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Key Points:

- Previously unrecognized volcanic features on Mars are studied
- Potential evidence of late-stage volcanism is identified on the eastern Hellas basin rim
- In situ volcanic activity both prior to and following the formation of outflow channels is indicated by relative ages

Supporting Information:

- Supporting Information S1

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Volcanic Structures Within Niger and Dao Valles, Mars, and Implications for Outflow Channel Evolution and Hellas Basin Rim Development

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Abstract Outflow channel formation on the eastern Hellas rim region is traditionally thought to have been triggered by activity phases of the nearby volcanoes Hadriacus and Tyrrhenus Montes: As a result of volcanic heating subsurface volatiles were mobilized. It is, however, under debate, whether eastern Hellas volcanism was in fact more extensive, and if there were volcanic centers separate from the identified central volcanoes. This work describes previously unrecognized structures in the Niger-Dao Valles outflow channel complex. We interpret them as volcanic edifices: cones, a shield, and a caldera. The structures provide evidence of an additional volcanic center within the valles and indicate volcanic activity both prior to and following the formation of the outflow events. They expand the extent, type, and duration of volcanic activity in the Circum-Hellas Volcanic Province and provide new information on interaction between volcanism and fluvial activity.

Plain Language Summary Mars used to exhibit at least pulses of a wetter environment than it has today. One result of this is the huge "outflow channel" canyons found in several places on the planet. Our study area, the eastern rim of the 2,000-km-wide Hellas basin, is one such region. Canyon formation there was probably triggered when volcanic heating melted subsurface ice deposits. Traditionally, the culprits are thought to have been the two nearby large volcanoes, Hadriacus Mons and Tyrrhenus Mons. However, there is an ongoing debate on whether additional volcanic centers exist in the region. This paper describes several probable volcanic structures: small volcanic cones, a 6.5-km wide shield volcano, and a 25-km complex caldera structure that has been highly modified by the later outflow channel formation. We base our interpretation on the sizes, shapes, appearances, and locations of these structures. Our analysis shows that these volcanoes (1) are located within the canyon Dao Vallis and its tributary Niger Vallis and (2) that they were formed both prior to and after the canyons. We suspect they played a part in the melting episodes and are key evidence of how the outflows could have been triggered by smaller-scale volcanism than previously thought.

1. Introduction

Dao Vallis is a large, >700 km long, 0.45–2.7 km deep, and 5–35 km wide outflow channel located on the smoothened Hellas basin rim (Figure 1) (Hargitai et al., 2017; Leonard & Tanaka, 2001; Mest et al., 2016; Price, 1998). It originates in the southern flank of the Hadriacus Mons volcano (Crown & Greeley, 1993; Crown & Greeley, 2007) from a 40 × 190-km head depression (floor elevation −5.6 km). The head floor is clustered with numerous knobs and blocks. Dao Vallis is morphologically prominent and uniform, whereas Niger Vallis, Dao's main tributary, has a complex appearance. Niger is ~1.5 km shallower than Dao, starting at a floor elevation of −4 km (Kostama et al., 2010). Niger is characterized by partly collapsed terrain consisting of interconnected troughs and circular-to-elongated depressions. Both valles are part of a larger fluvial system, which originates in two well-defined depressions, Ausonia and Peraea Cavi. The connecting shallow channels have acted as both surface and subsurface pathways (Crown & Greeley, 2007).

The Circum-Hellas Volcanic Province (CHVP) extends from Malea to Hesperia Planum (Williams et al., 2009, 2010). Hadriacus and Tyrrhenus Montes are the main central CHVP volcanoes within or near Hesperia Planum. Hadriacus is surrounded by a network of dikes that extends well beyond Dao and Niger Valles (Korteniemi et al., 2010). A single trough, possibly of magmatic dike origin, exists on the Dao Vallis head floor (Korteniemi & Kukkonen, 2012).

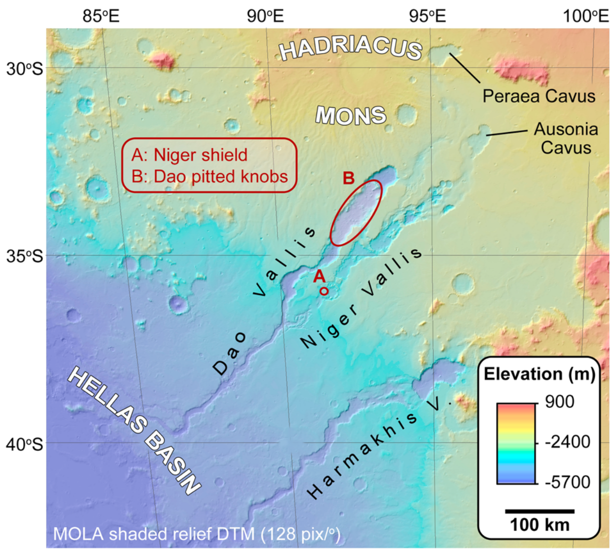

Figure 1. Regional context for the studied structures (circled).

Dao and Niger Valles were carved up during the Hesperian period (e.g., Crown et al., 1992; Leonard & Tanaka, 2001; Tanaka & Leonard, 1995), but "how" is still debated. Several formation models exist on the carving agents, using ice (Chapman & Tanaka, 2002; Lucchitta, 1982; Masursky et al., 1977; Tanaka & Leonard, 1995), lava (Leverington, 2004, 2011), and debris flow, either water-lubricated (Tanaka, 1999) or CO_2-gas supported *cryoclastic* density flow (Hoffman, 2000). However, most authors accept that the outflow channels were formed due to the release of massive amounts of subsurface volatiles (e.g., water) and subsequent collapse (e.g., Baker et al., 1992; Carr, 1979, 1996; Crown et al., 2005; Masursky et al., 1977; McCauley et al., 1972; McKenzie & Nimmo, 1999). In short, atmospheric water accumulated on the surface, infiltrated or was buried by sediments and volcanic materials, and was mobilized by volcanic and/or magmatic heating (Baker, 1982; Crown et al., 1992, 2005; Harrison & Grimm, 2009; Kostama et al., 2010; Squyres et al., 1987). This model is supported by the structure of the outflow channels, namely, collapse and subsurface flow (e.g., Baker et al., 1992; Carr, 1979, 1996; Crown et al., 1992, 2005; Kostama et al., 2010; Leonard & Tanaka, 2001; Price, 1998).

The outflow channels were further modified by erosion, mass wasting, and periglacial and eolian activities (Musiol et al., 2011). The valles floors are mostly covered by lineated valley fill (LVF) (Mest et al., 2017; Squyres, 1979; Squyres et al., 1987), although small uncovered patches of older floor still exist (Korteniemi & Kukkonen, 2013). The LVF texture and flow-like appearance indicate ice-rich materials, either sedimentary with interstitial ice, similar to terrestrial rock glacier flows (Bleamaster & Crown, 2010; Mangold, 2003; Pierce & Crown, 2003; Squyres, 1978), or, more probably, debris-covered glacier flows (Baker et al., 2010; Head, Marchant, et al., 2006; Head, Nahm, et al., 2006; Li et al., 2005). Both valles also exhibit gullies on their walls (Bleamaster & Crown, 2005; Carr, 1981; Mest & Crown, 2001).

This work describes and provides age estimates for two types of features identified within the valles: a complex shield-like structure on top of a mesa in Niger Vallis (henceforth *Niger shield*) and simple knobs with summit pits on Dao Vallis head floor (henceforth *Dao pitted knobs*). Our interpretation is that the features are probably the result of effusive volcanism. Volcanic vents directly associated with outflow channels are not entirely unexpected, as various other Martian outflow channels have been modified by volcanism in addition to fluvial activity (e.g., Chapman et al., 2010; Jaeger et al., 2007; Keske et al., 2015; Keske & Christensen, 2017). Volcanic vents are key pieces to understand the outflow channel formation process. The used data (Zuber et al., 1992; Smith et al., 2001; Christensen et al., 2004; Neukum et al., 2004; Jaumann et al., 2007; Malin et al., 2007; McEwen et al., 2007) and methods (CATWG, 1979; Neukum, 1984; Hartmann and Neukum, 2001; Ivanov, 2001; Michael & Neukum, 2008, 2010; Kneissl et al., 2011) are described in the supporting information.

2. The Studied Features

2.1. The Niger Shield

The studied feature in Niger Vallis (located at 35.90°S, 91.45°E; Figure 2) is a single shield-like structure. It is roughly circular in plain view, with ~100 m height, ~6.5 km diameter, and ~3° mean flank slopes. A shallow, 900-m long and 100-m wide arc-shaped trough is located just east of the summit. A second trough, prominent and linear, extends westward from the summit down the flank, but any possible connection between the two is obscured by an ~300-m-wide crater and its ejecta (Figure 2a). The Niger shield flanks are characterized by additional shallow troughs, which extend down to the surrounding terrain in the west, south, and east, while being mostly nonexistent on the northern slopes. The troughs often separate lobe-like structures (Figure 2b).

The Niger shield is located on the western margin of a large, semicircular system of depressions, mesas, and troughs in Niger Vallis (Figure 3). At the center of this complex (35.99°S, 91.69°E) is a 13.5-km-wide and 600-m-deep circular depression. It is enclosed by a collection of 15 mesas, most of which have $<$ 10 km2 surface areas. This mesa ring is further encircled by a 74-km-long, ~2-km-wide, and 250 to 400-m-deep horseshoe-shaped trough. The central depression and trough floors are covered by LVF deposits.

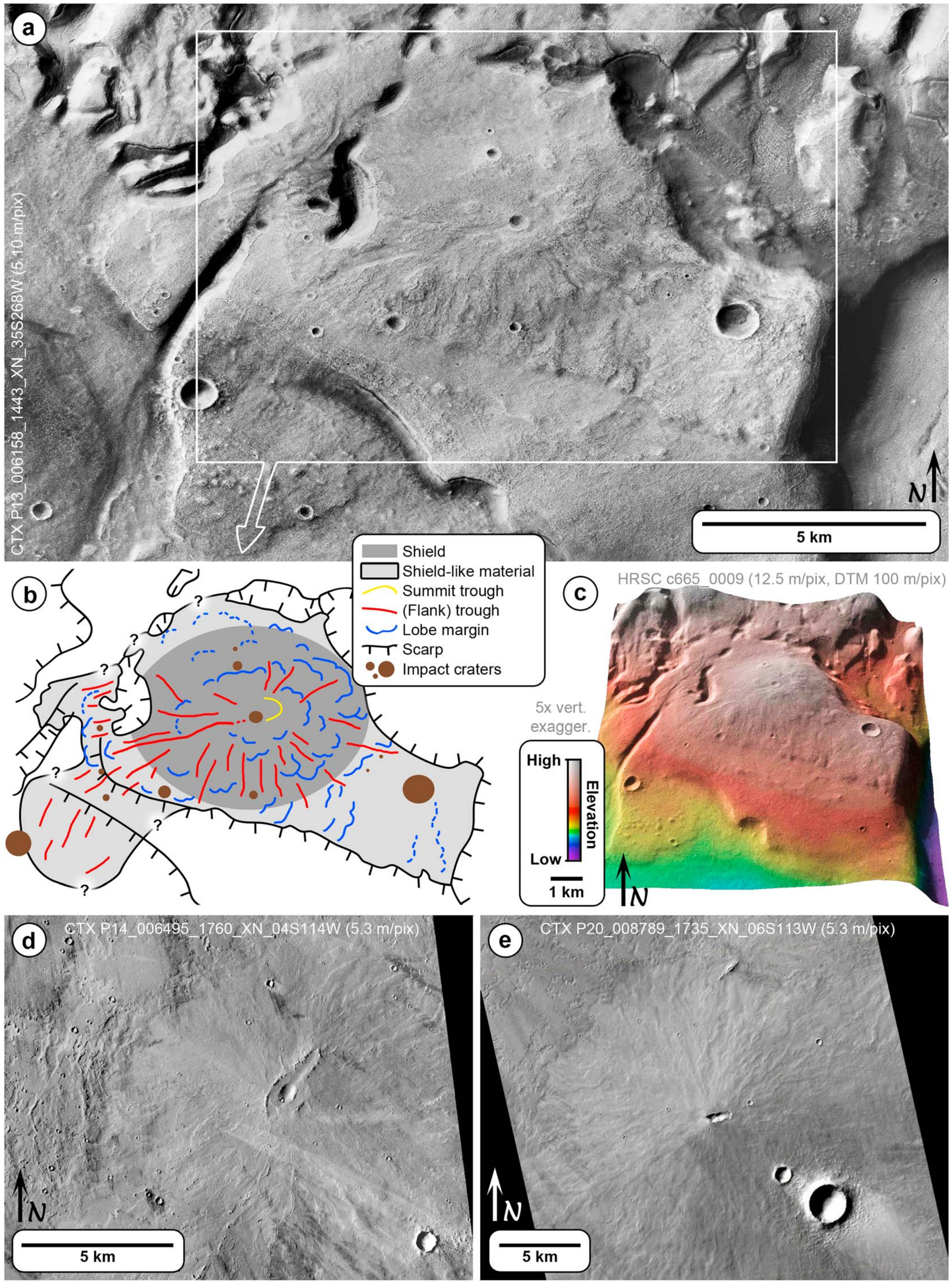

Figure 2. Niger shield details: (a) the Niger shield area, (b) sketch map of the main features, and (c) north-facing perspective view of regional topography. (d and e) Roughly analogous lava shields south of Pavonis Mons (4.67°S, 246.23°E and 6.50°S, 246.73°E).

The Niger shield stands on top of the westernmost ~130-km^2 mesa, which is extensively fractured and pitted in the north and cut in the south by a smooth fluvial channel from a Niger flooding episode. The Niger shield flanks are cut by both the fractures and the channel, although some shield material appears to have topped the latter. The shield material appears slightly brighter in nighttime IR than the surrounding terrain (Figure 3c).

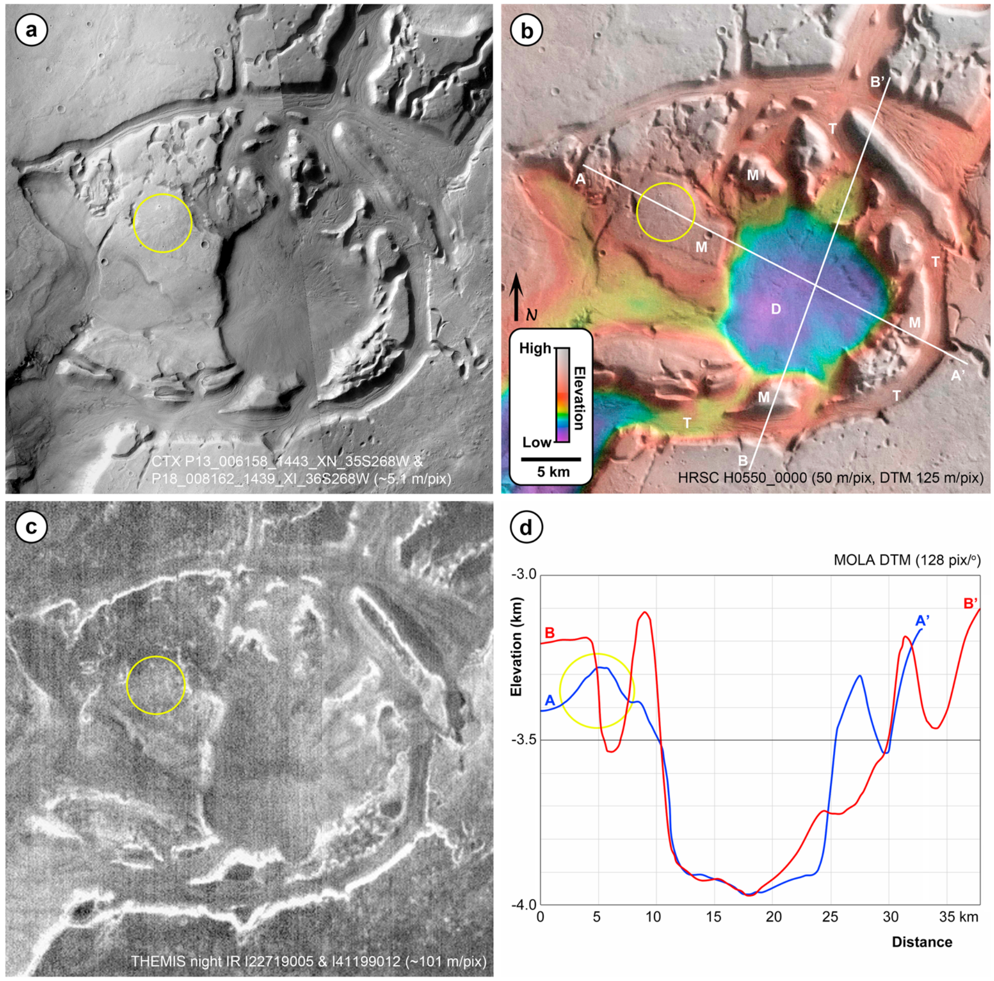

Figure 3. The complex structure surrounding the Niger shield (yellow circle) in (a) visible images, (b) topography, and (c) night-IR. Labeled features: central depression (D), surrounding mesas (M), and trough (T). (d) Elevation profiles across the structure (locations shown in Figure 3b).

No features along Niger Vallis or in the surrounding plains resemble the shield or the mesa-and-fracture complex. If similar shields did form nearby, they may have been destroyed (e.g., in Niger Vallis outflows), covered, or modified beyond recognition.

The Niger shield flank morphology is indicative of easily erodible materials (similar to Hadriacus Mons flanks, although the troughs there are kilometers wide and >100-m deep). We identified four possible sources for the Niger shield flank material. (1) Tephra deposits originating from Hadriacus Mons. However, piling such materials at a singular unique location >300 km from the Hadriacus caldera makes this unlikely. (2) Mud volcanism, driven by, for example, tectonic compression. An isolated structure is again unlikely, as mud cones or shields occur only in (large) groups elsewhere on Mars (e.g., Oehler & Allen, 2010; Skinner & Tanaka, 2007; Tanaka, 1999). Additionally, on an island-like mesa, the pressure would push the mud laterally along stratigraphic contacts, not upward. (3) Impact ejecta from the summit crater. Highly unlikely, as the continuous ejecta field would extend >10× the crater diameter (rule-of-thumb for craters is ~4×). The underlying shield would also remain unexplained. (4) The shield is a volcanic construct. This is supported by (i) the symmetrical shield shape, indicating the structure was most likely built from the center outwards; (ii) the flank troughs, similar to those on Hadriacus Mons flanks, and indicative of pyroclastic materials carved by water (Williams et al., 2007, 2008, 2009); (iii) the arced summit trough and the western linear trough, which we interpret as a vent and possibly an associated fracture, respectively; and (iv) the southern and eastern flank lobes radial to the summit, which we interpret as margins of erupted material flows. (v) While the shield surface morphology is indicative of Hadriacus-style erodible pyroclastic materials, the shield is also roughly analogous to several lava shields on the south and east side of Ascraeus and Pavonis Mons and in the summit caldera of Arsia Mons (e.g., Baptista et al., 2008; Bleacher et al., 2007, 2008; Hauber et al., 2009) (Figures 2d, 2e, and S1 in the supporting information). We suspect that a lava shield would also be more likely to survive the outflow channel formation than tephra (or mud) deposits. The surficial deposits may be of pyroclastic origin.

We obtained a cratering model age of 2.13 (+1.1/−1.5) Ga for the Niger shield and 2.21 (+0.99/−1.3) Ga for a reference area (Figure S2). Both correspond with the Amazonian period, during which the eastern Hellas outflow channels experienced their latest activity phases (Crown et al., 1992; Kukkonen & Kostama, 2018; Scott et al., 1995; Tanaka & Leonard, 1995). However, stratigraphic relationships imply both counting areas should predate the valles formation, estimated to have begun no later than during Late Hesperian (Tanaka & Leonard, 1995). This implies that our crater counting areas were not large enough to incorporate sufficient numbers of large craters to represent the formation age of the units. However, both sites exhibit similar resurfacing ages (2.1–2.2 Ga), in agreement with Williams et al. (2007), who estimated a model formation age of 3.80 (+0.10/−0.20) Ga for the nearby Hadriacus Mons flanks and a resurfacing age of 2.4 (±0.2) Ga.

The semisymmetrical shape of the ~25-km mesa-and-fracture complex surrounding the Niger shield suggests it too may have a unique history not shared by other Niger Vallis features. The complex may be a preexisting feature, exhumed and emphasized by later outflow channel-forming processes. Although the feature may be caused by chance alone, we propose three specific scenarios. (1) The complex is a deeply buried impact crater, in and around which volatiles were first deposited and later removed (either before or during Niger Vallis formation). This explains the central depression but not the surrounding mesa-and-fracture system: A typical crater rim would not survive erosion caused by Niger formation and be left standing as a circle of several hundred meter high steep-walled mesas. Alternatively, a peak ring crater formed on a multilayer target, akin to terrestrial Gosses Bluff or Serra da Cangalha impact structures (Kenkmann et al., 2011; Milton et al., 1972), could explain the entire complex. However, forming the Niger shield on top of the peak ring would be unlikely, if not impossible. (2) The complex is an extensively modified impact crater, the floor of which was fractured by magmatic intrusions and subsequently collapsed, akin to the nearby Gander crater (Korteniemi et al., 2010) or the chaos regions found in, for example, Arabia Terra (Meresse et al., 2007). However, this type of collapse occurs preferentially along a moat inside the crater, with mesas separated by radial and concentric fractures occupying the rest of the crater floor (Korteniemi et al., 2006, 2010; Schultz, 1976a, 1976b). The Niger complex bears no resemblance to impact craters: The mesa ring does not form a recognizable crater rim, and forming an additional horseshoe-shaped fracture around a crater via collapse or impact processes is highly unlikely. (3) The complex is a remnant of an ancient volcanic structure. The 13.5-km depression represents a caldera, surrounded by an intrusive ring dike (the mesa ring) and a horseshoe-shaped graben. The structure was buried and later exhumed by Niger Vallis, removing easily erodible materials and leaving the more durable dike semi-intact. The Niger shield would be a late-stage eruptive center. We find this scenario to be the most plausible one.

Eastern Hellas volcanic centers not directly associated with Hadriacus or Tyrrhenus Montes have previously been proposed, as the many regional features could not be otherwise explained (e.g., Greeley & Crown, 1990; Gregg, 2017; Gregg & Crown, 2005, 2007; Ivanov et al., 2010; van Gasselt et al., 2007). Interpreting the Niger shield and the surrounding mesa-and-fracture complex as volcanic constructs supports this. Based on its location and estimated formation time, it is also consistent with the CHVP scenario (Williams et al., 2009).

2.2. Dao Pitted Knobs

The Dao Vallis head floor is characterized by knobs and blocks; we estimate the number of 0.1 to 10-km knobs to be ~500. The knobs and blocks have traditionally been interpreted as remnants of collapsed materials during Dao formation (Crown et al., 1992, 2004). The highest knobs and blocks are generally conical, with sharp crests and flanks rendered featureless by scree and talus deposits. Smaller knobs often have hummocky tops. All cones are embayed by LVF and mass wasting deposits originating from the canyon walls. Cratering model ages of the embaying materials are 266 (±83) Ma (LVFs) and 354 (±180) to 430 (±100) Ma (mass wasting deposits) (Figure S3).

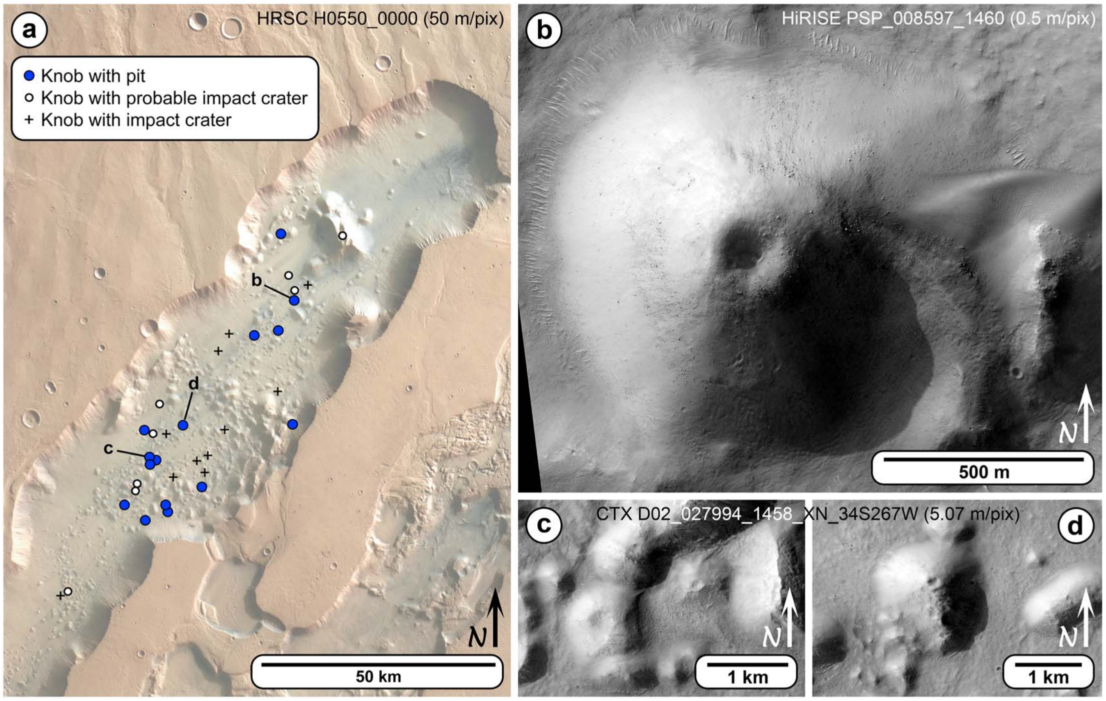

Figure 4. (a) Dao Vallis head depression with pitted and cratered knobs. (b–d) Close-up images show examples of various studied pitted knobs.

We identified 15 conical 0.5 to 2.3-km-wide and 10 to 350-m-high knobs, which exhibit pits on or close to their summits (Figure 4). These Dao pitted knobs have height-to-width ratios of 1–15%. The summit pit widths are 50–850 m, or 5–50% of the knob diameter (average ~18%).

The presence of similar small pitted knobs on Mars was first recognized from Viking Orbiter imagery (Allen, 1979; Frey et al., 1979). They are found especially on the northern plains, where a variety of mechanisms have been suggested. Typical terrestrial analogs are volcanic, such as scoria cones (Broz & Hauber, 2012; Farrand et al., 2005; Wood, 1979), tuff cones or rings (Broz & Hauber, 2013; Farrand et al., 2005), and pseudocraters or rootless cones (Bruno et al., 2004, 2006; Fagents et al., 2002; Frey et al., 1979; Frey & Jarosewich, 1982; Greeley & Fagents, 2001; Lanagan et al., 2001; Nouguchi & Kurita, 2015). The proposed nonvolcanic analogs include pingos (Lucchitta, 1981; Mackay, 1973; Nouguchi & Kurita, 2015) and mud volcanoes (Nouguchi & Kurita, 2015; Tanaka, 1997).

The Dao pitted knobs closely resemble volcanic cones in both size and shape, for example, in Syria Planum and Hydraotes Chaos and northwest of the Tharsis region (Figure 5). Probable pyroclastic cones in Ulysses and Hydraotes Colles were estimated to have typical cone height-width ratios of 3–14% and a pit-to-cone width ratios of 3–34% (Broz et al., 2015; Broz & Hauber, 2012). In comparison, the pit-to-cone width ratio of proposed mud volcanoes on Cydonia Mensae is 33–50% (average 41%; Farrand et al., 2005; Wood, 1979).

Ignoring the summit pits, the Dao pitted knobs do not exhibit obvious lava flows or otherwise significantly differ from the other knobs and blocks in their vicinity. The traditional interpretation that the knobs and blocks are remnants of collapsed materials cannot be ruled out, as the summit pits could be just conveniently located impact craters. Ejecta would easily be rendered unrecognizable in slope processes.

However, since the Dao pitted knobs do closely resemble volcanic cones elsewhere on Mars, and since other small-scale magmatic features have been identified on Dao floor and in the vicinity (Korteniemi et al., 2010; Korteniemi & Kukkonen, 2012), the volcanic hypothesis should not be ignored. The pitted knobs should be investigated further in order to determine their origin.

Identification of volcanic cones on the Dao head floor has great implications: If any of the pitted knobs are indeed, for example, tuff or scoria cones (e.g., Broz & Hauber, 2013; Farrand et al., 2005; Wood, 1979), it would show that volcanic activity on the eastern Hellas rim occurred also after outflow channel formation, but

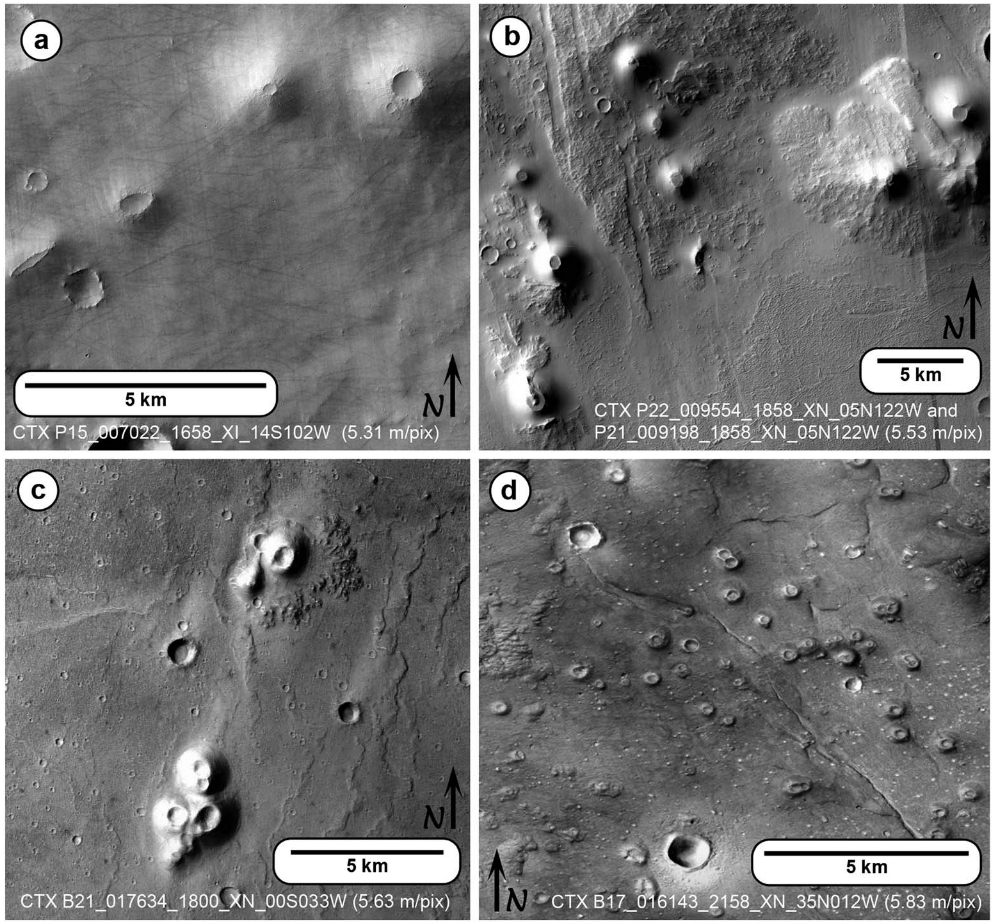

Figure 5. Examples of volcanic cones in (a) Syria Planum (12.80°S, 257.52°E), (b) near Ulysses Patera (5.83°S, 237.18°E), and (c) Hydraotes chaos (0.13°S, 326.30°E). (d) Pitted cones in Cydonia Mensae (37.56°N, 347.06°E) formed by mud volcanism and evaporate deposition around geysers or springs (Farrand et al., 2005).

before LVF emplacement. This would be consistent with the findings of Williams et al. (2007, 2008), who showed that the final stage of activity on Tyrrhenus and Hadriacus Montes occurred 0.8–1.5 Ga ago. Late stage volcanism may have been more widespread in the region than previously thought.

3. Conclusions

The eastern Hellas rim region is a key part in the CHVP. The central volcanoes are its most prominent structures. Their activity phases (namely, volcanic heating) supposedly controlled nearby melting episodes and triggered outflow channel formation. However, several studies have shown that the they cannot explain all the proposed regional volcanic (or supposedly volcanism-induced) features, and speculation about other activity centers in the eastern Hellas rim region has occurred (e.g., Greeley & Crown, 1990; Gregg, 2017; Gregg & Crown, 2005, 2007; Ivanov et al., 2010; van Gasselt et al., 2007).

We show that a previously unrecognized volcanic center exists in the vicinity of Dao and Niger Valles. First, a mesa within Niger Vallis harbors a shield-like structure. Radiating troughs and lobes on its flank, along with a semicircular trough close to its summit, suggest a volcanic edifice. The shield is located in the western parts of a much larger, roughly circular system of depressions, mesas, and fractures. This complex is distinct from other features along the entire Niger Vallis. We interpret the central depression to be an ancient caldera, surrounded by a ring dike and a horseshoe-shaped graben. Although the absolute formation age of the shield structure could not be estimated, stratigraphy and cross-cutting indicates that the shield predates Niger Vallis formation. This pushes the formation of the Niger shield and the underlying caldera at least into Late Noachian to Early Hesperian epoch.

The Dao Vallis head depression exhibits 15 knobs with pits on their summits. Their volcanic origin is supported by basic morphometry but cannot yet be declared unambiguously. Assuming they are volcanic, they indicate postoutflow igneous activity in the area. No model ages were determined for the knobs, but crater counts and stratigraphic analyses indicate that they are older than the surrounding LVF (266 ± 83 Ma) and mass wasting deposits (354 ± 180 Ma).

Hadriacus and Tyrrhenus Montes are located on Hellas-associated ring fractures, and their volcanism is proposed to have been controlled by those fractures (Peterson, 1978; Williams et al., 2009). This applies also to the now-described features.

The relative ages of the studied features indicate that the site experienced volcanic activity both prior to and following the formation of the Niger-Dao outflow channel complex. As such, they are key evidence for the valles formation and interaction between volcanism and fluvial activity. Our findings expand the identified regional volcanic activity into smaller scales along with the extent and periods of activity within the CHVP. We show that the outflow channel formation and development may have been a much more complex process than mere triggering by the volcanic heat of the central highland volcanoes.

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Erratum

In the originally published version of this article, several papers referenced as sources for the data and methods were omitted or incorrectly grouped together at the end of the introduction. The error has since been corrected, and this version may be considered the authoritative version of record.