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Amazonian volcanism inside Valles Marineris on Mars

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ABSTRACT

The giant trough system of Valles Marineris is one of the most spectacular landforms on Mars, yet its origin is still unclear. Although often referred to as a rift, it also shows some characteristics that are indicative of collapse processes. For decades, one of the major open questions was whether volcanism was active inside the Valles Marineris. Here we present evidence for a volcanic field on the floor of the deepest trough of Valles Marineris, Coprates Chasma. More than 130 individual edifices resemble scoria and tuff cones, and are associated with units that are interpreted as lava flows. Crater counts indicate that the volcanic field was emplaced sometime between ∼0.4 Ga and ∼0.2 Ga. The spatial distribution of the cones displays a control by trough-parallel subsurface structures, suggesting magma ascent in feeder dikes along trough-bounding normal faults. Spectral data reveal an opaline-silica-rich unit associated with at least one of the cones, indicative of hydrothermal processes. Our results point to magma–water interaction, an environment of astrobiological interest, perhaps associated with late-stage activity in the evolution of Valles Marineris, and suggest that the floor of Coprates Chasma is promising target for the in situ exploration of Mars.

1. Introduction

The Valles Marineris on Mars are a ∼4000 km-long system of WNW–ESE-trending subparallel troughs (Lucchitta et al., 1994) with linear to irregular plan-forms that run roughly along the equator east of the Tharsis bulge, the largest known volcano-tectonic centre in the Solar System (Phillips et al., 2001). Since their discovery in 1970 (Sharp, 1973), their origin has been a subject of debate. Two main classes of processes have been put forward: Extensional tectonics (Masson, 1977; Mège et al., 2003), collapse (Spencer and Fanale, 1990), or a combination thereof (Andrews-Hanna, 2012a).

Although they were often compared to terrestrial continental rifts (Masson, 1977; Frey, 1979), the tectonic architecture of the Valles Marineris differs significantly from terrestrial continental rifts (Hauber et al., 2010). One model of the evolution of Valles Marineris holds that an early phase of subsidence of so-called ancestral basins was followed by a later phase of extensional tectonism which formed long and narrow linear topographic depressions such as the Ius–Melas–Coprates troughs, which link the older depressions and are interpreted as tectonic grabens (Lucchitta et al., 1994; Schultz, 1998). While the origin of the ancestral basins is effectively unknown, the orientation of the tensional stresses responsible for graben formation was controlled by the evolution of the enormous lithospheric loading by Tharsis magmatism to the west (e.g., Banerdt and Golombek, 2000; Phillips et al., 2001). Recently, Andrews-Hanna (2012b) proposed a model in which stress focusing at the Valles Marineris is attributed to its location just south of the buried dichotomy boundary. The emplacement of substantial magmatic intrusions as dikes in this stress belt would have led to a reduction of flexural support of lithospheric blocks between individual dikes and subsequent trough subsidence (Andrews-Hanna, 2012b), with only moderate amounts of extension as inferred from steeply-dipping fault geometries (Andrews-Hanna, 2012a).

Evidence for Valles Marineris-parallel dikes has indeed been identified in exposed walls and on adjacent plateaus (e.g., Mège et al., 2003; Brustel et al., 2017), consistent with the evolution of terrestrial rifts (Ebinger et al., 2010), but these dikes obviously formed before the major phase of trough subsidence. On the other hand, post-subsidence volcanism inside the troughs was suspected (Lucchitta, 1987) but had not been confirmed by more recent high-resolution data (Malin and Edgett, 2001).

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Here we present our observations of a large field of pitted cones on the floor of the deepest trough of Valles Marineris, Coprates Chasma, previously described by Harrison and Chapman (2008), Brož et al. (2015), and Okubo (2016). A formation as mud volcanoes in a compressional setting was considered possible by Harrison and Chapman (2008), but these authors emphasised that an igneous scenario could not be excluded by their observations. Whereas Okubo (2016) favoured mud volcanism based on arguments discussed in detail below, Brož et al. (2015) concluded that at least six cones of this field represent small-scale igneous volcanoes, i.e. scoria cones, as their shape can be reconstructed numerically by tracking the ballistic trajectories of ejected particles and recording the cumulative deposition of repeatedly ejected particles. However, the morphological evidence for their conclusion was not provided. In this study we investigate in detail the morphology of the cones and associated landforms as well as spectral features and, hence, further test the hypothesis that igneous volcanism was responsible for the formation of the pitted cones inside Coprates Chasma.

2. Methods

This study includes image data obtained by the Context Camera (CTX; 5–6 m px^{-1}; Malin et al., 2007), and the High Resolution Imaging Science Experiment (HiRISE; ~30 cm px^{-1}; McEwen et al., 2007) on board the Mars Reconnaissance Orbiter spacecraft. CTX image data were processed with the USGS Astrogeology image processing software, Integrated System for Imagers and Spectrometers (ISIS3), and JPL's Video Imaging Communication and Retrieval (VICAR). The data were projected in a sinusoidal projection with the central meridian set at 298°E to minimise geometric distortion. Terrestrial data for comparative analyses were obtained from Google Earth (Google Inc., 2015). Crater model ages were determined from crater size–frequency distributions, utilising the software tool *CraterTools* (Kneissl et al., 2011), which ensures a distortion-free measurement of crater diameters independently from map projection, and the software *Craterstats* (Michael and Neukum, 2010) applying the production function of Ivanov (2001) and the impact-cratering chronology model of Hartmann and Neukum (2001). The mapped crater population was tested for randomness to avoid the inclusion of secondary crater clusters (Michael et al., 2012) and the ages were derived using Poisson statistics to obtain a likelihood function with intrinsic uncertainty (Michael et al., 2016). Craters were mainly counted on CTX images, and in one case on a HiRISE image.

We applied the two-point azimuth technique originally developed by Lutz (1986) and later modified by Cebriá et al. (2011) to identify any structural trends within the western part of the cone field. The method is based on a quantitative analysis of the azimuth angles of lines connecting each vent with all other vents, thus connecting all possible pairs of points in the investigated area (for N points, the total number of lines is $N(N-1)/2$). The method defines a minimum significant distance between vents to eliminate potential bias by a preferential alignment of points caused by the shape of the investigated area (Cebriá et al., 2011) – for example, if a vent cluster with a plan-view shape of a narrow ellipse were analysed without considering a minimum significant distance, then the results would display a dominant orientation in the direction of the semi-major axis of the ellipse. The minimum significant distance (d) is defined as $d \leq (x - 1\sigma)/3$, where x is the mean of all distances between vents, and σ is the standard deviation of the mean distance between vents. We determined the value of the minimum significant distance to be 5.6 km. A histogram of azimuth values (from 0° = north, 90° = east, 180° = south) was produced, with bins of 15°, containing the number of lines per bin for lines <5.6 km long. High frequencies indicate possible structural controls of vent locations (Lutz, 1986; Cebriá et al., 2011). The statistical significance was determined for the azimuth values to find out whether the high frequency bins lie within the 95% confidence interval.

Hyperspectral data used in this study were acquired by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM; ~18 m px^{-1}), also on board Mars Reconnaissance Orbiter (Murchie et al., 2007). CRISM samples the ~0.4–3.9 µm spectral range at a resolution of ~6.55 nm/channel. We focused on the 1.0–2.6 µm range, which includes the key spectral features of both mafic and hydrated minerals while avoiding the detector boundary at 1 µm and the lower-signal region beyond the deep atmospheric CO_2 band at ~2.7 µm. Standard photometric and atmospheric corrections were applied to CRISM I/F data, including the "volcano-scan" method of atmospheric CO_2 mitigation (McGuire et al., 2009). To highlight features of interest and further reduce systematic artefacts in the spectra, regions of interest were ratioed to bland areas in the same detector columns, as is typical for CRISM data analysis (e.g., Mustard et al., 2008; Murchie et al., 2009).

3. Results

Recent high-resolution images obtained with CTX (~6 m px^{-1}) and HiRISE (~30 cm px^{-1}) enable studying landforms with dimensions as small as a few hundred meters in diameter. We studied the floor of Coprates Chasma between longitudes 296°E and 304.5°E, the topographically lowest part of the entire Valles Marineris with a plateau-to-floor depth from 7 to 10 km. The margin of Coprates Chasma is defined by normal faults oriented in the ~NW–SE direction as evidenced by faceted spurs on the trough wall edges (Peulvast et al., 2001). The floor is locally covered by landslides from the adjacent trough walls. It is characterised by a relatively smooth and flat surface which is crossed by a series of small wrinkle ridges and punctuated by conical hills. We identified more than 130 edifices in two clusters. The western cluster (Fig. 1a) is formed by 124 edifices spread over an area of about 155 × 35 km; the eastern cluster (centred at 303.78°E, 14.96°S) contains 8 edifices spread over an area of 50 × 18 km. The individual edifices in the larger western cluster occur either isolated or, more commonly, they are grouped into smaller subclusters (Fig. 2a), in which individual cones may overlap each other. Edifices are between 0.2 km and 2 km in diameter, with a mean of 0.8 km (based on 59 edifices). Some edifices have clearly visible summit craters.

Cones are often associated with adjacent, topographically elevated units that display a lobate shape in plan-view (Fig. 2b and c where the elevated unit is bounded by dotted line). The surfaces of these units are characterised by flow-like features radiating outward from the edifices. In close-up view, the texture of these flow features is typically obscured by a few meter-thick mantle of material and only the general plan-view shape can be recognised (Fig. 2b). Observations at HiRISE scale, however, reveal that this mantling layer is locally absent. In such windows, fine-scale layering is apparent at some parts of the cones (Fig. 2d), and the textures of some flows associated with elevated units are also discernible. These flows are characterised by a pattern of small ridges and furrows which are sometimes arranged in channel-like patterns (marked by white arrows in Fig. 2e and by dotted black line in enlarged part of the image). Additionally, several flows show a positive relief with marginal clefts (marked by black arrows in Fig. 2e, f). Cones have well-preserved shapes and they do not show much evidence for significant degradation either by erosion or by impacts. However, small outward-facing scarps of unknown origin can be recognised at the bases of some cones, hence these cones do not transition smoothly into the surrounding plains.