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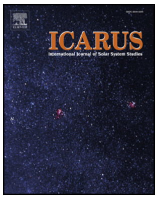

The spatial distribution of Mercury's pyroclastic activity and the relation to lithospheric weaknesses

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ABSTRACT

Mercury's surface preserves a rich history of volcanism, impact cratering, and tectonic deformation. Geological observations show that the earliest evidence of thrust faulting that was induced by the secular cooling and resulting global contraction of the planet coincided with the waning stages of effusive volcanism, but that explosive volcanism continued beyond this point. Stresses from global contraction, however, would have precluded efficient vertical magma ascent. Sites of pyroclastic activity—manifest as irregular depressions surrounded by diffuse, spectrally distinct halos—spatially coincide with lithospheric discontinuities, such as faults or those associated with impact craters. The vast majority of explosive vents are situated on the floors, rims, central peaks, or peak rings of impact structures. A substantial portion of such vents is also proximal to thrust faults: they are most spatially concentrated at or within 20 km of faults, with ever fewer vents progressively farther from tectonic structures. We statistically evaluated the spatial distribution of sites of pyroclastic activity with respect to faults and impact craters by generating sets of random point locations of equal count to those volcanic sites, computing their spatial relationship to the mapped faults and craters, and comparing them to our observations. We find that although the observed proximity of vents to faults is indistinguishable from a random distribution, their spatial association with impact craters is non-random. To examine the interrelatedness of several geospatial relationships of lithospheric weaknesses and pyroclastic activity, we performed a principal component analysis that tested correlations between vent size, the presence of vents within a crater, the diameters and degradation states of those craters, and vent distance from mapped faults, which help tie together interpretations of magma volumes and eruption energies, repeated utilization of magma pathways, and durations of eruptive events in the geological context of global contraction. Results reveal a predominance of small-sized vents indicative of short-lived, low-volume pyroclastic activity that are consistent with suppressed volcanism after the onset of global contraction. Greater size ranges of vents are found in large impact craters and when faults are nearby, which points to denser fracture networks facilitating magma ascent.

1. Introduction

Tectonism and volcanism on Mercury are closely intertwined, as both processes are tied to the thermal evolution of the planet. Its thermal history has largely been characterized by a long, sustained period of global contraction resulting from planetary cooling (Solomon, 1977). With the overall thermal state of the planet dominated by secular cooling, Mercury's continuously thickening lithosphere was subject to stresses from global contraction and so became increasingly inimicable to vertical magma ascent and widespread volcanic activity (Solomon, 1978; Wilson and Head, 2008). Instead, the contractional tectonic regime produced thrust faults (Solomon et al., 2008), manifest today as a global population of shortening landforms (Byrne et al., 2014; Figure 1) that began to form some 3–4 Ga ago (Banks et al., 2015; Crane and Klimczak, 2017). Geological observations and thermal evolution modeling together imply that widespread, dike-fed volcanism and major volcanic resurfacing were essentially limited to the time prior to global contraction (e.g., Solomon, 1978; Byrne et al., 2016).

However, geologic units interpreted as having been emplaced by explosive volcanism, on the basis of their spectral contrast with surrounding terrain, diffuse appearance, and spatial association with landforms thought to be volcanic vents (Head et al., 2009; Kerber et al., 2009), appear to have a broader range of ages (Goudge et al., 2014;

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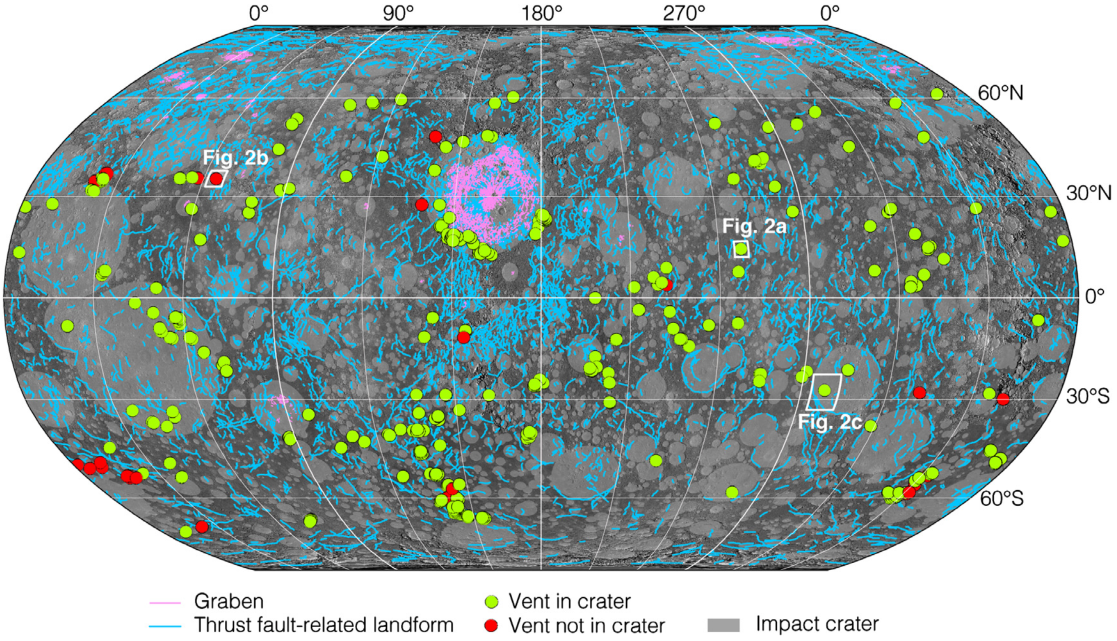

Fig. 1. The global distribution of vents associated with pyroclastic volcanism (dots), as well as normal- (pink lines) and thrust fault-related landforms (blue lines) shown on a global MESSENGER monochrome image mosaic in Robinson projection centered at 180°. Vents that occur in impact craters are in green; those that are not inside an impact crater are shown in red. Vent data after Thomas et al. (2015); fault data after Byrne et al. (2013, 2014). Impact craters (shown in light gray) after Fassett et al. (2011) and Kinczyk et al. (2016).

Thomas et al., 2014) that temporally overlapped with global contraction. Furthermore, many sites of pyroclastic activity occur within impact craters or along or near fault-related landforms (e.g., Goudge et al., 2014; Jozwiak et al., 2018).

Both fault-related landforms and impact craters represent lithospheric discontinuities. Faults are planar or zonal structures accommodating shear displacement via frictional sliding that include one or more slip planes (e.g., Schultz and Fossen, 2008), the fault core (a tabular zone of intense shear deformation: e.g., Childs et al., 1997), and a confining damage zone (e.g., Kim et al., 2004; Peacock et al., 2017). The largest faults on Mercury are found to reach depths of 35–40 km (e.g., Egea-Gonzáles et al., 2012). Impact craters create a damage zone beneath and surrounding the site of impact (e.g., Melosh, 1984; Ahrens and Rubin, 1993; Xia and Ahrens, 2001; Collins et al., 2004). In addition, complex craters and basins show abundant lithospheric-scale weaknesses with high degrees of deformation involving faulting and fracturing at the crater rim (e.g., Spray, 1997), crater floor (e.g., Kenkmann et al., 2013), and especially at central uplifts and peak ring structures (e.g., Morgan et al., 2000; Kenkmann et al., 2005; Osinski and Spray, 2005). The depth extent of impact crater damage zones is found to scale with a combination of factors, including impactor size, impact velocity, and target strength (e.g., Xia and Ahrens, 2001), so typically larger craters are expected to produce bigger and presumably deeper damage zones. The timescale and extent to which fractures on Mercury anneal through, for instance, formation of pseudotachylites or recrystallization in the lower crust remains largely unexplored. But crustal densities derived from Gravity Recovery and Interior Laboratory (GRAIL) measurements reveal that fractures introduced by impacts over the Moon's geologic past served to increase crustal porosities (e.g., Wieczorek et al., 2013), indicating that such fractures remain open and, thus, represent lithospheric weaknesses for a substantial amount of time.

In this study, we statistically evaluate if and how much impact craters and fault-related landforms and their associated lithospheric weaknesses are geospatially tied to sites of pyroclastic volcanism. Knowledge of how tectonic phenomena and pyroclastic volcanism interrelate has implications for the modes, locations, and timing of magma ascent on Mercury, especially for eruptions that occurred after the prevailing tectonic regime became dominated by global contraction.

2. Volcanic deposits and vents

Mercury's surface shows evidence for volcanic resurfacing, with plains interpreted to be volcanic in nature comprising almost a quarter of Mercury's surface (Denevi et al., 2013). These units are thought to have been emplaced as high-volume, short-duration flood basalts (Head et al., 2011; Byrne et al., 2013). The majority of such voluminous resurfacing ended at around the same time as the earliest evidence for thrust faulting is apparent (Byrne et al., 2016). Additionally, several hundred instances of pyroclastic deposits have been identified on Mercury, interpreted as such on the basis of their spectral contrast with surrounding terrain, diffuse appearance, geochemical signature, and spatial association with landforms regarded as volcanic vents (Kerber et al., 2009, 2011; Goudge et al., 2014; Thomas et al., 2015; Weider et al., 2016). The vents themselves are irregularly shaped depressions that lack the terraces and elevated rims that characterize impact craters.

The pyroclastic deposits show a broad geographic distribution (Kerber et al., 2011; Goudge et al., 2014; Thomas et al., 2015) (Fig. 1). Superposition relationships and crater size–frequency measurements indicate that the deposits collectively span a wide set of emplacement ages (Goudge et al., 2014; Thomas et al., 2014). Together, these observations indicate that pyroclastic activity on Mercury was much longer lived, although less voluminous, than effusive volcanism, and that explosive eruptions overlapped temporally with global contraction-induced thrust faulting (e.g., Banks et al., 2015; Crane and Klimczak, 2017). Furthermore, compound vents observed near the rim of the Caloris basin indicate that magma pathways may have been utilized repeatedly to produce multiple eruptions localized at these particular sites (Rothery et al., 2014). Volcanism, as a means of transporting material from depth to the surface, was therefore clearly not fully suppressed after the onset of global contraction.

We closely examined a number of pyroclastic units across Mercury