AMENTHES CONES, MARS: HYDROVOLCANIC (TUFF) CONES FROM PHREATOMAGMATIC EXPLOSIVE ERUPTIONS?

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Introduction: The existence of explosive volcanism on Mars was predicted on theoretical grounds [e.g., 1], but only few direct observations are available [2-7]. In a previous study [7], we suggested that a volcanic field in the Ulysses Fossae region (Tharsis province, Mars) exhibits pyroclastic cones probably formed by "dry" explosive eruptions driven by magma degassing. Since the shallow Martian subsurface contains water ice in varying amounts in wide areas [e.g., 8-11], and very likely contained even more water and/or water ice in the past, it is reasonable to expect that phreato-magmatic explosions left some evidence of "wet" explosive eruptions in the observable geologic record.

Here we present our observations of a large field of pitted cones that are located along the dichotomy boundary in the Amenthes region. The regional context displays several lines of evidence for subsurface water ice (rampart craters, pseudo-craters, the Hephaestus and Hebrus Fossae channels). The motivation of our study is to test the hypothesis of a (hydro)volcanic origin of the cones (Fig. 1).

Data: We used images from several cameras, e.g., HRSC, CTX, HiRISE, for morphological analyses. Topographic information (e.g., heights and slope angles) was determined from single shots of the Mars Orbiter Laser Altimeter (MOLA) in a GIS environment, and from stereo images (HRSC) and derived gridded digital elevation models (DEM).

Geologic setting: The cones are situated on a bench or boundary plain below the dichotomy scarp between ~95°E and 120°E, between Tyrrhena Terra in the south and the Utopia impact basin in the north (Fig. 2). The plain is gently sloping north towards the interior of Utopia. Recent results indicate that volcanism was common and long-lived in the region, not only at the Elysium bulge [12] and the Amenthes Fossae region [13], but also in the plains of Isidis Planita [14], locations in Utopia [6], and the Nephentes region to the southeast of our study area [15-17].

Previous studies of the cones are sparse. To our knowledge, the only in-depth study is that of Skinner and Tanaka [18]. Based on the morphologic interpretation of an assemblage of landforms (fractured rises, mounds, isolated and coalesced depressions, and the pitted cones studied here), the comparison to terrestrial analogues, and the sedimentary and tectonic setting, Skinner and Tanaka conclude that an origin as mud volcanoes best explains their formation [18]. An igneous volcanic origin is rejected by [18] because of (1) the large distance to known volcanic vents, (2) a lack of obvious structural control of dike-related eruptions, (3) the confinement to a specific latitude and elevation range, (4) the setting in a compressional tectonic regime, and (5) the pitted cones being part of a broader assemblage of landforms (see above).

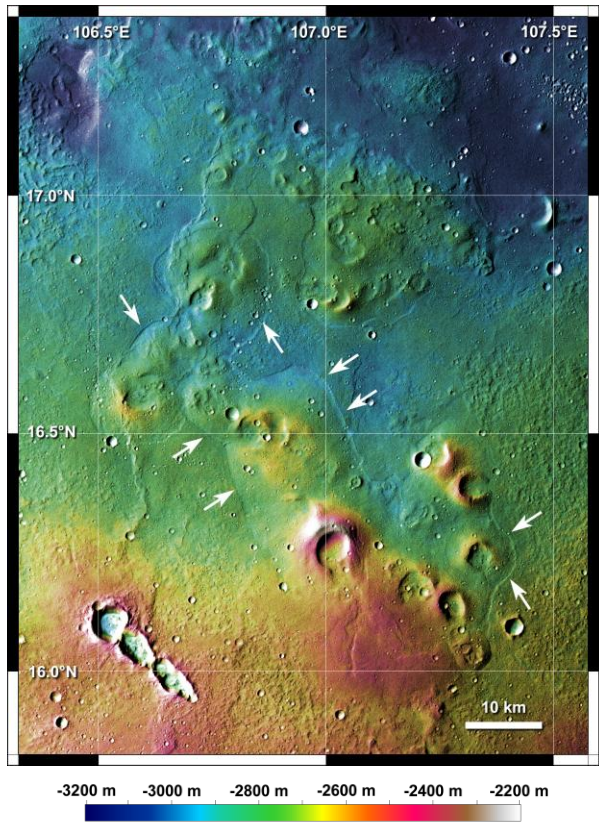

Fig. 1: An example of pitted cones. Note their clustered occurrence and the fact that several of the cones are breached in different directions. Smooth lobate material embays the cones (arrows). Image and color-coded DEM derived from HRSC imaging sequence h3032_0000.

Morphology: The study area displays >170 cones, often overlapping each other and forming chaotic clusters that widely spread throughout the Amenthes region. Individual cones are ~5 to 10 km wide and several hundred meters high. Cones often have well-developed central deep and wide craters (resulting in a large W_{cr}/W_{co} ratio: median 0.4). The crater floors have elevations that are above the surrounding plains. Cones are often breached, and in several cases lobate flows seem to have emanated from the breached cones and moved gravitationally downslope. Flank slopes of cones are mainly concave-upwards, but can turn to convex near the crater rims. High-resolution HRSC DEMs show that flank slopes are typically below 10°, but can reach up to about 20° in the steepest parts.

Discussion: Terrestrial volcanic fields are typically results of "dry" and/or "wet" explosive activity forming a wide variety of small volcanic edifices, such as cinder/spatter cones, tuff rings, tuff cones, and maars, often referred to as "monogenetic" volcanoes. The interaction of ascending magma with water or ice is one of the factors controlling the morphology of volcanic edifices. Typical results of phreatomagmatic eruptions are tuff cones, tuff rings, and maars [19]. Tuff rings and cones are "small (less than 5 km in diam), monogenetic volcanoes composed of tuff that results from hydrovolcanic (hydro-magmatic) explosions" [20, p. 386]. In general, the observed morphology, shape and size of the pitted cones in our study area are similar to those of terrestrial tuff cones or rings, except a larger absolute basal diameter. We note, however, that cone morphology alone is not a reliable indicator for eruptive conditions [21].

Regional context of volcanism. Is there a plausible scenario that would explain the occurrence of igneous volcanism in the study area? The cones occur within an elongated zone of ~1500 km length and 200 km width that is oriented roughly parallel to the highland-lowland scarp. In the light of recent results [6, 14-16], it appears that they might be part of a wide zone of magmatic activity that spans from the Elysium bulge in the east to Isidis Planitia to the west (Fig. 2). The exact location of the cones might be explained by one or a combination of the following two scenarios: (1) Loading stresses due to the magmatic infilling of large (compared to the planetary radius) impact basins can induce a favorable combination of extensional membrane stresses and upward-increasing extensional flexural stresses (positive "tectonic stress gradient") at basin margins that can drive the ascent of magma in dikes directly from mantle melt zones to the surface [22]. Indeed, the studies cones are located within the Utopia-circumferential zones of maximum likelihood of magma ascent [22], and the densest population of cones (in the western part of the study area) is situated near the overlap of this zone and the corresponding zone concentric to the Isidis basin. (2) The bench or boundary plain on which the pitted cones are located lies along a zone of extension that parallels the topographic scarp of the dichotomy boundary between eastern Arabia and Cimmeria Terrae [23] (Fig. 2). The cones are situated toward the north of the highland-lowland scarp, which also marks the transition of thicker crust in the south to thinner crust in the north [24]. Lower-crustal flow from thick crust in the south towards thinner crust in the north can induce extension (favorable for magma ascent) just north of the highland-lowland scarp [25]. It has also been speculated [cf. 24] that thick accumulations of volcanic material could explain the positive Bouguer anomalies along this part of the dichotomy boundary [26]. Hence, past volcanism seems to be plausible in our study site.

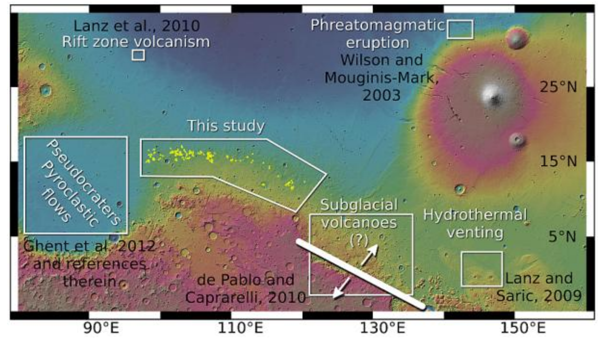

Fig. 2: Study area (with pitted cones marked as yellow symbols) in the regional context. White boxes mark areas where volcanism has recently been reported. White arrows mark extension as reported by [23].

Conclusions: We conclude that an origin as hydrovolcanic cones is consistent with the observed morphology and the regional geologic setting. While the consistent scenario of [18] can not be ruled out, we note the presence of extensional stresses and regional-scale volcanism (and volcanism can also occur in compressional settings [27], which weakens the rejection of volcanism on tectonic reasons). A contribution of phreatomagmatic explosions to the observed landscape morphology seems possible, which would further contribute to the notion that volcanism on Mars was widespread and morphologically diverse.

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