AMENTHES CONES, MARS: HYDROVOLCANIC (TUFF) RINGS AND CONES FROM PHREATOMAGMATIC EXPLOSIVE ERUPTIONS ON MARS

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Introduction: Mars was volcanically active throughout most, if not all, of its history [e.g., 1-4], and volcanism played a significant role in the formation of its surface. Another factor modifying the Martian surface is water, both in liquid and frozen state, and at and beneath the surface [e.g., 5]. Interactions of magma with water and/or ice should be common on Mars, therefore. On Earth, such interactions are known to trigger hydrovolcanism [6], the natural phenomenon of magma or magmatic heat interacting with an external water source [6] producing tuff rings, tuff cones and maars as typical landforms. The existence of explosive volcanism on Mars was predicted on theoretical grounds [7], but only few direct observations are available [8-13]. Moreover, no detailed studies of the reported hydrovolcanic landforms are available (with ref. [14] as aan exception).

Here we present observations of a large field of pitted cones along the dichotomy boundary in the Amenthes region (Figure 1), previously described by [15] as result of mud diapirism forming mud volcanoes. The aim of our study is to test the hypothesis of an igneous (hydro)volcanic origin of these cones.

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). Terrestrial data obtained from Google Earth software.

Geologic setting: The study area (10°N to 20°N and 95°E to 125°E) lies close to the dichotomy boundary, between cratered highlands in the south and smoother appearing northern plains and close to the two giant impact basins, Isidis and Utopia. Recent results indicate that volcanism was common and long-lived in the region, not only at the Elysium bulge [16] and the Amenthes Fossae region [17], but also in the plains of Isidis Planita [18], locations in Utopia [12], and the Nephentes region to the southeast of our study area [19].

Previous studies of the cones are sparse. To our knowledge, the only in-depth study is that of Skinner and Tanaka [15]. Based on the morphologic interpretation of an assemblage of landforms (fractured rises, isolated and coalesced depressions, mounds 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 [15]. An igneous volcanic origin is rejected by [15] 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.

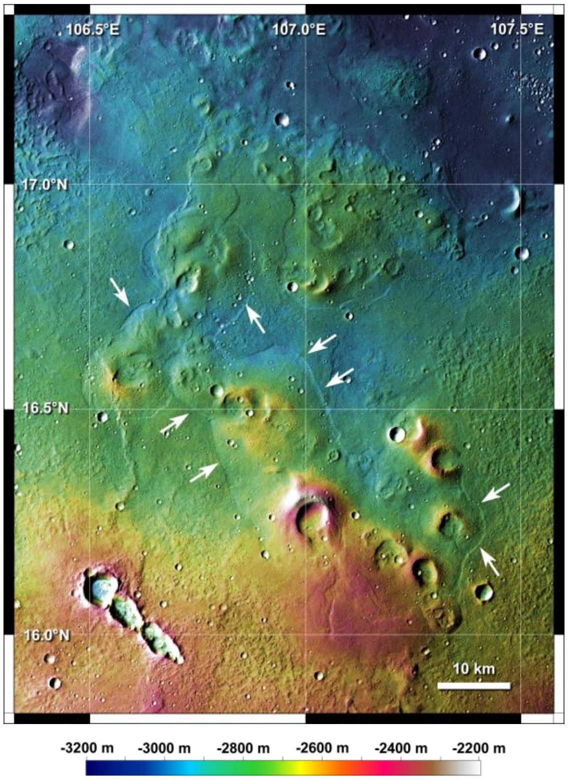

Fig. 1: An example of pitted cones. Note their clustered occurrence and the fact that several of the cones are breached in different directions. Smooth lobate material embays the cones (arrows). Image and color-coded DEM derived from HRSC imaging sequence h3032_0000.

Morphology: The study area displays >170 cones with texturally smooth flanks and typically wide central craters. Cones are often overlapping each other and forming chaotic clusters. In many cases, the rims of the central craters are breached, and only segments of a full cone are observed. Based on detailed morphological measurements, the investigated cones are ~3 to 15 km wide (mean 7.8 km) and ~30 to ~370 m high (mean ~120 m). Cones often have well-developed central deep and wide craters (resulting in a large W_{CR}/W_{CO} ratio: median 0.42). The crater floors have elevations that are above the surrounding plains.

Another type of positive topographic landform in Amenthes region is represented by small mounds with sub-circular to elliptical plan-form shapes already described by [15]. They are widely spread troughout the region. Many mounds have small summital cones or pits a few hundred meters across near their centres.

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 rings/cones, and maars [6]. 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 (Fig. 2). However, a similar relation can be observed for martian and terrestrial cinder cones (and low shield volcanoes), if compared. This might be associated to the lower gravity and atmospheric pressure, allowing a wider dispersion of ejected particles.

It also appears that the investigated cones are not very similar to mud volcanoes in Azerbaijan; previously used as their analogues. The crater floors of many investigated cones in the Amenthes region have elevations at or below the surrounding plains. However, this is not a common shape in cross-section for mud volcanoes in Azerbaijan (based on measurements in Google Earth software) and even for other terrestrial mud volcano fields on Earth [20]. We note, however, that cone morphology alone is not a reliable indicator for eruptive conditions [e.g., 21].

The second type of investigated landforms, the mounds, might be explained by igneous volcanism (as it was done for similar structures elsewhere on Mars, cf. [22]). Morphologically analogous features are well known from terrestrial volcanic fields, whether basaltic or more silica-rich in composition. These structures are a type of lava domes called coulees [23]. They form by more viscous magma, effusively erupted onto the planetary surface and laterally spreading outwards. Therefore they are not the result of mud volcanism. Also, we were able detect structures in association with clusters of pitted cones and mounds, which looked like double-collapsed *pseudocrater* [24]; a typical structure formed by interaction of lava with a water-rich substrate.

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 [15] can not be ruled out, we note the presence of extensional stresses and regional-scale volcanism (and volcanism can also occur in compressional settings [25], 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.

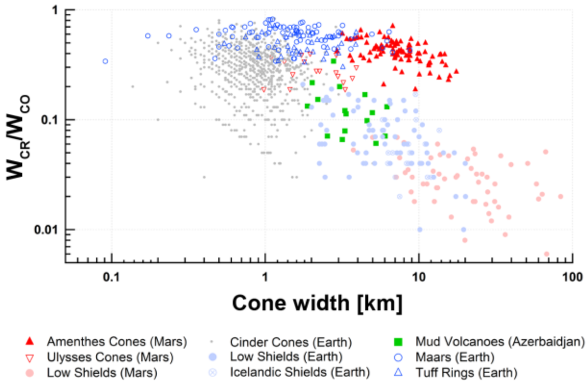

Fig. 2: Morphology of pitted cones in Amenthes region in comparison with several other types of terrestrial and martian volcanic cones displayed in plot of the ratio W_{CR}/W_{CO} versus the basal width (W_{CO}). Data for investigated cones in Amenthes and for terrestrial mud volcanoes in Azerbaijan this study, martian low shield volcanoes from [26], martian cinder cones (Ulysses Colles) from [13], tuff rings and maars from [27] and for terrestrial cinder cones from [28-29]. Note the difference in position and therefore W_{CR}/W_{CO} ratio between pitted cones in Amenthes and mud volcanoes offered as analogue by [15].

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