Chaos formation by sublimation of volatile-rich substrate: Evidence from Galaxias Chaos, Mars

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1. Introduction

Chaotic terrains are common on the martian surface, however the origin of this landform is enigmatic and many different formation models have been proposed.

Chaotic terrain was thoroughly described by Sharp (1973) as irregular jumbles of angular blocks of various size (kilometers to tens of kilometers) many preserving remnants of the upland surface and sometimes controlled by linear features. Generally the blocks are flat topped, their sizes decrease away from the bounding head scarp and the terrain consists of alcove-like depressions that commonly have a subcircular shape and can be divided into cells (Nummedal and Prior, 1981; Chapman and Tanaka, 2002; Rodriguez et al., 2006). Usually, the chaotic terrain lies several hundreds of meters up to a couple of kilometers below the surrounding plateau and thus, the topographic characteristics are very distinctive for chaotic terrain. Meresse et al. (2008) used topographic profiles from the Xanthe and Margaritifer Terra to resolve different stages of chaos formation, showing an initial stage of shallow ground subsidence of a few tens to hundreds of meters, where the ancient plateau is heavily fractured and collapse is limited. During the collapse, the highland material is fractured into mesas making the chaos margins well defined and resulting in a vertical displacement of 1000–3000 m. Equally, Rodriguez et al. (2005) has delineated different stages of chaos formation based on morphologic and topographic observations of the Xanthe Terra region.

Chaotic terrain is found widespread and is generally geographically associated with huge equatorial troughs like Valles Marineris, with outflow channels like Chryse outflow channels and with the dichotomy boundary (e.g., Soderblom and Wenner, 1978).

Several different geologic scenarios have been proposed as chaos forming processes, often involving H2O as an important agent. Sharp (1973) suggested both degradation of ground ice and excavation of magma as plausible formation processes and Soderblom and Wenner (1978) elaborated on a ground ice model suggesting that erosion of strata originating from different zones of H2O stability would form chaotic regions. Recently, Zegers et al. (2010) proposed a new variant of this hypothesis suggesting that water ice is a part of the rock sequence. As the rock overburden reaches a thickness of 1–3 km the ice begins to melt due to the thermal insulation caused by overlying sediment, and thus, the overlying material destabilizes and water escapes creating chaos terrain.

The close spatial connection between chaotic terrain and outflow channels has resulted in suggestions that chaotic terrains are source regions for channel formation. Carr (1978, 1979) argued...
that outflow channels emerging full born from chaotic regions are strongly suggestive for catastrophic flooding by rapid release of a confined aquifer under great pressure resulting in collapse in adjacent areas. Triggering mechanisms could either be impact cratering or pore pressure reaching lithostatic pressure. Magma-ground ice interactions is another possible triggering mechanism, both as a heat source for catastrophic melting of ground ice, as well as disrupting the cryosphere releasing a confined aquifer under pressure (Chapman and Tanaka, 2002; Head and Wilson, 2002; Meresse et al., 2008). This model has been supported by Gloch and Christensen (2005), who observed grey, crystalline hematite along with phyllosilicates and possible sulfate in Aram Chaos providing evidence for episodic pulses of water release as a chaos forming process. Cabrol et al. (1997) stress the importance of volcano tectonic strains as another triggering mechanism based on a survey of Shalbatana Vallis, where crossing fault systems are suggested to allow hydrothermal drainage of confined aquifers. Rodriguez et al. (2005) suggest that the different stages of chaos formation result from multiple episodes of reactivation of the hydraulic head and propose a suite of processes such as: renewed magmatic activity, topographic lowering with respect to the groundwater table, subsiding cavern roofs or thickening of a permafrost seal, as mechanisms for increased hydrostatic pressure. Analysis by Wang et al. (2006) show that freezing-induced pressurization is a possible mechanism for releasing groundwater, however not on the order of big outflow channel systems.

Debris flow mechanisms, triggered by large scale failures of subsurface material, have also been proposed to account for the development of chaos (Tanaka, 1999; Nummedal and Prior, 1981). Based on observations of the Simud/Tiu deposits, Tanaka (1999) proposed that seismic activity could liquefy water-rich sediments causing a collapse and lowering of the chaos surface versus the adjacent plateau, resulting from subsurface removal rather than rotational slumping or lobate landslide masses. Wang et al. (2005) support this idea by suggesting impacts as a quaking agent and find evidence for liquefaction in chaotic regions by checkerboard patterns of gaps between blocks of chaotic terrain, which is similar to liquefaction patterns on Earth.

Dissociation of clathrates as a mechanism of subsurface removal has also been put forward in several papers (e.g., Milton, 1974; Hoffmann, 2000; Komatsu et al., 2000; Rodriguez et al., 2006) starting with Milton (1974) who proposed carbon dioxide hydrate as a possible phase, under which explosive dissociation would result in a catastrophic dewatering. Komatsu et al. (2000) argue that the stress from decomposed clathrates releases a large quantity of CO₂ and CH₄, which would subject water-saturated sediments to so much stress that the sediment would liquefy. A similar model, including a series of runaway degassing events for Ganges Chaos, has been proposed by Rodriguez et al. (2006), who mention deep fracture propagation, magmatic intrusions and climatic thawing and thinning of the cryosphere as plausible trigger mechanisms.

2. Geologic setting

Galaxias Chaos is situated in a highly complex region in the transition zone between Elysium Rise to the south, Utopia Basin to the north, and is bounded by Hecates Tholus to the east and by Elysium/Utopia flows to the west (Fig. 1). Galaxias Chaos was first recognized by Schaber and Carr (1977) and later mapped by Scott and Carr (1978) (1:25,000,000) as a knobby material in a zone between the lowland surface of Vastitas Borealis and Noachian Terrain. Based on Viking imagery, Mougins-Mark (1985) and Mougins-Mark et al. (1984) suggested that the upland remnants rather were a part of the compound lava plains extending from Elysium Mons than Noachian terrain and emphasized that structural weakness seems to have played an important role. Likewise, Greeley and Guest (1987) suggested that the material of isolated patches of grooved terrain was lava and ascribed the formation to Late Hesperian. However, Tanaka et al. (1992) proposed an Early Amazonian origin related to Elysium lavas grooved due to flowage of subsurface material, possibly as a result of ground ice melting induced by volcanism, and Tanaka et al. (2005) later classified Galaxias Chaos as a part of the Vastitas Borealis Marginal unit.

Since the first observations of the huge Chryse outflow channels draining into the northern lowlands, including Utopia Basin, studies investigating a volcanic-rite past have been carried out and enhanced H₂O content in Utopia Basin has been observed by the Mars Odyssey Neutron Spectrometer (Feldman et al., 2002). This result confirmed several proposals for a volcanic-rite geologic history based on a suite of morphologies (e.g., Cave, 1993), who observed a high frequency of fluidized ejecta in Utopia Planitia.

Other observations have suggested either an ocean hypothesis or a glaciation hypothesis and Kargel and Strom (1992) and Kargel et al. (1995) have been in favor of the latter. They suggested an ancient continental glaciation in the martian northern plains based on observations of thumbprint terrain in association with sinuous troughs that contain medial ridges, resembling terrestrial glacial features like moraines, tunnel channels and eskers.

On the other hand, Parker et al. (1993) argued for an ocean hypothesis and mapped two potential shorelines, contact 1 and contact 2, based on a variety of features like cliffs, terraces and abrupt termination of outflow channels. Based on data from MOLA onboard Mars Global Surveyor, Head et al. (1999) checked whether the proposed shorelines were reflecting an equipotential line, finding that contact 2 was the best approximation to an equipotential line having a surface elevation of −3760 m with a standard deviation of 0.56 km. The discrepancies vary nonrandomly and deviations occur primarily in regions of Tharsis, Elysium and Isidis, where later modification of topography is likely. However, as Carr and Head (2003) pointed out, though the standard deviation is small, individual sections of contact 2 have significant ranges in elevation and by assessing the observational evidence for shorelines they found little evidence for that interpretation. Chapman (1994) and Chapman and Tanaka (2002) proposed that in absence of classical coastal morphologies, volcano–ice interactions might provide morphological evidence of an ice sheet. Like Allen (1979), who found evidence for analogs to terrestrial subglacial volcanism close to the Elysium volcanic region, she found examples of three hyaloclastite-like ridges on the NW flank of Elysium Rise indicating the existence of an ice sheet with a height at least slightly higher than the ridges, which reach an absolute elevation of −3753 m.

The preferred explanation by Carr and Head (2003) is that the Vastitas Borealis Formation (VBF) supports the former presence of water from large floods better than the proposed shorelines. The outer boundary of VBF lies in approximately −3660 m elevation and VBF is generally smooth with gentle slopes and has a distinctive 3 km scale background surface topography, which suggests a non-volcanic origin (Kreslavsky and Head, 2000). The homogeneous and fairly smooth nature of VBF at 100 m and longer wavelengths, its location in a basin and in the lower end of the outflow channels as well as the similarity in age between the outflow channels and VBF fit the hypothesis for VBF representing a sublimation residue from a standing body of H₂O created by the outflow channel effluents. Modeling the evolution of outflow effluents, Kreslavsky and Head (2002) show that freezing in a convection state under current martian conditions would occur over a period of 10⁴ years and hereafter sublimate. Thus, the presence of both an ocean and an ice sheet is a plausible result of a catastrophic water release from Chryse and the fast freeze up of the ocean might explain why a clear coastal morphology has not developed.
The Utopia/Elysium deposits west of Galaxias Chaos extend more than 1500 km from the base of Elysium Rise forming a lobate tongue of relatively smooth and flat channelized materials associated with broad levees (Christiansen and Greeley, 1981; Tanaka et al., 1992). Many of them originate from linear fracture or graben systems, which are aligned NW–SE suggesting influence of a regional stress field (Plescia, 1986; Hall et al., 1986).

The deposits have been interpreted as lahar flows based on observations of their lobate outline, steep snouts, smooth medial channels, their wet-looking nature and their association with volcanism. Different models for generating lahars have been suggested, including volcano–ice interactions, volcano–ground ice interactions and/or dike disruption of the cryosphere and groundwater release (Christiansen, 1989; Christiansen and Greeley, 1981; Christiansen and Hopler, 1986; Skinner and Tanaka, 2001; Russell and Head, 2001a,b, 2002, 2003; Tanaka et al., 1992).

Most recently, Russell and Head (2001a,b) investigated the Elysium/Utopia flows using MOLA data, including detrended and gradient topography, and they were able to resolve two main types of flows; lava flows and debris flows. They also interpreted the debris flows as lahar deposits because of their morphology, stratigraphic relationships and because of observed dendritic ridges, suggesting dewatering flow after the water-rich lahar deposits came to rest (Russell and Head, 2002). The distribution of the lahar deposits below elevations of ~3100 m to ~4300 m correlates with the distribution of fluvial channels, and led Russell and Head (2001b, 2003) to suggest that the configuration of deep radial fossae, lava flows and lahar deposits can be explained by propagating dikes disrupting a confined aquifer facilitating large amounts of water responsible for the lahar deposits. Thus, the clustering of channel deposits may reflect the minimum elevation of a subsurface water table at the time of dike emplacement. This evidence led Russell and Head (2007) to suggest that the global groundwater system proposed by Clifford (1993) should be elaborated on to incorporate multiple recharge centers at volcanic provinces including contribution of snow melt to outflow channel activity.

Hrad Fossae is the easternmost outflow channel, and it modifies the western part of Galaxias Chaos and continues as Hrad Vallis further to the west. Several investigations of this area have been carried out, some suggesting karst or thermokarst processes responsible for depressions and channel incisions, implying the presence of either carbonates, volcanoclastic materials or porous clastic material saturated with water/ice (De Hon, 1992). Mapping performed by De Hon et al. (1999) strongly suggests interplay of volcanism, near-surface volatiles and surface run off. Wilson and Mouginis-Mark (2003) propose that Hrad Vallis has a phreatomagmatic explosive origin generated by shallow sill intrusion interacting with ice-rich rock layers creating mudflows. This hypothesis is supported by Morris and Mouginis-Mark (2006) who outline observations of thermally distinct craters within the deposits and argue that the distribution of the craters and their morphology are a result of interactions between hot mud flows and ground ice.

Hecates Tholus, situated east of Galaxias Chaos, is one of the few martian volcanoes, which has been proposed to have an explosive volcanic origin, deviating from many other volcanic, Hesperian edifices by the presence of channel-incised flanks (e.g., Reimers and Komar, 1979; Fassett and Head, 2006). Recently, remarkable, smooth, lineated deposits with similar characteristics as lineated valley fill in a flank depressions at the base of Hecates Tholus were documented, and Hauber et al. (2005) interpreted them as evidence of young glacial deposits from recent climate changes. If this interpretation is correct, the close relation to Galaxias Chaos suggests that recent climate changes might have been a plausible modifying agent obscuring the primary processes that generated the chaos.

Though this example is the closest evidence of late Amazonian permafrost and periglacial modification to the study area, lots of morphologies related to recent climate in Utopia have been reported including gullies, scalloped terrain, pingos and small size polygonal patterned ground (e.g., De Pablo and Komatsu, 2007; Soare and Osinski, 2007; Soare and Kargel, 2007).
In addition, Utopia Basin, among other regions, has been muted by mantling material that has been proposed to be an ice-rich deposit emplaced symmetrically down to latitudes around 30° during periods of high obliquity. At high obliquities water could migrate atmospherically from the poles to mid-latitudes where it was deposited as snow and frost. Today, this deposit is undergoing reworking, degradation and retreat in response to instability due to climate changes (Carr and Schaber, 1977; Mustard et al., 2001; Head et al., 2003; Morgenstern et al., 2007).

3. Galaxias Chaos

Since the last investigations of Galaxias Chaos, a lot of new satellite data has been provided by Mars Global Surveyor (MGS), Mars Odyssey, Mars Express and Mars Reconnaissance Orbiter (MRO) allowing more thorough and detailed studies of chaos forming processes.

3.1. Description of data

The region of Galaxias Chaos is covered by several different data sets allowing a description of the area on a regional scale as well as extracting information on small scale processes. Topographic data like HRSC DEMs and MOLA data provide a new topographic perspective on Galaxias Chaos. The resolution of HRSC DEM varies between 75 m/pixel and ~100 m/pixel and covers most of the region, with the westernmost part as an exception. On the other hand the MOLA DEM covers the whole region with a resolution of 460 m/pixel, but the distribution of MOLA tracks reveals that there is up to 13 km spacing across individual tracks.

Fig. 2. (A) Topography of Galaxias Chaos displayed by MOLA digital elevation model draped over a THEMIS IR mosaic. The color code ranges from ~3550 m (red) to ~4000 m (dark blue). (B) Geologic map of Galaxias Chaos and surroundings. The chaos itself consists of the grooved unit (dark orange), sub-grooved unit (light orange) and trough unit (dark brown). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Several different data sets from cameras sensitive in the visible to the infrared region have been released since the last examination of Galaxias Chaos. Viking (230 m/pixel), THEMIS IR (100 m/pixel) and HRSC (12.5–25 m/pixel) provide a regional overview of Galaxias Chaos and THEMIS VIS (18–80 m/pixel) covers a great extent of especially the eastern part of Galaxias Chaos. MOC, CTX and HiRISE provide more sporadic, but detailed images with a resolution of 1.5–7 m/pixel, 6 m/pixel and 0.3–0.6 m/pixel, respectively.

3.2. Geomorphology of Galaxias Chaos

The region of Galaxias Chaos (142–150°E, 33–38°N) was mapped in 1:100,000, and in several places to greater detail where data allowed it. Galaxias Chaos is a mosaic of angular mesas, which covers an area of approximately 14,000 km² and the elevation varies from approximately −3550 m to −4000 m (Fig. 2A). Galaxias Chaos is bounded to the east by Hecates Tholus and to the west by the Elysium/Utopia flows and it is situated at the foot along the edge of Elysium Rise as a complex jigsaw of polygonal blocks, which are mapped as the dark orange, groove unit and as light orange, sub-grooved unit on the geologic map on Fig. 2B.

The groove unit of Galaxias Chaos is characterized by well-defined blocks, which vary in size from 0.25 km² to approximately 100 km² and there is no clear size progression away from Elysium Rise. Both rough hummocky knobs and smooth surface texture are observed on top of the blocks, but no relationship between the troughs and the surface texture is observed.

Some larger, topographically less pronounced blocks, which are several tens of kilometers across, are mapped as a sub-grooved unit. Due to their less distinct relief they are more difficult to map, and they are mainly distributed in the eastern part of Galaxias Chaos further away from the edge of Elysium. Many of the troughs do not penetrate this unit, resulting in blocks with a size up to 40 km × 70 km and in some places the unit seems to be submerged by material from the Utopia Basin. Like the grooved unit, rough and smooth surface textures are observed, which suggests that the surface material of both the grooved and sub-grooved unit is the same. The transition between the two units is abrupt and is displayed in Fig. 3A and D.

There is a huge morphological difference between the eastern and western part of the grooved unit. To the east, the unit is well defined and can be divided into subcircular cells, while the chaotic terrain in the western part has been modified by Galaxias Fossae and related outflow activity, which seems to submerge existing troughs (Fig. 3B).

Numerous smaller, angular to subangular blocks up to approximately 2–10 km across are observed in Utopia Basin and they exist both in the lobate plains material and plains material and are marked as purple on Fig. 2B and in addition are displayed in the top of Fig. 3D. At first sight it looks like these smaller blocks originate from Galaxias Chaos due to their close spatial relationship, their shape and their elevation. However, these blocks can be traced all the way to Phlegra Montes more than 1000 km NE of Galaxias Chaos as well as to the Isidis basin, more than 3000 km to the southeast. Furthermore, they do not display the same jigsaw-like pattern as the grooved and sub-grooved unit and are therefore not considered to be a part of Galaxias Chaos, consistent with the geologic map from Tanaka et al. (1992).

The main morphological difference between the lobate plains material and the plains material is the characteristic lobate plateau features with a distinct rim, which are distributed between the blocks (Fig. 3E) and both units contain unusual crater morphologies,
which have been described by Pedersen and Head (2009). The distinct rim associated with the plateaus in lobate plains material is in some places draping the flanks of angular blocks, and within the lobate plains material subdued knobs are observed and they seem occasionally to penetrate the lobate plains material (Fig. 3E).

For resolving the formation process of Galaxias Chaos, extra emphasis has been put on the data from the eastern and central part of Galaxias Chaos, where the chaos is best preserved.

After constraining the extent of the chaotic terrain (grooved, sub-grooved and trough unit) and the extent of later modifying processes (deposits from outflow activity; flood plain deposits, levee deposits and smooth flow) an analysis of the surface material was carried out by tracing layering and rough surface texture.

3.3. Surface material of Galaxias Chaos

MOC data reveal a dark surface layer observed in trough walls in Galaxias Chaos that can be traced from troughs within Elysium Rise into Galaxias Chaos (Fig. 4). The two images are 80 km apart and are from the eastern and central region of Galaxias Chaos, and they display a distinct dark, competent layer that can be mapped out across the troughs (marked by black arrows). This indicates that the same layer traced from Elysium Rise caps the polygonal blocks within Galaxias Chaos.

Similarly, distinct rough texture and associated flow fronts can be traced from Elysium Rise all the way to Galaxias Chaos (Fig. 5). Both these observations suggest that Galaxias Chaos is capped by Elysium lavas implying that Galaxias Chaos was a part of Elysium Rise before trough formation.

3.4. Trough development

The trough formation itself can be studied by investigating the variety of troughs, their geometry, and their spatial relationship to the blocks.

The troughs are generally round-headed, with a width around 600–800 m and they are approximately 100 m deep; they vary between being flat-floored and v-shaped. As displayed in Fig. 6,

![Fig. 4. Close-up of the surface layer in the central and eastern part of Galaxias Chaos. Two MOC images from the central and eastern part (m0304232 and r13044670, respectively) are located 80 km apart and both images display a dark surface layer that can be traced across troughs from the Elysium Rise (C and H) into the blocks of Galaxias Chaos (A, B and E–G) as shown by black arrows. This indicates that Galaxias Chaos is capped by the same material as the Elysium Rise unit that consists of lavas. Both MOC images are 3.8 km across.](image-url)
different stages of trough formation can be found. The early trough formation is displayed in Fig. 6A and B, and Fig. 6A shows a round-headed depression forming within a block marked by breakage of the competent surface layer. Likewise, Fig. 6B shows initial trough development forming within the block, but with a close relation to the edge of the block, which indicates that the trough formed due to instability of the slope of the block.

The troughs either continue to grow within the blocks, forming kilometers-long troughs or they incise the block from the edges. Fig. 6C shows an example of a trough which curves subparallel to the edge of the block and which to the northwest is abutting another trough separated by less than 10 m of block material. Moreover, the southwestern end of the trough seems to grow along a linear depression marked with black arrows. Similarly, two troughs on each side of a block seems to incise a block along a 70 m wide depression, dividing the block into two parts, if the trough incision process continues (Fig. 6D). An example of how the troughs coalesce and form cell-like trough systems making a jigsaw puzzle of mesas is displayed in Fig. 6E, and it is observed that minor or no rotation of the blocks has taken place. This indicates that chaos formation was not a catastrophic process, but a gradual development allowing different stages of trough formation to be preserved. Likewise the cell-like nature suggests that the trough formation has been ongoing in several places along the contact as multiple events of trough formation and collapse.

Moreover, the fact that the troughs form as depressions within blocks also implies that the trough formation is not governed by regional stresses, but rather local stress within and along block edges.

3.5. Topography of Galaxias Chaos

The mesas in Galaxias Chaos are developed at −3.6 km to −3.7 km elevation and individual blocks are 100–200 m high, reaching a maximum height around −3.5 km. In this manner, the topographic characteristics of Galaxias Chaos deviate from other described chaotic regions, where the blocks lie 1–2 km below the surrounding surface. In contrast, some of the blocks in Galaxias Chaos are higher than the adjacent slope (Carr, 1979; Rodriguez et al., 2005; Meresse et al., 2008). This is displayed in Fig. 7, where four selected MOLA profiles, going from the east to the west, cross the eastern part of Galaxias Chaos and the black arrows delineate the grooved unit. Profile 19875 (blue) and 13377 (red) show that individual blocks within Galaxias Chaos are slightly elevated with respect to the surrounding plateau.

At some places a plateau is developed in front of the chaos, as shown in profile 10660 (yellow), but generally the elevation of the blocks decrease away from Elysium Rise.

From THEMIS- and CTX-images it is observed that some of the blocks display chaotic tilting, resulting in a well-defined relief in
A–B and A not sustain further differential stress. The two topographic profiles age of the central part of the block as the surface material could material, while the flanks have experienced subsidence causing breakage of the superposed blocks due to unequal subsidence. In the case of Fig. 8C it seems that the central part of the fig. 8A and B). Furthermore some blocks partly superpose a competent material causing breakage of the superposed blocks due to unequal subsidence. In the case of Fig. 8C it seems that the central part of the two yellow, highlighted blocks stalled on a stable subsurface mate- some parts of a mesa, while other parts are more subdued indicating that the surface material of Galaxias Chaos superposes an unstable material and that they have experienced differential vertical displacement (Fig. 8A and B).

4. Model for formation of Galaxias Chaos

Galaxias Chaos is significantly different from other chaotic regions. First of all the topography is very different and in Galaxias Chaos the elevation of mesas is in the same range as the surroundings, whereas other chaotic terrains have a significant elevation difference up to several thousand meters between blocks and plateau. Moreover, Galaxias Chaos is not associated with huge outflow channels, and Hrad Vallis is modifying rather than fed by the western part of Galaxias Chaos. The different stages of trough formation clearly indicate a gradual trough formation with minor vertical movement, which contrasts to a catastrophic formation process. Thus, proposed formation models for chaotic regions around Chryse Planitia do not appear to be directly applicable to Galaxias Chaos.

The observations from Galaxias Chaos suggest that the surface material is Elysium lavas based on the distinct surface layer and the rough surface texture associated with flow fronts that have been traced from Elysium Rise into Galaxias Chaos. Moreover, the topography reveals that a differential amount of subsidence has caused different stages of trough formation indicating an unstable subsurface layer. The tilting of mesas and the fact that some blocks have elevations equivalent or slightly higher than the surrounding plateau also support a differential vertical displacement. This implies that some parts of Elysium Rise have experienced a slightly greater downward movement without causing breakage in the lava cap than the few elevated mesas within Galaxias Chaos. Additionally, the fact that troughs develop within the blocks indicate that the trough formation is not governed by regional stress fields, but by local stress fields, which fits an explanation of differential subsurface degradation and/or flow. Thus, a consistent formation model for Galaxias Chaos should include a substrate, which due to shrinkage/movement can cause gradual trough formation induced by local stresses.

All these observations exclude proposed chaos formation models such as magma excavation, clathrate dissociation, catastrophic groundwater release and melting of ice due to thermal insulation caused by overlying sediment. However, degradation of ground ice is a plausible mechanism of differential downward movement of a substrate creating gradual trough formation, tilt of blocks and variable local stresses.

Considering the close spatial relationship with lobate plains material, which Tanaka et al. (2005) assigned to be a part of Vastitas Borealis Formation, this unit would be a good candidate as a subsurface material from a stratigraphic point of view. Moreover, the observed morphologies of lobate plateau material draping angular blocks and subdued knobs that occasionally seems to penetrate the lobate plains material indicate degradation and shrinkage revealing the subsurface topography (Fig. 3E).

Additionally, the VBF has been considered to be a residue from a H₂O-rich material deposited by huge floods, as earlier mentioned (e.g., Kreslavsky and Head, 2002; Carr and Head, 2003). The thickness and the elevation of the outline of VBF fit both the depth and the elevation of the troughs (Carr and Head, 2003) and the...
Fig. 7. Four topographic profiles and their location in the eastern part of Galaxias Chaos. From the top the four profiles are selections of MOLA tracks; ap19875, ap10660, ap13377 and ap19863 starting from the east to the west. Black arrows point out the extent of the grooved unit.
estimated age of VBF is Early Amazonian, compared to the latest activity on the Elysium Rise (Tanaka et al., 1992, 2005), making it a plausible scenario that Vastitas Borealis Formation is sandwiched between Elysium lavas.

The suggested formation process for Galaxias Chaos is shown in Fig. 9, where a block diagram shows the stratigraphic relationships between Elysium lavas and VBF. VBF is displayed in variable light blue colors indicating variable volatile content and it is sandwiched between Elysium lavas in grey. The lava cap on top of VBF inhibits volatile sublimation, but in areas where there is no lava or where troughs have formed, volatiles sublime (indicated by wavy, orange arrows). Sublimation of volatiles within the VBF results in shrinkage and degradation of the unit and thereby facilitates subsurface movement. Where the VBF wedges out between Elysium lavas, VBF is so thin that mass movement and vertical displacement is so small that no trough formation occurs because of the strength of the lava cap itself. As the VBF increases in thickness the lateral transport of sediment and the potential vertical displacement increase, undermining the lava cap. Eventually the lava cap experiences higher stresses than it can support, creating depressions and later troughs as sublimation through the broken lava cap occurs. The most intense chaos formation will therefore occur in the parts of Elysium Rise where the thickness of the VBF is sufficient, and where the slope is steep enough to facilitate and concentrate subsurface movement. Where particularly intense and continued mass movements occur, tilted blocks as well as subsurface material submerging and superposing low lying blocks might result.

This model explains several observations. First of all, the troughs with highest elevation occur along an equipotential line having an altitude around -3.6 km to -3.7 km. This fits with a stratigraphy where the VBF was deposited with a surface elevation around -3660 m and later capped by Elysium lava flows. Thus, if the VBF was deposited as an equipotential surface, it would be expected that the occurrences of the most elevated troughs should be equipotential and it would have been a problem if chaos formed well above the suggested altitude of the VBF.

Secondly, the extent of VBF may very well explain the cell-like nature of the chaos development. Before the VBF was deposited the topography of Elysium Rise was controlled by its fingering flows creating a wavy topography. Thus, as the VBF was emplaced as an equipotential surface its outline and its thickness were controlled by this pattern filling up lows between lava flows with thicker VBF deposits than elsewhere along Elysium Rise. Therefore, as the volatile loss initiated the movement of the substrate, it was controlled by local topography under the volatile-rich unit, facilitating trough formation in the former lows between lava flows creating the cell-like nature of Galaxias Chaos. This is illustrated in Fig. 9 where a thicker deposit of the VBF occurs in the lows of the oldest Elysium lavas (dark grey).

Thirdly, this model explains the gradual development of troughs creating a jigsaw pattern, because Galaxias Chaos basically was a part of Elysium Rise, which was incised by troughs causing well preserved mesa surfaces, minor lateral movement of the blocks and no huge topographic difference between the mesas and the plateau itself.

Moreover, the fact that the mass movement is limited by the thickness of the VBF as well as by the dip of slope, might explain why the well defined grooved unit occurs within a belt. The sub-grooved unit is, like the grooved unit, capped by lava and the
deposits of the VBF must at least have been as thick as in the area of the grooved unit. However, the region of the sub-grooved unit has a significantly smaller dip (Fig. 7) resulting in smaller subsurface mass movement, which can explain less distinct trough development and mesa formation.

Finally, variable VBF thicknesses as well as heterogeneities within VBF will cause differential vertical displacement during the downwasting of the VBF. This explains why some mesas within Galaxias Chaos are higher than the plateau and why some blocks seem to have stalled due to a competent subsurface layer. Differential downwasting will make the surface layer bend and tilt until the stress is so high that the surface layer breaks (Fig. 8C). This is illustrated in the right part of the block diagram in Fig. 9, where the hatched signature symbolizes the competent subsurface layer.

The geologic history of Galaxias Chaos is summarized in Fig. 10. First Elysium lavas were emplaced in the Late Hesperian period in stage A (Tanaka et al., 1992, 2005). In the Early Amazonian period the Vastitas Borealis Formation was deposited and was later superposed by younger lavas due to continued volcanic activity (stage B). Because of sublimation of volatiles within VBF, either due to enhanced geothermal activity or climate changes, the VBF degraded, causing differential movement and undermining of the lava cap, resulting in local extension and subsiding troughs. Along the trough walls enhanced volatile evaporation caused the trough to grow headwards, producing a jigsaw puzzle of blocks as the troughs coalesce (stage C).

Finally after formation of the chaos, continued volcanic activity along the NW–SE trending fractures caused modification of the western part of Galaxias Chaos, producing outflow deposits (stage D).

5. Discussion

This proposed formation model raises several important questions considering the nature of VBF; what mechanisms controlled the sublimation of volatiles? And do other examples of similar stratigraphic relationships exist both in the region of Elysium and elsewhere?

The role of the VBF in the history of the martian hydrologic cycle is crucial, especially with respect to resolving mechanisms of deposition and later modification, linking the present day morphology to its origin. This work stresses the importance in estimating the amount of H$_2$O deposited and sublimated as well as understanding the nature of the VBF. This is particularly important in this study, because of the morphologies that developed during volatile loss, not only within the VBF, but also in the marginal areas, where the VBF might be superposed by other units. Kreslavsky and Head (2002) modeled the evolution of outflow channel effluents and proposed that after emplacement, intense sublimation and cooling, outflow effluents would freeze up solid, sublime and in the end a residual ice-rich sediment producing VBF would be left for later modification.

The porosity on Mars is considered to decay significantly slower than on Earth and Clifford (1993) calculated that a Moon-like crust scaled to martian conditions would have a porosity decay constant of 2.82 km. Thus, assuming that the lithostatic pressure is the only controlling factor on the porosity in the VBF, the porosity would be 97%, 93% and 90% of its initial porosity in 100 m, 200 m and 300 m depth, respectively. Basically, this means that if the VBF is an ocean deposit containing lots of very fine grained material, and with H$_2$O...
filling up the pore space, immense amounts of volatiles would have been present in the deposits. Moreover, freezing such a fine grained material would certainly result in cryosuction, for which reason ice segregation would produce massive ice lenses of ground ice producing stratified or veined sequences of sediment and ice (Clifford and Parker, 2001). Therefore, it is reasonably to believe that the volatile content in the VBF would be sufficient for shrinking the VBF to a degree, where it would undermine a lava cap producing troughs; moreover, the heterogeneous distribution of ice lenses would facilitate differential subsidence.

Another interesting question is: How was the degradation of the VBF below the lava cap initiated? Obviously, where the VBF was in contact with the atmosphere, an ice-rich sediment under current martian condition would sublime and cause shrinkage. The question, however, is whether this downsinking was significant enough to cause downward and lateral movement within the lava-capped part of the VBF initiating the trough formation, which would facilitate further volatile escape, or whether enhanced geothermal flux was essential. Gulick (1998) showed that in volcanic regions with intrusions greater than several hundreds of cubic kilometers, hydrothermally derived fluids can melt through 1–2 km thick permafrost in several thousand years, and since Galaxias Chaos is associated with Elysium Mons and Hecates Tholus, it is clear that a heat source for melting ground ice is available in the region. However, it is very likely that there will be no geomorphic difference, whether Galaxias Chaos originates purely due to climatically sublimed volatiles or whether enhanced geothermal flux existed, and it is questionable if mineralogical data from orbit would provide any evidence. Thus, the most plausible way to constrain this problem would be to estimate the amount of volatiles deposited in VBF and the amount of sublimed volatiles estimating that the vertical displacement of the exposed VBF would be sufficient to cause a gravitational subsurface flow in the region of Galaxias Chaos.

If one suggests that the stratigraphic relationship between the VBF and Elysium lavas is controlling the formation of Galaxias Chaos, an import question to raise is whether chaos formation occurs elsewhere on the edge of Elysium Rise. From the proposed formation model, one would expect to find chaos, where the VBF and Elysium lavas are interbedded, and from the geologic map made by Tanaka et al. (1992, 2005) this contact between VBF and Elysium lavas can be traced from west of Hecates Tholus along the boundary of Elysium Rise to the western part of Elysium Rise. However, the later Amazonian outflow channels have modified this contact heavily to the northwest of Elysium Rise, and therefore the western part of Elysium Rise is the only area where there might be remnants of chaos formation.

Fig. 11 displays chaotic terrains found on the western flank of Elysium and the similarities with Galaxias Chaos are striking. Skinner and Tanaka (2007) ascribed these terrains to fractured rises originating from laccolith-like intrusions, but because of the similar morphology and because they are situated approximately at the same elevation, they are here suggested to have formed the same way as Galaxias Chaos. The chaotic terrains can be seen on Fig. 11A as red areas, where the contour lines −3500 m, −3600 m and −3700 m are marked by orange, blue and green, respectively. Some chaotic terrains on the western flank are isolated features and seem to have been partly submerged by later lava flows (Fig. 11B and C), which might explain why some of the chaotic terrains are situated at −3400 m height. A similar stratigraphic relationship has been reported by Ivanov and Head (2003), where a zone of plateau breakup of young lava flows that have been superimposed onto the surface of a volatile-rich substratum has been reported along the contact between Syrtis Major and VBF in the transition zone between Syrtis to Isidis. Therefore, it reasonable to believe that the formation process of Galaxias Chaos is relevant to several transition zones producing chaotic terrains significantly different from the chaos regions in Valles Marineris and in the region of Chryse outflow channels.

6. Conclusion

Galaxias Chaos deviates significantly from other chaotic regions due to the lack of associated outflow channels, lack of large elevation differences between the chaos and the surrounding terrain, and due to gradual trough formation. A sequence of troughs in different stages is detected, and examples of closed troughs within blocks suggest that the trough formation is governed by a local stress field rather than a regional stress field. The geomorphic evidence suggests that Galaxias Chaos is capped by Elysium lavas, which superpose an unstable subsurface layer that causes chaotic tilting of the blocks as well as trough formation. Based on regional mapping we here suggest a formation model where the unstable subsurface material, which is interbedded with Elysium lavas, is the Vaestitas Borealis Formation, and which due to gradual volatile loss, causes shrinkage and differential substrate movement. This process would result in local extension and depression formation, ending with trough development and trough coalescence producing a jigsaw puzzle of blocks. Observations of chaos regions to the west of Elysium Rise indicate that this process might have been widespread along the contact between the Vaestitas Borealis Formation and Elysium lavas, but probably has been covered to the NW of the Elysium Rise by Elysium/Utopia flows, and has partly been submerged by younger lavas to the west.
Fig. 11. (A) Distribution of chaos terrain in the Elysium Volcanic Province. Chaos is marked as red areas and the elevations; -3700 m, -3600 m and -3500 m are marked by the green, blue and orange contour lines, respectively. Chaotic terrain is observed approximately in the same elevation along the northern transition zone and the western transition zone between Elysium Rise and the Utopia Basin. (B) Zoom in on the chaotic terrain on the western flank of Elysium, which seems to be partly submerged by later lava flows. THEMIS IR mosaic. (C) Chaotic terrain in the western part of Elysium with a similar polygonal jigsaw pattern as observed in Galaxias Chaos. The rough surface texture is associated with flow fronts and the troughs show rounded head scars like Galaxias Chaos. CTX-image P010013431967. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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