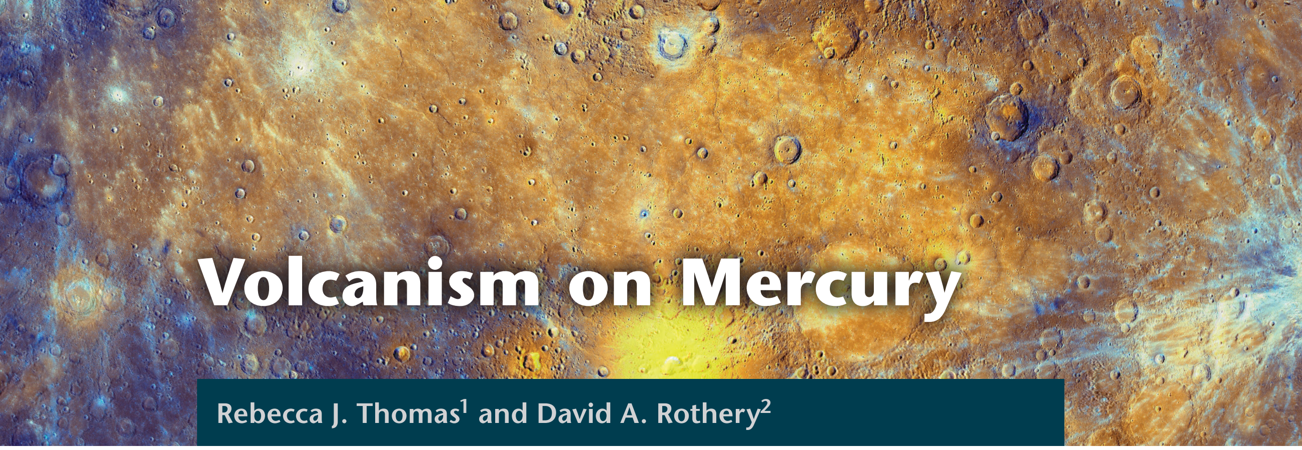

Volcanism on Mercury

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Mercury's volcanic nature has been revealed by NASA's *MESSENGER* mission. We now know that all, or most, of the surface has, at some point, been flooded by lavas, sometimes in extremely voluminous eruptions. The ages of Mercury's lava surfaces reveal that large-volume effusive volcanism ceased about 3.5 billion years ago due to planetary cooling. Mercury's crust then went into a state of global contraction, thereby impeding further magma ascent. However, some smaller-scale volcanism continued at zones of crustal weakness, particularly at impact craters. Much of this later volcanism has been violently explosive, with volatile gases potentially helping the magma rise and ripping it apart when released to the vacuum at the surface.

Keywords: lava plains, explosive volcanism, thermal evolution, Mercury

INTRODUCTION

Given its heavily impact-cratered surface, which makes it superficially similar to the ancient terrains of the Earth's Moon, it may come as a surprise that Mercury is now believed to have been almost totally resurfaced by volcanic activity. Evidence from the recent *MESSENGER* mission has supported the conclusion that all, or most, of Mercury's present surface materials were formed by voluminous volcanic outpourings, although modified by the effects of impact cratering.

The scientific journey that led to this new understanding was several decades in the making. Our first close-up images of Mercury, captured during flybys of NASA's *Mariner 10* spacecraft, provided only equivocal evidence for the origin of the planet's surface. It was quickly discovered that some regions are relatively smooth, forming plains both between impact craters in the more heavily cratered (and, thus, older) regions and in discrete relatively uncratered (younger) regions. However, it was unclear whether the resurfacing that formed these plains occurred through volcanism or nonvolcanic processes, such as impact events or the influence of mass wasting or even an early atmosphere (Strom et al. 1975).

In particular, the question of whether the younger plains are volcanic became a matter of extensive discussion. Arguing against a volcanic origin was the plains' similarity to the light-colored Cayley plains on the Moon. These lunar deposits had initially been thought to be volcanic but were later established to have formed by ponding of material fluidized during basin-forming impacts (Wilhelms 1976). It was argued that Mercury's smooth plains bore more similarities to these impact-produced plains than to the volcanic lunar maria (Latin for "seas") because of a less pronounced spectral contrast with the surrounding uplands, as well as a lack of associated volcanic constructs and the morphology of superposing tectonic structures. Offered in response, however, were the findings that the volume of Mercury's smooth plains is greater than would be expected to result from the formation of nearby basins. There is also some spectral contrast with surrounding material (if not as great as between the lunar maria and lunar highlands), and the areal density of impact cratering on the plains is generally lower than that on nearby basin rims and ejecta, indicating a younger age (Strom et al. 1975). All of this argued in favor of a volcanic genesis for the smooth plains, but the issue remained unresolved until the *MESSENGER* mission.

The images obtained from *MESSENGER* have greater resolution than those from *Mariner 10* and showed morphological and stratigraphic features that confirmed that the smooth plains are indeed the products of effusive volcanism. Furthermore, several strands of evidence showed that the slightly older intercrater plains are also volcanic. It is now understood that little, if any, of Mercury's surface is in situ primary crust and that virtually the entire surface was emplaced volcanically or was excavated and overturned by impacts. There is also evidence for explosive volcanism, potentially continuing long after the cessation of the large-volume plains-forming volcanism. Together, these observations provide crucial strands of evidence for the thermal and geological evolution of the planet.

MERCURY'S VOLCANIC PLAINS

Smooth Plains

Mercury's smooth plains cover about 27% of the planet's surface (Denevi et al. 2013) (Fig. 1). The largest expanse is at high northern latitudes; initially referred to as the Northern Volcanic Plains (NVP), it is now known as Borealis Planitia. A host of observations confirm that most of Mercury's smooth plains, including Borealis, are volcanic rather than impact melt (Head et al. 2008, 2011). Morphological evidence comes from fully buried ("ghost") and partially filled impact craters within plains that themselves usually occupy impact basins (Fig. 2A). The

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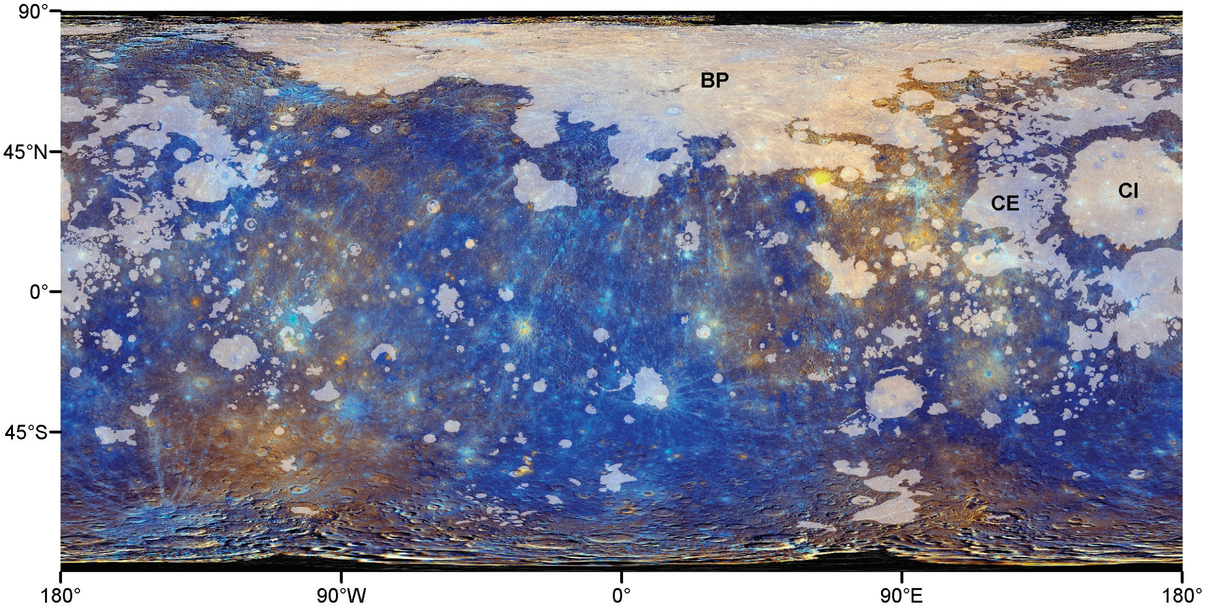

Figure 1 The extent of the smooth plains (white transparent overlay) as mapped by Denevi et al. (2013). Plains infill impact basins and occur outside them. The basemap is a global mosaic of Mercury with color enhanced to highlight spectral and, by extension, compositional variations. Symbols are as follows: BP = Borealis Planitia; CE = plains around the Caloris impact basin; CI = plains within the Caloris basin. Image courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.

presence of these underlying craters shows that enough time elapsed for impacts to occur on the basin floor after basin formation but before the emplacement of the infilling plains. Observations such as this demonstrate that the smooth plains must be significantly younger than the basin in which they occur and, so, are not directly related to the impact event that formed the basin.

Another strand of morphological evidence for the volcanic nature of the smooth plains is a characteristic type of shortening tectonic structure that is seen on these plains, the so-called “wrinkle ridge” (Fig. 2A). This landform is typical of lava plains on other terrestrial bodies. Though Mercury has no clear examples of vents or fissures from which the plains-forming flows were erupted, this does not undermine the volcanic interpretation because flood basalts on the Earth and Moon typically bury their own vents.

Spectral data, too, support a volcanic origin. Mercury’s smooth plains are sometimes spectrally distinct from the surrounding older terrain (Fig. 2B). This is good evidence that they are also compositionally distinct, which supports a volcanic origin involving changes in composition by means of partial melting. The final piece of evidence against the impact hypothesis for the smooth plains is their widespread distribution. Many large expanses of plains are situated far from any plausible source impact basin and have much greater volumes than would be predicted by an impact.

Other observed features enable a more subtle understanding of the form that this volcanism took. Multiple broad, branching channels containing streamlined landforms fringe one margin of Borealis Planitia (Fig. 3). It is extremely unlikely that liquid water could ever have existed on Mercury’s surface, so water can be discounted as a viable erosive agent. These channels must, therefore, indicate voluminous lava flows capable of streamlining obstacles in their path and, perhaps, carving the channels (Byrne et al. 2013). To accomplish this, flow must have been turbulent, with the lava moving quickly and likely having a low viscosity. Furthermore, analysis of the size and number of buried and nonburied impact craters across Borealis Planitia indicates that a 0.7–1.8 km thickness of lava was emplaced across this vast area—some 7% of the planet’s surface—over a relatively short period, perhaps on the order of 100 My.

Intercrater Plains

Although better preservation of morphological features makes it easier to determine that the smooth plains are volcanic, it has become clear that virtually all of Mercury’s

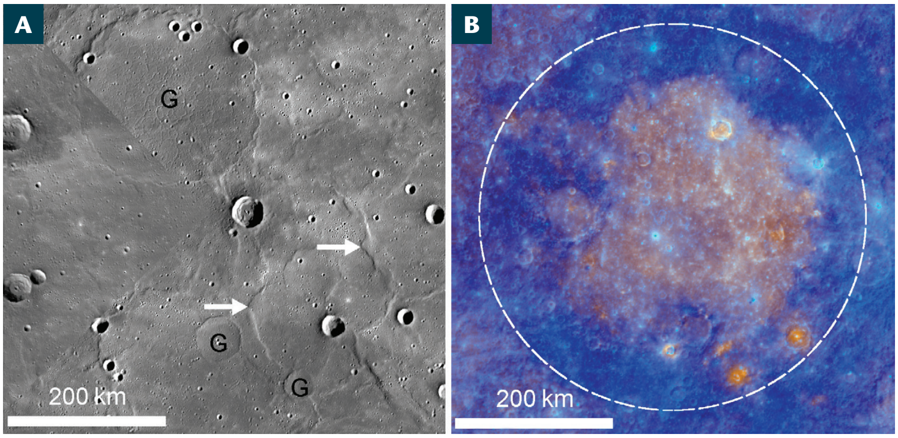

Figure 2 (**A**) Buried (‘ghost’) impact craters (marked ‘G’) and wrinkle ridges (indicated by white arrows) in Borealis Planitia. The background image is an excerpt from the global monochrome mosaic centered on 59.1°N, 38.5°E. Illumination is from the ESE. (**B**) Much of the floor of the Tolstoj impact basin (rim indicated by a white dashed line) is occupied by spectrally distinct smooth plains thought to be volcanic. The image is an excerpt from the enhanced color global mosaic centered on –16.4°N, –165.0°E. Images courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.

surface is likewise probably volcanic. There is a relative scarcity of impact craters in the 20–128 km diameter range on Mercury's surface compared with ancient lunar surfaces, indicating that there was a period of widespread resurfacing early in Mercury's history. This occurred before and during the heavy bombardment that occurred throughout the inner solar system up to about 3.8 billion years ago. That this resurfacing was the result of effusive volcanism is supported by an observed continuum in spectral character and morphology between the smooth plains (Fig. 2) and the more cratered intercrater plains (Fig. 4) (e.g., Whitten et al. 2014). Moreover, spectral data show no distinct break in spectral properties between smooth and intercrater plains (Murchie et al. 2015). Indeed, material excavated from beneath the surface of the older, darker plains has the same spectral properties as the smooth plains (Ernst et al. 2010). This observation suggests that the smooth and intercrater plains have comparable compositions and that their spectral contrast is a result of ongoing mixing with other material by impacts and space weathering, which tend to darken and redden surfaces over time. In essence, the only fundamental way that the two types of plains differ is in the areal density of superposed impact craters—and even in this, there can be continuity or overlap in crater density between areas mapped as the two different plain types (Whitten et al. 2014; Byrne et al. 2016).

Lava Composition

Evidence for voluminous lava eruption and turbulent flows inevitably raises the question of lava composition. Was turbulence a result of inherently low viscosity and/or high magma temperature, or did it result from exceptionally high effusion rates? The composition of Mercury's lavas is also a crucial probe into the planet's interior and could even tell of secular changes within the planet. As discussed by Nittler and Weider (2019 this issue), Mercury's surface is chemically heterogeneous but consistently high in magnesium and low in iron compared with other terrestrial bodies. When converted into normative mineralogy, this indicates alkali-rich komatiitic to boninitic compositions (Vander Kaaden et al. 2017). If found on Earth, such compositions would indicate moderate-to-high eruptive temperatures. Additionally, alkali (Ca and Na) concentrations are relatively high, particularly in Borealis Planitia.

The finding that Mercury's surface is dominantly volcanic indicates that the varied "geochemical terranes" discussed by Nittler and Weider (2019 this issue) relate to differences in lava composition. Broadly, such differences may result from changes in the depth and degree of mantle melting over time. More mafic, heavily cratered parts of the volcanic crust, for example, have been shown by crystallization experiments to require partial melting at approximately 360 km depth at a mantle potential temperature of 1,650 °C, whereas the more plagioclase-rich composition of relatively young smooth plains, such as Borealis Planitia and those inside the Caloris basin, is consistent with melting at only 160 km at 1,410 °C (Namur and Charlier 2017). However, the heterogeneity of lava compositions is much more complex than a simple "old versus young" dichotomy, and the observed chemistries of different regions cannot be related to each other in a straightforward evolutionary time series (Weider et al. 2015). For example, the most heavily cratered regions of Mercury show a wide range of Mg/Si ratios in X-ray spectrometer data. In contrast, the volcanic plains inside and outside the Caloris impact basin, which are compositionally distinct on the basis of spectral and elemental data, show evidence for interspersed or even contemporaneous plains emplacement (Rothery et al. 2017). Thus, spatial as well as temporal differences in mantle chemistry and degree of melting must account for

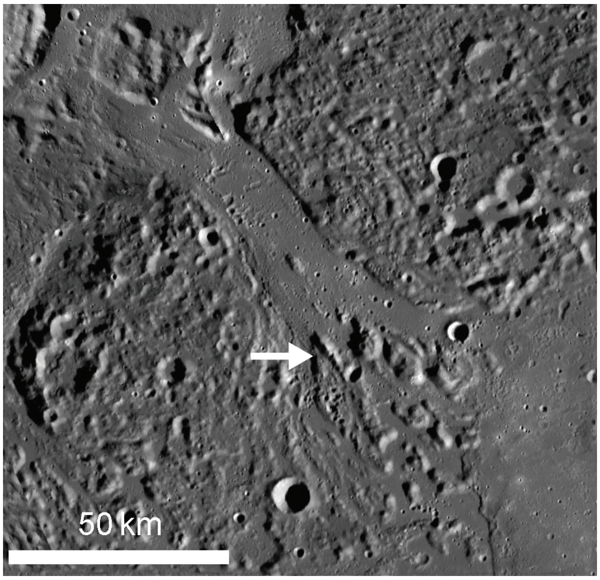

Figure 3 An example of a channel near Borealis Planitia thought to have been carved or modified by lava flow. "Islands" within the channel are streamlined into "teardrop" shapes (indicated by a white arrow), indicating erosion by a fluid. Illumination from the ESE. The image is an excerpt from the Mercury global monochrome mosaic centered on 57.7°N, 113.7°E. Image courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.

the wide variations in silicate geochemistry across Mercury. The spatial heterogeneity in source chemistry is particularly interesting with regard to the internal dynamics of the planet, as it indicates that mantle mixing was inefficient during the period of voluminous volcanic eruptions on Mercury.

Experimental and numerical modeling on the basis of the most recent lava compositions of Borealis Planitia indicate that these voluminous flows would have had a low viscosity (10–20 Pa s) because of their low Al_2O_3 and high Na_2O content. High effusion rates (>10,000 m^3/s), similar to those inferred for large igneous provinces on Earth, would have been required to emplace them over hundreds of kilometers to form the Borealis Planitia (Vetere et al. 2017). The extremely high buoyancy proposed for Mercurian magmas (Vander Kaaden et al. 2017) is consistent with such high effusion rates as long as crustal conditions were conducive for melt ascent to the surface.

MERCURY'S EXPLOSIVE VOLCANISM

We have already remarked on the absence of visible eruptive sources (fissures or vents) for Mercury's plains volcanism. However, numerous irregular pits have been discovered on Mercury that have been interpreted as explosive volcanic vents (Fig. 5). There are as many as 174 of these pits across the planet (e.g., Thomas et al. 2014a; Jozwiak et al. 2018). The interpretation of these landforms as vents, as opposed to impact craters, is supported by their elongate or irregular planform morphology; their uneven, multilevel floors (Rothery et al. 2014; Jozwiak et al. 2018); the lack of a thick blanket of surrounding ejecta; and the absence of a prominent raised rim. Additionally, most pits are surrounded by spectrally distinct low-albedo material with a diffuse outer margin known as a facula (Figs. 5B, 5D, 5F). The spectral distinctiveness of the faculae supports a volcanic origin, and the lack of associated flow features and the diffuse nature of their outer edges indicate a particulate-dominated deposit, pointing to an explosive volcanic

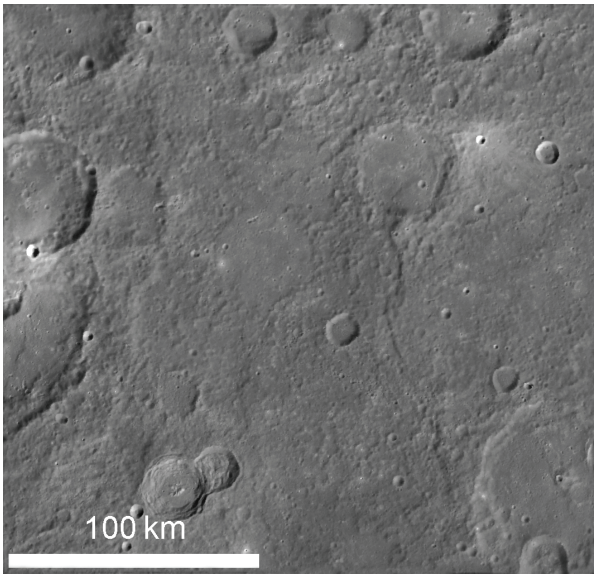

FIGURE 4 A view dominated by intercrater plains, which have been shown to be the result of early volcanism. Illumination from the ESE. The image is an excerpt from the Mercury global monochrome mosaic centered on 36.2°N, 107.5°E. IMAGE COURTESY OF NASA/JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY/CARNEGIE INSTITUTION OF WASHINGTON.

eruption (Kerber et al. 2009). Explosive volcanism occurs when a volatile component exsolves from, or is encountered by, erupting magma. Under Mercury's airless conditions, the violent expansion of such volatiles in the gaseous phase would have expelled particles ballistically from a point-like vent to produce an umbrella-like plume similar to those observed on Jupiter's volcanically active moon, Io. The deposits commonly show little topographic expression and rarely obscure the underlying landforms, indicating that they do not form substantial volcanic constructs but are, rather, a distally thinning mantling layer (Thomas et al. 2014b). Intriguingly, new numerical modelling indicates that, under Mercury's airless conditions, it would be impossible to build a more topographically distinct cone by purely pyroclastic processes (Brož et al. 2018).

The largest example of explosive volcanism is Nathair Facula, which lies northeast of the Rachmaninoff basin and extends for 130 km around a 4 km deep pit (FIGS. 5A, 5B). On average, the faculae are larger than pyroclastic deposits on the Moon, despite Mercury's higher gravity which would cause ballistically ejected particles to fall closer to a vent. This disparity in size may indicate that Mercury's explosive volcanism was powered by a higher proportion of volatiles than that on the Moon, perhaps on a par with those powering eruptions on Earth (Thomas et al. 2014b).

THE HISTORY OF VOLCANISM

The areal density of impact craters that are superposed on the intercrater plains dates the plains to the period of heavy bombardment, indicating that this was a period of widespread volcanic resurfacing. The lower cratering density on the smooth plains suggests that they were emplaced later, between approximately 3.9 Ga and 3.5 Ga (Byrne et al. 2016), indicating that volcanism became more localized after the heavy bombardment and that the volcanism of the large-volume plains ceased relatively early in the planet's history.

This fall-off in effusive volcanism is most likely due to the thermal evolution of the planet. Like other terrestrial bodies, Mercury will have undergone ongoing cooling as it lost its heat of formation, much of its core solidified, and its radiogenic isotopes decayed, providing decreasing opportunities for mantle melting over time (Peplowski et al. 2011). Furthermore, this cooling led to global contraction (Byrne et al. 2014) and, ultimately, to a lithospheric stress state dominated by horizontal compression. Such a stress state will tend to inhibit magma ascent to the surface. Indeed, where younger smaller-scale possible volcanic flow surfaces have been identified, they tend to occur on the floors of impact craters (e.g., Prockter et al. 2010). These sites are locations where the resetting of the compressive stress, the removal of overburden, the deposition of subsurface heat, and the presence of fractures and faults would best favor magma ascent in this later period when, more generally, global contraction came to dominate Mercury's geological character (Byrne et al. 2016).

The timing of Mercury's explosive volcanism fits well within this picture. In the vast majority of cases, explosive vents occur where the subsurface is likely fractured, thereby making this subsurface relatively conducive to magma ascent (e.g., Jozwiak et al. 2018; Klimczak et al. 2018). The structural connection to vent formation is supported by vent locations within craters: vents are often elongated circumferential to the crater rim (e.g., FIGS. 5C, 5D) or occur at the site where craters have a central uplift (e.g., FIGS. 5E, 5F). Vents are also frequently located along the leading edge of a lobate scarp (e.g., FIGS. 5E, 5F), the surface expression of a thrust fault that is a relatively advantageous structural location for magma migration to the surface. In some of the crater-hosted examples, the vent has punched up through crater-floor lava deposits, most famously where numerous vents and associated deposits fringe the volcanic infill of the Caloris basin, a few tens of kilometers inwards of its rim (Head et al. 2008; Rothery et al. 2014). This spatial relationship indicates a sequence of events where the basin was first infilled by voluminous lavas and then small vents and pyroclastic deposits were formed by late-stage, smaller-scale eruptions through the thinnest, rimward parts of the lava infill. Furthermore, where it is possible to date vents or deposits on the basis of superposition relationships, they are found to have been formed during all periods of Mercury's history, with some appearing to be less than a billion years old (Thomas et al. 2014a; Jozwiak et al. 2018). This indicates that explosive volcanic activity continued on Mercury well after the period when the most voluminous effusive eruptions had ceased.

It is not surprising that explosive volcanism should have been able to outlast voluminous effusive flow, given the horizontally compressive tectonic regime in effect at Mercury for the last few billion years. Volatiles are able to provide overpressure in addition to that provided by magma buoyancy alone so, where eruption was possible because of the presence of preexisting lithospheric fractures, volatile-enhanced magma (made so either through exsolution or assimilation of country rock during ascent) would be most able to make use of those zones of weakness.

Volatiles and Their Sources

The recognition of explosive volcanism on Mercury from *MESSENGER* flyby images was unexpected. Several of the formation models for Mercury that predated the *MESSENGER* mission had predicted that the planet would be depleted in volatiles, making explosive volcanism improbable. However, data from *MESSENGER* provided several independent lines of evidence for a nonvolatile-depleted surface (Nittler and Weider 2019 this issue). These new data indicate the abundant presence of elements such

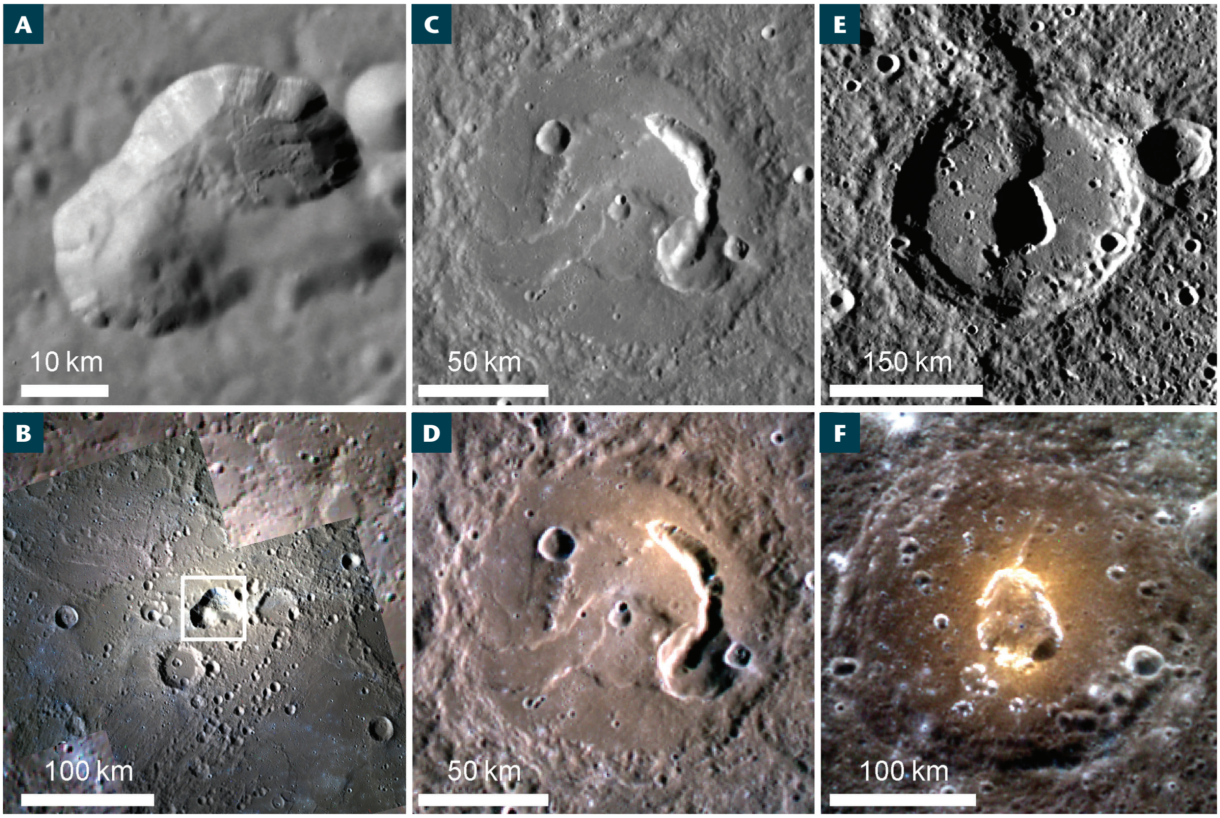

Figure 5 Pits and surrounding faculae (i.e., bright spots and areas that, in the images here, are relatively bright and/or red) on the surface of Mercury, interpreted collectively as explosive volcanic vents with surrounding pyroclastic deposits. (**A**) Close-up of the compound vent at the center of Nathair Facula, northeast of the Rachmaninoff impact basin at 35.8°N, 64.0°E, in monochrome (illumination from the SE). Base image: MESSENGER MDIS EW1014012379G. (**B**) Nathair Facula in its wider geographic context, northeast of the Rachmaninoff impact basin at 35.8°N, 64.0°E, in color (illumination from the W); the close-up of 5A is the central (and brightest) feature of 5B. Base image: color composites based on MESSENGER MDIS EW0239664243F and EW0254913709G and global color mosaic. (**C**) A pit with a surrounding facula circumferential to the rim of Picasso impact crater at 3.4°N, 50.4°E, in monochrome (illumination from the E). Note that the lobate structures on the crater floor are thought to be tectonic rather than volcanic. Base image: excerpt from the MESSENGER global monochrome mosaic (**D**) As for 5C but in color (illumination from the E). Base image: color composite based on MESSENGER MDIS EW1014443535I. (**E**) A pit surrounded by a facula at the center of the Geddes impact crater at 27.2°N, –29.5°E where it is crossed by the surface expression of a thrust fault (a lobate scarp), in monochrome (illumination from the W). Base image: excerpt from the MESSENGER global monochrome mosaic. (**F**) As for 5E but in color (illumination from the SE). Base image: MESSENGER MDIS color composite based on EW1020465015F. Images courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.

as carbon, chlorine, and sulfur that could form volatile species capable of powering explosive eruptions (Weider et al. 2016). However, some of the plausible volatile species would require oxidation in order to exsolve from Mercury's initially reducing magmas. To address this issue, it is desirable to identify the volatile species that powered Mercury's explosive eruptions and their sources.

Because we do not have access to samples, it is challenging to determine the composition of materials observed on Mercury. It is even more challenging to characterize what is now missing, i.e., the volatiles lost during eruption. The problem is exacerbated by the small spatial extent of the faculae thought to represent Mercury's pyroclastic deposits, which generally makes it impossible to detect them in *MESSENGER* compositional datasets. However, for the largest, Nathair Facula (Fig. 5B), there *is* some evidence of elemental depletion. X-ray spectrometer data acquired under uniquely advantageous conditions (a solar flare resulting in an abnormally high X-ray flux) showed a clear depletion in sulfur relative to both silicon and calcium compared with the surrounding material (see Fig. 3 in Nittler and Weider 2019 this issue). Additionally, neutron spectrometer data obtained at low altitude imply a depletion of 1%–2% in carbon (Weider et al. 2016). Interpretation of these results suggest that sulfur- and carbon-bearing volatile species may have powered the eruption, leaving behind a deposit depleted in these elements.

The involvement of sulfur (S) and carbon (C) is certainly not improbable on Mercury. It is now known that Mercury has a high surface concentration of S compared with other planets, and the importance of C (in the form of graphite) is being increasingly recognized (Nitter and Weider 2019 this issue). Furthermore, the level of observed depletion in these elements in Nathair Facula, if incorporated in Mercury-appropriate volatile species, is sufficient to produce an explosive volcanic eruption ejecting pyroclasts out to 130 km (Weider et al. 2016). However, S and C are highly soluble in Mercury's reducing interior, so the magma would need to have been oxidized by some means to cause volatile species to exsolve. Such exsolution could have occurred by the assimilation of oxide-bearing country rock or by oxide-bearing magmas assimilating C- and S-bearing country rock. This latter option is especially interesting in light of work indicating that Mercury's lower crust is graphite-bearing (Vander Kaaden and McCubbin 2015) and that explosive volcanism is common in regions where low-reflectance material such as graphite occurs in the substrate (Thomas et al. 2014b). Magmas encountering such material in the subsurface may have been the means by which melts attained the elevated volatile content required to propagate to the surface despite global contraction. Such an explanation would make Mercury's explosive eruptions somewhat akin to phreatic or phreatomagmatic eruptions on Earth, where the eruption is driven by the heat from the magma turning near-surface water into steam, rather than by expansion of exsolved magmatic volatiles.

A UNIQUE VOLCANIC PLANET

Mercury's surface is the product of a long history of volcanic activity, with most activity occurring within the first quarter of the solar system's history. Because of Mercury's chemistry, its lavas are unusually low in iron, high in magnesium, and high in alkalis. Mercurian explosive volcanism was probably powered by volatile species that are different from the H_2O, CO_2, and SO_2 phases that are usually responsible for such eruptions on Earth. The powerful Mercurian eruptions were capable of ejecting particles to great distances, most probably through volatile-release in oxidation reactions involving sulfur and carbon during the ascent of magma through the crust.

The means by which eruptions have occurred has been strongly governed by the planet's slow cooling history and the resulting global contraction. This phenomenon greatly restricted the routes available for lava to reach the surface, bringing large-volume effusive lava eruptions to a halt ~3.5 Ga. After that, the best means by which lava could reach the surface was via fractures opened by impact crater formation and by tectonic deformation. In some cases, the fractures below impact craters and lobate scarps may have allowed small-scale magma bodies to ascend and erupt onto crater floors. In others, eruption was aided by an enhanced concentration of volatiles, either intrinsic to or assimilated into the magma from crustal materials. Exsolution of these volatiles would have countered the unfavorable crustal stress state and so facilitated eruptions. Explosive eruptions of this type likely persisted into the last billion years. Thus, through a combination of surface fracturing by impacts and tectonic stresses and the availability of volatiles, Mercury has maintained some level of volcanic activity through the majority, if not all, of its history.

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