

Evidence for Young Volcanism on Mercury from the Third MESSENGER Flyby

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During its first two flybys of Mercury, the MESSENGER spacecraft acquired images confirming that pervasive volcanism occurred early in the planet's history. MESSENGER's third Mercury flyby revealed a 290-km-diameter peak-ring impact basin, among the youngest basins yet seen, having an inner floor filled with spectrally distinct smooth plains. These plains are sparsely cratered, postdate the formation of the basin, apparently formed from material that once flowed across the surface, and are therefore interpreted to be volcanic in origin. An irregular depression surrounded by a halo of bright deposits northeast of the basin marks a candidate explosive volcanic vent larger than any previously identified on Mercury. Volcanism on the planet thus spanned a considerable duration, perhaps extending well into the second half of Solar System history.

Images obtained by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft (*J*) during its first and second flybys of Mercury in 2008 established the presence and diversity of volcanism on Mercury early in the planet's history and indicated an association with ancient impact basins. A key missing element in our understanding of Mercury's global thermal evolution is the temporal extent of volcanic activity and, in particular, the timing of most recent activity (2). Previous analyses of the duration of geological activity led to the conclusion (3) that volcanism ended prior to the beginning of Mercury's Mansurian Period, ~3.5 to 1.0 Ga (billion years ago). Here we report on images obtained during MESSENGER's third Mercury flyby on 29 September 2009 of what may be among the youngest volcanic deposits on the planet.

During that most recent flyby, a ~290-km-diameter peak-ring (double-ring) impact basin, centered at 27.6°N, 57.6°E, was recognized (Fig. 1)(4). In terms of size, morphology, and state of preservation, the basin, named Rachmaninoff, closely resembles the 265-km-diameter Raditladi peak-ring basin (27°N, 119°E) that was imaged during MESSENGER's first Mercury flyby (5) and may have formed as recently as 1 Ga (6). Peak-ring basins are characterized by an outermost basin rim and an interior ring of contiguous peaks and are

transitional in form between complex craters and large multi-ring basins, which contain three or more rings. Peak-ring basins are common on Mercury (7), which has the highest density of peak-ring basins among the Moon, Earth, Mars, and Venus (8). Rachmaninoff may be transitional between a peak-ring basin and a multi-ring basin in that it has a partial third ring to the southwest, spanning an arc of about 120°. The inner ring of Rachmaninoff is approximately 130 km in diameter and slightly elongated in the north-south direction. The basin is surrounded by a continuous ejecta deposit and numerous secondary crater chains. Although it has no visible rays, its ejecta deposit, rim crest, wall terraces, and peaks are crisp and well preserved. On these grounds, the basin is younger than most other basins on Mercury and likely formed well after the end of the late heavy bombardment of the inner Solar System at about 3.8 Ga (3,6,9).

The floor of the Rachmaninoff basin contains several distinct plains units (Fig. 1). A smooth, relatively bright, high-reflectance plains unit has filled much of the floor within the peak ring (inner smooth plains, pink in Fig. 1B), and three relatively lower-reflectance plains units with broadly similar color characteristics are found within the annulus between the peak ring and the rim (annular smooth plains, green in Fig. 1B; annular hummocky plains, dark blue; and annular low-reflectance plains, purple; collectively hereafter grouped as "annular plains"). The bright, high-reflectance properties of the inner smooth plains are nearly identical to those of a large expanse of smooth plains located to the northeast of the basin that embay, and are thus younger than Rachmaninoff ejecta. Although smooth plains with similar color properties are common within craters and basins elsewhere on Mercury (10), only one other example has been found to date where these types of plains appear confined within a basin's central peak ring (the 225-km-diameter Renoir basin).

There is no apparent difference in color and reflectance between the annular plains units and the basin peak ring and terrace material (peak-ring material, light grey, and terrace material, light blue; Fig. 1B), all of which are up to 28% lower in reflectance than the inner smooth plains (Fig. 1C). These characteristics are consistent with those of low-reflectance material observed elsewhere on Mercury both as scattered deposits and concentrated in the central peaks and

ejecta deposits of craters and basins such as Tolstoj (10,11) (16°S, 195°E).

The geological characteristics of these units (Fig. 1B) provide further information on their origin. The plains units in the annulus between the peak ring and the basin wall are similar to typical rough-textured, hummocky units that characterize the floors of complex craters and basins on the Moon and Mercury (7,12,13). During the early modification stage of the cratering event that forms such structures, impact melt lines the interior of the crater cavity and drapes over the ejecta blocks, drains into lows, ponds to form smooth plains, and solidifies. In lunar basins, the color of the melt unit is commonly similar to that of the ejecta (13). Similar relationships are seen in the Rachmaninoff peak-ring basin (Fig. 1B), where annular hummocky deposits (dark blue unit; Fig. 1B) are concentrated outside of the uplifted peaks of the peak ring, and annular smooth and low-reflectance plains (green and purple units; Fig. 1B) are concentrated in the low topography along the base of the terraced wall. On the basis of these observations, we interpret the Rachmaninoff annular plains to be derived from impact melt.

In many fresh peak-ring and multi-ring basins on the Moon and Mercury, the plains interior to the peak ring are similar in reflectance, morphology, and color properties to smooth plains in the annulus and are thus also thought to be solidified impact melt (7,12-14). An impact-melt origin has been proposed for the plains found within Raditladi, which appear to be similar in age to the basin (5).

The inner smooth plains of the Rachmaninoff basin, however, differ from surrounding units in their reflectance, color properties, embayment relationships, structural characteristics, and density of superposed craters. The inner smooth plains have embayed the foot of the peak ring and have obscured its southern part (Fig. 1). On the basis of these relationships, we interpret the plains to have formed from fluid material that flowed across the peak ring to partly flood the units in the surrounding annulus in the southern part of the crater. These characteristics imply that the smooth plains within the peak ring formed from volcanic activity subsequent to the formation of the Rachmaninoff basin. A narrow (10-20 km wide) region of low-reflectance smooth material (inner peak-ring plains, turquoise unit; Fig. 1B) just inside the peak ring at the outer edge of inner smooth plains is reminiscent of relationships in lunar impact basins that have subsided as a combined result of subsurface cooling (15), volcanic flooding and embayment of the topographic low (13,16), and lithospheric flexure in response to the volcanic load (16). This unit could also have resulted from mass wasting of the peak ring onto the inner smooth plains.

Further evidence for volcanism in this region comes from the presence of a bright, high-reflectance patch located along the southeastern margin of the plains in the annulus between Rachmaninoff's peak ring and outer rim (bright material, yellow; Fig. 1B). The bright patch appears to be associated with rough-textured, hummocky material, which may be part of the deposit or may reflect underlying terrain over which the material is draped. The bright material is characterized by a diffuse distribution, a steep slope of the reflectance spectrum from visible to near-infrared wavelengths, and a reflectance 20% higher than that of high-reflectance plains to the north of the basin. About 480 km to the northeast of Rachmaninoff, a similar high-reflectance, diffuse halo over 200 km in extent surrounds a ~30-km-diameter, irregularly shaped, rimless, steep-walled depression (Fig. 2). The material within this halo deposit is nearly 70% higher in

reflectance than the high-reflectance plains to the north, placing it among the highest-reflectance features observed on the planet, including the fresh ejecta of Kuiperian craters (17). Although the distinctive color of the deposit could be interpreted as the result of more space weathering than has affected fresh crater ejecta, the combination of an especially steep spectral slope and very high reflectance implies that the deposit has a different composition or physical properties and that its color is not due to space weathering.

The reflectance properties of these halo deposits are similar to those of spectrally distinct deposits observed elsewhere on Mercury in association with crater and basin interiors and interpreted to be products of pyroclastic volcanism (18). Scalloped depressions similar to the one northeast of the Rachmaninoff basin have been identified elsewhere on Mercury, notably just inside the rim of the Caloris basin (e.g., at 22.4°N, 146.3°E), and have been interpreted as sites of explosive volcanic activity (18-21) where bright material was emplaced ballistically around a central source vent. The scalloped depression northeast of Rachmaninoff is remarkable in that it is not only larger than the largest previously identified candidate vent around the rim of Caloris, but its surrounding halo of bright material extends twice as far as the deposit around that vent (18). We do not find any scalloped depression that could be interpreted as a candidate source vent for the bright patch within the Rachmaninoff annulus, however.

Deformation postdated volcanism within the Rachmaninoff basin. Lying within the inner smooth plains unit is a set of narrow extensional troughs or graben (Fig. 1B). Extensional faulting on Mercury is rare and generally confined to impact basins (22,23). The pattern of graben in Rachmaninoff is similar to that in Raditladi, where the graben are dominantly basin-concentric and form an incomplete ring that is offset from the center of the basin (5). The cumulative length of imaged graben in Rachmaninoff (~460 km) is larger than in Raditladi (~180 km), indicating that the floor of Rachmaninoff experienced greater extensional strain. The extension within the Rachmaninoff and Raditladi basins likely accompanied uplift of the basin floors, as is thought to be the case for the larger Caloris and Rembrandt basins (22, 23). The observation that the extensional troughs in Rachmaninoff are confined to the volcanic inner plains suggests that the volcanism and uplift may have been related.

The very small number of superposed craters indicates that the inner smooth plains within the Rachmaninoff basin may be among the youngest volcanic deposits on Mercury. The volcanism must postdate the cratering event because the inner plains embay or overlie units related to basin formation. To assess the time interval between basin formation and volcanism, we measured the size-frequency distribution of impact craters superposed on the inner and annular plains. The inner plains of Rachmaninoff are clearly less cratered than the annular plains, and hence younger, a difference that is particularly noticeable for craters greater than ~2-3 km in diameter (which are unambiguously resolvable and difficult to remove by later geological activity). This result is consistent with a volcanic origin for the inner plains. The differences in the trends of the size-frequency distributions at crater diameters of 2-3 km between the two areas may reflect that craters of these sizes are most likely secondary craters with uneven population statistics (6). Comparison of crater counts in areas associated with formation of the Rachmaninoff basin (the annular plains, rim deposits, and inner ejecta blanket) with similar measurements for the

Raditladi basin (Fig. 3B) suggest that the Rachmaninoff basin formed somewhat earlier than the Raditladi basin. Although the crater size-frequency distributions for Raditladi and the two units within Rachmaninoff do not follow precisely the same trends, the inner plains of Rachmaninoff are clearly older than the floor of Raditladi but substantially younger than the Rachmaninoff annular plains.

In principle, we may estimate absolute ages for the Rachmaninoff basin and its related units by comparing these size-frequency distributions with models for the rate of production of craters on Mercury (9,24). Such models depend on differences in flux and impactor energies between the Moon and Mercury, assumptions about the properties of the surfaces impacted, and adopted scaling relationships, and they are influenced by uncertainties in the size distribution of inner Solar System asteroids. Whereas interpretations following Mariner 10 were that plains formation on Mercury ceased shortly after the end of the late heavy bombardment (~3.8 Ga), volcanism within Rachmaninoff (and formation of the plains within the younger Raditladi basin) extended well into the Mansurian and conceivably to times as recent as ~1 Ga. Models for crater retention age (9,24) involve primary cratering only, and most of the craters on the smooth plains in Fig. 3A may be secondary craters, given the pronounced steep slope of their size-frequency distribution (6). For this reason, the volcanism and associated deformation within Rachmaninoff could have ended even more recently.

References and Notes

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Supporting Online Material

www.sciencemag.org/cgi/content/full/science.1188186/DC1
SOM Text

Fig. S1

Table S1

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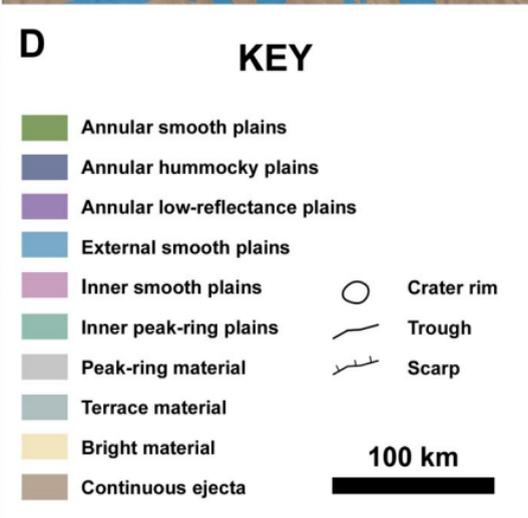
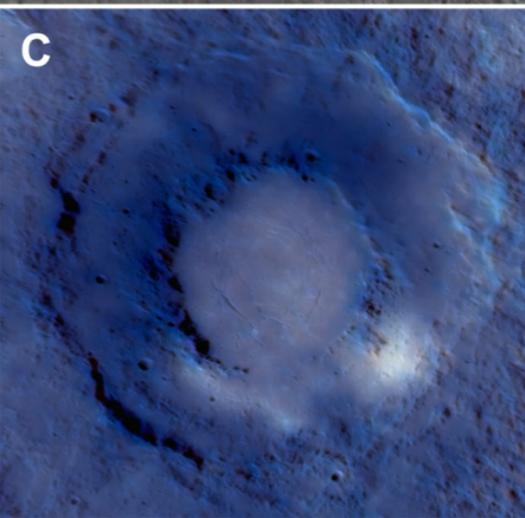
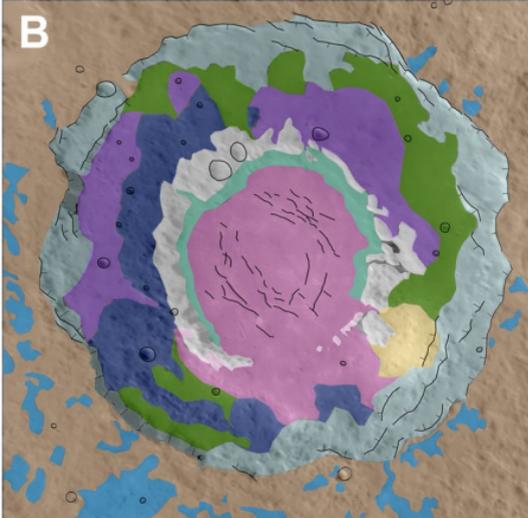
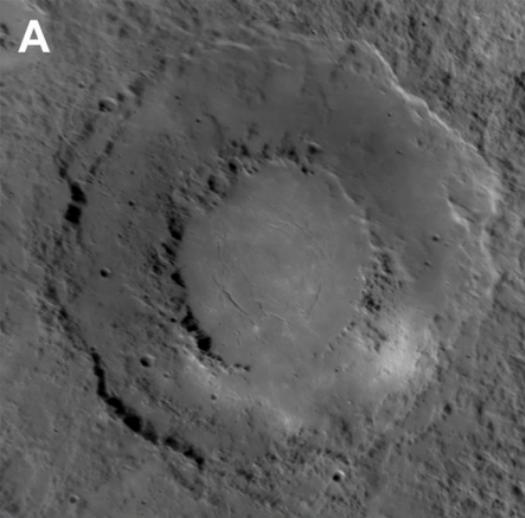
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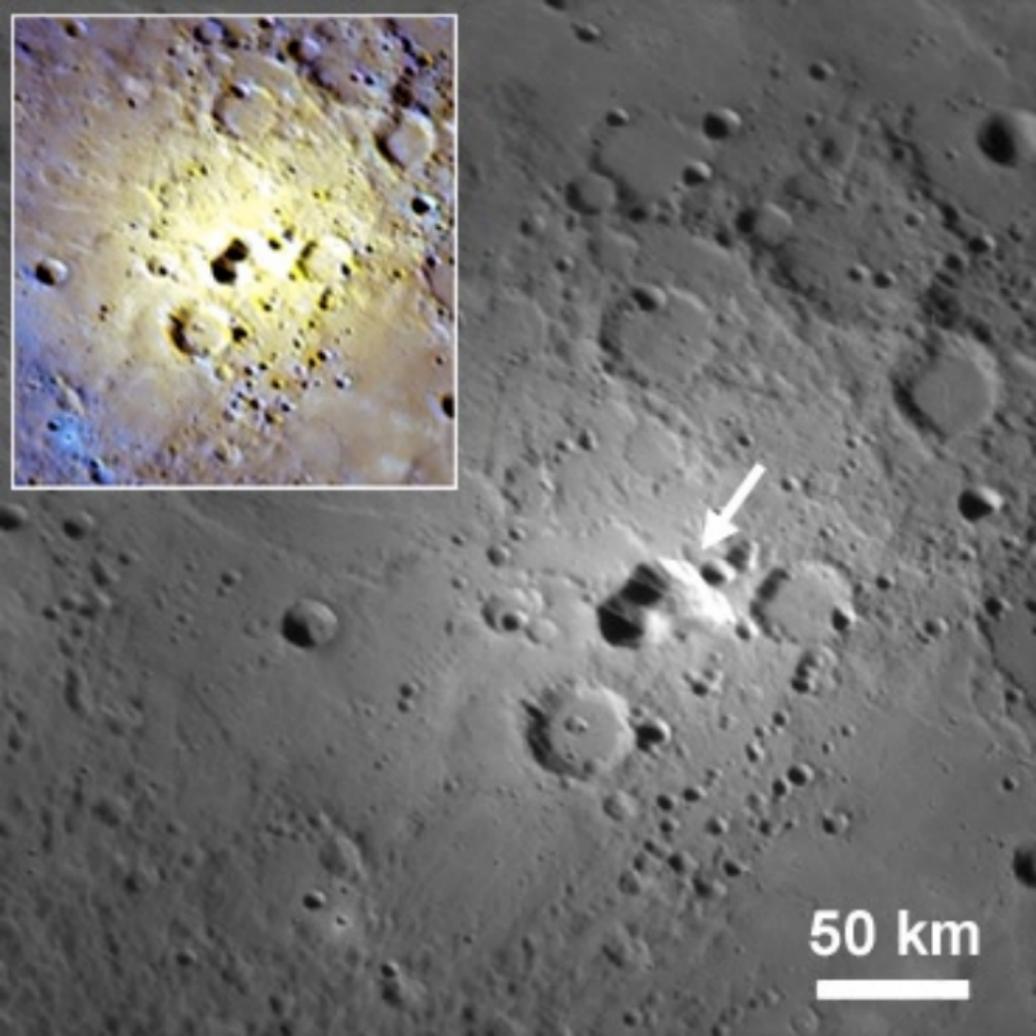
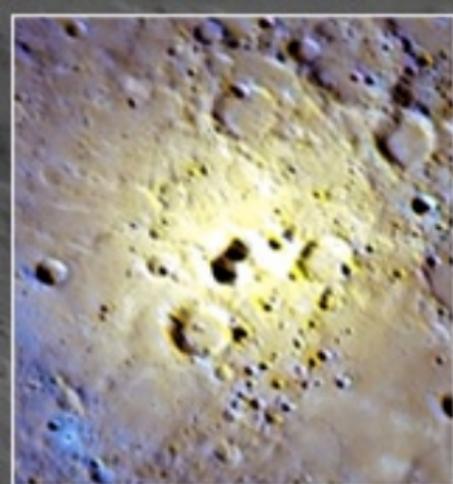
Fig. 1. Rachmaninoff peak-ring basin. (A) MDIS narrow-angle camera (NAC) mosaic (images 0162744128 and 0162744150); orthographic projection centered at 27.6°N, 57.6°E. (B) Geological sketch map of Rachmaninoff overlaid on (A), showing the variety of plains units in and around the basin. North is up. (C) Enhanced-color view (second and first principal component and 430-nm/1000-nm ratio in red, green, and blue, respectively) of the Rachmaninoff basin imaged with the MDIS wide-angle camera (WAC) during MESSENGER's third flyby of Mercury (WAC images 162741039 – 162741083). Lower-resolution WAC observations (5 km/pixel) were merged with the higher-resolution NAC mosaic (~440 m/pixel) to display color variations with geologic terrain. (D) Map legend.

Fig. 2. MDIS narrow-angle camera image of a diffuse, high-reflectance halo over 200 km in extent surrounding a ~30-km-diameter, irregularly shaped, rimless, steep-walled depression (arrow) (image 162744128). Inset: Enhanced-color view (as in Fig. 1C) showing the bright halo overlying a high-reflectance smooth plains unit that embays Rachmaninoff to the north and east. Equirectangular projection centered at 27°N, 57°E (WAC images 162741039 – 162741083); north is up.

Fig. 3. Size-frequency distributions of impact craters superimposed on the Rachmaninoff and Raditladi peak-ring basins and on the plains inside Rachmaninoff (see Supporting Online Material, or SOM). Error bars are proportional to $\sqrt{N/N}$, where N is the number of craters per given area within

an increment in diameter D . **(A)** “R plot” of the spatial density of craters within the inner peak ring of Rachmaninoff (solid symbols, excluding probable endogenic crater-form depressions associated with the graben) compared with that for the annular plains between the peak ring and the main basin rim of Rachmaninoff (open symbols) (25). Shown for comparison is a curve approximately fitting the size distribution for craters on the younger smooth plains within the Raditladi basin (dash-dot curve) [Fig. 3 of (6)]. The data for Raditladi are described in more detail in the SOM. **(B)** R plot of the spatial density of craters on the Rachmaninoff basin and its immediate ejecta (triangles), excluding the inner plains unit; these data are interpreted to represent the stratigraphic age of the Rachmaninoff impact. Similar measurements on the Raditladi basin and its immediate ejecta (open squares) reveal that Rachmaninoff is resolvably older than Raditladi. The dotted line shows the approximate size-frequency distribution for the rim of the Caloris basin (26).





50 km



