The volcanic geology of Morella Crater, Ganges Cavus and Elaver Vallis, Mars

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Research Article

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Abstract

Mars contains a large number of yet unexplained collapse features, sometimes spatially linked to large outflow channels. These pits and cavities are often taken as evidence for collapse due to the release of large volumes of pressurized groundwater. One such feature, Ganges Cavus, is an extremely deep (~6 km) collapse structure nested on the southern rim of Morella Crater, a 78-km-diameter impact structure breached on its east side by the Elaver Vallis outflow channel. Previous workers have concluded that Ganges Cavus, and other similar collapse features in the Valles Marineris area, formed due to catastrophic release of pressurized groundwater that ponded and ultimately flowed over the surface. However, in the case of Ganges Cavus and Morella Crater, I show that the groundwater hypothesis cannot adequately explain the geology. The geology of Morella Crater, Ganges Cavus and the surrounding plains, including Elaver Vallis, is dominantly volcanic. Morella Crater contained a large picritic to komatiitic lava lake (>3400 km$^3$), which may have spilled through the eastern wall of the basin. Ganges Cavus is a voluminous (>2100 km$^3$) collapsed caldera. Morella Crater, Ganges Cavus, and Elaver Vallis illustrate a volcanic link between structural collapse, formation and potential spillover of a large lake, and erosion and transport, but in this case, the geology is volcanic from source to sink. The geologic puzzle of Morella Crater and Ganges Cavus has important implications for the origins of other collapse structures on Mars and challenges the idea of pressurized groundwater release on Mars.

1. Introduction

The surface of Mars exhibits many large, complex collapse features. Since they were first discovered nearly 50 years ago, multiple hypotheses have been put forward to explain their formation. Many or most of these ideas have a common thread, which is that collapse of the Martian surface occurred due to removal of ground ice or groundwater (Carr, 1987).

A connection between surface collapse and ground ice or groundwater is reasonable. Mars is a cold planet with a porous crust where ground ice is predicted to be stable at various depths$^2$, and in some cases, is directly observed even today$^3$. Jumbled blocks of disrupted terrain termed “chaos” are spatially linked with outflow channels. These channels are seen by some as analogous to glacial outburst floods on Earth that form due to rapid and catastrophic melting of glacial ice, sometimes associated with warming climate and other times associated with subglacial volcanism$^4$–$^8$. On Mars, potentially contentious elements of the aqueous hypotheses include the existence, rapid release and recharge of vast quantities of groundwater and ground ice$^2$.

The link between ground ice, groundwater and surface collapse on Mars remains enigmatic. On Earth, catastrophic floods are never associated with significant surface collapse, but are sometimes associated with volcanism$^9$,$^{10}$. On Earth, many steep-sided collapse features result from removal of subsurface material physically (e.g. mining) or more often chemically (e.g. dissolution, cave formation, karsting, etc.$^{11}$). Though lava tubes exist on Mars$^{12}$, they are characterized by pit chains and are much smaller volume
than the collapse features associated with chaos terrain. The formation of caves by dissolution has been previously proposed \(^6,13\), but a more recent picture of the subsurface geology and mineralogy shows rocks susceptible to large-scale dissolution (e.g. carbonates and salts) are not present in large enough thickness or volume to facilitate surface collapse by subsurface dissolution \(^14\).

On Mars, many examples of major surface collapse have no association with channels or other evidence for aqueous processes, and likely have volcanic/magmatic origins \(^15\). Yet in some areas of Mars, a temporal and spatial link between jumbled, chaotic terrains and extremely large channel forms is undeniable \(^16\). There may be a causal link between collapse and formation of outflow channels, be it volcanism \(^17\) or groundwater release \(^18\). The idea of catastrophic collapse by groundwater release remains widely cited and accepted for Mars, but there are no known examples of an analogous type of large-scale surface collapse caused by groundwater on Earth or other planets. Caldera formation can however form a wide range of complex collapse features of comparable structure, size, depth and surface expression \(^19\). Channels of the scale of Martian outflow channels attributable to formation by flowing water have not been observed on Earth or other planets. However, some large channels of similar dimensions are observed on the Moon and Venus, where erosion by water is impossible \(^17\).

This paper investigates the geology of the Xanthe Terra region, and focuses primarily on the geology of Morella Crater, Ganges Cavus, and the Elaver Vallis outflow channel (Fig. 1). Morella Crater is a 70 km-diameter structure that occurs at 308.6E, 9.5S, directly south of Ganges Chasma (Fig. 1). The crater is breached on its east side by Elaver Vallis, a ~ 180 km long suite of outflow channels. Previous authors have concluded that Elaver Vallis formed during a megaflood sourced from release of pressurized groundwater in Morella Crater \(^20\). This work challenges the idea that Ganges Cavus and other collapse features in the Xanthe Terra region formed by catastrophic release of groundwater and further explores the hypothesis that surface collapse was instead driven by magmatism.

### 2. Results

#### 2.1. Geomorphology

Ganges Cavus is a deep, asymmetric, steep walled pit located on the southern edge of Morella crater (Fig. 1). The southern rim of the cavus has an elevation of 2000 m, which is 1000 m higher than the northern rim of the cavus. The hummocky, irregular floor of the cavus is tilted toward the north where it reaches its greatest depth at ~4000 m elevation. A conservative estimate of the current volume of the depression is > 2100 km\(^3\). The floor units are composed largely of light-toned, smooth, hummocky deposits, but other parts of the floor contain irregular boulders that span an array of colours in HiRISE false colour data. Thermal inertia values of materials in the lower slopes of the cavus are ~ 500 and values for the hummocky floor deposits are ~ 800, suggesting the presence of rocky material (Fergason et al., 2006). The elevation of the floor of the Ganges Cavus (~4000 m) is approximately the same as the
elevation of the floor of Ganges Chasma, the southern margin of which is located < 10 km from the northern rim of Morella Crater (Fig. 1).

The ~ 180 km-long Elaver Vallis outflow channel seemingly originates at a breach in the eastern wall of Morella Crater (Figs. 1 and 2a). It consists of two compound channels, a main northern channel and shorter southern channel. In longitudinal cross section, note that the maximum depth of the northern channel is ~ 400 m and the maximum depth of the southern channel is ~ 250 m. However, one critical point that has never been addressed is the fact that a cross section along the channel centre, in both cases, shows that the topographic high point of the channel occurs near the midpoint of the channel along its length. In other words, the elevation of the channel floor of the midpoint of Elaver Vallis is > 250 meters higher than both the origin and terminus of the channel.

Elaver Vallis is disrupted by chaos terrain, which composes the topographically higher ground near the midpoint of the channel (Fig. 2). The chaos occurs in multiple distinct patches (Fig. 2), with a total area of approximately 2000 km$^2$ and depths below the surrounding plains of ~ 500 m. The chaos blocks rise to ~ 100–500 m above the floor of the chaos unit.

The plains surrounding Elaver Vallis are mapped as Middle to Late Noachian undifferentiated units by Tanaka et al. (2014). Higher resolution views show that they are volcanic plains containing NE-SW trending fractures (Fig. 2). A ~ 11 km-diameter, 700 m-deep irregularly shaped, flat-floored depression might be a volcanic vent (See Supplementary Materials). The depth/diameter ratio for this feature is high for any crater, and extremely high for anything but a youthful crater unmodified by erosion (Michalski and Bleacher, 2013). But the depression is likely Hesperian, and therefore it is unlikely to be an impact crater based on morphometrics.

Smaller channels are also observed within Morella crater (Fig. 3a). These consist of a few nearly straight (low sinuosity) channels up to ~ 35 m length that flow into Ganges Cavus. The channels occur within gently sloping valleys, but the channels themselves occur in positive relief approximately 5–15 m above the adjacent terrain.

### 2.2. Surface mineralogy

Both thermal infrared emission (THEMIS and TES) and near infrared/short-wave infrared reflectance (CRISM and OMEGA) data detect olivine within crater floor deposits (Fig. 3b-c). THEMIS daytime DCS images colour stretched with bands 8, 7, and 5 as R, G, and B, respectively show olivine occurrences as purple $^{28}$, and provide a reliable way to map olivine occurrence on Mars in the thermal infrared (Fig. 3b). OMEGA global olivine index maps $^{29}$ and CRISM multispectral index maps $^{26}$ indicate the presence of olivine in the same locations (Fig. 3c). The OMEGA spectral indices suggest that the olivine is Mg-rich or fine-grained, based on comparison to laboratory spectra. High thermal inertia values (> 600) are not consistent with the fine-grained scenario, indicating the olivine is indeed Mg-rich. The precise Fo# of the Mg-rich olivine mapped with OMEGA and CRISM is difficult to constrain without detailed gaussian
modelling, but the olivine standard used to produce the maps of Martian olivine by Ody et al. (2013) is nearly pure forsterite.

The spectral detections of olivine-bearing materials are further constrained with TES data. Using data of a single orbit (called “ick” in this case), which minimizes difference potentially attributable to dynamic atmospheric conditions, the detection of olivine in Morella crater fill deposits is clear (See supplementary data). A simple approach to constraining the olivine mineralogy is to plot the position of (Mg,Fe)-O-Si absorptions observed in the mid-infrared as a function of Mg# (Mg-content), as measured in the lab; the results here suggest that the Mg# of the olivine is ≥Fo68 (See supplementary data). In addition, the wavelength position of the major Si-O surface can be used to estimate the SiO₂ content of the rocks. In this case, the wavenumber of the Si-O stretching in the olivine-bearing rocks is ~ 930 cm⁻¹, which corresponds to an approximate composition of the volcanic rocks ~ 44% SiO₂ (See supplementary data). In other words, the rocks are olivine-rich and relatively silica-poor, near the boundary of mafic-ultramafic composition.

The collapse of Ganges Cavus has resulted in exceptional exposures of the Morella Crater floor units. The south-facing, northern wall of Ganges Cavus reveals a > 1 km-thick succession of erosion-resistant rocks capped by a relatively thin (~100m) covering of re-worked materials (Fig. 4a). CRISM infrared data draped onto HiRISE image data show that the olivine-bearing deposits are continuous and > 1 km-thick (Fig. 4b); they are not just a surface veneer. These olivine-rich deposits represent a widespread crater-fill unit that is exposed throughout Morella crater. It is potentially thinnest in this location, which is located near what was once the southern wall of Morella crater and might be substantially thicker elsewhere in the basin. Even if a conservative 1-km-thick average is assumed, it still suggests that a lower estimate of ~ 3200 km³ of olivine-rich volcanic material fills the basin.

THEMIS thermal inertia data of the same south-facing, northern wall of Ganges Cavus show variation in TI within the olivine-bearing unit. Layers are observed, with TI values that vary by 60–100 TI units from layer to layer (Fig. 5). This observation is important for two reasons: 1) because it shows that multiple olivine-rich units are present and 2) because it shows that the volcanic processes that produced the olivine-rich unit were cyclical and potentially therefore sustained for some period of time. In this scenario, the lower TI values might correspond to fractured, eroded flow tops or lava lake surfaces, or potentially interbedded volcaniclastics.

Olivine-bearing materials within the floor of Morella crater (Fig. 6a) are composed of olivine-rich (Fig. 6b), fractured blocks of bedrock (Fig. 6c). As noted by (Leverington, 2009), this material is morphologically similar to rock exposures within the floor of Syrtis Major caldera (Wray et al., 2013). THEMIS thermal inertia data indicate that these materials have values of ~ 325–475, consistent with a mixture of bedrock and sandy particulates.

The interior of Morella Crater contains several arcuate scarps, which form terraces with flat surfaces several km-wide (Fig. 7). The terraces contain olivine-rich deposits of similar morphology and
composition to those on the floor of the basin, but the terraces are perched approximately 200 m above
the floor. The olivine-rich deposits have high thermal inertia (500–700) indicative of rocky materials. It
appears that this unit must have either been deposited effusively, and the adjacent floor was later
structurally down-dropped by hundreds of meters, or that the material was emplaced through air-fall.

The floor of Ganges Chasma, shows enrichment in olivine, including within a sedimentary apron at the
mouth of Elaver Vallis (See supplementary materials). Of course, volcanic materials would be mobilized
in the event of a catastrophic flood by water, but it is notable that the olivine in relatively concentrated in
those deposits.

3. Synthesis

The idea of megaflooding on Earth was originally considered outrageous, and acceptance of this concept
was achieved only through perseverance and accumulation of undeniable evidence. In the case of Mars,
the idea of megaflooding has been more readily accepted (Carr, 1987). Indeed, it is sensible that melting
of permafrost could result in release of large volumes of water capable of erosion. But several facts
remain: 1) there is no known case of catastrophic eruption of huge volumes of groundwater capable of
eroding such large channels from the subsurface on this planet or any other and the modelled dynamics
of such rapid groundwater release require some potentially unrealistic physical scenarios; 2) all known
eamples of catastrophic flooding on Earth can be linked to melting of ice dams in surface environments;
3) there are indeed cases of large channel erosion, of comparable scale those observed on Mars, found
on the Moon and Venus where erosion by liquid water is recognized to be actually impossible. Given
these facts, a volcanic origin for outflow channels deserves serious consideration, as has been proposed
in multiple works by Leverington and colleagues. Here I focus largely on one region (Xanthe Terra) and
specifically one channel system (Elaver Vallis), but this setting has implications for other locations on
Mars.

3.1. Discussion of volcanic processes

The geology of Morella Crater, Ganges Cavus and the surrounding plains is dominantly volcanic (Fig. 8).
The crater is filled with layered, olivine-rich units that may include both effusive and pyroclastic
deposits. The crater floor contains fractured, light-toned, olivine-rich units that are either fractured lavas or
pyroclastic units. The walls of Morella Crater basin contain terraces with olivine-rich units that are of
similar composition to those on the floor of the basin. The terminus of Elaver Vallis contains olivine-rich
fan deposits, and the floor of Ganges Chasma is olivine rich in general. The plains around Morella crater
do not have strong mineralogical signatures of olivine, but they do contain smooth, fractured plains that
are interpreted as volcanic throughout the region (Fig. 2b and Fig. 8).

Questions about hydraulic head and groundwater recharge are non-issues for the volcanic hypothesis.
Magma can build pressures to greater elevations than groundwater, and in any case there is abundant
evidence that volcanism did in fact occur as “break out” flood type deposits in the floor of Ganges
Chasma immediately to the north and Eos Chasm to the south. In fact, the chasmas all contain abundant evidence for olivine-rich materials (Fig. 8).

Collapse of Ganges Cavus can be explained in the volcanic model simply by removal of magma (Fig. 9). Edwards (2008) estimates that $\sim 10^5$ km$^3$ of olivine-rich lava was erupted on the floor of eastern Ganges and Eos Chasmas. In western Ganges Chasma (closer to the study area), olivine-rich materials cover $>10^4$ km$^2$ of the floor and in western Eos, approximately $10^5$ km$^2$. Assuming a thickness of 100 m to 1 km, this equates to $\sim 10^4$ to $10^5$ km$^3$ of extruded lava in the vicinity of Ganges Cavus. This volume, in addition to the $\sim 10^3$ km$^3$ of volcanic material within Morella Crater greatly exceeds the volume of the collapse feature in Ganges Cavus.

The only major challenge to the volcanic hypothesis is with regard to the formation of Elaver Vallis itself. Is it possible to form such a channel through physical or thermal erosion by lava and/or pyroclastics? As pointed out by Leverington, channels of comparable size and morphology are observed on Venus and the Moon, where they can only be interpreted as volcanic. Observations from the Archean Earth, described below, illustrate that thermal and mechanical erosion can both result in the formation of large-scale channels. In the case of Mars, unknowns in lava composition and temperature (i.e. viscosity) and uncertainties with regard to the composition, porosity and volatile content mean that models of lava channel erosion on Mars are not well constrained.

The structure, composition, and morphology of the collapse features and surface units are similar to well understood caldera structures on Earth. For example, the shape and depth/diameter ratio of Ganges Cavus is similar to that which occurs in the summit caldera of Kilauea and smaller pit crater Halemaʻumaʻu in Hawaii ($\sim 0.15$) (Fig. 10). Further, the hummocky and fractured textures observed within the olivine-rich floor material in Morella Crater (Fig. 6c) are strikingly similar to the lava units within Kilauea Iki in Hawaii (Fig. 10). The features in Kilauea Iki formed through cooling of a lava lake, resulting in columnar jointing at the scale of $\sim 4–5$ m. The fractures and resulting polygonal pattern in Morella Crater occur at the same spatial scale, which likely reflects similarities in cooling rate.

Morella Crater likely contained a lava lake in the late Noachian or Early Hesperian. High stands of olivine-rich material on the walls of Morella Crater might have been deposited when the lake was inflated to higher elevations, or they could represent airfall material from cyclic explosive activity. The lava lake might have spilled over the eastern rim of the crater, resulting in the formation of Elaver Vallis by thermal and/or mechanical erosion of the substrate by picritic or komatiitic lava.

### 3.2. Comparison to the Archean Earth

Komatiitic lavas occur in Archean and early Proterozoic terranes, but are vanishingly rare on Earth after the early Proterozoic. Though the rocks representing these high-temperature, low-viscosity lavas have been generally metamorphosed to greenschist facies or higher grade, their geochemical records and physical geometries are discernible. From source areas to down-flow regions, Archean komatiite lavas in western Australia show increasing chemical contamination caused by thermal erosion of substrate
bedrock, which was melted and chemically incorporated into the flow \cite{43}. Where geometries are mappable, it appears that extremely high flux, giant komatiite flows in the Perseverance area have physically and thermally eroded hundreds of meters into the substrate and may have flowed for 10s to 100s of km down-channel \cite{44}. Ten-km scale lava channels, forming erosional troughs tens of metres deep and up to 200m wide are developed associated with the nickel sulfide ores at Kambalda \cite{45}. Lava temperature and effusion rate clearly affect the turbidity of flows and their erosive potential, but a significant factor controlling erosion by komatiite lavas is the geology of the substrate. As noted by Williams and others, the composition, porosity and water content of the bedrock significantly impacts the erosion depth of lava channels. The Kambalda channels, developed on basalt, represent a lower limit on the expected extent of erosion by ultramafic lavas \cite{45}. Erosion of long lava channels on Mars is possible if the substrate is unconsolidated material and/or appreciable volatiles \cite{46}. It is likely that the surface layer of Mars would have contained unconsolidated, volatile-bearing and likely sulfate-bearing megaregolith in the Early Hesperian. This material would have been susceptible to thermo-mechanical erosion by lava.

### 3.3. Convoluted evidence for volcanic and aqueous processes

Numerous authors have proposed that outflow channels in general and Elaver Vallis in particular formed as the result of catastrophic release of groundwater \cite{6,20,47-49}. In general, all of the models depend on the past existence of vast quantities of groundwater pressurized beneath a cryosphere that was catastrophically breached. Though there are no known examples of this type of process on Earth or elsewhere in the Solar System, it is potentially conceivable that such a process could occur at low elevations on a water-rich planet with significant pore space, high permeability and an adequate water recharge mechanism. But, Xanthe Terra is among the topographically highest regions of the planet and a recharge mechanism seems untenable even if the highlands were icy with some glacial meltwater to recharge the subsurface \cite{50,51}.

Coleman (2013) proposed that Elaver Vallis was eroded in a week by > 2000 km$^3$ of water released from an ice-dammed lake in Morella Crater, and ultimately from the subsurface in the Ganges Cavus area. Not only does this imply what are potentially unrealistic pore volumes in the subsurface below the release zone, it also requires the need for significant hydraulic head \cite{36}. Coleman points out that a challenge to the subsurface water hypothesis is the need for significant hydraulic head in the close proximity to Ganges Chasma, which is as deep as Ganges Cavus and would have likely experienced breakouts along the floor and wall long before head could be built to flood high on the adjacent plains.

In fact, the evidence for an aqueous origin of Elaver Vallis and Ganges Cavus rests entirely in the observation of a channel with a grooved floor and streamlined eroded features. Komatsu et al. point out that Morella Crater contains no direct evidence for a lake having existed (\textit{e.g.} no deltas, no shorelines, and no lacustrine deposits), though they nonetheless interpret the geology of the area as having formed by catastrophic flooding from release of pressurized groundwater. Komatsu et al also point out that the
terminus of Elaver Vallis contains a large fan complex on the floor of Ganges Chasma, but note that they detect no mineralogical evidence for aqueous deposits.

In the aqueous outflow model for Elaver Vallis, the release of 1000s of km$^3$ of groundwater resulted in collapse of the surface, resulting in the formation of Ganges Cavus. It has even been suggested that vast subsurface caverns might be responsible for the migration of huge volumes of water in the subsurface. Though the lower gravity environment of Mars compared to Earth would result in more pore space to greater depth on Mars compared to Earth, there is no evidence for subsurface caverns or even large amounts of soluble rocks in the subsurface that could plausibly result produce sink hole-type geology on Mars. Spectral imaging of the walls of Ganges Chasma provide a window into the subsurface in the area, and these data show the presence of pyroxene-rich materials indicative of a relatively dense igneous basement. There are no soluble units in the subsurface in this area. Furthermore, even the largest sinkholes on Earth are ~ 4–5 orders of magnitude smaller volume than Ganges Cavus.

4. Conclusions

Morella Crater is a ~ 75 km diameter basin of likely impact origin, though it could possibly be a caldera. Regardless of its formation mechanism, the basin has been filled with olivine-rich lava in the Late Noachian or Early Hesperian forming a lava lake. Polygonal-fractured textures within the volcanic floor deposits are analogous to cooling joints seen in the lava lake at Kilauea Iki and other similar contexts. Olivine-rich shelves preserved along the basin walls might represent airfall volcaniclastic deposits but are most easily explained in the context of a high-stand of the lava lake.

Ganges Cavus is a deep, steep, voluminous (> 2100 km$^3$) collapse feature that formed within Morella Crater. The walls of the collapse structure expose ≥ 1 km-thick olivine-rich volcanic floor deposits. Though Ganges Cavus is significantly larger and deeper than Halema‘uma‘u in Hawaii, the morphology, structure, slope and depth/diameter ratio (~ 0.15) is the approximately the same in both structures.

The east wall of Morella Crater is breached at the boundary of the ~ 180 km-long Elaver Vallis outflow channel, which terminates further eastward at the rim of Ganges Chasma. The mid-point of the channel(s) is approximately 250 m higher elevation than the channel origin or terminus, and the higher elevation terrain in the channel is composed of chaos blocks. The chaos might represent previously ice-rich terrain that was disrupted by the extreme volcanism in and around Morella Crater. I propose that late stage aqueous activity occurred, mobilizing volcanic materials and confusing evidence for aqueous versus volcanic processes. In this scenario, the volume of water involved would have been significantly less than what has been previously proposed, and huge volumes of water are not required because water is not the primary agent of erosion.

Most of the channel deposits appear to be buried within the floor of Ganges Chasm, but it is notable that fan deposits at the terminus of the outflow channel show olivine enrichment, but this might also reflect
younger volcanic material deposited onto the fan deposits. In any case, Ganges Chasma is the sink of the channel deposits and the floor of the chasma contains abundant olivine.

Previous authors have argued that the collapse of Ganges Cavus and the formation of Elaver Vallis can all be explained through the catastrophic release of pressurized groundwater. The aqueous model for the origins of Ganges Cavus and Elaver Vallis rely on the release of huge volumes of groundwater (> 2000 km³) to form an ice-dammed lake, which failed, resulting in a jokulhaup that carved the channel. Any aqueous model is unable to explain the origin, recharge mechanism or hydraulic pressures required for such a model to operate in this region.

Though there are no known analogs for catastrophic release of groundwater on any planet, there is significant context to interpret nearly all features of this system in terms of volcanic processes. Ganges Cavus is a caldera formed by collapse of the magma chamber due to extrusion of lava, subsurface migration of magma or likely, both. Volcanic deposits within Morella are demonstrably forsteritic olivine-rich and seemingly low silica. The lavas could reasonably be interpreted as komatiitic or picritic and would have been high temperature, low viscosity lavas. It is plausible that the lava lake breached the eastern wall of Morella Crater and that the low-viscosity lava carved Elaver Vallis, at least in large part. The chaos deposits east of Morella might represent terrain that was previously ice-rich, but which became disrupted during thermal erosion of the substrate. In this way, a late stage of aqueous activity, albeit of much lower volumes and character than what has been proposed, might have occurred, potentially flowing from the mid-point of the channel both eastward into Ganges Chasma and westward into Morella Crater.

Given that Mars is a cold, volatile-rich planet that has experienced sustained volcanic activity for billions of years, it is inescapable that magma or lava, groundwater, and surface or near-surface ice have affected each other through time. It would not be wise to frame the geological puzzle of the origins and evolution of outflow channels as having resulted entirely due to volcanism or aqueous activity. In the case of Ganges Cavus, Morella Crater and Elaver Vallis, the geology is clearly volcanic from source to sink. That is not to say that aqueous processes played no role at all in shaping the morphology of this area, but the conclusion is that volcanism was the dominant process driving surface collapse, deposition of (lava) lake deposits, channel erosion and resurfacing.

**Methods**

The geology of Morella Crater was studied primarily using remote sensing data from the following missions: Mars Global Surveyor (MGS), Mars Odyssey (MO), Mars Express (MEx), and Mars Reconnaissance Orbiter (MRO). Data were obtained and organized using the JMARS software developed and operated by Arizona State University.

Topography was analysed using multiple datasets. MGS Mars Orbiter Laster Altimeter (MOLA) data merged with elevation derived from the MEx High Resolution Stereo Camera (HRSC) 21. This is a unique
dataset available within JMARS amounting to a global Digital Elevation Model (DEM) informed by both MOLA and HRSC, at 200 m/pixel resolution. Geomorphology was evaluated using visible and thermal infrared images. Thermal infrared data from the MO Thermal Emission Imaging System (THEMIS) available in a global 100 m/pixel mosaic within JMARS provide a mesoscale base map. Visible images used here include high resolution data available from HRSC at 10–20 m/pixel, CTX at ~6 m/pixel and HiRISE at ~0.25 m/pixel. Data were obtained in radiometrically corrected and geometrically projected format and ingested into a geographic information system (GIS) for analysis and interpretation. Visible images were draped over digital topography in order to create 3D views of bedding and surface morphology.

Thermophysical properties were evaluated using THEMIS and MGS Thermal Emission Spectrometer (TES) data (Fergason et al., 2006; Golombek et al., 2005). The TES data were previously processed into a global thermal inertia dataset, though at relatively coarse spatial resolution (8 pixels per degree). Despite the coarse spatial resolution, these data provide a stable and reliable measure of thermal inertia ($J m^{-2} K^{-1} s^{-1/2}$). Areas with high THEMIS TI translate to surfaces with coarser grains, rocky materials, better indurated materials or some combination of all three of these scenarios.

Surface mineralogy was investigated using multiple near infrared, short-wave infrared and mid-infrared datasets. THEMIS daytime IR radiance images were processed using a decorrelation stretch method (DCS), which emphasizes spectral radiance differences attributable to compositional variation. Spectral interpretations of bulk surface mineralogy were further constrained using basic applications of TES atmospherically adjusted emissivity spectra. Near infrared data from the MEx Observatoire pour la Minéralogie, l’Eau, les Glaces et l’Activité (OMEGA) and the MRO Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) were processed to correct for instrument effects and minimize atmospheric absorptions using a standard data analysis pipeline. Both datasets rely on the use of an atmospheric transmission spectrum scaled by elevation (path length) with atmospheric effects estimated for a given Martian $L_s$ (day of Martian year). As a result, (due to the estimated rather than measured atmospheric properties) there are usually some residual atmospheric effects even in the corrected spectra. These can be minimized by using spectral ratios, which divide a spectrum of interest (numerator) by a spectrum from the same scene over a spectrally unremarkable terrain of comparable albedo (denominator) (e.g., This technique has the advantage of emphasizing unique spectral features related to a certain surface of interest (usually mineralogical absorptions of interest), but it has the disadvantage of converting the spectra from units of $I/F$ (which is comparable to radiance) into unit-less spectra, comparable in shape to laboratory spectra but not comparable in absolute units.

We analysed all CRISM images targeted within Morella crater. Our analyses focused primarily on CRISM observations corresponding to: Full Resolution Targeted (FRT) images (18/pixel), with some Half Resolution Long (HRL) images (36 m/pixel) and Half Resolution Short (HRS) images. Some of the images used in this work were acquired by CRISM after 2012, when the one of the cryo-coolers failed. As a result of this normal system decay, data collected after that date contain more noise than data
collected before the cooler failed. Images collected in the newer observing mode are called Full Resolution Short (FRS). CRISM I/F images were also converted to spectral summary products. These data products were created using the CAT_ENVI software package using combinations of spectral ratios tuned for sensitivity to various minerals or mineral groups. Such maps are useful for evaluating the likely presence of a particular mineral and for mapping relative signal strength corresponding to the unique features associated with that mineral, but these maps do not correspond to actual mineral abundances and they require verification in order to validate mineral occurrences.

Geologic mapping was carried out using THEMIS daytime IR and CTX image data as the base. Geological units were defined based on their geomorphological expression, response to erosion, texture, mineralogy and relative age relationships. Elevation data were used to delineate chaos and channel boundaries.

Declarations

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Author Contributions

J. Michalski carried out the entire project.

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**Figures**

![Image of a map and diagram illustrating outflow channels and topography.](attachment:image.png)
Figure 1

MOLA elevation data draped over THEMIS daytime IR show the relationship among Morella Crater, Elaver Vallis, and Ganges Cavus (a), all located to the south of Ganges Chasma. An inset of Ganges Cavus shown in “b” contains a different elevation scale, illustrating the depth and steep walls of the collapse feature. The topographic profile from N to S located in “a” is illustrated in “c.”

Figure 2
HRSC/MOLA blended elevation data overlaid on THEMIS daytime IR are shown in “a.” A geologic map of the Elaver Vallis area is shown in “b.”

**Figure 3**

An HRSC color image shows the geomorphology of Morella Crater (a). Note the layered materials present in the northern wall of Ganges Cavus and the relatively smooth floor of Morella Crater, overlaid by darker toned channel materials. The interior walls of Morella are terraced in places with short segments of
arcuate scarps that bound floor deposits. Morella Crater contains abundant olivine-rich material. THEMIS daytime decorrelation stretch (DCS) images displaying bands 8, 7, and 5 as RGB show olivine-rich deposits as purple colors (b). A mosaic of OMEGA olivine maps (Ody et al., 2013) and CRISM multispectral mapping data are shown in “c.” The OMEGA data correspond to olivine spectral index values from Ody where higher values indicate the presence of Mg-rich and/or fine-grained olivine. The CRISM olivine index corresponds to parameters described by Viviano-Beck et al (2014).

Figure 4

A HiRISE image of the northern wall of Ganges shows layered, cliff-forming units present in the uppermost kilometers of the pit wall (a). A CRISM spectral index applied overlaid on the HiRISE data shows olivine occurrence in green (b). The elevation difference between the top and bottom exposure of the sub-horizontal, olivine-rich unit is on average ~1100 m.
THEMIS thermophysical data reveal important clues about the nature of olivine-rich deposits. THEMIS nighttime IR data (a) are a proxy for thermal inertia, showing coarser materials or more indurated deposits as brighter tones corresponding to warming surfaces. THEMIS thermal inertia data (b) show clear differences among the layered, olivine-rich wall units (seen in Figure 4). A profile of TI data on the wall (c) shows differences values of ~350 corresponding to recessive (labelled “r”) units and ~450-475 corresponding to cliff-forming units (labelled “cf”).

**Figure 5**

THEMIS thermophysical data reveal important clues about the nature of olivine-rich deposits. THEMIS nighttime IR data (a) are a proxy for thermal inertia, showing coarser materials or more indurated deposits as brighter tones corresponding to warming surfaces. THEMIS thermal inertia data (b) show clear differences among the layered, olivine-rich wall units (seen in Figure 4). A profile of TI data on the wall (c) shows differences values of ~350 corresponding to recessive (labelled “r”) units and ~450-475 corresponding to cliff-forming units (labelled “cf”).
Figure 6

THEMIS daytime IR (a) and DCS data (b) of the floor of Morella Crater show outcrops of olivine-rich deposits. The color stretch is the same as in Figure 3a, where purple corresponds to olivine. HiRISE false color (infrared, red, blue-green) data show high-resolution views of the olivine-bearing deposits. The relatively light-toned deposits are composed of bedrock fractured into 5-10 m blocks, as seen in HiRISE data (c).
Figure 7

MOLA-HRSC topography draped over THEMIS daytime IR (a) show the western part of Morella Crater. Note terraces present in the wall with flat benches that are ~200 m higher than the floor. THEMIS DCS data (b) show in purple the occurrence of olivine in materials draping these benches. THEMIS thermal inertia data (c) show that the terrace materials are relatively high inertia (600-700), corresponding to indurated or rocky deposits. CTX visible data (d) show the light-toned olivine-bearing unit.
Figure 8

The regional context of Ganges Cavus, Morella Crater and Elaver Vallis with regard to topography, geology and mineralogy. The plains are approximately 1000-1500 m elevation and the collapse floors are approximately -4000 m (a). Geology from Tanaka et al. (2014) is shown in “b,” but fractures and scarps in white were mapped here. Map units are: Middle Noachian highland units (mNu); Late Noachian highland units (lNu); Hesperian transition outflow units (Hto); Hesperian transition units (Ht); Hesperian transition undifferentiated units (Htu); and Hesperian-Amazonian impact crater materials (Ahi). The volcanic plains to the north of Ganges Chasma contain a dense network of NE-SW-trending fractures and collapse features (a-b). The collapse units contain abundant olivine (c), as noted by some previous authors (Edwards et al., 2008; Ody et al., 2013).
Figure 9

A schematic cross section shows a simplified version of Morella Crater, flooded by lava from a deep magma source. In “a,” the topography of the crater is accurate, except that Ganges Cavus is omitted to show the pre-cavus configuration. Panel “b” shows the actual north-south topographic profile with interpreted geology. Note the outcropping of crater-fill lava in the cavus wall. Withdrawal of magma, likely driven in part by the movement of magma toward Ganges Chasma to the north resulted in collapse of the
magma chamber. Collapse was controlled in part of the existence of impact-related structural discontinuities.

Figure 10

Lidar elevation data draped over a hillshade map show the summit caldera of Kilauea and smaller pit crater Halema‘uma‘u in Hawaii (a). The dashed line shows location of a topographic profile shown in the lower right of “a.” Worldview 3 false pan-sharpened color data of Kilauea Iki (b) show hummocky and platy textures similar to those observed on the floor of Morella Crater on Mars (Figure 7c).

Supplementary Files

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- SupplementaryMaterialsFeb11.pdf