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The Formation of Mercury's Smooth Plains[1]

WALTER S. KIEFER AND BRUCE C. MURRAY

Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125

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There has been extensive debate about whether Mercury's smooth plains are volcanic features or impact ejecta deposits. We present new indirect evidence which supports a volcanic origin for two different smooth plains units. In Borealis Planitia, stratigraphic relations indicate at least two distinct stages of smooth plains formation. At least one of these stages must have had a volcanic origin. In the Hilly and Lineated Terrain, Petrarch and several other anomalously shallow craters apparently have been volcanically filled. Areally extensive smooth plains volcanism evidently occurred at these two widely separated areas on Mercury. These results, combined with work by other researchers on the circum-Caloris plains and the Tolstoj basin, show that smooth plains volcanism was a global process on Mercury. Present data suggest to us that the smooth and intercrater plains may represent two distinct episodes of volcanic activity on Mercury and that smooth plains volcanism may have been triggered by the Caloris impact. High-resolution and multispectral imaging from a future Mercury spacecraft could resolve many of the present uncertainties in our understanding of plains formation on Mercury.

INTRODUCTION

The origin of Mercury's plains is crucial to understanding both the geologic history (Murray *et al.* 1975, Strom *et al.* 1975) and thermal history (Solomon 1976, 1977) of the planet. At Mariner 10 resolution, two basic types of Mercurian plains, intercrater plains and smooth plains, can be distinguished. Intercrater plains cover about 40% of the imaged part of Mercury and are more heavily cratered than the smooth plains. Smooth plains cover about 15–20% of the imaged area of Mercury (Trask and Guest 1975). The formation of the intercrater plains was discussed by Trask and Guest (1975), Malin (1976), Strom (1977), and Leake (1981). Only the smooth plains will be considered here.

Because of lighting and resolution conditions, diagnostic volcanic landforms, such as domes and flow fronts, are difficult to identify on Mariner 10 images of smooth plains (Schultz 1977, Malin 1978). Only a few such features have been postulated so far. These include several craters located on or near smooth plains which may have been endogenetically altered (Schultz 1977), several irregular, rimless pits which may be volcanic collapse structures (Strom *et al.* 1975, Schultz 1977), and a possible pyroclastic deposit (Schultz 1977). The absence of recognizable volcanic landforms does not disprove a volcanic origin, however, because under Mariner 10 lighting and resolution conditions it is also difficult to identify known volcanic landforms on the Moon (Malin 1978). In the absence of definitive evidence for volcanism, two alternative hypotheses developed concerning the origin of the smooth plains. One group (Murray *et al.* 1975, Strom *et al.* 1975, Trask and Strom 1976) argued that the

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smooth plains are volcanic features analogous to the lunar maria; the second group (Wilhelms 1976, Oberbeck *et al.* 1977) contended that the smooth plains are ejecta deposits, analogous to the lunar Cayley plains.

Because direct evidence for volcanism on Mercury is lacking, advocates of volcanism attempted to show that Mercury's smooth plains could not be produced as ejecta deposits, and thus must be volcanic in the absence of a viable alternative. For example, Strom *et al.* (1975) noted the presence of partially filled ghost craters on the floors of several basins which contain smooth plains. Such craters must have formed after the basin but prior to plains formation. This proves that these plains are not ejecta deposits from the basin-forming impact. However, it leaves open the possibility that the plains are ejecta deposits from younger, distant basins.

As the largest and youngest known basin on Mercury, Caloris is an obvious potential source basin for ejecta deposits. Strom *et al.* (1975) suggested several reasons why Caloris ejecta cannot explain the observed smooth plains. Strom *et al.* were unable to detect the presence of ancient basins in the region surrounding Caloris. They assumed that other basins must have formed in this region and are now buried. From this, they estimated an average thickness of 10 km and a total volume of 5×10^7 km^3 for the circum-Caloris smooth plains. They argued that this volume of plains material is too large to be derived solely as Caloris ejecta. However, more detailed geologic mapping of this region has revealed evidence for numerous basin rings (Spudis and Strobell 1984, Spudis and Guest 1987). This discovery removes the rationale for the Strom *et al.* thickness estimate and hence invalidates their volume estimate. A study of partially filled craters on the smooth plains indicates an average plains thickness of less than 1 km, comparable to the thickness of the lunar mare (DeHon 1979). DeHon's thickness estimate assumes that all partially filled craters formed on the preplains surface, so the amount of crater filling is a direct measure of the plains thickness. If some of the ghost craters studied by DeHon actually formed on a preexisting smooth plains surface, then the average plains thickness is somewhat larger than DeHon estimated. Nevertheless, there is currently no evidence to support the Strom *et al.* estimate of the average smooth plains thickness. Arguments based on the total volume of circum-Caloris smooth plains should therefore be viewed with skepticism.

Strom *et al.* also considered the spatial distribution of smooth plains units. They argued that the presence of smooth plains more than 3 basin radii from the Caloris rim is inconsistent with an origin as Caloris ejecta. This argument has merit, because Mercury's relatively high surface gravity restricts ballistic transport of ejecta to shorter ranges than is possible on the Moon (Gault *et al.* 1975). It is more difficult to quantitatively estimate how far ejecta may be transported in the form of debris flows, but it appears unlikely that such flows could extend to several basin radii from their source.

A more useful constraint on the possible contribution of Caloris ejecta to smooth plains formation comes from cratering statistics which indicate the temporal relationship between the Caloris impact and the smooth plains. Spudis and Guest (1987) compiled data for craters with diameters larger than 20 km for a variety of regions on Mercury. They reported cumulative crater densities ($D \geq 20$ km) of $5.8 \pm 1.3 \times 10^{-5}$ km^{-2} for the Caloris ejecta deposits, $3.9 \pm 1.2 \times 10^{-5}$ km^{-2} for the smooth plains on the Caloris floor, and 2.8 ± 0.7 and $2.4 \pm 0.7 \times 10^{-5}$ km^{-2} for two different regions of circum-Caloris smooth plains. These reported crater densities indicate that the circum-Caloris smooth plains are significantly younger than the Caloris basin and thus cannot be Caloris ejecta units. An independent set of crater counts for craters larger than 10 km done by Watkins (1980) also indicates that the circum-Caloris plains are younger than the Caloris ejecta units. Watkins also noted that the slope of the diameter versus cumulative crater frequency curve for the Caloris ejecta units (the Van Eyck, Odin, and Caloris Montes formations of McCauley *et al.* 1981) decreased markedly for craters smaller than 25 km in diameter. A similar change in the slope of the size–frequency distribution was not observed for the smooth plains. Watkins interpreted the relative dearth of small craters within the Caloris ejecta units as the result of an episode of small crater obliteration which occurred after the formation of the ejecta units. This may indicate a late-stage period of volcanism within the Caloris ejecta units.

The absence of identifiable volcanic features on the smooth plains led Wilhelms (1976) and Oberbeck *et al.* (1977) to compare Mercury's smooth plains with the lunar light plains. Based on their morphology, the lunar light plains were once believed to be a mixture of volcanic flows and pyroclastic deposits (Wilhelms 1970). Apollo 15 samples have shown that one such light plains unit, the Appenine Bench Formation, is composed of KREEP basalt (Hawke and Head 1978, Spudis 1978). On the other hand, Apollo 16 samples of another light plains unit, the Cayley plains, consist only of impact breccias and thus indicate that the present Cayley plains surface is not volcanic in origin (see Wilhelms 1984, pp. 156–159 for a review). However, remote sensing studies of dark halo craters on the Cayley plains indicate that mare basalt may occur in the shallow subsurface, perhaps within a few hundred meters of the current surface (Schultz and Spudis 1979, Bell and Hawke 1984). Thus, at least part of the Cayley plains' morphology, particularly their topographic smoothness, may be due to the underlying mare units. These lunar examples make it clear that simple morphologic comparisons between the Mercurian smooth plains and proposed lunar analogs cannot conclusively prove either a volcanic or an ejecta origin for the smooth plains.

Other arguments for an ejecta origin of the smooth plains are also inconclusive. Trask and Guest (1975) mapped the smooth plains as occurring primarily in a swath around the Caloris basin. Oberbeck *et al.* (1977) used this Caloris-centered distribution of plains as their primary argument for an ejecta origin of the plains. More recent geologic mapping, however, suggests that smooth plains are more widespread on Mercury than initially thought (Spudis and Guest 1987). Also, radar observations of the hemisphere of Mercury not imaged by Mariner 10 suggest the presence of additional smooth plains units far from Caloris (Harmon *et al.* 1986). This growing recognition of a more global distribution of smooth plains on Mercury diminishes the Oberbeck *et al.* (1977) main argument for an ejecta origin of the circum-Caloris smooth plains.

In a few areas of Mercury, such as the Tolstoj basin, it is possible to distinguish plains and cratered units on the basis of albedo and color data. Generally, however, there is very little albedo contrast between plains and cratered units on Mercury, a situation which is very different from the lunar maria and highlands (Hapke *et al.* 1975, Dzurisin 1977). The absence of albedo contrasts can be interpreted as evidence for compositional similarity between the plains and cratered terrain. This in turn would be consistent with an ejecta origin for the plains, but other interpretations also exist. On the Moon, albedo contrasts are due primarily to variations in Fe and Ti content and Fe oxidation state (Hapke *et al.* 1975). Mercury is believed to have an Fe rich core approximately 1800 km in radius (Basaltic Volcanism Study Project, 1981, pp. 678–682). Such a large core requires very efficient segregation of Fe from the planetesimals which accreted to form Mercury. Thus, the Mercurian mantle may be Fe poor relative to the Moon, reducing the range of possible surface albedo variations on Mercury. Similarly, different formation conditions could lead Mercury to be Ti deficient relative to the Moon, further reducing the possible range of albedo variations on Mercury. The observed lack of albedo variations therefore does not necessarily imply either compositional homogeneity or an ejecta origin for the Mercurian plains. By making observations at high spectral and spatial resolution, a future Mercury orbiter may be able to detect subtle variations in crustal composition. Such observations will provide important clues to Mercury's early evolution.

In our opinion, the evidence summarized above favors a volcanic origin for at least some of Mercury's smooth plains. Nevertheless, the lack of direct evidence for volcanism remains a source of lingering uncertainty concerning the nature of Mercury's smooth plains. A decade ago, the debate over the nature of Mercury's plains focused solely on two end-member processes, volcanism and ballistic emplacement of impact ejecta. A third possibility, intermediate between the first two, is that large impacts may have triggered volcanic activity. Impact-triggered volcanism has been suggested in the case of the Earth (Grieve 1980), but has not been previously considered on Mercury.

Thus, a reexamination of the issue of smooth plains formation is needed. We begin by examining stratigraphic, morphologic, and photometric relationships in two regions, Borealis Planitia and the Hilly and Lineated Terrain. In both regions, we show

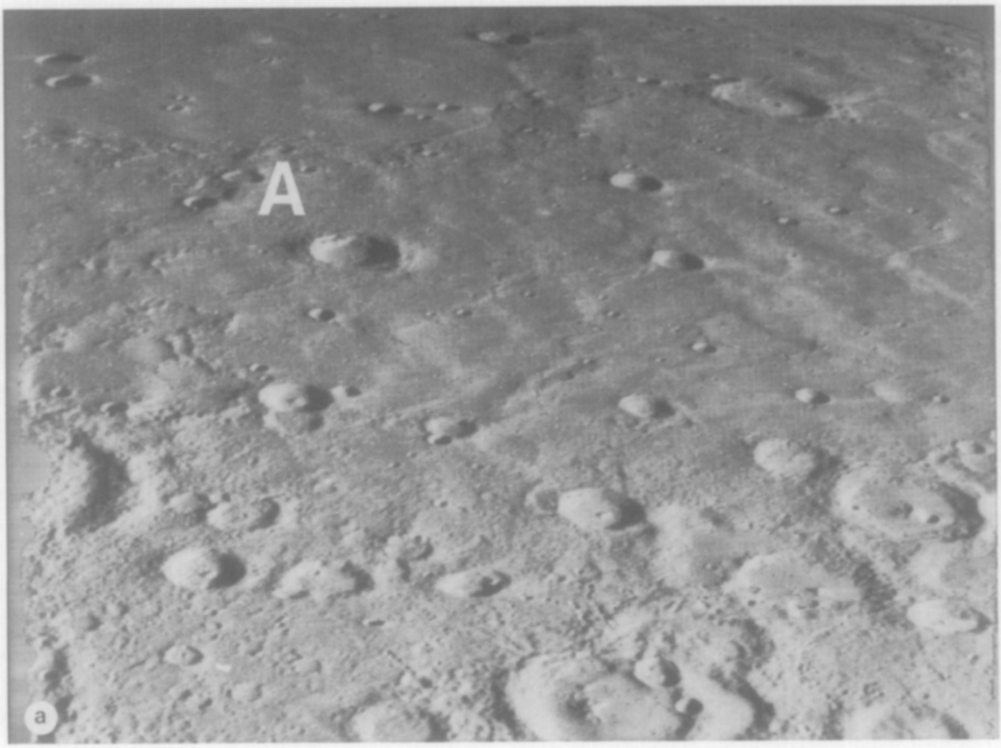

FIG. 1. (a) Smooth plains in Borealis Planitia. The 340-km-diameter basin Goethe is visible at the upper left and is also covered with smooth plains. Numerous low, sinuous ridges occur on the Borealis plains but do not extend onto the Goethe plains or onto the cratered terrain at the bottom of the image. A crater whose rim may have been tectonically disrupted by the underlying ridge occurs to the left of the letter A. Mariner 10 FDS 160. (b) A rectified mosaic of the Borealis Planitia region. The tectonic disruption of the crater rim shown in (a) is clearly seen in this image. Adapted from Davies *et al.* 1978.

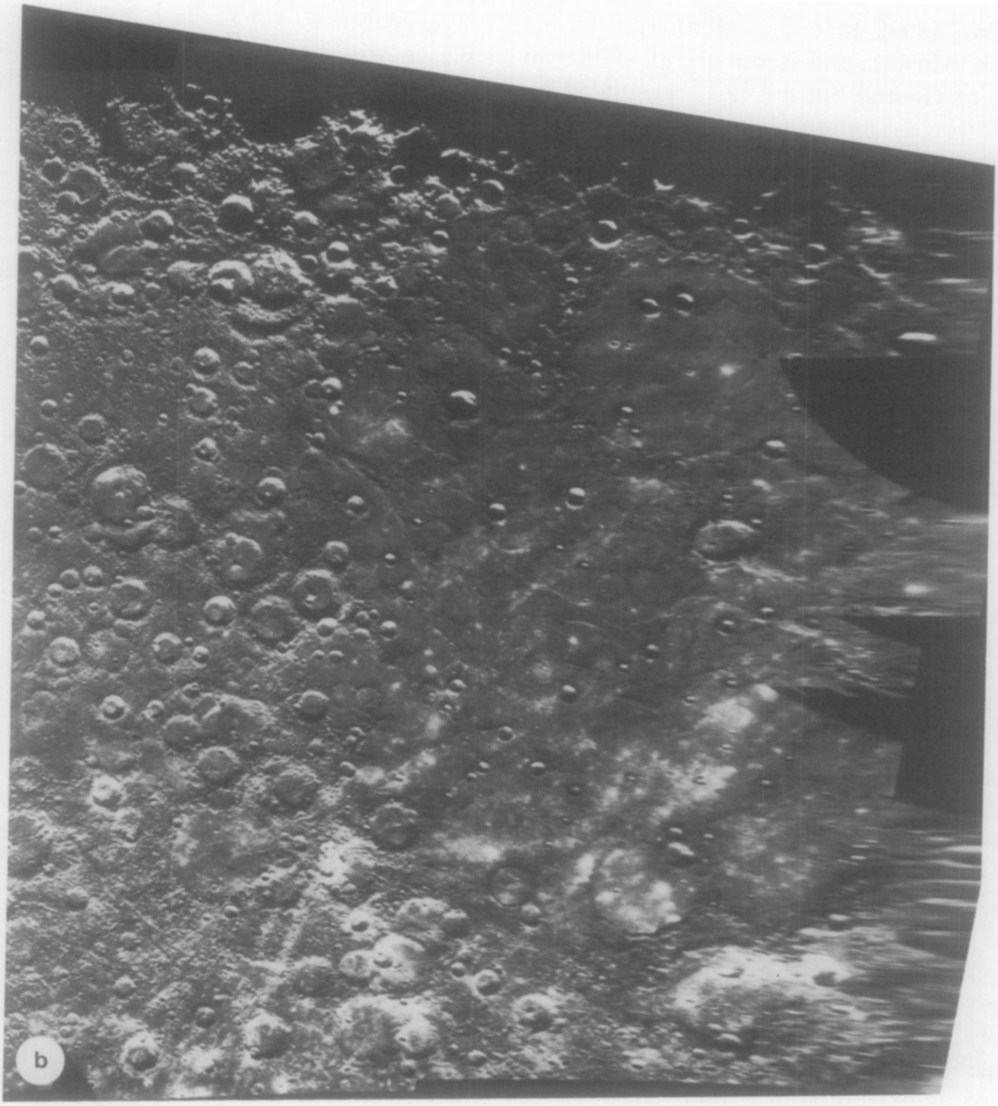

FIG. 1—*Continued.*

that the observations are best understood by a volcanic origin for the plains units. Our observations, combined with the work summarized above, suggests that smooth plains volcanism was widespread on Mercury as a whole. Next, we consider whether Mercury's smooth and intercrater plains represent a continuous sequence of plains formation or two discrete events. We conclude by considering how the Caloris impact may have affected subsequent volcanic activity on Mercury.

BOREALIS PLANITIA

Borealis Planitia (Fig. 1) is a smooth plains unit which occupies a quasi-circular region, presumably an ancient, degraded impact basin, approximately 1000 km in diameter. These plains surround asymmetrically the 340-km-diameter Goethe basin, which also is filled with smooth plains. The Borealis plains cover the ejecta deposit from Goethe, indicating that they formed after the Goethe impact. Trask and Strom

(1976) noted that the Mercurian basins Bach, Mozart, and Rodin are all similar in size to Goethe but are not surrounded by widespread smooth plains. They therefore argued that the Borealis plains are unlikely to represent Goethe ejecta. Partially filled ghost craters on the floor of Goethe indicate that the Goethe smooth plains did not form simultaneously with the basin impact and therefore cannot be impact deposits from the basin-forming event (Strom 1984, Fig. 3.27).

Borealis Planitia is covered by a number of low, somewhat sinuous ridges. These ridges may be either flow fronts or tectonic features. We prefer a tectonic origin for several reasons. Known flow fronts on the lunar maria are typically monoclinal scarps separating two relatively level surfaces of different elevations (Schultz 1976, Plates 192 and 193). The features in Fig. 1 have a different morphology, resembling lunar wrinkle ridges rather than monoclinal scarps. In addition, a crater on the large ridge (Fig. 1a, A) appears to have its rim disrupted by the ridge. This is most obvious in the rectified mosaic (Fig. 1b). Both of these observations favor a tectonic origin for the ridges, but limitations of image resolution and oblique viewing geometry prevent a firm conclusion.

In no case can the ridges be mapped as extending from Borealis Planitia onto the surrounding cratered terrain. This indicates that the ridges are not part of Mercury's global network of thrust scarps, for in that case one would expect to find at least a few ridges crossing the boundary between the plains and the cratered terrain. Since this is not observed, we conclude that the ridges are a basin-scale phenomenon rather than part of a global-scale phenomenon. If the evidence cited above for a tectonic origin of the ridges is correct, then the ridges may be the result of basin subsidence after the plains were emplaced. Many lunar mare ridges are believed to be tectonic features formed by basin subsidence (Solomon and Head 1980).

The presence of the ridges makes it possible to distinguish at least two distinct stages of smooth plains emplacement in this region. Because the ridges are widely distributed across Borealis Planitia, the stress field which produced the deformation must also have been a basin-wide feature. The existence of the ridge extending to Goethe's rim (Fig. 1a, A) indicates that the stress field extended at least to the rim of Goethe. Because the ridge is well developed at Goethe's rim, the associated stress field must have extended onto Goethe's floor. In this case, similar tectonic deformation should have formed on the Goethe plains. This is not observed, indicating that the deformation of the Goethe plains has been obscured by a subsequent stage of plains formation. Because the ridges postdate the plains in Borealis Planitia and predate the plains in Goethe, at least two stages of plains formation must have occurred in this region.

Wilhelms (1976) suggested that the smooth plains shown in Fig. 1 are ejecta deposits from a hypothetical source basin lying over the terminator. Wilhelms' conjecture cannot plausibly account for the different ages and morphologies observed for the two smooth plains units in this region. We therefore conclude that at least one of these plains units must have a volcanic origin.

HILLY AND LINEATED TERRAIN

The Hilly and Lineated Terrain (Fig. 2) is probably the most unusual landform on Mercury. Hills in this region are typically 5 to 10 km wide and 0.1 to 1.8 km high (Trask and Guest 1975). Lineations are typically 40 to 150 km long, 5 to 15 km wide, and 100 to 500 m deep and have preferred orientations near N40–60°E and N40–60°W (Dzurisin 1978). Many of the crater rims in this region have been dissected into alternating sequences of hills and depressions (Fig. 3). Extensive patches of smooth plains occur on the floors of several craters, but are scarce outside of craters.

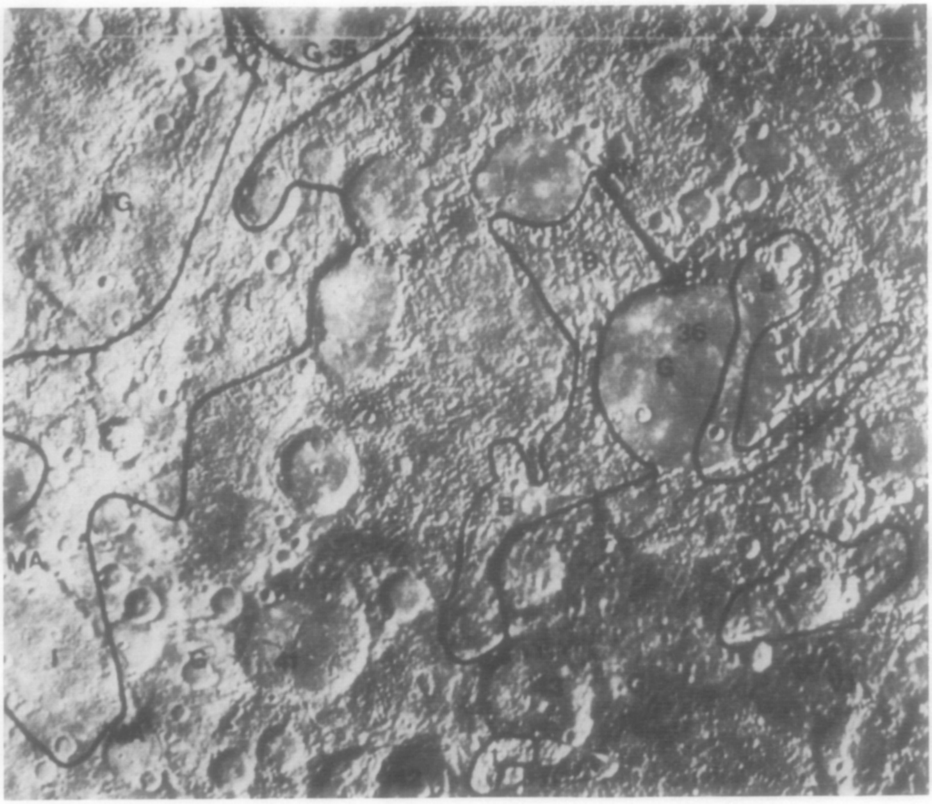

FIG. 2. An overview of the Hilly and Lineated Terrain. Petrarch, a 160-km-diameter crater, is labeled 36. The lines represent contours of Mariner 10 color-ratio data, with the letters I, B, and G representing a sequence of units which are progressively redder in color. Color-ratio data courtesy of Bruce Hapke, University of Pittsburgh.

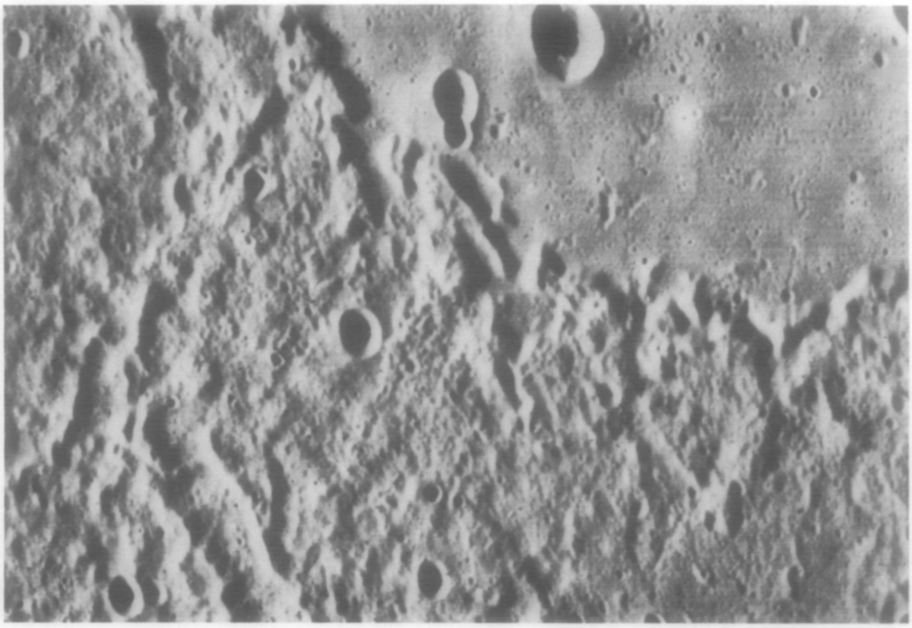

FIG. 3. A close-up of the southwest part of Petrarch's rim. The dissected nature of the rim is evidence of mass wasting. The extreme shallowness of the crater suggests that it has been partially filled by volcanic activity. FDS 27469.

A variety of theories, including volcanism, ballistic emplacement, and mass wasting, have been advanced to explain the peculiar landform degradation observed in this region. Murray *et al.* (1974) noted the variety of crater degradation states in this region and inferred that the Hilly and Lineated Terrain formed over an extended time interval. They argued that the extended formation interval and limited geographical extent of this terrain are best understood in terms of a volcanic origin for this unit.

Wilhelms (1976) suggested that the lineated features in this region are the result of secondary cratering from a hypothetical basin just beyond the terminator. There are several objections to this theory. First, if the Hilly and Lineated Terrain was formed by basin ejecta, similar units should be observed around other Mercurian basins, but no similar features are known on Mercury. Second, if the lineations are due to basin secondaries, they should be approximately radial to the source basin. The lineations actually form a consistent rectilinear pattern across the entire Hilly and Lineated Terrain. Finally, if the lineations are secondary crater chains, then ejecta from two separate basins is necessary to produce the two observed lineament orientations. In this case, one set of lineaments should be superimposed on the other, but this is not observed. Furthermore, the smooth plains which occur on the floor of Petrarch and other nearby craters (Figs. 3 and 4) are not ejecta deposits. If they were, then similar quantities of smooth plains deposits should also occur outside of craters in this region. An example of such a plains unit outside a crater occurs at the bottom of Fig. 4, but such deposits are rare in the Hilly and Lineated Terrain as a whole.

Schultz and Gault (1975) suggested that

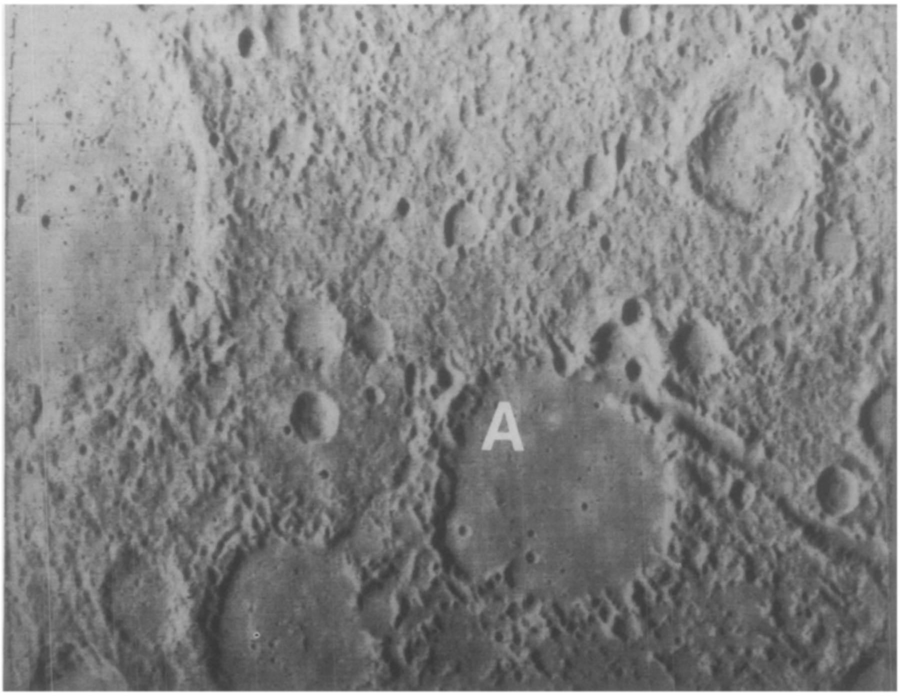

FIG. 4. A close-up of the region to the northwest of Petrarch. The large crater labeled A is 94 km in diameter and probably has been volcanically filled. To the south of this crater, there is a region of plains which do not lie within craters. Such deposits are rare in the Hilly and Lineated Terrain as a whole. FDS 27424.

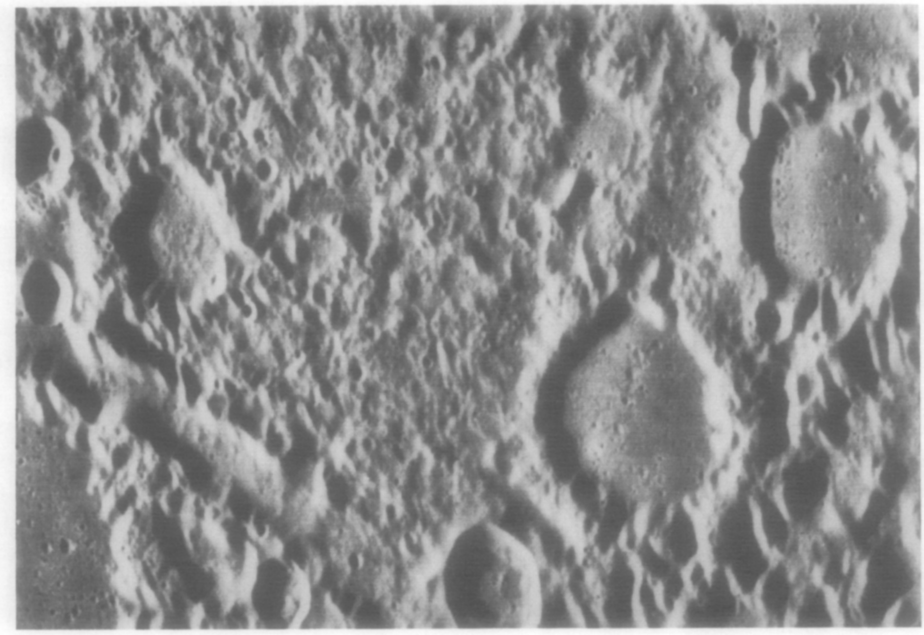

FIG. 5. The scalloped walls of the Arecibo Vallis (the linear trough at the lower left) and some of the crater rims indicate modification by mass wasting. FDS 27470.

the Hilly and Lineated Terrain may be a product of seismicity induced by the Caloris impact. The Hilly and Lineated Terrain is approximately antipodal to the Caloris basin, so Schultz and Gault suggested that the convergence of seismic waves near the antipode caused large-scale slope failure and mass wasting in the Hilly and Lineated Terrain. They pointed out that the variety of crater degradation states did not necessarily imply an extended formation interval for this terrain unit, as Murray *et al.* (1974) had suggested. Instead, it could represent the catastrophic alteration of craters with different degrees of precatastrophic degradation. The preferred orientation of the lineations in this region can be readily understood in the Schultz and Gault model as due to preferential failure along preexisting zones of structural weakness. Such preexisting zones of weakness could result, for example, from an earlier episode of tidal despinning (Melosh and Dzurisin 1978).

Several lines of evidence help support the Schultz and Gault (1975) model. First, the scalloped appearance of many crater rims and the walls of Arecibo Vallis provides direct visual evidence for extensive mass wasting in this region (Fig. 5). Second, similar terrain deformation also exists on the Moon antipodal to the Imbrium and Orientale basins (Schultz and Gault 1975). Finally, numerical simulations of basin-impact-induced seismicity indicate that a Caloris size impact could produce large amplitude oscillations of the free surface near the antipode and could induce tensional failure at shallow depths. Such conditions are ideal for causing extensive mass wasting (Hughes *et al.* 1977).

We accept the importance of the Schultz and Gault (1975) mass wasting mechanism for creating many of the landforms in this region, but we wish to suggest that volcanism also played a role. Specifically, we suggest that the smooth plains material on the floor of Petrarch and several nearby craters is volcanic and that this volcanic episode occurred after the Caloris-induced mass wasting episode. This suggestion differs from that advanced by Murray *et al.* (1974) in at least two ways. In the Murray *et al.* model, volcanism was considered to be widespread throughout the Hilly and Lineated Terrain and to have occurred over an extended time interval. In our model, by contrast, volcanism is restricted to a few specific sites and occurs only after most of the Hilly and Lineated Terrain formed.

Any theory for the origin of the smooth plains in the Hilly and Lineated Terrain must be able to explain the observed plains distribution, the observed plains volume, and the color of the plains relative to their surroundings. Earlier, we noted that ballistic emplacement of ejecta cannot explain the observed concentration of smooth plains on the floors of craters within this region. Other possible plains-forming mechanisms, such as impact melt and mass wasting from crater walls, could conceivably limit plains production to the interiors of craters. Because the deep fracture systems associated with large craters form ideal magma conduits, volcanic activity can also be concentrated in the interiors of craters. Clearly, mass wasting has contributed to the plains formation process in this region. The issue is whether other processes contributed as well.

The strongest constraint on the origin of these plains comes from estimates of their volume. By comparing the observed crater depth, as determined from shadow measurements, with the expected crater depth from the Gault *et al.* (1975) depth–diameter relationship, it is possible to estimate the thickness of the plains material on the crater floors. From the measured lengths of shadows cast by Petrarch's rim (Fig. 3), we estimate a depth of 1.3 km, with an estimated uncertainty of ±200 m. A morphologically fresh crater of Petrarch's diameter (160 km) has an expected depth of 3.6 km (Gault *et al.* 1975). Thus, the smooth plains unit on Petrarch's floor may be approximately 2.3 km thick. This shows that the plains are not impact melt, for in that case the crater should have an approximately normal depth–diameter ratio.

The Gault *et al.* (1975) depth–diameter relationship formally applies only to morphologically fresh craters. Since Petrarch's rim has been degraded, Petrarch should be somewhat shallower than predicted by the Gault *et al.* formula. In several places in Fig. 3, smooth plains material appears to flow between gaps in Petrarch's rim and onto the surrounding terrain. This relationship indicates that the interior and exterior of the crater are at essentially the same topographic level. Thus, shadow measurements of crater depth also give a rough estimate of 1.3 km for Petrarch's external rim height. Direct measurements of Petrarch's rim height on other images (not shown) also give values of about 1.3 km, but with large uncertainties due to low image resolution. Cintala (1979) gave a rim height versus diameter relationship for fresh Mercurian craters less than 40 km in diameter. Extrapolating this relationship to larger crater diameters should provide an upper bound on the expected rim height of large craters. For Petrarch, this gives an expected original rim height of 1.6 km. From the current rim height of 1.3 km and the estimated initial rim height of 1.6 km, we estimate that a maximum of about 300 m of vertical rim erosion has occurred. When the effect of rim degradation is corrected for, our original estimate for plains thickness of 2.3 km now becomes 2.0 km, for a total volume of 40,000 km^3 for the plains inside Petrarch. Our estimate of plains thickness is uncertain both because of uncertainties in the measured crater depth and because the initial crater depth may not have followed the Gault *et al.* relationship exactly. Nevertheless, the estimated plains volume is probably correct to within ±20%.

If our estimate of 300 m of vertical erosion is representative of the Hilly and Lineated Terrain as a whole, it is clear that mass wasting can account for most of the landforms observed in this region. The widespread volcanism suggested by Murray *et al.* (1974) is not necessary to explain the observed features. The situation at Petrarch is different. The volume of smooth plains on Petrarch's floor is too large to be due solely to mass wasting from the crater walls. At most, mass wasting probably contributed only a few thousand cubic kilometers of material to Petrarch's smooth plains. Most of the plains, probably more than 90% of their volume, must have a volcanic origin.

Another crater which has apparently been flooded by volcanic material is the 94-km-diameter crater which is just northwest of Petrarch (Fig. 4). It should be 3.2 km deep if unmodified, but is only about 1.7 km deep. The uncertainty on this depth is larger than on the other measurements, about ±400 m, because the image resolution is lower than on Fig. 3. Qualitatively, the rim degradation is comparable to that observed at Petrarch. The measured external rim height is also similar, about 1.3 km. Thus, as at Petrarch, mass wasting probably played only a minor role in producing the observed smooth plains on the crater floor. Most of these crater-filling plains are probably volcanic units. Similar depth measurements of some smaller craters in this region suggest that they may also have been partially filled by volcanic material, but the evidence is less strong than it is for the larger craters.

Additional support for the volcanism theory comes from color data. If the plains are mass wasted material, then they should be the same composition, and hence the same color, as the current rim material. On the other hand, color differences between rim and floor materials indicate compositional differences between the two regions. Such differences are consistent with a volcanic origin of the plains. Color variations in this region, determined by ratioing Mariner 10 orange and UV filter images, are shown in Fig. 2 (Hapke *et al.* 1980). About 70% of Petrarch's rim is significantly bluer than the floor. An arm of blue material does stretch across Petrarch's floor, but it coincides with a high albedo crater ray and thus does not represent the true color of the floor material. The color data indicate that Petrarch's rim and floor differ in composition, consistent with the volcanic origin inferred earlier. Similarly, the 94-km-diameter crater northwest of Petrarch has a significant portion of its rim which is bluer than the floor material, although it also has an extensive section of the rim which is similar in color to the floor.

DISCUSSION

We have examined the stratigraphic, morphologic, and photometric relationships for two regions of smooth plains on Mercury. In both cases, our observations are best explained by a volcanic origin for the plains. In this study, we have not directly examined any of the circum-Caloris smooth plains. As summarized under Introduction, available crater counts indicate that Budh, Sobkou, Suisei, and Tir Planitia are all younger than the Caloris impact (Watkins 1980, Spudis and Guest 1987). These plains cannot be Caloris ejecta units and thus are probably volcanic features.

Another region of possible smooth plains volcanism is the Tolstoj basin (Fig. 6). Trask and Strom (1976) and Schultz (1977) summarized a variety of arguments in favor of volcanic origin of this plains unit, including partially filled ghost craters, color and albedo anomalies, a possible volcanic collapse feature, and a possible pyroclastic deposit. These results for the circum-Caloris region and the Tolstoj basin, combined with our analysis of smooth plains elsewhere on Mercury, indicates that most Mercurian smooth plains probably have a volcanic origin.

Certainly, not all plains on Mercury are volcanic. We noted earlier, for example, that some of the smooth plains material in the Hilly and Lineated Terrain probably has a mass wasting origin. In the circum-Caloris region, the unit known as the hummocky plains (Trask and Guest 1975) or Odin Formation (McCauley *et al.* 1981) is

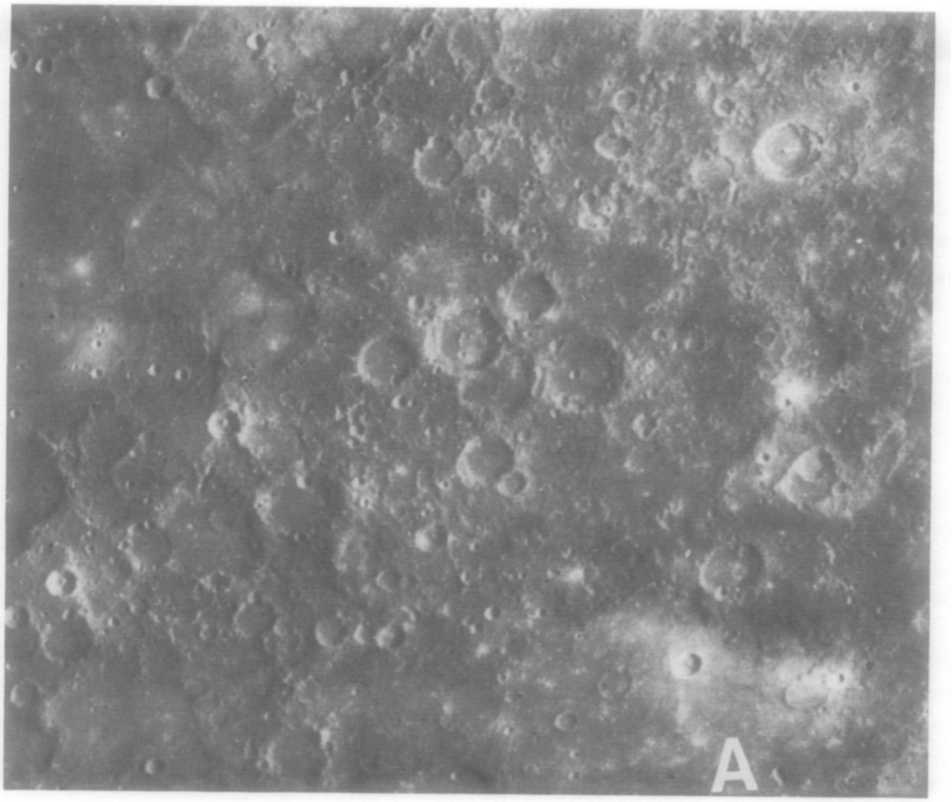

FIG. 6. A portion of the Tolstoj basin occurs in the lower right. The feature labeled A is an irregular, rimless pit, which Schultz (1977) suggested may be a volcanic collapse structure. FDS 244.

clearly Caloris ejecta, analogous to ejecta facies observed around impact basins on the Moon. Even within the Caloris ejecta units, however, some volcanic activity may have occurred. McCauley *et al.* (1981) suggested that the Odin Formation was partially buried by smooth plains at some time after the Caloris ejecta was emplaced. This late-stage flooding of the ejecta by smooth plains probably represents a volcanic episode. The inferred volcanic event would explain the episode of small crater obliteration which Watkins (1980) inferred from his crater counts of the Caloris ejecta units.

An important additional issue in understanding Mercury's volcanic and thermal evolution is the genetic relationship between the smooth and intercrater plains. Specifically, do the two types of plains represent discrete episodes of volcanic activity or do they form a gradational sequence? Thomas *et al.* (1982) estimated the areal coverage of plains as a function of age. They found that the rate of formation of intercrater plains was a sharply decreasing function of time. They suggested that Mercury's smooth plains represent a "strong and short reactivation" of volcanic activity following the Caloris impact (Thomas *et al.* 1982, Fig. 2). Data compiled by Leake (1981, Figs. 86–88) for a smaller fraction of Mercury are consistent with this idea. Thus, the idea that the smooth and intercrater plains represent separate stages of volcanic activity presently appears to be a viable hypothesis. It should be remembered, however, that over half of Mercury's surface was not imaged by Mariner 10 and new data from the unimaged hemisphere could force revisions of this idea.

If the smooth plains do represent a reactivation of volcanism on Mercury, then this reactivation was probably a direct consequence of the Caloris impact. One way in which a large impact might trigger volcanism is through the postimpact isostatic rebound of the basin floor. Grieve (1980) pointed out that material uplifted during this rebound can undergo pressure-release partial melting and suggested that this process might have been important on the early Earth. Although triggered by an impact, it is appropriate to call this activity volcanism because it involves both pressure-release melting and magma transport through the mantle and lithosphere. A similar process may have occurred following the Caloris impact, although the efficiency of pressure-release melting is less on Mercury than on Earth due to Mercury's lower gravity. If the Caloris impact did lead to pressure-release melting, then the resulting magma could have contributed to the formation of the smooth plains in Caloris Planitia. At present, no quantitative theory exists for determining how much magma would be produced by such a process. However, because the isostatic rebound is confined to the interior of the basin, whatever magmatic activity that does occur should also be concentrated on the Caloris floor. Thus, rebound of the Caloris basin cannot plausibly account for smooth plains far from Caloris. Many of these plains occur within other basins (Schaber *et al.* 1977, Frey and Lowry 1979). However, because these basins all predate Caloris and most or all of the smooth plains postdate Caloris, pressure-release melting due to isostatic rebound of these basins probably did not contribute significantly to the present smooth plains surface in these basins.

A second way in which the Caloris impact may have affected volcanic activity on Mercury is through the seismic effects of basin formation. Hughes *et al.* (1977) showed that the seismic effects of a Caloris size impact could cause tensile failure at shallow depths everywhere on Mercury. If global compression on Mercury had begun to shut down volcanic activity prior to the Caloris impact (Solomon 1978), then the results of Hughes *et al.* suggest that Caloris-induced seismicity may have temporarily rejuvenated deep fracture systems on Mercury. This could allow magma bodies at depth easier access to the surface and may have resulted in a temporary reactivation of volcanic activity. In their analysis, Hughes *et al.* (1977) neglected the effects of Mercury's core on seismic wave propagation. For an 1800-km-radius core overlain by a 600-km-thick silicate mantle (Basaltic Volcanism Study Project 1981, pp. 678–682), a seismic shadow zone occurs beyond about 80° from the source. Within this shadow zone, direct P and S waves are prevented from reaching the surface. However, significant seismic energy is still able to enter the shadow zone via surface waves and via body waves which are reflected by the free surface or the core (e.g., phases such as PP and PKP). It therefore appears unlikely that inclusion of a core would qualitatively alter the conclusions of Hughes *et al.* (1977). Thus, Caloris-induced seismicity may have caused a temporary global reactivation of volcanic activity on Mercury and provided the key event in the origin of the smooth plains.

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