The global distribution of pyroclastic deposits on Mercury: The view from MESSENGER flybys 1–3

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ABSTRACT

We present a global survey of candidate pyroclastic deposits on Mercury, derived from images obtained during MESSENGER flybys 1–3 that provided near-global coverage at resolutions between 5 and 0.5 km/pixel. Thirty-five deposits were identified and characterized and are located principally on the floors of craters, along rims of craters, and along the edge of the Caloris basin. Deposits are commonly centered on rimless, often irregularly shaped pits, mostly between 5 and 45 km in diameter. The deposits identified are generally similar in morphology and absolute reflectance to lunar pyroclastic deposits. Spectrally the deposits appear brighter and redder than background Mercury terrain. On the basis of the available coverage, the candidate pyroclastic deposits appear to be essentially globally distributed. The diameters of the deposits, when mapped to lunar gravity conditions, are larger than their lunar counterparts, implying that more abundant volatiles were present during the typical eruptive process than on the Moon. These observations indicate that if these deposits resulted from hawaiian-style eruptions, the volatile contents required would be between ~1600 and 16,000 ppm CO or an equivalent value of H2O, CO2, SO2, or H2S (for a more oxidizing interior), or N2, S, S2, Cl, Cl2, or COS (for a more reducing interior). These abundances are much greater than those predicted by existing models for Mercury's formation. An apparent lack of small deposits, compared with the Moon, may be due to resolution effects, a topic that can be further assessed during the orbital phase of the MESSENGER mission. These results provide a framework within which orbital observations by MESSENGER and the future BepiColombo mission can be analyzed.

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1. Introduction

During the first flyby of the planet Mercury by the MErcury Surface, ENEvironment, GEOchemistry, and Ranging (MESSENGER) spacecraft (Solomon et al., 2008), several deposits were discovered that were hypothesized to be composed of pyroclastic material (Head et al., 2008, 2009; Murchie et al., 2008; Robinson et al., 2008; Blewett et al., 2009a; Kerber et al., 2009). Pyroclastic deposits are explosive volcanic eruption products formed by the fragmentation and upward propulsion of magma particles driven by the expansion of volatile species released from rising bodies of magma (e.g., Wilson and Head, 1981). A wide range of pyroclastic eruption types and deposit morphologies is anticipated during planetary explosive eruptions. On airless bodies such as the Moon and Mercury, eruptions range from gasless, effusive eruptions to explosive hawaiian, strombolian, or vulcanian eruptions, depending on the gas content and rise rate of the magma body and gas bubbles. Pyroclastic and other volcanic deposits thus represent important sources of information about planetary structure, composition (including volatile content), stress state, and thermal history (Wilson, 2009). Compositional information, derived from visible to near-infrared spectroscopic remote sensing, as well as X-ray, neutron, and gamma-ray spectrometry, can be used to characterize a surface deposit as well as to make inferences about the parent magma from which it was derived and the depth of its generation. The presence of volcanism on the surface of Mercury implies conditions sufficient to generate melts within the planet, combined with a planetary stress state conducive to allowing the magma generated to propagate to the surface (Wilson and Head, 1981, 2008). Precise global mapping of volcanic features can demonstrate trends in the thermal history of the planet through time and space and can aid...
in assessing the amount and distribution of volatile and heat-producing elements within the interior (e.g., Solomon and Chaiken, 1976; Wilson, 2009).

The discovery of pyroclastic deposits on the surface of Mercury has already provided an important constraint on the interior volatile budget of the planet (Kerber et al., 2009), which had previously been hypothesized to be extremely volatile poor (e.g., Boynton et al., 2007). The presence of pyroclastic and other volcanic deposits has also revealed that the stress state of the crust of Mercury has not, on a global basis, been sufficiently compressive throughout its history to prohibit the propagation of dikes to the surface (Wilson and Head, 2008). In this work we provide a detailed documentation of what we interpret to be pyroclastic deposits identified in the course of the three MESSENGER flybys of Mercury and an analysis of their morphologies, physical properties, and distribution. This analysis is used to provide a framework for future study of pyroclastic deposits by MESSENGER after its insertion into orbit about Mercury (scheduled for March 18, 2011) and by the later BepiColombo mission, which is expected to begin data collection in 2020 (Benkhoff et al., 2010), by identifying key areas for targeting, outlining major science questions and objectives, and summarizing techniques and analyses successfully used to study lunar pyroclastic deposits. Given the recent and projected influx of data from both Mercury and the Moon, the extremely rich opportunity to study pyroclastic deposits on the two bodies in concert is also discussed.

2. Characteristics of pyroclastic deposits on Mercury

Possible pyroclastic deposits on Mercury were first identified in Mariner 10 data. Rava and Hapke (1987) identified, on the floor of the crater Lermontov, a candidate pyroclastic deposit characterized by diffuse borders, high reflectance, and relatively red color (i.e., displaying a more steeply sloped reflectance spectrum from visible to near-infrared wavelengths). MESSENGER has provided additional evidence to support the inference that this deposit is indeed pyroclastic in nature. Several other diffuse, low-albedo, relatively blue deposits were suggested to be either ballistically emplaced ejecta deposits or pyroclastic deposits (Robinson and Lucey, 1997). New, higher-resolution data and multi-band color information acquired by the Mercury Dual Imaging System (MDIS) narrow-angle camera (NAC) and wide-angle camera (WAC) (Hawkins et al., 2007) have suggested that several of these low-albedo, relatively blue deposits (northwest of Lermontov crater and within Homer basin) are most likely of impact origin (Blewett et al., 2009b).

During the first MESSENGER flyby, five additional candidate pyroclastic deposits were identified, mostly immediately inside the southern rim of the 1550-km-diameter Caloris impact basin (Head et al., 2008; Murchie et al., 2008; Robinson et al., 2008; Blewett et al., 2009a; Kerber et al., 2009). These deposits have diffuse boundaries and are generally bright and red with respect to nearby units (Robinson et al., 2008; Blewett et al., 2009a; Kerber et al., 2009). Many of the deposits are associated with irregularly shaped vent-like depressions (Head et al., 2008, 2009; Murchie et al., 2008; Robinson et al., 2008; Kerber et al., 2009).

Subsequent flybys provided many more observations from which additional pyroclastic deposits could be identified. From images obtained during the second flyby, Blewett et al. (2009b) identified two additional pyroclastic deposits, one within the crater Mistral and another within a crater modified by Antoniadi Dorsum, and Denevi et al. (2009) mentioned a possible pyroclastic deposit in Praxiteles crater. With the completion of the third flyby, it is possible now to identify, describe, and map pyroclastic deposits on a global basis.

2.1. Identification of pyroclastic deposits

We have identified candidate pyroclastic deposits globally on Mercury on the basis of spectral character, morphology, and surface texture inferred from a combination of WAC 11-band color image mosaics (with bands centered at 430, 480, 560, 630, 700, 750, 830, 900, 950, 1000, and 1020 nm wavelength, and a resolution of ∼5 km/pixel), and NAC high-resolution image mosaics (centered at 750 nm, with a resolution of 500 m/pixel) (Hawkins et al., 2007; Robinson et al., 2008; Becker et al., 2009; Domingue et al., 2010). The image mosaics were calibrated to irradiance/solar flux (I/F), photometrically adjusted to the standard bidirectional geometry of 30° solar incidence and 0° emission angle (Robinson et al., 2008; Domingue et al., 2010), and analyzed using ENVI, an image visualization software package. Representative spectra were selected from the pyroclastic deposit studied in detail by Kerber et al. (2009), here termed RS-03 (after Red Spot 3, the designation given to the feature by Blewett et al., 2009a); Caloris interior plains material; bright crater-fill material; dark crater material; and plains materials exterior to Caloris. A linear spectral unmixing (end-members summing to unity using a weight of 4) was then performed to highlight the units that had spectra that are most similar to the spectrum of RS-03. One representation of the result of the spectral unmixing is shown in Fig. 1a and b, for which red (R) is pyroclastic material, green (G) is bright crater-fill material, and blue (B) exterior Caloris plains. The locations of the end-member spectra are indicated in Fig. 1a.

Several other spectral unmixing procedures were performed with other types of deposits chosen as the end-members. These results were compared to RGB color composite images obtained with several combinations of WAC bands (e.g., 430, 750, and 1000 nm). The areas consistently identified as similar to RS-03 were targeted for further analysis. For regions where Mariner 10 images had a resolution or viewing angle that was preferable to that provided by MESSENGER NAC data, these images provided supplementary information for morphological identification. Areas with high incidence angles or non-ideal viewing geometry appear around the edges of the spectral classification composite image.

Fig. 1. (a) Spectral classification results (resolution ~5 km/pixel), based on the calibrated WAC color mosaic (Hawkins et al., 2007; Robinson et al., 2008; Becker et al., 2009; Domingue et al., 2010). Representative end-member spectra were selected from (1) RS-03 (the pyroclastic deposit studied by Kerber et al., 2009), (2) plains material interior to the Caloris basin, (3) bright crater-fill material, (4) dark crater material, and (5) plains material exterior to Caloris (end-member locations indicated). A linear spectral unmixing was performed to identify the units that had spectra most similar to that of RS-03. Three end-member abundance images are presented here as an R–G–B composite: (R: pyroclastic material; G: bright crater-fill material; B: plains exterior to Caloris); (b) Locations of candidate pyroclastic deposits. The deposits are generally named after the crater in which they are found. In cases where there is more than one deposit in a crater, the location of the deposit in the crater is added at the end (e.g., Praxiteles NE is a deposit in the northeastern part of Praxiteles crater). In cases where the deposit is not within a crater but there was a named crater nearby, the deposit name indicates the named crater, with the direction of the deposit from the crater added at the beginning (e.g., NE Rachmaninoff is a deposit located to the northeast of Rachmaninoff basin). Deposits associated with an unnamed crater are designated as such and numbered. (c) Composite image showing the maximum incidence angles for areas imaged by MESSENGER. Areas in red were imaged at high Sun (low incidence angle), and areas in blue at low Sun (high incidence angle). Most of the pyroclastic deposits that were identified appear in the areas between these two extremes, because sufficient color and morphologic indicators were both present. Future searches should be directed toward the reddest and bluest areas shown here, as these are the areas where deposits were most likely to have been missed.
(Fig. 1a) as blue, purple, and pink. Although low-incidence-angle (high Sun) data are preferable for spectroscopic analysis, high-incidence-angle (low Sun) data are preferable for morphologic analysis and identification of potential volcanic vents. A map of the maximum incidence angles for images collected by MESSENGER is shown in Fig. 1c. Pyroclastic deposits located in the areas of high incidence angle (blue on the figure) would be difficult to identify spectroscopically, whereas deposits located in the areas of low incidence angle (red on the figure) would be difficult to identify morphologically. As can be seen in Fig. 1c, most of the pyroclastic deposits that were identified are located in the regions between these extremes.
Specific criteria used to identify possible pyroclastic deposits included the presence of an irregular central depression, an albedo anomaly with diffuse boundaries, and a distinct spectral signature similar to that of the previously identified pyroclastic deposit RS-03. These criteria are similar to those used to identify lunar pyroclastic deposits, though lunar deposits are also distinguished by their low albedo compared with surrounding terrain (Pieters et al., 1974; Weitz et al., 1998; Gaddis et al., 2003), whereas mercurian pyroclastic deposits tend to have a higher albedo than surrounding terrain.

On the basis of these criteria, a total of 35 candidate pyroclastic deposits have been identified on Mercury, including 19 newly documented deposits and multiple distinct deposits at some of the previously identified sites (Fig. 2, Table 1). Most of the pyroclastic deposits so identified fit all three criteria, though several large deposits lack a discernible central vent, and several deposits are located in the areas for which sufficient WAC color data are not yet available. The Beckett crater deposit is an example of a feature with good lighting for morphological analysis but poor lighting geometry for spectral analysis, whereas the Melville, Hemingway, and RS-04 deposits are examples of features with good lighting geometry for spectral analysis but poor lighting for morphological analysis (Fig. 2). The additional candidate pyroclastic deposits identified from images obtained during the second and third flybys are generally located on the floors of impact craters, though some are located along crater peak rings, and one (Melville) is located just outside the rim of a crater (Table 1).

Note added in proof: Four additional pyroclastic deposits were identified after this manuscript was submitted. These four features, which bring the total number of candidate pyroclastic deposits to 39, are included in Figs. 1 and 2 and Table 1 (labeled Penta and unnamed crater 5a–c, after the areas in which they are found) but are not included in the analyses that follow.
2.2. Pits and pit craters

Irregular pits interpreted to be vents have been identified in just over half of the identified deposits. Pits are distinguished from impact craters on the basis of their non-circular shape, rimless margins, lack of an ejecta deposit, and lack of association with secondary crater chains. Deposits without irregular central pits often have a rough interior that may consist of several vents (designated Fig. 2. (continued))
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<th>Longitude</th>
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<th>Measured radius (km)</th>
<th>Adjusted lunar radius (km)</th>
<th>Size class</th>
<th>Geologic setting</th>
<th>Pit length</th>
<th>Pit width</th>
<th>Pit morphology</th>
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Table 1
Candidate pyroclastic deposits on Mercury.
Comparison of the central pits of the Lermontov NE deposit on Mercury

Fig. 3 compares the pit associated with the Lermontov NE deposit in these cases is comparable to that of ejecta deposits from nearby craters of a similar size. The long axis of the pits ranges from 6 to 43 km, and the short axis of the pits ranges from 3 to 28 km (Table 1). Fig. 3 compares the pit associated with the Lermontov NE deposit with that associated with the lunar pyroclastic deposit Sulpicius Gallus (Lucchitta and Schmitt, 1974; Gaddis et al., 2003). The pits appear to be morphologically similar, although the pit in Lermontov is approximately twice as large as the lunar pit. In general, while both lunar and mercurian pits have irregular shapes and sloping interiors, the mercurian pits tend to be wider and larger.

"Pit craters" and the "pit-floor craters" that host them were identified and mapped by Gillis-Davis et al. (2009) on the basis of images from the first MESSENGER flyby. These authors found evidence to support an endogenic hypothesis for pit-crater formation. Specifically, they argued that pit craters formed by either explosive volcanic activity from dikes in the near subsurface or withdrawal of magma from a near-surface reservoir followed by subsequent reservoir roof collapse. Because of the seeming paucity of pyroclastic-like deposits surrounding the pit craters and the association of pit craters with nearby smooth plains, Gillis-Davis et al. (2009) favored the latter hypothesis. Given the morphological similarities between the pit craters and the irregular pits discussed above, we reassessed the possibility that these pits are related to pyroclastic activity. Of the seven pit craters identified by Gillis-Davis et al. (2009), three (located in unnamed crater 3 [now named Geddes], Scarlatti, and Glinka; see Figs. 1 and 2) show a color signature similar to that of pyroclastic material elsewhere on Mercury. One of the examples given by Gillis-Davis et al. (unnamed crater 1 in that work, now named To Ngoc Van) has a diffuse deposit with a bright albedo and a color anomaly that may be similar to pyroclastic material elsewhere on the planet, but the data quality at that location makes this interpretation inconclusive (see Figs. 1 and 2b). Three of the pit craters identified by Gillis-Davis et al. (2009) do not show spectral evidence for pyroclastic activity [located in Beckett, unnamed crater 4, and newly named Gibran (previously unnamed crater 2)]. However, these features are all located in the areas where either WAC viewing geometry or illumination angle were not ideal, so the lack of a pyroclastic signature need not preclude the possibility that they are pyroclastic in origin (Figs. 1, 2b and d). For example, the pit in Gibran crater is associated with a diffuse deposit with a high albedo, thus meeting two of the three criteria discussed above (Fig. 2b). We conclude that the majority of the pit craters identified by Gillis-Davis et al. (2009) meet the three criteria expected of pyroclastic deposits. We chose to include the remaining three pit craters in Table 1 on the basis of the morphological similarity of their pits to those associated with pyroclastic deposits and the presence in some cases of a diffuse, high-albedo anomaly. For these deposits, measurements of their areal extents are less certain (Table 1). It is intended that their inclusion will motivate further data collection and analysis, allowing a more definitive conclusion to be made regarding the relation of pit craters to pyroclastic deposits.

2.3. Global distribution

The sites of candidate pyroclastic deposits on Mercury are shown in map view in Fig. 4. Their locations on the floors of craters and along the edges of basins are similar to those seen on the Moon (Fig. 4), where approximately half of the deposits are found on crater floors and most of the remainder are located at the edge of mare deposits near large basins (Gaddis et al., 2003). However, the global distribution of the pyroclastic deposits discerned so far suggests that pyroclastic deposits on Mercury are more widely distributed than those on the Moon. Thus far, pyroclastic deposits have been identified in most areas of the planet where good coverage is available, with less certain detections in the areas where data coverage, phase angle, and viewing geometry make positive identification more difficult. Additionally, whereas the largest pyroclastic deposits on the Moon are often located on the edges of mare-filled basins, large pyroclastic deposits are less certain in their association with mare deposits on Mercury.
deposits on Mercury occur in a variety of geographical locations and are often located on crater floors. Unlike many pyroclastic deposits on the Moon (Gaddis et al., 2003), pyroclastic deposits on Mercury do not appear to be associated with floor-fractured craters, though they can be associated with crater peak rings.

The distribution of pyroclastic deposits on Mercury may suggest a more even distribution of heat-producing elements or interior volatiles, or a more uniform crustal thickness, each of which might allow magma to form and propagate to the surface with a more widespread distribution than seen on the Moon. Alternatively, the different spatial distribution of basins may exert a control on the distribution of pyroclastic deposits on the Moon and Mercury. The apparently more widespread and more global distribution of plains on Mercury relative to the Moon (e.g., Head et al., 2008; Denevi et al., 2009) may also be associated with this difference.

2.4. Physical properties

The area and the average radius were measured for each candidate pyroclastic deposit. NAC and WAC image mosaics (Becker et al., 2009) were placed on an azimuthal-equidistant projection centered on the deposit being measured. Areas were calculated using ArcGIS, a geographic information system software package, by defining the edges of each feature. Radii were determined by averaging 12 transects from the center of the candidate vent (or the approximate center of the deposit in cases where a vent was not obvious) to the edge of the deposit (Table 1). For this reason, size rankings according to area are not always the same as size rankings according to average radius, depending on the irregularity of the deposit and the location of the features interpreted to be vents (Table 1). Because the edges of pyroclastic deposits are commonly diffuse, radius measurements are approximate and can be uncertain by up to several kilometers. Deposit edges were determined using a combination of albedo variations in the 500 m/pixel NAC monochrome image mosaic supplemented by ∼5 km/pixel WAC color boundaries. Due to the lower resolution of WAC images, NAC albedo variations were usually more precise, except for areas where lighting or viewing geometry was not ideal. Some of the large, broad, diffuse deposits lacked a coherent shape or a visible vent. The measured radii are least accurate for these deposits, as they could be composed of several overlapping deposits from different vents. Because of poor image quality in the vicinity of unnamed crater 4 (Fig. 2d), this deposit was not measured. Radii calculated from the area (under the assumption that each deposit is circular in extent) result in radii equal to (when the vent is nearly circular) or larger than (when the vent is highly irregular) radii directly measured and averaged from the images. Features were classified as “very large (1001–49,000 km²),” “large (401–1000 km²),” “medium (201–400 km²),” “small (101–200 km²),” and “very small (1–100 km²)” according to the size classification used by Gaddis et al. (2003) for the Moon (shown in Fig. 4). The measured radii were tabulated, and a graphical representation of these results is

![Diagram showing the global distribution of candidate pyroclastic deposits on Mercury compared with those on the Moon (from Gaddis et al., 2003) using the same schematic representation. Deposits on each body are numbered in order of decreasing size (1 is the largest). The mercurian deposits are referenced by number in Table 1 of Gaddis et al. (2003). Whereas lunar pyroclastic deposits tend to cluster near mare deposits, mercurian pyroclastic deposits are more widely distributed. There is a clustering of deposits at the edges of the Caloris basin, which is partially filled with volcanic material (Head et al., 2008; Murchie et al., 2008). The background image of the Moon (Gaddis et al., 2003) is the global 750-nm Clementine mosaic. The background image for Mercury is the 750-nm MESSENGER NAC mosaic from flybys 1, 2, and 3 (Becker et al., 2009). Some clustering in the Mercury distribution is likely to be a consequence of variations in viewing angle and incidence angle affecting the identification of pyroclastic features, as depicted in Fig. 1.](image-url)
compared with a similar plot for lunar deposits in Fig. 5a. Area measurements of Gaddis et al. (2003) were used to calculate approximate radii (under the assumption of circular deposits) for this figure.

Although the radii of mercurian pyroclastic deposits appear to be broadly similar to those of the lunar pyroclastic deposits, they are not directly comparable. Two eruptions of identical energies on each of the bodies would result in deposits with markedly different radii because of the effect of the different surface gravitational accelerations on the ballistic emplacement of the pyroclasts. The radii for the mercurian deposits can be scaled to lunar conditions by recalling that the range of a ballistically emplaced object is inversely proportional to gravitational acceleration $g$. According to the laws of projectile motion, the horizontal range, $X$, of a particle in a vacuum is

$$X = \frac{v_0^2 \sin \theta}{g},$$

where $v_0$ is the initial eruption velocity from the vent; $\theta$ is the ejection angle (measured from the zenith), and

$$t = \frac{2v_0 \cos \theta}{g}.$$
yielding (for an angle of 45°, chosen to determine the minimum energy needed to emplace the particles)

\[ X = \frac{2v^2\sin\theta \cos\theta}{g} = \frac{v^2\sin2\theta}{g} = \frac{v^2}{g} \times \frac{1}{g}. \]

In this way we may scale a deposit radius measured on Mercury to what it would be on the Moon for the same initial ejection velocity

\[ \frac{X_{\text{Moon}}}{X_{\text{Mercury}}} = \frac{g_{\text{Moon}}}{g_{\text{Mercury}}} = \frac{3.7 \text{ m/s}^2}{1.6 \text{ m/s}^2} \Rightarrow X_{\text{Moon}} = 2.3X_{\text{Mercury}}. \]

From this scaling, it can be seen that the candidate pyroclastic deposits thus far identified on Mercury required markedly higher eruption velocities (and hence more energy) to achieve their observed radial extents than their lunar counterparts (Fig. 5b). If mercurian deposit radii calculated from area measurements are used instead of directly measured radii, this difference is enhanced.

The surface area of Mercury is approximately two times greater than that of the Moon, suggesting that, all else being equal, two times as many pyroclastic deposits would be expected on Mercury. Only about half as many pyroclastic deposits have been identified on Mercury to date, however, as have been identified on the Moon. This difference may mean that pyroclastic volcanism was less common on Mercury or that pyroclastic deposits were more commonly buried by other types of deposits on Mercury than on the Moon. However, many of the deposits documented on the Moon are “small” or “very small” deposits. No “small” or “very small” deposits have yet been found on Mercury (shown in Fig. 4, where the deposits are displayed with symbols corresponding to the same size classes). This absence of small pyroclastic deposits on Mercury could be an effect of resolution, and as the resolution of data for Mercury improves it is expected that additional smaller pyroclastic deposits may be discovered.

Milkovich et al. (2002) estimated from analysis of lunar volcanic features at different resolutions that small volcanic domes required both low Sun and resolutions between 100 and 500 m/pixel in order to be identifiable in images. The current NAC mosaic has a spatial resolution of approximately 500 m/pixel, and that for the WAC mosaic is closer to ~5 km/pixel (Becker et al., 2009). The orbital phase of the MESSENGER mission will generate higher-resolution data, including NAC image mosaics with an average resolution of better than 250 m/pixel and targeted images with resolutions of 25 m/pixel. WAC color data will be available with resolutions of 1.1 km/pixel, and targeted images will have resolutions of approximately 300 m/pixel, meaning that smaller volcanic features on Mercury should be resolvable (Milkovich et al., 2002).

2.5. Color and albedo

Multi-band spectral reflectance data from the MDIS WAC instrument obtained during the MESSENGER flybys allow for broad correlations between spectrally similar units. However, limited data taken at a variety of phase angles and viewing geometries make detailed compositional analysis of individual spectra difficult, especially for smaller pyroclastic deposits and those located at high latitudes or along the limb of the planet. Pyroclastic deposits on Mercury generally appear to be brighter and redder (that is, displaying higher reflectance and a more steeply inclined visible to infrared reflectance slope) than average background terrain (Robinson et al., 2008; Blewett et al., 2009a; Kerber et al., 2009). On Mercury, volcanic fire fountains are expected to have a greater optical density than fire fountains on the Moon. Together with shorter flight times due to the greater gravitational acceleration of Mercury, this effect would result in a larger percentage of pyroclasts falling to the surface warm on Mercury than on the Moon (Kerber et al., 2009). Pyroclasts deposited in this way would be more likely to crystallize as opposed to being quenched as glasses.

On the Moon, crystallized pyroclastic beads are darker than quenched glasses because of the crystallization of opaque minerals such as ilmenite, which also tends to make the deposit relatively “blue” (Pieters et al., 1974). Lunar pyroclastic deposits that are relatively bright and red relative to other lunar pyroclastic deposits appear to be lower in iron (Lucey et al., 1995). The bright and red character of the pyroclastic deposits on Mercury may thus indicate that they are relatively low in iron compared with surrounding terrain (which may already be low in iron). Although pyroclastic deposits on Mercury may be more likely to have crystallized than their lunar counterparts, they apparently did not crystallize a large amount of opaque minerals. The lack of a 1000-nm ferrous iron band in any of the pyroclast spectra supports the conclusion that the deposits are low in ferrous iron and is consistent with the general paucity of iron in silicates at the surface of Mercury (Blewett et al., 2002, 2009a; Warell and Blewett, 2004; Robinson et al., 2008; Denevi et al., 2009). An absence of opaque minerals could reflect a paucity of titanium, if the most common opaque mineral was ilmenite.

Reflectance spectra of mercurian pyroclastic deposits can be broadly compared with reflectance spectra derived from five-band Clementine data for lunar pyroclasts (Gaddis et al., 2003) by removing the WAC bands that are not shared between the two instruments (the 415 nm Clementine and 430 nm WAC bands are left to illustrate the visible continuum; Fig. 6). The reflectance values of the mercurian pyroclastic deposits fall within the general range reported for the lunar deposits (Fig. 6). Thus, whereas mercurian pyroclastic deposits appear brighter than surrounding terrain, and lunar deposits appear dark compared with their surroundings, this difference in contrasts appears to have more to do with the relative albedos of the surrounding terrain than with the pyroclastic deposits themselves. Further compositional analysis of pyroclastic deposits will be possible following the detailed photometric and scattered-light calibration of the WAC multi-spectral image data (e.g., Domingue et al., 2010). Deposits of particular interest are those that appear to resemble other pyroclastic deposits but are located in the areas for which the spectral data are uncertain (e.g., NE Rachmaninoff, Rachmaninoff SE, Beckett, unnamed crater 4, and Gibran).

3. Implications of deposit dimensions for interior volatile contents

The presence of volatile elements deep within the interior of Mercury sufficient to drive pyroclastic eruptions has implications for the planet’s mode of formation and subsequent evolution (e.g., Kerber et al., 2009). It had long been thought that Mercury’s interior would be volatile-poor, since it is likely to have accreted in a hot part of the solar nebula (Wetherill, 1994). In addition, the large core-to-mantle ratio of Mercury has been hypothesized to be due to some type of later heating episode, either by the nebula (Cameron, 1985; Fegley and Cameron, 1987) or by a giant impact (Wetherill, 1988; Benz et al., 1988, 2007). Both types of heating event would have further devolatilized the planet’s interior. However, the presence of pyroclastic volcanism on Mercury suggests that the devolatilization of the planet was not complete, or that the initial volatile budget of the planet was greater than previously hypothesized, perhaps due to the incorporation during accretion of planetesimals formed over a large range of solar distances, excursions of the semi-major axis of Mercury’s orbit in the early stages of accretion (Wetherill, 1988), or bombardment by volatile-rich embryos from the outer solar system (Morbidelli et al., 2000).
The recent documentation of water and other volatiles in lunar pyroclastic glasses (Saal et al., 2008) and water in lunar minerals (McCubbin et al., 2010) suggest that lunar formation models predicting near-complete devolatilization may bear revisiting. These findings need not imply, however, that water incorporated during accretion was the only, or even the major, volatile responsible for explosive volcanism on the Moon. It has been suggested, for instance, that lunar pyroclastic deposits could have been fueled by an oxidation reaction producing CO from elemental carbon through the reduction of $\text{C}_2\text{O}_2$, $\text{TiO}_2$, or $\text{FeO}$ (e.g., Sato, 1976; Fogel and Rutherford, 1995; Nicholis and Rutherford, 2005).

Zolotov (2011) explored this process for Mercury and suggested that several other species (S, Cl, and N) could survive devolatilization events because they are stable in their solid, reduced forms. The inferred dry, reducing conditions of the mantle of Mercury would result in volatile species that are distinct from those commonly encountered on Earth, perhaps including $\text{N}_2$, CO, $\text{S}_2$, $\text{S}_2\text{Cl}$, Cl, Cl$_2$, and COS, rather than $\text{H}_2\text{O}$, CO$_2$, SO$_2$, $\text{H}_2\text{S}$, and HCl (Zolotov, 2011). The dominant volatiles expected to drive pyroclastic eruptions would depend on the initial composition of the accreted planet (e.g., elemental carbon may not be as abundant in planetesimals that formed in the inner parts of the solar nebula), the redox state of the mantle, and the temperature and pressure conditions encountered during the rise of the erupting magma (which affect how the volatile components partition into the gas phase) (Zolotov, 2011).

Analysis following the first MESSENGER flyby (Kerber et al., 2009) indicated that in order to produce a deposit the size of RS-03 (the fifth largest in Table 1; Fig. 2a), approximately 5550 parts per million (ppm) of CO (or an equivalent amount of another volatile) would be required. This calculation can be made because the horizontal range, $X$, of any ballistic particle is directly proportional to $\nu^2/g$, as described above, and thus is also directly proportional to the kinetic energy of the particle at the time of eruption, $(1/2)mv^2$, where $m$ is particle mass. The kinetic energy at the time of eruption is, to a good approximation, directly proportional to the released magma gas fraction by mass, $f$ (Wilson, 1980), so $fv/g$ is proportional to $X$. Wilson and Head (1981) determined that approximately 500 ppm of CO (equivalent to an eruption speed of 90 m/s) would be needed to emplace pyroclasts to a distance of 5 km on the Moon. From the relationship above, it would take 2.3 times the amount of a particular volatile species to emplace pyroclasts to the same distance on Mercury.

In this way, we converted each measured deposit radius into the equivalent proportion of volatiles needed to eject a pyroclastic particle to this distance on Mercury. The results, displayed in Fig. 7 and Table 2, are shown in ppm CO because CO is a volatile species that could be produced on Mercury under a variety of conditions, and the values can be easily compared with values discussed for the Moon, where CO is considered a likely volatile (Nicholis and Rutherford, 2005). It is more likely in practice that an eruption on Mercury would be driven by a combination of volatile species. The required amount of different volatile species can be readily calculated, as the energy available from the expansion of a gas is inversely proportional to its molecular weight. These calculations hold for any type of explosive eruption, as they address only the amount of energy imparted to the entrained pyroclasts as they exit the vent and are not dependent on the manner or timing of degassing. However, depending on the type of eruption, volatiles could have passively degassed from the magma, causing a depletion in volatiles needed for an explosive eruption, or they could have become concentrated during the dike propagation and eruption processes, yielding calculated abundances that are greater than their original abundances in the melt.
It is possible, especially in the case of Vulcanian eruptions, to concentrate a volatile-rich magmatic foam at the tip of a propagating dike or below a plug blocking the vent mouth. In such a situation, magma containing a moderate amount of volatiles can eventually lead to an energetic eruption composed of mostly gas and fragmented foam (Wilson, 1980; Wilson and Head, 1981; Fagents and Wilson, 1993).

The majority of the newly recognized pyroclastic deposits on Mercury are smaller in size than the original deposit analyzed by Kerber et al. (2009). Of the four deposits that are larger than RS-03 in areal extent, only one (NE Rachmaninoff; Fig. 1a) has well-defined edges and a prominent central irregular depression. However, with a radius almost three times that of RS-03, the proportion of volatiles needed to emplace pyroclasts to that distance is almost three times as great. For comparison, measurements made from eruptions of Kilauea volcano in Hawaii implied volatile abundances in the hotspot mantle source of ~3000 ppm H₂O, ~6500 ppm CO₂, and ~1300 ppm S (Gerlach, 1986). If the NE Rachmaninoff deposit was formed through a fire-fountaining, Hawaiian-like explosive eruption, where calculated volatile contents would be similar to those found in the mantle source, the deposit dimensions would imply volatile contents in the source region of up to 11,000 ppm H₂O, 26,000 ppm CO₂, 13,000 ppm SO₂, or a combination of these or other volatiles (see Zolotov, 2011). If the volcanic gas was created through the oxidation of carbon, nitrogen, or similar species, a somewhat oxidizing crust would be required in order to supply oxygen for the process (Zolotov, 2011). It is possible that these high volatile abundances could be achieved through concentration of gas in a vulcanian eruption, as discussed above. The NE Rachmaninoff deposit currently lies at the edge of the usable MESSENGER WAC color data and will be an important target during the orbital phase of the mission.

The presence of large pyroclastic deposits on Mercury and the implied amount of volatile species needed to create them suggests that Mercury may be more volatile-rich than previously thought. The observation that there appears to be a greater proportion of large pyroclastic deposits on Mercury than there is on the Moon may yield clues to the relative abundances of interior volatiles or solid phases of C, S, N, or Cl present in the two bodies when they formed.

4. Future analyses

Mercury and the Moon are similar in that they are both small, airless bodies with generally ancient silicate surfaces. Both bodies have similar dominant surface processes: impact cratering, volcanism, structural deformation, and space weathering (e.g., Hiesinger and Head, 2006). However, Mercury differs from the Moon in its surface area (~2 times that of the Moon), the radius of its core (at least ~5 times that of the Moon), the composition of its crust (silicates with very low FeO content), and the distribution and expression of its volcanic output.

The Moon, because it is closer to Earth, better studied, and sampled, provides an excellent framework for an increased understanding of Mercury. Conversely, Mercury, lacking the complicating factors of the Moon’s proximity to (and likely origin from) the Earth (e.g., Hartmann and Davis, 1975; Cameron and Ward, 1976; Benz et al., 1986), provides a good context through which we may better understand the Moon. New data currently being acquired by missions to the Moon will provide a wealth of information about that body. The concurrent exploration of Mercury will provide a rich context that will lead to a substantial and synergistic increase in understanding of both bodies.

The MESSENGER mission and the upcoming BepiColombo mission provide an opportunity to begin to understand Mercury’s surface processes in ways that were first possible on the Moon almost a half-century ago. Several techniques may be used to better understand pyroclastic deposits, each contributing to progress on the outstanding issues discussed above. First, MESSENGER NAC images have made it possible to view large portions of the planet in much greater detail than was previously available. This improved resolution allows for the careful inventory and characterization of the morphologies of possible pyroclastic deposits, including their shapes and dimensions and characteristics of their central vents (e.g., Figs. 2 and 5, Table 1). On the Moon, morphological studies have allowed the classification of...
features into different volcanological regimes (Wilson and Head, 1981) that depend on the availability of magma, the abundance of volatiles, and the stress state of the lithosphere (Head and Wilson, 1992). Similar analyses have begun on Mercury (Wilson and Head, 2008) and will be greatly facilitated by the high-resolution data resources is shown in Table 3.

### Table 3

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5. Discussion and conclusions

The discovery of pyroclastic deposits on the surface of Mercury (Rava and Hapke, 1987; Head et al., 2008, 2009; Murchie et al., 2008; Robinson et al., 2008; Blewett et al., 2009a; Kerber et al., 2009) yielded several important insights. Pyroclastic deposits on Mercury were found to be similar to those on the Moon in that both are mantling deposits with diffuse edges often distributed around an approximately central, irregularly shaped depression (Fig. 3).
Although the particular mercurian deposit (RS-03) analyzed by Kerber et al. (2009) appears bright compared with the planetary average, in contrast to lunar pyroclastic deposits that appear dark compared with the lunar average, the RS-03 deposit has reflectance values in the general range of pyroclastic deposits on the Moon. It was determined by Kerber et al. (2009) that the magmatic volatile abundances needed to form RS-03 were comparable to those found in terrestrial oceanic basaltic magmas.

The identification and characterization of pyroclastic deposits across the surface of Mercury in this paper has yielded further insight. First, it was found that there are many deposits similar to RS-03, including four deposits that are larger in areal extent and eight deposits that are larger in average radius than RS-03. Three of these deposits have more than twice the radius of RS-03 (Table 1, Fig. 5). Pyroclastic deposits on Mercury are found to be systematically larger (after accounting for the difference in gravitational accelerations between bodies) than those found on the Moon (Fig. 5), with implied volatile contents in some cases many times greater than those found in terrestrial oceanic basaltic pyroclastic deposits, like other surface materials on Mercury, have little ferrous iron in silicate phases (Gaddis et al., 2003), and several mercurian pyroclastic deposits are seen at the edge of the volcanic plains (Murchie et al., 2008) interior to the Caloris basin. The widespread distribution of pyroclastic deposits on Mercury may indicate a more uniform distribution of heat-producing elements or interior volatiles or a more uniform crustal thickness on Mercury than on the Moon.

Other outcomes of this study include the finding that pyroclastic deposits on Mercury generally have larger vents than deposits on the Moon, perhaps reflecting a higher explosivity (Fig. 2, Table 1). Mercurian pyroclastic deposits lack the ubiquitous 1000-nm ferrous iron band seen in lunar pyroclastic deposits, indicating that pyroclastic deposits, like other surface materials on Mercury, have little ferrous iron in silicate phases (Fig. 6) (Blewett et al., 2002, 2009a; Warell and Blewett, 2004; Robinson et al., 2008; Kerber et al., 2009).

It was also found that mercurian pyroclastic deposits exhibit a range of albedos, but all values appear to be within the range of albedos for lunar pyroclastic deposits (Fig. 6).

Further study of Mercury's pyroclastic deposits will benefit from a variety of anticipated data sets, as indicated in Table 3, including morphological analysis, dating, and correlation with other volcanological features from images obtained with MESSENGER's MDIS NAC (in conjunction with existing Mariner 10 images and future BepiColombo images); compositional analysis provided by MESSENGER's MDIS WAC, MASCS, and XRS; further modeling of the ascent and eruption of magma-filled dikes (e.g., Wilson and Head, 2008), combining the stress fields suggested by tectonic features such as wrinkle ridges and lobate scarps (e.g., Watters et al., 2009) with the eruption energies calculated here; and theoretical comparisons with recent lunar sample laboratory findings (Saal et al., 2008), including the volatile contents and types of coatings that would be predicted for the particles forming pyroclastic deposits on Mercury. Predictions that can be made from the analysis of data collected so far by MESSENGER include the likelihood that many small pyroclastic deposits, currently below the limit of detection, will be discovered when higher-resolution images are available; the possibility that larger, regional deposits will, with higher-resolution imaging, be separable into several deposits erupted from different vents; and that subtle morphologic and compositional differences among pyroclastic deposits on Mercury will provide information about their inferred eruption mechanisms, source regions, ages, and subsequent space weathering or impact gardening that has altered them from their pristine states. Validation of each of these predictions, while informative in itself, will provide important contextual information on a variety of broader questions on Mercury's interior structure, composition (including volatile budget), stress state, and thermal history. Equally important will be the synergy created through analysis of new data being gathered for pyroclastic deposits on the Moon.

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