EFFUSIVE VOLCANISM ON MERCURY FROM MESSENGER MISSION DATA: NATURE AND SIGNIFICANCE FOR LITHOSPHERIC STRESS STATE AND MANTLE CONVECTION.

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Introduction: Analysis of the generation, ascent, and eruption of magma on the Earth and planets provides substantial information about the geological history and thermal evolution of each body. Here we synthesize the array of extrusive features and landforms seen on the terrestrial planets [1,2] and those observed to date on Mercury by the MESSENGER spacecraft [3-8] and explore how they provide insight into eruption styles, lithospheric stress states, and mantle convection on Mercury.

Volcanic Features and Styles on the Terrestrial Planets: Surface elemental compositions of the terrestrial planets are consistent with a range of mantle compositions, but all are likely to produce mafic to ultramafic melts. The main controls on the types of surface volcanic features and accumulations are thus expected to be differences in 1) magma compositions and volatile contents, 2) tectonic regimes, 3) crustal densities, 4) crust and lithosphere thicknesses, and 5) mantle convective style. Preferred locations for magma reservoirs appear to be either at depth within a planetary interior or relatively shallow within a volcanic edifice. Deeper reservoirs can form near the rheological change at the base of the lithosphere, at upwellings due to pressure-release melting, or at vertical discontinuities in density such as at the base of the crust. Evidence for reservoirs in edifices is seen in calderas. Evidence for deeper magma bodies is seen in giant dike swarms. The position of ascending mantle flow is often marked by broad rises formed from thermal uplift, enhanced crustal construction, and individual edifices built by surface eruptions (e.g., Iceland and Hawaii on Earth, Tharsis on Mars, Beta Regio on Venus). On Venus, volcanic complexes and rises are often accompanied by large annular deformational features (coronae) produced by some combination of uplift and accommodation of intrusive and extrusive loads.

Shallow magma reservoirs are commonly formed within volcanic edifices on Earth, Mars, and Venus. Building a volcanic edifice and reservoir requires multiple pulses of magma to rise frequently within a spatially restricted region over an extended period of time. On the Moon, in contrast, low eruption frequencies and great flow lengths ensure that typical large edifices will not form. Shallow reservoirs form within edifices at levels of neutral buoyancy. Repeated, relatively small-volume eruptions from these shallow reservoirs (Fig. 1) progressively build shield volcanoes of a range of sizes and aspect ratios on Earth, Mars, and Venus. These shield volcanoes commonly host collapse calderas at their summits, produced when substantial volumes of magma are erupted on the volcano flanks.

Deeper magma reservoirs have certainly existed on Earth, Venus, and Mars. Giant dike swarms can be recognized by eroded outcrops (Earth and Mars), the radial patterns of volcanic vents that they feed (Venus), and/or the graben formation that they cause (Venus and Mars). These giant dikes are close analogs to the large dikes that fed magma to the surface of the Moon from near the base of its crust. When mantle magma rises to a density step at the crust-mantle boundary, a stress regime characterized by net horizontal extension will favor upward propagation of dikes, whereas horizontal compression will favor initial sill formation.

Evidence for volcanism from surface features on Mercury: On the basis of Mariner 10 [3-5], MESSENGER flyby data [6-7], and initial orbital observations from MESSENGER [8], we see no evidence for large shield volcanoes on Mercury like those on Earth, Mars, and Venus, and we see only small numbers of low shield-like constructs and candidate calderas, some reminiscent of those on the Moon. No evidence has been discerned for extensive centers of volcanism as seen on Mars (e.g., Tharsis, Elysium) or Venus (e.g., Beta and Atla Regiones), or less well-developed ones as seen on the Moon (e.g., Marius and Rumker Hills). Nor has evidence been seen for any Venus-like corona or related annular deformational features displaying associated volcanism. Only one radial graben structure (Pantheon Fossae), centrally located in the Caloris basin, has been documented [7].

Observations of Mercury to date also reveal no evidence for several types of volcanic features (cones, leveed flows, or sinuous rilles). Instead, we see evidence on Mercury for extensive flooding of the surface to form regional smooth plains that appear to be very extensive lava sheet flows, and intercrater plains (found between large, old impact craters) that may also be formed by volcanic eruptions [3]. Volcanic plains filling the interior of the Caloris basin show generally uniform ages and spectral characteristics [10-11] and are up to several kilometers thick [12]. Exterior plains of volcanic origin have similar to slightly younger ages [10-11]. Contiguous plains at northern high latitudes cover ~6% of the surface of Mercury, have surface ages and spectral properties that show no resolvable variation, and reveal no specific source regions or associated edifices [8]. Generally the Caloris-related and northern volcanic plains show no signs of broad, rifted rises, constructional landforms (shield volcanoes), or individual linear, leveed flow fronts. The general characteristics of the plains deposits and features on Mercury strongly suggest that they were emplaced by flood-lava-style eruptions (Fig. 1) [5] rather than collections of narrow, leveed flows typical of small dike-emplacement events and more limited-volume surface eruptions.

This overview of the range of volcanic and associated tectonic landforms seen on Mercury from Mariner 10 and MESSENGER data indicates little deformational or constructional evidence for localized convective upwelling (e.g., radially/concentrically deformed structures, volcanic rises/edifice concentrations, coronae) or the presence of local shallow crustal magma reservoirs (e.g., large shields, abundant floor-fractured craters, calderas, narrow channelized flows, aggregation of small volcanic constructs). Magma delivery to the surface in the presence of convection occurs as both the host rock and melt rise together in convection cells and encounter more brittle rocks; dikes then transport melt to the surface in the vicinity of a rising mantle diapir. Where convection is suppressed or absent, the process is different; a vertically and laterally extensive melt layer can form beneath a conductively cooled lithosphere and as the amount of partial melting increases, the corresponding volume increase causes an increase in pressure in the growing melt layer [13]. Expansion of the melt layer exerts extensional stresses on the overlying lithosphere, inducing vertical fractures that form dikes through which melt escapes. In non-convecting mantles the elastic lithosphere will tend to be thinner and more susceptible to penetrative dike formation than for convecting systems, and flood volcanism will be favored. Analysis of magma transport and delivery from depth predicts eruptive fissure widths of ten to several tens of meters and lengths in the 40-90 km range, consistent with flood volcanism [13].

The typical mode of eruption of magma in the flood lava mode has been explored [6,13] for a range of mafic mantle melts. The great lengths of fissures and large dike widths cause broad sheet flows rather than long, narrow, leveed and channelized lava flows. Lava is released at high volume fluxes from these long, wide fissures to flow downslope in a turbulent manner. A typical flow will be 1.4-1.9 times thicker than comparable flows on Earth, reaching distances of ~300 km in ~20-60 hours. Flow fronts cease to advance not due to cooling but instead due to cessation (or major reduction) of supply at the vent (flows are volume-limited, not cooling-limited). Under these conditions, the vast majority of lava-flow emplacement events will be in the flood lava mode, and lava distribution will vary as a function of global magma generation history and longer-term thermal evolution. Direct eruption from depth will slow and cease as lithospheric horizontal stresses increase. These conclusions hold equally well for both basaltic magma and magma with compositions intermediate between basaltic and komatiitic [14], because the changing stresses exert more influence on the ability of a dike to remain open through the full vertical extent of the lithosphere than on the speed with which magma can flow through the dike.

In summary, magmatism on Mercury appears to be characterized predominantly by: 1) deeper magma sources of large volume, 2) minimal shallow crustal storage of magma, 3) vertically extensive and wide dikes penetrating completely through the lithosphere and crust, and 4) high-volume eruption rates of lava and correspondingly voluminous outpourings producing long/wide lava flows covering extensive areas.

These observations are interpreted to mean that the ability of magma to reach the surface on Mercury has been strongly influenced by 1) the presence or absence of mantle convection and 2) the lithospheric stress state. The comparatively small vertical extent of Mercury's mantle [15] may inhibit convection and favor sublithospheric magma buildup and extensional lithospheric stresses on local to regional scales in the planet's early history. A late-stage tectonic history dominated by horizontally compressive lithospheric stresses could account for the termination of an early period of voluminous volcanic activity. Modeling of the effect of increasing horizontal compressive stress on the ability of dikes to penetrate and remain open through the full thickness of Mercury's lithosphere of Mercury [5] has shown that lithospheric magma transport was suppressed when compressive stresses exceeded critical values in the range of several tens of MPa, similar in magnitude to the stresses thought to form the global system of lobate scarps and other contractional landforms [16].

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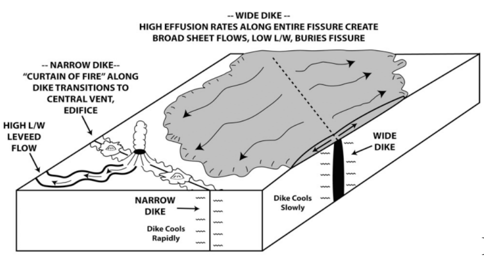

Fig. 1.