The Apparent Absence of Kilometer-sized Pyroclastic Volcanoes on Mercury: Are We Looking Right?

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Key Points:

- Kilometer-sized constructional explosive volcanoes have not been identified on Mercury despite high-resolution data.
- Instead of steep constructional volcanoes, as on Earth and Mars, Mercurian pyroclastic deposits likely form a wide and gentle blanket.
- Pyroclastic cones may not form at all on airless bodies; such landforms already recognized on the Moon and Io are likely composite cones.

Plain Language Summary

Volcanic eruptions have occurred on planetary bodies throughout the Solar System, including Mercury. Eruptions have different styles, which affect the volcanoes they build. On Earth, small-volume explosive eruptions, which occur because expanding gas bubbles in the magma fragment the erupting molten rock, can form piles of material called scoria cones. Features resembling scoria cones have been observed on the Moon and Mars, but not yet on Mercury. We used computer simulations to calculate where rock chunks would accumulate during explosive eruptions with different eruption volumes, speeds, and angles, under Mercury gravity. We found that, under most plausible scenarios, explosive eruptions on Mercury ejected material over too great an area to build a cone, but instead built gentle slopes that would be undetectable in data from the MESSENGER mission. This is because Mercury has no atmosphere to reduce the maximum range of ejected rock and cause it to build up close to the vent. We suggest that BepiColombo, the next spacecraft to visit Mercury, should concentrate on searching for compositional, rather than topographical, evidence for explosive volcanism. We suggest that volcanic cones on the Moon may have formed differently to scoria cones on Earth, since the Moon also has no atmosphere.

Abstract

Spacecraft data reveal that volcanism was active on Mercury. Evidence of large-volume effusive and smaller-scale explosive eruptions has been detected. However, only large (>~15 km) volcanic features or vents have been found so far, despite abundant high-resolution imagery. On other volcanic planets, the size of volcanoes is anti-correlated with their frequency; small volcanoes are much more numerous than large ones. Here, we present results of a numerical model

that predicts the shapes of ballistically emplaced volcanic edifices and hence can explain the lack of kilometer-sized constructional explosive volcanoes on the surface of Mercury. We find that due to the absence of the atmosphere, particles are spread on this planet over a larger area than is typical for Earth or Mars. Erupted volumes are likely insufficient to build edifices with slope angles that enable their easy recognition with currently available data or that could survive destruction by subsequent impact bombardment.

1 Introduction

Images obtained from the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission have revealed evidence of effusive (e.g., *Head et al*., 2008; 2011; *Byrne et al*. 2016) and explosive (e.g., *Head et al.,* 2009; *Thomas et al*., 2014a; 2014b; *Jozwiak et al*., 2018) volcanism on the surface of planet Mercury. While the products of putative effusive volcanism are in the form of solidified lavas forming the majority of the planet's smooth plains units, covering around 27% of the planet's surface (*Head et al*., 2011; *Denevi et al*., 2013), the explosive products are characterized by bright spots (dozens of kilometers across, and recently allocated the descriptor term *facula/faculae*) with diffuse boundaries and without substantial positive topographic expression. These faculae often contain an irregular depression in their centers (e.g., *Kerber et al*., 2009; *Thomas et al*., 2014a) and are overwhelmingly located near impact craters and faults (*Klimczak et al*., 2018). While explosive vents are of the scale of kilometers to tens of kilometers, vents associated with effusive volcanism are almost wholly absent, presumably because they are buried by large volumes of highly mobile lavas capable of flowing over long distances. Interestingly no kilometer-sized volcanic constructional edifices have been unambiguously recognized on Mercury to date despite considerable searching.

The only exceptions observed so far are two kilometer-sized landforms that may represent individual volcanic cones: one situated within the Heaney impact crater and the other near the northwest edge of the Caloris basin (*Wright et al*., 2018). Each of these has a central summit crater, and their shapes are consistent with their formation by effusion of relatively viscous lavas. Their volcanic origin is also favored from their geological context; they are situated within the areas where volcanism almost certainly occurred in the past. However, their origin by nonvolcanic means cannot be excluded due to the limitations in the resolution of MESSENGER data (*Wright et al*., 2018). Nevertheless, regardless of the mechanism of their origin, the extreme scarcity of kilometer-sized constructional volcanic edifices is a surprising fact itself, as such features are frequent on other terrestrial bodies within the Solar System where volcanism has taken place, such as Earth (*Kereszturi & Németh*, 2013), the Moon (e.g., *Lawrence et al*., 2013) and Mars (e.g. *Hauber et al*., 2009; *Brož & Hauber*, 2012; *Brož et al*., 2015, 2017). On those bodies, the observed kilometer-sized volcanoes are results of the accumulation of low volumes of lava and/or pyroclastic material in the immediate vicinity of the vents from which the material was erupted by effusive or explosive means.

The scarcity of kilometer-sized volcanoes on Mercury led *Wright et al*. (2018) to propose that volcanic eruptions with sufficiently low eruption volumes and rates and short flow lengths, which would be suitable for the construction of low-volumetric volcanoes by effusive lavas, were highly spatiotemporally restricted during the preserved portion of Mercury's geological history. In a broader perspective, such a conclusion could also be applied to explain the absence of kilometer-sized constructional volcanoes resulting from explosive eruptions. This is because the horizontally compressive stresses prevailing in the crust of Mercury, due to global contraction, can hinder magma ascent (*Byrne et al*., 2014) and thus not allow explosive constructional volcanoes to form. In this analysis, however, we propose a hypothesis in which the absence of small-volume explosive volcanoes can be resolved through wide dispersal of the ballistic pyroclastic material around the vent due to the specific conditions prevailing on Mercury's surface. Such dispersal would prevent the formation of constructional edifices resolvable with MESSENGER imagery and topographical data. Therefore, under this interpretation, small-volume explosive volcanoes could be present on the surface of Mercury, but at present we do not have data suitable to detect them.

2 The mechanism of the formation of pyroclastic cones

Whether a volcanic eruption is effusive or explosive depends on the amount of volcanic gases dissolved within the magma and/or the availability of the external volatiles that magma can interact with during its ascent (*Cashman et al*., 1999). Volcanic gases or external volatiles, in sufficient volumes, are able to transport exploded rock fragments (“pyroclasts”) from the vent according to their sizes either ballistically and/or by turbulent jets (e.g., *Wilson and Head*, 1994; *Riedel et al*., 2003). However, those transport mechanisms are heavily influenced by the presence of an atmosphere. On airless bodies with an almost perfect vacuum, such as Mercury, the Moon, or Jupiter’s moon Io, the transport mechanism is simpler as there are no interactions (or they are so insignificant that they can be neglected) of the ejected particles with the atmosphere. Material is therefore ejected from the vent along ballistic trajectories only, without particle deceleration by atmospheric drag.

The final shape of explosive volcanoes on airless bodies is therefore controlled by the ballistic ranges of particles, which depends mainly on ejection velocity and gravity, and by the subsequent redistribution of the material by avalanches, which occur when the flank slope of the cone exceeds the angle of repose (e.g., *Riedel et al*., 2003). However, as shown in the example of putative Martian scoria cones by *Brož et al*. (2014), it is difficult to achieve the angle of repose on a body with a low-density or absent atmosphere and with substantially lower surface gravity than on Earth. This is because particles are spread over a much larger area on such bodies, even if they were thrown out by an explosion with an otherwise identical set of parameters as on a larger world with an atmosphere. As a consequence, on Mars the erupted volumes of pyroclasts are not large enough for the flank slopes to attain the angle of repose, in contrast with Earth where this is common (and hence can be attained with lower erupted volumes). Martian analogues therefore show gentler flank slopes and larger basal diameters (*Brož et al*., 2015).

Although the current pressure on Martian surface is only about 600 Pa and the air density is a factor of 100 lower than on Earth, the air drag on Mars can significantly affect the transportation of ejected particles and hence the final shapes of pyroclastic features. Ballistic pyroclastic particles would be spread even farther if Mars had no atmosphere at all. Therefore features on airless bodies form with even gentler flank slopes, and hence more subtle topography, than observed on Earth or even Mars (e.g., *Kereszturi & Németh*, 2013; *Brož et al*., 2015). To investigate these variations and to predict possible shapes of such small-scale explosive volcanoes on Mercury we conducted numerical simulations, based on those by *Brož et al*. (2014) for Mars, which calculate the ballistic trajectories of particles ejected under different conditions plausible for Mercury, and trace the cumulative deposition from repeated ejections of particles over time (for details about the used model see sections S1-S3 in the Supporting Information [*Brož et al*., 2014; *Gouhier and Donnadieu*, 2010; *Harris et al*., 2012]).

The ejection speed, which is independent of the particle size in our model, is described by a log-normal probability function with standard deviation σ_μ and mean $\log_{10}\mu$, where μ is the most probable ejection speed. The ejection angle, measured from the vertical, is characterized by a normal distribution centered at 0 with standard deviation σ_α which represents the mean angular radius of the ejection cone (see Figures S1-S4 in the Supporting Information for details). The shape of the ballistic feature is thus fully determined by only three parameters (μ, σ_μ, and σ_α) and by the gravitational acceleration at the surface of the planet (which is almost identical for Mercury and Mars, i.e., a mean gravity of 3.7 m/s^2 versus 3.71 m/s^2). For Mars, *Brož et al*. (2014, 2015) attempted to reproduce the shapes of the putative scoria cones using Earth-like values of σ_μ and including the effect of air resistance. They found that the largest known scoria cones on Mars are consistent with $\mu \approx 100$ m/s and $\sigma_\alpha \approx 30°$. For Mercury, we assume that air resistance is negligible and the ballistic trajectory of a particle depends only on its initial speed and ejection angle.

3 The shapes of pyroclastic volcanoes on airless bodies

The lack of identified low-volume volcanoes on Mercury, and hence the unavailability of any data about their volumes, motivates us to assume in a first pass that pyroclastic cones would be formed by the same amount of material on Mercury as the most voluminous Martian putative scoria cone (4.2 km^3: *Brož and Hauber*, 2012; *Brož et al*., 2015), and that the parameters of the eruption would be the same on both bodies (see description of Figure 1 for details, or *Brož et al*., 2014; 2015). The only difference in model setup we consider here is the lack of an atmosphere for Mercury.

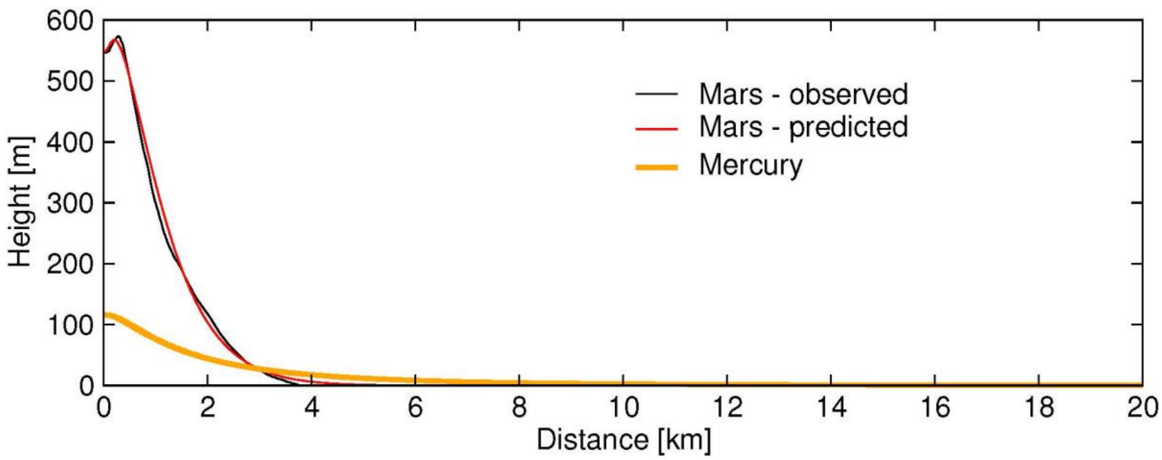


Figure 1: Comparison of the observed topographic profile of one putative 4.2 km^3 Martian scoria cone (in black, the cone informally named UC2 in *Brož et al*., 2015) with the profiles of similar volumes computed for speed μ=100 m/s, log-normal distribution scaling σ_μ=0.2 and radius of ejection cone σ_α= 30° in the environment of Mars (in red) and Mercury (in orange). The absence of an atmosphere on Mercury causes ~4.4 times wider dispersion of particles and the formation of feature only ~18% as high compared with Mars.

The results of our modeling show (Figure 1) that, although ~99% of the ejected material on Mars would be deposited within a circle ~4.5 km in radius, the same amount of material on Mercury would be deposited within an area ~20 km in radius, i.e., about 4.4 times farther. As a consequence, the material is dispersed on Mercury over an area ~20 times larger than on Mars. For the same volume of ejected material (4.2 km^3) on Mercury as on Mars, the wider dispersal would cause a dramatic decrease in the height of the cone and a corresponding reduction in slope angles (for definition of the slope angle, see section S4 in the Supporting Information). On Mars, the deposition of material would cause the formation of conical edifices with a height of ~570 meters, and flanks would retain a slope angle of 24° in the steepest part of the profile (red profile in Fig. 1). In contrast, the eruption of the same volume of material on Mercury would create a surface feature ~100 meters high and with flank slopes which would maximally reach only 2.8° (orange profile in Fig. 1). The reduction in height of the resulting feature would be so substantial, that the shape would not be an obvious cone at all, but rather a slightly elevated broad and gently sloping hump with subtle topography.

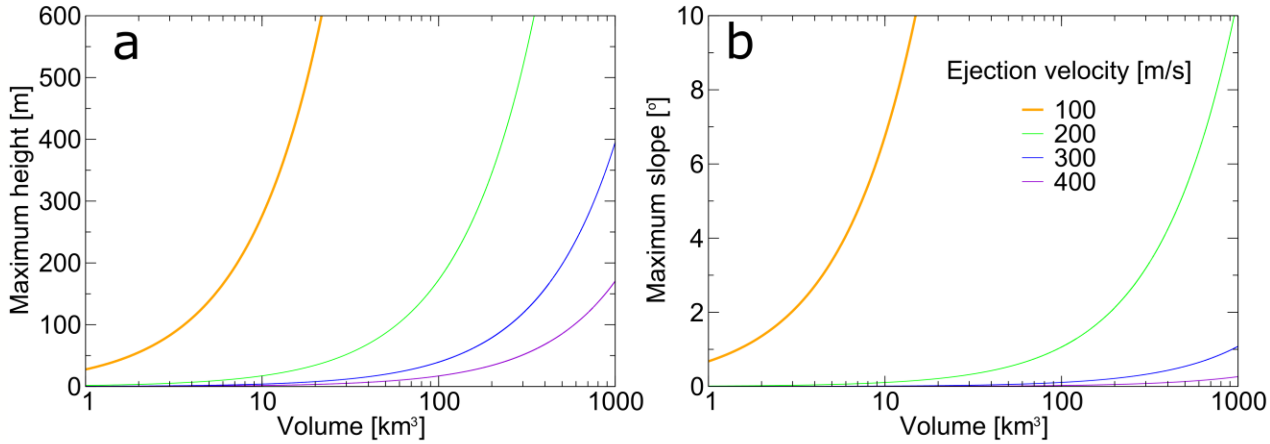


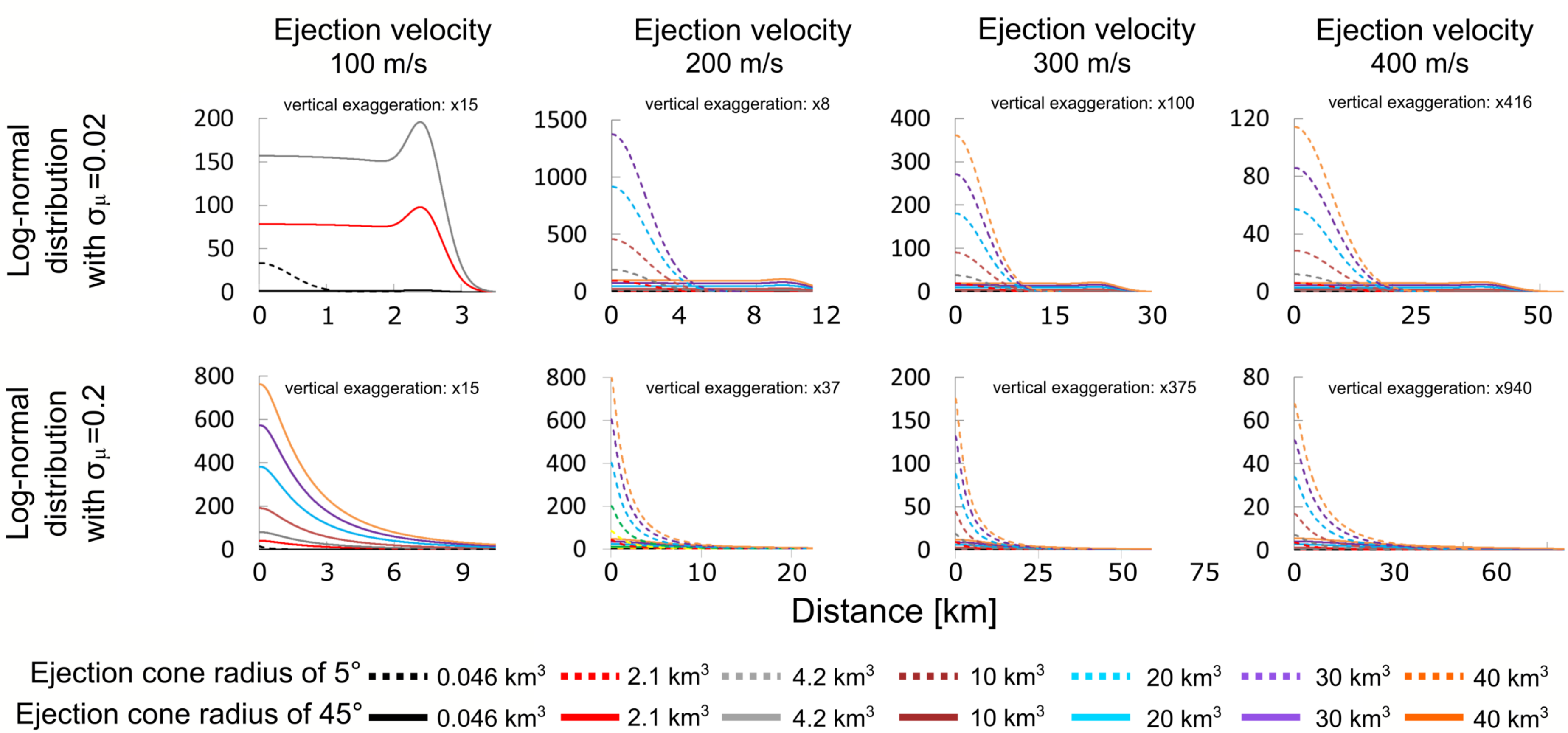
Figure 2: Dependency of the maximum height (panel a) and maximum flank slopes (panel b) of a pyroclastic edifice on the total volume of erupted material in the environment of Mercury. Lines of different colors show results for different ejection speeds, namely for 100 m/s (orange), 200 m/s (green), 300 m/s (blue), and 400 m/s (violet). Parameters σ_α and σ_μ are as described in the caption of Figure 1.

In the next step, we investigate how the maximum height and flank slopes of ballistically emplaced features would be affected by the variation of the volume of ejected material in the Mercurian environment. The results are summarized in Figure 2. To achieve the same height of our test-case cone on Mars (~570 m), the volume of erupted material on Mercury must be increased by factor of ~5 (corresponding to ~20.7 km^3 of ejected material) for the same initial speeds and ejection angles we considered earlier. If the material is ejected at higher initial speeds on Mercury than expected for Mars, the amount of material necessary to construct a landform of such height must further increase (Figure 2a). However, the results also show that even if the height of the Martian cone could be reached on Mercury, the resulting shape would be different. The final edifices would have gentler flank slopes (maximally 13.8° on Mercury versus 24° on Mars in the steepest part of the cones) for the same sets of parameters for both eruptions, including an ejection speed of 100 m/s. However, if the initial speeds of ejected particles were higher on Mercury than on Mars, the flank slopes of the final edifices would be even more topographically subtle; specifically, for ejection speed of 200 m/s, 300 m/s and 400 m/s the final slope angles would be maximally reaching the value of 3.5°, 1.6°, and 0.9° respectively.

Until now, we have considered only solutions based on the assumption that explosive volcanism would occur on Mercury with a similar set of parameters as determined for low-volume explosive eruptions on Mars (*Brož et al.*, 2014; 2015 and references therein). However, such assumptions may not be equally applicable to airless bodies. Due to the lack of an atmosphere, some (or all) of these parameters may differ drastically from those Martian values.

For example, *Wilson and Head* (2003) suggested that the lack of atmosphere on the Moon would affect the way in which the ascending picritic magma would be degassed once it reached the lunar surface. Once the tip of a dike breaks through the crust, free gas at the tip would escape quickly so the lava foam forming the upper part of the dike would be exposed to the vacuum. The gas bubbles formerly at a pressure of ~100 MPa within the lava foam would therefore rapidly expand. As a consequence, an expansion wave(s) able to travel at high speed downward through the dike would be generated. This wave would likely cause rapid disintegration of the lava foam and hence rapid release of the trapped volcanic gases, leading to much higher ejection speeds for the small pyroclastic particles (up to 760 m/s) than speeds common on Earth and Mars. Also, *Glaze and Baloga* (2000) and *Wilson and Head* (2007) assumed that the presence of an atmosphere and its associated density can also affect the ejection angles at which magma fragments are ejected, such that on bodies with lower atmospheric pressure, wider ($\sigma_\alpha \geq 30°$) ejection cones than on Earth should be expected.

Since the angular radius of an ejection cone (σ_α) and the values of ejection speeds (μ, σ_μ) are unknown for Mercury, we performed a set of numerical runs with parameters that spanned a range of plausible values. Specifically we investigated how narrow ($\sigma_\alpha = 5°$) and wide ($\sigma_\alpha = 45°$) ejection cones, the initial speed of ejected particles (μ=100 m/s, 200 m/s, 300 m/s, and 400 m/s), and scale in the coefficient of the log-normal distribution of ejection speed (σ_μ 0.02 and 0.2) would change the distribution of the ejected particles and thus the resulting shapes of explosively emplaced, constructional volcanic features on Mercury. The results are summarized in Figure 3, where the eight panels show the topography generated for a given set of the parameter values discussed above. The dashed and solid lines in the panels show predicted topographies for narrow and wide ejection angles respectively, and different colors show variations in volume. Only those solutions that do predict slopes at the angle of repose (30°) are shown here as the model cannot simulate additional transport by subsequent avalanching and hence the additional growth in diameter and height.



Ejection velocity 100 m/s
Ejection velocity 200 m/s
Ejection velocity 300 m/s
Ejection velocity 400 m/s
Log-normal distribution with σμ=0.02
Log-normal distribution with σμ=0.2
vertical exaggeration: x15
vertical exaggeration: x8
vertical exaggeration: x100
vertical exaggeration: x416
vertical exaggeration: x15
vertical exaggeration: x37
vertical exaggeration: x375
vertical exaggeration: x940
Distance [km]
Ejection cone radius of 5°
Ejection cone radius of 45°
0.046 km3
2.1 km3
4.2 km3
10 km3
20 km3
30 km3
40 km3

Figure 3: Comparison of the predicted topographies of putative explosive volcanic features on Mercury, as a function of ejection speeds (increasing from left to right), scaling parameter σ_μ of the log-normal distribution of ejection speed (increasing from up to down), volumes (marked by different colors), and the angular radius of ejection cone (dashed versus solid lines). Note the vertical exaggeration, which varies between panels. For $\sigma_\alpha = 45°$, only ejection angles smaller than 60° are considered.

The results show that the larger the angular radius of the ejection cone is or the higher the ejection speed, or the larger the coefficient of log-normal distribution, or a combination thereof, the greater the area over which the ejecta is dispersed. For a fixed eruption volume, wider dispersal necessarily leads to a decrease in the height of the final shape and to proportionately shallower flank slopes. This finding is in agreement with previous predictions of the explosive eruptions on the Moon or Mars (*Wilson and Head*, 2003; *Brož et al*., 2015) and also with the observations of large *faculae* (up to 260 km in diameter) surrounding putative volcanic vents on Mercury, which show little (<1°) or no topographic relief at all (*Thomas et al*., 2014a).

We also focus on the effect of the ejected volume on the shapes of modeled features; however, the absence of observational evidence of kilometer-sized explosive volcanoes on Mercury required us again to assume a range of possible erupted volumes. We chose volumes from 0.046 km^3 up to 40 km^3 with intermediate steps of 2.1 km^3, 4.2 km^3, 10 km^3, 20 km^3, and 30 km^3. The lower limit was chosen to resemble the typical volume of terrestrial scoria cones (determined from 986 edifices based on data from *Pike* [1978] and *Hasenaka and Carmichael* [1985]) and the upper limit of 40 km^3 was chosen as this is the median volume of putative large-scale explosive vents on the surface of Mercury (*Thomas et al*., 2014a). We chose the median volume of large vents as the upper limit of our experiments because if the explosive eruptions that excavated these large vents ejected only crustal material, and under the assumption that no subsurface withdrawal of material occurred, then the volume of their pyroclastic deposits would be approximately equal to the volume of their source vents. However, it is currently unknown what the typical volume ratio of juvenile volcanics to crustal material is in *faculae* on Mercury (*Thomas et al.*, 2015a), therefore we consider the volume of the large vents to be a lower limit for the volumes of their pyroclastic deposits. Thus, we can make only a first approximation of the topography generated by the large-scale vent-forming eruptions.

Our modeling reveals that for particles ejected at high initial speeds and with a large angular radius of the ejection cone, a wide and flat edifice with low topography and very gentle flank slopes forms regardless of the chosen erupted volume. This landform shape is a result of the dispersal of the erupted material across such a large area that even an amount of material larger by three orders of magnitude than is typical for Earth would be insufficient to build a substantial (at least several hundreds of meters high) topographic feature composed of accumulated pyroclastic ejecta. In other words, conical edifices would not be formed. Similar shapes would be achieved even with narrow ejection angles if the particles were ejected at speeds near the upper range of our considered values. Such low-relief shapes are in contrast to pyroclastic volcanoes on Earth or Mars, where a conical edifice is generated, because atmospheric drag decreases the speed of the ejected particles and prevents widespread dispersal of the particles from the vent (e.g., *Riedel et al*, 2003; *Brož et al*., 2014).

To produce a kilometers-wide and hundreds-of-meters-high constructional edifice with a conical shape on Mercury, it is necessary for the initial speeds to be within the low range of considered values, and/or for the material to be ejected within an exceptionally small range of ejection angles (less than 5°). However, the lack of identified conical features on Mercury plausibly of volcanic origin (see *Fassett et al*., 2009), of which >90% of its surface is now covered by high-resolution images of suitable illumination (>90% of the MESSENGER ~166 m/pixel global mosaic is composed of images with solar incidence angles >68°, which enable visual observations of hundred meter-scale topographic features) enabling their detection, suggests that, although theoretically possible, these parameters are improbable. Moreover the environmental properties do not favor such conditions at all: the absence of an atmosphere tends to increase the initial speeds of ejected particles due to the rapid expansion of volcanic gasses several times than is typical on Earth or Mars (e.g., *Wilson and Head*, 2003; *Brož et al*., 2014; 2015; *Thomas et al*., 2015b), and also cause a greater spread of ejection angles around a mean ejection angle (*Glaze and Baloga*, 2000). These controlling effects of an atmosphere, or for Mercury the lack thereof, directly promote conditions inimical to the formation of kilometer-sized conical edifices on this body.

We therefore assume that wide ejection cones and high ejection speeds are characteristic aspects of explosive volcanism on Mercury, not only for those vents associated with dozens of ten-kilometer-scale bright putative pyroclastic units (faculae) and formed by large volume eruptions (*Thomas et al*., 2015a, 2015b; *Jozwiak et al*., 2018), where the width and sometimes compound nature of the vent suggests broad dispersal (e.g., *Rothery et al*., 2014), but also for those that would potentially result from the emplacement of low volumes of pyroclastic material. If so, the low volume of ballistically emplaced pyroclastic volcanoes on Mercury would not form pronounced conical edifices as common on Earth and Mars, but instead would result in very topographically subtle features difficult or even impossible to detect with current data. For example, if we assume that the same amount of material as is commonly erupted in a single event on Earth (0.046 km^3) or on Mars (4.2 km^3) is dispersed from a vent with an initial speed of 300 m/s comparable to the average speed calculated from the dispersal of particles forming faculae surrounding putative Mercurian volcanic vents of 284 m/s (Thomas et al., 2015a, 2015b) then the maximum final thickness of an accumulated pyroclastic pile would be less than 0.02 m and 1.25 m respectively. Such a topographically insignificant landform would likely quickly be destroyed or significantly modified by impact gardening or other surface modifications processes (including subsequent volcanism). This would make the discovery of such volcanoes a complicated task even with the high-resolution data expected to be returned by the ESA–JAXA BepiColombo spacecraft mission (*Benkhoff et al., 2010; Rothery et al*., 2010).

Another aspect which has to be considered in the attempt to find these pyroclastic features is their survivability on the surface of Mercury. Their subtle topography and the resulting easy erodibility may cause that all such features could be already destroyed by resurfacing events. However, the example of the Moon, which has had a similar history of impact erosion to Mercury (*Fassett and Minton*, 2013) and on which evidences of pyroclastic deposits has been observed both from orbit and by *in situ* investigation, indicates that if small-scale volcanic constructions are widespread enough, evidence of their presence can survive billions of years of geological time and therefore should also leave some detectable traces on the surface of Mercury.

4 Conclusions

Our study shows that the environmental properties on Mercury lead to wide dispersal of pyroclastic ejecta and preclude the formation of constructional volcanic edifices of the forms recognized on Earth and Mars. The final constructional shapes on Mercury may instead resemble a wide and very gentle blanket of pyroclastic deposits. However, the real width of the Mercurian pyroclastic deposits could be even greater than generally considered (e.g., *Kerber et al*., 2011; *Thomas et al*. 2014a,b). This is because the areal extent of the spectral anomalies, which commonly denote large deposits interpreted as pyroclasts (e.g., *Thomas et al*., 2015b), or morphological properties (e.g. breaks in slope angles) of explosive volcanic edifices (e.g. *Brož et al*., 2015), are measured by approaches that conservatively exclude the tenuous outer fringes of deposits which are barely detectable with current data (*Besse et al*., 2015, 2018). This approach, however, likely underestimates the volume of erupted pyroclastic material and in turn supports average values of initial speeds of ejected particles that are too low. Therefore, in reality, the pyroclastic deposits emplaced as the result of low-volume eruptions on Mercury (and also on the Moon) may be even thinner, in the range of centimeters to millimeters, so the volume necessary to create a detectable landform with orbital data might not be reached at all. For this reason, finding evidence of such explosive volcanic activity, such as the spherules of volcanic glasses similar to those discovered on the Moon, may require currently impractical *in situ* investigation. It may be more helpful, then, for future investigation of low volume pyroclastic deposits on Mercury (e.g., with data returned by the BepiColombo mission) to focus on physical and chemical variations of the surface material, rather than to search for subtle topographic signatures of those pyroclastic deposits formed by explosive volcanism.

Because there are other terrestrial bodies within the Solar System without an atmosphere (e.g., the Moon or Io), our results have implications beyond Mercury. We predict that on those airless bodies steep conical edifices cannot be constructed purely by the ballistic emplacement and accumulation of cold pyroclastic particles. Other processes, such as periodic effusive eruptions causing spattering of the ejected particles and/or formation of lava flows, may be required to steepen edifices into cones, such as those observed in the Marius Hills region on the Moon (*Lawrence et al*. 2013). Per nomenclature for Earth, cones constructed in this fashion are more properly referred to as “composite cones” and as a consequence, the concept of pyroclastic cones or scoria cones on airless bodies may not apply.

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