Infiltration of Martian outflow channel floodwaters into lowland cavernous systems

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1. Introduction


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The Martian outflow channels were excavated by the largest estimated flood volumes in our solar system [Carr, 1979; Clifford and Parker, 2001; Tanaka et al., 2005]. These waters were released from aquifers [Carr, 1979; Clifford and Parker, 2001] and/or surface lakes [Irwin et al., 2004] and may have resulted in the formation of transient oceans [Parker et al., 1993; Fairén, 2003], lakes [Fairén, 2003], continental-scale ice sheets [Kargel et al., 1995], and regionally extensive debris flow deposits [Tanaka et al., 2001]. The study region (Figure 1a and 1b), centered at 19°N., 125°E., includes the Hebrus Valles (HV) and Hephaestus Fossae (HF). It occurs along the SE margin of the 2000-km diameter Utopia impact basin on the lower flank of the Elysium volcanic rise, and it is also positioned along the global topographic dichotomy separating ancient southern cratered highland terrains and the Vastitas Borealis Formation (VBF), which consists of relatively younger sedimentary deposits forming the floors of the northern lowland basins [Tanaka et al., 2005].

2. Data Sources and Methods

This geologic investigation has been performed using Environmental Systems Research Institute’s (ESRI) ArcGIS software. Geologic feature mapping (Figure 1b and 1c) and characterization (Figure 2a–2h) were carried out using Mars Reconnaissance Orbiter (MRO) Context Camera (CTX, 5.15 to 5.91 m/pixel), and Mars Odyssey Thermal Emission Imaging System (THEMIS) visible wavelength multiband (VIS, 17 to 40 m/pixel/day IR, 100 m/pixel) images. Topographic information and volumetric estimations have been derived utilizing Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) digital elevation models (DEMs) at ~460 m/pixel horizontal and 1 m vertical resolutions.

3. Results

Cone features interpreted to be mud volcanoes form extensive fields within the northern plains of Mars [Oehler and Allen, 2010, 2012], which include the southern Utopia boundary plains, where the study region is located [Skinner and Tanaka, 2007] (auxiliary material, Text S1). At some locations within the study region, features interpreted as mud volcanoes cluster into linear ridges (black arrow in Figure 2f). These ridge patterns align with networks of individual pits, pit chains and troughs, all of which show variable degrees of integration (Figure 1c, white arrow in...
Figure 2f). At other locations, poorly integrated networks of linear depressions extend and interconnect these features (white arrows in Figure 2g). We suggest that within the study region, collapsed sections of cavern systems are expressed at the surface by these linear depressions. The apparent system connectivity of mud volcanoes and the pit and trough networks suggests a genetic link between mud volcanism and the development of cavern networks.

The distal reaches of HV form two distributaries, each of which terminates within isolated pit and trough networks (sites 1 and 2 in Figure 1c), suggesting drainage of floodwaters into the subsurface [Christiansen and Hopler, 1987; Carr and Malin, 2000; Tanaka et al., 2005]. The subsurface pathway of distal floodwaters is here demonstrated by the identification of local channel incision by knickpoint retreat (Figure 2a–2e), coupled with a decrease in channel capacity downstream from some pits (white arrows in Figure 2a and 2d), and the particularly abrupt transition that the fluvial morphology exhibits at site 1 into the branching, rectilinear pit and trough networks (white dashes in Figure 2a).

The absence of evidence of ponding upstream of pits and troughs (e.g., Figure 2b and 2e) and presence of channel pendant bars that extend into troughs (e.g., black arrow in Figure 2e) are indicative of rapid and unobstructed flow [Baker, 1982, 2009] into the subsurface. Stream disappearance into sinkholes is common on Earth [Lorenz, 2006] and conduits fed by surface streams through sinkholes can transmit large quantities of bed load and suspended load [White, 1988].

An end-member case scenario would indicate that the HV floods and transported sediments were mostly captured into the subsurface. The estimated cumulative volume of the Hebrus outflow channels (206 km$^3$) exceeds that of the trough networks in their terminal regions by two orders of magnitude (site 1, 6.5 km$^3$; site 2, 8.8 km$^3$). However, we note that these trough networks likely represent only the portions of the cavern networks that underwent collapse. In addition, the neighboring HF pit and trough network has a cumulative volume of 637.8 km$^3$, suggesting that caverns extensive enough to accommodate the estimated discharge volumes could have developed regionally. On the other hand, although our mapping shows that only a few small channels do not terminate in the trough networks (Figure 1c), which indicates that a fraction of the floods must have escaped infiltration at these sites, we do not rule out that extensive fluvial sedimentation occurred.
but the deposits are no longer recognizable because they were weathered and removed.

4. Discussion

4.1. Cavern Formation Associated With Northern Plains Mud Volcanism

[Carr and Malin [2000] suggested that the HF system may indicate a subsurface karst landscape formed by the dissolution of buried carbonate deposits. However, the only carbonate deposits that have so far been identified within the northern plains were exhumed from depths of ~6 km during an impact crater forming event [e.g., Michalski and Niles, 2010]. At site 1 a channel extends to the floor of a ~300 m deep trough from a zone of knickpoint retreat occurring at depths of just 10s of meters of outflow channel dissection (respectively, elevation profiles A-A' and B-B' in Figure 2c). These observations are indicative of caverns having existed at shallow depths within the study region. In the absence of the identification of shallowly buried carbonate deposits, we offer an alternative mechanism for the formation of the pseudo-karst landscape. Our model invokes the role of mud volcanism in the formation of subsurface caverns.

High hydraulic pressures are thought to have led to mud volcanism along the SE margins of the Utopia basin [Tanaka et al., 2003; Skinner and Tanaka, 2007], as well as within other regions of the northern plains [Oehler and Allen, 2010, 2012]. The high occurrence of mud volcanoes along boundary plains (Figure 3a) is consistent with the hydraulic head being driven by the relief aquifers extending across the highland-lowland boundary [Rodriguez et al., 2010].

Possible sites of Late Hesperian/Early Amazonian groundwater discharge, perhaps emanating from a groundwater zone that extended into more elevated terrains in the southern cratered highlands [Clifford and Parker, 2001], have been identified on the flanks of the Elysium rise [Tanaka et al., 2005; Skinner and Tanaka, 2007]. These sites are located at elevations ranging between approximately 3500 and 5000 m above the study region. Thus, provided that a regional groundwater zone existed at the time (1 in Figure 3b), this relief may have provided a hydraulic head (h (relief in meters) x g (for Mars 3.711 m/s²) x ρ (water density, ~1 g/cm³)) between ~13–18.5 MPa, values which are comparable to those postulated to have produced superlithostatic pressures and driven large-scale hydrologic resurfacing in southern circum-Chryse [Andrews-Hanna and Phillips, 2007]. An alternative geologic scenario is that instead of a regional groundwater zone leading to superlithostatic pressures, pressurized groundwater systems resulted from intrusive magmatism into the cryosphere, including dikes (5 in Figure 3b), which during Early Amazonian Elysium volcanism [Tanaka et al., 2005] extended ~350 km [Rice et al., 2002; Scott et al., 2002; Russell and Head, 2003] from the Elysium rise to the southeast. Craft and Lowell [2012] show that pressurized
aquifers could have resulted from the melting and vaporization of regional permafrost deposits by intrusive dikes. They propose that these aquifers could have produced some catastrophic outflow channel discharges.

[11] Our model proposes that excess pressure within an aquifer(s) produced hydrofractures that penetrate an overlying cryosphere (1 in Figure 3c). Fluid circulation along the fractures led to the development of feeder conduits through which fluid-sediment mixtures erupted to construct mud volcanoes. This mechanism is supported by observations on Earth [Brown, 1990; Davies and Stewart, 2005; Stewart and Davies, 2006] (2 in Figure 3c). In their models, subsurface flow through extensive and complex networks of feeder conduits converging underneath eruption sites [Morley, 2003; Davies and Stewart, 2005] may have resulted in thermo-karstic and pseudo-karstic (by suffusion) erosion along feeder conduits, which led to cavern development and enlargement [Deville et al., 2003; Davies et al., 2007; Davies, 2008] (3 in Figure 3c).

[12] We note, however, that other than the mud volcanic cones, no large volumes of surficial deposits have been identified, which could be indicative of the volume of excavated subsurface geologic materials significantly exceeding the volumes of the overlying mud volcanoes, perhaps by as much as a few orders of magnitude [Valentine et al., 2010]. For example, it is possible that the VBF consisted of primarily ice-rich permafrost, and thus relatively low volumes of lithics were ejected during mud volcanism [Mouginot et al., 2012]. Alternatively, a significant portion of the
deposits could have been subject to weathering and reworking by small impact craters (Text S1), and aeolian mobilization during the 3.5 Gyr [Werner et al., 2011] since emplacement and are currently degraded beyond possible recognition in the used datasets.

[13] Fluid evacuation from the caverns could have resulted from (1) lowering of the regional water table as aquifers drained and/or hydrothermal systems cooled down (2 and 6 in Figure 3b), (2) eruptive phases of water expelling mud followed by evaporation, (3) eruptive phases of gases expelling mud, or (4) a combination of these processes. We note that alternating eruptive phases of mud, water and gases separated by periods of inactivity are known to occur in terrestrial mud volcanism [Deville et al., 2010]. In addition, unerupted water-saturated sediment infilling portions of the feeder conduits’ network would have eventually desiccated [e.g., Grimm and Painter, 2009], thereby producing further subsurface void space.

4.2. Geologic Conditions Promoting Structural Stability of Evacuated Caverns

[14] Mud volcanism originating from under-compacted mud-rich strata within terrestrial clastic basin settings is known to lead to the formation of transient cavern systems, which upon structural failure lead to zones of surface collapse and subsidence [e.g., Brown, 1990; Davies and Stewart, 2005; Davies et al., 2007; Stewart and Davies, 2006; Roberts et al., 2011]. In contrast, the inferred magnitude of floodwater infiltration within the study region (4 and 8 in Figure 3b) points to the existence of structurally stable caverns that were largely evacuated of fluids and sediments prior to HV outflow channel activity (2, 3 and 6, 7 in Figure 3b; 4 in Figure 3c).

[15] During the Early Amazonian, the Martian northern plains are thought to have consisted of extensive permafrost deposits [e.g., Clifford and Parker, 2001; Mouginot et al., 2012]. Mud volcanism occurring within permafrost is indicated by mud flows that extend from the eruptive cones into polygonal fractures [Oehler and Allen, 2010]. At ~60°C, a predicted typical mean annual surface temperature for the investigated latitudes [Mellon et al., 2004], permafrost could have had a mechanical strength close to that of limestone [Kuribayashi et al., 1985; Ladyanì, 2003], which could have allowed for the formation of structurally stable evacuated caverns. On Earth, caverns are known to occur in ice-welded sediments such as in association with networks of ice wedges in permafrost [Costard et al., 2012] and ice-welded moraine deposits [Moorman, 2005]. Some glacier caverns are known to have remained stable over decades [Halliday, 2007].

[16] The gravity of Mars is 0.38 times that of Earth, which would have allowed for the development of 2.5 times deeper cavern systems, particularly within the Martian northern plains, which appear to consist of low density (~1 g/cm³) deposits [Mouginot et al., 2012]. Conduit compartmentalization into nested systems of smaller pipes [Davies and Stewart, 2005] could have also promoted the caverns’ mechanical stability, particularly if these were chemically cemented (Text S2). In terms of cavern closure, terrestrial caverns occur to a maximum depth of ~2 km [Klimchouk et al., 2008], thus gravity differences alone could allow Martian caverns to resist closure to ~5 km depth, particularly if deep-seated carbonates form extensive deposits within the northern lowland’s upper crust [Michalski and Niles, 2010]. We note, however, that large subglacials lakes existing at depths of ~4 km under the Antarctic Ice Sheet [Eyles, 2006], indicate that, on Earth, fluid-filled glacial caverns can exist at depths significantly greater than 2 km. In addition, the maximum stable width of a cavern increases with the inverse square root of gravitational acceleration [Haruyama, 2009]. Consequently, on Mars caverns within geologic materials that have similar mechanical strength could have ~60% wider roofs than on Earth. If maximum cavern dimensions all scale similarly, Martian caverns could be more voluminous than Earth’s, perhaps four times (1.6') greater.

4.3. Geologic Conditions Leading to Outflow Channel Discharges Following the Cessation of Mud Volcanism

[17] The absence of mud volcanoes along the floor of HV (Figure 2h) indicates that regional mud volcanism ceased prior to outflow channel activity. Mud volcanism could have ceased as aquifers depleted (2 in Figure 3b), and/or hydrothermal systems cooled (6 in Figure 3b), which would have led to a reduction of hydraulic pressure within the regional aquifer(s) and a lowering of the water table. The formation of HV during the Early Amazonian [Tanaka et al., 2005] is indicative of a second stage of aquifer development and pressurization, which could have been produced by the localized subsurface melting of an ice-rich cryosphere during intrusive magmatism [Rice et al., 2002] (3 and 7 in Figure 3b). The absence of evidence indicative of a second stage of mud volcanism following outflow channel formation suggests that aquifer development did not result in regional groundwater dispersion, but instead the aquifers were drained during catastrophic discharge.

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References


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