Modeling Dike Emplacement and Pyroclastic Eruptions on Mercury: Implications for Volatile Sources, Abundances, and Fates

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Background

-Volcanism on Mercury?: The question of whether Mercury's smooth plains were of volcanic or impact origin was resolved by the MESSENGER Mission.

-MESSENGER also revealed that volcanism on Mercury differed from that of the Earth Moon and Mars:
- -Shorter duration.
- -Little evidence of Floor-Fractured Craters.
- -Scant evidence of sinuous rilles.
- -No major volcanic rises.
- -No large shield volcanoes.
- -Style more akin to flood basalt volcanism.

-The presence of Pyroclastic Vents and Deposits was a major surprise!

-Initial physical volcanological analyses of the pyroclastic deposits and their source vents (1,2) suggested that the magmas associated with these eruptions were very volatile-rich, similar to some lunar and terrestrial magmas.

-Unknown, however, is the composition of the mantle of Mercury, its oxidation state, and the effects of partial melting and speciation on magma generation, ascent and effusive and explosive eruptions.

The Problem

Do the source vent and pyroclastic deposit morphology and morphometry contain definitive information on the volatile abundance and composition of mantle melts?

-To address this question we ask:

-What can 1) the nature of the source vents, and 2) the ranges of pyroclastic deposits from their associated source vents, tell us about:
1) The eruption style (effusive degassing, explosive, plinian, hawaiian, strombolian, vulcanian)?
2) The eruption duration, episodicity, and length of any repose period (single event or repeated activity)?
3) Can the pyroclastic eruption vent and deposits be confidently used to infer the volatile content of the source magma?
4) What is the nature of the eruption source (active dike, stalled dike, sill, thrust fault, shallow intrusion, etc.)
5) What are the ages of the pyroclastic vents and deposits and how are they related to the record of effusive volcanism?
6) What can the geologic setting and associations of the source vents and pyroclastic deposits tell us about these questions?

Our Approach

-Pyroclastic eruptions represent rapid transfer of magmatic volatiles from depth to the surface.

-The nature, morphology, mineralogy and age of deposits and vent structures provide important evidence for assessing modes of eruption, volatile species and abundances, dispersal, transient atmosphere contributions and potential surface alteration processes.

-On Mercury, a large number of individual pyroclastic vents and deposits have been documented and many ages extend to post-extensive volcanic plains geologic history.

-We use deposit and vent characteristics and volumes, and their relatively young ages, to assess the nature of candidate dike-emplacement events and related periods of gas venting to the surface.

-We find that primary gas formation (propagating dike-tips) combined with significant secondary gas enrichment (stalled dikes) could result in rapid transient volatile venting to the surface in concentrations that do not necessarily represent the abundances in the primary magma.

Explosive Volcanism on Mercury

-Explosive volcanic activity was not anticipated for Mercury, which was expected to be depleted in volatiles.

-However, at least 39 deposits morphologically consistent with emplacement by explosive activity have been identified.

-The contrast between the small volumes of pyroclastics and the large volumes of flood lavas on Mercury is striking.

-The sources of the deposits are rimless, generally irregular pits, ~5- 45 km in diameter.

-Consideration of the energetics of eruptions in a vacuum shows that to reach the observed deposit radii, mainly in the range 20-50 km, required the erupting magma to contain ~4000 to 12000 ppm CO or the equivalent (inversely proportional to the molecular weight) of other volatiles.

-Candidate volatiles depend on the oxidation state of Mercury's interior and include CO, N_2, S_2, CS_2, S_2Cl, Cl, Cl_2 or COS (reducing interior, most likely) or CO, CO_2, H_2O, SO_2, or H_2S (oxidizing interior, less likely).

-Equilibrium release from ascending magmas of up to 12000 ppm volatiles is not expected given the current understanding of Mercury's composition and oxidation state.

-Also the mechanism of formation of the pits associated with the deposits is unclear.

-This suggests that some process may be required to concentrate volatiles into the tops of ascending dikes that fail to breach the surface to form lava flows.

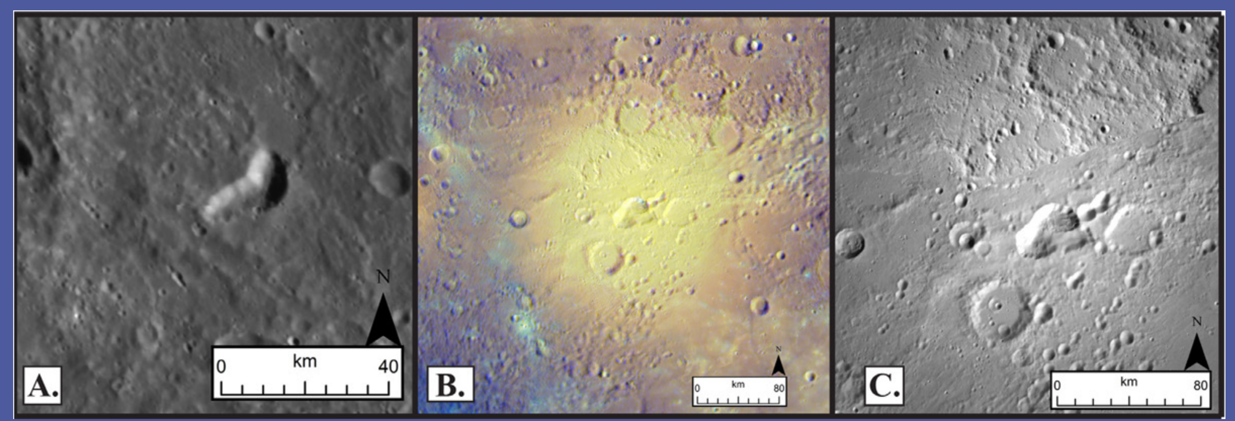

Fig. 1. Three identification criteria for pyroclastic vents on Mercury. A) Vent morphology distinct from secondary crater. B) "Red Spot" color anomaly seen in MDIS false-color mosaic. C) High reflectance anomaly associated with deposit material.

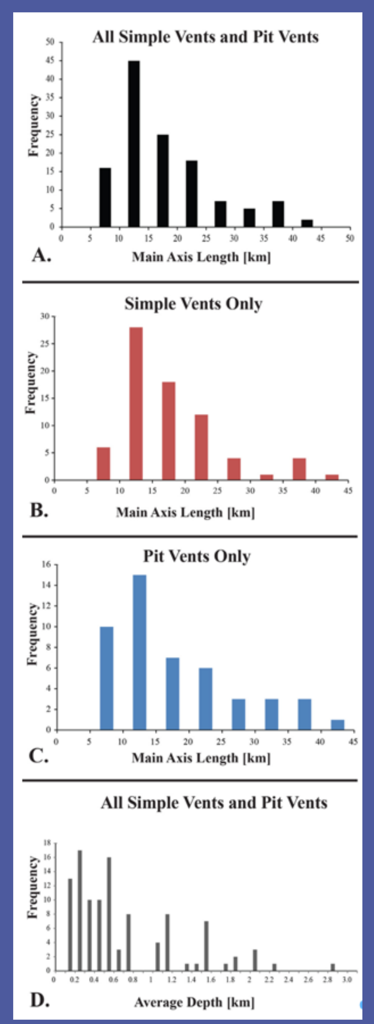

Fig. 2. Frequency distributions of: A) long axis lengths for simple and pit vents. B) simple vent long axis lengths. C) pit vent morphology main axis length. D) average depth for both simple and pit vents.

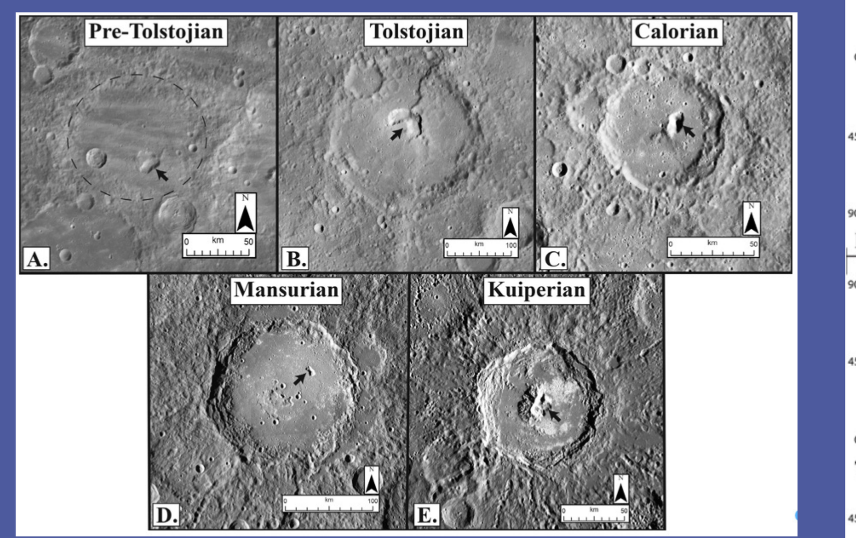

Fig. 4. Host crater degradation states and associated mercurian chronostratigraphic period.

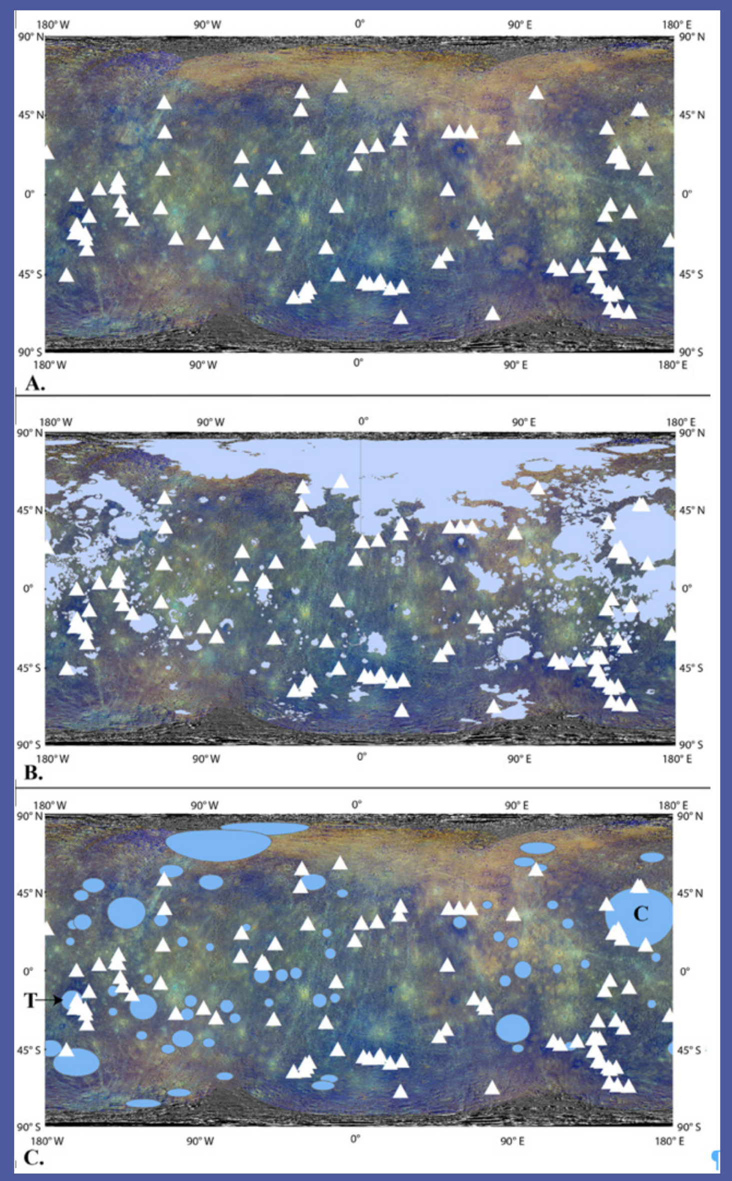

Fig. 3. A) Global distribution of pyroclastic vents (Jozwiak et al, 2018). B) Compared with distribution of smooth plains deposits (after Denevi et al., 2013). C) Compared with locations of impact basins greater than 200 km in diameter (Fassett et al., 2011).

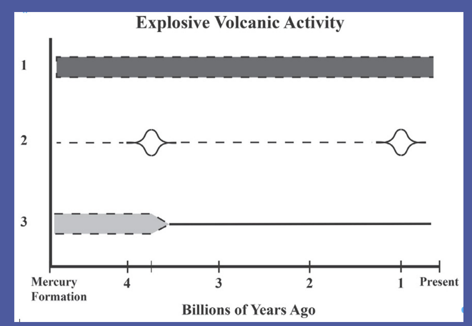

Fig. 5. Proposed scenarios for the history of explosive volcanism on Mercury. Scenario 1: Sustained explosive volcanism throughout mercurian history. Scenario 2: Two pulses of explosive volcanic history: initial pulse is centered near onset of global contraction (3.7 Ga), accounts older volcanic vents; second centered in relatively recent history, accounts for few volcanic vents in craters formed in Mansurian/Kuiperian periods. Scenario 3: Majority of explosive activity occurred early, tapering off after transition to global compressive stress state (~3.5 Ga); solid line indicates continued pattern of explosive activity at a reduced rate.

Candidate Formation Models

A) Lunar floor-fractured crater formation model: (Schultz, 1976; Jozwiak et al., 2012, 2015). Sill/laccolith formation in shallow subsurface beneath crater, leading to uplift of crater floor and peripheral diking from sill edges.

B) Sill/laccolith with dike-tip overshoot model: (Wilson and Head, 2018). Geometry similar to A, but includes dike-tip overshoot, leading to crater floor uplift, localization of volcanic morphologies over dike-tip region.

C) Surface dike degassing model: Dike propagates to surface without interruption and explosively vents.

D) Stalled dike degassing model: Dike stalls at some depth beneath crater floor, secondary volatile buildup, leading to explosive degassing after sufficient volatile build-up.

E) Thrust fault degassing model: Dike propagating from depth intersects existing thrust fault, causes magma and or volatiles to propagate along thrust fault and explosively vent at surface along leading edge of thrust fault-related landform.

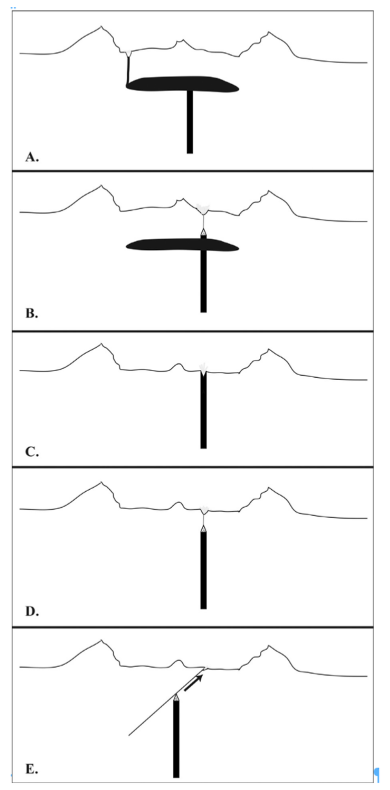

Fig. 6. Candidate formation geometries for mercurian explosive volcanic deposits (Jozwiak et al., 2018).

Ongoing Work

-On the basis of the close correlation of:
1) pit craters,
2) pyroclastic deposits,
3) the floors of complex flat-floored impact craters,
4) often contiguous/nearby wrinkle ridges/lobate scarps interpreted as thrust faults,
5) some occurrences in demonstrably younger (Mansurian/Kuiperian-aged) craters

-We are investigating four hypotheses:

1) Could the strong global compressive state of stress in the Mercury lithosphere in post-3.5 Ga history inhibit magma rise and cause dikes to stall at depth below the crater, leading to secondary gas buildup and subsequent propagation of the dike to the surface to produce an explosive eruption forming the pit crater and the deposit?

2) The occurrence on the floors of complex impact craters suggests the role of a basal impact breccia lens in the formation of these examples of pits and pyroclastic deposits: How do the geometries of such lenses in the Mercury cratering environment differ from those of the Moon and lunar floor fractured craters and what are the consequences?

3) Could the strong global compressive state of stress cause dikes to stall at depth below the crater leading to "lunar floor-fractured crater"-like sills that form at such depths that crater-floor uplift and floor-fracturing is inhibited? Subsequent secondary gas formation and buildup in the deep sill would lead to dike propagation and a pyroclastic eruption.

4) Does the association with contiguous/nearby wrinkle ridges/lobate scarps interpreted as thrust faults support the "venting along the thrust fault plane" hypothesis, or could it be related to the closure of the dike associated with gas venting?

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