a). The lower frequency of craters >30 km in diameter on the exterior PrL could be due to obscuration and destruction by later impact events. Several impact craters were not included in the crater counts because either (1) the ejecta or crater rim-crest appear embayed or (2) the crater rim and ejecta are so degraded that it was difficult to determine whether the crater was superposed on the plains. Fresh impact craters, including Amaral (~109 km in diameter, 26.5°S 117.9°E) and two unnamed craters (17.3°S 110.4°E, 23.3°S 112.2°E), obscure much of the terrain northeast of Rembrandt basin (Fig. 5). Due to the high density of craters in various states of degradation it is difficult to map plains deposits to the northeast of Rembrandt. A high density of relatively more degraded craters obscures the original stratigraphy to the west, and HRP smooth plains (Denevi et al., 2013) cover much of the terrain south of Rembrandt basin.

An R-plot (see Crater Analysis Techniques Working Group, 1978) of the PrL superposed crater population (Fig. 6c and d) shows a characteristic steep Population 1 shape indicative of a heavy bombardment crater population (Strom et al., 2005). The paucity of impacts >30 km in diameter into the PrL has caused the trend to flatten out at the largest diameters instead of continuing to increase, as observed in the shape of Population 1 craters. The R-plot of the PrL crater populations (Fig. 6c) has a shape intermediate between the steep Population 1 and the flat Population 2 pattern indicative of the post-heavy bombardment crater population (Strom et al., 2005). The change from a negative slope to a positive slope around 10 km in diameter in an R-plot indicates the presence of secondary impact craters (e.g., Strom et al., 2008, 2011); in the PrL and PrH crater counts the shapes of the crater size–frequency distributions (Fig. 6c and d) show no evidence for a statistically significant population of secondary craters >10 km in diameter.

Crad density values were also computed for the plains units within and around Rembrandt basin (Fig. 7, Table 2). The rim-crest of Rembrandt basin has an N(20) of 58 ± 16 (Watters et al., 2009a). This crater density is comparable to the N(20) values determined for the PrL, which vary from 29 ± 21 to 63 ± 16. The similarity and overlap in the cumulative size–frequency of the PrL indicates that these deposits formed near-contemporaneously and can be considered as one unit, therefore, the N(20) value for the combined PrL is 53 ± 11. The N(20) values for the PrH, both the interior and exterior deposits, are 45 ± 15 and 10 ± 7, respectively (Table 2). Denevi et al. (2013) reported an N(20) value of 45 ± 12 for the Rembrandt interior plains, which is in agreement with our calculated value. The exterior PrH have a low N(20) value, comparable to other smooth plains elsewhere on Mercury, including the Rudaki plains (N(20) = 10 ± 10) and the plains south of Rachmaninoff basin (N(20) = 17 ± 7) (Table 2) (Denevi et al., 2013).

6. Estimated volumes of mapped plains deposits

The volume of the exterior plains was estimated using morphologic measurements of embayed craters to derive thickness estimates (Fig. 8). Embayed craters that appeared to have sharper rims were preferentially selected for this analysis to ensure that the calculated plains thicknesses were not over-predicted. All of the exterior plains deposits, both PrH and PrL deposits, were estimated to be between 0.20 and 0.38 km thick (Table 4). Two embayed craters were measured for each of the exterior plains deposits except for Unit 5 (Fig. 1a), which only had one identifiable embayed crater in the map area. Stereo photogrammetric topographic profiles were measured to ascertain the current rim height of the selected embayed craters. This current rim height estimate was subtracted from the predicted rim height (Pike, 1988) to determine the plains thickness (Fig. 8a). When two embayed craters were present within a given plains deposit the thickness estimates were averaged together. The embayed craters measured in the exterior PrH produce an average deposit thickness of 0.20 km (Unit 1; Fig. 1a, Table 4). It was assumed that the PrL initially formed as a flat surface, not the topographically undulating surface that is observed today, so that measured embayed craters could be used to estimate the deposit thickness. Thickness estimates for the exterior PrL are, 0.38, 0.38, 0.38, and 0.33 km respectively (Table 4); the exterior PrL had an average thickness of 0.37 km.
The thickness estimates and measurements of areal extent were then used to calculate the volume of each exterior plains deposit (Table 4). Unit 2 (Fig. 1a) is the most areally extensive deposit \((9.0 \times 10^4 \text{ km}^3)\), located in the northeastern portion of the Rembrandt basin exterior, and is comparable in extent to the smooth plains in Beethoven basin \((\sim 630 \text{ km in diameter})\) (Denevi et al., 2013). The remaining PrL, Units 3–5 (Fig. 1a), have volumes between \(1.7 \) and \(3.6 \times 10^4 \text{ km}^3\). Combined, the PrL are \(1.7 \times 10^5 \text{ km}^3\), volumetrically similar to the Columbia River Flood basalts \((\sim 1.7 \times 10^5 \text{ km}^3);\) Tolan et al., 1989). Unit 1 (Fig. 1a), the one deposit of exterior PrH measured, has an estimated volume of \(1.8 \times 10^4 \text{ km}^3\).

7. Discussion

7.1. Distribution and stratigraphy of the Rembrandt plains

Two different plains units have been identified in and around Rembrandt basin on Mercury: (1) interior and exterior PrH, and (2) exterior PrL. The interior PrH have a smooth surface morphology (Fig. 1c), a high surface reflectance (Fig. 4), and a relatively low density of superposed impact craters (Fig. 6 and 7; Table 2). A comparison of Rembrandt crater rim and interior PrH \(N(20)\) values, \(58 \pm 16\) (Watters et al., 2009a) and \(45 \pm 15\), indicates these two plains units were formed in close succession. Stratigraphic observations support the sequence of events predicted by the \(N(20)\) values, that the interior PrH plains were emplaced subsequent to the basin formation event. The interior PrH would have been destroyed if emplaced prior to the Rembrandt basin formation event; the preservation of a relatively smooth surface and the southern boundary of the PrH defined by the basin rim-crest argue for emplacement inside Rembrandt after formation. The overlapping shapes of the crater size–frequency distributions and the overlap in \(N(20)\) values suggest the interior PrH formed soon after basin formation (Figs. 6a and 7).

High-reflectance smooth plains, similar to the Rembrandt interior PrH, have been interpreted to be of volcanic origin on the basis of flooding and embayment relationships and distinct color contrasts with surrounding terrain (Murchie et al., 2008; Head et al., 2011; Denevi et al., 2013). The combination of the low crater density, the high-reflectance, sharp morphologic and reflectance boundaries, and embayment relationships of these interior plains provides strong evidence for a volcanic origin. Additionally, a volcanic origin for the interior PrH is supported by the similarity in location to the mare basalts within the well-preserved lunar Orientale basin (Watters et al., 2009a). For instance, the large quasi-circular interior PrH deposit in Rembrandt fills the center of the basin, similar to Mare Orientale. Small mare patches, known as Lacus Veris and Lacus Autumni, occur along the interior of the Cordillera and Outer Rook basin rings of Orientale (e.g., Head, 1974; Scott et al., 1977; Whitten et al., 2011); the location of the elongated ENE-WSW-trending interior PrH deposit in the north of Rembrandt basin (Fig. 1a, orange arrow) is comparable to the position of Lacus Veris and Lacus Autumni in the lunar Orientale basin. The fact that volcanic deposits are expected along basin rings, as exemplified by the well-preserved lunar Orientale basin, provides further support for a volcanic origin for the Rembrandt interior PrH.
The exterior PrH share the same morphologic (Fig. 1b and c), reflectance (Fig. 4), and stratigraphic (Figs. 6 and 7; Table 2) properties as the interior PrH. However, the exterior PrH are significantly younger than the interior PrH (Figs. 6 and 7; Table 2). N(20) values for the interior (45 ± 15) and exterior (10 ± 7) PrH do not overlap, suggesting that these plains were not formed contemporaneously. The distribution of the exterior PrH is controlled by topography as almost all deposits are confined in topographic lows throughout the map region. This concentration in topographic lows, combined with a smooth to gently undulating surface, indicates that the exterior PrH were not significantly modified post-emplacement and that the terrain has not been substantially modified by tectonic activity since plains emplacement. Based on the evidence presented here, the exterior PrH are interpreted to be volcanic in origin. This conclusion is supported by previous studies of smooth plains deposits on Mercury (e.g., Head et al., 2011; Denevi et al., 2009, 2013).

The measured characteristics of the PrL are more ambiguous to interpret than either PrH deposit. PrL are more textured than the PrH due to the higher density of superposed craters (Figs. 6 and 7; Table 2). N(20) values for the interior (45 ± 15) and exterior (10 ± 7) PrH do not overlap, suggesting that these plains were not formed contemporaneously. The distribution of the exterior PrH is controlled by topography as almost all deposits are confined in topographic lows throughout the map region. This concentration in topographic lows, combined with a smooth to gently undulating surface, indicates that the exterior PrH were not significantly modified post-emplacement and that the terrain has not been substantially modified by tectonic activity since plains emplacement. Based on the evidence presented here, the exterior PrH are interpreted to be volcanic in origin. This conclusion is supported by previous studies of smooth plains deposits on Mercury (e.g., Head et al., 2011; Denevi et al., 2009, 2013).

The measured characteristics of the PrL are more ambiguous to interpret than either PrH deposit. PrL are more textured than the PrH due to the higher density of superposed craters (Figs. 6 and 7; Table 2). R-plots show that the PrL N(20) areal crater density values are not obviously affected by the presence of secondary craters (see Section 5, Fig. 6c and d). Additionally, previous research suggests that it is rare for secondary impact craters to attain diameters >20 km on the Moon and also be located <3 crater radii from the basin rim (Wilhelms et al., 1978). Due to the higher surface gravity of Mercury, ejecta and secondary craters may be present <2 crater radii from the basin rim-crest, according to scaling relations presented in Gault et al. (1975). This scaling would place most Rembrandt secondary
craters well away from the mapped PrL. Thus, the location of an inflection in the crater size–frequency distribution at 10 km (Fig. 6c and d) and the expected radial distance of basin secondary craters provide evidence that N(20) areal crater density values reflect real variations in the primary crater population and can be used to infer the sequence of events at Rembrandt.

A critical observation is that the PrL are comparable in age to the Rembrandt basin formation event; Rembrandt basin has an N(20) value of 58 ± 16 (Watters et al., 2009a) which substantially overlaps with the average value for the PrL, N(20) = 53 ± 11 (Table 2). Based on observations of the PrL on the basin rim–crest (Fig. 1a) and the N(20) values (Fig. 7, Table 2), the PrL were emplaced soon after the basin formation event. The distribution of the PrL is not controlled by the current topography around Rembrandt basin. All five PrL units contain high and low-lying topography, including relief variations between 1.3 km and 2.8 km. Units 4 and 5 have rapid changes in topography owing to the presence of Enterprise Rupes (Fig. 2); however, not all of the relief changes over such a short distance. The large topographic variations (Fig. 2) and the tectonic modification (Fig. 3a) of the PrL indicate that these plains were modified post-emplacement. Thus, these observations alone do not clarify the formation mechanism responsible for the deposition of the PrL deposits. The two prevailing formation hypotheses for plains deposits are related to: (1) impact-related ejecta deposition, in the form of deposition of distal ejecta (Trask and Guest, 1975; Wilhelms, 1976; Oberbeck et al., 1977), or proximal deposition of impact melt (e.g., Hawke and Head, 1977; Hawke and Cintala, 1977; Osinski, 2004), and (2) volcanism (Murray et al., 1974, 1975; Strom, 1977; Kiefer and Murray, 1987; Spudis and Guest, 1988). Below we review in detail the evidence for and against each formation mechanism for the PrL deposits around Rembrandt basin.

7.2. Low-reflectance plains: Impact or volcanic origin?

Ejecta scaling laws indicate that due to the higher gravitational acceleration that characterizes Mercury, the continuous ejecta deposits and secondary crater fields for impact craters and basins on Mercury were emplaced much closer to the rim-crest compared with lunar impact features (Gault et al., 1975; Melosh, 1989). The higher gravitational acceleration at the surface of Mercury could have led to more well-preserved impact ejecta deposits because these deposits would be more areally extensive close to basin and crater rims compared with the Moon. Smooth distal lunar basin ejecta deposits, referred to as either the Cayley Formation or light plains, are formed by the impact of distal primary ejecta fragments that excavate many multiples of their own mass which produce a flow of debris that ponds in low-lying areas, resulting in relatively smooth plains surfaces dominated by local material (e.g., Oberbeck et al., 1973). This typically produces discrete smooth, low-lying deposits (e.g., Wilhelms, 1968; Eggleton and Schaber, 1972; Oberbeck et al., 1973, 1975, 1977) 2–4 basin radii outward from a lunar basin rim-crest (Meyer et al., 2013). Scaling these lunar values to Mercury (Gault et al., 1975), the smooth ejecta deposits would be expected within 1.3–2.6 basin radii. For Rembrandt basin, the secondary ejecta-produced smooth plains would be expected in an annulus between 470 km and 935 km from the basin rim (hatched area in Fig. 5). The majority of mapped PrL deposits are actually interior to this annulus (Fig. 9, blue units). This discrepancy between the predicted location of distal impact-produced smooth plains deposits and the PrL suggests that the PrL do not originate from this secondary cratering process. However, the close proximity of the PrL to the basin rim-crest (Fig. 9, dashed circle) suggests that these plains deposits may be related to proximal basin impact melt.

Impact melt deposits are found to occur on impact crater rims on Mercury (Hawke and Cintala, 1977), similar to results for the Moon (e.g., Hawke and Head, 1977; Neish et al., 2014). The distance between the PrL deposits and the Rembrandt rim-crest and their location varies azimuthally around the basin (Fig. 9). There are no PrL along the northwest exterior of the basin (Fig. 9). PrL on the southeast half are closest to the rim (to the right of the 45–255° line, Fig. 9). The remaining PrL, located in the northwest half of the map region, are within ~200 km of the basin rim. The discontinuous distribution of PrL around the basin is consistent with more recent models of impact ejecta emplacement that predict impact melt flows out of the transient cavity onto the proximal continuous ejecta deposit during crater modification and collapse (Osisinski et al., 2011). If the PrL are impact melt, then the observed distribution may provide information about the impact event, as oblique impacts are expected to produce asymmetric ejecta deposits (e.g., Howard and Wilshire, 1975). Larger impact features on Mercury, such as the small young impact basins Raditladi (258 km in diameter) and Rachmaninoff (306 km in diameter) (Prockter et al., 2010; Marchi et al., 2011), have smooth plains deposits interpreted as exterior impact melt ponds adjacent to the rim-crest (Fig. 10). These impact melt ponds were identified based on having a flat, smooth surface texture and being superposed onto the much rougher and radially striated continuous ejecta deposit. The exterior smooth plains around Raditladi (Fig. 10a) and Rachmaninoff (Fig. 10b) are preferentially distributed around the basins with the most areally extensive plains concentrated in the northwest and southwest, respectively. Rachmaninoff is the larger of the two basins and has substantially more areally extensive impact melt. Both of these basins are less than half the size of Rembrandt and, thus, cannot be used for a direct volumetric comparison due to the non-linear aspects of melt scaling (Cintala and Grieve, 1998). However, the location of impact melt deposits on the basin rim of Raditladi and Rachmaninoff...
indicates that the close proximity of the Rembrandt PrL deposits to the basin rim-crest provides supporting evidence of an impact melt origin.

To estimate the volume of impact melt expected from a basin impact event the size of Rembrandt, we used the methods of Cintala and Grieve (1998). Other volume estimation methods (Abramov et al., 2012) produced values of similar magnitude to the results presented here. The volume of total impact melt produced is approximated by the equation:

\[ V_m = \frac{c}{D_{tc}} \]

where \( V_m \) is the volume of impact melt produced, \( D_{tc} \) is the diameter of the transient cavity, and \( c \) and \( d \) are constants dependent on the impactor properties (e.g., composition and velocity, Cintala and Grieve, 1998). The transient crater diameter was estimated using the equations of Schmidt and Housen (1987), where the transient crater diameter is dependent on the projectile density, projectile diameter, target density, impact velocity, and surface gravitational acceleration of the planetary body in question:

\[ D_{tc} = 1.16 \left( \frac{\rho_p}{\rho_t} \right)^{1/8} d_p^{0.78} v_i^{0.44} g^{-0.22} \]

For simplicity, the density of the target (\( \rho_t \)) and projectile (\( \rho_p \)) were taken as equal (Roberts and Barnouin, 2012; Ernst et al., 2010). The impact velocity (\( v_i \)) was assumed to be 42.5 km/s, the average value for Mercury (Le Feuvre and Wieczorek, 2008). The projectile diameter (\( d_p \)), \( \sim 42.4 \) km in diameter, was estimated using Eq. (7a) from Cintala and Grieve (1998). From these equations, the diameter of the transient cavity of Rembrandt basin was determined to be \( \sim 385 \) km which produces a volume of impact melt of \( \sim 1.5 \times 10^6 \) km$^3$. The total amount of melt estimated to remain in the impact cavity is approximately 64% (Cintala and Grieve, 1998). Therefore, \( \sim 5.4 \times 10^5 \) km$^3$ of impact melt should be ejected from Rembrandt basin and emplaced in the surrounding terrain.
Other impact basins on Mercury with smooth plains deposits (gray), interpreted to be impact melt ponds, near the rim-crests. (a) Raditladi basin (Fig. 10). This estimate of ejected impact melt volume is only 3.2 times greater than our estimate for the volume of the exterior PrL, which provides evidence for a volcanic origin for the Rembrandt exterior PrL.

This estimate of ejected impact melt volume is only 3.2 times greater than our estimate for the volume of the exterior PrL, 1.7 × 10^5 km^3.

Extensive volcanic deposits occur across the surface of Mercury. The northern smooth plains (Head et al., 2011) and the circum-Caloris plains (Fassett et al., 2009; Denevi et al., 2013) are some of the largest identified volcanic deposits. However, the areal extent and implied volumes of relatively young volcanic plains vary substantially as volcanic deposits also fill in smaller impact craters (exterior PrH, Fig. 1a). Superposed crater populations on volcanic smooth plains (i.e., northern smooth plains, Rachmaninoff interior plains) indicate that they are some of the youngest deposits on Mercury. Typically, identified young volcanic deposits have been associated with high-reflectance (Robinson and Lucey, 1997; Robinson et al., 2008; Denevi et al., 2009) and smooth, flat to gently undulating surfaces (Trask and Guest, 1975; Head et al., 2009, 2011; Denevi et al., 2013). In contrast, the PrL surrounding Rembrandt basin do not have a high reflectance and are not smooth. Young volcanic units are associated with high reflectance values (Denevi et al., 2009, 2013), but proposed older volcanic deposits, such as the intercrater plains do not have high surface reflectance (Whitten et al., 2014). The color properties of intercrater plains are more similar to the global average reflectance than to the young volcanic plains. If the low reflectance values associated with the intercrater plains are due to compositional differences between these older volcanic deposits and the young smooth plains, instead of impact gardening processes, then older volcanic materials may be compositionally distinct from the young volcanic smooth plains, which provides evidence for a volcanic origin for the Rembrandt exterior PrL.

Embayed craters within smooth plains also provide evidence for a volcanic origin. The morphology of embayed craters can vary. In some cases, these craters have breached rim-crests and the crater has been filled with material of similar color characteristics and texture to the surrounding terrain. Elsewhere, a crater may be unfilled but its ejecta deposits are not superposed on the surrounding terrain and are instead truncated or embayed. In the PrL surrounding Rembrandt basin there are many embayed craters present (Fig. 8b–j). However, it is difficult to place all of these craters within a stratigraphic framework with the basin sculpture (Fig. 11a and b) and the PrL formation. For instance, if the PrL are composed of impact melt, then these embayed craters would have had to form prior to the basin impact event and their crater rims should show evidence of basin ejecta sculpture, based on their proximity to the basin. A few craters (Fig. 8d and j) may show some indication of radial lineations along their rims, but the degradation state of most craters makes it difficult to determine for certain if the crater rim is sculpted. Within some of the Rembrandt secondary crater chains there are small (<5 km in diameter) superposed craters (Fig. 11e) that may be embayed. This would

Fig. 9. Diagram that examines the possibility that the Rembrandt PrL are some type of basin ejecta deposit. The geologic map of the distribution of plains deposits (Fig. 1a; blue is PrL and orange is PrH) is overlain by a hatched area representing the region predicted to contain smooth plains deposits (Gault et al., 1975; Meyer et al., 2013) produced from the ponding of basin-secondary crater impact ejecta (Oberbeck et al., 1973, 1977). The inner boundary of the torus is 470 km from the basin rim and its outer edge is 935 km away. Most of the mapped PrL are not contained within this annulus and, instead, are located just within the expected zone where distal debris flows produced from primary ejecta fragments pond in low-lying topography. In addition, there is a superposed reference frame to investigate the azimuthal distribution of the PrL (0° = North, 90° = East, 180° = South, 270° = West). Using this reference system, the majority of the PrL are located between 45° and 225°, on the southeast half of the basin; these deposits are also the closest to the basin rim-crest (black dashed circle). Lambert azimuthal equal area projection centered over Rembrandt basin. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 10. Other impact basins on Mercury with smooth plains deposits (gray), interpreted to be impact melt ponds, near the rim-crests. (a) Raditladi basin (~258 km in diameter). (b) Rachmaninoff basin (~306 km in diameter). Similar to PrL around Rembrandt, the largest impact melt deposits around Raditladi and Rachmaninoff show a preferential distribution. The impact melt ponds around Raditladi are concentrated in the northwest and those surrounding Rachmaninoff are focused in the southwest. Rachmaninoff, the larger of the two basins, has more areally extensive exterior impact melt deposits. MDIS 250 m/pixel monochrome mosaic. Stereographic projection centered over each basin.
suggest that Rembrandt basin and the secondary crater chain formed, then these small craters occurred on material deposited within the secondary chain, and that these craters were then embayed by PrL. The potential time delay between the formation of the small impact craters (Fig. 11e) within a Rembrandt basin secondary crater chain and the embayment of these craters by PrL could provide evidence for a volcanic origin for the exterior PrL. On the other hand, one current model of impact melt production (Osinski, 2004; Osinski et al., 2011) proposes that ejecta is emplaced in several stages, where the continuous ejecta deposit is emplaced followed by impact melt flows. If this model is correct, then post-basin formation impact melt could have embayed these small craters superposed on the continuous ejecta deposit. Both a volcanic and impact melt-related formation is plausible for the embayment of small craters within a secondary crater chain (Fig. 11e) and, therefore at current image resolutions, the craters cannot provide definitive evidence for a volcanic or impact-related origin for the exterior PrL.

Several craters adjacent to the Rembrandt basin rim-crest have sculpted rims (craters A and B in Fig. 11b), but are filled with PrH material (Fig. 1a). On the western side of Rembrandt there is another crater filled with PrL material that is characterized by radial basin sculpture on the part of its rim nearest to the basin (Fig. 1a, white arrow). This second example provides evidence that the crater was pre-Rembrandt and the PrL were emplaced afterwards. There are a few examples of craters that may be embayed by PrL and show no evidence of basin sculpture on their rims (Fig. 11d and e). For one of these craters (Fig. 11d), it may lack basin sculpture because it is too far from the basin rim to have been modified by basin sculpture and therefore cannot aid in determining the relative stratigraphy of the PrL. It is possible that these small craters have been embayed by PrL. The image resolution is not sufficient to definitely determine if these small craters have been embayed. (c–e) MDIS 250 m/pixel 750 nm mosaic. (f) Impact craters, including Ptolemaeus and Flammarion U (labeled), in the lunar central highlands with Imbrium basin sculpture (oriented northwest–southeast) on their crater rims. Those craters that formed after the Imbrium basin impact event do not have lineations on their crater rims from the basin ejecta. Lunar Reconnaissance Orbiter Camera 100 m/pixel mosaic. Stereographic projections centered on Rembrandt (a–e) and Ptolemaeus (f). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

On the Moon, large (Ptolemaeus, 153 km in diameter) and small (Flammarion U, 11 km in diameter) impact craters show evidence of Imbrium basin sculpture on their rims (Hartmann, 1963) (Fig. 11f) as far away as 820 km from the basin rim. Scaling that distance to Mercury (Gault et al., 1975), basin radial sculpture might be expected to occur at distances up to 530 km from the basin rim-crest, which coincides with the interior boundary of the ponded secondary crater ejecta from Fig. 9 (hatched area). The mapped Rembrandt basin sculpture (Fig. 11a, yellow lines) extends no further than ~480 km from the basin rim-crest in the
southwest and northeast; little to no radial sculpture is preserved along the northwest and southeast portions of the basin rim-crest. Thus, there is no observed morphologic evidence to suggest that basin sculpture on Mercury extends to theoretical distances of 530 km from the basin rim-crest.

We interpret the PrL to have originated through the formation and emplacement of impact melt. The PrL occur closer to the Rembrandt basin rim than is expected for distal basin-related smooth plains (Fig. 9), such as the lunar Cayley Formation. In addition, the PrL do not fit the expected morphology of distal, basin-related smooth plains deposits (discrete deposits confined to topographic lows and pre-existing impact craters) (Wilhelms, 1968; Eggelton and Schaber, 1972; Oberbeck et al., 1973, 1975, 1977). The similarity in the measured and calculated exterior impact melt volumes, the location of PrL near the basin rim-crest, the overlapping basin rim and PrL \( N(20) \) values, and the similar reflectance properties between the PrL and the basin interior hummocky plains (Table 1), all provide strong supporting evidence for an impact melt origin. Image resolutions (>250 m/pixel) of the currently available MESSENGER data are unable to provide unambiguous evidence that the PrL contain embedded craters with sculpted rims. Thus, with the currently available data it appears that the circum-Rembrandt PrL are impact melt deposits from the basin formation event.

7.3. Comparison of Rembrandt and Caloris exterior smooth plains

The Caloris and Rembrandt impact basins formed at approximately the same time (Watters et al., 2009a) (Fig. 7) and are the largest well-preserved basins on Mercury. Both Rembrandt and Caloris have interior smooth plains composed of the high-reflectance red plains (HRP) MDIS color unit and low-reflectance exterior deposits classified as either low-reflectance blue plains (LBPr) or low-reflectance material (LRM) (Denevi et al., 2009; Ernst et al., 2015). For Caloris specifically, the MDIS color variations between interior and exterior smooth plains (Robinson et al., 2008; Denevi et al., 2009) are consistent with a formation model where the exterior deposits are associated with basin formation and the interior smooth plains have a distinct volcanic origin (Fassett et al., 2009). Morphologic and stratigraphic analyses of exterior smooth plains suggest both volcanic and impact-related formation mechanisms (Denevi et al., 2013). However, an impact-related formation hypothesis for the exterior smooth plains is inconsistent with crater density values derived for the Caloris basin rim \( N(20) = 54 \pm 12 \), interior \( N(20) = 23 \pm 4 \), and exterior \( N(20) = 25 \pm 9 \) smooth plains deposits (Fassett et al., 2009): the large contrast in crater density between the Caloris basin event \( (54 \pm 12) \) and the exterior plains \( (25 \pm 9) \) indicates that these units did not form contemporaneously and thus the exterior plains cannot be basin ejecta or impact melt. Several workers have interpreted crater size–frequency distributions and crater density values to mean that both the exterior and interior Caloris plains are volcanic in origin (e.g., Strom et al., 2008; Fassett et al., 2009), despite the observed MDIS color variations.

The plains deposits around Rembrandt basin tell a slightly different story that may help to elucidate the formation mechanisms for circum-basin smooth plains. The MDIS color units at Rembrandt are similar to those observed at Caloris; Rembrandt interior and exterior smooth plains show distinct color variations, with HRP interior plains (interior PrH) and exterior plains composed of HRP, LBP, and LRM materials (interior PrH and PrL). The majority of the exterior plains surrounding Rembrandt are LBP and LRM, similar to the original basin materials (pre-basin target material excavated during the impact event that could originate from the lower crust or upper mantle; Ernst et al., 2010, 2015). Crater size–frequency distributions and areal crater density values for the interior and exterior plains, however, do not show exactly the same temporal relationship as the Caloris data (Fig. 7); most of the circum-Caloris plains \( N(20) \) values are farther removed from the basin formation event compared with the exterior PrL and Rembrandt basin. The formation of Rembrandt basin, its emplacement of exterior PrL, and infilling of PrH occurred in quick succession. The smooth and level morphology of the two PrH units, Rembrandt interior and exterior PrH, embayment relationships with basin rim materials, and the MDIS HRP color unit assignments, are consistent with a volcanic deposit that was emplaced after basin formation. The near-contemporaneous ages implied from the \( N(20) \) crater density values, combined with the similarity in MDIS color properties between the exterior PrL and Rembrandt rim, suggest an impact origin for the PrL. At Rembrandt, the reflectance properties, morphologic and stratigraphic relationships, and relative crater populations combine to provide a consistent story about the geologic history of the basin and adjacent materials.

The results of this study suggest that the Rembrandt exterior PrL were formed during basin formation and are likely impact melt deposits, in contrast to the circum-Caloris plains that are interpreted to be predominantly volcanic in origin (Fassett et al., 2009). Analysis of the Rembrandt exterior plains indicates that there should be large deposits of impact melt close to basin rim-crests on Mercury. At Caloris there does not appear to be any obvious preserved impact melt, likely a result of later resurfacing by volcanism and impact processes. Thus, only in well-preserved circum-basin regions will it be possible to detect basin impact melt deposits. The oldest deposits on Mercury, known as the intercrater plains, are interpreted to have formed as a series of smooth volcanic plains deposits that were emplaced during the early geologic history of Mercury (Malin, 1976; Strom, 1977; Denevi et al., 2009; Whitten et al., 2014); however, the results from this study of areally extensive basin impact melt deposits provide another important mechanism for large-scale resurfacing events.

8. Conclusions

MESSENGER image data have been used to map the distribution of plains deposits within and around the Rembrandt impact basin on Mercury and to determine the origin of those identified plains. Additionally, this analysis of plains deposits around the young and well-preserved Rembrandt basin has provided information about basin ejecta deposits and the relationship between basin formation and emplacement of volcanic deposits. We find that:

1. Two different types of plains exist within and around Rembrandt basin, the high-reflectance interior and exterior plains (PrH), and low-reflectance exterior plains (PrL). The exterior PrL have the greatest areal extent.
2. Both the interior and exterior PrH are interpreted as volcanic in origin based on their high-reflectance values, sparse superposed crater populations, smooth surface textures, and embayment relationships. The demonstrably younger age of the exterior PrH compared with the Rembrandt basin formation age (Fig. 7, Table 2) provides further support for a volcanic origin for this particular plains unit.
3. The Rembrandt exterior PrL are interpreted as basin impact melt deposits. This plains deposit has a high density of superposed craters and a low surface reflectance; these characteristics are shared with Rembrandt rim materials interpreted to represent excavated pre-basin target material,

and are also consistent with ejecta deposits around other impact basins such as Tolstoj (e.g., Denevi et al., 2009). Additionally, scaling relationships and the distribution of the PrI immediately adjacent to and on the Rembrandt basin rim-crest support an impact melt origin.

(4) The morphology and distribution of Rembrandt PrI indicates that basin impact deposits were volumetrically and areally extensive enough to resurface large portions of the planet, up to 64% of the surface. If all detected impact basins with diameters greater than 700 km in diameter produced the same amount (or more) of impact melt as Rembrandt then basin impact melt would comprise a larger proportion of the regolith than previously thought, covering up to 50% of the surface area of Mercury.

Acknowledgments

A special thank you is extended to C.M. Ernst and G.R. Osinski for their constructive reviews of this manuscript. We gratefully acknowledge funding from the MESSENGER project (DTM-3250-05), which is supported by the NASA Discovery Program under contracts NASW-00002 to the Carnegie Institution of Washington and NAS5-97271 to The Johns Hopkins University Applied Physics Laboratory.

References


