Morphology and geology of the ILD in Capri/Eos Chasma (Mars) from visible and infrared data

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ABSTRACT

Layered deposits have been observed in different locations at the surface of Mars, as crater floors and canyons systems. Their high interest relies in the fact they imply dynamical conditions in their deposition medium. Indeed, in opposition to most of the rocks of the martian surface, which have a volcanic origin, bright layered deposits seems to be sedimentary outcrops.

Capri Chasma, a canyon located at the outlet of Valles Marineris, exhibits such deposits called Interior Layered Deposits (ILD). A large array of visible and infrared spacecraft data were used to build a Geographic Information System (GIS). We added HiRISE images, from the recent MRO mission, which offer a spatial resolution of 25 cm per pixel. It allowed the mapping and the analysis of morphologies in the canyon. We highlighted that the ILD are several kilometers thick and flat-top stratified deposits. They overlap the chaotic floor. They are surrounded and cut by several flow features that imply that liquid water was still acting after the formation of these stratified deposits. The density of crater on the floor of Capri Chasma was quantified. The current topography was aged to 3 Gyr. All these morphological information allow us to suggest a plausible geological history for Capri Chasma. We propose that the Interior Layered Deposits have formed during the Hesperian, during or after the opening of the canyon. Some observations argue that water discharges have happened at several times before and just after the formation of the ILD. Liquid water must have played a major role in the formation of these deposits after 3.5 Gyr, implying that it was present in surface at least locally and temporarily. If this can be applied to ILD in others canyons of Valles Marineris, it would imply that liquid water was stable in surface or sub-surface during the Hesperian. Or in the actual conditions, with a cold and dry martian surface, long-term standing water bodies are not possible. Thus we suggest that either the climate at the Hesperian was cold, but wetter, or as warm as the Noachian climate, what is less likely. Nevertheless, the global climate change which has occurred at the beginning of Mars history may have been later than announced.

1. Introduction

Layered deposits were first observed in 1971 on Mariner 9 images. They have been referred as thick deposits with internal layering, and a relatively high albedo (Lucchitta et al., 1994). They have been identified on the floors of some large craters, in some inter-crater plains (Rossi et al., 2008) and in the deep canyons of Valles Marineris. The last ones, commonly called ‘Interior Layered Deposits’ (ILD), have been widely studied these last years.

McCauley (1978) first described them as kilometers thick flat-top layered deposits located in the center of several chasmata in Valles Marineris. However if their morphology is well constrained, their origin and age remain uncertain (Weitz et al., 2003). ILD have successively been referred has lacustrine deposits (McCauley, 1978; Nedell et al., 1987; Komatsu et al., 1993), erosional waste of the canyon walls (Lucchitta et al., 1994), subice volcanic structure (Chapman and Tanaka, 2001; Komatsu et al., 2004), or non-aqueous aeolian or volcanic deposits (Peterson, 1981).

Catling et al. (2006) have studied images of Juventae Chasma, and suggested that these layered deposits could be a Noachian bedrock, exhumed later by tectonic processes, as the opening of Valles Marineris during the Hesperian. Other authors (Tanaka, 1986; Komatsu et al., 1993) have noticed that these deposits were overlapping the canyon floor in some location and could be younger than the canyon itself, dating from the Hesperian to the Amazonian.
This wide range of suggested ages increases the uncertainties on the origin of the ILD.

Recently, observations from the Observatoire pour la Mineralogie, L'Eau, les Glaces et L'Activite (OMEGA) spectrometer, on board of Mars Express (ESA, 2003) have shown the presence of hydrated minerals, especially sulfates, in association with the ILD (Gendrin et al., 2005).

New high resolution data from the Mars Reconnaissance Orbiter (NASA, 2005) are available and could precise the context of these detections, and previous morphological observations.

The present study is focused on some layered deposits in the region of Capri Chasma (Fig. 1), which have never been studied in details previously.

In this paper, we give a detailed description of the morphologies observed in Capri Chasma. The age of its current topography was quantified with crater counts, and we build a possible geological history for this canyon, including the formation of the layered deposits.

2. Regional context

Capri Chasma is located at the outlet of Valles Marineris, in the continuation of Coprates Chasma, and at the head theater of the outflow channels that are spreading over at the east, like Eos Chasma (Fig. 1). This canyon extends over 650 by 350 km. Its floor has an average elevation of −4000 m, and the surrounding plateaus are above +2000 m. The western part of Capri Chasma shows a depression which is the lowest point of Valles Marineris, with elevations close to −5000 m. ILD in Capri Chasma are mainly located in the center of the canyon, where they form three mesas of variable sizes, ranging from 370 by 170 km to 60 by 20 km. Their thickness is close to 3 km,
which gives them an elevation comparable to half the plateaus one. One of the major interests of Capri Chasma is that we observed these layered deposits associated with typical morphologies of outflow channels like catastrophic flow features and chaotic floors.

3. Datasets

A Geographic Information System (GIS) was built to gather data from different martian missions. Themis Visible and day and night Infrared data from the Mars Odyssey Spacecraft were used, in association with the Mars Orbiter Camera (MOC) data from the Mars Global Surveyor mission, and the High Resolution Imaging Science Experiment (HiRISE) grayscale images and Context Camera (CTX) data from the Mars Reconnaissance Orbiter mission. These images spread over a wide range of resolution, from 0.25 m per pixel for the HiRISE, to 18 m for the Themis Visible. The list of HiRISE images used during this survey and their key observations is provided in Table 1. Themis day and night Infrared data were juxtaposed as mosaics of a spatial resolution of 200 m per pixel. A MOLA DEM at 450 m per pixel was added to this image collection, providing elevation data. HiRISE color images were used to complement grayscale ones, by distinguishing the nature of layers.

The images corresponding to the area of Capri Chasma were processed, georeferenced and integrated into the GIS. This whole combination of images provides a full spatial-coverage of the canyon. 3D models were also built, using MOLA as base height for Themis IR data.

4. Geomorphological units of Capri Chasma

Different geological units have been mapped in Fig. 1c, and will be explained in details.

4.1. The canyon floor

The floor of Capri Chasma is formed by kilometers-wide angular mounds (Fig. 2), called chaotic terrains. Chaotic terrains are typical outflow channel head theater floors (Glotch and Christensen, 2005). They have an average elevation ranging from hundreds of meters to a few kilometers, with slopes around 20°. The top of the mounds often shows horizontal layering of dark coarse rocks. In the western part of Capri Chasma, which is the lowest point of Valles Marineris, chaotic mounds exhibit multiple terraces on their surrounding areas (Fig. 3a). The transversal profile (Fig. 3b) shows convex shapes for the deposits around the original mound. These aprons are limited to a few kilometers around the mounds. Between the chaotic mounds, the floor of the canyon is mainly covered with dark dust. The material composing the floor is visible inside craters. Crater ramparts let outcrop horizontal layers of dark coarse rocks similar to those of the chaotic mounds. The floor of these craters, the top of small mounds and the base of the outcrop slopes are covered by dune fields.

Table 1

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<th>HiRISE ID</th>
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<td>Wall: layering lavas</td>
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Fig. 2. Remarkable features at the embouchure east of Capri Chasma (white arrows) on the Themis IR mosaic at 200 m per pixel. Arrow 1: chaotic mound. Arrow 2: line-streaks delimited north by a remnant bar. Arrow 3: multiple terraces on the wall of the canyon. Arrow 4: Alluvial fans recovering line-streaks.
Between the major mesa of the ILD, and the two outliers south and east, we noticed large line-streaks oriented west–east, over approximately 500 × 40 km, that become denser and end at the outlet east of Capri Chasma (Fig. 2).

4.2. Canyon walls

Walls of canyons in Capri Chasma have typical morphologies in ‘spur and gullies’, as previously described in other canyons of Valles Marineris (Peulvast et al., 2001). They are around 6 km high. They reach more important values in the north–west part of the canyon. The topmost part exposes horizontal layering of dark coarse rocks similar to those observed in the bottom of the canyon and on chaotic mounds (HiRISE images PSP_1970_1655_RED and PSP_3671_1655_RED, PSP_7508_165_RED and PSP_7864_1655_RED). In very few locations, lighter material is observed as patches covering the wall bulk material (HiRISE PSP_3671_1655_RED and PSP_7943_1640_RED). Harrison and Chapman (2008) have reported the presence of benches in the western walls of the canyon. Multiple terraces are also seen in the eastern flanks of Capri Chasma outlet, at the bottom of the plateaus fractured terrains, and where line-streaks stop (Fig. 2). Around 10 terraces are spreading over almost 37 km and have elevation ranging from −200 to −3500 m; thus they impact a significant part of the walls.

At some places, walls are covered by two kinds of fans. The first type consists in debris aprons, which are well observed in two different locations in Capri Chasma. First, at the eastern outlet of the canyon, fans overlap outflow features on nearly 30 km (Fig. 2). The side shows gullies and spurs brinks, masked at the base where fans are spreading out. The fans are dissected by channels. The top of the aprons is around −1430 m of elevation, they become wide and scattered after −2450 m. HiRISE image PSP_7389_1665_RED was acquired just east of these fans and shows sinuous and joining channels, a few hundred meters wide, and around 5 km long. They are cross-cutting some multiple terraces described above (Fig. 4a).

The second type of fans is emplaced at the outlet of head valleys cutting the Valles Marineris plateaus. A 45 km wide lobate deposit was formed at the outlet of a small valley, carved into the plateau, in the western flank of Capri Chasma (Fig. 4b). This fan has been described by Harrison and Chapman (2008), and is covered by HiRISE images PSP_6796_1655_RED and PSP_6651_1665_RED. Several channels surrounded by light-toned indurated material are observed. The fan stops sharply leading to a convex shape profile. The lobate end of the fan is affected by at least three small terraces, not high enough to be resolved by MOLA data.
Landslides are also observed in a few locations in the northern flank of Coprates, near the border with Capri Chasma. The head theaters of landslides are free of spurs and gullies and the landslide deposit is characterized by widespread lobate debris aprons (Lucchitta, 1979; Quantin et al., 2004), as it can be seen on HiRiSE images PSP_1970_1655_RED and PSP_3671_1655_RED.

4.3. Plateaus

Plateaus south and east of Capri Chasma are heavily fractured. They seem to have collapsed around the outlet of Capri Chasma. These features are observed close to the walls of the canyon and extend over 300 km toward the south.

Plateaus also exhibit light-toned deposits south–west of the canyon. The light-toned material extends over almost 50,000 km² (HiRISE image PSP_4383_1625_RED and PSP_5016_1640_RED). Inverted channels are observed in some location (HiRISE PSP_5016_1640_RED) (Le Deit et al., 2009). There may be some more deposits north–west of the canyon, but their limits are at the edge of detection.

4.4. Interior Layered Deposits

In Capri Chasma, the Interior Layered Deposits (ILD) are made up of a major mesa, 370 by 170 km wide, approximately 3 km thick, and of two smaller outliers of 60 by 50 km and 60 by 20 km, respectively located at the south and the east of this large mesa (Fig. 2). Their top is flat and dark, while the fresh outcrops in their flanks exhibit lighter rocks. These light-toned deposits are massive, but layering is visible in some location.

Several layers can be distinguished, as shown in Figs. 5–8. The main part of the ILD flanks or cliffs is made of a massive bright unit referred as LM (light-toned massive deposits, Figs. 6a and 7a, c, and e), while its upper part, referred as LE1 and LE2 (light-toned erodible layers, Figs. 6a and 7a, c and e), seems more finely stratified, less bright and is probably more erodible. LE2 is distinct from LE1 as LE2 is the bottom part of this layer, underlying the bright deposits with really sharp cliffs. LE1 is less steep and eroded in small platforms, leading to the recession of the cliff at its top. When the slope is more gentle, massive bright deposits (LM) are absent and replaced by light-toned outcrops with an alveolus facies (LA) (Figs. 6b and 7b and d). This is probably the same layer having different appearance depending on the topography. There are no exposed thin and dark layer in the ILD, the top of light-toned rocks is covered by a blocky or rubbly dark layer, referred as DB (Figs. 6c and 7d, HiRISE images PSP_8958_1665_RED and PSP_9881_1670_RED). This layer is located at a higher altitude than the light-toned deposits, which is also the highest elevation point of the main mesa. Its extension is very limited (about a few square kilometers).

In one location, north–east of the main impact crater affecting the ILD, the top of light-toned rocks is covered by a blocky or rubbly dark layer, referred as DB (Figs. 6c and 7d, HiRISE images PSP_6958_1665_RED and PSP_9881_1670_RED). This layer is located at a higher altitude than the light-toned deposits, which is also the highest elevation point of the main mesa. Its extension is very limited (about a few square kilometers).

In a few places, we also observed stratified and fractured layers of a lower albedo (LC, Figs. 6d and 7d). They have always been found at a lower elevation than the high albedo deposits. These features are well observed in the flank and on the floor of the 32 km crater affecting the northern part of the major mesa of the ILD (Fig. 9). CTX images T01_000901_1667_XN_13S047W, P03_002128_1667_XL_13S047W, P06_003473_1657_XN_14S047W and P07_003684_1657_XN_14S047W; and HiRISE images PSP_002128_1670_RED and PSP_008958_1665_RED exhibit this dense, stratified and fractured layer overgrown by the light-toned alveolus deposits LA (Figs. 7d and 8).

Sequences, elevations and thicknesses of these different layers can be compared on the different HiRISE images covering the ILD flanks. Thicknesses may not be relevant in Fig. 7d, due to the impact effects. This figure has to be taken as some qualitative information about the layer series.
The LE level is for instance always found above brighter deposits of units LM and LA (Figs. 7a, c, and e and 8). It is morphologically close to the LC layer, except its grains are not as coarse. This layer is comprised between $-2300$ and $-3200$ m west of the main mesa (HiRISE PSP_008378_1670_RED) and between $-500$ m and $-1700$ m at the east (Fig. 8). This could indicate a tip towards the west, but layers seem rather horizontal. They could also be hidden faults among the mesa. Another possibility is that there could be two of these darker layers, one around $-1000$ m, and another, discontinuous, around $-2200$ m. The two layers would underlie and be separated by bright deposits. There could even be another of these layer included in the ‘ground’ unit, as some morphology on lower resolution images seems to be similar. Bright deposits are covering most of the escarpment, they look massive when the slope is steep, what is quite common, and alveolus otherwise. Elevations of the capping layer are not regular, but as it is exactly molding the topography, it seems to be more like a recent aeolian or ash deposit draping, rather than a part of the original ILD sequence.

Light-toned material has also been found far away from the ILD main mesa, in others places inside the canyon. On HiRISE images PSP_9446_1650_RED and PSP_7943_1640_RED they seem to overlap the canyon walls or the chaotic floor, as if they were just dumped on them.

5. Timing constraints

5.1. Stratigraphic relationship

3D representations of different locations in the canyon show that each mesa of the ILD was overlapping the chaotic floor (Fig. 10). The light-toned material of the ILD is always observed over chaotic mounds. Moreover, chaotic mounds have never been observed on the smooth and flat top of the ILD. There are no pressure lines around the ILD that would have indicated that they could have pierced the surface. The floor of the main craters north–east of Capri Chasma and in the floor of the canyon itself were analysed. No light-toned deposits in the floor or in their flanks, that could have indicated the presence of an old stratified layer, can be seen.

The walls of the canyon are entirely made of lava. All these observations imply that the ILD are subsequent to the chaotic floor, and were thus settled after the formation of the canyon itself (Komatsu et al., 1993; Flahaut et al., 2009a).

Other morphologies described previously can be dated relatively with each other. The line-streaks we did observed in the canyon were separating and eroding the different mounds of the ILD, they must have acted later. In the east, these linear features are covered with the debris aprons: the fans are thus younger. Fans in the western part of Capri Chasma are also crosscut by terraces, as well as the chaotic mounds: the event responsible for the formation of these terraces must therefore be the more recent one.

From the high resolution data, a chronology between the ILD different layers was built (Figs. 8 and 9). A major impact crater affects the ILD and shows stratified layers with a lower albedo (LC) under the light-toned deposits (LM or LA, depending on the slope). In one location, bright outcrops are covered with a dark blocky layer (DB) that must be more recent than the light-toned outcrops, but older than the capping layer that overlaps it. The whole outcrop is covered with this capping layer (CL), which is sometimes affected by dunes.

5.2. Crater counts

The absolute age of terrains at the surface of Mars can be evaluated with crater counts (Hartmann and Neukum, 2001). We aim at dating the current surface at a large scale, meaning the floor of the canyon and the erosion of the ILD as they are today. We cannot date the ILD themselves, as they have been modified since their formation, but we can constraint the end of their large scale erosion.

The density of craters in Capri Chasma was quantified at the scale of the Themis IR mosaic (200 m of spatial resolution). 111 Craters were measured. They were counted over the canyon floor and the ILD themselves. Crater diameters transferred onto a Hartmann graph date the current topography of the canyon from between 1 and 3 Gyr (Fig. 11). At this time ILD were already set and eroded into their current shape. However the distribution of the largest craters indicates intense resurfacing before this time.
Fig. 7. Stratification inside the light-toned outcrops at high resolution. (a)–(e) are close-ups on portions of the previous HiRISE images, coupled with interpretative schemes. Several layers can be distinguished between the layer deposits and have been classified (CL, DB, LE1, LE2, PB, LA, LM, LC, and GR).

Fig. 8. Stratigraphical columns summarizing the different layers observed according to their elevation and thickness, for the five HiRISE images described in Fig. 5 (from the west to the east), using the same coding as Fig. 7.
Craters between 8 and 32 km are missing. This intense resurfacing may indicate the outflow channel activity of this area.

6. Discussion

6.1. Geological history

The morphologies previously described can be interpreted as a succession of geological events.

First, outflow features that constitute the floor of the canyon must have formed early after its opening. It has been shown previously that they are the oldest morphology among all those observed. Similar outflow features have been concisely described in Aram Chaos by Glotch and Christensen (2005) and Massé et al. (2008). They could have formed by removal of material, either by (1) melting of ground ice, or by (2) discharge of magma by volcanism (Sharp, 1973). Dissolution of sub-surface rock materials (3) has also been proposed as a responsible mechanism but it is less likely. In each case, it appears that brief and intense sub-surface water floods, triggered by volcanism or not, are responsible for the formation of this ground pattern.

3D representations show that the ILD are overlapping this floor (Fig. 10). These deposits do not show any constrain marks and have not been found in the neighborhood craters or walls, thus they are

Fig. 9. (a) lower albedo stratified layer at the bottom of the major crater impacting the northern flank of the major mound of the ILD (CTX images T01_000901_1667_XN_13S047W, P03_002128_1667_XL_13S047W, P06_003473_1657_XN_14S047W and HiRISE images PSP 002128_1670 RED and PSP 008958_1665 RED). This layer is found at lower altitude than the light-toned deposits. The bold line is demarcating the boundary between these two layers. (b) Zoom on a portion of the CTX image T01_000901_1667_XN_13S047_W (6 m per pixel), the lower albedo layer is stratified and exhibits some little faults.

Fig. 10. 3D model of the southern mound of the ILD, built with MOLA data as base height of Themis IR data. ILD material is dark and smooth. The outlier in the middle is approximately 60–50 km and 2 km high. The white arrows indicate the locations where ILD material is overlapping chaotic mounds. No chaotic features are observed on the ILD top.
not likely to be an underlying layer. These sedimentary deposits have consequently filled the canyon during or after its formation.

Water releases are responsible for others features observed in Capri Chasma, as the long line-streaks observed on the floor of the canyon. They have been reported as flow features in outflow channel by Costard and Baker (2001). They are intersecting the ILD mounds, and must therefore be younger. They could have participated to their erosion. Nevertheless they show at low resolution (on Themis Visible images) small some craters on their top, what makes them older than the late Amazonian.

Debris flows are overlapping these flow features, implying that they are more recent. The presence of a channel on their center indicates that they must be alluvial fans, probably formed by the streaming of small amount of water as precipitation. The presence of sinuous joining channels cut into the wall near this fan strengthened this idea. However, the large alluvial fan, in the flank northwest of Capri (Fig. 4b) is fed by a valley, which may indicated that the amount of flowing water was more important there. Terraces in the flanks of the canyon have been reported as witnesses of multiple flooding events by Costard and Baker (2001). They can be linked here with the water releases of the chaotic floor formation or the one responsible for the line-streak marks, which are separated in time by the formation of the ILD. The history of Capri Chasma implies at least two distinct episodes of huge and repeated water releases during the Hesperian. The first one sets the chaotic ground; the second one formed the line-streak marks that are spreading to the east. These marks could correspond to the resurfacing processes that erased a part of the craters of the canyon.

Fig. 12 shows a summary of the previous considerations. Related to the chronology we built before, we can suggest a possible geological history for Capri Chasma.

The canyon could have open around 3.5 Gyr ago (age of the oldest craters), by tectonic processes. Indeed, normal faults and grabens have been reported in several places around Valles Marineris, such as in Coprates Catena, near Capri Chasma (Peulvast et al., 2001; Weitz et al., 2006). The floor of the canyon must have been quickly eroded by huge flooding, possibly originating from ice melting. The opening of the canyon could be contemporary to this first flooding episode. No volcanic features were observed in the area of Capri Chasma, and the topography has not been modified since 3 Gyr, meaning that this canyon may not have encounter any volcanism since its formation. The melting and expulsion of the ground ice would have triggered the collapse of the fractured terrains at the south–east of Capri.

The formation of outflow chaotic features has been followed by the setting of the Interior Layered Deposits. Their origin is still unknown, but considering the previous remarks, we consider that they are sedimentary deposits, aeolian, volcanic or aqueous, filling the void of the canyon. They would have formed a constant horizontal layer that has been eroded in mesas later. The only remnants that can be seen over the flanks of the canyon are fine patches of light-toned deposits south–west of the canyon (HiRISE image PSP_007943_1640_RED). The removal of some ILD by a new flooding episode is the next step in the canyon history. Repeated liquid water discharges could have drawn the linear-streaks and possibly the terraces at the embouchure of Capri. The material of the ILD must be relatively soluble or transportable compared to the chaotic mounds, which have not been eroded after this episode. These last flooding must have happened around 3 Gyr ago, during the Hesperian, giving the canyon its current topography. Since this period, only a few modifications at a very small scale have been made. Alluvial fans have recovered some of the wall of the canyon after this episode, implying small amount of liquid water, at least locally.

The ages found in the previous part are consistent with the opening of the Valles Marineris complex at the beginning of the Hesperian, and the age of the terrains of the northern hemisphere of Mars. If the previous history is accurate, this implies the action...
of important amount of liquid water in the area of Capri Chasma at least and probably in the whole Valles Marineris system, during the Hesperian. Big flooding episode would have happened at least at two different times in the history of Capri, separated by the formation of the ILD.

6.2. ILD formation

We noticed an internal stratification inside the ILD, and horizontal layering. A lower albedo layer lies underneath lighter deposits within the ILD. This layer is at a constant lower altitude than the light-toned deposits, except in the major impact crater remparts. This could be explained by the excavation of deep layers during the impact processing, that can reach a depth of 3 km for such a crater (Melosh, 1989). The summit of the light-toned deposits seems more erodible. All these observations may indicate an evolution or a change of conditions during their formation.

All the ILD are covered with the dark capping layer. It seems made of a fine unconsolidated material, which can easily be transported by wind, as it forms dunes, and blankets the light-toned deposits when the slope is more gentle, leading to the alveolus appearance. It lies uncomfortably above the ILD, it may thus be a recent draping, with an aeolian or an ash deposit origin.

This analysis of Capri Chasma’s ILD has not allowed us to come to a decision between the different formation hypotheses. Their origin remains uncertain. ILD could be non-aqueous aeolian or volcanic deposits (Peterson, 1981), lacustrine deposits (McCaulley, 1978; Nedell et al., 1987; Komatsu et al., 1993), erosional waste of the canyon walls (Lucchita et al., 1994), or subice volcanic structure (Chapman and Tanaka, 2001; Komatsu et al., 2004). All the ILD of Valles Marineris could also have multiple and different sources (Komatsu et al., 1993).

The recent information on their mineralogy, brought by the spectrometer OMEGA of the Mars Express mission, give priority to some of these hypothesis. While some authors have proposed that the ILD might contain carbonates (McKay and Nedell, 1988; Spencer and Fanale, 1990), OMEGA has detected mono- and polyhydrated sulfates in sufficient amount at their location, in particular in Capri Chasma. They do not appear to be a superficial layer, resulting of alteration, but they rather seem to form the bulk component of the mounds (Gendrin et al., 2005). These findings have been confirmed with the most recent CRISM observations, of the Mars Reconnaissance Orbiter mission (Roach et al., 2008, 2009; Bishop et al., 2009; Murchie et al., 2009). Both types, monohydrated and polyhydrated sulfates, have been detected in Capri Chasma, associated to different layers inside the ILD mounds (Flahaut et al., 2009a,b; Roach et al., 2008). These particular hydrated minerals can be the primary rock, or have been formed secondary by aqueous alteration. On Earth, sulfates formed primarily in small amount in volcanic or sub-aeolian environments. There are more substantial deposits in aqueous or sub-aqueous environment as lakes, where they formed as evaporitic sequences. If the sulfates are primary minerals in the ILD of Capri, considering their thickness, they should be inherited from this latest environment. The ILD would then be lacustrine deposits entirely made of these hydrated minerals.

If the sulfates have formed secondary, they would be the result of the alteration of the primary mounds by liquid water. To reach the whole mound, and form then the bulk component, an unfined groundwater rising repeatedly would be more efficient than precipitation. The ILD of Capri could then be aeolian or aqueous deposits transformed secondary.

However, previous considerations imply that liquid water was present in surface or sub-surface during the Hesperian, when the ILD were formed. In all cases, their formation has to be linked with the presence of water, especially in Capri Chasma, where liquid water has played a significant role in the history. Nevertheless, the current surface conditions on Mars are dry and cold, not allowing liquid water to be stable. Therefore, we argue that the climate at the time of the ILD formation must have been milder than today, allowing liquid water to endure, at least locally. Since the Viking missions, it has already been discussed that Mars should have been warmer earlier in the history of the planet. Lots of fluvial features have been reported in old terrains of Mars. Bibring et al. (2006) have detected hydrated minerals as phyllosilicates in these old areas. It has been estimated that the major climatic change would have occurred at the end of the Noachian. Even if the reasons for this climatic change are still unclear, it would have let Mars surface dry for 3.7 Gyr at least. The previous results partly disagree with these conclusions. Liquid water discharges have happened during the Hesperian, and the formation of the ILD implies the action of liquid water between 3.5 and 3.0 Gyr. The climate of the Hesperian must have been a transition between the ‘warm and wet’ and ‘cold and dry’ conditions, allowing liquid water to exist at least locally. We suggested here that the climate of the Hesperian was rather cold but maybe wet, mainly unstable, allowing liquid water to be stable in surface of sub-surface temporarily. This would be coherent with the formation of sulfates in the ILD at this time, as predicted by Bibring et al. (2006). Anyway, the formation of the ILD is closely linked with the question of liquid water on Mars, and consequently the climatic enigma. We showed in Capri Chasma that liquid water has been acting at least before and just after their formation. Comparison of the studies of the ILD of different canyons of Valles Marineris could help the understanding of these features.
7. Conclusion

Morphological analysis and crater counts allow us to build a plausible history for Capri Chasma. We showed that water discharges were frequent in this particular area of chaos and layered deposits at the beginning of its history. The canyon must have known at least two large episodes of flooding, separated by the formation of the Interior Layered Deposits during the Hesperian. The setting of the Interior Layered Deposits must have post-dated the canyon opening, but must be older than 3 Gyr, which is the maximum age range of the current topography.

These observations imply that liquid water was stable in surface during the Hesperian, at least temporarily. Climatic considerations have to be taken into account, as it implies that the Hesperian must have been wetter that today. The analysis of other areas of layered deposits on Mars should be done and compare with previous ones (Le Deit et al., 2008; Mangold et al., 2008; Bishop et al., 2009; Murchie et al., 2009) and bring hints about this current topic of debate. In particular, the analysis of new CRISM spectral data could provide a fine-scale mineralogy of the layer deposits, and especially of different units (Flahaut et al., 2009b).

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